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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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):

![Solar radiation diagram]

**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.

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,

$$R_t = R_b + R_d + R_r \quad \text{------------------ (1.1)}$$
1.3 Sun – Earth angles

1.3.1 Latitude (ϕ)

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.

\[-90° \leq \phi \leq +90°\]

![Diagram of Latitude Angle](image)

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.
\[ \delta = 23.45 \sin 360 \frac{(284+n)}{365} \]  

(Where, \( n \)- number of days)

\( \delta < 0 \) – for winters in northern hemisphere

\( \delta > 0 \) – for summer in northern hemisphere

**Example 1:** Calculate declination angle for March 22 in a non-leap year.

Solution: On March 22, \( n = 31 \) (January) + 28 (February) + 22 (22\textsuperscript{nd} March)

\[ n = 81 \text{ days} \]

So,

\[ \delta = 23.45 \sin 360 \frac{(284+81)}{365} = 0 \]

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

**Example 2:** Calculate declination angle for March 31 in a leap year.

Solution: On March 22, \( n = 31 \) (January) + 29 (February) + 31 (31\textsuperscript{st} March)

\[ n = 91 \text{ days} \]

So,

\[ \delta = 23.45 \sin 360 \frac{(284+91)}{365} = 4.016^\circ \]

**1.3.3 Hour angle (\( \omega \))**

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

\[ \omega = 15 \, (ST - 12) \quad \cdots \cdots \quad (1.3) \]

Where, \( ST \) – solar time

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

Solution: \( \omega = 15 \, (ST - 12) \)

\[ \omega = 15 \, (14.5 - 12) = 37.5° \]

1.3.4 **Altitude Angle (\( \alpha \)) and Zenith angle (\( \theta_Z \))**

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

\[ \theta_Z = 90° - \alpha \quad \cdots \cdots \quad (1.4) \]

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

\[ \cos \theta_Z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega \quad \cdots \cdots \quad (1.5) \]

![Fig.1.5 Altitude angle and Zenith angle](image-url)
1.3.5 Surface azimuth angle (γ) and solar azimuth angle (γ_s)

Consider a surface with slope “β”. Draw an 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.

\[
\cos \gamma_s = \frac{\cos \theta_z \cdot \sin \phi - \sin \delta}{\sin \theta_z \cdot \cos \phi}
\]

(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 1\textsuperscript{st} at latitude of 23°N.

Solution: \( \phi = 23° \), \( n = 244 \) days

\[ \omega = 15(9 - 12) = 45° \]

\[ \delta = 23.45 \sin 360 \left( \frac{284 + 244}{365} \right) = 7.724° \]

\[ \cos \theta_Z = \sin (23°) \sin (7.724°) + \cos (23°) \cos (7.724°) \cos (45°) \]

\[ \theta_Z = 45.87° \]

\[ \cos \gamma_s = \frac{\cos 45.87 \sin 23 - \sin 7.724}{\sin 45.87 \cos 23} \]

\[ \gamma_s = 78.01° \]
2.1 Introduction

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 Solar thermal energy application

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.

![Diagram of flat plate solar collector]

**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**-

![Diagram of Solar Water Heater](image)

**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**-

![Solar space heater diagram](image)

**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”

\[
C = \left( \frac{A_a}{A_b} \right) \tag{2.1}
\]

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.
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-

![Solar distributed collector electric power plant diagram](image)

**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 paraboloidal dishes with centre focus.

The flat plate collectors are not used in power plants because their 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-

![Diagram of solar central receiver electrical 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

\[ \frac{mc_p \Delta T}{Vs} \]  

(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

\[
Q = m \left[ C_s(t_m - t_{\text{min}}) + h_m + C_L(t_{\text{max}} - t_m) \right] \text{ joule} \tag{2.4}
\]

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 \((J/Kg)\)
- \(t_{\text{min}}\) - Minimum storage temperature \((^\circ C)\)
- \(t_{\text{max}}\) - Maximum storage temperature \((^\circ C)\)
- \(t_m\) - Melting temperature of PCM storage medium \((^\circ C)\)

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 \((t_{\text{max}})\)

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
3.1 Solar photovoltaic (PV) energy conversion (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 –

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, \( I = I_L - I_1 \)

\[
I = I(L) - I(0)\left[\exp\left(\frac{eV}{kT}\right) - 1\right] \quad \text{------------------- (3.1)}
\]

3.2.1 Short circuit current \( (I_{SC}) \)-
When \( R=0 \) and \( V = 0 \) then \( I = 0 \)

so \( I = I_L = I_{SC} \)  

\[ (3.2) \]

### 3.2.2 Open circuit voltage (\( V_{OC} \))-

When \( R=\infty \) then \( I = 0 \)

\[
0 = I(L) - I(0) \left[ \exp \left( \frac{eV}{kT} \right) - 1 \right] \\
I(L) = I(0) \left[ \exp \left( \frac{eV}{kT} \right) - 1 \right] \\
V_{OC} = \frac{kT}{e} \left[ \ln \left( 1 + \frac{I(L)}{I(0)} \right) \right] 
\]

\[ (3.3) \]

### 3.2.3 Power delivered to load-

\( P = V \cdot I \)

\[
P = V \cdot \left[ I(L) - I(0) \left( \exp \left( \frac{eV}{kT} \right) - 1 \right) \right] 
\]

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

By solving, \( 1 + \frac{I(L)}{I(0)} = \exp \left( \frac{eV_m}{kT} \right) \cdot \left[ 1 + \frac{eV_m}{kT} \right] \)  

\[ (3.4) \]

Where \( V_m \) is the voltage which produces maximum power

### 3.2.4 Maximum Current -

If we put the value of \( \exp \left( \frac{eV_m}{kT} \right) \) from equation 4 to equation 1, we get the maximum value of current (I_m)

### 3.2.5 Maximum Power -

the maximum power is obtained by multiplying \( V_m \) and \( I_m \)

\[ P_m = V_m \cdot I_m = V_m \cdot \frac{eV_m.(I_L+I_o)/kT}{1+eV_m/kT} \]

\[ (3.5) \]
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,

\[ \%n = \frac{P_m}{P_{in}} \times 100 \]

\[ \%n = \frac{V_m \cdot I_m}{I_A} \times 100 \] \hspace{1cm} (3.6)

Where, \( P_m \) - maximum power(watt), \( P_{in} \) - input power(Watt), \( V_m \) - maximum voltage(Volt), \( I_m \) - maximum current(Amp), \( I_A \) - 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 \( V_{oc} \) and \( I_{sc} \)

\[ FF = \frac{V_m \cdot I_m}{V_{oc} \cdot I_{sc}} \] \hspace{1cm} (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/m², Area= 4 cm².

