Renewable energy generation technologies:

2- Solar energy (PV & Thermal energy):

The solar constant is the radiant flux density incident on a plane normal to the sun's rays at a distance of 1.49×10^8 km from the sun and is given by the area under the curve in Fig. 1.17. It has a value of

$$G_o^* = 1367 \text{ W/m}^2$$

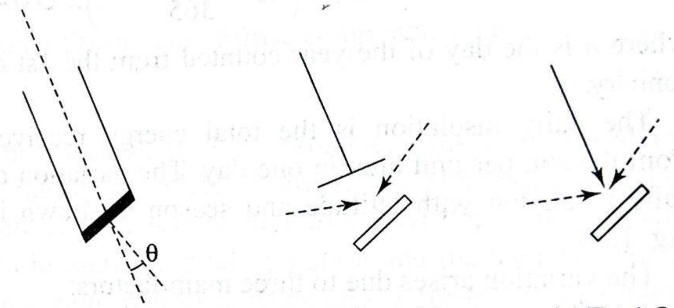
The received flux density varies by ±1.5% during the day's course due to variations in the sun's output, and by about ±4% over the year due to the earth's elliptic orbit. The solar spectrum can be divided into three main regions:

1. Ultraviolet region ($\lambda < 400$ μm) 9%;
2. Visible region (400 nm < λ < 700 nm) 45%; and
3. Infrared region (λ > 700 nm) 46%.

The radiation in the wavelengths above 2500 nm are negligible.

The earth's atmosphere absorbs various components of the radiation to different levels. The short wave UV and X-ray regions are almost completely absorbed by oxygen and nitrogen gases and ions; the ozone absorbs UV rays. The atmosphere unaffected by dust or clouds acts as an open window for the visible region. Up to 20% of the IR (Infrared) radiation is absorbed by the water vapour and CO_2. The carbon dioxide concentration in the atmosphere is about 0.03% by volume and is beginning to rise with pollutants being let off into the atmosphere. The water vapour concentration can vary greatly (up to 4% by volume). Dust, water droplets and other molecules scatter the sun's radiation.

The sun's radiation at the earth's surface is composed of two components: *beam radiation* and *diffuse radiation*. Beam or direct radiation consists of radiation along the line connecting the sun and the receiver as shown in Fig. 1.18(a). Diffuse radiation is the radiation scattered by the atmosphere without any unique direction as in Fig. 1.18(b). There is also a reflected component due to terrestrial surface. Total radiation is shown in Fig. 1.18(c).



(a) Beam component G_{bc} (b) Diffuse G_{dc} (c) Total G_{tc}

Fig. 1.18 *Components of solar radiation reaching earth*

It easily follows from these figures that [21]

$$G_{bc} = G_b^* \cos \theta \tag{1.7}$$

For a horizontal surface, the relation becomes

$$G_{bh} = G_b^* \cos \theta_z \tag{1.8}$$

Here, θ_z (called the Zenith angle) is the angle of incidence of beam component of solar radiation for a horizontal surface. θ is shown in Fig. 1.18(a). G_b^* is intensity of beam component of normally incident solar radiation on a surface. Adding the beam of the diffuse components, we get

$$G = G_{tc} = G_{bc} + G_{dc} \tag{1.9}$$

1.10.2 Variation of Insolation

Practically the earth is a sphere of radius 6400 km which rotates once in 24 h about its own axis. The axis defined by the North and South poles is shown in Fig. 1.19.

Any point P on the earth's surface is determined by its latitude ϕ and longitude ψ. The latitude is positive in the northern hemisphere, and negative in the southern hemisphere. The longitude is measured positive eastward from Greenwich, England. The vertical North-South plane through P is called *Local Meridional Plane*. Solar noon at P and all places of the same longitude is defined, when the sun is included in the meridional plane. However, clocks do not necessarily show solar time as they are set to civil time common

1.10.5 Applications of Solar Energy

Solar energy finds many applications, some of these being water heating, solar drying, desalination, industrial process heating and passive/active heating of buildings. However, because of the well known advantages of electrical power, the methods of converting solar radiation into electricity have attracted the greatest attention. There are two essential ways of converting solar energy into electricity.

1. *Solar thermomechanical systems:* Here, the solar radiation is used to heat a working fluid which runs turbines.
2. *Solar photovoltaics*: Solar photovoltaics (SPV) convert radiant energy directly into an electric current.

In both of these systems, collecting systems are used to receive the radiant energy. These are described below.

