CHAPTER THREE
Solar Photovoltaic System

3.1 Introduction

Photovoltaic power generation is a method of producing electricity, using solar cells. **A solar cell** is a device that /converts solar optical energy (solar radiation) directly into electrical energy. It is essentially a semiconductor device fabricated in a manner which generates a voltage when solar radiation falls on it.

3.2 Semiconductor Materials and Doping

A few semiconductor materials such as silicon (Si), cadmium sulphide, (CdS) and gallium arsenide (GaAs) can be used to fabricate solar cells. **Semiconductors** are divided into two categories: intrinsic (pure) and extrinsic, An intrinsic semiconductor has negligible conductivity, which is of little use. To increase the conductivity of an intrinsic semiconductor, a controlled quantity of selected impurity atoms is added to it to obtain an extrinsic semiconductor. The process of adding the impurity atoms is called **doping**.

a pure semiconductor, electrons can stay in, one of the two energy bands the conduction band and the valence band, The conduction band has electrons at a higher energy level and is not fully occupied, while the valence band possesses electrons at a lower-energy level but is fully occupied (Figure 3-1). The energy level of the electrons differs between the two bands and this difference is called the **band gap energy**.

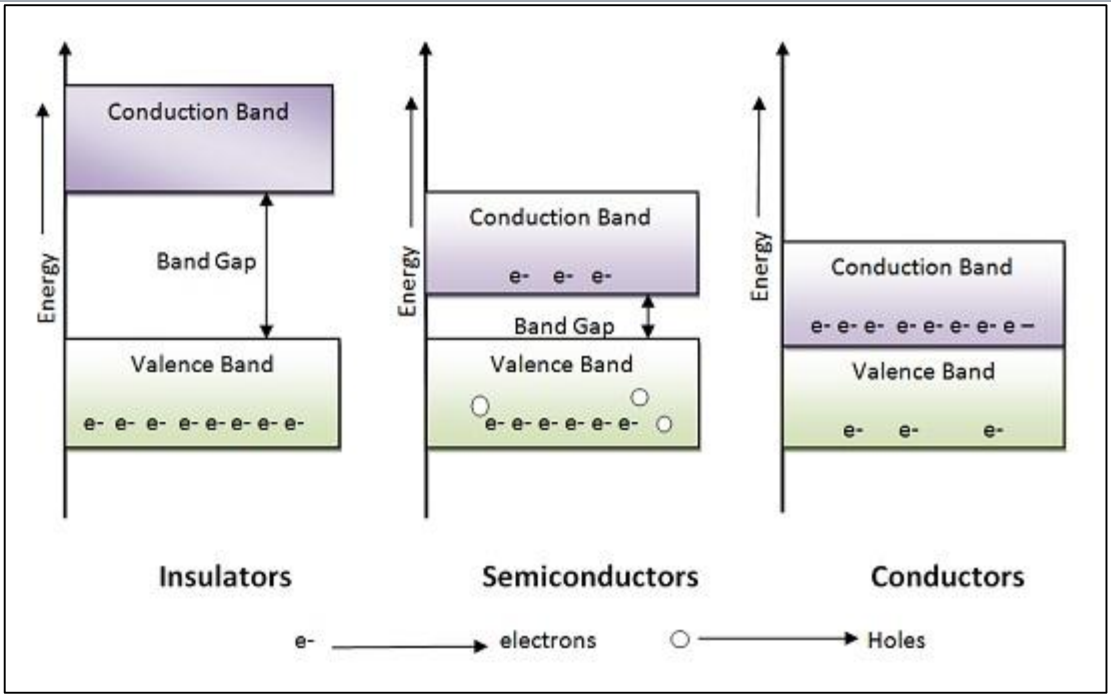


Figure (3-1): Energy bands in materials

The **Fermi energy level**, E_f, is the energy position which exists at the mid-point of the energy gap for an intrinsic semiconductor (see figure 3-2a)

A semiconductor when doped by a donor impurity (phosphorus, arsenic, antimony) increases electrons in the conduction band and become **n-type material**. When a semiconductor is doped by an acceptor impurity (boron, gallium, indium) it becomes the **p-type material** with excess holes. Both n and p-type doped semiconductors (called **extrinsic semiconductors**) have higher electrical conductivity than the pure (intrinsic) material.

Fermi energy level moves closer to E_c (i.e., increases) in n-type semiconductors (see figure 3-2(b)) where E_d represents the level of electrons from donor impurities ; similarly in a p-type semiconductor the Fermi level will lie close to E_v (see figure 3-2(c)) where E_a represents the level of excess holes provided by acceptor impurities.

