Topic 4: Solar Photovoltaic System

Introduction

Photovoltaic (PV) system is a method of generating electrical power by converting solar radiation into direct electricity with the help of semiconductors that exhibit the photovoltaic effect. The photovoltaic power generation employs solar panels constructed of a number of solar cells made-up of a photovoltaic material. Owing to the growing demand for renewable energy sources, the technology of manufacturing of solar cells and photovoltaic arrays has improved considerably in recent times. Driven by advances in technology and increase in production of solar cells, the cost of solar cells has declined considerably. The cost of electricity from photovoltaic is currently competitive with what is produced by conventional methods.

Learning Outcomes of Topic 4

Upon completion of this study unit, you should be able to:

1. discuss the principle of the photovoltaic effect
2. describe solar cell, module, panel and array
3. discuss solar cell characteristics
4. explain the materials for solar cells
5. classify solar PV systems

Solar Photovoltaic System

4.1 INTRODUCTION

Photovoltaic (PV) system is a method of generating electrical power by converting solar radiation into direct electricity with the help of semiconductors that exhibit the photovoltaic effect. The photovoltaic power generation employs solar panels constructed of a number of solar cells made-up of a photovoltaic material. Owing to the growing demand for renewable energy sources, the technology of manufacturing of solar cells and photovoltaic arrays has improved considerably in recent times. Driven by advances in technology and increase in production of solar cells, the cost of solar cells has declined considerably. The cost of electricity from photovoltaic is currently competitive with what is produced by conventional methods.

4.2.2 Photovoltaic Effect

- **What do you understand by photovoltaic effect?**

or

- **What is the principle of solar photovoltaic?**

Photovoltaic effect is a process in which two dissimilar materials in close contact produce an electrical charge when struck by light or any other radiant energy. When light strikes crystals such as silicon or germanium (*p-n* junction) in which electrons are usually not free to move from *n*-region to *p*-region due to the potential barrier, the light provides the energy (e.m.f.) needed to free some electrons from the bound condition depending on the absorption of solar energy (Figure 4.6). Free electrons cross the junction between two dissimilar crystals more easily in one direction than in the other, giving one side of the junction a negative charge, and this results in a negative voltage with respect to the other side, as in the case of a battery in which one electrode has negative voltage with respect to the other. The photovoltaic effect can continue to provide voltage and current as long as light falls on the junction of two materials.

- **What is solar power?**

Solar power is the production of electricity directly from sunlight. The solar photovoltaic (PV) power is produced using photovoltaic effect so that when sunlight strikes a solar voltaic cell, it releases electrons from the *p-n* junction of the cell and pushes these electrons across a potential barrier or electric field at the junction. These electrons then travel through an external circuit to return to their usual state and in this process create electric power.

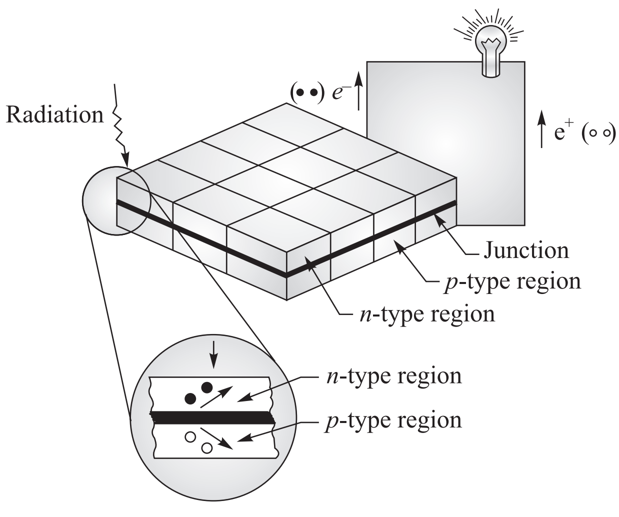

Figure 4.6 Generation of "emf" across junction to move the charge carriers.

The photovoltaic effect is the basic physical process through which a PV or solar cell converts sunlight into electricity. Sunlight is composed of energy packets called photons.

These photons contain different amounts of energy that correspond to different wavelengths of the solar spectrum. When photons strike a PV cell, they may be reflected, absorbed or can pass through the *p-n* junction. The absorbed photons in the *p-n* junction generate electricity.