**Solution** -

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

\[
P_m = V_m \times I_m = 0.91 \text{ m Watt}
\]

\[
\%\eta = \frac{0.14 \times 0.0065}{24 \times 0.0004} \times 100 = 9.48 \%
\]

### 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

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy Gap (ev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.1</td>
</tr>
<tr>
<td>CdTe</td>
<td>1.44</td>
</tr>
<tr>
<td>CdS</td>
<td>2.42</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.40</td>
</tr>
<tr>
<td>InP</td>
<td>1.27</td>
</tr>
<tr>
<td>ZnTe</td>
<td>2.2</td>
</tr>
<tr>
<td>AlSb</td>
<td>1.63</td>
</tr>
</tbody>
</table>

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.

![Series Connection of Three Solar Cells](image)

**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

\[(\text{Voltage of one solar cell}) \times (\text{Number of solar cells}) = \text{Output of solar module}\]  

\[\text{(3.8)}\]
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

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.

\[
\text{Area covered by solar cell} = \text{Area of PV module} \times \text{Packing Factor} \quad (3.9)
\]

Non packing factor area (Area between two solar cells) = \((1 - \text{PF}) \times \text{Module Area}\) \quad (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.

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 \((N_p) = \frac{\text{Operating current of Solar Array}}{\text{Current of Solar Module}} \quad \text{(3.11)}\)

No. of modules connected in series \((N_s) = \frac{\text{Operating voltage of Solar Array}}{\text{Voltage of Solar Module}} \quad \text{(3.12)}\)

Total no. of modules in solar generator\(= N_s \times N_p \quad \text{(3.13)}\)
**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/m² and the area of each module is 0.61 m².

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

<table>
<thead>
<tr>
<th>V (Volt)</th>
<th>I (Amp.)</th>
<th>P (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>2.4</td>
<td>0.0</td>
</tr>
<tr>
<td>2.7</td>
<td>2.1</td>
<td>5.67</td>
</tr>
<tr>
<td>8.9</td>
<td>2.0</td>
<td>17.80</td>
</tr>
<tr>
<td>12.0</td>
<td>1.8</td>
<td>21.60</td>
</tr>
<tr>
<td>14.1</td>
<td>1.7</td>
<td>23.97</td>
</tr>
<tr>
<td>14.6</td>
<td>1.6</td>
<td>23.36</td>
</tr>
<tr>
<td>15.4</td>
<td>1.5</td>
<td>23.10</td>
</tr>
<tr>
<td>16.8</td>
<td>1.0</td>
<td>16.80</td>
</tr>
<tr>
<td>17.0</td>
<td>0.8</td>
<td>13.60</td>
</tr>
<tr>
<td>18.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>V (Volt)</th>
<th>I (Amp.)</th>
<th>P (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.8</td>
<td>0.0</td>
</tr>
<tr>
<td>0.2</td>
<td>1.7</td>
<td>0.34</td>
</tr>
<tr>
<td>1.5</td>
<td>1.6</td>
<td>2.40</td>
</tr>
<tr>
<td>7.1</td>
<td>1.5</td>
<td>10.65</td>
</tr>
<tr>
<td>9.6</td>
<td>1.4</td>
<td>13.44</td>
</tr>
<tr>
<td>12.8</td>
<td>1.3</td>
<td>16.64</td>
</tr>
<tr>
<td>14.2</td>
<td>1.2</td>
<td>17.04</td>
</tr>
<tr>
<td>14.6</td>
<td>1.0</td>
<td>14.60</td>
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<tr>
<td>14.9</td>
<td>0.8</td>
<td>11.92</td>
</tr>
<tr>
<td>15.6</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

(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 volt.

So, \( V_{oc} = 18 \) Volt (for semitransparent module)

Similarly \( V_{oc} = 15.6 \) 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 \((R=0 \ \Omega)\) 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, \( I_{sc} = 2.4 \) Amp. (For semitransparent module)

Similarly \( I_{sc} = 1.8 \) Amp (For opaque module)

(III) **Fill Factor:**

\[
FF = \frac{V_m \cdot I_m}{V_{oc} \cdot I_{sc}}
\]

For semitransparent module:

From the characteristics curve of semitransparent PV module,

\( V_m \cdot I_m = P_m = 24 \) Watt, \( V_{oc} = 18 \) Volt, \( I_{sc} = 2.4 \) Amp.

Hence, \( FF = \frac{24}{18 \times 2.4} = 0.55 \)
For opaque module:
From the characteristics curve of opaque PV module,
\[ V_m, I_m = P_m = 20 \text{ Watt}, \quad V_{oc} = 15.6 \text{ Volt}, \quad I_{sc} = 1.8 \text{ Amp.} \]
Hence, \[ FF = \frac{20}{15.6 \times 1.8} = 0.71 \]

(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 Solar power Plant-

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-

![Block diagram of off grid / autonomous solar plant](image)

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-

![Grid connected solar power plant](image)

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 Limitations of solar photovoltaic energy conversion-

- 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
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

![Cash Flow Diagram](image)

**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 $t=\text{T}$ is less than value at $t=\text{T} + \Delta \text{T}$ because the same money can be invested over the time period of $\Delta \text{T}$

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

\[
\begin{align*}
\text{X} & \quad \text{X} \{1 + r\} \\
(\text{At} \ t=0) & \quad (\text{At} \ t=1)
\end{align*}
\]

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, \[ X (1 + d) = \frac{X (1+r)}{(1+i)} \]

\[ d = \frac{r-1}{1+i} \]

‘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 1\(^{st}\) year = P (1+d)

Equivalent value of ‘P’ at the end of 2\(^{nd}\) year = P (1+d) + P (1+d) d

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

Equivalent value of ‘P’ at the end of T\(^{th}\) year = P (1+d)\(^T\)
Single cash flow compound amount factor, $F = (1 + d)^T$

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

**Example 1: 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.

\[C_0 = A_5 + A_4 (1+d) + A_3 (1+d)^2 + A_2 (1+d)^3 + A_1 (1+d)^4\]  

Where ‘$C_0$’ 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 batteries 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.

