SOLAR ENERGY

Fundamentals, Economic and Energy Analysis

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Foreword

The world is facing depleting natural fuel such as coal, natural gas for power generation and ever increasing demand of electricity. In this scenario everybody is looking for non-conventional, renewable energy sources such solar power, wind energy etc. The present book "Solar Energy – Fundamentals, Economic & Energy Analysis" is based on present knowledge on solar energy technology written by Mr. Saurabh Kumar Rajput, gives hands on information for practicing engineers. This book is useful for budding engineers and researchers also. Many industries including textiles and garment industries are installing solar power plants in large scale. This will be useful for the energy engineers of these industries.

Dr. Arindam Basu

Director General, NITRA

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Brief Contents

Table of contents

Chapter 6: Simulation and analysis of photovoltaic (PV) system with Maximum Power Point Tracking (MPPT) system **(66-76)**

Chapter 1

Basics of solar energy

1.1 Introduction

Energy is defined as capacity to produce an effect to do work. Energy has been an important component to meet the day to day needs of human beings. Human society require increasing amount of energy for industrial, commercial, domestic, agriculture, and transport uses. Different forms of energy are defined as primary and secondary energy, commercial and noncommercial energy, renewable and nonrenewable energy.

1.1.1 Primary and Secondary energy-

Primary energy refers to all types of energy extracted or captured directly from natural resources. Primary energy can be further divided into two parts namely renewable and non renewable energy.

Primary energy is transformed into more convenient form of energy such as electricity, steam etc. these form of energy are called secondary energy

1.1.2 Commercial and Noncommercial energy-

Energy that is available in the market for a definite price is known as commercial energy. The most important forms of commercial energy are electricity, coal, refined petroleum products and natural gas.

Any kind of energy which is sourced within a community and its surrounding area, and which is not normally treated in the commercial market is termed as noncommercial energy such as firewood, cattle dung, agriculture waste etc.

1.1.3 Renewable and nonrenewable energy-

Renewable energy is obtained from natural sources. These resources can be used to produce energy again and again eg. Solar energy, wind energy, tidal energy etc.

Non renewable resources cannot be replaced once they are used eg. Coal, oil, gas etc. these energy resources are limited and would be exhausted within prescribed period of time.

1.2 Solar energy and solar radiation-

The earth receives the solar energy in the form of solar radiation. These radiations comprising of ultra-violet, visible and infrared radiation. The amount of solar radiation that reaches any given location is dependent on several factors like geographic location, time of day, season, land scope and local weather. Because the earth is round, the sun rays strike the earth surface at different angles (ranging from 0° to 90°). When sun rays are vertical, the earth's surface gets maximum possible energy.

Most of the part of India receives 4 to 7 kWh of solar radiation per square meter per day. India receives solar energy equivalent more than 5000 trillion kWh per year.

Solar radiation (Direct, diffuse and total solar radiation):
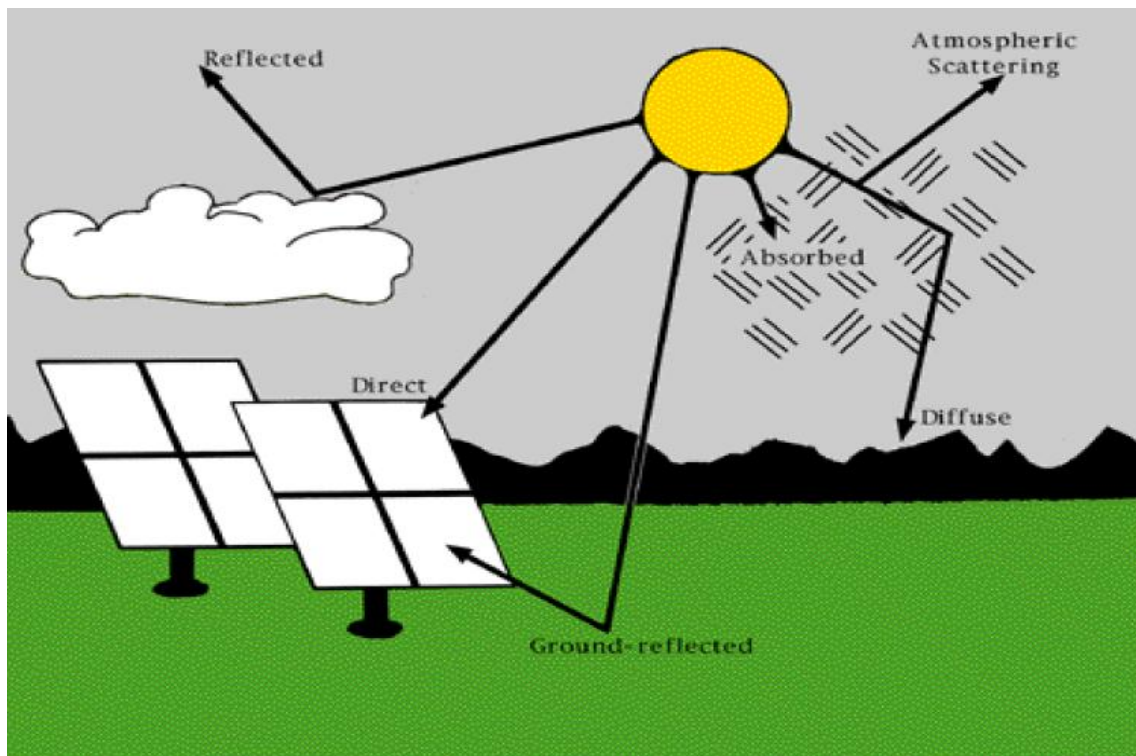
Fig. 1.1 Solar radiation

The solar radiation that reaches the surface of the earth without being diffused is called direct beam solar radiation. It is measured by instrument named as pyrheliometer.

As sun light passes through the atmosphere, some part of it is absorbed, scattered and reflected by air molecule, water vapours, clouds, dust and pollutants. This is called diffuse solar radiation. The diffuse solar radiation does not have unique path.

The sum of the direct and diffuse solar radiations is called total radiation or global solar radiation. Pyranometer is used for measuring the total radiation.
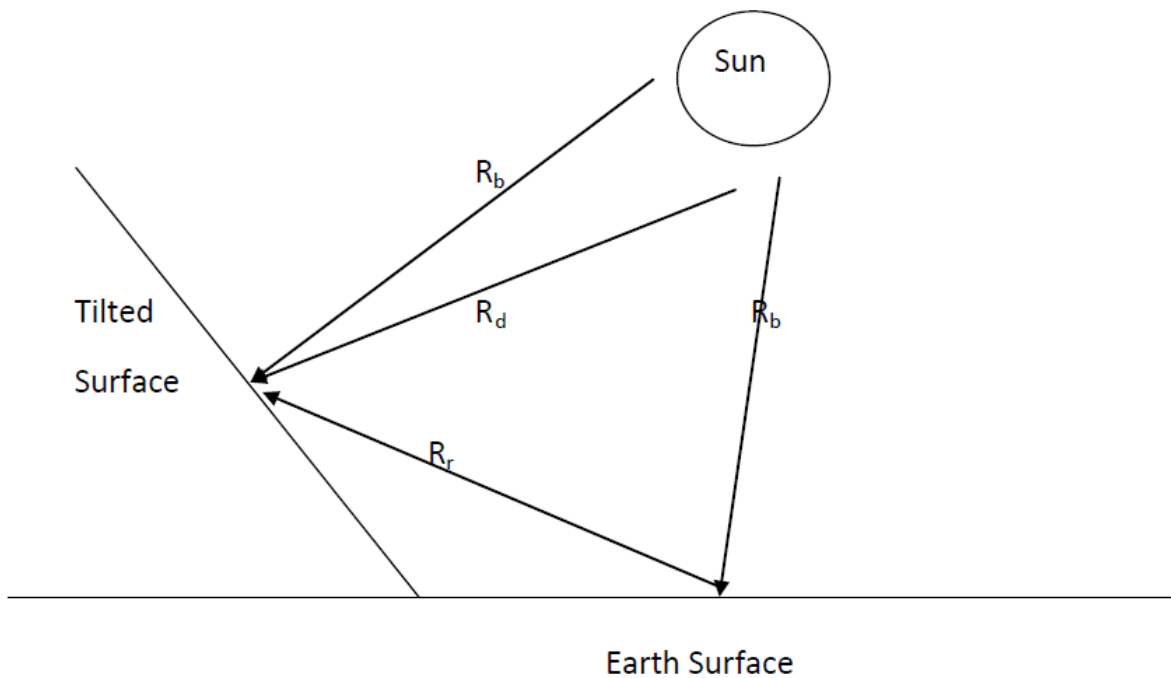
Fig.1.2 Direct, diffuse and total solar radiation

If,

R_b- Beam Radiation (direct solar radiation)

R_d- Diffuse Radiation (solar radiation after diffusion)

R_r- Reflected radiation (solar radiation after reflection from surface)

R_t- Total solar radiation on tilted surface

Then,

$R_t = R_b + R_d + R_r$ --------------- (1.1)

1.3 Sun – Earth angles

1.3.1 Latitude (ф)

The latitude of a location is the angle made by the radial line joining the location to the centre of the earth with the projection of the line on the equatorial plane.

$-90° \leq ф \leq +90°$
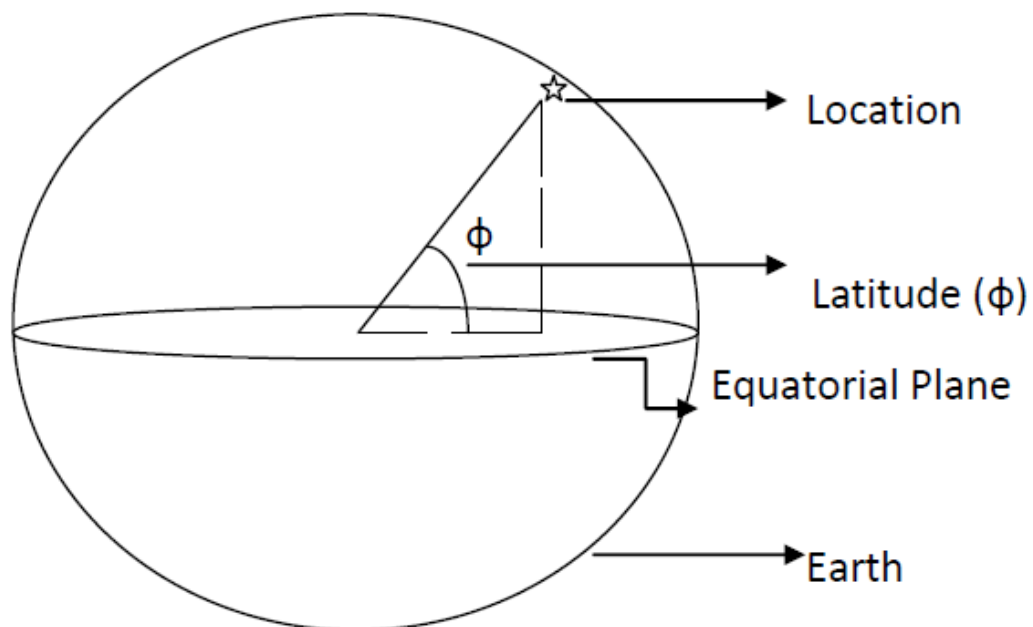
Fig. 1.3 Latitude angle

1.3.2 Declination (δ)

The declination angle is the angle made by the line joining the centre of the sun and the earth with its projection on equatorial plane.

The declination angle varies from a maximum value of +23.45° on June 21 to a minimum value of -23.45 on December 21.

$\delta = 23.45 \, \text{Sin} \, 360 \frac{(284+n)}{365}$ -------------- (1.2)

(Where, n- number of days)

$\delta < 0$ – for winters in northern hemisphere

$\delta > 0$ – for summer in northern hemisphere

Example1: Calculate declination angle for March 22 in a non-leap year.

Solution: On March 22, n= 31 (January) + 28 (February) + 22 (22nd march)

$\qquad\qquad$ n= 81 days

So,

$\delta = 23.45 \, \text{Sin} \, 360 \frac{(284+81)}{365} = 0$

On march 22 and September 22, the declination is zero so these days are called equinoxial day

Example2: Calculate declination angle for March 31 in a leap year.

Solution: On March 22, n= 31 (January) + 29 (February) + 31 (31st march)

$\qquad\qquad$ n= 91 days

So,

$\delta = 23.45 \, \text{Sin} \, 360 \frac{(284+91)}{365} = 4.016°$

1.3.3 Hour angle (ω)

It is the angle through which the earth must be rotated to bring the meridian of the plane directly under the sun
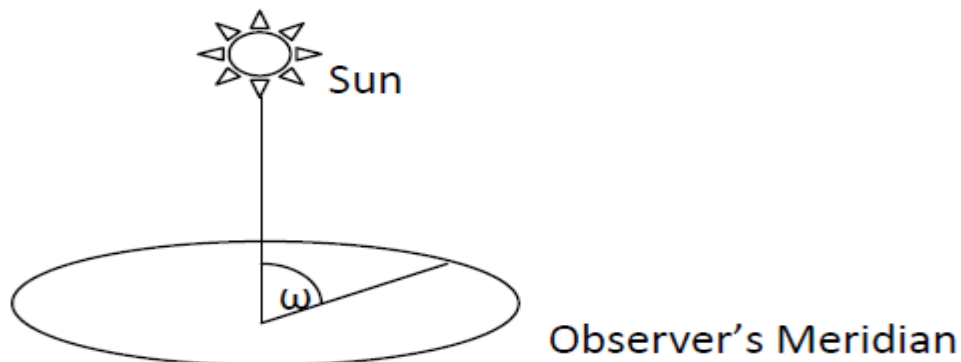
Fig. 1.4 Hour angle

Because it is 24 hours for 360° of rotation, so each one hour correspond to 15°

ω = 15 (ST – 12) ----------------- (1.3)

Where, ST – solar time

Example3: Calculate the hour angle at 02:30 PM.

Solution: ω = 15 (ST – 12)

ω = 15 (14.5 – 12) = 37.5°

1.3.4 Altitude Angle (α) and Zenith angle (θ_Z)

Altitude angle is the angle between the incident sun ray and the projection of sun's rays on the horizontal plane.

Zenith angle is the complementary angle of sun's altitude angle

θ_Z= 90° - α   -------------------- (1.4)

zenith angle is the angle between the incident sun ray and the perpendicular line to the horizontal plane.

Cos θ_Z = Sin ф Sin δ + Cos ф Cos δ Cos ω ---------------- (1.5)
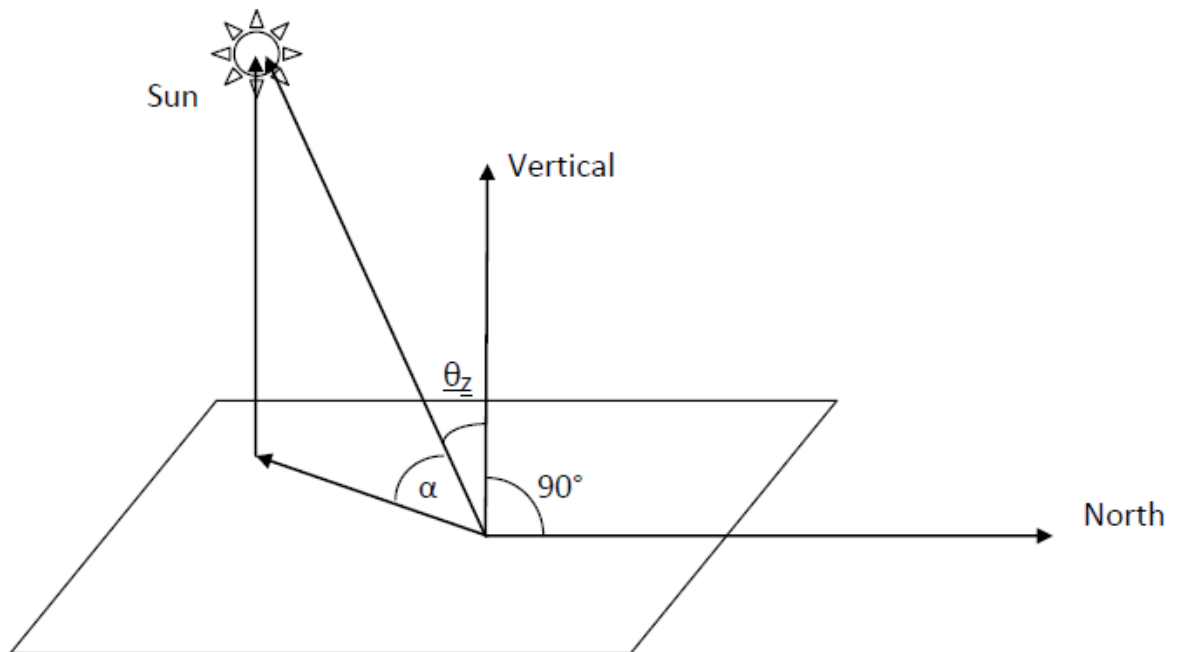
Fig.1.5 Altitude angle and Zenith angle

1.3.5 Surface azimuth angle (γ) and solar azimuth angle (γ$_S$)

Consider a surface with slope "β". Draw a outer normal to this surface and take a projection of normal on horizontal plane.

Surface azimuth angle is the angle between line due south and the projection of normal to the surface on horizontal plane.

Solar azimuth angle is the angle between line due south and the projection of sun rays on horizontal plane.

$$Cos\ \gamma s = \frac{Cos\ \theta z\ .Sin\ \phi - Sin\ \delta}{Sin\ \theta z\ .cos\ \phi}$$ ---------------------------- (1.6)
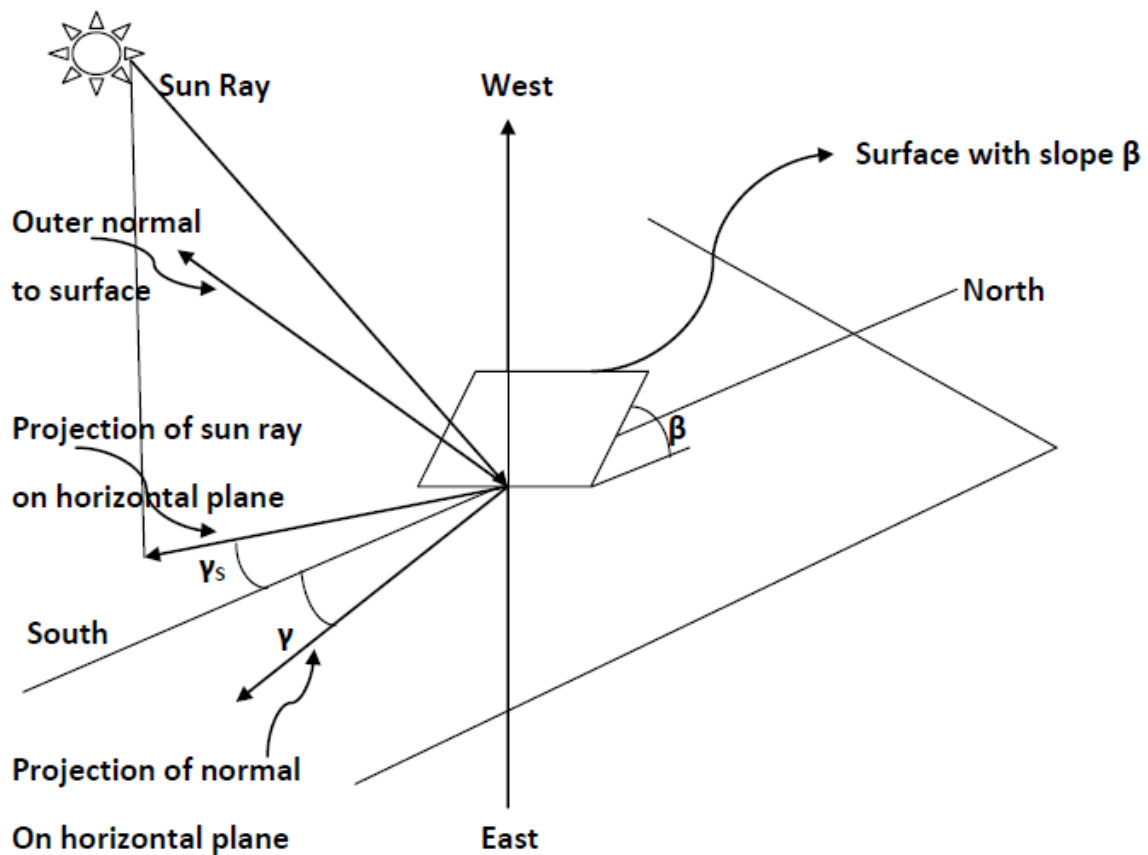
Fig.1.6 surface azimuth angle and solar azimuth angle

Example 4: Calculate the sun's altitude and azimuth angle at 9 AM solar time on September 1st at latitude of 23°N.