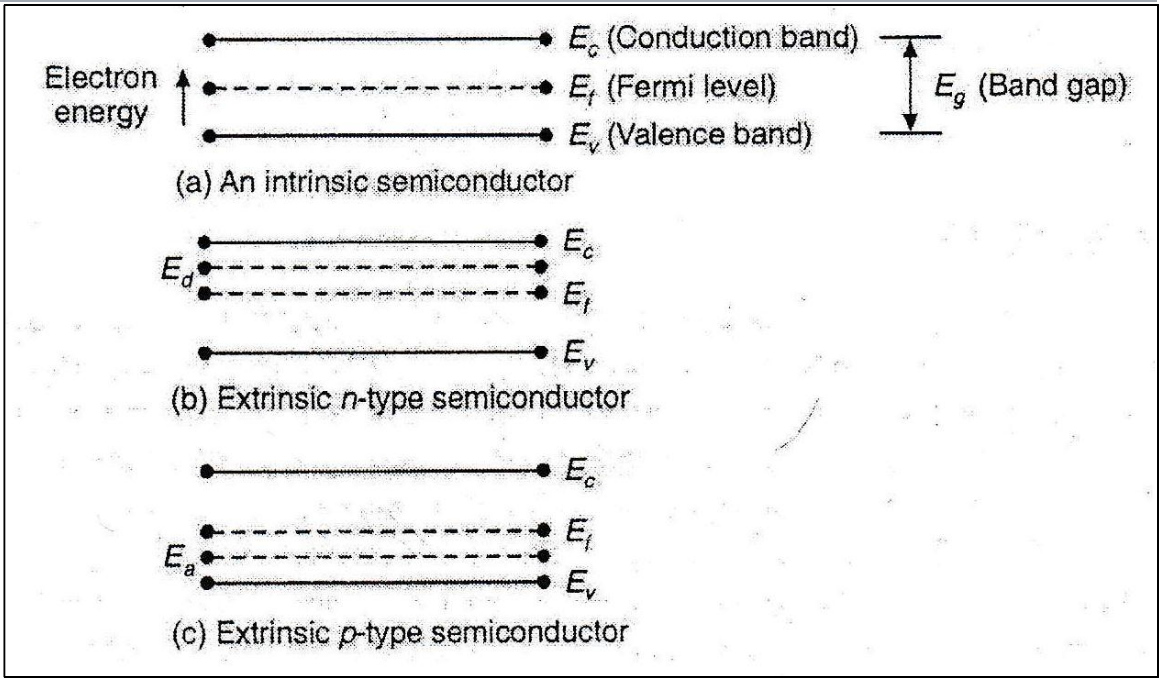


Figure (3-2): Diagram of energy levels in semiconductors

3.3 P-N Junction

When n-type and p-type materials joined, a junction is formed as detailed in figure 3.3. The number of elections in the n-type material is large; so when an n-type material is brought into contact with a p-type material, electrons on the n-side flow into holes of the p-material. Thus, in the vicinity of the junction, the n-material becomes positively charged and the p-material negatively charged. The process of diffusion of carriers continues till the junction potential reaches an equilibrium value at the time of equal flow of electrons and holes from both directions. This is known as the unbiased condition of the p-n junction. In this condition, V is the contact potential (i.e., not an externally imposed potential) developed between the p-n junction. The contact potential so developed is a property of the junction itself.

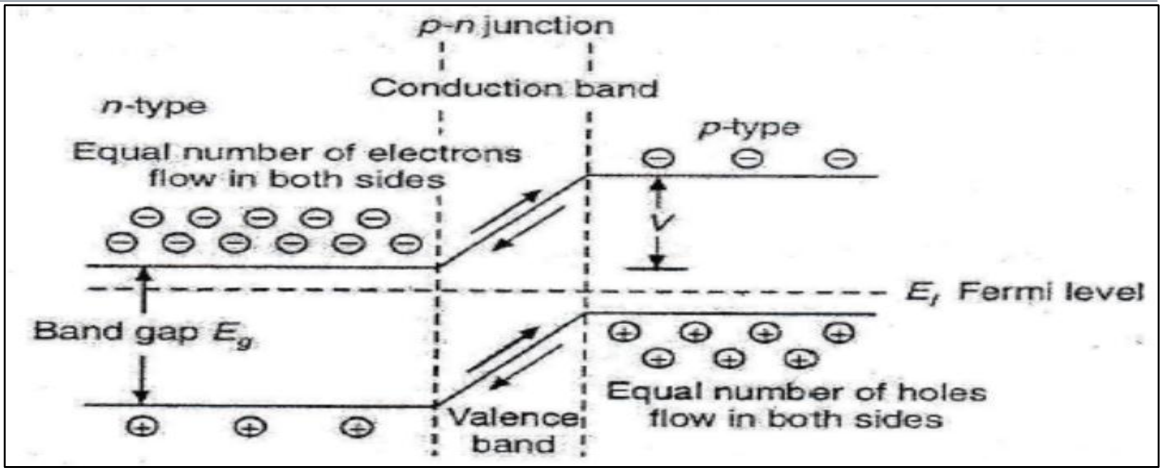


Figure (3-4): A p-n junction

When there is no illumination (dark) the flow of junction current I_j with imposed voltage V in a p-n junction is expressed by:

$$I_j = I_0\left[\exp\left(\frac{eV}{kT}\right)-1\right] \qquad (3\text{-}1)$$

Where I_o is the saturation current (also called the dark current) under and e is the electronic charge, and the other variables carry usual meanings.

3.4 Photon Energy

Sunlight is composed of tiny energy capsules called photons. The number of photons present in solar radiation depend upon the intensity of solar radiation and their energy content on the wavelength band. The solar spectrum constitutes three main regions which are Ultraviolet region, Visible region and Infrared region. The distribution of extraterrestrial solar energy (1367 W/m^2) in three different wavelength ranges (UV, Visible, and IR) is given in Table 3-1.

Table (3-1): Distribution of extraterrestrial solar energy (1367 w/m^2) in three different wavelength ranges

	UV	Visible	IR
Wavelength range (µm)	0–0.38	0.38–0.78	0.78 → ∞
Energy (W/m^2)	88	656	623
Percentage in range	6.4%	48%	45.6%

3.5 Photovoltaic Effect

The interface between the two layers (P and N) produces an electric field and forms the so-called a "cell junction". When the solar cell (p-n junction) is exposed to sunlight, a certain percentage of the incoming photons are absorbed in the region of the junction, freeing electrons in the silicon crystal (see figure 3-5).