![Cash flow diagram](image)

Fig. 4.3 Cash flow diagram

The installation cost of solar power plant is $C_0$. After completion of one year from the installation, the benefit is $B_1$ and maintenance cost is $C_1$ so the net profit will be $A_1 = (B_1 - C_1)$. Similarly at the end of second year the net profit is $A_2 = (B_2 - C_2)$ and so on.

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

$F = A_1 (1+d)^{T-1} + A_2 (1+d)^{T-2} + \cdots + A_j (1+d)^{T-j} + \cdots + A_T$

$F = \sum A_j (1+d)^{T-j}$
Special case: if $A_j = A$ \quad \forall j = 1, 2, \ldots, T$ (uniform series of cash flow)

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

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

- Uniform series compound amount factor:

$$\frac{F}{A} = \left[ \frac{(1+d)^{T-1}}{d} \right] \quad \text{-------------------------} \quad (4.2)$$

- Uniform series sinking fund factor:

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

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

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

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

\large \text{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,

\[ P = \frac{A_1}{(1+d)} + \frac{A_2}{(1+d)^2} + \ldots + \frac{A_j}{(1+d)^j} + \ldots + \frac{A_T}{(1+d)^T} \]

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

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

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

- Uniform series present worth factor

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

- Uniform series capital recovery factor

\[ \frac{A}{P} = \left[ \frac{d (1+d)^T}{(1+d)^T - 1} \right] \] \hspace{1cm} (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
Example 3: 1 kW (rated) wind turbine of capital cost $C_0 = \text{Rs. 1, 20,000} = \text{Rs. 1, 20,000}$ 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

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

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

\[ = \text{Rs. 18,818.9} \]

Hence unit cost of electricity = 18818.9 / 2190

\[ = \text{Rs 8.6 / kWh.} \]

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 (DSWH).

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

(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>
<thead>
<tr>
<th>Fuel</th>
<th>Unit cost</th>
<th>Efficiency of utilization</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>Rs. 4 /kWh</td>
<td>0.95</td>
<td>3.6 MJ/kWh</td>
</tr>
<tr>
<td>LPG</td>
<td>Rs. 26 /kg</td>
<td>0.65</td>
<td>44 MJ/kg</td>
</tr>
<tr>
<td>Fuel wood</td>
<td>Rs. 3 /kg</td>
<td>0.15</td>
<td>18 MJ/kg</td>
</tr>
</tbody>
</table>

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

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

\[
\begin{align*}
\text{Total annual cost} &= \{ A = P \left[ \frac{d (1+d)^T}{(1+d)^T - 1} \right] \} + \{ 1000 \} \\
&= \{ A = 30000 \left[ \frac{0.12 (1+0.12)^{30}}{(1+0.12)^{30} - 1} \right] \} + \{ 1000 \} \\
&= \text{Rs 4724/=}
\end{align*}
\]
Annual thermal energy output = \((M \cdot C_p \cdot ΔT) \times 365 \text{ days} \times \text{CUF}\) 
\[= (100 \text{ kg}) \times (60 - 10 \degree\text{C}) \times (4.2 \text{ kJ/kg}°\text{C}) \times (365 \text{ days}) \times (\text{CUF})\]
\[= 6132 \text{ MJ}\]

Unit cost of useful thermal energy delivered = \(\frac{4724}{6132} = \text{Rs} \ 0.77 / \text{MJ}\)

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 = \(3.6 \times 0.95\) 
  \[= 3.4 \text{ MJ/kWh}\]
  Unit cost = \(\frac{4}{3.4}\) 
  \[= \text{Rs} \ 1.17 / \text{MJ}\]

- **Comparison with LPG water heater:**  
  Useful energy = \(44 \times 0.65\) 
  \[= 28.6 \text{ MJ/kg}\]
  Unit cost = \(\frac{26}{28.6}\) 
  \[= \text{Rs} \ 0.9/\text{MJ}\]

- **Comparison with 1kg fuel wood water heater:**  
  Useful energy = \(18 \times 0.15\) 
  \[= 2.7 \text{ MJ/kg}\]
  Unit cost = \(\frac{3}{2.7}\) 
  \[= \text{Rs} \ 1.11/\text{MJ}\]

Table 4.3 Comparison chart

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Solar</th>
<th>Electricity</th>
<th>LPG</th>
<th>Fuel wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit cost</td>
<td>Rs 0.77 / MJ</td>
<td>Rs. 1.17 /MJ</td>
<td>Rs. 0.9/MJ</td>
<td>Rs. 1.11/MJ</td>
</tr>
</tbody>
</table>

- **Net annual benefits:**  
  Annual amount of electricity saved = \(\frac{(0.8) \times (365) \times (100) \times (4.2)}{(0.95) \times (3600 \text{ kJ/kWh})}\)  
  \[= 1793 \text{ kWh}\]
  Annual benefits due to electricity saving = \((1793 \text{ kWh}) \times (\text{Rs} \ 4/\text{kWh})\)  
  \[= \text{Rs} \ 7172\]
  Net annual benefits = \(7172 - 1000 = \text{Rs} \ 6172\)
\[ P = \frac{(1+d)^T-1}{d(1+d)^T} \]

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

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 \( \xi \) 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

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

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

Present worth with fuel price escalation-

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

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. $5 \times 10^6$. 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**

<table>
<thead>
<tr>
<th>Component</th>
<th>Life span</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV modules</td>
<td>20 years</td>
</tr>
<tr>
<td>Batteries</td>
<td>7 years</td>
</tr>
<tr>
<td>Solar inverter</td>
<td>15 years</td>
</tr>
<tr>
<td>System balance</td>
<td>15 years</td>
</tr>
</tbody>
</table>