A solar cell is essentially a *p-n* junction with a large surface area. The *n*-type material is kept thin to allow light to pass through it and strike the *p-n* junction. The light travels in packets of energy called photons. The generation of electric current takes place inside the depletion zone of the *p-n* junction. The depletion zone as explained previously is the area around the *p-n* junction where the electrons from the *n*-region diffuse into the holes of the *p*-region. When a photon of light is absorbed by one of these atems in *n*-region of silicon, it will dislodge an electron from any atom, thereby creating a free electron and hole pair. The free electron and hole pair has sufficient energy to jump out of the depletion zone. If a wire is connected from the cathode at *n*-type silicon to an anode of *p*-type silicon, electrons flow through the wire. The electron is attracted to the positive charge of *p*-type material and travels through the external load (bulb or resistance), thereby creating a flow of electric current. The hole created by the dislodged electron is attracted to the negative charge of the *n*-type material and travels to "back electrical contact". As the electron reaches the *p*-type silicon from the "back electrical contact", it combines with the hole, thereby restoring the electrical neutrality (Figure 4.7).

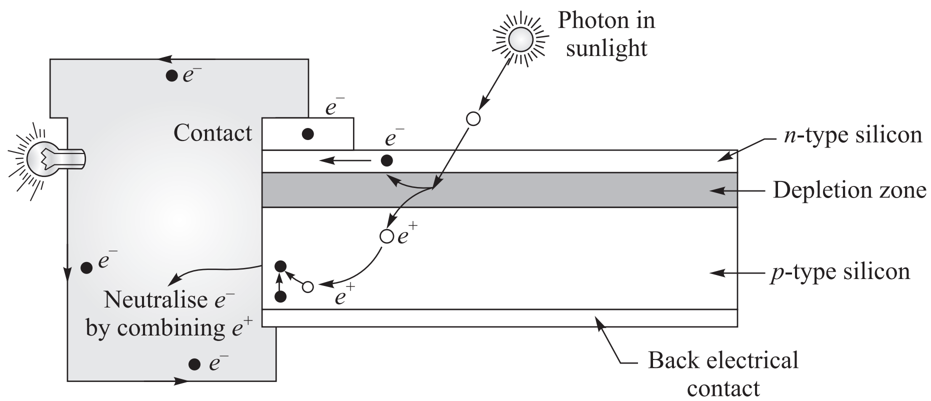

Figure 4.7 Photon generating pairs of electron and hole to move electric current in the external circuit.

4.3 SOLAR CELL, MODULE, PANEL AND ARRAY

4.3.1 Solar Cell

- **Explain the construction of a solar cell.**

The solar cell consists of (i) *p*-type silicon material layer, (ii) *n*-type silicon material layer, (iii) front metallic grid and (iv) opaque back metal contact as shown in Figure 4.8.

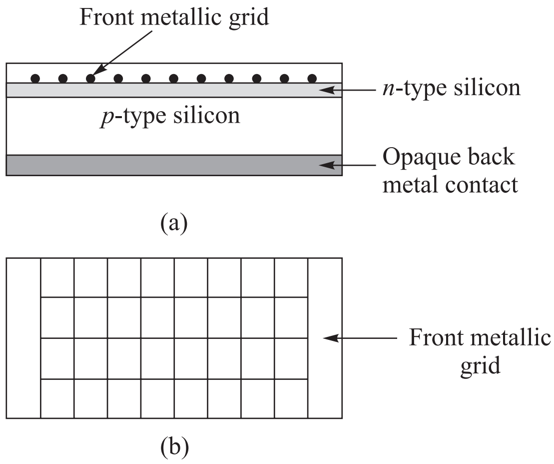

Figure 4.8 Construction of a solar cell. (a) Side view of the solar cell. (b) Top view of the solar cell.

The bulk material consists of *p*-type silicon having thickness about 100–350 μm. A thin layer of *n*-type silicon having thickness of about 2 μm is diffused on this bulk material, providing *p*-*n* junction. A metallic grid at top with *n*-type material and an opaque back metal contact at the bottom of *p*-type material are provided which also act as negative and positive terminals.

4.3.2 Solar PV Module

- **What is a solar PV module?**

A single solar cell cannot be used as such as it has (i) a very small output and (ii) no protection against dust, moisture, mechanical impacts and atmospheric harsh conditions. Suitable voltage and adequate power can be obtained by suitably interconnecting a number of solar cells. This assembly of solar cells is called solar module. Solar cells are provided with transparent cover and these are hermetically sealed for assembly into solar module. A solar module has generally 32–36 solar cells connected in series to charge a 12 V battery. It is necessary that all solar cells should match as closely as possible with each other so that peak power of the module is the algebraic sum of the peak power of individual solar cells. A typical module is shown in Figure 4.9.