Solution: ф=23°, n= 244 days

ω= $15(9 - 12) = 45°$

$\delta = 23.45 \, Sin \, 360 \frac{(284+244)}{365} = 7.724°$

Cos θ_Z = Sin (23°) Sin (7.724°) + Cos (23°) Cos (7.724°) Cos (45°)

$\theta_Z = 45.87°$

$Cos \, \gamma s = \dfrac{Cos \, 45.87 \, . \, Sin \, 23 - Sin \, 7.724}{Sin \, 45.87 \, . \, cos \, 23}$

$\gamma s = 78.01°$

Solar thermal and application

2.1 <u>Introduction</u>

The Sun is most prominent source of energy in our system. The source of solar energy is process of thermonuclear fusion in the sun's core. This energy is radiated from sun in all directions and a fraction of this energy is reaches to the earth.

The sun's outer visible layer is called the photosphere and has a temperature of about 6000°C. Above the photosphere there is a transparent layer of gases known as chromospheres. The light emitted by the chromospheres is of short wave length. Finally there is the corona. The corona is the outer part of the sun's atmosphere. in this region, prominence appear. Prominence is immense clouds of glowing gas that erupt from upper chromospheres. The corona can only be seen during total solar eclipse.

2.2 <u>Solar thermal energy application</u>

Solar thermal energy is used for water heating, space heating, electric power generation, solar cooker for cooking of food etc.

2.2.1 Flat plate solar collector

Solar collector absorbs the incident solar radiation and converts it to the useful heat which is use for heating a collector fluid such as water, oil or air.

Flat plate collector are used where temperature below 100°C are required.

The important parts of flat plate collectors are shown below
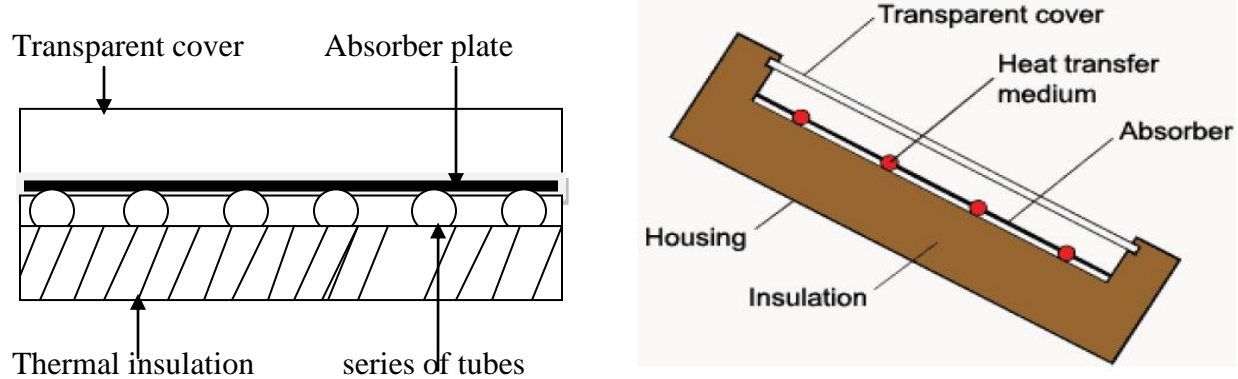
(Heat transfer medium)

Fig. 2.1 Flat plate solar collector

Construction

Transparent Cover-

This allows solar energy to pass through, but reduces the heat loss examples are tempered glass, transparent plastic materials etc

Absorber plate-

Plate is blackened in order to absorb the maximum amount of solar radiations.

The absorber consists of a thin sheet. This sheet is made of conductor material (aluminum, steel, copper etc.) because the metal is a good conductor of heat. Black coating is applied to this conductor / metal plate in order to absorb the maximum amount of solar radiations.

Copper is best material for absorber plate because it has high thermal conductivity, adequate tensile strength and good corrosion resistance.

Series of tubes-

The absorber plate with several parallel tubes is fabricated from copper tube and sheet by soft soldering.

Heat transport fluid (Water)-

To remove heat from the absorber, fluid is usually circulated through tubes to transfer heat from the absorber to an insulated water tank.

Thermal insulation-

It is used to provide insulation on the sides and bottom so as to prevent losses and thereby attain high temperatures. Examples of thermal insulations are crown white wool, glass wool, calcium silicate etc.

Working-

When solar radiation passes through the transparent cover and incident on blackened absorber surface of high absorptivity, a large portion of this energy is absorbed by the plate and then transferred to the fluid (Air, Water etc)

Thermal insulation is used to reduce conduction losses and transparent cover is used to reduce convection losses.

Note – when air is used as heat transport fluid, it is flat plate air collector which is used for space heating (solar space heater) and when liquid is used as heat transport fluid, it is flat plate liquid collector which is used for water heating (solar water heater)

2.2.1 (a) Solar flat plate collector type water heating system-
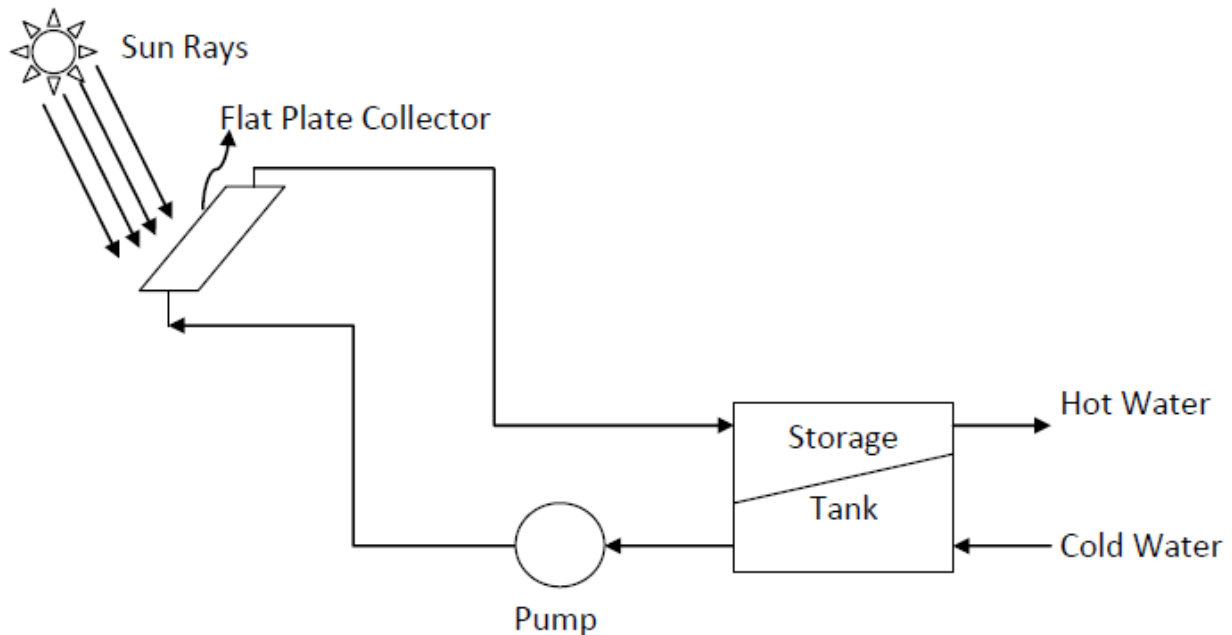
Fig. 2.2 Solar water heater

Cold water is pumped to the flat plate collector, collector absorbs the heat by solar radiation and heated water is stored in the tank.

2.2.1 (b) Solar flat plate collector type space heating system-
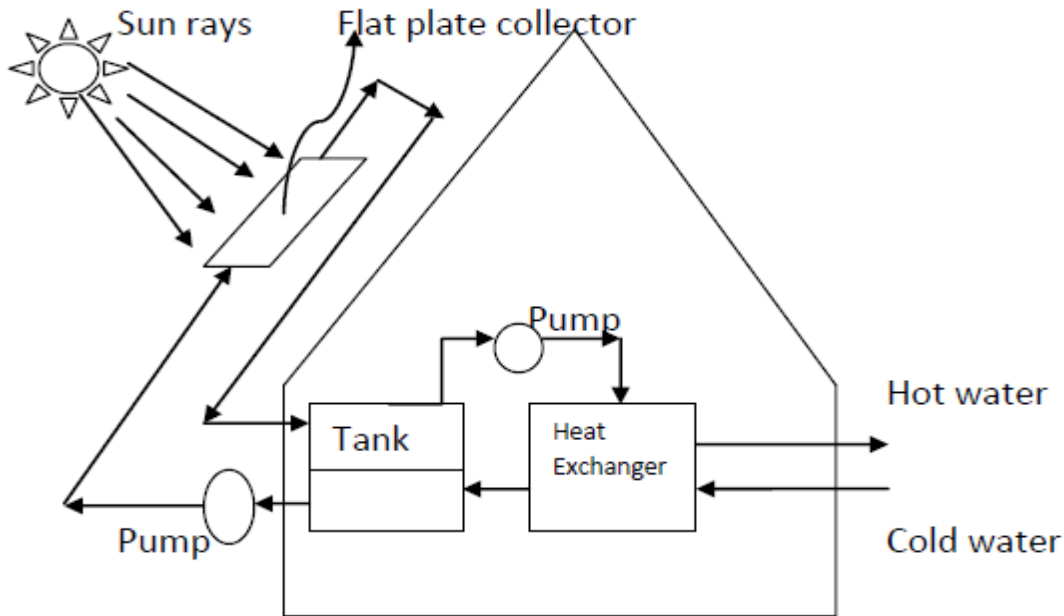
Fig. 2.3 Solar space heater

Water is heated by incident solar radiation on flat plate collector. This heated water is collected in a tank.

The energy is transferred to the air circulating in the house by water to air heat exchanger.

2.2.2 Concentrating collectors / focusing collectors (Cylindrical trough Solar collector)

Focusing collector has less heat loss so they operate at higher temperature. Flat plate collectors operate on temperature about 100°C in summer and 40°C in winter. So, in order to increase the temperature range of collectors, focusing of collectors are used.

In focusing collectors, a parabolic mirror is used. The sun rays are focused on the focal point of the mirror by reflection from its surface.

A tube is placed along the focal line of the mirror and fluid is circulated through the tube this fluid absorb the heat from reflected solar radiation.
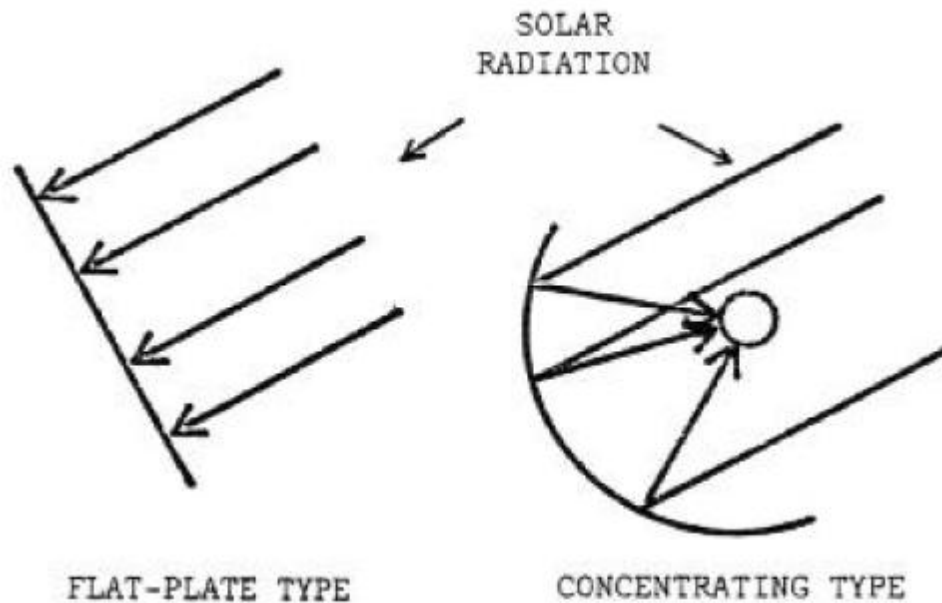
Fig. 2.4 focusing of collector

With these collectors, temperature of 200°C - 300°C or above may be obtained. In some mechanism, seasonal tracking of sun is also provided to get the maximum heat from sun light.

The focusing collectors can have two arrangements namely cylindrical parabolic concentrator (100°C < T < 200°C) and parabolic mirror arrays (T > 200°C)

The concentrator increases the intensity of solar radiation by a concentration ratio "C"

$C = (A_a / A_b)$ ---------------------------- (2.1)

A_a - Aperture area, A_b - Absorber area

The C value of 20 to 100 can be achieved by a linear concentrator such as parabolic trough concentrator and the C value of 100 to 4000 can be achieved by a point focus concentrator such as parabolic dish.
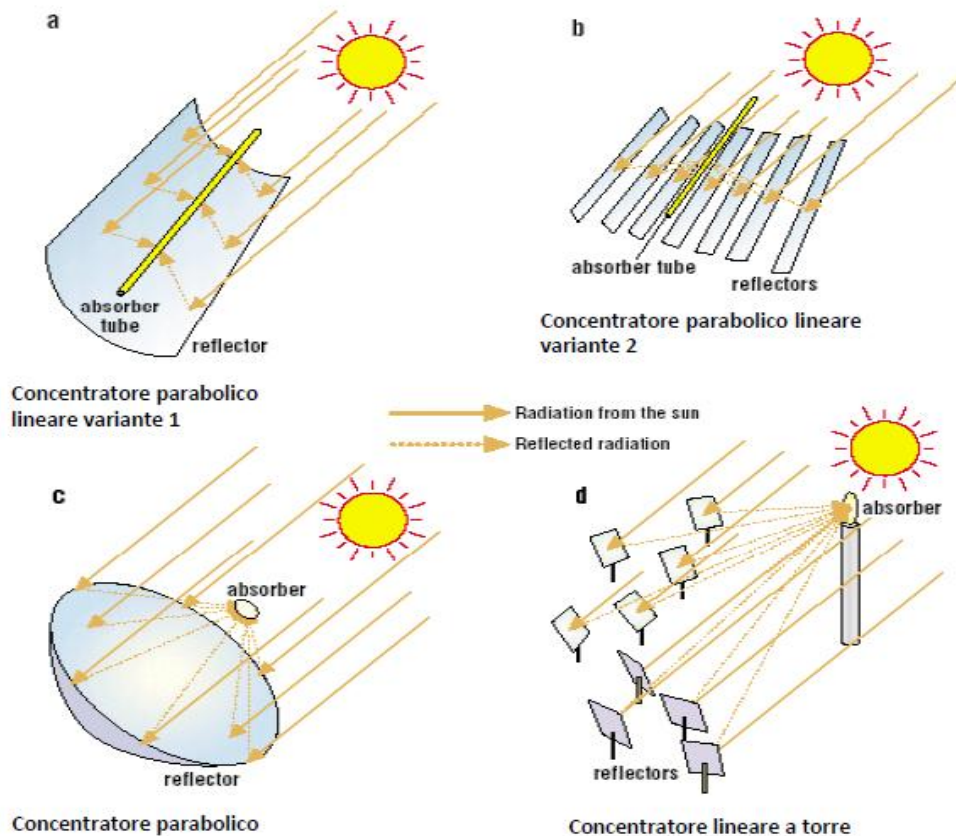
Fig. 2.5 Different types of concentrating / focusing collectors

Materials for concentrators-

Reflector-

Reflector should have high reflectivity. Therefore mirror glass may be used. Glass is the most durable with low iron content so it is a good reflector. Aluminium and silver are also good reflecting surface. Plastics are also used as reflector now days.

Receiving material-

Glass and transparent plastic films are generally used as cover material for receivers. Glass should have low iron content to reduce absorption by it.

Coatings are required to have strong solar absorptivity. Weather resistance, stability at high temperature Examples are black paints, black chrome etc.

2.2.3 Solar thermal power plant-

In solar thermal power plants, the concentrating collectors are used for generation of electricity. There are two types of solar thermal power plants namely solar distributed collector power plant and solar central receiver power plant.

2.2.3 (a) Solar distributed collector power plants-
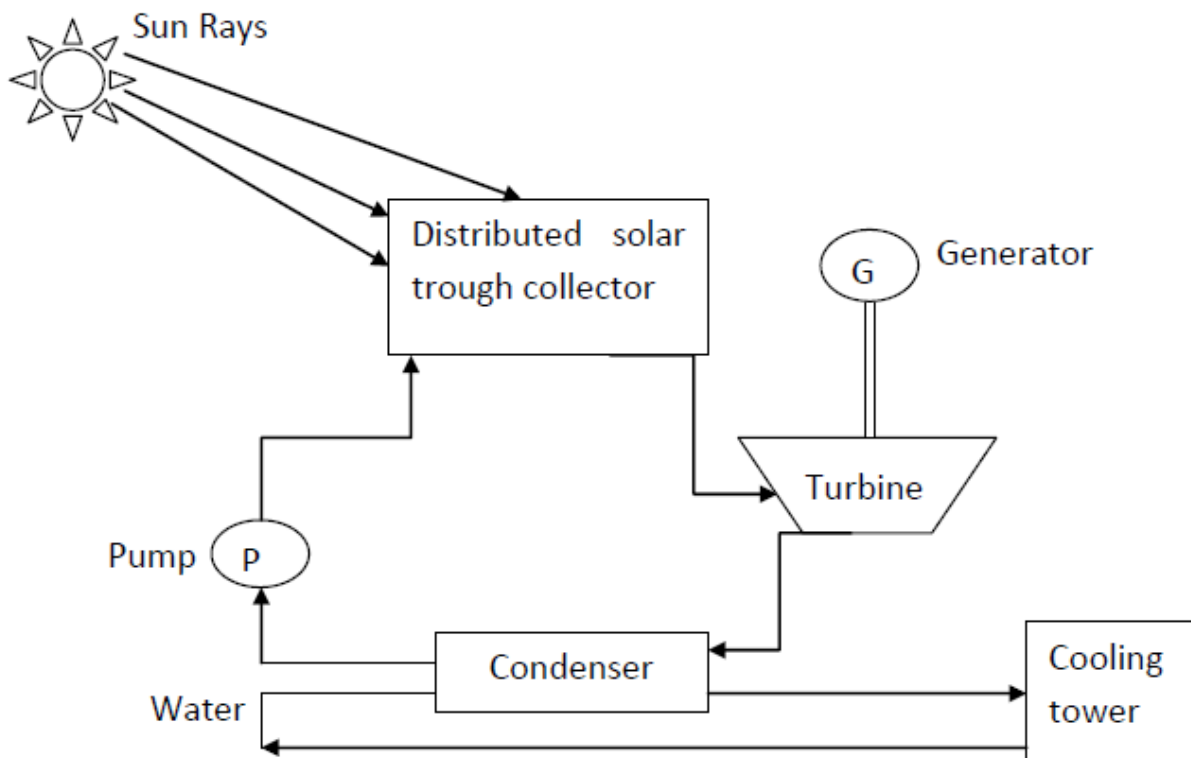
Fig. 2.6 Solar distributed collector electric power plant

In this type of power plants, collectors are used. Collectors may be parabolic trough unit with line focus or parabolidal dishes with centre focus.

The flat plate collectors are not used in power plants because there efficiency is very poor and operating temperature is very low.

Water is heated by the collector and stored in the storage tank. This heated water is converted into steam by boiler and steam is provided to turbine to make it run. This turbine is coupled with generator so rotation of turbine makes generator to rotate hence electricity is generated.

The steam is condensed in the condenser and feed water is provided to boiler for reuse.

2.2.3 (b) Solar central receiver power plant-
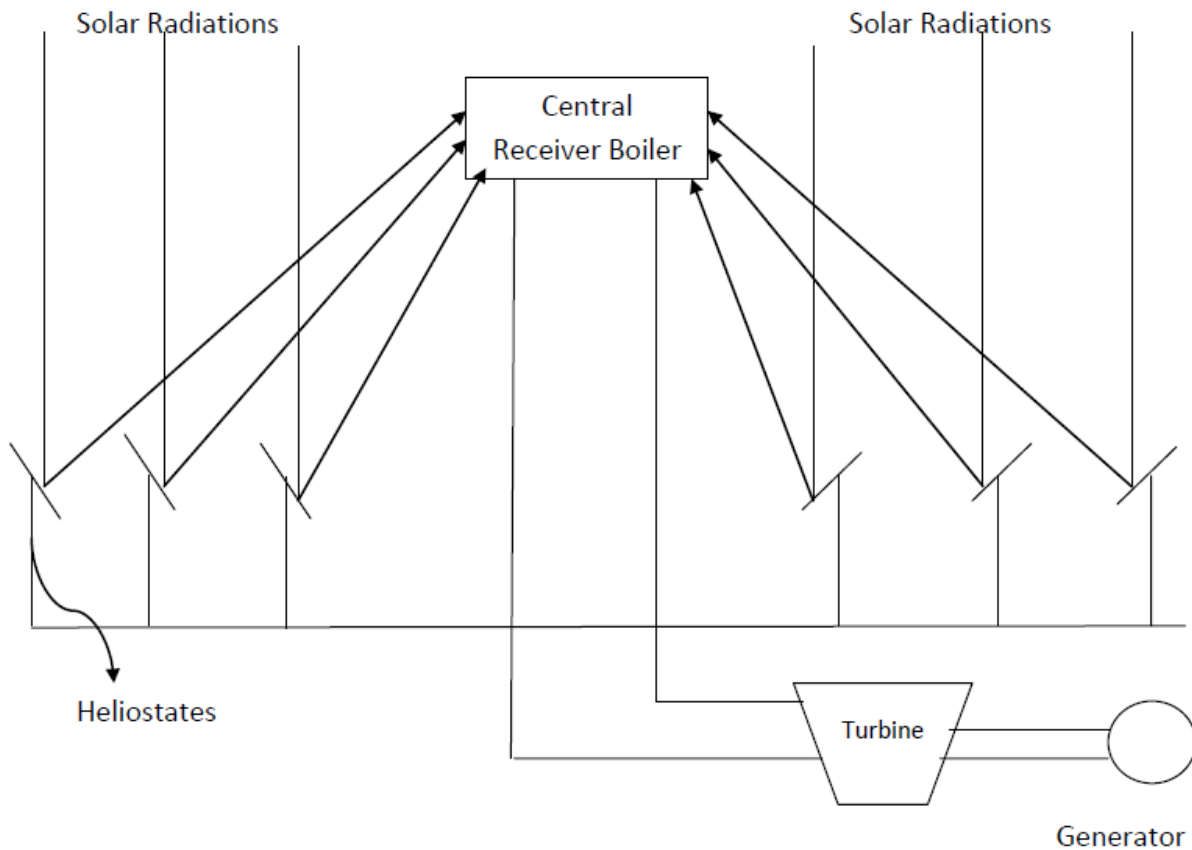
Fig. 2.7 Solar central receiver electrical power plant

In this system, a large number of linear reflectors are used. These are called heliostat. Heliostat focus on the central receiver as shown in the figure

When solar radiations fall on heliostat, sun rays after getting reflected from the heliostat are focused on the boiler.