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 = $A_1 = P \left[ \frac{d \ (1+d)^T}{(1+d)^T-1} \right]$

$$A_1 = (0.44 \times 5 \times 10^6) \left[ \frac{0.05 (1+0.05)^{10}}{(1+0.05)^{10} - 1} \right]$$

$A_1 = Rs. 176533.7$

Annualized capital cost of batteries = $A_2 = P \left[ \frac{d \ (1+d)^T}{(1+d)^T-1} \right]$
\[ A2 = (0.1 \times 5 \times 10^6) \left[ \frac{0.05 (1+0.05)^7}{(1+0.05)^7 - 1} \right] \]

\[ A2 = \text{Rs. } 86409 \]

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

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

\[ A3 = \text{Rs. } 38537 \]

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

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

\[ A4 = \text{Rs. } 183050.3 \]

So total annualized cost = \text{Rs. } 634530.86/= 

A 1 kW photovoltaic module will produce 1 kW output power if it is irradiated by 1000 W/m² and the temperature is maintained at 25°C.

Average energy output of 75 kWh / day from PV array

Total annual average energy output = 75 \times 365

Unit price of electricity generated = \[
\frac{634530.86}{75 \times 365} = 23.18 \text{ /kWh}
\]

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.

\[ \sum_{j=1}^{Tsp} (B_j - C_j) = C_0 \]

If \((B_j - C_j)\) is same every year ie. uniform net annual benefit then \(Tsp \cdot (B - C) = C_0\)

\[ Tsp = \frac{C_0}{(B-C)} \quad \text{(For uniform net annual benefit)} \quad (4.9) \]

**4.8.1 (b) Discounted payback period (Tdp)**

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

\[ \sum_{j=1}^{Tdp} \frac{(B_j - C_j)}{(1+d)^j} = C_0 \]

Special case: if \((B_j - C_j) = (B - C)\) \quad \forall j = 1, 2, ..., j (For uniform net annual benefit)

\[ C_0 = (B - C) \left[ \frac{(1+d)^{Tdp} - 1}{d \cdot (1+d)^{Tdp}} \right] \]

\[ 1 - (1+d)^{-Tdp} = \frac{dC_0}{(B-C)} \]

\[ (1+d)^{-Tdp} = 1 - \frac{dC_0}{(B-C)} = \frac{(B-C) - dC_0}{(B-C)} \]

\[ (1+d)^{+Tdp} = \frac{(B-C)}{(B-C) - dC_0} \]

\[ Tdp = \frac{\ln(B-C) - \ln((B-C) - dC_0)}{\ln(1+d)} \quad \text{------------------------ (4.10)} \]

- 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)

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

(4.11)

Where ‘T’ is useful life of system and ‘S’ is salvage 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
<table>
<thead>
<tr>
<th>Project</th>
<th>C0</th>
<th>NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000</td>
<td>50000</td>
</tr>
<tr>
<td>B</td>
<td>100000</td>
<td>50000</td>
</tr>
</tbody>
</table>

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 \(d = 0\)) = \(\sum_{j=1}^{T} \frac{(B_j - C_j)}{(1+d)^j} + \frac{S}{(1+d)^T} - C0\)
- NPV (at \(d = \infty\)) = -C0
- NPV curve

![NPV Curve](image)

**Fig. 4.7 NPV Curve**

- If \((B_j - C_j) = B - C\) \(\forall j = 1,2,...,T\)
  
  \[
  \text{NPV} = (B - C) \left[ \frac{(1+d)^T-1}{d(1+d)^T} \right] + \frac{S}{(1+d)^T} - C0
  \]

- If ‘B’ increases every year by a fraction ‘\(\xi\)’ of its previous year value and ‘C’ is uniform across the useful life of project.
  
  \[
  \text{NPV} = \frac{B}{(d-\xi)} \left[ \frac{(1+\xi)^T}{1+d} \right] - C \left[ \frac{(1+d)^T-1}{d(1+d)^T} \right] + \frac{S}{(1+d)^T} - C0
  \]
4.8.3 Benefit to cost ratio (B/C) and internal rate of return (IRR):

- Benefit to cost ratio:
  \[
  \frac{B}{C} = \frac{\sum_{j=1}^{T} \frac{(B_j-C_j)}{(1+d)^j} + \frac{S}{(1+d)^T}}{C_0} \tag{4.12}
  \]

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
    \[(d)_{NPV=0} > d \text{ (for profitable project)}\]

\[
\begin{align*}
\text{NPV} &= \frac{B}{C} - C_0 \\
\text{NPV} &= \left( \frac{B-C}{1+d} \right) + \frac{B-C}{(1+d)^2} + \cdots - C_0 \\
\text{NPV} &= \frac{B-C}{1-\frac{1}{1+d}} - C_0 \\
\text{NPV} &= \frac{(B-C)}{d} - C_0 \tag{4.13}
\end{align*}
\]

At \(d=\text{IRR}\), \(NPV = 0\), \(\frac{(B-C)}{\text{IRR}} - C_0 = 0\)
Solar Energy

Economics of Solar Systems

\[ IRR = \frac{(B-C)}{C_0} \] \hspace{1cm} (4.14)

### 4.9 Case Study: Roof-top PV system for textile unit

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 280m\(^2\). 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:

<table>
<thead>
<tr>
<th>PV Panel Specification</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel rated power</td>
<td>305 Wp</td>
</tr>
<tr>
<td>Maximum power (Pm)</td>
<td>305 Wp</td>
</tr>
<tr>
<td>Open circuit voltage (Voc)</td>
<td>44.9 Volt</td>
</tr>
<tr>
<td>Maximum power voltage (Vm)</td>
<td>36.6 Volt</td>
</tr>
<tr>
<td>Power tolerance</td>
<td>8.73 Amp.</td>
</tr>
<tr>
<td>Maximum power current</td>
<td>8.33 Amp.</td>
</tr>
<tr>
<td>Solar intensity</td>
<td>1000 W/m(^2)</td>
</tr>
<tr>
<td>Temperature</td>
<td>25°C</td>
</tr>
<tr>
<td>Dimension</td>
<td>(1956<em>992</em>40) mm(^3)</td>
</tr>
<tr>
<td>Maximum system voltage (Vm)</td>
<td>1000 Volt</td>
</tr>
<tr>
<td>Number of panels</td>
<td>84</td>
</tr>
<tr>
<td>Inverter rating</td>
<td>30 kVA</td>
</tr>
<tr>
<td>Solar PV plant capacity</td>
<td>25 kWp</td>
</tr>
<tr>
<td>Roof-top area</td>
<td>275 m(^2)</td>
</tr>
<tr>
<td>Annual unit generation</td>
<td>31700 kWh</td>
</tr>
<tr>
<td>Degradation of solar output</td>
<td>3% in first year &amp; 0.7% in second year onwards</td>
</tr>
<tr>
<td>Life time of system</td>
<td>25 years</td>
</tr>
<tr>
<td>capacity utilization factor (CUF)</td>
<td>14.5%</td>
</tr>
<tr>
<td>Electricity price escalation</td>
<td>2% (per year)</td>
</tr>
<tr>
<td>Structure weight</td>
<td>27 kg</td>
</tr>
<tr>
<td>Overall system cost (including PV array, inverter, mounting structure, cables, metering instruments)</td>
<td>Rs. 18,75,000/=</td>
</tr>
</tbody>
</table>
- The PV system is in operation for 360 days in a year with capacity utilization factor (CUF) of 14.5%. Then,

\[ \text{Unit (kWh) generation} = \text{kW output} \times \text{CUF} \times 24\text{hours} \times 360\text{days} \]

- 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**

<table>
<thead>
<tr>
<th>Year</th>
<th>System Output</th>
<th>kW Output</th>
<th>kWh (Unit)</th>
<th>Unit cost-Rs(Delhi)</th>
<th>Benefit (Rs)</th>
<th>(O&amp;M+ Insurance) Cost</th>
<th>Savings (Rs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st year</td>
<td>100</td>
<td>25</td>
<td>31320.0</td>
<td>8.400</td>
<td>263088</td>
<td>46875</td>
<td>216213</td>
</tr>
<tr>
<td>2nd year</td>
<td>97</td>
<td>24.250</td>
<td>30380.4</td>
<td>8.568</td>
<td>260299.27</td>
<td>46875</td>
<td>213424.27</td>
</tr>
<tr>
<td>3rd year</td>
<td>96.321</td>
<td>24.080</td>
<td>30167.7</td>
<td>8.739</td>
<td>263646.72</td>
<td>46875</td>
<td>216771.72</td>
</tr>
<tr>
<td>4th year</td>
<td>95.647</td>
<td>23.912</td>
<td>29956.6</td>
<td>8.914</td>
<td>267037.9</td>
<td>46875</td>
<td>220162.9</td>
</tr>
<tr>
<td>5th year</td>
<td>94.977</td>
<td>23.744</td>
<td>29746.8</td>
<td>9.092</td>
<td>270470.67</td>
<td>46875</td>
<td>223595.67</td>
</tr>
<tr>
<td>6th year</td>
<td>94.312</td>
<td>23.578</td>
<td>29538.5</td>
<td>9.274</td>
<td>273948.45</td>
<td>46875</td>
<td>227073.45</td>
</tr>
<tr>
<td>7th year</td>
<td>93.652</td>
<td>23.413</td>
<td>29331.8</td>
<td>9.460</td>
<td>277471.98</td>
<td>46875</td>
<td>230596.98</td>
</tr>
<tr>
<td>8th year</td>
<td>92.997</td>
<td>23.249</td>
<td>29126.7</td>
<td>9.649</td>
<td>281041.97</td>
<td>46875</td>
<td>234166.97</td>
</tr>
<tr>
<td>9th year</td>
<td>92.346</td>
<td>23.087</td>
<td>28922.8</td>
<td>9.824</td>
<td>284656.1</td>
<td>46875</td>
<td>237781.1</td>
</tr>
<tr>
<td>10th year</td>
<td>91.699</td>
<td>22.925</td>
<td>28720.1</td>
<td>10.039</td>
<td>288314.96</td>
<td>46875</td>
<td>241439.96</td>
</tr>
<tr>
<td>11th year</td>
<td>91.058</td>
<td>22.765</td>
<td>28519.4</td>
<td>10.240</td>
<td>292025.56</td>
<td>46875</td>
<td>245150.56</td>
</tr>
<tr>
<td>12th year</td>
<td>90.42</td>
<td>22.605</td>
<td>28319.5</td>
<td>10.444</td>
<td>295779.06</td>
<td>46875</td>
<td>248904.06</td>
</tr>
<tr>
<td>13th year</td>
<td>89.787</td>
<td>22.447</td>
<td>28121.3</td>
<td>10.653</td>
<td>299582.58</td>
<td>46875</td>
<td>252707.58</td>
</tr>
<tr>
<td>14th year</td>
<td>89.159</td>
<td>22.290</td>
<td>27924.6</td>
<td>10.866</td>
<td>303436.95</td>
<td>46875</td>
<td>256561.95</td>
</tr>
<tr>
<td>15th year</td>
<td>88.535</td>
<td>22.134</td>
<td>27729.2</td>
<td>11.084</td>
<td>307339.54</td>
<td>46875</td>
<td>260464.54</td>
</tr>
<tr>
<td>16th year</td>
<td>87.915</td>
<td>21.979</td>
<td>27535.0</td>
<td>11.305</td>
<td>311291.02</td>
<td>46875</td>
<td>264416.02</td>
</tr>
<tr>
<td>17th year</td>
<td>87.299</td>
<td>21.825</td>
<td>27342.0</td>
<td>11.531</td>
<td>315292.08</td>
<td>46875</td>
<td>268417.08</td>
</tr>
<tr>
<td>18th year</td>
<td>86.688</td>
<td>21.672</td>
<td>27150.7</td>
<td>11.762</td>
<td>319347.08</td>
<td>46875</td>
<td>272472.08</td>
</tr>
<tr>
<td>19th year</td>
<td>86.082</td>
<td>21.521</td>
<td>26960.9</td>
<td>11.997</td>
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<tr>
<td>20th year</td>
<td>85.479</td>
<td>21.370</td>
<td>26772.0</td>
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<td>327614.97</td>
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<tr>
<td>21st year</td>
<td>84.881</td>
<td>21.220</td>
<td>26584.7</td>
<td>12.482</td>
<td>331829.48</td>
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<td>22nd year</td>
<td>84.286</td>
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<td>12.732</td>
<td>336093.48</td>
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<td>20.924</td>
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<td>24th year</td>
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<td>25th year</td>
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<td>25848.1</td>
<td>13.511</td>
<td>349230.16</td>
<td>46875</td>
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</table>
Table: Saving and Payback calculation