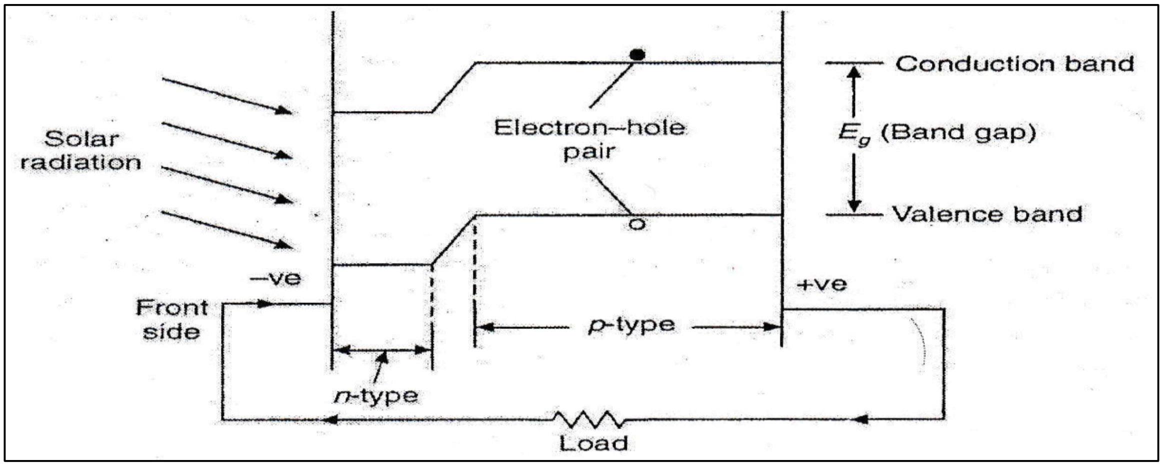


Figure (3-5) Semiconductor band structure.

If the photons have enough energy, the electrons will be able to overcome the electric field at the junction and are free to move through the silicon and into an external circuit. The direction of the electric current is opposite to its direction if the device operates as a diode (see figure 3-6).

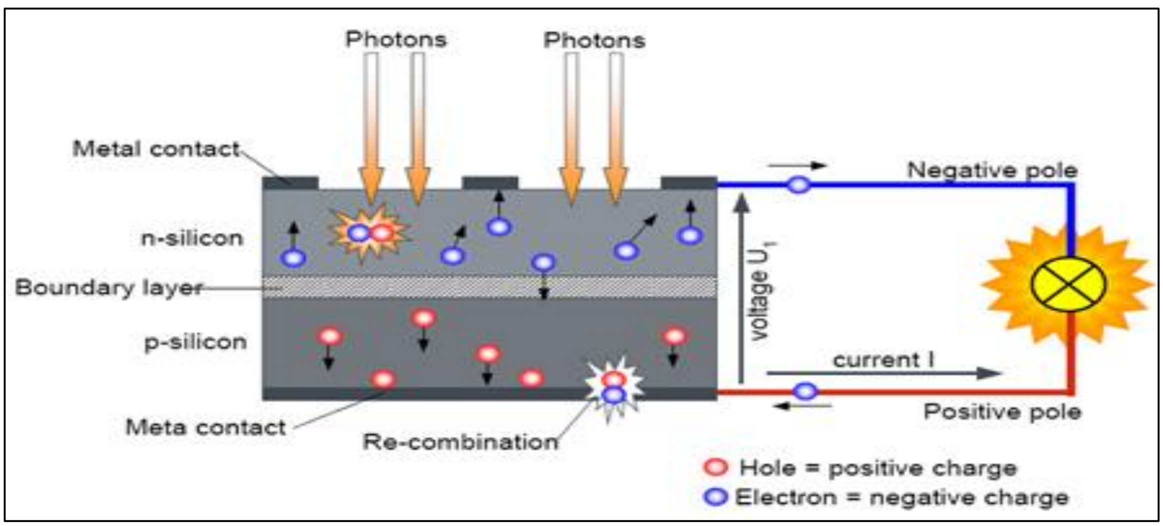


Figure (3-6) Solar cell operation

The electric current obtained I is the difference between the solar light generated current I and the diode dark current I_j, i.e.,

$$I = I_L - I_j \tag{3-2}$$

$$I = I_L - I_0\left[\exp\left(\frac{eV}{kT}\right) - 1\right] \tag{3-3}$$

This phenomenon is known as the **photovoltaic effect**

3.6 Efficiency of Solar Cells

Electrical characteristics of a solar cell are expressed by the current-voltage curves plotted under a given illumination and temperature conditions as shown in Figure 3-7. The significant points of the curve are short-circuit current I_{sc}. And open circuit voltage V_{oc}. Maximum useful power of the cell is represented by the rectangle with the largest area.

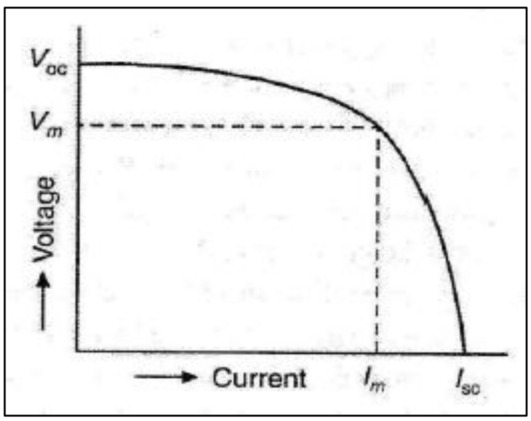


Figure (3-7): Current (I)-voltage (V) characteristic of a solar cell.

The open circuit voltage, Voc, occurs on a point of the curve where the current is zero, so that Voc is equal to:

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{I_L}{I_o} + 1\right) \tag{3-4}$$

Where kT/q, is the equivalent thermal voltage, I_L, I_o, are photocurrent and reverse saturation current, respectively.