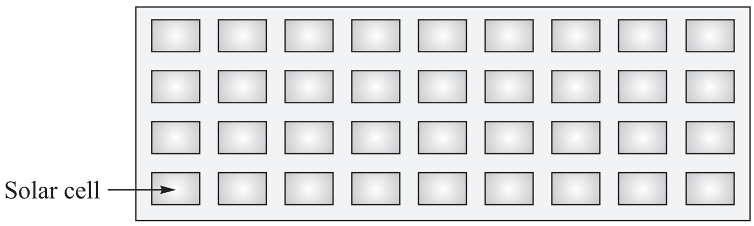

Figure 4.9 Solar PV module with 36 solar cells.

4.3.3 Solar PV Panel

• **Describe the construction of a solar PV panel.**

Solar PV panel consists of a number of solar PV modules connected in series and parallel to obtain the power of desired voltage and current. When modules are connected in series, it is desirable that each module should produce maximum power at the same current. When solar PV modules are connected in parallel, it is desirable that each module should produce maximum power at the same voltage. A frame is used to mount several modules to form a solar PV panel as shown in Figure 4.10.

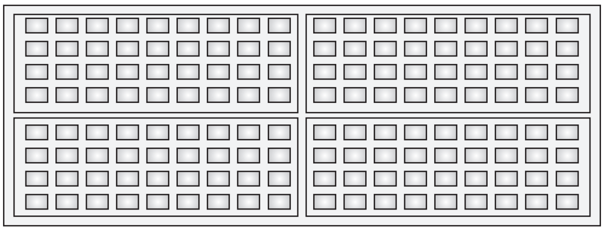

Figure 4.10 A solar PV panel of four modules.

In the panel, bypass diodes are installed across each module so that any defective module can be bypassed by the output of remaining modules. The blocking diodes are connected in series with each series string of modules which enable the output of the remaining series strings should not be absorbed by the failed string. A typical panel with the series and the parallel connections is shown in Figure 4.11.

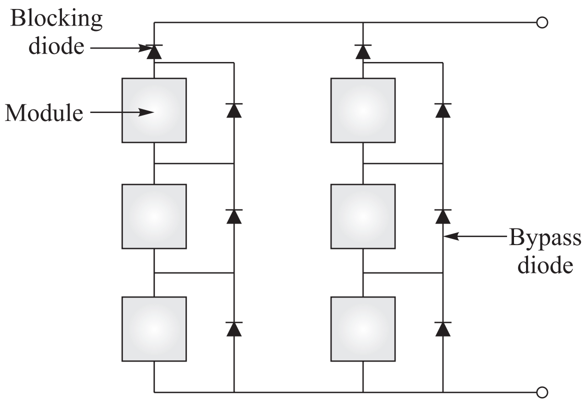

Figure 4.11 A typical panel with the series and the parallel connection.

4.3.4 Solar PV Array

• **What do you understand by a solar PV array?**

A PV array consists of a number of solar panels which are installed in an array field. The solar panels may be installed as stationary facing the sun or installed with some tracking mechanism. The installation should ensure that no panel should cast shadow on any of the neighbouring panels and those panels can be easily maintained.

4.4 SOLAR CELL CHARACTERISTICS

- **How does the *p-n* junction act as a diode, thereby facilitating flow of current when it is forward biased?**

In case the *p-n* junction is forward biased, electrons from *p*-region start moving towards the positive terminal of the battery, thereby reducing the potential barrier at the junction (Figure 4.12). This facilitates the flow of current through the *p-n* junction. In case the junction is reversed biased, the potential barrier at the junction increases, which further reduces the possibility of any flow of current through the junction. The Current–Voltage (*I*–*V*) characteristic of a *p-n* junction is shown in Figure 4.13.

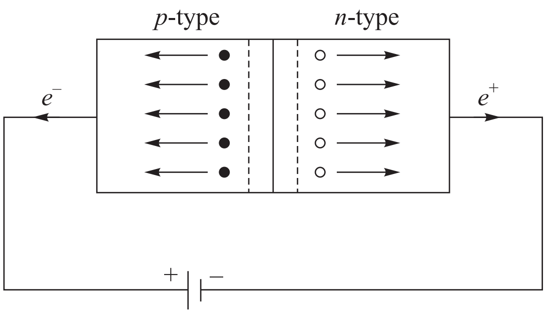

Figure 4.12 The *p-n* junction forward biased.