Flat-plate Collectors These are used in low efficiency photovoltaics and low medium temperature thermal systems. In thermomechanical system, the flat-plate collector acts as a heat exchanger; transferring the radiant energy to a working fluid. The advantages of flat-plate collectors over concentrators are as follows:

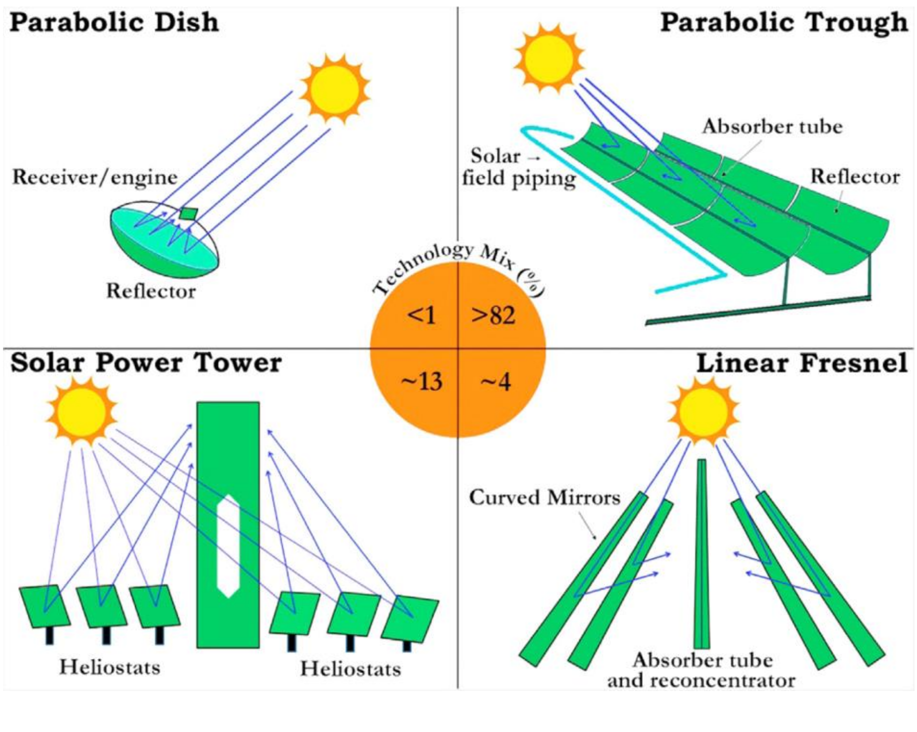
1. Absorb the diffuse, direct and reflected components of the radiation;
2. Comparatively easy to fabricate and is cheaper; and
3. Since these are usually fixed in tilt and orientation, tracking is not required—this makes them maintenance free, except for surface cleaning.

For a solar-thermal flat-plate collector the components are as follows:

1. A flat metallic plate painted black to absorb radiation;
2. Channels attached to the plate where a working fluid removes the thermal energy; and
3. Thermal insolation at the back and sides of the collector, and a glass cover to minimise thermal losses.

Flat-plate collectors are popular in water heating systems.

Concentrating Collectors They are used in high temperature solar thermal systems and some high efficiency photovoltaics. There are various methods of classifying solar concentrators. They may be classified as refracting or reflecting, imaging or non-imaging, and on the basis of the type of reflecting surface as parabolic, spherical or flat. High temperatures are obtained by using central tower receivers and *heliostats*.



1.10.6 Solar Thermomechanical Systems

In solar thermomechanical systems, solar energy is converted to thermal energy of a working fluid. This thermal energy gets converted into shaft work by a turbine which runs generators. Heat engines (turbine) are based on the Rankine cycle, Sterling cycle or the Brayton cycle. Usually a fossil fuel heat source is also present as standby.

A schematic flow diagram for a solar power plant operating on Rankine cycle is shown in Fig. 1.22. The maximum theoretical *thermal efficiency*, the ratio of useful work done to the heat supplied, is expressed for the Carnot cycle in terms of the temperature of the reservoirs with which it is exchanging heat.

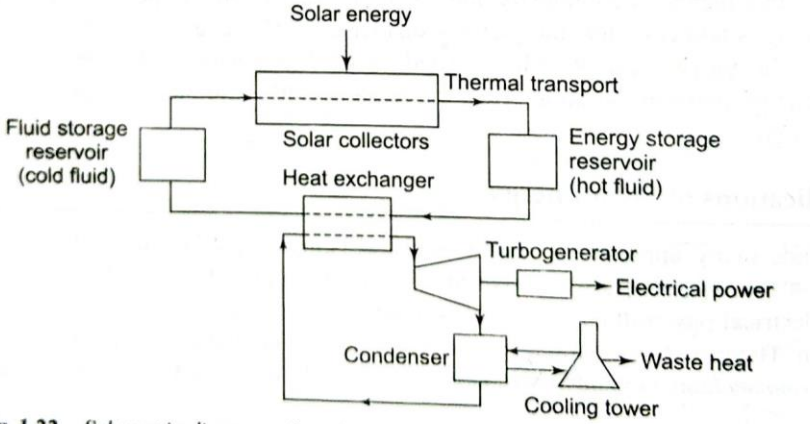


Fig. 1.22 *Schematic diagram of a solar power plant operating on the Rankine cycle*

$$\eta = 1 - \frac{T_L}{T_H} \quad (1.17)$$

where,

η = thermal efficiency of the Carnot cycle

T_L = absolute temperature (°C + 273) of the sink

T_H = absolute temperature of the source

For a solar energy system collecting heat at 121°C, the maximum thermal efficiency of any heat engine using this heat and rejecting heat to atmosphere at a low temperature of 10°C is

$$\eta = 1 - \frac{273 + 10}{273 + 121} = 0.282 \text{ or } 28.2\%$$

The efficiency of a real engine will be considerably less.