The output of boiler is high temperature steam which is provided to the turbine. This will rotate turbine. As the generator is also coupled with the turbine so with the rotation of turbine, generator will also rotate and electricity will produce.

2.3 Thermal energy storage for solar heating and cooling-

Thermal energy storage is essential for both domestic water and space heating applications. Thermal energy can be stored in well insulated fluids or solids.

There are two ways for thermal energy storage namely sensible heat storage and latent heat storage.

2.3.1 Sensible heat storage-

In sensible heat storage the temperature of the medium changes during charging and discharging of the storage

In this, there is no change in phase. The basic equation for energy storage is given by

$Q = mc_p\Delta T$ ------------------------------- (2.2)

Where

Q- Total thermal capacity

m- Mass of storage medium

c_p- Specific heat

Heat stored per unit volume (Q/Vs) is given by

$$\frac{mCp\,\Delta T}{Vs}$$ ------------------------------------ (2.3)

Where Vs is the volume of the given storage container

Water is generally used for storing thermal energy at low temperature. Heat transfer oils are used in sensible heat storage system for temperature range 100 - 300°C

Solid materials like rocks, metals, concrete, sand and bricks etc. are also used for thermal storage.

Water is also used as heat transfer fluid for heat flow to and from (but the temperature range is limited)

2.3.2 Latent heat storage-

In latent heat storage, the temperature of the medium remains more or less constant, since it undergoes a phase transformation ie. The transition from solid to liquid or liquid to vapour

In a latent heat storage system, the heat is stored in a material when it melts and heat is extracted from material when it freezes example of such materials are paraffin wax, calcium chloride hexahydrate, magnesium nitrate hexahydrate, ice, sodium hydroxide etc.

For latent heat storage charging, phase transition solid- liquid (melting) is most suitable and for storage discharging, liquid- solid (solidification) is most suitable.

The basic equation for energy storage is given by

$Q = m [C_s(t_m - t_{min}) + h_m + C_L(t_{max} - t_m)]$ joule --------------------------------(2.4)

Where

m- Mass of phase change material (PCM) storage medium

C_s- Specific heat of PCM – solid state (J/KgK)

C_L- Specific heat of PCM – liquid state (J/KgK)

h_m – Specific melting enthalpy of PCM storage medium (J/Kg)

t_{min}- Minimum storage temperature (°C)

t_{max}- maximum storage temperature (°C)

t_m- Melting temperature of PCM storage medium (°C)

the latent heat storage charging process comprises three stages-

First stage is heating of the phase change material in solid state

Second stage is melting of phase change material at constant temperature for pure substance or in the range of temperatures for mixed composition

Third stage involve heating of the molten phase change material to the maximum temperature (t_{max})

2.4 Limitations of Solar thermal energy

- Low energy density 0.1 to 1 KW/ m^2
- Large area is required to collect solar thermal energy
- Direction of rays changes continuously with time
- Energy not available during night and during clouds
- Energy storage is essential
- It has high cost
- Solar central power plants in MW range are not economical

Chapter 3

Solar photovoltaic (PV) and application

3.1 Solar photovoltaic (PV) energy conversion (Photovoltaic effect) -
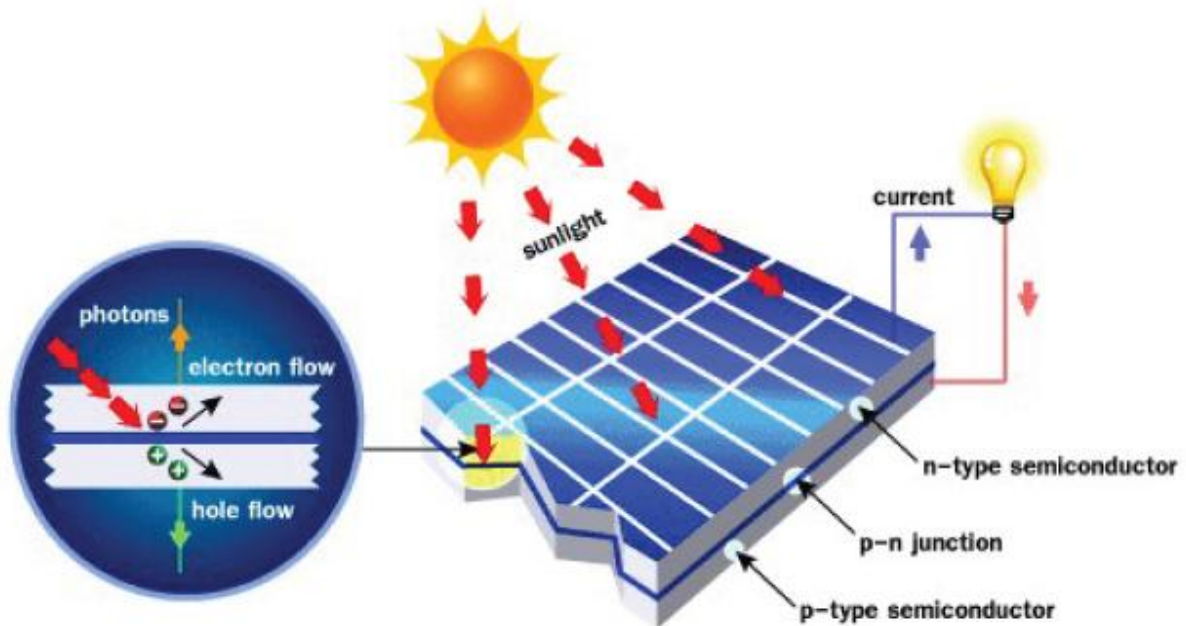
Fig. 3.1 Photovoltaic effect

A solar cell is nothing but a PN junction diode under light illumination. Sun light can be converted into electricity due to photovoltaic effect. Sun light composed of photons (packets of energy). These photons contain various amount of energy corresponding to different wave lengths of light. When photons strike a solar cell they may be reflected or absorbed or pass through the cell. When solar radiation is absorbed in PN junction diode, electron-hole pairs (EHP) are generated.

- Electron hole pair (EHP) generated in depletion layer-

    Electrons of EHP will be repealed towards N side because of electric field and holes of EHP will be repealed towards P side because of electric field.

- Electron hole pair (EHP) generated in quasi neutral region-

    In this region, the electron and holes of EHP will wander around in the region randomly. There is no electric force to guide them in any direction.

- Minority carriers of P and N regions-

    The minority carrier near the depletion region will also get direction by electric field.

In this way there will be increase of positive charge at P side and increase of negative charge at N side. This build up of positive and negative charge causes a potential difference to appear across the PN junction due to light falling on it. This generation of photo voltage is known as photovoltaic effect.

3.2 Performance analysis of photovoltaic (PV) cell –
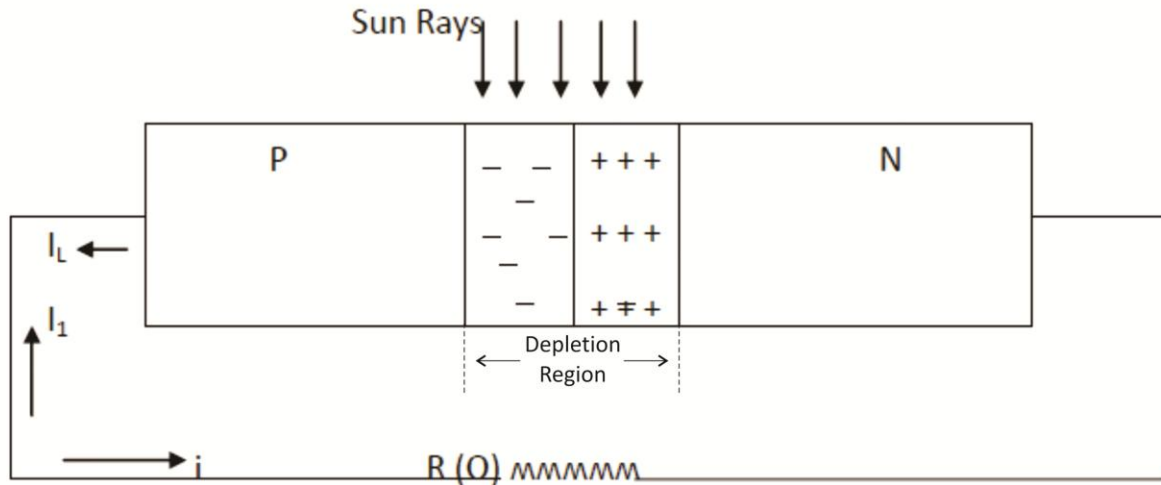
Fig. 3.2 Photovoltaic cell performance

Consider a PN junction with resistive load as shown in figure. When solar cell is illuminated, electron hole pair is generated in the depletion region. This electron hole pair when separated from each other across junction then a current (I_L) flows in external circuit by photovoltaic effect.

This photo current (I_L) produces a voltage drop across resistive load and this voltage will forward bias the PN junction. Forward bias voltage produces forward current (I_1).

So the net current will be, $I = I_L - I_1$

$$I = I(L) - I(0)\left[\exp\left(\frac{ev}{kT}\right) - 1\right]$$ ------------------- (3.1)

3.2.1 Short circuit current (I_{SC})-

When R=0 and V = 0 then I_1 =0

so I = I_L = I_{SC} -- (3.2)

3.2.2 Open circuit voltage (V_{OC})-

When R=∞ then I = 0

$$0 = \text{I(L)} - \text{I(0)}[\exp\left(\frac{ev}{kT}\right) - 1]$$

$$\text{I(L)} = \text{I(0)}[\exp\left(\frac{ev}{kT}\right) - 1]$$

$$\text{Voc} = \frac{kT}{e}\left[\ln\left(1 + \frac{I(L)}{I(0)}\right)\right]$$ -- (3.3)

3.2.3 Power delivered to load-

P= V.I

$$\text{P}= \text{V}. \left[\text{I(L)} - \text{I(0)}\left[\exp\left(\frac{ev}{kT}\right) - 1\right]\right]$$

for maximum power delivered to load, $\frac{dP}{dV} = 0$

By solving, $1 + \frac{I(L)}{I(0)} = \exp\left(\frac{e.Vm}{kT}\right) . \left[1 + \frac{e.Vm}{kT}\right]$ ------------------------- (3.4)

Where Vm is the voltage which produces maximum power

3.2.4 Maximum Current -

If we put the value of " $\exp\left(\frac{e.Vm}{kT}\right)$ " from equation 4 to equation 1, we get the maximum value of current (Im)

3.2.5 Maximum Power -.

the maximum power is obtained by multiplying vm and Im

$$\text{Pm} = \text{Vm.Im} = Vm\frac{e.Vm.(IL+Io)/kT}{1+eVm/kT}$$ -- (3.5)
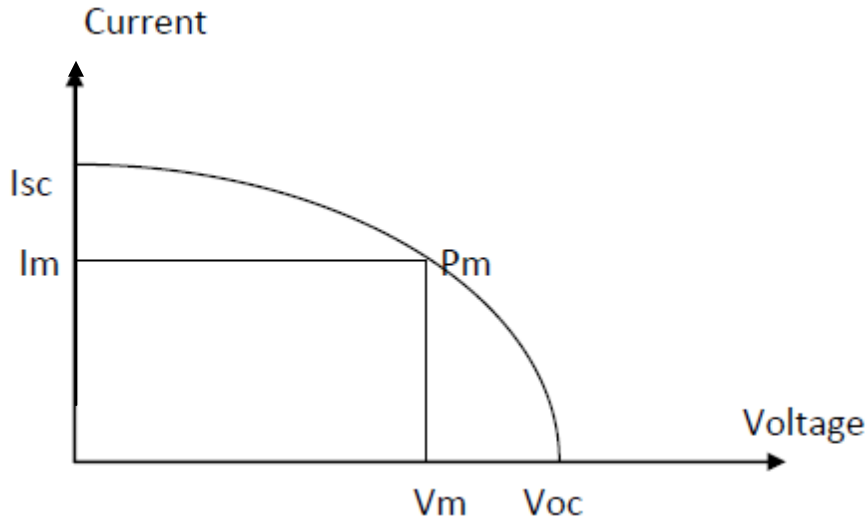
Fig. 3.3 I-V characteristics of solar cell

3.2.6 Efficiency of solar cell-

Conversion efficiency of solar cell is defined as the ratio of output power to incident optical power. For maximum power output,

$$\%n = \frac{Pm}{Pin} \times 100$$

$$\%n = \frac{Vm.Im}{I.A} \times 100 \text{ --- (3.6)}$$

Where, Pm- maximum power(watt), Pin- input power(Watt), Vm- maximum voltage(Volt), Im- maximum current(Amp), I- solar intensity(watt/m^2), A- area(m^2)

3.2.7 Fill Factor (FF)-

It is the ratio of maximum power to the product of Voc and Isc

$$FF = \frac{Vm.Im}{Voc.Isc} \text{ --- (3.7)}$$

3.2.8 Limitation of solar cell -

There are several factors that limit the efficiency of solar cells, these are:

Photons with energy below the band gap energy, cannot generate electron hole pair so there energy is not converted into useful output. These electron generate only heat and reduces the electrical efficiency of solar cell

Photons with energy above the band gap energy, only a fraction of energy is used for generating free electrons for conduction. Remaining energy will produce heat and reduce electrical efficiency of solar cells.

When sun light fall on solar cell, some part of it is reflected back, some part is absorbed and some part is transmitted, only absorbed solar light is converted into electricity so its efficiency is poor

Example 1: Calculate Fill factor, maximum power and cell efficiency with following parameters- Voc= 0.24 volt, Isc= 10mAmp, Vm= 0.14 volt, Im= 6.5 mAmp., Intensity = 24 W/m^2, Area= 4 cm^2

Solution-

$$FF = \frac{0.14 \times 0.0065}{0.24 \times 0.001} = 0.379$$

Pm = Vm × Im = 0.91 m Watt

$$\%n = \frac{0.14 \times 0.0065}{24 \times 0.0004} \times 100 = 9.48 \%$$

3.3 Solar cell material -

The solar cells are made of various materials. Silicon is the most commonly used material for solar cells. The electrical properties of silicon depend on the type and amount of dopants. Phosphorous and boron are most widely used doner and accepter dopant respectively.

The choice of material depends upon the energy gap, efficiency and cost. In order to reduce the cost, the level of efficiency should be high. The cost can be reduced by using thin film technology. A variety of compound semiconductor are to be used to manufacture thin film solar cell. These materials are CdS, CdTe, InP, GaAs, ZnTe, AlSb (Aluminium Antimonide).

Table 3.1 Energy Gap of some materials

Material	Energy Gap (ev)
Si	1.1
CdTe	1.44
CdS	2.42
GaAs	1.40
InP	1.27
ZnTe	2.2
AlSb	1.63

According to types of crystal, the solar cells are of three types

First is mono crystalline silicon cells (Maximum efficiency= 24%)

Second is poly crystalline silicon cells (Maximum efficiency= 17.8%)

Third is amorphous silicon cell (Maximum efficiency= 13%)

3.4 Solar Cells, Solar Modules and Solar Array-

Solar cell is basic unit of solar electricity generator. It is made up of semiconductor material. When sun light falls on solar cells, it produces electricity by photovoltaic effect. One solar cell produces 0.5 Volt DC voltages.

Current = I_{cell}
Voltage = 3 x V_{cell}
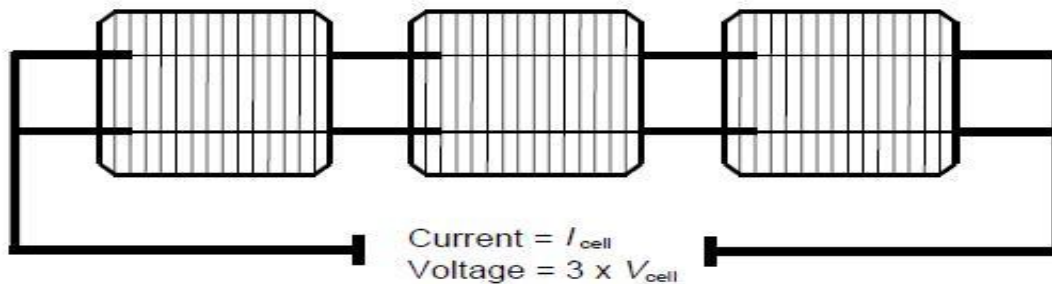
Fig. 3.4 Series connection of three solar cells

When solar cells are connected in series to produce high voltage, it is called as solar module. The number of solar cells in solar module is determined by the required voltage. Generally solar modules are made to produce output voltage of 18 Volt DC voltage

(Voltage of one solar cell) × (Number of solar cells) = Output of solar module ------------- (3.8)

By using this formula, we can say that 36 solar cells of 0.5 Volt each will be required for producing 18 Volt output voltage module. These 36 solar cells will be connected in series as shown in the figure
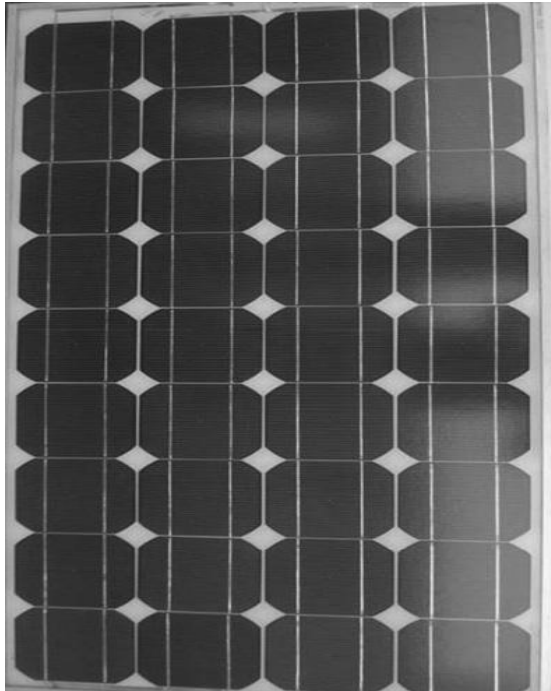
3.5 (a) Opaque PV Module   **3.5(b) Semitransparent PV Module**

Solar modules are of two types namely Opaque module and Semitransparent module. In opaque modules, front side is transparent glass cover and back side is insulating tedler material which is not transparent.

In semitransparent type module, both the front and back side is transparent glass cover (ethyle vinyl acetate).

Packing factor (PF) is defined as the ratio of area covered by solar cell to the area of PV module. In case of rectangular solar cells, packing factor is 1.

Area covered by solar cell = Area of PV module × Packing Factor -------------------------- (3.9)

Non packing factor area (Area between two solar cells) = (1 - PF) × Module Area ------- (3.10)

The efficiency of semitransparent module is higher than opaque module because in semitransparent PV module only un-used solar energy by cell is responsible for raising the cell temperature and energy received by space between two solar cells is transmitted outside so it is not responsible for increment in temperature ie. Top heat loss and bottom heat loss is more in semitransparent PV module.

While in case of opaque module, energy received by space between two solar cells is reflected back so it also responsible for increment in temperature ie. Top heat loss and bottom heat loss is less in opaque PV module.

From semitransparent PV module, we get electrical energy, space heating and illumination while from opaque PV module, we get electrical energy and space heating only.

When sun rays falls on PV module, heat s transferred inside by convection. To regulate this heat, we have to provide force movement of air from top to bottom. For this, use a DC fan.