The short circuit current, Isc, occurs on a point of the curve where the voltage is zero. At this point, the power output of the solar cell is zero. The series resistance Rsi of the solar cell contributes highly on power loss as the current reaches its maximum limits. The point, **Pm**, on the knee of the curve, marks the value of current and voltage at which the module delivers the greatest power for a given level of sunlight. Under standard test conditions (Irradiance 1000 W/m², air mass (AM 1.5), angle of incidence (AOI 0°) and Temperature 25°C), the maximum current (Im) and maximum voltage (Vm) at maximum output power (Pm) defined the rated power of the module. The other characteristics of solar module are conversion efficiency and Fill factor. **The conversion efficiency** is defined as the ratio of output electrical power to incident optical power. For maximum power output, we can write :

$$\eta = \frac{P_m}{P_{in}} \times 100\% = \frac{I_m V_m}{P_{in}} \times 100\% \tag{3-5}$$

And **the Fill factor, FF**, is the ratio of the maximum output power to the product $I_{SC}.V_{OC}$:

$$FF = \frac{I_m V_m}{I_{SC} V_{OC}} \tag{3-6}$$

Example : A solar cell (0.9 cm^2) receives solar radiation with photons of 1..8 eV energy having an intensity of 0.9 mW/cm^2. Measurements show open-circuit voltage of 0.6 V/cm^2, short-circuit current of 10 mA,/cm^2, and the maximum current ts 50% of the short-circuit current. The efficiency of cell is 25%. Calculate the maximum voltage that the cel1 can give and find the fill factor.

$$\eta = \frac{V_{max} I_{max}}{P_{in}}$$

$$V_{max} = \frac{P_{in} \times \eta}{I_{max}} = \frac{0.9 \times 10^{-3} \times 0.25}{5 \times 10^{-3}}$$

$$= 0.045 \text{ V/cm}^2$$

$$P_{max} = V_{oc} \times I_{sc} \times \text{FF}$$

$$\text{FF} = \frac{I_{max} \times V_{max}}{V_{oc} \times I_{sc}} = \frac{5 \times 10^{-3} \times 0.045}{0.6 \times 10 \times 10^{-3}}$$

$$= 0.0375$$

3.7 Limits to Cell Efficiency

Photovoltaic cel1s have low efficiency of 15%-only about 1/6th of the sunlight striking the cell generates electricity. The low efficiency is due to the following major losses:

(i) When photons of light energy from the sun strike the cell, some of them are reflected (since reflectance from semiconductors is high).

(ii) Photons of quantum energy $h\nu < E_g$ cannot contribute to photoelectric current production. This energy is converted into thermal energy and lost.

(iii) Excess energy of active photons ($h\nu > E$) given to the electrons beyond the required amount to cross the band gap cannot be recovered as useful electric power. It appears as heat and is lost.

(iv) Photovoltaic cells are exposed directly to the sun. As the temperature rises, leakage across the cell increases, consequently, there is reduction in power output relative to input of solar energy. For silicon, the output decrease by 0.5% per ^{o}C.

(v) limitations of absorbing photons by solar cell materials.

(vi) a mesh of metal contacts cover a definite area which reduces the active surface and prove an obstacle to incident solar radiation.

(vii) The far end of the infrared region. i.e., greater than 1.15 μm, has a big part of solar irradiance and this energy is not utilized by solar cells.

The band gap of a semiconductor is required to match the solar spectrum, and for obtaining a high efficiency, the band gap range is from 1.1 to 1.4 eV. Cells need to have absorptance so as to absorb the maximum number of photons in solar spectrum. This can be achieved by using series of solar cells with varying band gaps planned in a multilayer structure.

3.8 Types of Solar Cells

1. Single crystal silicon

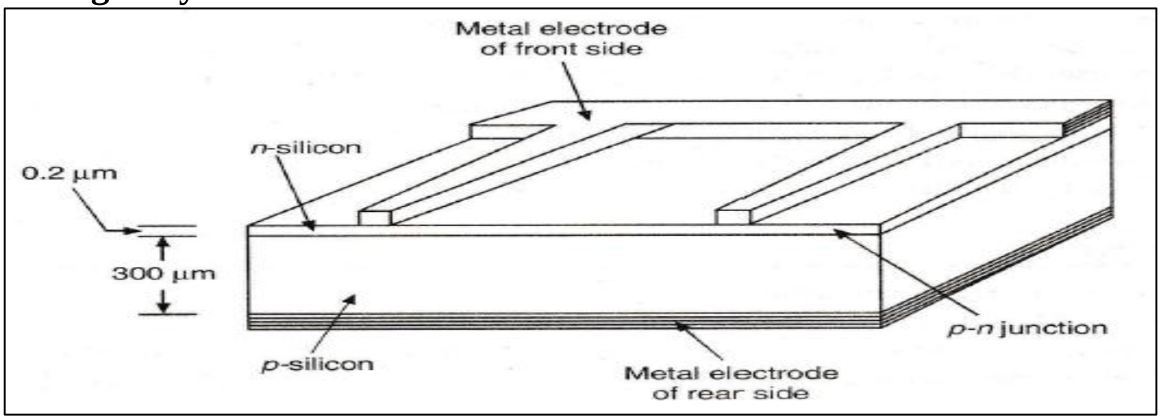


Figure (3-8) Cross section of a silicon cell.

2. Polycrystalline Silicon Cells

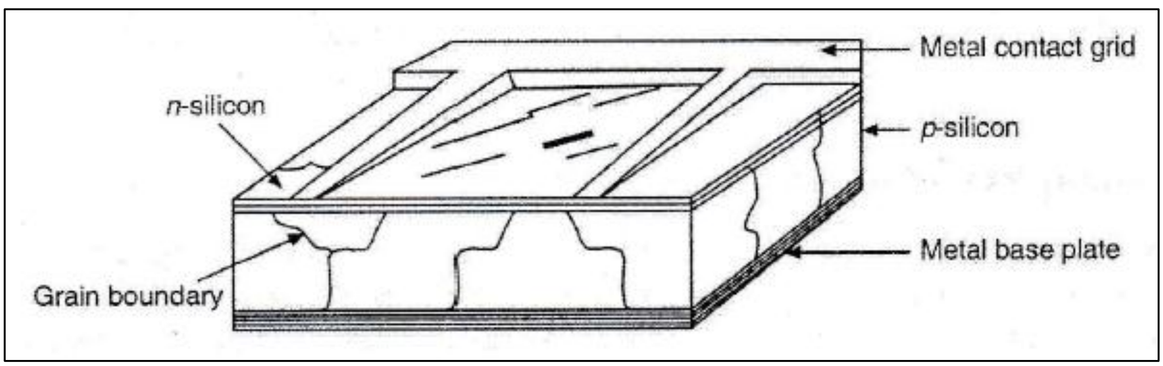


Figure (3-9): Cross section of a polycrystalline silicon cell.