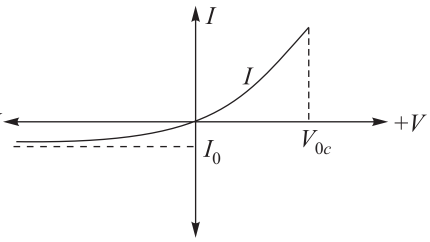

Figure 4.13 Current–Voltage characteristic of *p-n* junction when forward and backward biased.

As the voltage (*V*) increases, the current (*I*) in the junction also increases. However, there is a very small reverse saturation current (I_0) instead of zero current when reversed voltage is applied. The flow of current can be given by diode current equation (Schottky equation):

$$I = I_0\ [e^{V/V_T} - 1]$$

where I_0 is the reverse saturation current and V_T is the voltage equivalent of temperature and it is given by

$$V_T = \frac{kI}{q}$$

Here, k is the Boltzmann constant,
T is the temperature in kelvin and
q is the charge of an electron.

4.4.1 Voltage–Current Characteristic of *p-n* Junction (Solar Cell)

- **Explain the current–voltage characteristics of a solar cell and define fill factor. What is the significance of the fill factor?**

or

- **Explain how the variation of isolation (incident solar radiation) and temperature affects the current–voltage characteristics of a solar cell.**

The current-voltage characteristics of a *p-n* junction (solar cell) gets modified due to photon or solar generated current (I_{sc}) flowing through the *p-n* junction as this (I_{sc}) is added with the reverse leakage current (I_0). The diode current equation is now modified as

$$I = -I_{sc} + I_0\,[e^{V/V_T} - 1]$$

and $$I = -I_{sc}$$

when $V = 0$; that is junction is short circuited.

Also, when $$I = 0,\ I_{sc} = I_0\,[e^{V/V_T} - 1]$$

or $$V = V_{sc} = V_T \log\left(\frac{I_{sc}}{I_0} + 1\right)$$

where V_{sc} is the open circuit voltage.

The above relation shows that when junction is radiated with sun's ray and it is short circuited at its terminals, there is a finite current called short circuit current (I_{sc}) that flows through the external circuit made with the short circuiting of the junction terminals. The magnitude of I_{sc} depends upon solar radiation. Figure 4.14 shows current–voltage characteristics at different isolations which include (i) dark, (ii) lesser amount of radiation, and (iii) larger amount of radiation. Hence, *p-n* junction can be considered an energy source or e.m.f having open circuit voltage as V_{oc} and short circuit current as I_{sc}.

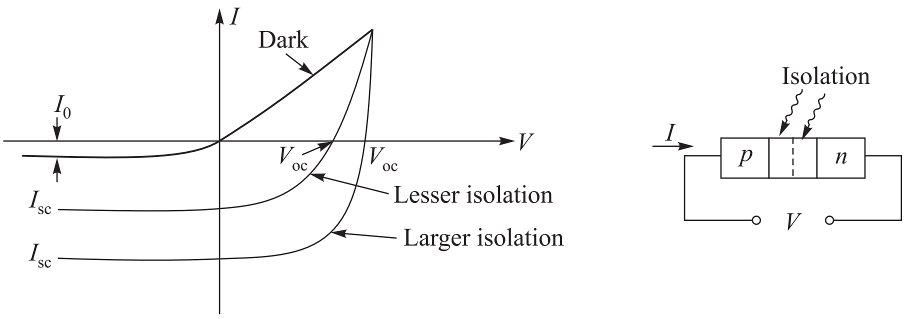

Figure 4.14 Current–voltage characteristics at different isolation levels.

In case we use standard convention in which current flowing out from a positive terminal of any energy source is always taken as positive and apply the same convention on a solar cell, the current and voltage characteristic can be redrawn with suitable modification as shown in Figure 4.15, and mathematically the current–voltage relationship can be written as follows:

$$I = I_{sc} - I_0 \times [e^{V/V_T} - 1]$$

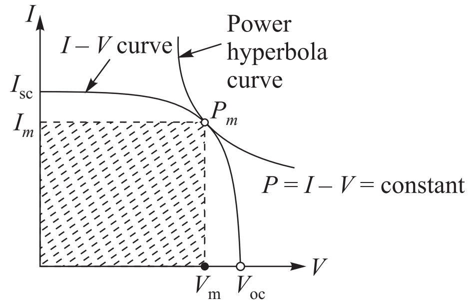

Figure 4.15 Current–voltage characteristics of solar cell and maximum power point (P_m).