For obtaining efficiencies close to those of fossil fuel based stations, T_H must be raised to the same order of value. This is achieved by installing an array of mirrors, called heliostats, tracking the sun. One proposed scheme is shown in Fig. 1.23 for major generation of electricity with reflectors (with concentration factor of 30 or more) concentrating the sun's rays on to a single boiler for raising steam. A collector area of 1 km^2 would raise 100 MW of electrical power. The cost of such a scheme at present is prohibitive.

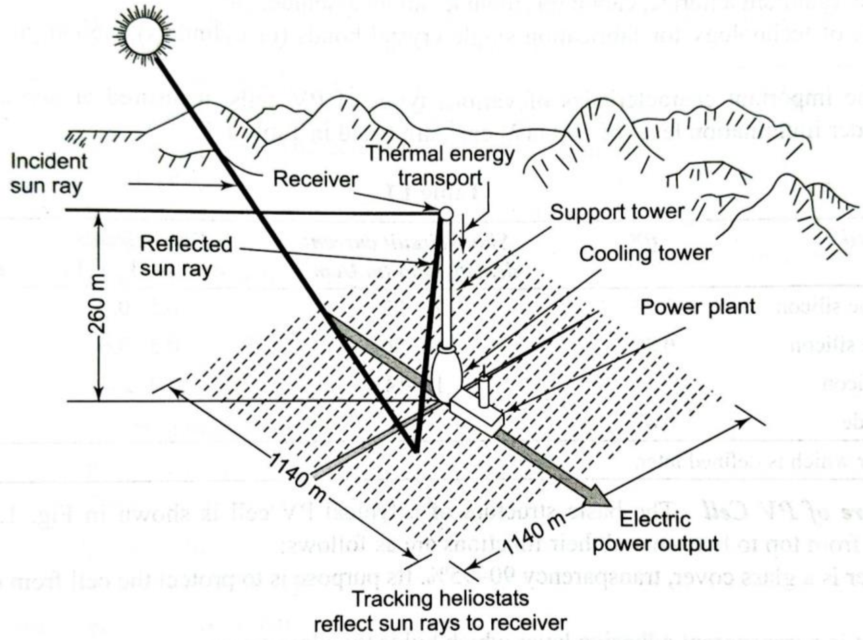


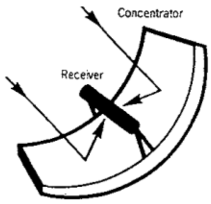
Fig. 1.23 *Proposed scheme for a large central solar-thermal electric generation*

A less attractive alternative to this scheme (because of the lower temperatures) is the use of many individual absorbers tracking the sun unidirectionally, the thermal energy being transferred by a fluid (water or liquid sodium) to a central boiler.

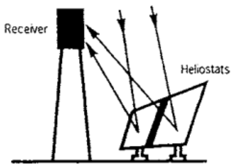
Solar-thermal electric systems have certain inherent disadvantages of a serious nature. These are as follows:

1. Low efficiency. Raising efficiency to acceptable value brings in prohibitive costs.
2. The efficiency of the collecting system decreases as its temperature increases, but the efficiency of the heat engine increases with temperature.
3. All solar-thermal schemes essentially require storage because of the fluctuating nature of the sun's energy, although it has been proposed that the schemes be used as pure fuel savers.
4. In general, mechanical systems need great maintenance.
5. For a reliable system, fossil fuel backup may be needed.

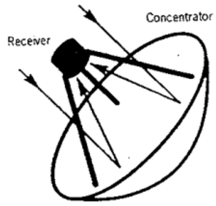
Because of these factors considerable research effort is being devoted to solar photovoltaics as a viable alternative.



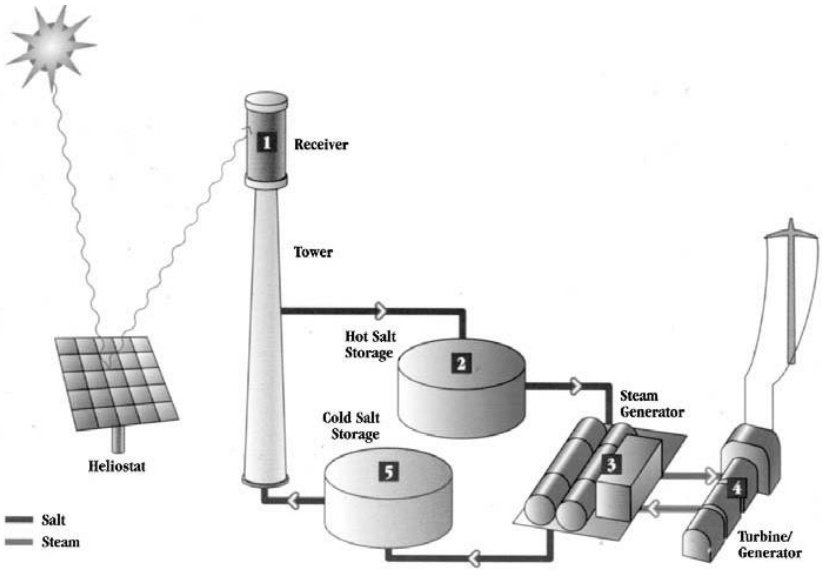
(a) Trough



(b) Central Receiver



(c) Dish



1 Generalities on photovoltaic (PV) plants

1.1 Operating principle

A photovoltaic (PV) plant transforms directly and instantaneously solar energy into electrical energy without using any fuels. As a matter of fact, the photovoltaic (PV) technology exploits the effect through which some semiconductors suitably "doped" generate electricity when exposed to solar radiation.