3. Amorphous Silicon Cells

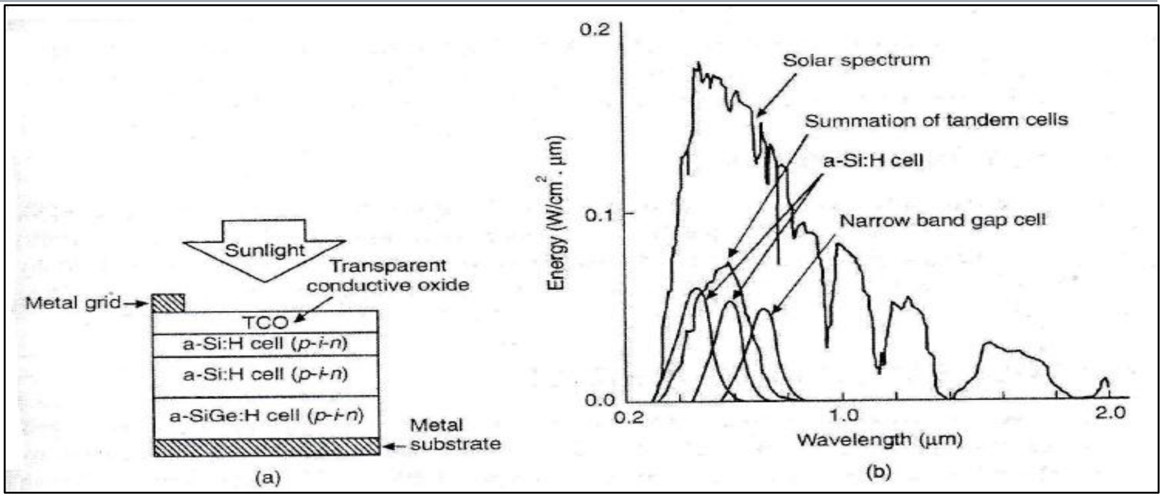
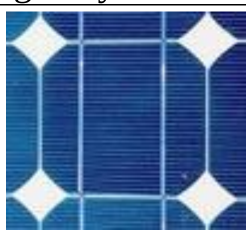
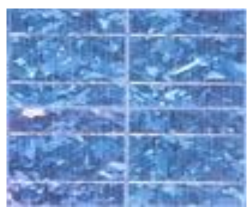


Figure (3-10) (a) Schematic of a three-layer tandem cell, and (b) spectral response of a tandem cell'

Table(3-2): Comparison between types of solar cell

Single crystalline Si	Polycrystalline Si	Amorphous Si
		
the products have been widely used for space and ground facilities	Lower space-efficiency.	Low space-efficiency
Monocrystalline solar panels live the longest. Most solar panel manufacturers put a 25-year	solar panels live less than Monocrystalline	solar panels live the shortest.
High temperatures have more impact on solar panel performance.	High temperatures have less impact on solar panel performance than monocrystalline.	High temperatures have less impact on solar panel performance.
shading have more impact on solar panel performance.	shading have less impact on solar panel performance.	shading have less impact on solar panel performance.
Its efficiency 14-17%	its efficiency 12%	Its efficiency 5-7%

The production cost is quite high	The production cost is less than single crystalline silicon cell	The production cost is lower than single and poly crystalline
There is no grain boundaries	Cells are made with care so that the grain boundaries cause no major interference with the flow of electrons and grains are larger in size , than the thickness of the cell	There is no crystal properties

3.9 Components of a PV system

The primary components of PV system consist of :

- PV module
- Energy storage (Battery)
- Charge regulator
- Inverter
- Load

Components other than PV module are collectively known as Balance of System (BOS) which includes storage batteries, an Charge regulator and an inverter