The output power from solar cell is the product of voltage and current ($P = I \times V$). It is desirable to operate the solar cell to produce maximum power. The power is product of voltage and current and power curve is hyperbola. In case hyperbola ($P = I \times V$) of power is drawn on *I–V* characteristic curve, the hyperbola of power curve is tangential to *I–V* characteristic at the point of maximum power as shown by point P_m in Figure 4.15. The voltage and current corresponding to P_m are V_m and I_m respectively. Hence, there is only one point on the voltage–current characteristic curve of *p-n* junction at which the *p-n* junction produces maximum power for a given isolation or illumination level. In case we operate the *p-n* junction at any other point on *I–V* characteristic curve, power produced will be lesser than the maximum power, resulting in certain amount of solar radiation energy being wasted out as thermal power. The maximum power output can be determined when the value of the product of voltage and current is maximum. The product of voltage and current has the greatest value when the rectangle having sides equal to these voltage and current, as well as incribed within the characteristic curve, has the largest area. The rectangle having the largest area with sides V_m and I_m and depicting maximum solar power output (shown with hatched lines) is shown in Figure 4.15.

Fill factor (FF)

The maximum power output from a solar cell is possible when the output power from rectangle can fill up or utilise as much area as possible of the characteristic curve. The fill factor indicates the quality of solar cell, that is, how much power or area of the characteristic curve is being used. In ideal case, the fill factor should be unity when the complete area between the characteristic curve and axes has been utilised that is, the product of V_{oc} and I_{sc}.

The fill factor is defined as the ratio of peak power to the product of V_{oc} and I_{sc}.

Hence,

$$FF = \frac{V_m \times I_m}{V_{oc} \times I_{sc}}$$

The typical value of fill factor is in the range of 0.5–0.83. The fill factor can be improved by the following ways:

(i) Increasing the photocurrent and decreasing the reverse saturation current of a solar cell.
(ii) Minimising the internal series resistance
(iii) Maximising the shunt resistance.

Solar efficiency

It is the ratio of maximum possible solar cell power output $V_m \times I_m$ which is converted to the solar energy supplied to the cell.

$$\text{Efficiency} = \frac{V_m \times I_m}{\text{Solar power}}$$

Fill factor is given by the following equation:

$$FF = \frac{V_m \times I_m}{V_{oc} \times I_{sc}}$$

Hence, efficiency can also be given as

$$\eta = \frac{V_m \times I_m}{\text{Solar power}}$$

$$= \frac{FF \times V_{oc} \times I_{sc}}{\text{Solar power}}$$

4.4.2 Energy Losses of Solar Cell

- **Explain various factors contributing to losses in solar cell. How is the efficiency reduced due to these factors?**

or

- **What are the parameters limiting the performance of a cell?**

The highest conversion efficiency of a solar cell is about 24%. There are many factors which lead to energy losses and limit the conversion efficiency of the cell. The factors are as follow:

Reflection losses

Some of the incident radiation is lost due to reflection from the cell surface.

Incomplete absorption

The cell should be made of a material which can absorb the energy associated with the photons of solar radiation. The energy of a photon is related to its wavelength (λ) by the following relation:

$$E = \frac{h \times c}{\lambda}$$

where

h = Planck's constant (= 3×10^{-27} ergs)

c = Velocity of light (= 3×10^{8} m/s)

If we put these values in the equation we get energy as

$$E = \frac{1.24}{\lambda}$$

The materials suitable for absorbing the energy of photons of sunlight are silicon, cadmium sulphide and gallium arsenide. The difference between conduction and valence band is called band gap energy. Hence, photons having energy (E) larger than band gap energy (1.1 eV for silicon) will be absorbed in the cell material and will excite some of the electrons, thereby creating electron–hole pairs. Other photons of lower energy are wasted in generation of thermal energy. The higher is the band gap of the material, the greater is the wastage.

Partial utilisation of photon energy

Many photons in solar radiation generate electron and hole pairs which have more energy than that is needed for proper functioning of *p-n* junction, that is making the current flow through external circuit. The excess energy is dissipated as heat. The higher is the energy gap, the smaller is the wastage. The semiconductors with the energy gap of 0.9–1.1 eV would be best suited and thickness required to absorb is about 300 μm.

Collection losses

The electron–hole pair carriers formed due to solar radiation must be collected so as to contribute to the output current instead of recombining to generate heat. The collection efficiency is the ratio of the actual short circuit current density to the short circuit current density which would be obtainable when no recombining takes place. The collection efficiency depends upon (i) the absorption characteristics of semiconductors which determine the generation of electron and hole pairs (ii) the junction depth, (iii) the width of depletion layer, (iv) the recombining rate of electrons and holes, (v) the distance which carriers have to move for recombining, (vi) the thickness of *p* and *n* regions and (vii) the existence and strength of any built-in electric field which help to accelerate carriers.