When solar modules are electrically connected in series or parallel, the arrangement is called solar array / solar generator. For series connection of two solar modules, the plus terminal of one module is connected to the minus terminal of second module. When two modules are connected in series then total output voltage will be 24 Volt.
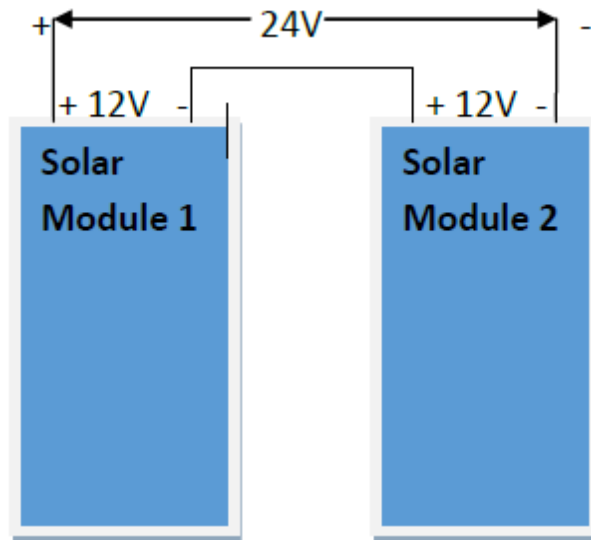
Fig. 3.6 Series connection of two PV Modules to form a PV array

For increasing output current and power, a number of modules are connected in parallel. The modules which are being connected in parallel, they must have same output voltage.

No. of modules connected in parallel $(Np) = \dfrac{\text{Operating current of Solar Array}}{\text{Current of Solar Module}}$ ------------- (3.11)

No. of modules connected in series $(Ns) = \dfrac{\text{Operating voltage of Solar Array}}{\text{Voltage of Solar Module}}$ ------------- (3.12)

Total no. of modules in solar generator$= Ns \times Np$ -------------------------- (3.13)

Example 2: The semitransparent and opaque PV modules are tested under sun light in order to measure the module parameters. The intensity of sun light is measured by solarimeter, which is 746 W/m^2 and the area of each module is 0.61 m^2.

The module voltage, current and power is measured by multimeter under variable load condition. These measurements are shown below in observation tables

Semitransparent module			Opaque module		
V (Volt)	**I (Amp.)**	**P (Watt)**	**V (Volt)**	**I (Amp.)**	**P (Watt)**
0.0	2.4	0.0	0.0	1.8	0.0
2.7	2.1	5.67	0.2	1.7	0.34
8.9	2.0	17.80	1.5	1.6	2.40
12.0	1.8	21.60	7.1	1.5	10.65
14.1	1.7	23.97	9.6	1.4	13.44
14.6	1.6	23.36	12.8	1.3	16.64
15.4	1.5	23.10	14.2	1.2	17.04
16.8	1.0	16.80	14.6	1.0	14.60
17.0	0.8	13.60	14.9	0.8	11.92
18.0	0.0	0.0	15.6	0.0	0.0

(I) Draw Current vs Voltage & Power vs Voltage characteristics for both the modules

(II) Find open circuit voltage & short circuit current for both the modules

(III) Calculate Fill factor for both the modules

(IV) Calculate the efficiency of both the modules

Solution

    (I)   Current vs Voltage & Power vs Voltage characteristics of semitransparent module:
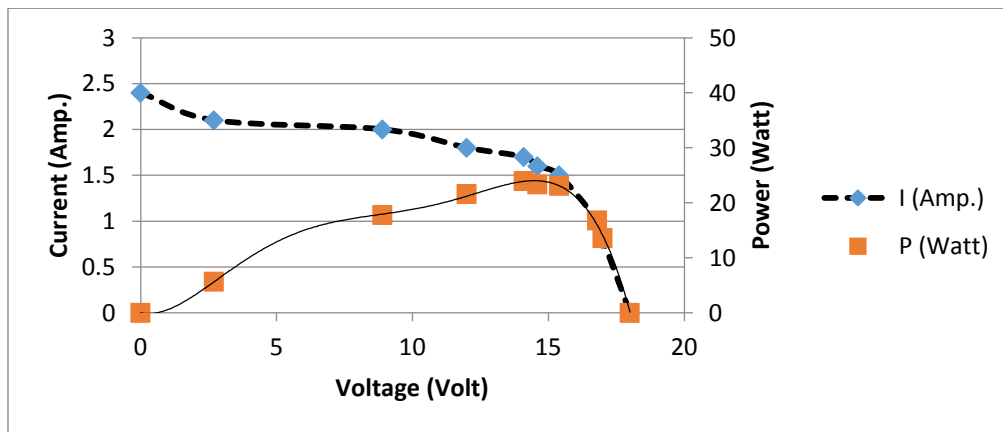
Current vs Voltage & Power vs Voltage characteristics of opaque modules:
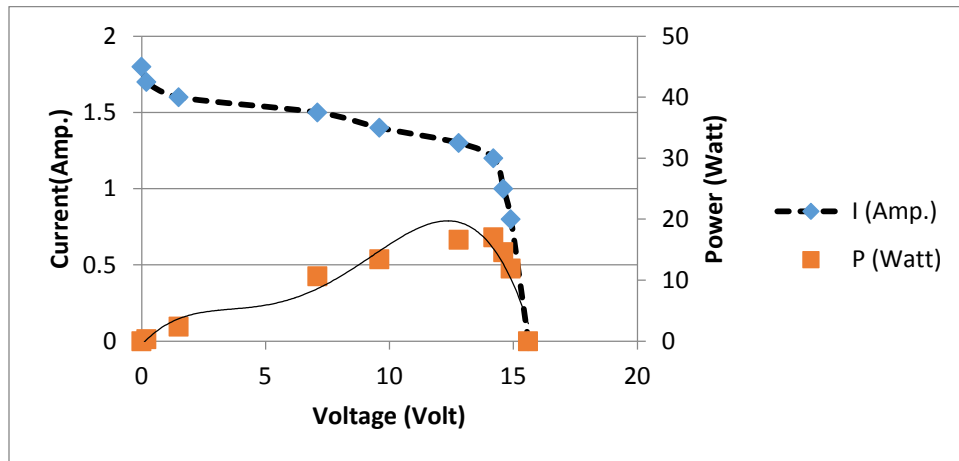
(II)   **Open circuit voltage:** it is the voltage when the current flowing through the PV module is zero ie. It is the voltage measured when no load is connected with PV circuit.

The open circuit voltage is measured across the open terminals of circuit.

By observation table of semitransparent module, when current (I) is zero then voltage measured is 18 vollt.

So, Voc = 18 Volt (for semitransparent module)

Similarly Voc = 15.6 Volt (for opaque module)

Short circuit current: it is the current when the voltage across the PV module terminal is zero ie. It is the current measured when there is short circuit (R=0 Ω) with PV circuit.

The short circuit current is measured across the shorted terminals of circuit.

By observation table of semitransparent module, when voltage (V) is zero then current measured is 2.4 Amp.

So, Isc = 2.4 Amp. (For semitransparent module)

Similarly Isc = 1.8 Amp (For opaque module)

(III)   **Fill Factor:**

$$FF = \frac{Vm.\ Im}{Voc.\ ISC}$$

For semitransparent module:

From the characteristics curve of semitransparent PV module,

Vm. Im = Pm= 24 Watt, Voc = 18 Volt, Isc = 2.4 Amp.

Hence, $FF = \frac{24}{18 \times 2.4} = 0.55$

For opaque module:

From the characteristics curve of opaque PV module,

Vm. Im = Pm= 20 Watt, Voc = 15.6 Volt, Isc = 1.8 Amp.

Hence, $FF = \dfrac{20}{15.6 \times 1.8} = 0.71$

(IV)   Electrical efficiency of modules:

Electrical efficiency of module is given by

$$\eta_m = \frac{\text{Max. Power}}{\text{Intensity} \times \text{Module Area}}$$

For semitransparent module:

$$\eta_m = \frac{24}{746 \times 0.61} \times 100 = 5.27\ \%$$

For opaque module:

$$\eta_m = \frac{20}{746 \times 0.61} \times 100 = 4.39\ \%$$

The output power of opaque PV module is less than semitransparent PV module because in opaque PV module, the glass cover is used on front side of module and insulating material (white tedlar) is used on back side of module. In opaque PV module, the unused solar energy in solar cells of module is responsible to raise the solar cell temperature and the energy received by the space between two solar cells (non packing area) is also responsible for increasing the cell temperature. In semi transparent PV module, the glass cover is used on both front and back side of module. In it whatever solar energy falls on non packing area goes directly out which is called as direct gain. So in such modules, only unused solar energy is responsible to raise the cell temperature. The bottom heat loss is less in opaque module in comparison to the semitransparent module because of insulating material (white tedlar) at its back surface and this is responsible for increasing the cell temperature of opaque PV modules. When the cell temperature increases, the saturation current also increases with intrinsic carrier concentration so the open circuit voltage of module reduces and the short circuit current of module increases. But the effect of increasing module temperature on short circuit current is small than open circuit voltage so the overall effect of increased module temperature is a reduction in output power of module hence the efficiency of module reduces.

3.5 <u>Solar power Plant</u>-

Solar cell power plants are of two types namely autonomous power plant (Off grid power plant) and Grid connected power plants.

3.5.1 Autonomous Solar Power Plant-
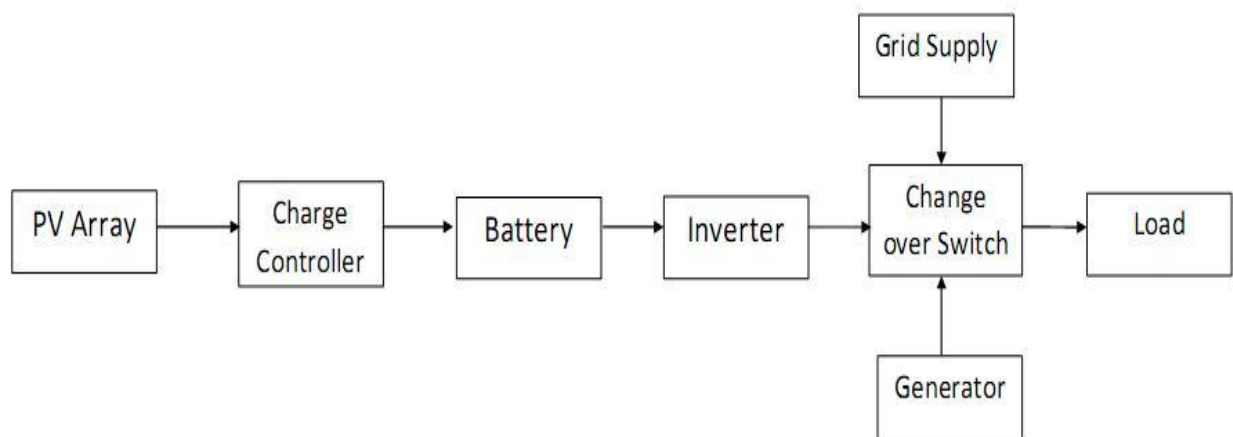
Fig. 3.7 Block diagram of off grid / autonomous solar plant

Description of different components of Installed PV System:

PV Array

In this system, PV modules are connected in parallel and mounted on an inclined structure. The inclination of the system is kept at latitude of location to receive maximum annual insolation.

Charge Controller

This device regulates rates of flow of electricity from the PV Array to the battery and the load. This controller keeps the battery full charged without over charging it. When the load is drawing power, the controller allows the charge to flow from the PV Array into the battery, the load or

both. When the controller senses that the battery is fully charged, it reduces or stops the flow of electricity from the PV Array.

A charge controller may be used to power DC equipment with solar panels. The charge controller provides a regulated DC output and stores excess energy in a battery as well as monitoring the battery voltage to prevent under /over charging, it will also perform maximum power point tracking.

Inverter

An inverter converts the DC electricity from sources such as battery to AC electricity. The electricity can be at any required voltage; in particular it can operate AC equipment designed for mains operation, or rectified to produce DC at any desired voltage.

A solar inverter or PV inverter is a critical component in a photovoltaic system. It converts the variable DC output of the solar panel into a utility frequency alternating current that can be fed into the commercial electrical grid or used by a local, off-grid electrical network. Solar inverters have special functions adapted for use with PV arrays, including *maximum power point tracking*

- **Stand-alone inverters**, used in isolated systems where the inverter draws its DC energy from batteries charged by photovoltaic arrays. Many stand-alone inverters also incorporate integral battery chargers to replenish the battery from an AC source, when available.
- **Maximum power point tracking** is a technique that solar inverters use to get the maximum possible power from the PV array. Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency known as the *I-V curve*. It is the purpose of the MPPT system to sample the output of the cells and apply a resistance (load) to obtain maximum power for any given environmental conditions. Essentially, this defines the current that the inverter should draw from the PV in order to get the maximum possible power (since power equals voltage times current).

Battery

A battery stores electricity produced by a solar electric system. The energy storage capacity of a battery is measured in watt-hours, which is the amp-hour rating times the voltage.

Kerosene Generator

Generators are useful appliances that supply electrical power during a power outage and prevent discontinuity.

An electric generator is a device that converts mechanical energy obtained from an external source into electrical energy as the output.

Working of Installed PV System:

PV Modules use light energy (photons) from the sun to generate electricity through the photovoltaic effect. The output of PV Array is given to the charge controller. Charge controller regulates rates of flow of electricity from the PV Array to the battery and the load. This controller keeps the battery full charged without over charging it. The output of charge controller is given to the Battery. This stores electricity produced by a solar electric system. Now the battery output is connected with inverter input. An inverter converts the DC electricity from This AC output of Inverter is now provided to the load connected with it.

When battery is not sufficiently charged to supply the loads, Generator is used.

3.5.2 Grid connected solar power plants-
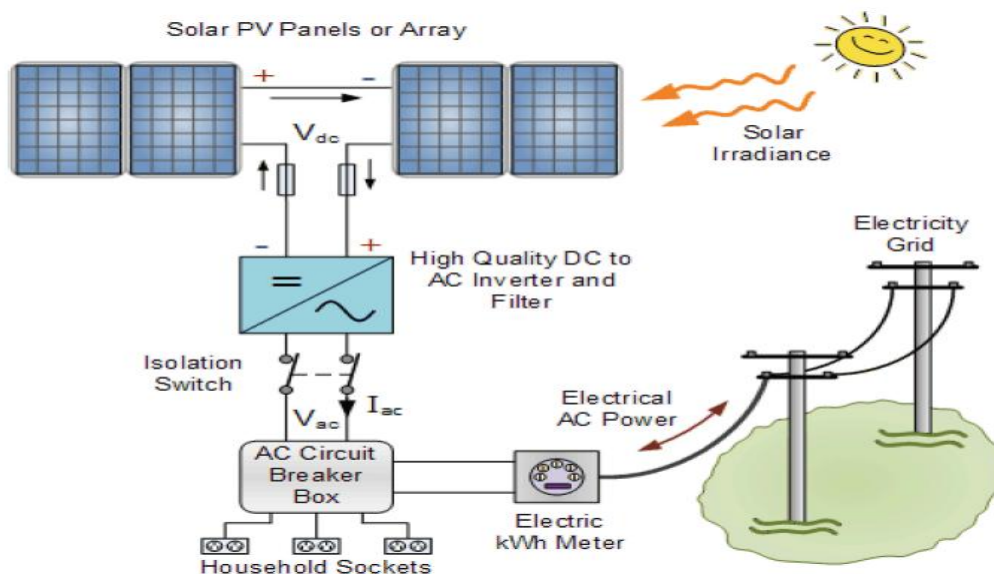
Fig.3.8 Grid connected solar power plant

In grid connected system power is fed into the grid during day time and taking power from the grid during night. PV array supplies the current only when sun light fall on it, Photovoltaic array produces DC power and this must be converted into ac power for local use and feeding into grid so inverters are used along with PV array. Inverter converts DC supply into AC and feeds the solar power to grid or supply to the consumer. In case of low power availability from PV generator, the local load can be fed from the grid (as shown in diagram)

At the time of excessive generation, the energy can be stored and maybe used at the time of low generation. Regulation and dispatch unit regulates the flow of power from photovoltaic power system into grid and vice-versa.

Grid connected system require additional components to regulate voltage, frequency, and waveform to meet the requirement of feeding the power into grid

3.6 <u>Limitations of solar photovoltaic energy conversion</u>-

- High initial cost
- Irregular supply of solar energy
- Require battery storage for supply power at night
- Low efficiency
- Require large area
- Do not generate power during cloudy season

Chapter 4

Economics of Solar Systmes

4.1 Economics of renewable energy system-

Economics of any system is based on cost and benefit analysis.

Cost of system involve

- Initial cost ie. Capital cost (Co at t = 0). It include cost of purchase, installation, training to be given to user
- Cost of operation
- Cost of maintenance and replacement of items
- Incremental cost (property) - tax

Benefits which we get from the system are of two types namely tangible benefits and intangible benefits. Tangible benefits can be converted in to monetary terms but intangible benefits cannot be converted in to monetary terms.

Tangible benefits of system are monetary worth of fuel saved, temporal & spatial dimension (besides being user specific). While intangible benefits are reduced environment emission, employment generation etc.

4.2 Economics of solar system-

Economics of solar system is based on cost and benefit analysis of solar system. The costs of solar energy system are-

- Capital cost- Solar energy harnessing will involve high capital cost because a large area needs to be used for PV installation
- Cost of operation is low
- Repair and maintenance will also be low
- Property tax will increase annually so solar energy sources are cost intensive

The benefits of solar energy system are-

- If solar energy replacing straw then it is not lucrative, generally solar energy installation are set to live long life span (about 40 years). These benefits are called tangible benefits this means the benefits which can be converted in to monetary worth.
- While intangible benefits are reduced environment emission, employment generation etc.

4.3 Cash Flow diagram-

A pictorial representation of cash flow of a project is used for economical analysis of system. This representation includes both cost and benefits as shown in the *cash flow diagram* below
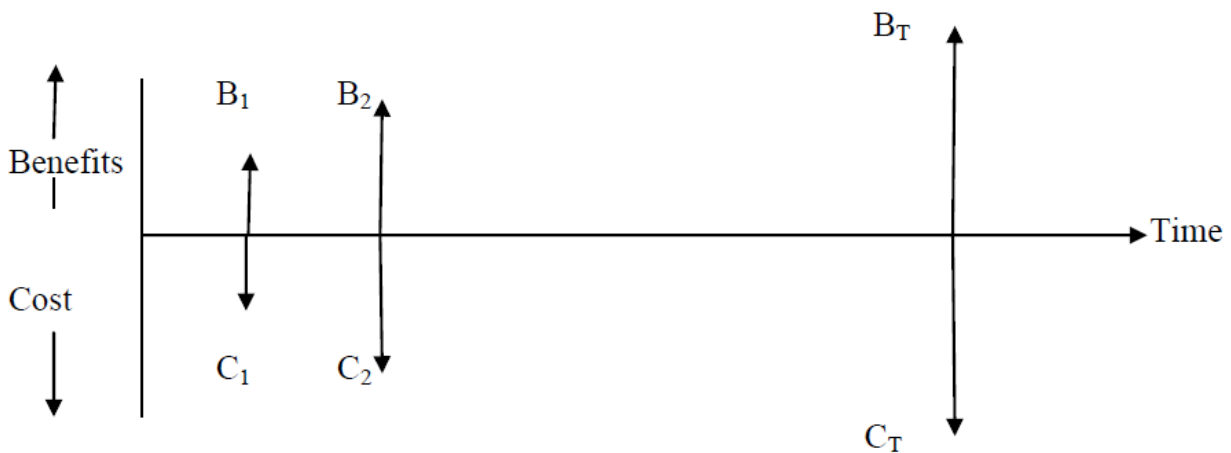
Fig.4.1 Cash flow diagram for benefit – cost analysis

Money has time value ie. Value of money for user changes with time, value at t=T is less than value at t= T +ΔT because the same money can be invested over the time period of ΔT

Hence benefits or costs cannot be algebraically added over the total period in the cash flow diagram instead bring benefits and costs in a common time frame then add all benefits together and add all costs together then subtract total benefits with total costs.

4.4 Time value of money-

With time, the value of money changes, if one invest Rs 'X' at t = 0, then at an annual return of Rs 'r', he will get back X (1 + r) after one year

       X   X {1 + r}

   (At t=0)   (At t=1)

Also purchasing power of money changes with time. So, if annual inflation rate be 'I', then after one year it will become (1 + I)

So to accommodate these two factors in cash flow diagram, we define a term 'discount rate' to express the time value of money from one reference frame to another reference frame.

If one invest Rs 'X' at t = 0, then at an discount rate of Rs'd', it will become X (1 + d) after one year

So, $X (1 + d) = \dfrac{X (1+r)}{(1+I)}$

$$d = \dfrac{r-I}{1+I}$$

'd' value insures that value of money is same at t=0 & t=1, taking into account the rate of inflation. Rupees 100 today in bank returned at a discounted rate of 10% would give Rs 110 where both 100 & 110 hold values what Rs 100 holds today.

Inflation rate 'I' varies from country to country and from time to time.