The main advantages of photovoltaic (PV) plants can be summarized as follows:
- distributed generation where needed;
- zero emission of polluting materials;
- saving of fossil fuels;
- reliability of the plants since they do not have moving parts (useful life usually over 20 years);
- reduced operating and maintenance costs;
- system modularity (to increase the plant power it is sufficient to raise the number of modules) according to the real requirements of users.

However, the initial cost for the development of a PV plant is quite high due to a market which has not reached its full maturity from a technical and economical point of view. Moreover, the generation of power is erratic due to the variability of the solar energy source.

The annual electrical power output of a PV plant depends on different factors. Among them:
- solar radiation incident on the installation site;
- inclination and orientation of the modules;
- presence or not of shading;
- technical performances of the plant components (mainly modules and inverters).

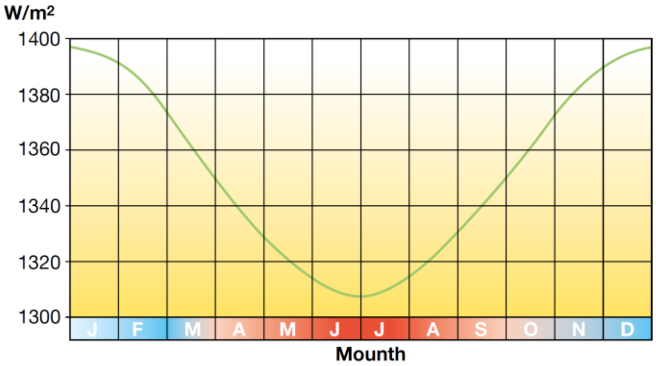
The main applications of PV plants are:
1. installations (with storage systems) for off-grid loads;
2. installations for users connected to the LV grid;
3. solar PV power plants, usually connected to the MV grid.

Feed-in Tariff incentives are granted only for the applications of type 2 and 3, in plants with rated power not lower than 1 kW.
A PV plant is essentially constituted by a generator (PV modules), by a supporting frame to mount the modules on the ground, on a building or on any building structure, by a system for power control and conditioning, by a possible energy storage system, by electrical switchboards and switchgear assemblies housing the switching and protection equipment and by connection cables.

1.2 Energy from the Sun

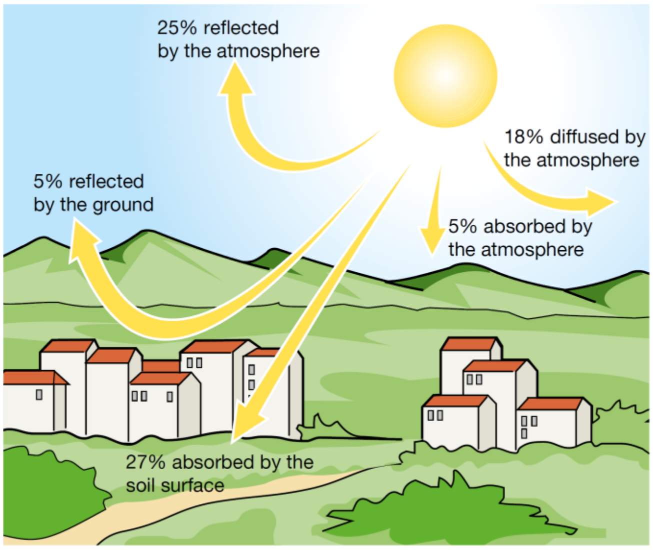
Thermonuclear fusion reactions occur unceasingly in the core of the Sun at millions of degrees; they release huge quantities of energy in the form of electromagnetic radiations. A part of this energy reaches the outer part of the Earth's atmosphere with an average irradiance (solar constant) of about 1,367 W/m^2 ± 3%, a value which varies as a function of the Earth-to-Sun distance (Figure 1.1) and of the solar activity (sunspots).

Figure 1.1 - Extra-atmospheric radiation



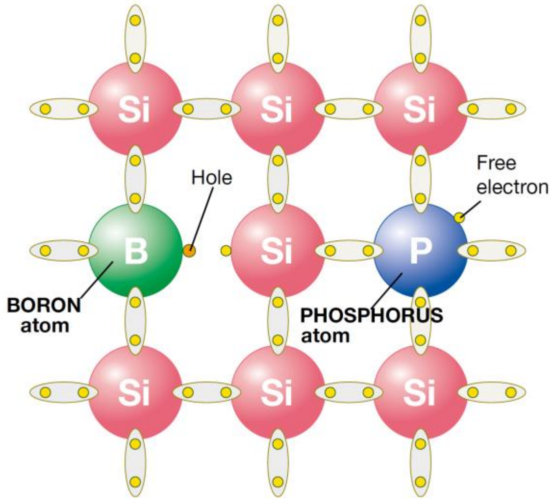
With ***solar irradiance*** we mean the intensity of the solar electromagnetic radiation incident on a surface of 1 square meter [kW/m^2]. Such intensity is equal to the integral of the power associated to each value of the frequency of the solar radiation spectrum.
When passing through the atmosphere, the solar radiation diminishes in intensity because it is partially reflected and absorbed (above all by the water vapor and by the other atmospheric gases). The radiation which passes through is partially diffused by the air and by the solid particles suspended in the air (Figure 1.2).