Open circuit voltage

The open circuit voltage is always less than the band gap energy due to lower level of illumination and doping of semiconductor which lowers the potential difference at *p-n* junction.

The increase in barrier potential increases V_{oc} but reduces I_{sc}. There is an optimum value of V_{oc} and I_{sc} for generation of the maximum power output.

Curve factor

The maximum power output is always less than the product of V_{oc} and I_{sc}. The characteristic curve does not have a rectangular shape. Hence, the area of the characteristic curve is always less than the product of V_{oc} and I_{sc}.

Series resistance losses

The voltage and current characteristic curves are flattened due to power loss resulting from series resistance. The output power decreases as the area under the characteristic curve reduces.

Thickness of cell

Photons of high energy can pass through the cell material without any absorption if thickness is inadequate. *A* reflecting back ohmic contact is generally provided to enhance the absorption of high-energy photons.

4.4.3 Maximising the Performance

- **How can the performance of a solar cell be maximised?**

The performance of a solar cell can be increased by taking the following steps:

(i) **Maximising V_{oc} and I_{sc}.** The efficiency of solar energy conversion depends upon V_{oc} and I_{sc} same time I_{sc} depends upon photocurrent and V_{oc} depends upon the ratio of I_{sc} to I_0.

(ii) **Low series resistance.** It will give high fill factor, that is more output power possible as the area of characteristic curve increases. Reduction of resistance requires high doping of semiconductor.

(iii) **High shunt resistance.** Shunt resistance can be increased by preventing any leakage occurring at the perimeter of the cell. This is achieved by passivating the surface of the solar cell.

(iv) **Optimum solar cell size.** As the area of solar cell increases, it becomes difficult to maintain homogeneity of the material in solar cell and performance of the cell reduces.

- **Calculate the range of wavelength of solar radiation capable of creating electron–hole pair in silicon having energy gap of 1.12 eV.**

$$E = \frac{hc}{\lambda} = \frac{1.24}{\lambda} \quad \text{or} \quad \lambda = \frac{1.24}{E} = \frac{1.24}{1.12} = 1.11\ \mu\text{m}$$

- **Considering solar radiation of 200 J/m^2 and per unit time during daylight, find the area of PV cells needed to generate enough electric power to run**
  - **(i) a desktop computer using 400 W,**
  - **(ii) an electric geyser using 1 kW and**
  - **(iii) a toaster using 500 W.**

  Assume the efficiency of *PV* to be 25%

The photovoltaic cell power output is given by following equation:

$$\eta = \frac{\text{Power output}}{\text{Solar power}} = 0.25$$

$$\therefore \quad \text{Power output} = 0.25 \times 200 = 50 \text{ W}$$

Case 1: Desk type computer

$$\text{Power of appliance required} = 400 \text{ W}$$

$$\text{Area of PV cells} = \frac{400}{50} = 8 \text{ m}^2$$

Case 2: Electric geyser

$$\text{Power required} = 1000 \text{ W}$$

$$\text{Area of cells} = \frac{1000}{50} = 20 \text{ m}^2$$

Case 3: Toaster

$$\text{Power required} = 500 \text{ W}$$

$$\text{Area required} = \frac{500}{50} = 10 \text{ m}^2.$$

$$\text{Total load} = 400 + 1000 + 500 = 1900 \text{ W}$$

$$\text{Total area} = 8 + 20 + 10 = 38 \text{ m}^2$$

4.5 MATERIALS FOR SOLAR CELLS

- **What are different materials used for fabrication of solar cells?**

or

- **Explain the main features of different types of solar cells on the basis of materials used in fabrication.**

or

- **What are the steps involved in formation of silicon cells?**

or

- **What do you understand by thin film solar cells?**

The solar cells depending on the type of material used can be classified as single crystal silicon solar cell, polycrystalline and amorphous silicon cell, cadmium sulphide-cadmium telluride cell, copper indium diselenide cell and gallium arsenide cell.