4.4.1 Equivalence formula involving time value of money:

- A single cash flow at present (t=0)

  to

  An equivalent 'single' cash flow at t=T in future

- A 'single' cash flow expected in future at t=T

  to

  An equivalent present (t=0) value of expected cash flow in future

- A series of cash flows at regular periodic intervals of time between present t=0 and t=T in future

  to

  An equivalent single value in future at t=T

- A single cash flow expected in future at t=T

  to

  An equivalent series of uniform cash flows from present (t=0) to time (t=T) in future

Equivalent value of 'P' at the end of 1st year = P (1+d)

Equivalent value of 'P' at the end of 2nd year = P (1+d) + P (1+d) d

$$= P (1+d)^2$$

Equivalent value of 'P' at the end of Tth year = P (1+d)^T

Single cash flow compound amount factor, $\frac{F}{P} = (1+d)^T$

Single cash flow present worth factor, $\frac{P}{F} = (1+d)^{-T}$

Example1: solar plant construction

Generally the time from which the solar plant starts working is taken as t=0. But before this a lot of money is invested at different years as shown in the cash flow diagram below
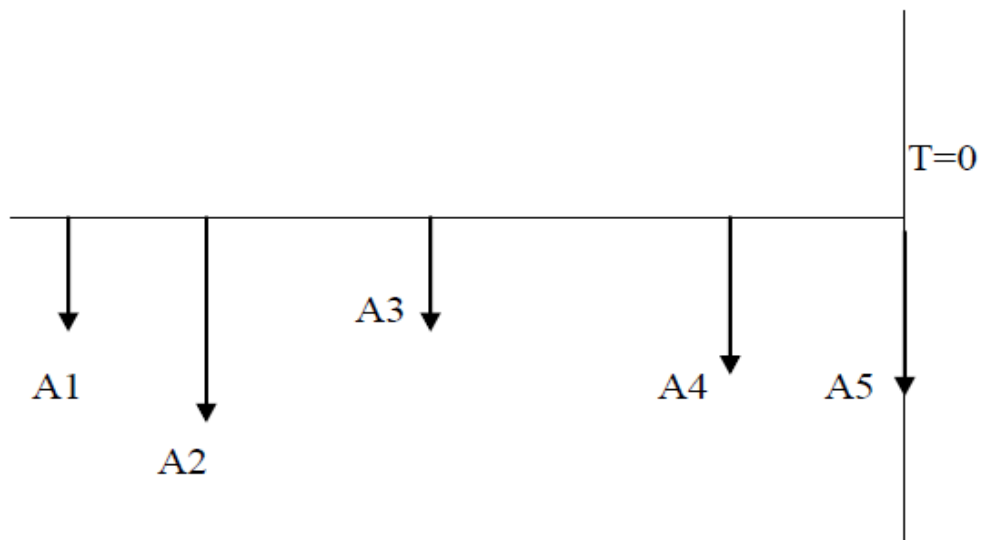
Fig. 4.2 Cash flow analysis for construction of a solar plant

C_0 = A5 + A4 (1+d) + A3 (1+d)^2 + A2 (1+d)^3 +A1 (1+d)^4 ---------------------------------- (4.1)

Where 'C0' is the cost at time t=0

    'd' is discount rate

    A1, A2, A3, A4, A5 are the expenditure on construction of plant

4.5 Salvage value:

It is the value of a project at the end of useful life. If the salvage value at the end of useful life (at t= T) is 'S' then its equivalent value at present (t=0) will be S / (1+d)^T

Salvage value is converted to t=0 time frame so that it can be compared with the cost invested. This is also termed as equivalent present value of expected cash flow in future and is given by formula- $S / (1+d)^T$.

(Where 'T' is the life of project and 'S' is the salvage value at T^{th} year)

The salvage value of a project may also be negative for example in case of solar PV system, to dispose a lot of lead acid battery safely; we need to spend money for it instead of getting the same.

4.6 Profit cost analysis:

The profit cost analysis can be done either by bringing everything to present or by bringing everything to future.

4.6.1 Profit cost analysis by converting to future time frame

Consider a cash flow diagram as shown below
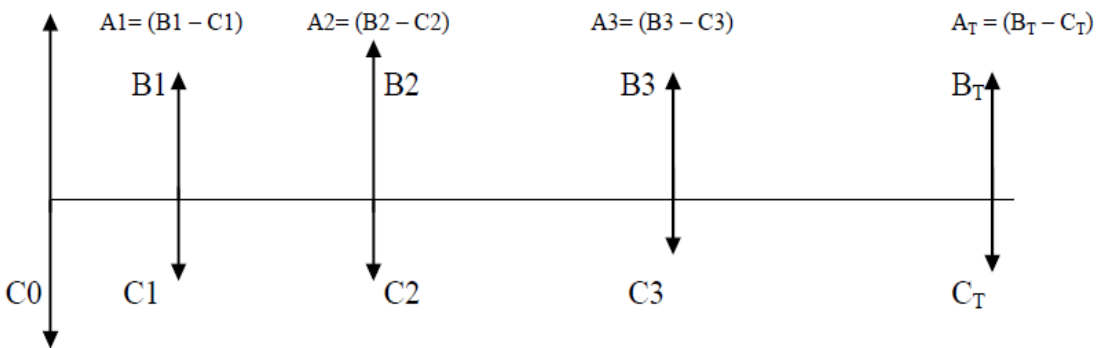
Fig. 4.3 Cash flow diagram

The installation cost of solar power plant is C0. After completion of one year from the installation, the benefit is B1 and maintenance cost is C1 so the net profit will be A1 (=B1 – C1). Similarly at the end of second year the net profit is A2 (=B2 – C2) and so on.

Now converting all the values into future time frame , cumulative future worth of all series cash flows at t = T

F= A1 $(1+d)^{T-1}$ + A2 $(1+d)^{T-2}$ + -------- + Aj $(1+d)^{T-j}$ + ------- + A_T

F= $\sum$ Aj $(1 + d)^{T-j}$

Special case: if $A_j = A$ $\forall\, j = 1,2, ... T$ (uniform series of cash flow)

$F = A\,(1+d)^{T-1} + A\,(1+d)^{T-2} + \text{--------} + A\,(1+d)^{T-j} + \text{-------} + A$

$F = A\,[\dfrac{(1+d)^T - 1}{(1+d)- 1}]$

$F = A\,[\dfrac{(1+d)^T - 1}{d}]$

- Uniform series compound amount factor:

$$\dfrac{F}{A} = [\dfrac{(1+d)^T - 1}{d}] \text{ --------------------------------- (4.2)}$$

- Uniform series sinking fund factor:

$$\dfrac{A}{F} = \dfrac{d}{(1+d)^T - 1} \text{ -- (4.3)}$$

- 'A' would give the amount to be saved every year so that after 'T' years, 'F' amount can be generated.

$$A = \dfrac{F\cdot d}{(1+d)^T - 1} \text{ -- (4.4)}$$

Where there is replacement cost such as batteries of PV system which has to be replaced every 5 years (suppose) then villagers need to save Rs 'A' every year to be able to collect cost of replacement 'F' after 5 years

4.6.2 Profit cost analysis by converting to 't=0' time frame

Consider a cash flow diagram as shown below
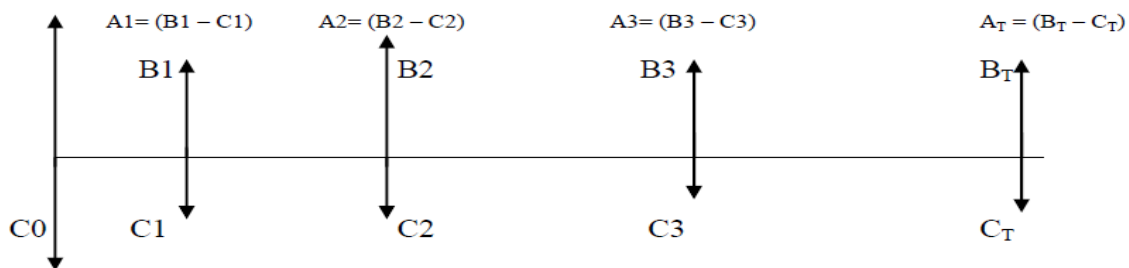
Fig. 4.4 Cash flow diagram

The installation cost of solar power plant is C0. After completion of one year from the installation, the benefit is B1 and maintenance cost is C1 so the net profit will be A1 (=B1 − C1). Similarly at the end of second year the net profit is A2 (=B2 − C2) and so on.

Now converting all the values into time t=0 frame, cumulative present worth of a series of cash flows,

$$P = \frac{A1}{(1+d)} + \frac{A2}{(1+d)^2} + \ldots\ldots\ldots + \frac{Aj}{(1+d)^j} + \ldots\ldots + \frac{AT}{(1+d)^T}$$

$$P = \frac{A}{(1+d)} \left[\frac{1 - \left\{\frac{1}{1+d}\right\}^T}{1 - \left\{\frac{1}{1+d}\right\}} \right]$$

Special case: if Aj = A   ∀ j = 1,2, ... T (uniform series of cash flow)

$$P = A \left[\frac{(1+d)^T - 1}{d\ (1+d)^T} \right] \text{--- (4.5)}$$

- Uniform series present worth factor

$$\frac{P}{A} = \left[\frac{(1+d)^T - 1}{d\ (1+d)^T} \right] \text{--------------------------------------- (4.6)}$$

- Uniform series capital recovery factor

$$\frac{A}{P} = \left[\frac{d\ (1+d)^T}{(1+d)^T - 1} \right] \text{--------------------------------------- (4.7)}$$

   It is used for EMI calculations

Example 2: Capital cost of box type solar cooker is Rs. 2500. Its net annual benefit is Rs. 800 for expected life of 10 years and discount rate is 0.10. By considering its zero salvage value, draw the cash flow diagram and calculate cumulative present value.

Solution: C0=Rs.2500, A= Rs. 800, d=0.10, T=10 years, S=0
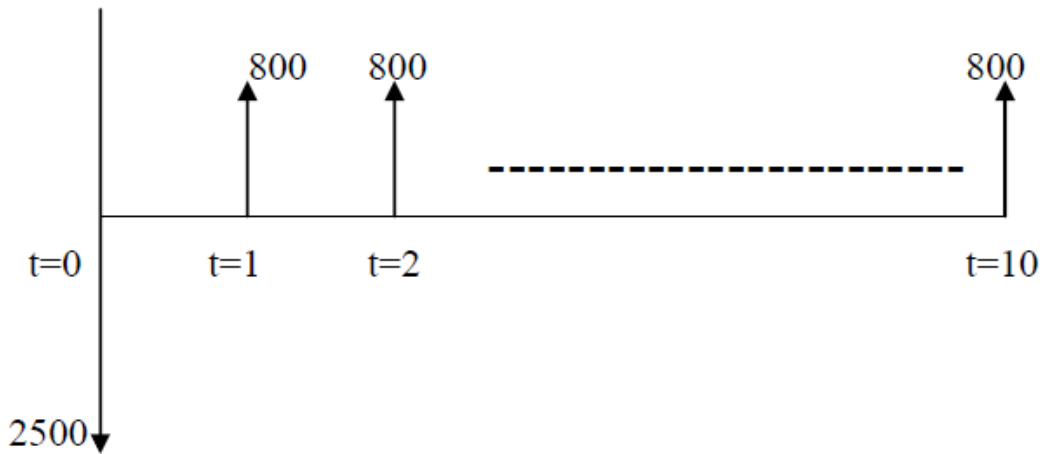
$$P = A \left[\frac{(1+d)^{T}-1}{d\,(1+d)^{T}}\right]$$

$$P = 800 \left[\frac{(1+0.1)^{10}-1}{0.1\,(1+0.1)^{10}}\right]$$

$$= Rs\ 4915$$
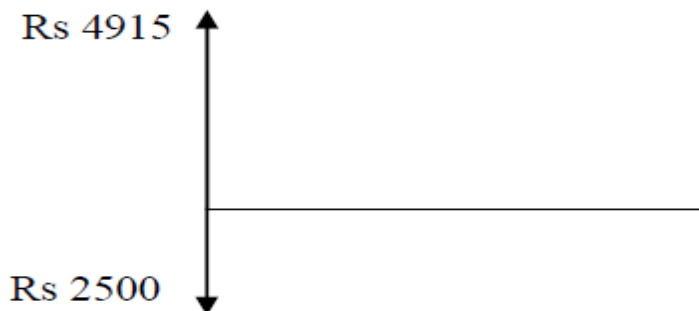
Example 3: 1 kW (rated) wind turbine of capital cost C0= Rs. 1, 20,000/= has useful life of 15 years and discount rate of 12%. If annual cost of operation & maintenance is 1% of its capital cost and capacity utilization factor is 25%, calculate unit cost of electricity produced by wind turbine in Rs / kWh.

Solution: Annual electricity output $= 0.25 \times 1 \times 365 \times 24$

$$= 2190\ kWh$$

Total annual cost = Annual capital cost + annual cost of operation & maintenance

$$= \left\{ A = P \left[\frac{d\ (1+d)^T}{(1+d)^T - 1}\right] \right\} + \left\{ 1\% \text{ of } 1,20,000 \right\}$$

$$= \left\{ A = 1,20,000 \left[\frac{0.12\ (1+0.12)^{15}}{(1+0.12)^{15} - 1}\right] \right\} + \left\{ 0.01 \times 1,20,000 \right\}$$

= Rs. 18,818.9

Hence unit cost of electricity = 18818.9 / 2190

$$= Rs\ 8.6\ /\ kWh.$$

4.7 Unit cost analysis of solar systems-

Unit cost analysis of solar system means the cost of energy produced by solar system. In case of solar thermal system, it involves the calculation of cost of thermal energy produced by the system and in case of solar photovoltaic (PV) system; it involves the calculation of cost of electrical energy produced by the system.

4.7.1 Estimation of unit cost of useful thermal energy delivered by a domestic solar water heating system (DSWHS).

Unit cost analysis of domestic solar water heating system involves the estimation of total annual cost of system and annual thermal energy output of the system. It is calculated in Rs/MJ.

By this analysis, the unit cost of different systems can also be compared to find a system which provide the highest thermal energy (MJ) output with minimum cost (Rs)

Example 4: The design and operation parameters of DSWHS are listed in table 4.1 below

Table 4.1 Operation parameter of DSWHS

Term	Value
Nominal capacity of DSWHS	100 liter/day
Initial water temperature	10°C
Delivery water temperature	60°C
Useful life of system	30 years
Capital cost	Rs 30,000/=
Discount rate	12%
Annual cost of operation and maintenance	Rs 1000
Annual capacity utilization factor of DSWHS	0.8

(Initial water temperature and delivery water temperature are design values; it also includes solar radiation on collector)

For comparative study of unit cost for DSWHS with unit cost of other water heating systems (operated by electricity / LPG / Fuel wood), the data is given below in table 4.2

Table 4.2 Unit cost, efficiency of utilization and calorific value of different fuels

Fuel	Unit cost	Efficiency of utilization	CV
Electricity	Rs. 4 /kWh	0.95	3.6 MJ/kWh
LPG	Rs. 26 /kg	0.65	44 MJ/kg
Fuel wood	Rs. 3 /kg	0.15	18 MJ/kg

Calculate: (I) Unit cost of useful thermal energy provided by DSWHS

(II) Compare unit cost of DSWHS with Electricity, LPG and Fuel wood

(III) Find net annual benefit due to electricity saving by DSWHS

Solution:

➢ Calculation of unit cost of useful thermal energy provided by DSWHS:

Total annual cost = Annual capital cost + annual cost of operation & maintenance

$$= \left\{ A = P \left[\frac{d\,(1+d)^T}{(1+d)^T - 1} \right] \right\} + \left\{ 1000 \right\}$$

$$= \left\{ A = 30000 \left[\frac{0.12\,(1+0.12)^{30}}{(1+0.12)^{30} - 1} \right] \right\} + \left\{ 1000 \right\}$$

$$= Rs\ 4724/=$$

Annual thermal energy output = (M.Cp.ΔT) × 365 days × CUF

$$= (100 \text{ kg}) \times (60 - 10 \text{ °C}) \times (4.2 \text{ kJ / kg°C}) \times (365 \text{ days}) \times (\text{CUF})$$

$$= 6132 \text{ MJ}$$

Unit cost of useful thermal energy delivered = 4724 / 6132 = Rs 0.77 / MJ

- ➢ Now we will compare the unit cost of electricity, LPG and fuel wood with DSWHS:
- • Comparison with electric geyser:

  (Neglecting capital cost compared to operational cost)

  Useful energy = 3.6 × 0.95

    = 3.4 MJ/kWh

  Unit cost = 4 / 3.4

    = Rs. 1.17 /MJ

- • Comparison with LPG water heater:

  Useful energy = 44 × 0.65

    = 28.6 MJ/kg

  Unit cost = 26 / 28.6

    = Rs. 0.9/MJ

- • Comparison with 1kg fuel wood water heater:

  Useful energy = 18 × 0.15

    = 2.7 MJ/kg

  Unit cost = 3 / 2.7

    = Rs. 1.11/MJ

Table 4.3 Comparison chart

Fuel	**Solar**	**Electricity**	**LPG**	**Fuel wood**
Unit cost	Rs 0.77 / MJ	Rs. 1.17 /MJ	Rs. 0.9/MJ	Rs. 1.11/MJ

- ➢ Net annual benefits:

  Annual amount of electricity saved $= \dfrac{(0.8) \times (365) \times (100) \times (4.2) \times (50°C)}{(0.95) \times (3600 \frac{\text{kJ}}{\text{kWh}})}$

    $= 1793 \text{ kWh}$

  Annual benefits due to electricity saving = (1793 kWh) × (Rs 4/ kWh)

    = Rs. 7172

  Net annual benefits = 7172 − 1000 = Rs. 6172

$$P = A \left[\frac{(1+d)^T - 1}{d(1+d)^T}\right]$$

$$P = 6172 \left[\frac{(1+0.12)^{30} - 1}{0.12(1+1.12)^{30}}\right] = \text{Rs. } 49716 /=$$

So the worth of the savings made is Rs. 49716 whereas the investment was only Rs. 30,000. Hence the process of installing a DSWHS is still profitable.

Also the unit cost of electricity may increase every year from present unit cost of Rs. 4/kWh. Let ξ be the annual rate of escalation in the price of the electricity
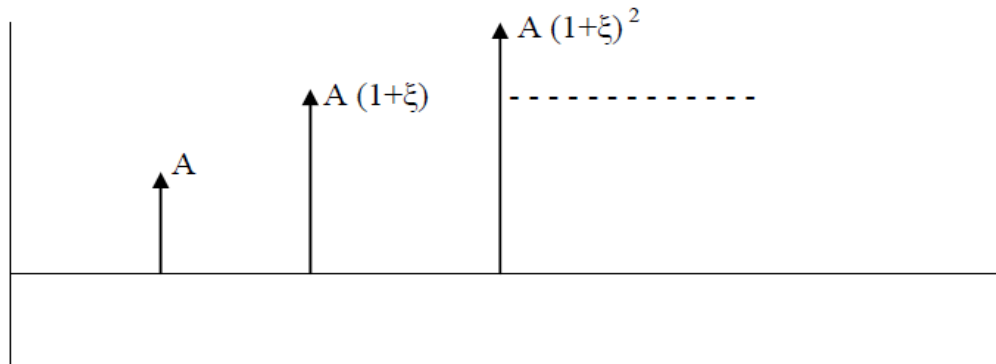
Fig. 4.5 cash flow diagram considering escalation in the price of the electricity

$$P = \frac{A}{(1+d)} + \frac{A(1+\xi)}{(1+d)^2} + \ldots\ldots\ldots + \ldots\ldots + \frac{A(1+\xi)^{T-1}}{(1+d)^T}$$

$$P = \frac{A}{(1+d)} \left[\frac{1 - \left\{\frac{1+\xi}{1+d}\right\}^T}{1 - \left\{\frac{1+\xi}{1+d}\right\}}\right]$$

Present worth with fuel price escalation-

$$P = \frac{A}{(d-\xi)} \left[1 - \left\{\frac{(1+\xi)}{(1+d)}\right\}^T\right] \text{------------------------------------ (4.8)}$$

4.7.2 Unit cost analysis of electricity generated by solar PV system

Unit cost analysis of solar Photovoltaic (PV) system involves the estimation of total annual cost of system and annual electrical energy output of the system. It is calculated in Rs/kWh.

By this analysis, the unit cost of different systems can also be compared to find a system which provides the highest electrical energy (kWh) output with minimum cost (Rs).

Example 5: Consider a solar plant, installed with initial investment of Rs. 5×10^6. Out of which 44% was used in PV array, 10% was used in battery systems, 8% were used in installation cost and 38% was used in system balance.

The individual components of PV system have different life span as shown below in table 4.4

Table 4.4 Components and their life span

Component	Life span
PV modules	20 years
Batteries	7 years
Solar inverter	15 years
System balance	15 years

Calculate: (I) Annualized total cost of solar PV system

(II) Calculate the unit cost of electricity generated by PV system

(Consider average energy output of 75kWh / day from PV array for one year)

Solution:

Because individual components have different life span, we need to calculate the annualized capital cost separately.