<table>
<thead>
<tr>
<th>Saving after 1 year</th>
<th>Saving after 2 years</th>
<th>Saving after 3 years</th>
<th>Saving after 4 years</th>
<th>Saving after 5 years</th>
<th>Saving after 6 years</th>
<th>Saving after 7 years</th>
<th>Saving after 8 years</th>
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<td>237781.1</td>
<td>237781.1</td>
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</tbody>
</table>

| 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.
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,

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

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.

  $$\chi_a = \frac{Eaout}{Ein} = \frac{1}{T(\text{epb})}$$

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

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

Where

- $E_{out}$ – Total net energy output over life of the system (kwh).
- $E_{in}$ – Embodied Energy of the system(kwh).
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

\[
\phi = \frac{E_{\text{out}} - E_{\text{in}}}{E_{\text{sol}} \times T(\text{LS})}
\]

\[
= \frac{E_{\text{out}}}{E_{\text{sol}}} (1 - \frac{1}{\eta \times T(\text{LS})})
\]

\[
= \frac{E_{\text{out}}}{E_{\text{sol}}} (1 - \frac{1}{\eta T})
\]

\[
= \eta (1 - \frac{1}{\eta T})
\]

- 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 m²), a charge controller (efficiency – 84%), a battery
Solar Energy

Energy analysis of solar system

(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

![Block diagram of rooftop photovoltaic (PV) system](image)

**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

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Time</th>
<th>Intensity (W/m²)</th>
<th>Short Circuit Current, Isc (Amp.)</th>
<th>Open Circuit Voltage, Voc (Volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>09 am</td>
<td>500</td>
<td>23.20</td>
<td>19.80</td>
</tr>
<tr>
<td>2</td>
<td>10 am</td>
<td>640</td>
<td>34.60</td>
<td>19.60</td>
</tr>
<tr>
<td>3</td>
<td>11 am</td>
<td>820</td>
<td>42.50</td>
<td>19.40</td>
</tr>
<tr>
<td>4</td>
<td>12 noon</td>
<td>895</td>
<td>46.50</td>
<td>19.60</td>
</tr>
<tr>
<td>5</td>
<td>01 pm</td>
<td>860</td>
<td>47.60</td>
<td>19.40</td>
</tr>
<tr>
<td>6</td>
<td>02 pm</td>
<td>740</td>
<td>44.60</td>
<td>19.40</td>
</tr>
<tr>
<td>7</td>
<td>03 pm</td>
<td>620</td>
<td>34.20</td>
<td>19.50</td>
</tr>
<tr>
<td>8</td>
<td>04 pm</td>
<td>360</td>
<td>18.20</td>
<td>19.20</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>S N</th>
<th>Material</th>
<th>Embodied Energy (kWh/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Silicon Purification and Processing (Metallurgical grade silicon production / Electronic grade silicon production / Silicon crystal growth)</td>
<td>670.00</td>
</tr>
<tr>
<td>2</td>
<td>Solar Cell Production</td>
<td>120.00</td>
</tr>
<tr>
<td>3</td>
<td>PV Module Lamination and Assembly (Steel infrastructure / Ethyle vinyl acetate / Tedler production / Glass Sheet production / Aluminum frame production / Other materials)</td>
<td>190.00</td>
</tr>
</tbody>
</table>

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

Table 5.3 Embodied energy

<table>
<thead>
<tr>
<th>S.N</th>
<th>Item</th>
<th>Embodied Energy</th>
<th>Total Weight (kg) / Total Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Support Structure (Iron stand / Screw)</td>
<td>7.70 (kwh/kg) 8.63 (kwh/kg)</td>
<td>40 kg. 1.00 kg.</td>
</tr>
<tr>
<td>2</td>
<td>Charge Controller</td>
<td>210.00 (kwh/kw)</td>
<td>0.36 kw.</td>
</tr>
<tr>
<td>3</td>
<td>Battery</td>
<td>46.00 (kwh/m²)</td>
<td>7.32 m².</td>
</tr>
<tr>
<td>4</td>
<td>Inverter</td>
<td>210.00 (kwh/kw)</td>
<td>0.50 kw.</td>
</tr>
<tr>
<td>5</td>
<td>Wires</td>
<td>3.00 (kwh/m²)</td>
<td>7.32 m².</td>
</tr>
</tbody>
</table>
• The embodied energy used in human labor and transportation is 9.84 kWh/m² and 53.50 kWh/m² respectively.

Calculations:
• Calculation of electric power output of PV array:

<table>
<thead>
<tr>
<th>SN</th>
<th>Time</th>
<th>Intensity (W/m²)</th>
<th>Short Circuit Current, Isc (Amp.)</th>
<th>Open Circuit Voltage, Voc (Volt)</th>
<th>Electrical Power Generated (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>09 am</td>
<td>500</td>
<td>23.20</td>
<td>19.80</td>
<td>367.49</td>
</tr>
<tr>
<td>2</td>
<td>10 am</td>
<td>640</td>
<td>34.60</td>
<td>19.60</td>
<td>542.53</td>
</tr>
<tr>
<td>3</td>
<td>11 am</td>
<td>820</td>
<td>42.50</td>
<td>19.40</td>
<td>659.60</td>
</tr>
<tr>
<td>4</td>
<td>12 noon</td>
<td>895</td>
<td>46.50</td>
<td>19.60</td>
<td>714.24</td>
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<tr>
<td>5</td>
<td>01 pm</td>
<td>860</td>
<td>47.60</td>
<td>19.40</td>
<td>738.75</td>
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<tr>
<td>6</td>
<td>02 pm</td>
<td>740</td>
<td>44.60</td>
<td>19.40</td>
<td>692.19</td>
</tr>
<tr>
<td>7</td>
<td>03 pm</td>
<td>620</td>
<td>34.20</td>
<td>19.50</td>
<td>533.52</td>
</tr>
<tr>
<td>8</td>
<td>04 pm</td>
<td>360</td>
<td>18.20</td>
<td>19.20</td>
<td>279.55</td>
</tr>
</tbody>
</table>

Average Intensity during the day (\( \bar{I} \)) = 679.37 W/m².

