Experiment: 3 (b) Energy yield analysis of a PV module in fixed and 2D-tracked mode of operation

3 (c) Calculation of economic payback period of tracking system retrofitted in a 10 MW Solar PV power plant

Aim:

1) To find out I-V characteristics of a solar photovoltaic module and calculate P_m corresponding to different times and module orientations.
2) To calculate the energy output (kWh) corresponding to different time periods and module orientations.
3) To compare the energy yields for fixed and tracked operation of same PV module.
4) Extrapolate the energy gain for a 10 MW solar PV power plant retrofitted with 2D sun tracking system and calculate LCC (life cycle cost) of the power plant with and without tracking, SPP (simple payback period) of the retrofit/tracking. Specify assumptions wherever it is used. Also, express your views based on the results.

Apparatus used:

Solar photovoltaic module fitted with manual tracking system, pyranometer, ammeter/multimeter, voltmeter/multimeter, variable resistive load.

Theory:

The sun, a natural fusion reactor that has been burning over 4 billion years is the cause of all these energy resources either directly or indirectly. The Earth receives an incredible supply of solar energy. The power from the sun intercepted by the earth is approximately 1.8×10^{11} MW which are many thousands of times larger than the present consumption rate on the earth of all commercial energy sources. The amount of solar energy reaching the surface of the planet is so vast that in one year it is about twice as much as will ever be obtained from all of the Earth's non-renewable resources of coal, oil, natural gas, and mined uranium combined. Thus solar energy could supply the present and future energy needs of the world in a renewable way.

There are various ways to harness this freely available solar energy but use of solar Photovoltaics has its own advantages like: higher efficiency potential, direct conversion to electricity (high grade energy), modular, distributed, high power to weight ratio, pollution free, direct accessibility, sharing of existing infrastructure (rooftops), instant conversion, easy to install, lower maintenance etc.

Basically 'solar cell' is a solid state semiconductor device working on the principle of photovoltaic (PV) effect which directly converts sunlight into electricity. Mainly two important steps are involved in the principle of working of a solar cell: 1) Creation of pairs of positive and negative charges (called electron-hole pairs) in the solar cell by absorbed solar radiation and 2) Separation of the positive and negative charges by a potential gradient within the cell.

Energy E of a photon is $E = (hc)/\lambda$

Where,

$h = 6.62 \times 10^{-34}$ Js

$c = 3 \times 10^{8}$ m/s

$E = 1.24/\lambda$ (E in eV and λ in μm)