If consider the interest rate of 5% then

Annualized capital cost of PV modules $= A1 = P \left[\dfrac{d\,(1+d)^T}{(1+d)^T - 1}\right]$

$$A1 = (0.44 \times 5 \times 10^6) \left[\frac{0.05\,(1+0.05)^{20}}{(1+0.05)^{20} - 1}\right]$$

$$A1 = Rs.\ 176533.7$$

Annualized capital cost of batteries $= A2 = P \left[\dfrac{d\,(1+d)^T}{(1+d)^T - 1}\right]$

$$A2 = (0.1 \times 5 \times 10^6) \left[\frac{0.05 \ (1+0.05)^7}{(1+0.05)^7 - 1}\right]$$

$$A2 = Rs. \ 86409$$

Annualized capital cost of solar inverter = A3 = P $\left[\frac{d \ (1+d)^T}{(1+d)^T - 1}\right]$

$$A3 = (0.08 \times 5 \times 10^6) \left[\frac{0.05 \ (1+0.05)^{15}}{(1+0.05)^{15} - 1}\right]$$

$$A3 = Rs. \ 38537$$

Annualized capital cost of system balance = A4 = P $\left[\frac{d \ (1+d)^T}{(1+d)^T - 1}\right]$

$$A4 = (0.38 \times 5 \times 10^6) \left[\frac{0.05 \ (1+0.05)^{15}}{(1+0.05)^{15} - 1}\right]$$

$$A4 = Rs. \ 183050.3$$

So total annualized cost = Rs. 634530.86/=

A 1 kW photovoltaic module will produce 1 kW output power if it is irradiated by 1000 W/m^2 and the temperature is maintained at 25°C.

Average energy output of 75kWh / day from PV array

Total annual average energy output = 75 × 365

Unit price of electricity generated = $\dfrac{634530.86}{75 \times 365}$ = 23.18 /kWh

Unit cost of electricity delivered is more than unit cost of electricity generated due to T & D charges and losses. In remote areas where resource is available, we can locally generate electricity by PV system and cut down T & D losses and cost.

4.8 Measures of financial (economical) performance -

4.8.1 Payback period

It is the time elapsed between the point of initial investment and the point at which accumulated savings (benefits) net of other accumulated costs become equal to the capital cost. In simple words, it is the time period in which the invested money on the system is recovered by getting profits from the system.

Payback period can be of two type namely simple payback period and discounted payback period.

4.8.1 (a) Simple payback period (Tsp)

It is payback period without considering time value of money.

$$\sum_{j=1}^{Tsp}(Bj - Cj) = C0$$

If (Bj – Cj) is same every year ie. uniform net annual benefit then Tsp (B – C) = C0

$$Tsp = \frac{C0}{(B-C)} \quad \text{(For uniform net annual benefit)} \text{-------------------------------- (4.9)}$$

4.8.1 (b) Discounted payback period (Tdp)

It is payback period with consideration of time value of money.

$$\sum_{j=1}^{Tdp}\frac{(Bj-Cj)}{(1+d)^j} = C0$$

Special case: if (Bj – Cj) = (B – C) $\forall\, j = 1,2, \dots\dots j$ (For uniform net annual benefit)

$$C0 = (B - C)\left[\frac{(1+d)^{Tdp}-1}{d\,(1+d)^{Tdp}}\right]$$

$$1 - (1+d)^{-Tdp} = \frac{dC0}{(B-C)}$$

$$(1+d)^{-Tdp} = 1 - \frac{dC0}{(B-C)} = \frac{(B-C)-dC0}{(B-C)}$$

$$(1+d)^{+Tdp} = \frac{(B-C)}{(B-C)-dC0}$$

$$Tdp = \frac{\ln(B-C)-\ln[(B-C)-dC0}{\ln(1+d)} \text{--- (4.10)}$$

- When we do discounted payback analysis, the payback period will be longer than simple payback period (Tdp > Tsp).

- The acceptability criteria for any project is that the payback period should be less than useful life of project
- The payback period should be as minimum as possible
- In case of both simple and discount payback analysis, payback period does not necessarily take entire useful life into account because in most of solar energy projects, the life time is long.
- Simple payback is tool which emphasizes rapid recovery of initial capital investment.

4.8.2 Net Present Value (NPV)

$$A = \sum_{j=1}^{T} \frac{(B_j - C_j)}{(1+d)^j} + \frac{S}{(1+d)^T} - C_0 \text{-- (4.11)}$$

Where 'T' is useful life of system and 'S' is salvage value

Fig. 4.6 Cash flow diagram for Net Present Value

This method takes care of entire life

- It takes care of time value of money
- It gives value in terms of money (units of money)
- A system will be acceptable if NPV > 0
- For mutually exclusive projects, select one with highest positive NPV

Demerits of NPV:

Consider two projects 'A' and 'B' with initial cost (C0) and NPV as shown below in table 4.5

Table 4.5 Projects with their initial cost and NPV

Project	C0	NPV
A	1000	50000
B	100000	50000

The common sense says project 'A' is better but unfortunately NPV does not consider for what C0 we are getting. It does not distinguish projects with equal NPV

Key points:

- NPV (at d = 0) $= \sum_{j=1}^{T} \frac{(Bj - Cj)}{(1+d)^j} + \frac{S}{(1+d)^T}$ - C0

- NPV (at d = ∞) = -C0

- NPV curve
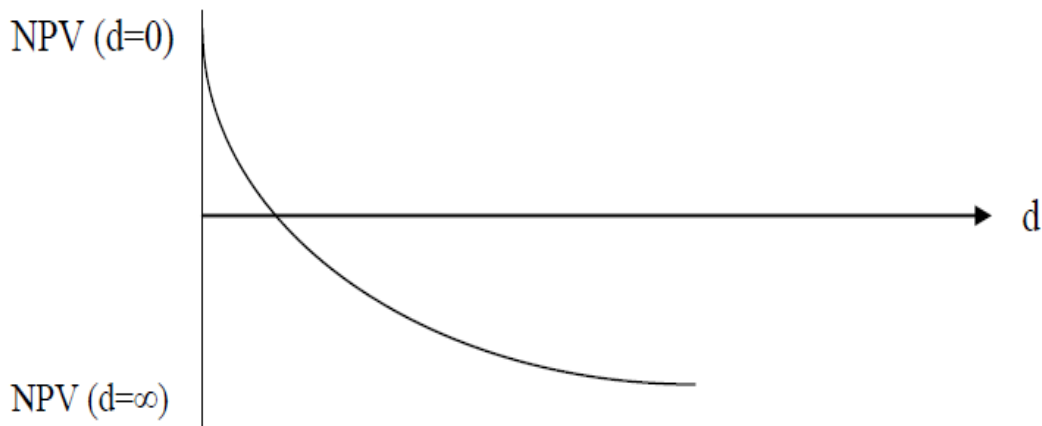
Fig. 4.7 NPV Curve

- If (Bj – Cj) = B – C $\forall j = 1, 2, \ldots \ldots T$

  NPV = (B – C) $[\frac{(1+d)^T - 1}{d(1+d)^T}] + \frac{S}{(1+d)^T}$ - C0

- If 'B' increases every year by a fraction 'ξ' of its previous year value and 'C' is uniform across the useful life of project.

  NPV $= \frac{B}{(d-\xi)} [1 - (\frac{1+\xi}{1+d})^T] - C [\frac{(1+d)^T - 1}{d(1+d)^T}] + \frac{S}{(1+d)^T}$ - C0

4.8.3 Benefit to cost ratio (B/C) and internal rate of return (IRR):

➢ Benefit to cost ratio:

$$\frac{B}{C} = \frac{\sum_{j=1}^{T}\frac{(Bj-Cj)}{(1+d)^j} + \frac{S}{(1+d)^T}}{C0} \quad \text{-------------------------------------- (4.12)}$$

Key points:

- Merit:- In this method, C0 of project is considered
- Demerit: - in this method, added benefit and reduced cost is not considered.

➢ Internal rate of return (IRR):

It is the value of discount rate for which NPV is zero.

If the value'd' is less than breakdown value of'd' then project will make profit

$(d)_{NPV=0} > d$ (for profitable project)
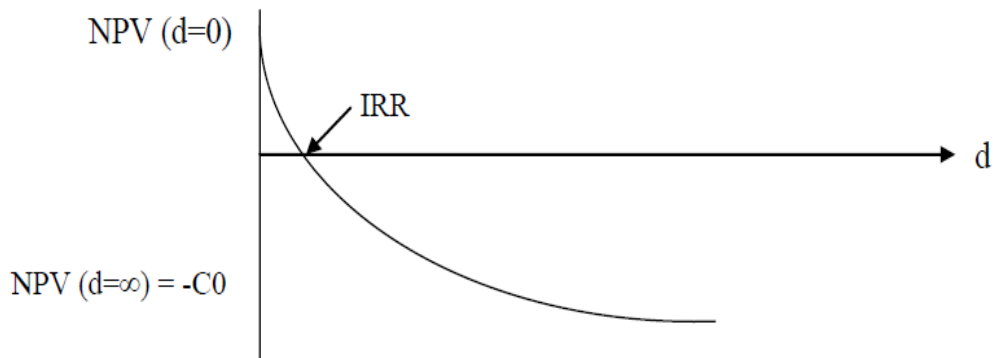
Fig. 4.8 IRR Curve

Now economist comes up with one idea that instead of purely guessing a value, we can approximately get an initial value

$$\text{NPV} = \{ \ \frac{(B-C)}{(1+d)} + \frac{(B-C)}{(1+d)^2} + - - - - - \} - C0$$

$$\text{NPV} = [\frac{\frac{(B-C)}{(1+d)}}{1-\frac{1}{1+d}}] - C0$$

$$\text{NPV} = \frac{(B-C)}{d} - C0 \ \text{……………………… (4.13)}$$

At d=IRR, NPV= 0, $\frac{(B-C)}{IRR} - C0 = 0$

$$IRR = \frac{(B-C)}{C0}$$ …………………………. (4.14)

4.9 <u>Case Study: Roof-top PV system for textile unit</u>

Following is a case study of a textile unit located in New Delhi. The unit has contracted demand of 100kVA. Total available roof top area is 280m². Hence, management has decided to install a grid connected rooftop PV plant of 25kWp. Solar is preferred source of energy, energy available from the solar plant is utilized first and the remaining requirement is fulfilled by grid supply.

The specifications of rooftop PV system are:

PV Panel Specification-	
Panel rated power	305 Wp
Maximum power (Pm)	305 Wp
Open circuit voltage (Voc)	44.9 Volt
Maximum power voltage (Vm)	36.6 Volt
Power tolerance	8.73 Amp.
Maximum power current	8.33 Amp.
Solar intensity	1000 W/m²
Temperature	25°C
Dimension	(1956*992*40) mm³
Maximum system voltage (Vm)	1000 Volt
Number of panels	84
Inverter rating	30 kVA
Solar PV plant capacity	25 kWp
Roof-top area	275 m²
Annual unit generation	31700 kWh
Degradation of solar output	3% in first year & 0.7% in second year onwards
Life time of system	25 years
capacity utilization factor (CUF)	14.5%
Electricity price escalation	2% (per year)
Structure weight	27 kg
Overall system cost (including PV array, inverter, mounting structure, cables, metering instruments)	Rs. 18,75,000/=

- The PV system is in operation for 360 days in a year with capacity utilization factor (CUF) of 14.5%. Then,

  Unit (kWh) generation = kW output $\times$ CUF $\times$ 24hours $\times$ 360days

- Benefit is the amount which is saved by generating kWh electricity units by PV system
- Operation, maintenance and insurance cost is considered as 2.5% of initial investment on system
- Annual saving = Annual benefit – (O&M+ Insurance) cost

Table: Benefit-Cost analysis

	System % Output	kW output	kWh (Unit) generation	Unit cost-Rs (Delhi)	Benefit (Rs)	(O&M+ Insurance) Cost	Savings (Rs)
1st year	100	25	31320.0	8.400	263088	46875	216213
2nd year	97	24.250	30380.4	8.568	260299.27	46875	213424.27
3rd year	96.321	24.080	30167.7	8.739	263646.72	46875	216771.72
4th year	95.647	23.912	29956.6	8.914	267037.9	46875	220162.9
5th year	94.977	23.744	29746.8	9.092	270470.67	46875	223595.67
6th year	94.312	23.578	29538.5	9.274	273948.45	46875	227073.45
7th year	93.652	23.413	29331.8	9.460	277471.98	46875	230596.98
8th year	92.997	23.249	29126.7	9.649	281041.97	46875	234166.97
9th year	92.346	23.087	28922.8	9.842	284656.1	46875	237781.1
10th year	91.699	22.925	28720.1	10.039	288314.96	46875	241439.96
11th year	91.058	22.765	28519.4	10.240	292025.56	46875	245150.56
12th year	90.42	22.605	28319.5	10.444	295779.06	46875	248904.06
13th year	89.787	22.447	28121.3	10.653	299582.58	46875	252707.58
14th year	89.159	22.290	27924.6	10.866	303436.95	46875	256561.95
15th year	88.535	22.134	27729.2	11.084	307339.54	46875	260464.54
16th year	87.915	21.979	27535.0	11.305	311291.02	46875	264416.02
17th year	87.299	21.825	27342.0	11.531	315292.08	46875	268417.08
18th year	86.688	21.672	27150.7	11.762	319347.08	46875	272472.08
19th year	86.082	21.521	26960.9	11.997	323456.94	46875	276581.94
20th year	85.479	21.370	26772.0	12.237	327614.97	46875	280739.97
21st year	84.881	21.220	26584.7	12.482	331829.48	46875	284954.48
22nd year	84.286	21.072	26398.4	12.732	336093.48	46875	289218.48
23rd year	83.696	20.924	26213.6	12.986	340415.65	46875	293540.65
24th year	83.111	20.778	26030.4	13.246	344797.02	46875	297922.02
25th year	82.529	20.632	25848.1	13.511	349230.16	46875	302355.16

Table: Saving and Payback calculation

Saving after 1 year	Saving after 2 years	Saving after 3 years	Saving after 4 years	Saving after 5 years	Saving after 6 years	Saving after 7 years	Saving after 8 years	Saving after 9 years
216213	216213 + 213424.27	216213 + 213424.27 + 216771.72	216213 + 213424.27 + 216771.72 + 220162.90	216213 + 213424.27 + 216771.72 + 220162.90 + 223595.67	216213 + 213424.27 + 216771.72 + 220162.90 + 223595.67 + 227073.45	216213 + 213424.27 + 216771.72 + 220162.90 + 223595.67 + 227073.45 + 230596.98	216213 + 213424.27 + 216771.72 + 220162.90 + 223595.67 + 227073.45 + 230596.98 + 234166.97	216213 + 213424.27 + 216771.72 + 220162.90 + 223595.67 + 227073.45 + 230596.98 + 234166.97 + 237781.1
Rs. 216213	Rs. 429637.267	Rs. 646408.98	Rs. 866571.885	Rs. 1090167.55	Rs. 1317241	Rs. 1547838	Rs. 1782005	Rs. 2019786.1

The overall cost of roof-top PV system is Rs. 18,75,000/= and total saving after 9 years is Rs. 2019786.1/= hence the payback time for this rooftop PV system for generation of 25kWp power is 8.5 years.

A system is said to be economical if the payback time is less than life time of system. Also the payback time should be as minimum as possible. In the case study as discussed above, the payback time is one third of life time of the system so the system is economical.

Chapter 5

Energy analysis of solar system

5.1 Energy Metrics-

In order to study the economical aspects of the PV system, a careful energy analysis of the system is required. This includes Energy payback time (EPBT), Electricity production factor (EPF), Life cycle conversion efficiency (LCCE). These three terms combinely called as Energy Metrics.

5.1.1 Embodied Energy

The concept of embodied energy is relatively new area of environmental assessment that has started to be included in life cycle energy calculations of buildings. Embodied energy is defined as; "the quantity of energy required by all the activities associated with a production process, including the relative proportions consumed in all activities upstream to the acquisition of natural resources and the share of energy used in making equipments and in other supporting functions i.e. direct energy plus indirect energy", Treloar (1994). Thus the aim of any embodied energy analysis is to quantify the amount of energy used to manufacture a material or component. This involve the assessment of the overall expenditure of energy required to extract the raw material, manufacture a product or components, installation and maintain the component element whichever is being assessed.

5.1.2 Energy payback time (EPBT)

EPBT is the period in which embodied energy is recovered.

The EPBT depends on the energy spent to prepare the materials used for fabrication of the system and its components, i.e. embodied energy and the annual energy yield (output) obtained

from such system. To evaluate embodied energy of various components of system, the energy densities of different materials are required. It is the total time period required to recover the total energy spent to prepare the materials (embodied energy) used for fabrication of the hybrid PVT systems. It is the ratio of embodied energy and the annual energy output from the system

Which can be expressed as,

$$T\,(epb) = \frac{Ein}{Eaout}$$

Ein – Embodied energy (kWh)

Eaout – Total annual output (kWh/ Year)

5.1.3 Electricity production factor (EPF)

It is used to predict the overall performance of the system. It is defined as the ratio of the output energy to the input energy.

It can also be expressed as the inverse of EPBT,

Energy production factor is defined by two types

- **On annual basis**

  It is the ratio of annual energy output to the energy input.

  $$\chi a = \frac{Eaout}{Ein} = \frac{1}{T\,(epb)}$$

- **On life time basis**

  It is the ratio of energy output to the energy input on life time basis.

  $$\chi(LT) = \frac{Eout}{Ein} = \frac{Eaout \times T(LS)}{Ein} = \frac{T(LS)}{T\,(epb)} = \chi a \times T\,(LS)$$

  Where

  E_{out} – Total net energy output over life of the system (kwh).

  E_{in} – Embodied Energy of the system(kwh).

T_{LS} – Life time of the system (years).

5.1.4 Life cycle conversion efficiency (LCCE)

LCCE is the net energy productivity of the system with respect to the solar input (radiation) over the life time of the system

$$\phi = \frac{Eout - Ein}{Esol \times T(LS)}$$

$$= \frac{Eaout}{Esol} \left(1 - \frac{1}{\chi a \times T(LS)}\right)$$

$$= \frac{Eaout}{Esol} \left(1 - \frac{1}{\chi LT}\right)$$

$$= \eta \left(1 - \frac{1}{\chi LT}\right)$$

- Energy metrics of an energy efficient system:

EPBT should be less than the life time of system. For an energy efficient system, EPBT should be as minimum as possible.

LCCE is always less than one. For an energy efficient system, LCCE should approach to 1.

EPF is greater than one and for an energy efficient system, EPF should be as maximum as possible.

- Energy metrics of a system in which total output energy from a system is equal to embodied energy of that system then

EPBT = Life time of system, LCCE = 0, EPF = 1

5.2 Case Study: Energy analysis of rooftop photovoltaic (PV) system

A roof-top PV system is designed to supply the domestic load. The system contains 12 PV modules (area of each PV Module is 0.61 m^2), a charge controller (efficiency – 84%), a battery

(150 Ah), an inverter (efficiency – 85%) and load (single phase AC operated). The block diagram of this system is shown below in the fig. 5.1

| PV Array | → | Charge Controller | → | Battery | → | Inverter | → | Load |
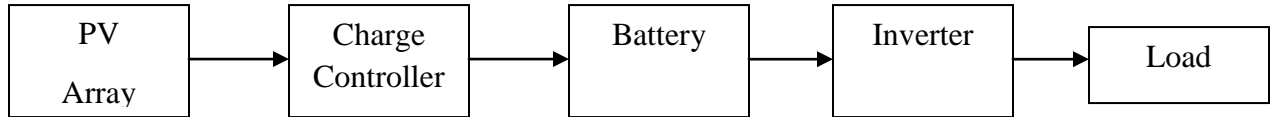
Fig. 5.1 Block diagram of rooftop photovoltaic (PV) system

➢ **Observations:** The solar intensity, short circuit current and open circuit voltage of installed roof-top PV system is observed. The solar insolation (intensity) is measured by solarimeter from 09:00 AM to 04:00 PM on daily hourly basis and corresponding open circuit DC voltage and short circuit DC current by the PV array is measured by multimeter. These observations are as shown in table 5.1

Table 5.1 Average hourly data of installed solar system

S.N.	Time	Intensity (W/m^2)	Short Circuit Current, Isc (Amp.)	Open Circuit Voltage, Voc (Volt)
1	09 am	500	23.20	19.80
2	10 am	640	34.60	19.60
3	11 am	820	42.50	19.40
4	12 noon	895	46.50	19.60
5	01 pm	860	47.60	19.40
6	02 pm	740	44.60	19.40
7	03 pm	620	34.20	19.50
8	04 pm	360	18.20	19.20

➤ **Embodied Energy data:**

• The embodied energy of different material used in making of solar panels is as given below in table 5.2

Table 5.2 Embodied energy

S N	Material	Embodied Energy (kWh/m^2)
1	Silicon Purification and Processing (Metallurgical grade silicon production / Electronic grade silicon production / Silicon crystal growth)	670.00
2	Solar Cell Production	120.00
3	PV Module Lamination and Assembly (Steel infrastructure / Ethyle vinyl acetate / Tedler production / Glass Sheet production / Aluminum frame production / Other materials)	190.00

• The embodied energy and weight of items used in supporting structure is as shown below in table 5.3

Table 5.3 Embodied energy

S.N	Item	Embodied Energy	Total Weight (kg) / Total Area(m^2)
1	Support Structure (Iron stand / Screw)	7.70 (kwh/kg) 8.63 (kwh/kg)	40 kg. 1.00 kg.
2	Charge Controller	210.00 (kwh/kw)	0.36 kw.
3	Battery	46.00 (kwh/m^2)	7.32 m^2.
4	Inverter	210.00 (kwh/kw)	0.50 kw.
5	Wires	3.00 (kwh/m^2)	7.32 m^2.

- The embodied energy used in human labor and transportation is 9.84 kWh/ m^2 and 53.50 kWh/ m^2 respectively.