Single crystal silicon

It is produced from silicon dioxide which is reduced to silica with 1% impurities. It is first purified to polycrystalline form and then further converted into the single crystal state. The conversion process into single crystal state is very expensive. The single crystal *p*-type silicon is obtained in the form of a long cylindrical block (diameter of about 6–15 cm). The block is sawed using diamond cutter to obtain a number of silicon slices or wafers having thickness of about 300 μm. The *p*-type silicon wafers are then exposed to phosphorous vapour (doping material) in a furnace so that phosphorous can diffuse into the silicon wafer for a short depth, thereby forming *n*-silicon region over the *p*-silicon bulk material. The efficiency of single crystal silicon is about 22%. It is most efficient and robust. It has two main drawbacks:

(i) it needs high energy to produce and hence is costly and
(ii) it requires high intensity of radiation to produce solar electricity.

Polycrystalline and amorphous silicon

The cells made of these materials are cost-effective but these have lower efficiency compared to a single crystal silicon cell. The process to produce polycrystalline silicon cells is similar to that of single crystal silicon except that the costly step of converting polycrystalline state to the single crystal is not required. The polycrystalline silicon is directly melted, doped with phosphorous and cooked to the desired shape and size. This helps in economy of materials and energy consumption for the production of cells.

Amorphous silicon cells are produced using thin film technology. These cells are a cheaper alternative to single crystal or multicrystallinc cells. The main drawbacks are that they have low efficiency (4–8%) and they degrade easily when used in outdoor applications. These cells are useful for indoor lights, pocket calculator, electronic watches and electronic instruments.

Cadmium sulphide–cadmium telluride cells

These cells are also produced using thin film technology. The cells require very less material. In thin film technology, the semiconductor (cadmium telluride) is vapourised and its film (10 μm) is deposited on a thin layer (12 μm) of cadmium sulphide. A barrier layer of copper sulphide is then deposited on top of the CdS–CdTe cell. The cell consists of *n*-type CdS and *p*-type CdTe. The cell has efficiency of 10% and it has no deterioration during outside applications.

Copper indium diselenide

It is a thin film polycrystalline cell made from copper indium diselenide. It has an efficiency of about 14%. Its properties remain stable. It has an easier manufacturing process.

Gallium arsenide

The cell has thin film of *n*-type and *p*-type gallium arsenide (GaAs) grown on a suitable substrate. The efficiency of the cell is about 20%, but it has high cost of production. The cell has high performance in extraterrestrial applications.

4.6 SOLAR PV SYSTEMS

- **How can solar PV systems be classified?**

  or
- **With the help of block diagrams, explain the operations of stand-alone and grid interactive solar PV systems.**

The classification of solar PV systems is shown in Figure 4.16

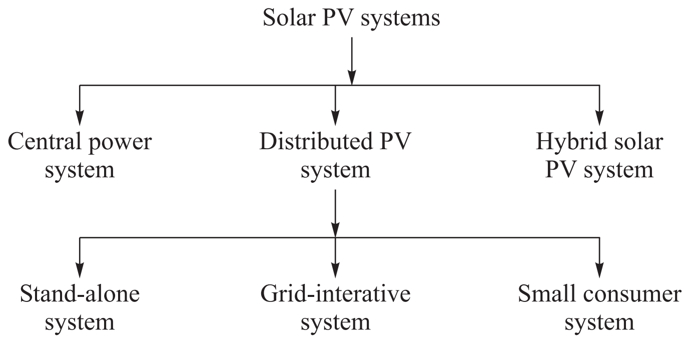

Figure 4.16 Classification of solar PV systems.

4.6.1 Central Power Station System

- **Explain central power station system.**

This type of solar power station is similar to other conventional power stations which are required to feed generated power into some national grid. This type of solar power stations are designed to meet high peak daytime load only and these have large generation capacity in megawatt (up to 6 MW). Only few such power stations have been installed worldwide as the capital cost of these plants is high.

4.6.2 Stand-Alone System

- **Write briefly about stand-alone system.**

Solar PV power station is planned and located at the load centre. Its complete electricity generation is meant to meet the electrical load of any remote area, village or installation. Energy storage is essential to meet the requirement during non-sunshine hours. A typical stand-alone solar PV system is shown in Figure 4.17. The maximum power point tracker (MPPT) senses the voltage and current outputs from the solar array and then suitably adjusts the operating point to obtain maximum power output from the solar array as possible from the climatic conditions. The solar electric output in direct current is converted into alternating current and it is fed into the load. The excess power is preferably stored by charging the battery and otherwise excess is dumped in the electric heaters. When the sun radiation is unavailable, the batteries supply the electricity through the converter.