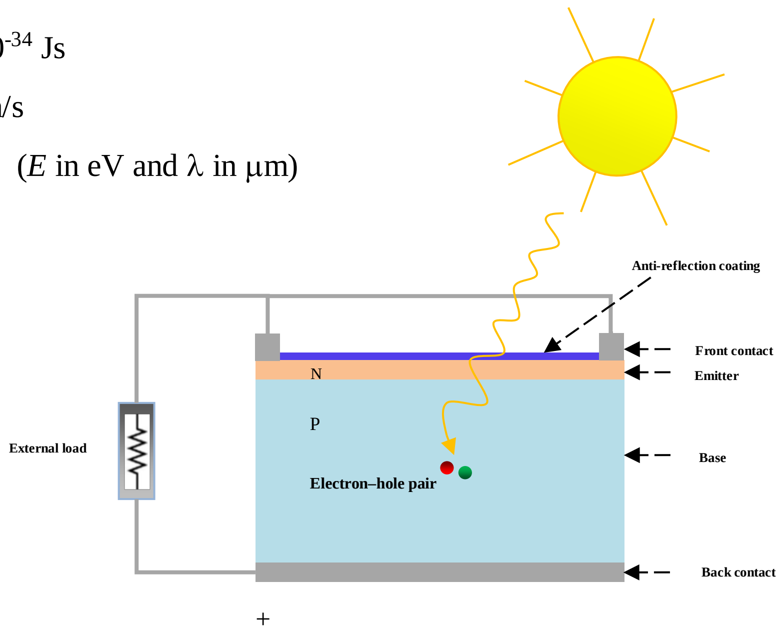

Figure 1: Operation of p-n junction Si solar cell

The semiconductor materials like Si, CdTe, CdS, GaAs etc. are suitable for absorbing the energy of photons. When photons of sunlight having energy greater than the band gap energy E_g are absorbed in the cell material, they excite some of the electrons. These electrons jump across the band gap from the valence band to the conduction band leaving behind holes in the valence band. Thus electron-hole pairs are created as shown in Fig. 1. The electrons in the conduction band and the holes in the valence band are mobile. They can be separated and made to flow through an external circuit if a potential gradient exists within the cell. This potential gradient is obtained by making a p-n junction.

The solar cells are connected in various series-parallel combinations corresponding to particular module current- voltage ratings. Various types of modules are available in the market in terms of ratings and technology and again these modules can be integrated depending on the specific application like: stand-alone PV systems, hybrid PV systems, solar PV water pumping system, grid connected PV power plant etc.

I-V characteristics in solar PV: The behavior of solar cell/module is depicted by plotting its current-voltage characteristic. The intercepts of the curve on the voltage and current axes are termed the open circuit voltage (V_{oc}) and short circuit current (I_{sc}) respectively. The maximum useful power that module can deliver, corresponds to the point on the curve, which yields the rectangle with the largest area.

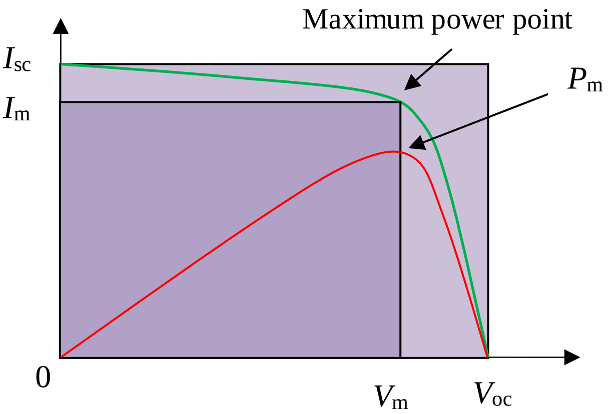

Figure 2: I-V characteristics (green) and P-V characteristics (red) of the solar cell

Let I_m and V_m denote the current and voltage corresponding to maximum power.

Then, Fill factor $FF = I_m \cdot V_m / I_{sc} \cdot V_{oc}$ (1)

Let, I_T = incident solar flux (calculated using pyranometer readings)

A_c = area of the cell/module

Then maximum electrical conversion efficiency,

$$\eta_{max} = I_m \cdot V_m / I_T \cdot A_c \quad (2)$$

$$= FF \cdot I_{sc} \cdot V_{oc} / I_T \cdot A_c \quad (3)$$

Simple payback period (SPP) and life cycle costing (LCC): The simple payback period (**SPP**) is the time period (usually in years) to recover the initial investment in a project. It is very easy and helpful for an initial analysis of a project but it does not account for the savings that may continue from a project after the initial investment is paid back, maintenance cost over the period, inflation rate and the time value of money.

$$\mathrm{SPP} = \frac{\text{Initial Investment}}{\text{Cash Inflow per Period}} \qquad \text{(Cash flows per period are even)} \tag{4}$$

Here initial investment is the cost of retrofit (sun tracking system) and cash inflows are the cost of annual net (after deducting the energy supply to the tracking system) energy gains.

When cash inflows are uneven, we need to calculate the cumulative net cash flow for each period.

$$\mathrm{SPP} = A + \frac{B}{C} \qquad \text{(Cash flows per period are uneven)} \tag{5}$$

Where,

A = Last period with a negative cumulative cash flow

B = Absolute value of cumulative cash flow at the end of the period *A*

C = Actual Cash Flow during the period after *A*

Life cycle cost (**LCC**) is the total cost of any equipment, machinery or project including its cost of maintenance operation and replacement. It is summation of cost estimates from inception to disposal for both equipment and projects as determined by an analytical study and estimate of total costs experienced in annual time increments during the project life with consideration for the time value of money. LCC is calculated before making a purchase. The objective of LCC analysis is to choose the most cost effective approach from a series of alternatives to achieve the lowest long-term cost of ownership.