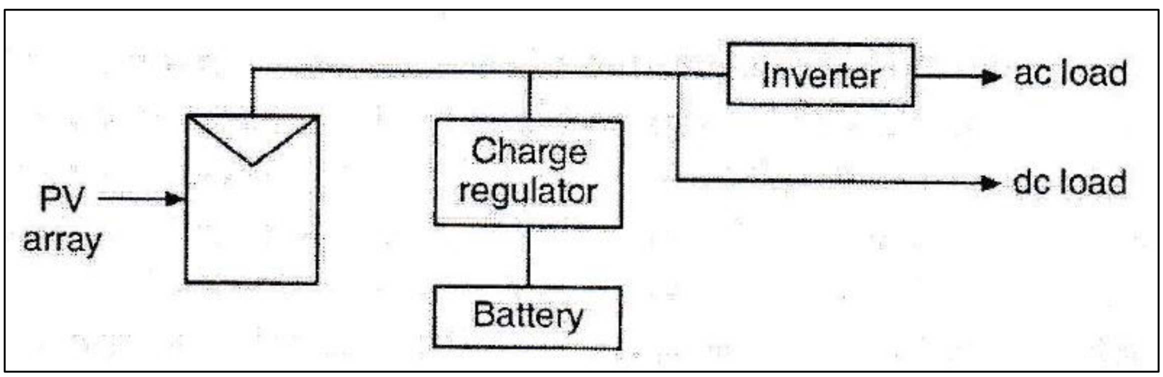


Figure (3-11): The components of a PV system

3.9.1 PV module

The solar cell is the basic unit of a PV system. An individual solar cell produces direct current and power typically between 1 and 2 W. in case of crystalline silicon solar cells with a typical area of 10 × 10 cm an output power is typically around 1.5 Wp, with Voc ≈ 0.6 V and Isc ≈ 3.5 A. For actual usage, the solar cells are interconnected in series/parallel combinations to form a **PV module.** In the outdoor environment the magnitude of the current output from a PV module directly depends on the solar irradiance and can be increased by connecting solar cells in parallel. The voltage of a solar cell does not depend strongly on the solar irradiance but depends primarily on the cell temperature. PV modules can be designed to operate at different voltages by connecting solar cells in series. The modules are manufactured in various sizes and are able to deliver power ranging from 5 to 240 W. For large-scale generation of solar electricity the solar modules are connected together into a solar array (see figure 3-12).

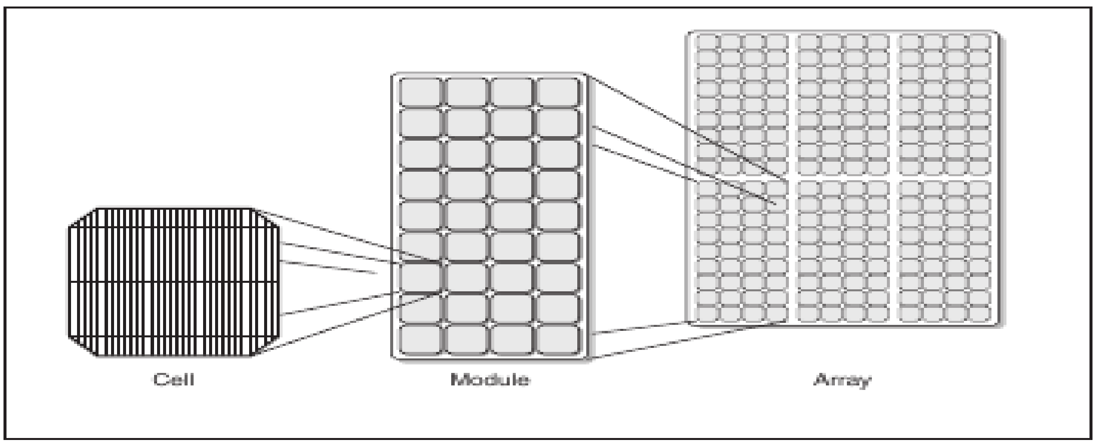


Figure (3-12): PV cells, modules and arrays

Table 3-3 contains typical parameters that are used in module specification sheets to characterize PV modules. Electrical parameters are determined at standard test conditions, i.e. 1000 W/m^2 solar irradiance, 25°C cell temperature and AM1.5 solar radiation.

Table (3-3): specification sheets to characterize PV modules

Module type	Shell SM50-H
Solar cell type	Mono c-Si
Rated Power P_{max} (W)	50
Rated current I_{mmp} (A)	3.15
Rated voltage V_{mpp} (V)	15.9
Short circuit current I_{sc} (A)	3.4
Open circuit voltage V_{oc} (V)	19.8
Cells per module	36
Dimensions (mm)	1219×329

3.9.2 Energy Storage (Battery)

Batteries are charged during the day and supply power to loads during periods of cloudy day and during nights. The capacity of a battery is expressed in ampere-hours (Ah). Most of batteries used in PV systems are lead-acid batteries. In some applications, for extreme climate conditions nickel-cadmium batteries are used which is the relative high cost.

3.9.3 Charge regulators

Charge regulators are the link between the PV modules, battery and load. They protect the battery from overcharge or excessive discharge by regulate the input and the output currents. Charge and discharge voltage limits should be carefully selected to suit the battery type and the operating temperature.

3.9.4 Inverters

The inverter's main functions are: transformation of DC electricity into AC, wave shaping of the output AC electricity, and regulation of the effective value of the output voltage.

3.9.5 Load

The appliances, lights and equipment being powered by a PV solar system constitute electric loads of the PV system. Energy-efficient loads contribute to overall system efficiency and economy.

3.10 Types of PV Systems

Three main types of PV systems: stand-alone (off-grid), grid-connected, and hybrid.

3.10.1 Stand-Alone Systems (off-Grid PV Systems)

Stand-alone systems rely on PV power only. These systems can comprise only PV modules and a load or can include batteries for energy storage. When using batteries charge regulators are included, which switch off the PV modules when batteries are fully charged, and switch off the load in case batteries become discharged below a limit. The batteries must have enough capacity to store the energy produced during the day to be used at night and during periods of poor weather.

Solar street light as shown in figure (3-13) describes a standalone PV power generating device. It comprises a compact fluorescent lamp, two 35 watt solar modules and an 80 Ah tubular cell battery.

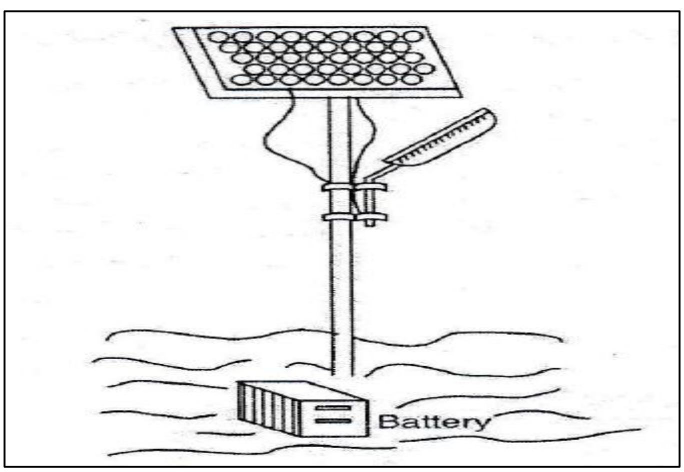


Figure (3-13) An SPV street light installation

Individual farmers typically use an 1800 watt PV array to operate a 2 hp DC motor pump set as shown in Figure.(3-14). It can give water discharge of 140,000 liters per day from a depth up to 7 meters.