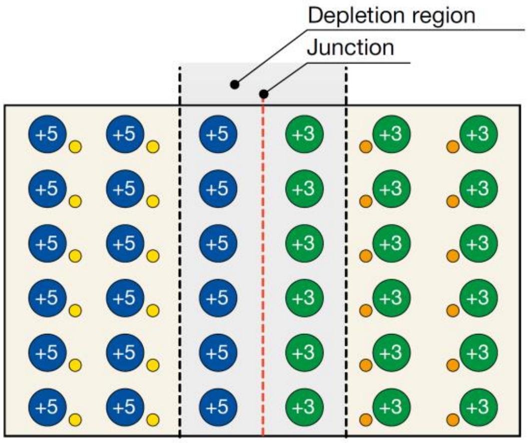
Figure 1.2 - Energy flow between the sun, the atmosphere and the ground



[1] *Due to its elliptical orbit the Earth is at its least distance from the Sun (perihelion) in December and January and at its greatest distance (aphelion) in June and July.*

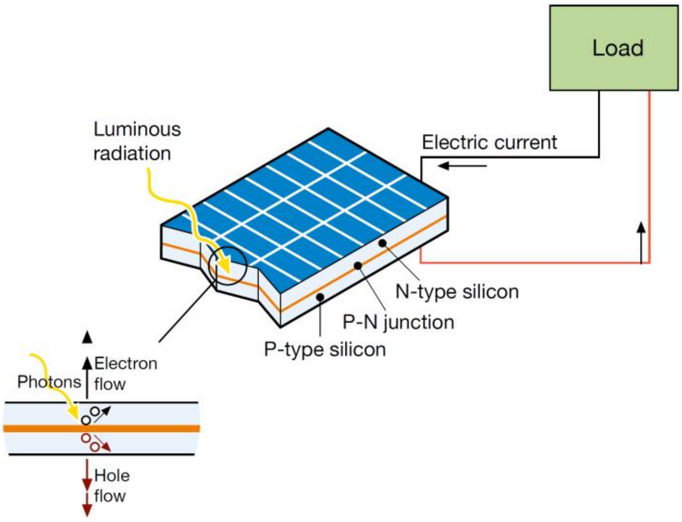
Doped silicon





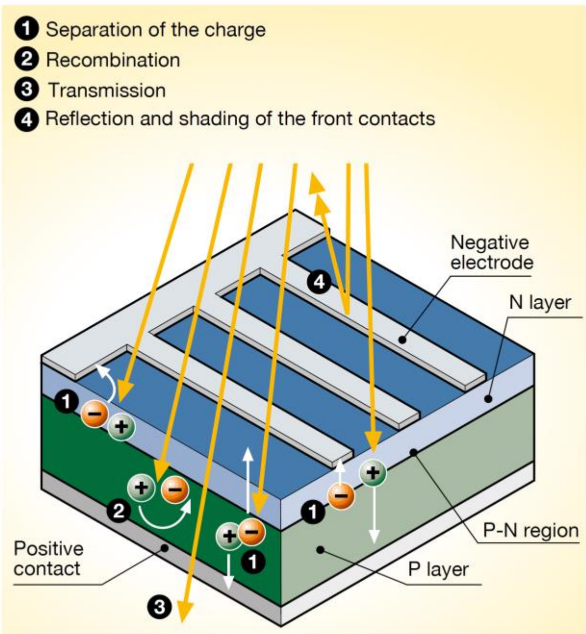
having lower potential, as long as the cell is illuminated (Figure 1.8).

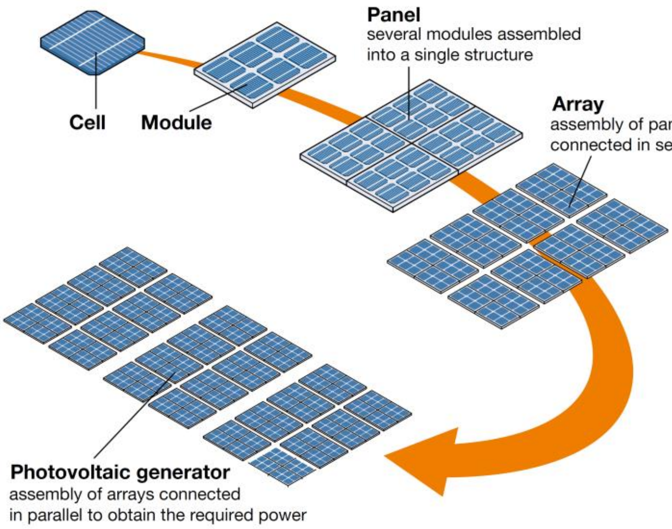
Figure 1.8 - How a photovoltaic cell works