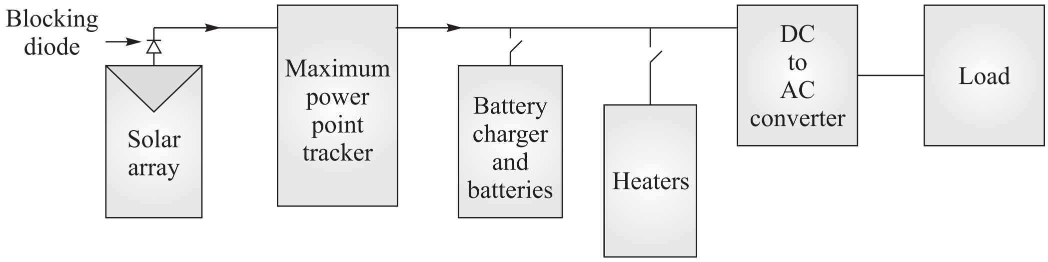

Figure 4.17 A schematic layout of a stand-alone solar PV system.

4.6.3 Grid Interactive Solar PV System

- **Write briefly about grid interactive solar PV system.**

In grid interactive solar PV system, the system first meets the requirement of house, village or installation and then all excess power is fed to an electric grid during sunshine hours (Figure 4.18). This arrangement helps in preventing any dumping of electricity as required in the stand-alone solar PV system. The second advantage of this system is that during absence of insufficient sunshine, the supply of electricity is maintained from the electric grid, thereby eliminating any need of battery. This system is very popular in the United Kingdom, where two-way electric meters provided to record (i) the electricity generated and supplied by rooftop PV system of various houses to the electric grid system during non-peak sunshine hours and (ii) electricity supplied to the houses from the electric grid during non-sunshine hours. The difference of two is paid to consumers or vice versa.

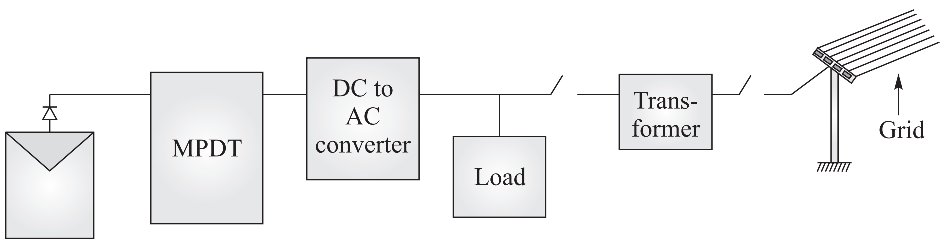

Figure 4.18 Grid interactive solar PV system.

4.6.4 Small Consumer Systems

- **Write briefly about small consumer systems.**

These systems are designed to meet the power requirement of low energy devices which are generally used for indoor applications, such calculators, watches and electric devices.

4.6.5 Hybrid Solar PV System

- **What do you understand by hybrid solar PV system?**

The hybrid solar PV system is designed to provide electric power by some other means besides solar electricity. It is difficult and uneconomical to provide all of the power from only solar PV system. It may be more economical to meet the power requirement by some other means, such as windmills, fuel cells and diesel or petrol generators. The best hybrid solar PV system is the one in which no amount of solar PV generated power is wasted.

4.6.6 Advantages and Disadvantages of PV System

- **What are the advantages and disadvantages of PV system over conventional power system?**

Advantages are as follows:

(i) It directly converts solar energy to electric power without any use of moving parts.
(ii) It is more reliable, durable and maintenance free.
(iii) It works without any noise.
(iv) It is non-polluting.
(v) It has long lifespan.
(vi) It can be located near the point of load and requires no distribution system.

Disadvantages are as follows:

(i) It has high cost of installation.
(ii) It has low efficiency.
(iii) It requires a large area for installation to produce sufficient power.
(iv) Its output is intermittent, thereby requiring some means to store energy to use during non-sunshine hours.

4.6.7 Solar PV System and Cost

- **Write down your comments on cost reduction of solar cells.**

There is gradual reduction in the cost of solar PV system due to (i) development of new improved techniques to produce solar cells and (ii) increase in the production volume. Cost reduction has been achieved by innovative manufacturing techniques used in thin film solar cells. These techniques have speeded up manufacturing process, reduced material wastage and helped to produce large size cells. Cost reduction has also been effected by the development of thin film devices, thereby requiring much less quantity of materials and less costly materials. The use of solar concentrators to focus the sun's rays in solar PV system has also helped in the cost reduction. The cost of solar power generation is reduced from the earlier cost of several thousand dollars per peak watt to the present cost of about one dollar per watt.

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