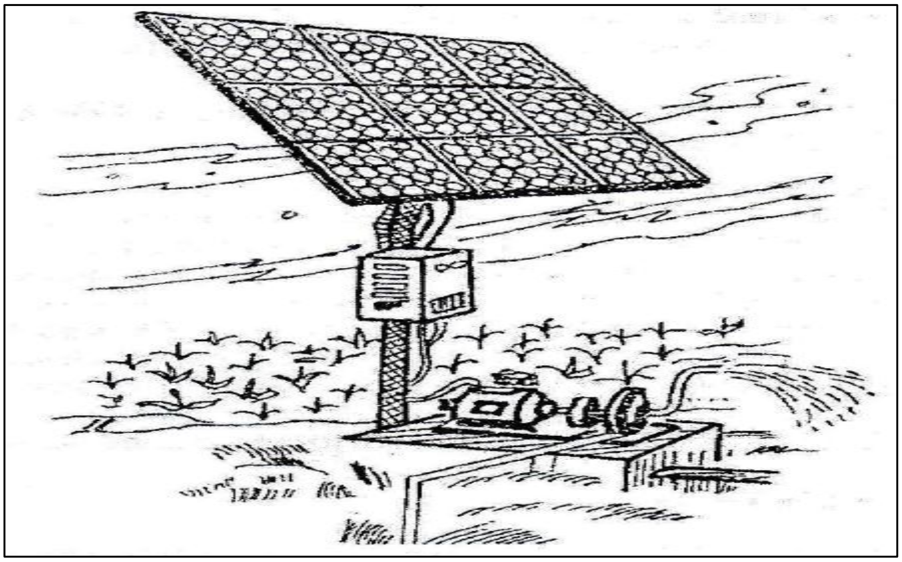


Figure (3-14) An SPV water Pump set

3.10.2 Grid-Connected Systems

A grid-connected photovoltaic power system is connected with the state electric grid and do not require batteries. The system operates to supplement the grid power during the daytime when a substantial quantum of solar energy is extracted from the sunlight. During night the grid power alone feeds the load. This system also supplies emergency power during any short period of grid failure as shown in Figure (3-15). This system requires additional equipment to control voltage, Frequency and waveform so as to conform to conditions for feeding the power into the grid.

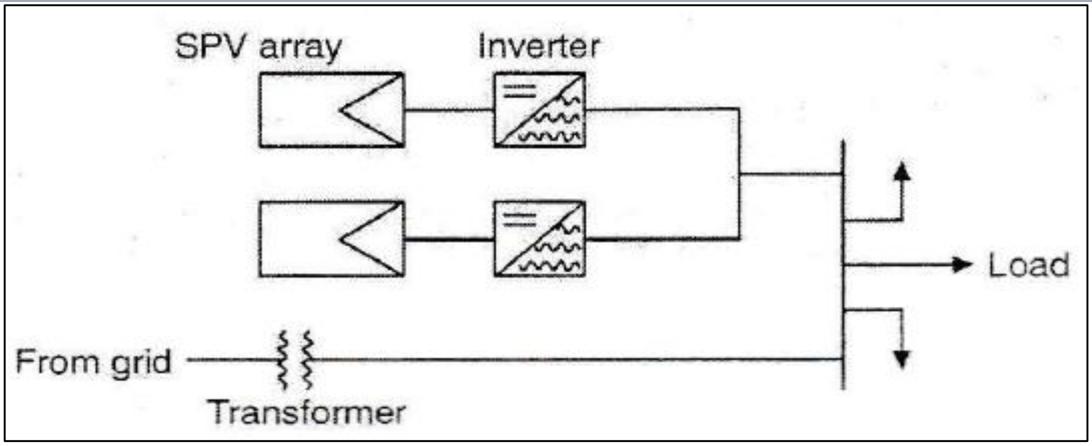


Figure (3-15) Grid-connected PV system.

3.10.3 Hybrid Systems

Hybrid systems consist of combination of PV modules and a complementary means of electricity generation such as a diesel and gas or wind generator. Schematically is a hybrid system shown in Figure 3-16. In order to optimize the operations of the two generators, hybrid systems typically require more sophisticated controls than stand-alone PV systems. For example, in the case of PV/diesel systems, the diesel engine must be started when battery reaches a given discharge level and stopped again when battery reaches an adequate state of charge.