[2] *The photovoltaic effect occurs when an electron in the valence band of a material (generally a semiconductor) is promoted to the conduction band due to the absorption of one sufficiently energetic photon (quantum of electromagnetic radiation) incident on the material. In fact, in the semiconductor materials, as for insulating materials, the valence electrons cannot move freely, but comparing semiconductor materials with insulating materials the energy gap between the valence band and the conduction band (typical of conducting materials) is small, so that the electrons can easily move to the conduction band when they receive enough energy from the outside. Such energy can be supplied by the luminous radiation, hence the photovoltaic effect.*

Figure 1.9 - Photovoltaic effect





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1.10.7 Direct Conversion of Sunlight into Electricity

Introduction Photovoltaic (PV) or solar cell is a semiconductor device that converts sunlight directly into electricity. Initially PV cells had very limited use, e.g., in supplying electricity to satellites in space or for meeting energy requirements of defence personnel stationed at remote areas. However, with a gradual reduction in the cost of PV cells, current international price is now between 5–10$ per peak-watt and its use has been increasing steadily. It is projected that by the year 2015 or so, its share in power generation may be around 10–15%.

A PV cell can be classified–

1. in terms of materials: noncrystalline silicon, polycrystalline silicon, amorphous silicon, gallium arsenide, cadmium telluride, cadmium sulphide, idium arsenide, etc.
2. in terms of technology for fabrication single crystal bonds (or cylinders), ribbon growth, thin-film, etc.

Some of the important characteristics of various types of PV cells, measured at normal temperature (25°C) and under illumination level of 100 mW/cm^2, are listed in Table 1.1.

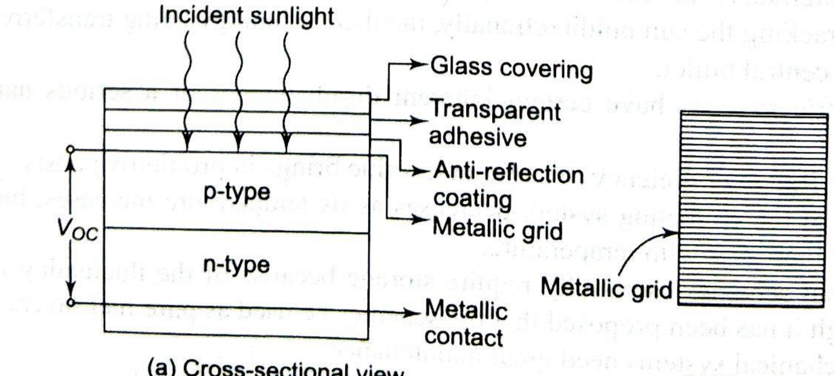
Table 1.1

PV cell	*ff**	*Short-circuit current density (Isc) (mA/cm^2)*	*Open-circuit voltage (V_{oc}) (V)*	*Conversion efficiency (%)*
Monocrystalline silicon	0.85	20–22	0.5–0.6	13–14
Polycrystalline silicon	0.85	18–20	0.5–0.6	9–12
Amorphous silicon		13–14	2.2–2.4	5–6
Gallium arsenide	0.87	–	–	20–25

* *ff* is fill-factor which is defined later.

Basic Structure of PV Cell The basic structure of a typical PV cell is shown in Fig. 1.24(a) and (b). Various layers from top to bottom and their functions are as follows:

1. Top layer is a glass cover, transparency 90–95%. Its purpose is to protect the cell from dust, moisture, etc.
2. The next is a transparent adhesive layer which holds the glass cover.
3. Underneath the adhesive is an antireflection coating (ARC) to reduce the reflected sunlight to below 5%.



(a) Cross-sectional view

(b) Top view

4. Then follows a metallic grid (aluminium or silver) (Fig. 1.24(b)) which collects the charge carriers, generated by the cell under incidence of sunlight, for circulating to outside load.
5. Under the lower side of the metallic grid lies a p-layer followed by n-layer forming a pn-junction at their interface. The thickness of the top p-layer is so chosen that enough photons cross the junction to reach the lower n-layer.
6. Then follows another metallic grid in contact with the lower n-layer. This forms the second terminal of the cell.

Operation and Circuit Model The incidence of photons (sunlight) causes the generation of electron-hole pairs in both p and n-layers. Photons generated minority carriers (electrons in p-layer and holes in n-layer) freely cross the junction. This increases the minority carrier flow manyfolds. Its major component is the light generated current I_G (when load is connected across the cell terminals). There is also the thermally generated small reverse saturation current I_s (minority carrier flow in same direction as I_G), also called *dark current* as it flows even in absence of light. I_G flows in opposite direction to I_D, the forward diode current of the junction. The cell feeds current I_L to load with a terminal voltage V.