To calculate the LCC, all three cost components (capital, operation & maintenance and replacement) should be known before decision making. Capital cost is known at the time of investment but other cost components will occur in future. So cost estimation (in terms of current value of money or present worth) of future investment is required and time value of money comes into picture. There are two things by which value of money changes with time; 1) due to inflation and due to interest (or discount rate).

Inflation rate is a measure of decline in the value of money over time. If C_o is the today's product cost, then future cost of the product in n years C(n); due to inflation rate (i) is be given by

$$C(\mathrm{n}) = C_0(1+i)^n \tag{6}$$

Discount rate is the interest rate due to which value of money increases over time. If M_o is the today's value of money, then future value of money in n years M(n); due to discount rate d (d is in decimal and not in percentage) is be given by

$$M(\mathrm{n}) = M_0(1+d)^n \tag{7}$$

$$Discount\ Rate\ (d) = \frac{\text{Future value} - \text{Present value}}{\text{Future value}} \tag{8}$$

$$Interest\ Rate\ = \frac{\text{Future value} - \text{Present value}}{\text{Present value}} \tag{9}$$

Both the inflation rate and discount rate depends on future conditions and they are unpredictable, so reasonable rates can be taken as per the dominating conditions.

Hence by incorporating the inflation and discount rates we can calculate the present worth of future investments.

If the present cost of a product is Co, then its **present worth (PW) for actual one-time investment** n years down the line is given by:

$$\mathrm{PW_{one}} = C_0\, F_{\mathrm{PW-one}} = C_0\left(\frac{1+i}{1+d}\right)^n \tag{10}$$

Where, present worth factor for future one-time investment is given by

$$F_{\text{PW-one}} = \frac{\text{Future cost}}{\text{Future value}} = \frac{\mathrm{X}(1+i)^n}{\mathrm{X}(1+d)^n} = \left(\frac{1+i}{1+d}\right)^n \tag{11}$$

<u>Note</u>: If future investments are recurring in nature, then recurring investment is considered as one-time investment for each year of operation. Thus present worth of recurring expenses ($\mathrm{PW}_{\mathrm{rec}}$) can be obtained by summing up the present worth of one time investments for the entire life of the system as given by:

$$\mathrm{PW}_{\text{rec-beg}} = C_0 + C_0\left(\frac{1+i}{1+d}\right)^1 + C_0\left(\frac{1+i}{1+d}\right)^2 + \cdots + C_0\left(\frac{1+i}{1+d}\right)^{\mathrm{n}-1} \tag{12}$$

(When investment is made in the beginning of the year)

$$\mathrm{PW}_{\text{rec-end}} = C_0\left(\frac{1+i}{1+d}\right)^1 + C_0\left(\frac{1+i}{1+d}\right)^2 + \cdots + C_0\left(\frac{1+i}{1+d}\right)^n \tag{13}$$

(When investment is made at the end of the year)

Here, n is the number of purchases made in the life time of the system. Above two equations can be simplified in terms of parameter k and given by

$$\mathrm{PW}_{\text{rec-beg}} = C_0\, F_{\text{PW-rec-beg}} = C_0\left(\frac{1-k^n}{1-k}\right) \tag{14}$$

$$\mathrm{PW}_{\text{rec-end}} = C_0\, F_{\text{PW-rec-end}} = C_0\, k\,\left(\frac{1-k^n}{1-k}\right) \tag{15}$$

Where,

$$k = \left(\frac{1+i}{1+d}\right) \tag{16}$$

Normally k is in the range of 0.95 to 1.05 and it gives almost same value of $F_{\text{PW-rec-beg}}$ and $F_{\text{PW-rec-end}}$. In many situations, the investment may not be made at the end or at the beginning but in the middle of the year or throughout the year. So it is difficult to decide which equation to be used but in practice either of the equation gives good estimate of cumulative recurring cost.