➢ **Calculations:**

- Calculation of electric power output of PV array:

SN	Time	Intensity (W/m^2)	Short Circuit Current, Isc (Amp.)	Open Circuit Voltage, Voc (Volt)	Electrical Power Generated (Watt)
1	09 am	500	23.20	19.80	367.49
2	10 am	640	34.60	19.60	542.53
3	11 am	820	42.50	19.40	659.60
4	12 noon	895	46.50	19.60	714.24
5	01 pm	860	47.60	19.40	738.75
6	02 pm	740	44.60	19.40	692.19
7	03 pm	620	34.20	19.50	533.52
8	04 pm	360	18.20	19.20	279.55

Average Intensity during the day ($\bar{I}$) = 679.37 W/m^2 .

Total Electrical Energy generated by the PV Array (E) = 4.53 kwh. (Per day).

Total Electrical Energy provided to the load for one day, E $_{per\ day}$

E $_{per\ day}$ = E × Efficiency of Charge Controller × Efficiency of Inverter

E $_{per\ day}$ = 4.53 × 0.84 × 0.85 = 3.24 kwh.

Total Electrical Energy provided to the load for one year, E $_{per\ year}$

E $_{per\ year}$ = E $_{per\ day}$ × No. of clear days.

E $_{per\ year}$ = 3.24 × 300

E $_{per\ year}$ = 971.05kwh.

- Calculation of Embodied Energy of Installed PV System:

Calculation of material production Energy (E$_{mpe}$):-

SN	Material	Embodied Energy (kwh/m^2)	Total Area (m^2)	Total Embodied Energy (kwh)
1	Silicon Purifation and Processing (Metallurgical grade silicon production / Electronic grade silicon production / Silicon crystal growth)	670.00	7.32	4904.40
2	Solar Cell Production	120.00	7.32	878.40
3	PV Module Lamination and Assembly (Steel infrastructure / Ethyle vinyl acetate / Tedler production / Glass Sheet production / Aluminum frame production / Other materials)	190.00	7.32	1390.80

Total Material Production Energy (E_{mpe}) = 7173.60 kwh.

- Calculation of PV System Installation Energy (E_{inst}):-

S.No	Item	Embodied Energy	Total Weight (kg) / Total Area(m^2)	Total Embodied Energy (kwh)
1	Support Structure (Iron stand / Screw)	7.70 (kwh/kg) 8.63 (kwh/kg)	40 kg. 1.00 kg.	308.00 (kwh) 8.63 (kwh)
2	Charge Controller	210.00 (kwh/kw)	0.36 kw.	75.60 (kwh)
3	Battery	46.00 (kwh/m^2)	7.32 m^2.	336.72 (kwh)
4	Inverter	210.00 (kwh/kw)	0.50 kw.	105.00 (kwh)
5	Wires	3.00 (kwh/m^2)	7.32 m^2.	21.96 (kwh)

Total Material Production Energy (E_{inst}) = 855.91 kwh.

- Calculation of energy used in maintenance (E_{main}):-

S.No	Item	Embodied Energy (kwh/m^2)	Total Area (m^2)	Total Embodied Energy (kwh)
1	Human Labor	9.84	7.32	72.03

- Calculation of energy used in administration (E_{admin}):-

S.No	Item	Embodied Energy (kwh/m^2)	Total Area (m^2)	Total Embodied Energy (kwh)
1	Transportation	53.50	7.32	391.62

Total manufacturing energy (E_{mfg}) = E_{mpe} + E_{main}

$$= 7173.60 + 72.03$$

$$= 7245.63 \text{ kwh.}$$

- Calculation of embodied energy of complete PV system:

Total Material Production Energy (E_{inst}) = 855.91 kwh.

Total Energy Used in Administration (E_{admin}) = 391.62 kwh.

Embodied Energy (E_{in}) = E_{mfg} + E_{inst} + E_{admin}

$$= 7245.63 + 855.91 + 391.62$$

$$= 8493.16 \text{ kwh.}$$

- Calculation of Energy Metrics of Installed PV System

(I)   Energy Pay Back Time (EPBT) $= \dfrac{\text{Embodied Energy}}{\text{Electrical Energy Generated (Yearly)}}$

$$T_{epb} = \frac{8493.16}{971.05}$$

$$T_{epb} = \textbf{8.75 Years}$$

(II)   Electricity Production Factor (EPF) $= \dfrac{\text{Electrical Energy Generated (Yearly)}}{\text{Embodied Energy}}$

$$\chi = \dfrac{971.05}{8493.16}$$

$\chi = $**0.12 per year**

(III)   Life Cycle Conversion Efficiency (LCCE) $= \dfrac{\text{Eaout} \times \text{TLS} - \text{Ein}}{\text{Esol} \times \text{TLS}}$

$$\Phi = \dfrac{(971.05 \times 30) - (8493.16)}{(679.37 \times 7.32) \times (35)}$$

$\Phi = $**0.12**

5.3 <u>Energy analysis of solar evaporative cooling system</u>

For energy analysis of solar evaporative cooling system, costs and embodied energy involved to wet the roof for day time (say from 10:00 AM to 04:00 PM) are given below in table 5.4

Table 5.4 cost and embodied energy of items used in evaporative cooling

SN	Item	cost	Embodied energy
1	Jute cloth	J	E_1
2	Spray	S	E_2
3	Water	W	E_3
4	Electricity (by PV system)	E	E_4

The embodied energy is calculated by equation

$$\text{Ein} = \sum_{i=1}^{4} \text{Ei}$$

$\text{E1} = \sum_{j=1}^{m} \text{e1j}$ $\text{E2} = \sum_{j=1}^{m} \text{e2j}$ $\text{E3} = \sum_{j=1}^{m} \text{e3j}$ $\text{E4} = \sum_{j=1}^{m} \text{e4j}$

('m' shows that how many the items are replaced with new items during the total life of system)

If reference temperature T_{R0} is reduced to T_{R1} by evaporative cooling, energy saved par day is calculated by measuring hourly energy saving (from 10:00 AM to 04:00 PM) as shown below in table 5.5

Table 5.5 Average hourly energy saving

Time	T_{R0}	T_{R1}	ΔT	$Q = (MC)_{eff.} \Delta T$
10:00 AM				
11:00 AM				
. . .				
04:00 AM				

$Q_{daily} = Q_{10AM} + Q_{11AM} + Q_{12NOON} + Q_{01PM} + Q_{02PM} + Q_{03PM} + Q_{04PM}$

By this process, monthly and yearly saving can be calculated

$$Eoutput = \sum_{m=1}^{k} (e)output, m$$

Now the energy back time of solar evaporative cooling system can be calculated by using the formula:

$$Energy\ Pay\ Back\ Time\ (EPBT) = \frac{Ein}{Eoutput\ (yealy)}\ years$$

5.4 Energy analysis of solar day lighting system

Consider a room without any glass window ie. There is no provision for providing the day light inside the room. Now by designing a window of 1 m^2 area and thickness 5 mm, the day light is provided in the room. Providing day lighting is simply related to saving of electrical power. If window is there, no need of bulb of 40 Watt for lighting. If it is used for 10 hours per day then

Energy saved annually = 40 (Watt) × 10 (hours per day) × 250 (working days in a year)

$$= 100\ kWh.$$

If the life of building is 100 years (in India), the life of glass is assumed to be infinite (if it is not broken), cost of maintenance can be assumed zero; the embodied energy of glass is considered as 50 kWh / m^2 (Ein = 50 kWh).

The energy output of system for life time of 100 years is -

$E_{out,T}$ = 100 (kWh yearly) × (100 years)

$E_{out,T}$ = 10^4 kWh

If consider the average intensity 500 W / m^2 then yearly solar energy can be calculated as

E solar (yearly) = 500 (W / m^2) × 1 (m^2) × 250 (days) × 10 (hours per day)

E solar (yearly) = 125000 kWh

The energy metrics of the system is now calculated as:-

- Energy Pay Back Time (EPBT) $= \dfrac{\text{Ein}}{\text{Eoutput (yealy)}}$ years

  $\text{EPBT} = \dfrac{50}{100} = 0.5$ year

- Life Cycle Conversion Efficiency (LCCE) $= \dfrac{\text{Eaout×TLS}-\text{ Ein}}{\text{Esol×TLS}}$

  $\text{LCCE} = \dfrac{10000-50}{125000} = 0.0796$

- Electricity Production Factor (EPF) $= \dfrac{\text{Electrical Energy Generated (Yearly)}}{\text{Embodied Energy}}$

  $\text{EPF} = \dfrac{10000}{50} = 200$ year

Chapter 6
Simulation and analysis of Photo-voltaic (PV) system with Maximum power point Tracking (MPPT)

6.1 Simulation of PV Systems-

6.1.1 Introduction

Nowadays simulation based analysis is very common in all engineering fields in order to minimize the cost incurred during physical testing of systems. In renewable energy systems PV modules are one of the most important components. Recently there are a number of component based simulation packages available for simulation based studies of renewable energy systems. However the most commonly used software package for research and educational purpose is MATLAB. In MATLAB/ Simulink, the simulation environment Simpower system toolbox provides all necessary block sets for simulation power system.

6.1.2 Model of Solar Cell

Solar cell are basically a p-n junctions fabricated in a thin wafer or layer of semiconductor. The electromagnetic radiation of solar energy can be directly converted electricity through photovoltaic effect. Being exposed to the sunlight, photons with energy greater than the band-gap energy of the semiconductor are absorbed and create some electron-hole pairs proportional to the incident irradiation. Under the influence of the internal electric fields of the p-n junction, these carriers are swept apart and create a photocurrent which is directly proportional to solar radiation. PV system naturally exhibits a nonlinear I-V and P-V characteristics which vary with the radiant intensity and cell temperature.
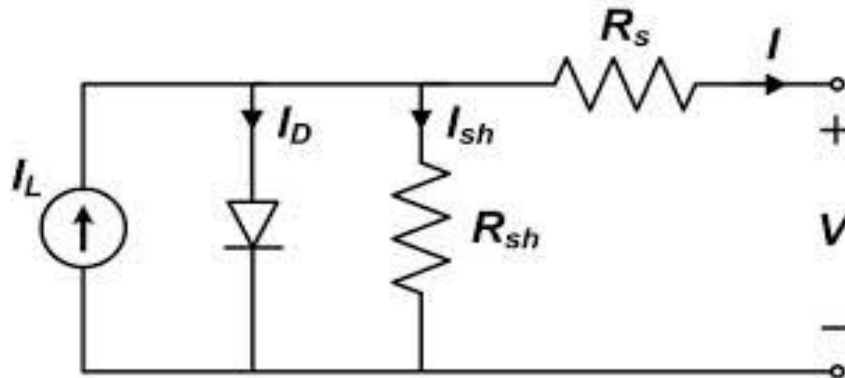
Fig. 6.1: Equivalent circuit of PV cell

The simplest equivalent circuit of a solar cell is an ideal current source in parallel with a diode as shown in figure 1. The current source represents the current generated by photons (often denoted as I_{ph}) and its output is constant under constant temperature and constant incident radiation of light. The diode determines the I-V characteristics of the cell. Increasing sophistication, accuracy and complexity can be introduced to the model by adding in turn

- Temperature dependence of the diode saturation current.
- Saturation current contribution due to diffusion process.
- Saturation current contribution due to recombination in the space layer effect dominant at higher bias region.
- In small size solar cells leakage current has an effect on the low bias region.
- Temperature dependence of the photo current I_{ph}

Shunt resistance R_{Sh} in parallel with the diode. Series resistance R_S, which gives a more accurate shape between the maximum power point and the open circuit voltage. Either allowing the diode ideality factor A to become a variable parameter (instead of being fixed at either 1 or 2) or introducing two parallel diodes (one with A=1, one with A=2) with independently set saturation currents. The voltage-current characteristic equation of a solar cell is given as Eq. (6.1).

I= I_{ph} – (IS exp (q (V + IRs) / kTcA) – 1) – (V + IRs) / Rsh ------------------------------- (6.1)

Where I_{ph} is the photocurrent or light generated current

q is charge of an electron (1.6×10-19 C)

k is Boltzmann's constant (1.38×10-23 j/K)

Tc is the cell working temperature in Kelvin

A ideality factor

Rs and Rsh are the series and parallel resistances

The Iph mainly depends on the solar radiation and cells working temperature which is described as Eq (6.2)

$$I_{ph} = Isc + Ki (Tc - Tref) \lambda \text{ --- (6.2)}$$

Where Isc is the short circuit current at 25^0C and solar radiation of 1kW/m^2

Ki is the cell temperature coefficient of current

Tref is the reference temperature of the cell

λ is the solar radiation in kW/m^2

The cells saturation current varies with the cell temperature which is described as Eq (6.3)

$$I_s = I_{RS} \left(\frac{T_c}{T_{ref}} \right)^3 \exp\left[qE_g \left(\frac{1}{T_{ref}} - \frac{1}{T_c} \right) / kT_c A \right] \text{ --- (6.3)}$$

Where Irs is the cells reverse saturation current at reference temperature and solar radiation and Eg is the Band-gap energy of the semiconductor used in the cell.

The shunt resistance Rsh in inversely related with shunt leakage current to the ground. In general, the PV efficiency is insensitive to variation in Rsh and this shunt- leakage resistance can be assumed to approach infinity without leakage current to ground. On the other hand, a small variation in Rs will significantly affect the PV output power. Eq. can be rewritten as

$$I = Iph - (Is \exp (q (V+ IRs) / kTcA) -1) \text{ -- (6.4)}$$

For an ideal PV cell the values of Rsh is infinity and Rs is equal to zero. The simulated PV system is shown in Fig 6.2.
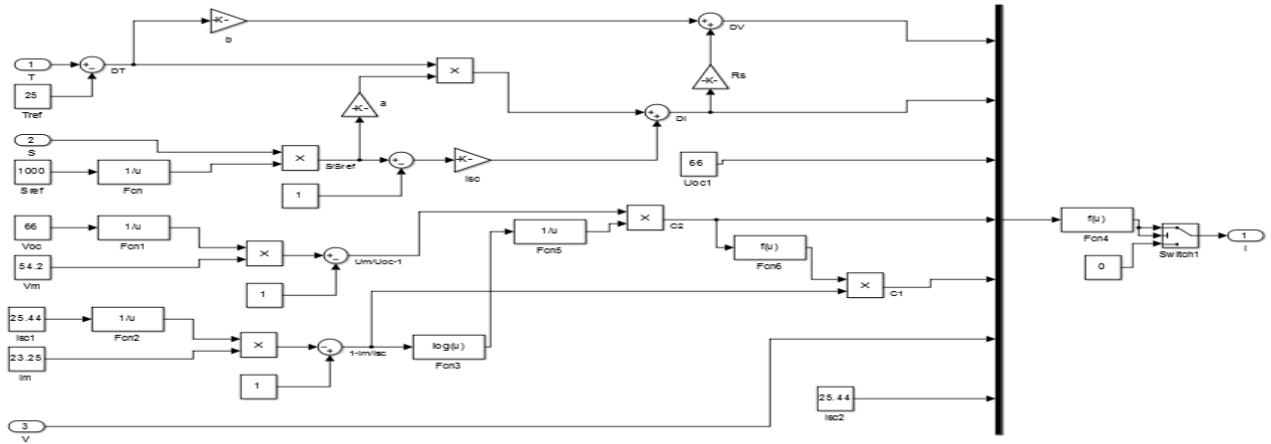

Fig.6.2. Simulated PV System

6.2   Maximum Power Point Tracking System-

The output power of the solar PV module changes with change in direction of the sun, change in solar insolation level and change in temperature. Also there is a single maximum power point in the PV characteristics of the PV module for a particular operating condition. It is desired that the PV module operates close to this point, i.e., output of the PV module approaches near to MPP. The process of operating PV module at this condition is called as maximum power point tracking (MPPT). Maximization of PV power improves the utilization of the solar PV module. Maximum power point tracking or MPPT, is the automatic adjustment of the load of a photovoltaic system to achieve the maximum possible power power output. PV cells have a complex relationship between current, voltage and output power, which produces a non –linear output. This output is expressed as the current-voltage characteristic of the PV cell.

Constant fluctuations in external variables such as temperature, irradiance and shading cause constant shifts of the I-V curve upwards and downwards. A change in temperature will have an inversely proportional affect on output current.

As seen here, an increase in temperature will decrease output voltage, while a decrease in sunlight will decrease output current. This means that to maintain the MPP in instances of varying irradiance, a voltage must be found must be found to complement the raised or lowered output current from the panel, in order to produce the maximum amount of power.

For a given I-V characteristic, with temperature and irradiance held constant, there is a single point at the knee of the curve with a current-voltage pair that produces maximum power output. A corresponding Resistance, R=V/I, is the resistance required across the terminals of the PV cell to achieve this maximum power point (MPP). The purpose of the MPPT system is to monitor the power output of the PV system and adjust the resistance to achieve maximum power as the I-V characteristic shifts with changing irradiance and temperature MPPT systems are connected between the PV array and its load, and are comprised of a control structure which allows them to search for the max power point, as well as a way of varying the resistance across the terminals, for example by varying the duty cycle of a DC/DC converter.

6.2.1 Perturb & Observe

The method used in this work to implement maximum power point tracking function is the perturbation and observation method, which is the most popular method. The advantages of the perturbation and observation method include simple structure, less measured parameters and no need of measurement in advance. Perturb & Observe (P&O) is the simplest method. In this we use only one sensor, that is the voltage sensor, to sense the PV array voltage and so the cost of implementation is less and hence easy to implement. The time complexity of this algorithm is very less but on reaching very close to the MPP it doesn't stop at the MPP and keeps on perturbing on both the directions. When this happens the algorithm has reached very close to the

MPP and we can set an appropriate error limit or can use a wait function which ends up increasing the time complexity of the algorithm.

6.2.2 Perturb & Observe Algorithm

The Perturb & Observe algorithm states that when the operating voltage of the PV panel is perturbed by a small increment, if the resulting change in power _P is positive, then we are going in the direction of MPP and we keep on perturbing in the same direction. If P is negative, we are going away from the direction of MPP and the sign of perturbation supplied has to be changed.
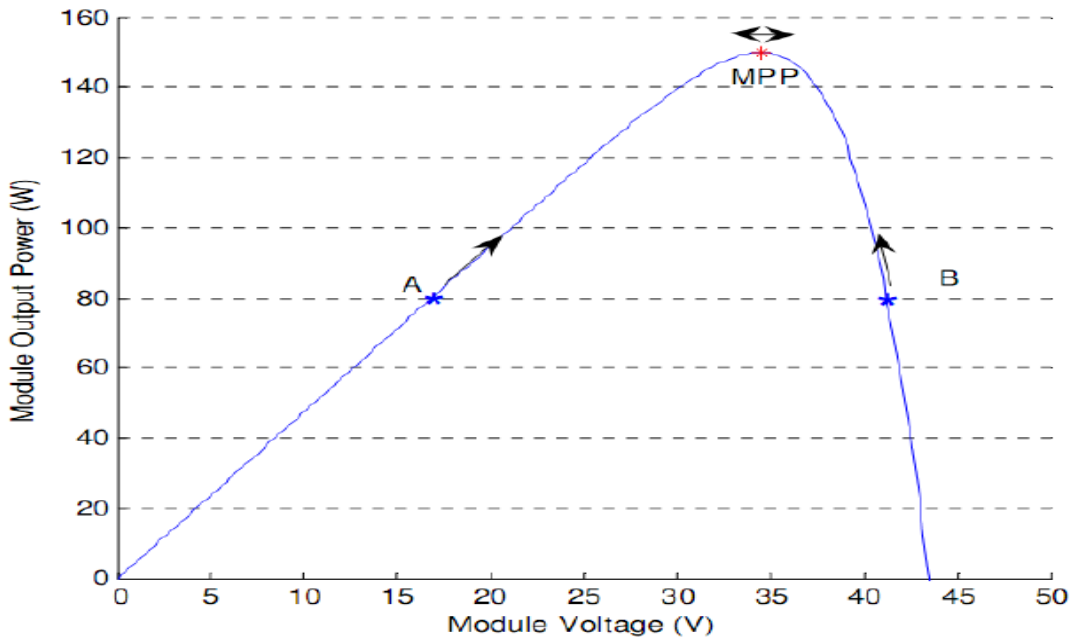

Fig.6.3: Solar panel characteristics showing MPP and operating points A and B

Figure 6.3 shows the plot of module output power versus module voltage for a solar panel at a given irradiation. The point marked as MPP is the Maximum Power Point, the theoretical maximum output obtainable from the PV panel. Consider A and B as two operating points. As shown in the figure above, the point A is on the left hand side of the MPP. Therefore, we can move towards the MPP by providing a positive perturbation to the voltage. On the other hand, point B is on the right hand side of the MPP. When we give a positive perturbation, the value of