The above operation suggests the circuit model of a PV cell as drawn in Fig. 1.25. The following Eq. (1.19) can be written from the circuit model and the well-known expression for

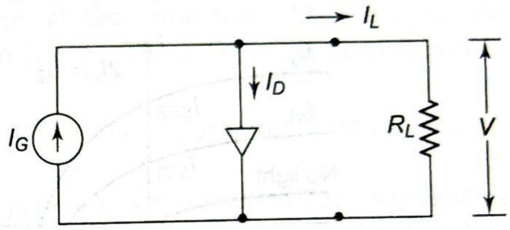


Fig. 1.25 *Circuit model of PV cell*

$$I_D = I_s\,(e^{\lambda V} - 1);\ \lambda = \frac{e}{kT} \tag{1.18}$$

where,

k = Boltzmann constant,

e = electronic charge and

T = cell temperature in degree K.

Load current $\quad I_L = I_G - I_D$

$$= I_G - I_s\,(e^{\lambda V} - 1) \tag{1.19}$$

From this equation, it easily follows that

$$V_{OC}\,(I_L = 0) = \frac{1}{\lambda}\ \ln\left(\frac{I_G}{I_s} + 1\right) \tag{1.20}$$

and $\quad I_{SC}\,(V = 0) = I_G \quad$ (1.21)

Solar radiation generated current I_G is dependent on the intensity of light. The I–V characteristics of the cell are drawn in Fig. 1.26(a) for various values of intensity of solar radiation. One typical I–V characteristic of the cell is drawn in Fig. 1.26(b). Each point on this curve belongs to a particular power output. The point Q indicated on the curve pertains to the maximum power output at which the cell should be operated. At this point,

$$P_{max} = V_{Pmax}\, I_{Pmax} \tag{1.22}$$

The *fill-factor* (ff) of a cell is defined as

$$ff = \frac{P_{max}}{I_{SC} V_{SC}} \tag{1.23}$$

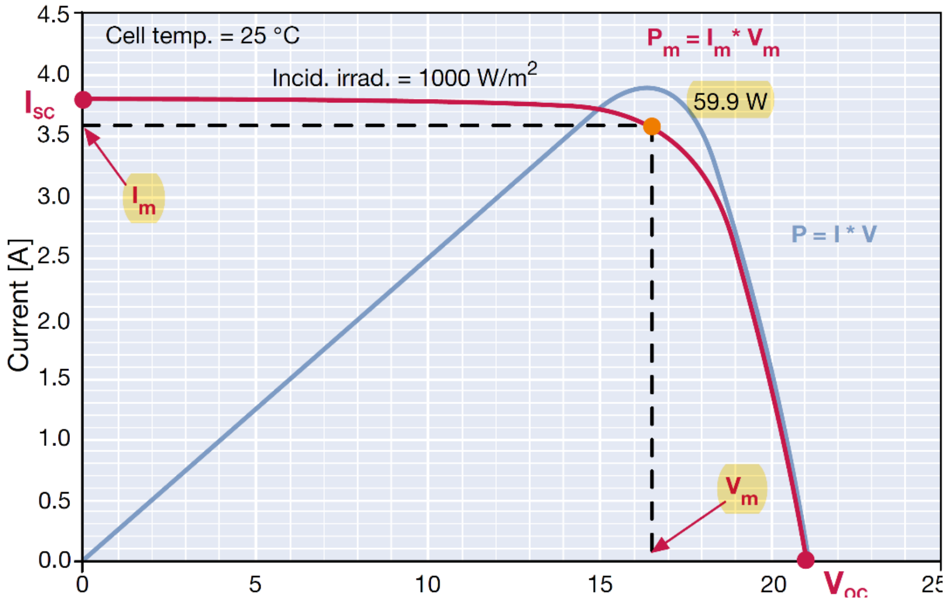
The major factors influencing the electrical design of the solar array are as follows:

- the sun intensity.
- the sun angle.
- the load matching for maximum power.
- the operating temperature.

2.2 Voltage-current characteristic of the module

The voltage-current characteristic curve of a PV module is shown in Figure 2.2. Under shortcircuit conditions the generated current is at the highest (I_{sc}), whereas, with the circuit open, the voltage (V_{oc}=open circuit voltage) is at the highest.
Under the two above mentioned conditions, the electric power produced in the cell is null, whereas under all the other conditions, when the voltage increases, the produced power rises too: at first it reaches the maximum power point (Pm) and then it falls suddenly near to the open circuit voltage value.

Figure 2.2



Then, the characteristic data of a PV module can be summarized as follows:

- I_{sc} short-circuit current;
- V_{oc} open circuit voltage;
- P_m maximum produced power under standard conditions (STC);
- I_m current produced at the maximum power point;
- V_m voltage at the maximum power point;
- FF filling factor: it is a parameter which determines the form of the characteristic curve V-I and it is the ratio between the maximum power and the product ($V_{oc} \cdot I_{sc}$) of the no-load voltage multiplied by the short-circuit current.

The cell efficiency is given as

$$\eta = \frac{P_{out}}{P_{in}} \tag{1.24}$$

where P_{out} is the power delivered to load and P_{in} is the solar power incident on the cell.