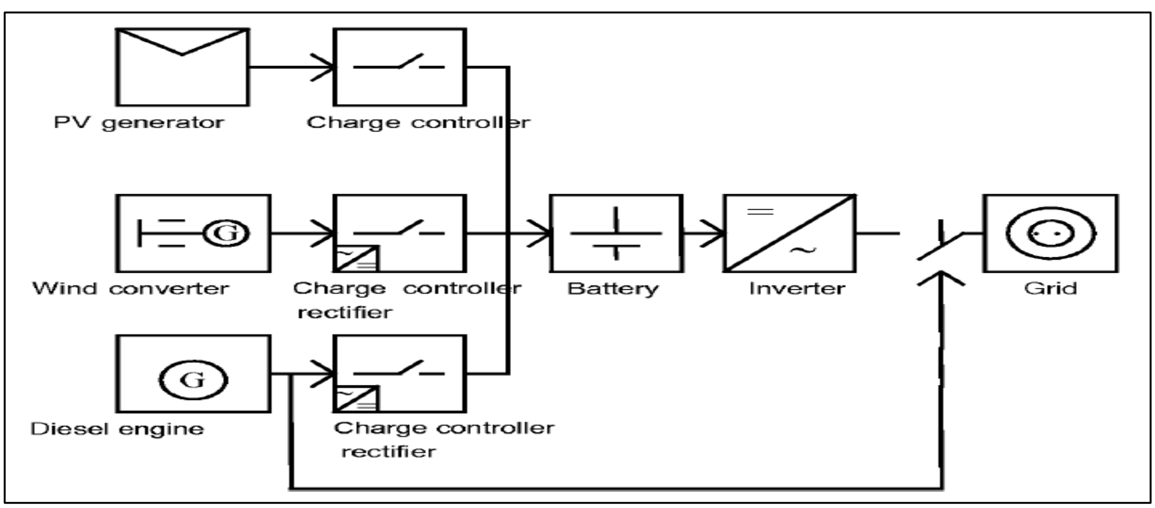


Figure (3-16): Schematic principle of a hybrid system with PV, wind, and diesel generators

3.11 PV System Design Guide

An estimate of the sizing of a PV array and batteries can be calculated using the following design rules.

1. Determine the total load current and operational time
2. Add system losses
3. Determine the solar irradiation in daily equivalent sun hours
4. Determine total solar array current requirements
5. Determine optimum module arrangement for solar array
6. Determine battery size for recommended reserve time

1. Determine the total load current and operational time

- Determining the nominal operational voltage of the PV system. Usually, one can choose between 12V or 24V nominal voltage.
- Express the daily energy requirements of loads in terms of current and average operational time expressed in Ampere-hours [Ah].
- In case of DC loads the daily energy [Wh] requirement is calculated by multiplying the power rating [W] of an individual appliance with the average daily operational time [h].
- Dividing the Wh by the nominal PV system operational voltage, the required Ah of the appliance is obtained.

EXAMPLE: A 12 V PV system has two DC appliances A and B requiring 15 and 20 W respectively. The average operational time per day is 6 hours for device A and 3 hours for device B. Calculate the daily energy requirements of the devices expressed in Ah.

Ans.) Device A: 15W×6h = 90Wh

Device B: 20W×3h = 60Wh

Total: 90Wh+60Wh = 150Wh 150Wh/12V = **12.5** Ah

In case of AC loads, The DC equivalent of the energy use of an AC load is determined by dividing the AC load energy use by the efficiency of an inverter, which is typically 85%. By dividing the DC energy requirement by the nominal PV system voltage the Ah is determined

EXAMPLE: An AC computer (device C) and TV set (device D) are connected to the PV system. The computer, which has rated power 40W, runs 2 hours per day and the TV set with rated power 60W is 3 hours per day in operation. Calculate the daily energy requirements of the devices expressed in DC Ah.

- Device C: 40W×2h = 80Wh
- Device D: 60W×3h = 180Wh
- Total: 80Wh+180Wh = 260Wh
- DC requirement: 260Wh/0.85 = 306Wh 306Wh/12V = **25.5** Ah

2. Add system losses

Some components of the PV system, such as charge regulators and batteries use energy to perform their functions. We denote the use of energy by the system components as system energy losses. Therefore, the total energy requirements of loads, which were determined in step 1, are increase by a factor of 20 to 30% in order to compensate for the system losses.

EXAMPLE: The total DC requirements of loads plus the system losses (20%) are determined as follows: (12.5Ah + 25.5Ah) × 1.2 = 45.6Ah

3. Determine the solar irradiation in daily equivalent sun hours (EHS)

the average annual solar irradiation can be expressed in 221000 kWh/m^2 = 1000 equivalent sun hours, which means 1000 h/356 days = 2.8 h/day..

EXAMPLE: in PV system, the daily ESH is 3 hours.

4. Determine total solar array current requirements

The current that has to be generated by the solar array is determined by dividing the total DC energy requirement of the PV system including loads and system losses (calculated in step 2 and expressed in Ah) by the daily equivalent sun hours (determined in step 3).

EXAMPLE: The total DC requirements of loads plus the system losses are 45.6Ah. The daily ESH is 3 hours. The required total current generated by the solar array is 45.6Ah/3h = 15.2A.

5. Determine optimum module arrangement for solar array

The number of modules in parallel is calculated by dividing the total current required from the solar array (determined in step 4) by the current generated by module at peak power (rated current in the specification sheet). The number of modules in series is determined by dividing the nominal PV system voltage with the nominal module voltage (in the specification sheet under configuration). The total number of modules is the product of the number of modules required in parallel and the number required in series.

EXAMPLE: The required total current generated by the solar array is 15.2A. We have Shell SM50-H modules available. The rated current of a module is 3.15A. The number of modules in parallel is 15.2A/3.15A = 4.8 < 5 modules. The nominal voltage of the PV system is 12V and the nominal module voltage is 12V. The number of modules in series is 12V/12V = 1 module. The total number of modules in the array is 5 × 1 = 5 modules.

6. Determine battery size for recommended reserve time

This reserve capacity is referred to a period of time that the system is not dependent on energy generated by PV modules, and is rated in days which depends on the type of loads. For residential use it is usually 5 days or less. The capacity [Ah] of the batteries is calculated by multiplying the daily total DC energy requirement of the PV system including loads and system losses (calculated in step 2 and expressed in Ah) by the number of days of recommended reserve time. In order to prolong the life of the battery it is recommended to operate the battery using only 80% of its capacity. Therefore, the minimal capacity of the batteries is determined by dividing the required capacity by a factor of 0.8.

EXAMPLE: The total DC requirements of loads plus the system losses are 45.6Ah. The recommended reserve time capacity for the installation side is 5 days. Battery capacity required by the system is 45.6Ah × 5 = 228Ah. The minimal battery capacity for a safe operation is 228Ah/0.8=285Ah.