P becomes negative, thus it is imperative to change the direction of perturbation to achieve MPP. The flowchart for the P&O algorithm is shown in Figure 6.4.
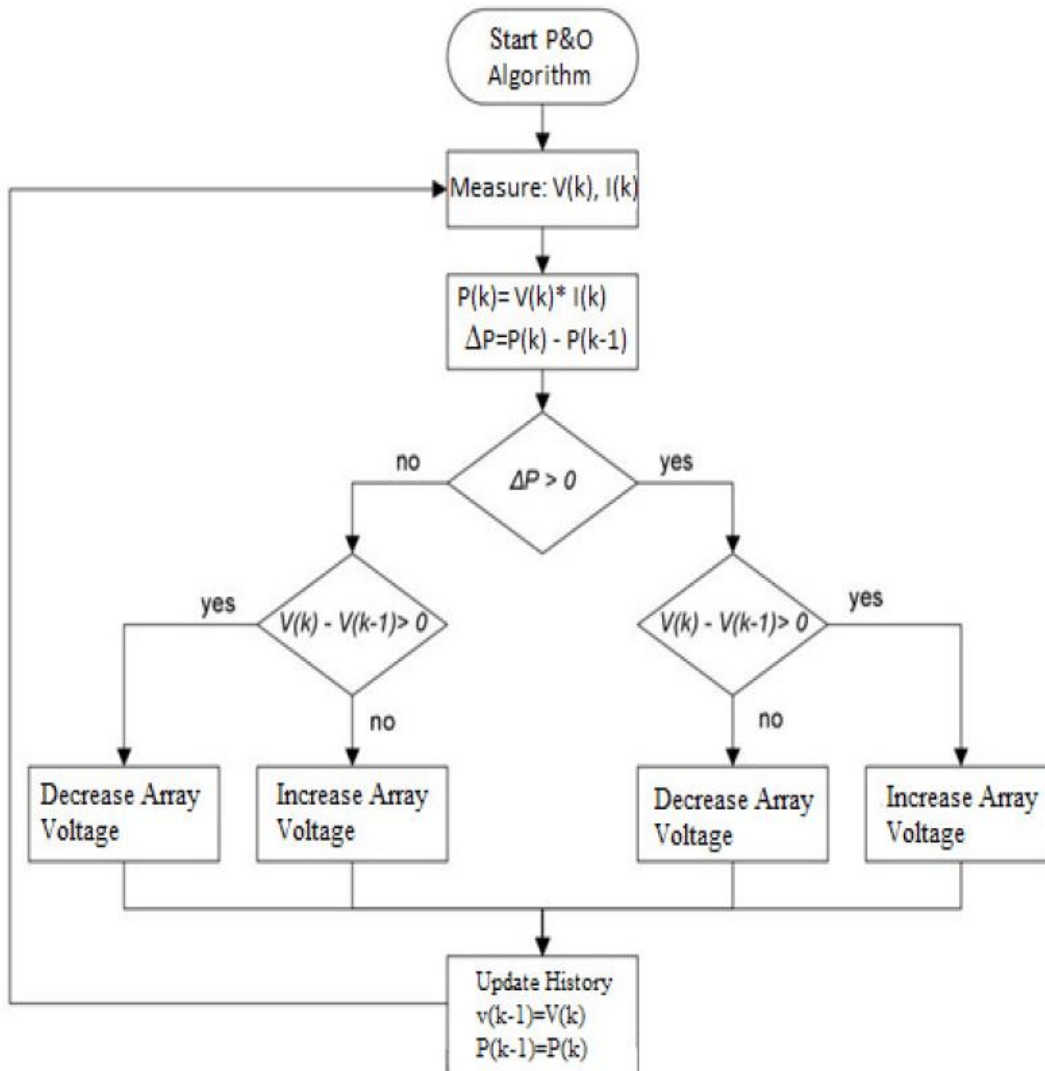

Fig. 6.4: Flowchart of Perturb & Observe algorithm

6.3   Simulation of Overall PV System

6.3.1   PV system without MPPT

As per the model of PV cell shown in the previous section, a PV system has been developed in order to obtain the voltage and current characteristics. The developed PV system is shown in Fig

6.5. In order to normalize the current, a current controlled source is connected in conjunction with PV cell. The voltage and current characteristics are then obtained with the help of scope1 and scope2 respectively.
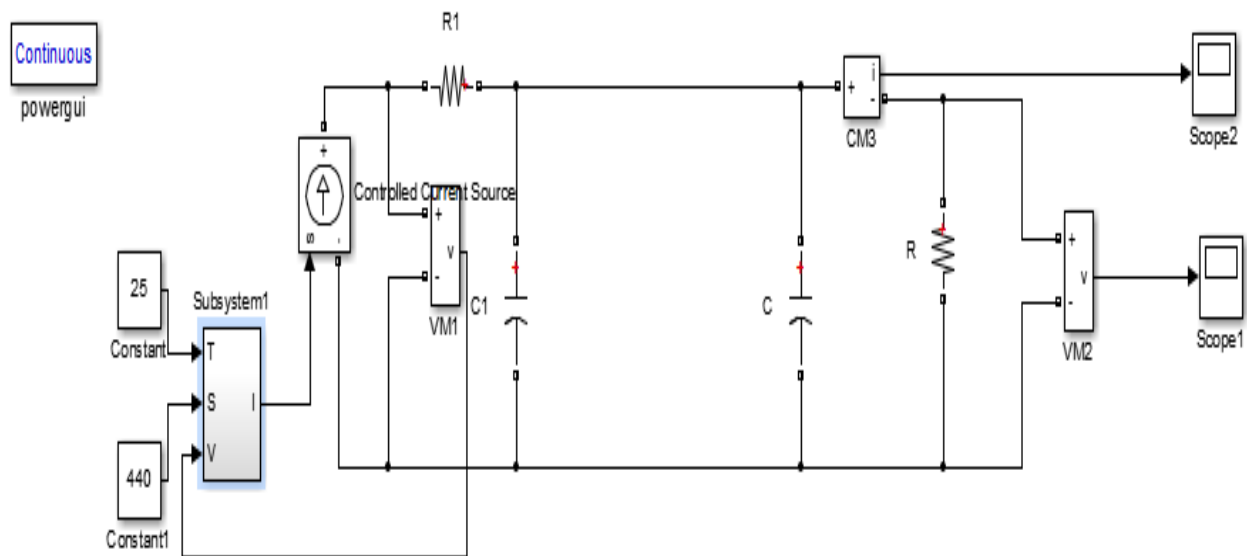

Fig.6.5 Overall PV system without MPPT

6.3.2   PV system with MPPT

Based on the models developed in the previous section an overall model of PV system section with MPPT has been obtained. The previously developed PV system and MPPT has been contained along with an inverter and load in order to simulate the system under study. The overall developed system with MPPT has been shown in Figure 6.6.
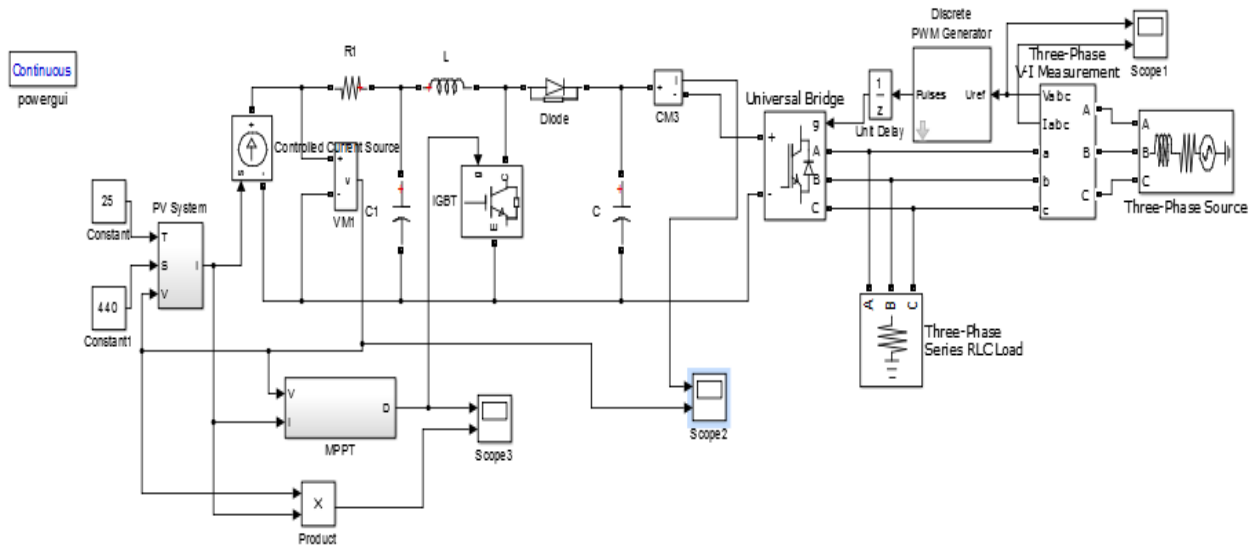
Fig.6.6 Overall PV system with MPPT

The working of the system can be understood by analyzing the model shown in figure 6.6. The maximum power has been tracked with the help of MPPT. The output of the MPPT has been given to the IGBT gate in order to trigger the IGBT. This in the will allow the PV array to itself at maximum power point. The output of PV array, through a current controlled source is fed to a universal bridge which is acting as an inverter in this model. The inverted supply has been fed to the load or to the grid of in excess.

6.4   Simulation Results

 When the model shown in fig. 6.5 is run, the waveforms have been obtained. The waveform for voltage and current are shown in figure 6.7 and 6.8 respectively.
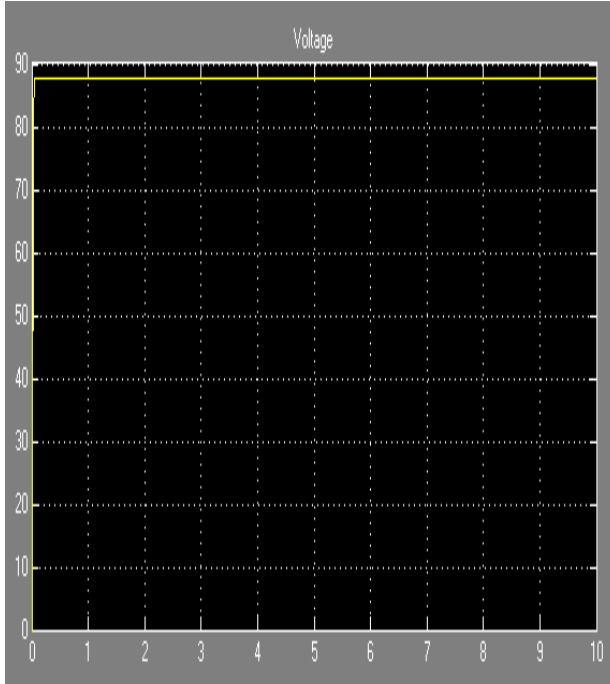
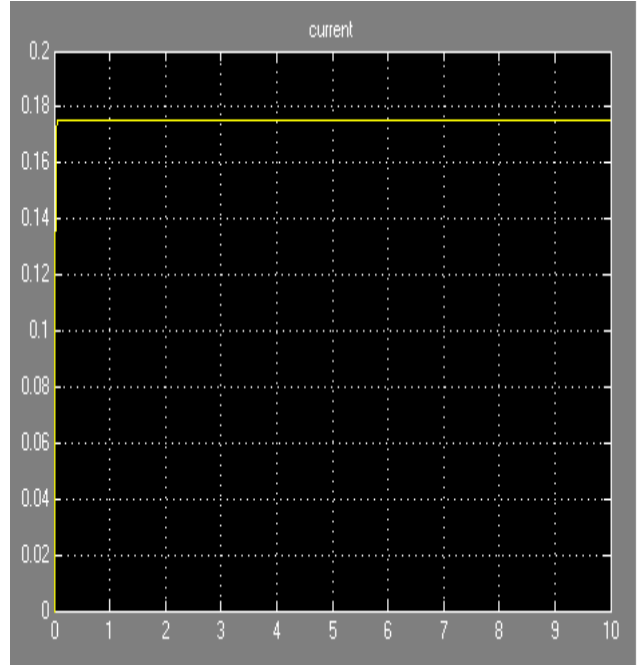**Fig.6.7: Voltage waveform**   **Fig.6.8: Current waveform**

When the model shown in fig. 6.6 is run, the waveforms have been obtained. The waveform for voltage and current are shown in figure. 6.9. The waveform for power is shown in figure 6.10.
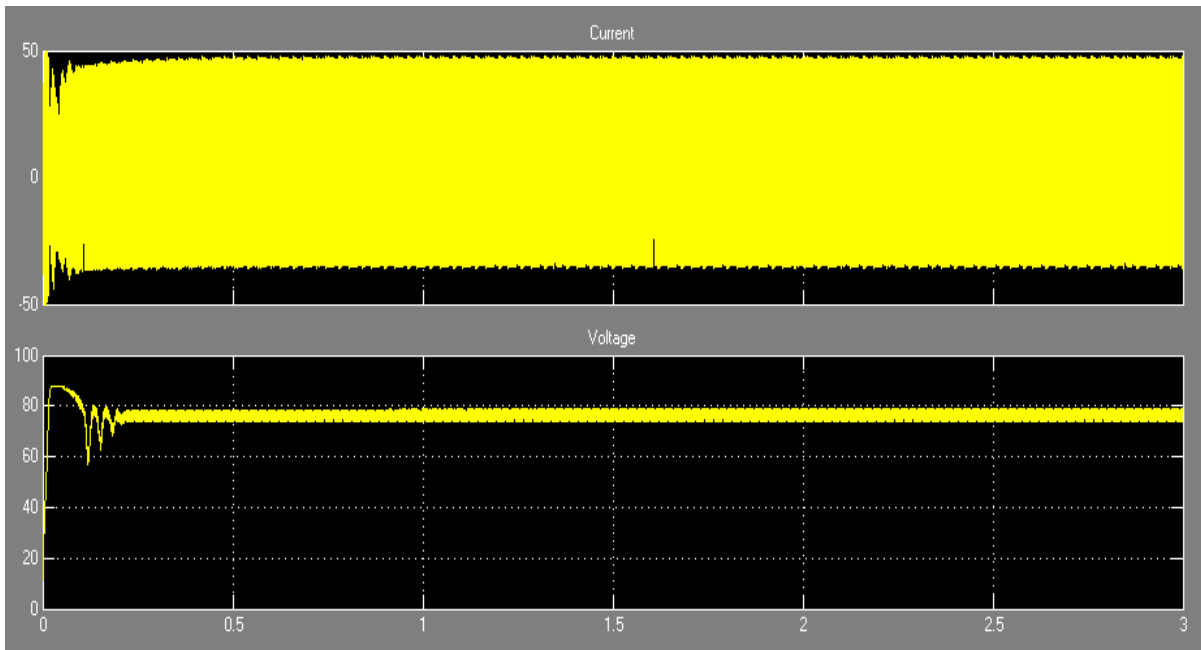

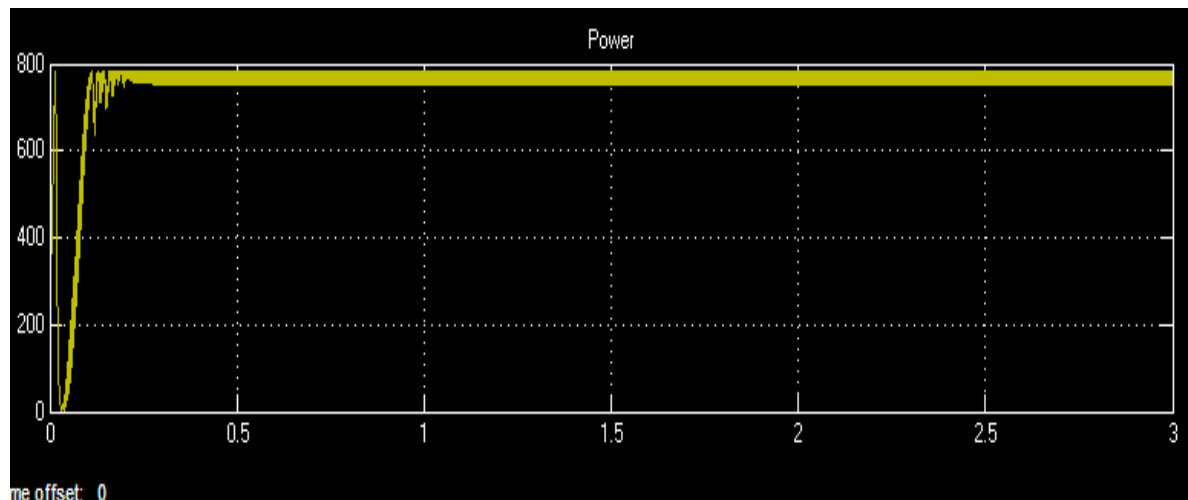**Fig.6.9: Voltage and current waveform**

Fig.6.10 Power waveform

The nature of waveform is in compliance with the actual behavior of the system. The distortion present in the waveform are due to the presence of ripples/harmonic while conversion from DC to AC.

6.5   Calculation of Energy Metrics Using Matlab

MATLAB is a useful tool for such energy analysis. Energy metrics, as discussed in chapter five, has been evaluated using MATLAB. Generalized codes have been developed in MATLAB in order to calculate the energy metrics for PV systems with and without MPPT. The data required for the evaluation is the open circuit voltage, short circuit current, fills factor, insulation, embodied energy and left term of the system. The data, as shown in observation table has been given as input to the software and the codes are run. The results obtained from software are presented in the table 6.1.

Table 6.1: Comparison of energy metrics with and without MPPT

ENERGY METRICS	WITHOUT MPPT	WITH MPPT
EPBT	8.18	7.92
EPF	0.122	0.126
LCCE	0.1746	0.178

As can be inferred from table, the EPBT of the system with MPPT is slightly more than that of system without MPPT. This is justified as an embodied energy for the system with MPPT has increased which in turn has increased the energy payback time of the system.

The EPF and LCCE for system with MPPT have also increased since the MPPT directs the PV array towards the maximum power point. This increased the production factor and efficiency of the system.

Appendix

Relevant data for Solar based project

> **Solar Energy Corporation of India Limited, New Delhi has provided some relevant data for Solar PV and Solar Thermal projects**

Table 1: Data sheet

Perticulars	Value
Average cost of grid connected rooftop solar systems	About Rs. 75 per watt or Rs. 7.5 crore per MWp capacity
Size of grid connected rooftop solar system	The rooftop solar systems from 1 kWp upto 500 kWp or in combination can be set up on the roofs.
Roof area required to set up the grid connected rooftop solar system	About 10sq.m area is required to set up 1 kWp grid connected rooftop solar system
Potential available in India	According to a study conducted by NISE (2014-15), a potential of 749 GWp SPV Rooftop plants has been estimated in the country. This can be achieved through active supports from the States
What is the present status about sanctions under the grid connected rooftop solar programme	The Ministry has so far commissioned aggregate capacity of 4675.31 MWp grid connected rooftop solar systems in the country (2015)
Cost of a 1 MW solar PV plant	In the year 2014-15, Central Electricity Regulatory Commission has given the benchmark capital cost for solar PV projects as 691 lakhs/ MW. Actual cost would depend on site location, components selection, contractor hired etc.

Source: SECI, New Delhi

> **Cost of various solar appliances provided by Solar Energy Corporation of India Limited, New Delhi (2013)**

Table 2: Data sheet

SPV System		Capacity	Benchmark cost (Rs./Wp)
Solar lighting System, home-lights, lanterns, power packs(Multi use)	CFL	Up to 300 Wp	270
	LED	Up to 300 Wp	450
Solar Water Pumping System	With DC motor	Up to 5kWp	190
	With AC motor	Up to 5kWp	161.50
Solar Street light		Up to 100 kWp	300

Source: SECI, New Delhi

> **CENTRAL ELECTRICITY REGULATORY COMMISSION, NEW DELHI**

CERC, New Delhi has release an order in the matter of determination of Benchmark Capital Cost Norm for Solar PV power projects and Solar Thermal power projects and in response, written comments/ suggestions/ objections are received from different stakeholders.

By commission's proposal and suggestions received an analysis is done and decision is taken to make a benchmark for capital cost norms for Solar PV power projects and Solar Thermal power projects

On Date 23rd March 2016, commission released an order for Solar PV power projects and Solar Thermal power projects applicable during FY 2016-17

Benchmark capital cost norm for Solar PV projects for FY 2016-17 shall be INR 530.02 lakhs/MW, with breakup as follows

Table 3: Data sheet

Perticulars	Capital cost norm proposed for FY 2016-17 (Rs. Lacks/MW), for Solar PV pojects	% of Total Cost
PV Modules	328.39	61.96
Land Cost	25	4.7
Civil & General Works	35	6.6
Mounting Structures	35	6.6
Power Conditioning Unit	35	6.6
Evacuation Cost up to inter-connection Point (Cables and Transformers)	44	8.3
Preliminary and Pre-Operative Expenses including IDC & Contigency	27.63	5.21
Total Capital Cost	530.02	100

Source: CERC, New Delhi.

Table 4: Data sheet

Details	Solar PV	Solar Thermal
Useful life in years	25	25
Rate of depreciation for 12 years (%)	5.83	5.83
Rate of depreciation after 12 years (%)	1.54	1.54

Source: CERC, New Delhi.

> **Apart from that, the usual ball-park figures used in solar sector are:**
> - Project Cost: Around 5.5-6.5 Cr./MW
> - Area required (Ground mounted): 4.5-5 Acres/MW
> - Area required (Roof-Top): 10-12sq.meters/MW

- Lenders generally give loans depending on the credibility of the developers. And for Indian lenders CERC ranges it at around 12-13%. International banks go as low as 9-10%.
- Payback period is around 6-8 years. Return on Investment is about 13%

(Source: SECI, New Delhi)

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