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

Total Electrical Energy provided to the load for one day, \( E_{\text{per day}} \)

\[ E_{\text{per day}} = E \times \text{Efficiency of Charge Controller} \times \text{Efficiency of Inverter} \]

\[ E_{\text{per day}} = 4.53 \times 0.84 \times 0.85 = 3.24 \text{ kwh}. \]

Total Electrical Energy provided to the load for one year, \( E_{\text{per year}} \)

\[ E_{\text{per year}} = E_{\text{per day}} \times \text{No. of clear days}. \]

\[ E_{\text{per year}} = 3.24 \times 300 \]

\[ E_{\text{per year}} = 971.05 \text{kwh}. \]

• Calculation of Embodied Energy of Installed PV System:

Calculation of material production Energy (\( E_{\text{mpe}} \)):
### Solar Energy

**Energy analysis of solar system**

<table>
<thead>
<tr>
<th>SN</th>
<th>Material</th>
<th>Embodied Energy (kwh/m²)</th>
<th>Total Area (m²)</th>
<th>Total Embodied Energy (kwh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Silicon Purification and Processing (Metallurgical grade silicon production / Electronic grade silicon production / Silicon crystal growth)</td>
<td>670.00</td>
<td>7.32</td>
<td>4904.40</td>
</tr>
<tr>
<td>2</td>
<td>Solar Cell Production</td>
<td>120.00</td>
<td>7.32</td>
<td>878.40</td>
</tr>
<tr>
<td>3</td>
<td>PV Module Lamination and Assembly (Steel infrastructure / Ethyle vinyl acetate / Tedler production / Glass Sheet production / Aluminum frame production / Other materials)</td>
<td>190.00</td>
<td>7.32</td>
<td>1390.80</td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th>S.No</th>
<th>Item</th>
<th>Embodied Energy</th>
<th>Total Weight (kg) / Total Area (m²)</th>
<th>Total Embodied Energy (kwh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Support Structure (Iron stand / Screw)</td>
<td>7.70 (kwh/kg) / 8.63 (kwh/kg)</td>
<td>40 kg. / 1.00 kg.</td>
<td>308.00 (kwh) / 8.63 (kwh)</td>
</tr>
<tr>
<td>2</td>
<td>Charge Controller</td>
<td>210.00 (kwh/kw)</td>
<td>0.36 kw.</td>
<td>75.60 (kwh)</td>
</tr>
<tr>
<td>3</td>
<td>Battery</td>
<td>46.00 (kwh/m²)</td>
<td>7.32 m².</td>
<td>336.72 (kwh)</td>
</tr>
<tr>
<td>4</td>
<td>Inverter</td>
<td>210.00 (kwh/kw)</td>
<td>0.50 kw.</td>
<td>105.00 (kwh)</td>
</tr>
<tr>
<td>5</td>
<td>Wires</td>
<td>3.00 (kwh/m³) / 7.32 m³.</td>
<td></td>
<td>21.96 (kwh)</td>
</tr>
</tbody>
</table>

Total Material Production Energy (E_{inst}) = 855.91 kwh.
Calculation of energy used in maintenance ($E_{\text{main}}$):

<table>
<thead>
<tr>
<th>S.No</th>
<th>Item</th>
<th>Embodied Energy ($kwh/m^2$)</th>
<th>Total Area ($m^2$)</th>
<th>Total Embodied Energy ($kwh$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Human Labor</td>
<td>9.84</td>
<td>7.32</td>
<td>72.03</td>
</tr>
</tbody>
</table>

Calculation of energy used in administration ($E_{\text{admin}}$):

<table>
<thead>
<tr>
<th>S.No</th>
<th>Item</th>
<th>Embodied Energy ($kwh/m^2$)</th>
<th>Total Area ($m^2$)</th>
<th>Total Embodied Energy ($kwh$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Transportation</td>
<td>53.50</td>
<td>7.32</td>
<td>391.62</td>
</tr>
</tbody>
</table>

Total manufacturing energy ($E_{\text{mfg}}$) = $E_{\text{mpc}} + E_{\text{main}}$

$$= 7173.60 + 72.03$$

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

Calculation of embodied energy of complete PV system:

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

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

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

$$= 7245.63 + 855.91 + 391.62$$

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

Calculation of Energy Metrics of Installed PV System

(1) Energy Pay Back Time (EPBT) = \(\frac{\text{Embodied Energy}}{\text{Electrical Energy Generated (Yearly)}}\)

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

$$T_{\text{epb}} = 8.75 \text{ Years}$$
Electricity Production Factor (EPF) = \frac{\text{Electrical Energy Generated (Yearly)}}{\text{Embodied Energy}}

\chi = \frac{971.05}{8493.16}

\chi = 0.12 \text{ per year}

Life Cycle Conversion Efficiency (LCCE) = \frac{E_{\text{out}} \times TLS - E_{\text{in}}}{E_{\text{sol}} \times TLS}

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

\Phi = 0.12

5.3 Energy analysis of solar evaporative cooling system

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

<table>
<thead>
<tr>
<th>SN</th>
<th>Item</th>
<th>cost</th>
<th>Embodied energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Jute cloth</td>
<td>J</td>
<td>E_1</td>
</tr>
<tr>
<td>2</td>
<td>Spray</td>
<td>S</td>
<td>E_2</td>
</tr>
<tr>
<td>3</td>
<td>Water</td>
<td>W</td>
<td>E_3</td>
</tr>
<tr>
<td>4</td>
<td>Electricity (by PV system)</td>
<td>E</td>
<td>E_4</td>
</tr>
</tbody>
</table>

The embodied energy is calculated by equation

Ein = \sum_{i=1}^{4} E_i

E_1 = \sum_{j=1}^{m} e_1j \quad E_2 = \sum_{j=1}^{m} e_2j \quad E_3 = \sum_{j=1}^{m} e_3j \quad E_4 = \sum_{j=1}^{m} e_4j

(‘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
5.4 Energy analysis of solar day lighting system

Consider a room without any glass window i.e. There is no provision for providing the day light inside the room. Now by designing a window of 1 m² 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

\[
\text{Energy saved annually} = 40 \text{ (Watt)} \times 10 \text{ (hours per day)} \times 250 \text{ (working days in a year)}
\]

\[
= 100 \text{ kWh.}
\]
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$^2$ ($E_{in} = 50$ kWh).