Effect of Temperature on Solar Cell Efficiency As the temperature increases, the diffusion of electrons and holes in the length of Si (or GaAs) increases causing an increase in the dark current and a decrease in V_{OC}. The overall effect causes a reduction in the efficiency of solar cell as the temperature increases. The practical efficiency of Si solar cell is about 12% and that of GaAs solar cell is 25% at the normal temperature of 300 K. With each degree rise in temperature, the efficiency decreases by a factor of 0.0042%.

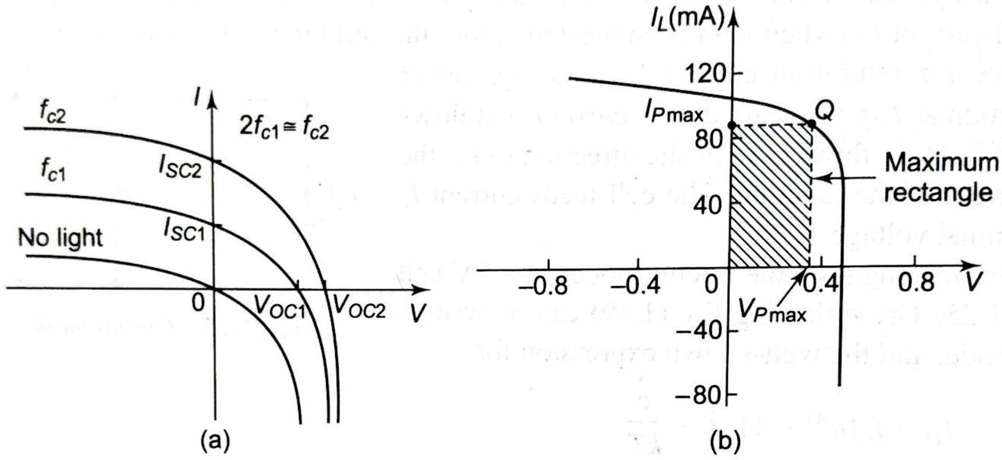


Fig. 1.26 *I–V (current–voltage) characteristics of a PV cell*

Spectral Response It is seen from the spectral response curves of Fig. 1.27 that the Selenium cell response curve nearly matches that of the eye. Because of this fact Se cell has a widespread application in photographic equipments such as exposure meters and automatic exposure diaphragm. Silicon response also overlaps the visible spectrum but has its peak at the 0.8 μm (8000 Å) wavelength, which is in the infrared region. In general, silicon has a higher conversion efficiency and greater stability and is less subject to fatigue. It is therefore widely used for present day commercial solar cells.

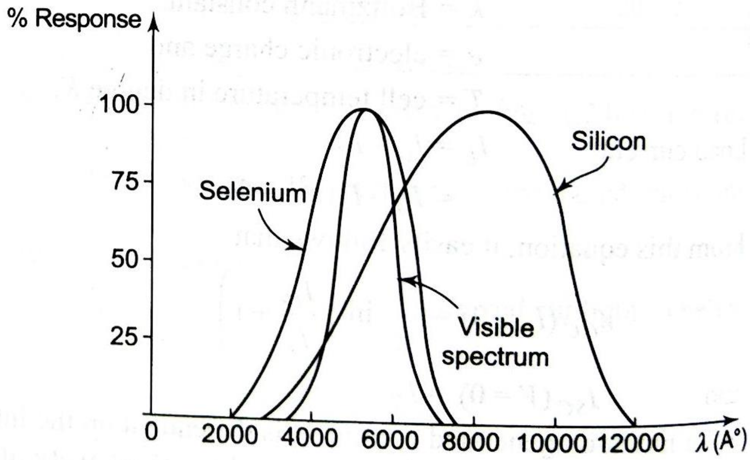


Fig. 1.27 *Spectral response of Si, Se and the naked eye*

1.10.8 Prevalent Technologies for Fabricating Silicon PV Cell

The most commonly used methods of manufacturing silicon PV cell from purified silicon feedstock are as follows:

1. Single crystal silicon with a uniform chemical structure.
2. Polycrystalline silicon-series of crystalline structures within a PV cell.
3. Amorphous silicon with a random atomic chemical structure.

Figure 1.16 – Monocrystalline silicon module

Figure 1.17 – Polycrystalline silicon module

Comparison:

- Panels made from ***polycrystalline cells*** are the most common and cheapest. Their conversion efficiency **9% to 12%** (sunlight to electricity). However, under elevated temperatures of 50° C panel temperature, the efficiency drops by around 20%.

- Panels made from ***monocrystalline cells*** are used in high reliability applications such as telecommunications and remote power. Their conversion efficiency is typically **13-14%** (higher than the polycrystalline cells). However, at elevated temp, the efficiency only drops by 10-15% so they are more consistent in output.

- Panels made from ***amorphous cells*** have been used in portable items for many years. Their conversion efficiency of sunlight to electricity is **5-6%**, about half that of the other panels but unlike the other types, their output does not decrease in elevated temperatures.

- Panels made **thin *film cell CIGS technology*** are flexible, durable, and provide slightly higher efficiency than other flexible solar cells. Typical sizes less than 60W.They can be mounted to curved surfaces and any backpack, tents or jackets.