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

$E_{out,T} = 100 \text{ (kWh yearly)} \times (100 \text{ years})$

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

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

$E_{solar \ (yearly)} = 500 \text{ (W / m}^2\text{)} \times 1 \text{ (m}^2\text{)} \times 250 \text{ (days)} \times 10 \text{ (hours per day)}$

$E_{solar \ (yearly)} = 125000 \text{ kWh}$

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

- Energy Pay Back Time (EPBT) = $\frac{E_{in}}{E_{out, \text{ yearly}}} \text{ years}$

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

- Life Cycle Conversion Efficiency (LCCE) = $\frac{E_{out,T} \times \text{TLS} - E_{in}}{E_{solar} \times \text{TLS}}$

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

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

$\text{EPF} = \frac{10000}{50} = 200 \text{ year}$
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.
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 $(1.6 \times 10^{-19} C)$

$k$ is Boltzmann’s constant $(1.38 \times 10^{-23} j/K)$

$T_c$ is the cell working temperature in Kelvin

A ideality factor

$R_s$ and $R_{sh}$ are the series and parallel resistances

The $I_{ph}$ mainly depends on the solar radiation and cells working temperature which is described as Eq (6.2)

$$I_{ph} = I_{sc} + K_i (T_c – T_{ref}) \lambda$$

Where $I_{sc}$ is the short circuit current at $25^\circ C$ and solar radiation of $1kW/m^2$

$K_i$ is the cell temperature coefficient of current

$T_{ref}$ is the reference temperature of the cell

$\lambda$ is the solar radiation in $kW/m^2$

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

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

Where $I_{rs}$ is the cells reverse saturation current at reference temperature and solar radiation and $E_g$ is the Band-gap energy of the semiconductor used in the cell.

The shunt resistance $R_{sh}$ is inversely related with shunt leakage current to the ground. In general, the PV efficiency is insensitive to variation in $R_{sh}$ and this shunt leakage resistance can be assumed to approach infinity without leakage current to ground. On the other hand, a small variation in $R_s$ will significantly affect the PV output power. Eq. can be rewritten as
I = Iph – (Is exp ( q(V+IRs)/kTcA) -1) ----------------------------------------- (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 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, \( R = \frac{V}{I} \), 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.

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.

![Flowchart](image.png)

**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.
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

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
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

<table>
<thead>
<tr>
<th>ENERGY METRICS</th>
<th>WITHOUT MPPT</th>
<th>WITH MPPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPBT</td>
<td>8.18</td>
<td>7.92</td>
</tr>
<tr>
<td>EPF</td>
<td>0.122</td>
<td>0.126</td>
</tr>
<tr>
<td>LCCE</td>
<td>0.1746</td>
<td>0.178</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Perticulars</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average cost of grid connected rooftop solar systems</td>
<td>About Rs. 75 per watt or Rs. 7.5 crore per MWp capacity</td>
</tr>
<tr>
<td>Size of grid connected rooftop solar system</td>
<td>The rooftop solar systems from 1 kWp upto 500 kWp or in combination can be set up on the roofs.</td>
</tr>
<tr>
<td>Roof area required to set up the grid connected rooftop solar system</td>
<td>About 10sq.m area is required to set up 1 kWp grid connected rooftop solar system</td>
</tr>
<tr>
<td>Potential available in India</td>
<td>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</td>
</tr>
<tr>
<td>What is the present status about sanctions under the grid connected rooftop solar programme</td>
<td>The Ministry has so far commissioned aggregate capacity of 4675.31 MWp grid connected rooftop solar systems in the country (2015)</td>
</tr>
<tr>
<td>Cost of a 1 MW solar PV plant</td>
<td>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.</td>
</tr>
</tbody>
</table>

Source: SECI, New Delhi

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

Table 2: Data sheet

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

Source: SECI, New Delhi
CENTRAL ELECTRICITY REGULATORY COMMISSION, NEW DELHI

CERC, New Delhi has released 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

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Capital cost norm proposed for FY 2016-17 (Rs. Lacks/MW), for Solar PV projects</th>
<th>% of Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Modules</td>
<td>328.39</td>
<td>61.96</td>
</tr>
<tr>
<td>Land Cost</td>
<td>25</td>
<td>4.7</td>
</tr>
<tr>
<td>Civil &amp; General Works</td>
<td>35</td>
<td>6.6</td>
</tr>
<tr>
<td>Mounting Structures</td>
<td>35</td>
<td>6.6</td>
</tr>
<tr>
<td>Power Conditioning Unit</td>
<td>35</td>
<td>6.6</td>
</tr>
<tr>
<td>Evacuation Cost up to inter-connection Point (Cables and Transformers)</td>
<td>44</td>
<td>8.3</td>
</tr>
<tr>
<td>Preliminary and Pre-Operative Expenses including IDC &amp; Contingency</td>
<td>27.63</td>
<td>5.21</td>
</tr>
<tr>
<td>Total Capital Cost</td>
<td>530.02</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: CERC, New Delhi.

Table 4: Data sheet

<table>
<thead>
<tr>
<th>Details</th>
<th>Solar PV</th>
<th>Solar Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Useful life in years</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Rate of depreciation for 12 years (%)</td>
<td>5.83</td>
<td>5.83</td>
</tr>
<tr>
<td>Rate of depreciation after 12 years (%)</td>
<td>1.54</td>
<td>1.54</td>
</tr>
</tbody>
</table>

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): 10-12 sq. 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)
BIBLIOGRAPHY