Now, after calculating the present worth factors ($F_{PW\text{-}one}$ and $F_{PW\text{-}rec\text{-}beg}$ or $F_{PW\text{-}rec\text{-}end}$), they are multiplied with appropriate present cost and added to find total operational/maintenance/ replacement cost over its life time.

For example: in a PV project of 10 years life time has a capital cost C_1 (in terms of present cost). It requires replacement of some components (e.g. battery) in each 5 years, having a cost C_2 (in terms of present cost). The system also has an annual maintenance cost of C_3 (in terms of present cost). Then LCC of the system is given by

$$\mathrm{LCC} = C_1 + F_{\mathrm{PW-one}}\,(5\text{ years}) \times C_2 + F_{\mathrm{PW-rec-end}}\,(10\text{ years}) \times C_3 \tag{17}$$

If there are other cost components associated with the system operation, they can also be added with proper present worth factor in the same fashion as discussed above.

For simplicity tables are given to find present worth factors for different values of inflation and discount rates. Thus LCC analysis is helpful to compare the cost of systems with different deign components in serving a purpose for a given period of time and chose the most cost-effective option.

Procedure:

1. Clean the dust particles present on PV module. Also measure the aperture area (A_c) of module.
2. Measure the solar radiation data using pyranometer and pyranometer fitted with shading ring (i.e. I_g and I_d, respectively).
3. Measure short circuit current (I_{sc}) and open circuit voltage (V_{oc}) of the module corresponding to short circuit (zero resistance) and open circuit (infinite resistance) conditions respectively.
4. Connect a variable resistive load across the PV module for the current-voltage data collection corresponding to various resistances imposed by rheostat. Keep on varying the resistance and note down the corresponding voltages developed across the load and the current flowing through it. For data collection, divide the whole potential range (V_{oc}) of the

module in sufficient number of steps (~10-15) so that a smooth curve can be drawn using this data.

5. Plot the I-V characteristics using current-voltage data and determine point of maximum power (P_{max}). This is done by determining that point in the curve (for a particular intensity) for which the product $V.I$ *is* maximum, i.e. the area under the curve is maximum. Also calculate P_{max}, η and FF.
6. For finding maximum possible energy yield of the module, we have to operate the system over a period of time. But the solar intensity is continuously changing with time. So for energy yield calculation over a period of time, we repeat (step 2 to 5) the measurements after particular intervals and get different I-V curves and determine corresponding P_{max}, η and FF. Assuming constant solar intensity over this period, we can calculate the energy yield for each interval by multiplying P_{max} and corresponding time interval. Summation of all these energy yields will be the total energy yield over this given period of time. This is the energy yield for PV module fixed at a particular orientation i.e. south facing (γ =0) and tilted at the latitude angle of the place (β=ϕ). At this orientation the yearly average energy yield is highest for fixed module operation.
7. While using Sun tracking system for normal incidence of sun rays to the module, the energy yield is even higher than the fixed mode of operation. Here the surface of PV module is made perpendicular to the direction of incident solar radiation by ensuring that the shadow of the align bolt is always at its base. We repeat (step 2 to 6) the measurements and calculations to get maximum possible energy yield in sun tracking mode for a period of time.
8. For both the modes (fixed and tracking) the measurements can be club together because the variation in solar irradiation will be larger if we separately do the measurements for both the modes of operation.
9. Also plot P_{max} vs I_T and FF vs I_T for both the modes of operation.
10. For LCC and SPP analysis, extrapolate the present system (in terms of energy yield) to a 10 MW PV plant retrofitted with sun tracking system. Find out and assume the relevant cost of tracking (₹/m^2 of module area).

Observations

Module specifications at STC:

P_{max} = ------ W, I_{sc} = ------ A, V_{oc} = -------V.

Module Orientation:

Declination angle (δ) = ----, Latitude of the location (ϕ) = ----,

Inclination of module for fixed module installation (β) = ----

Time interval (if constant) after which measurements are repeated (Δt) = ----

Table 1: Measurements when the PV module is due south and fixed at latitude angle of place

S. No.	Time period (Δt_1)		Time period (Δt_2)		Time period (Δt_3)		………………..		Time period (Δt_n)	
	Time:		Time:		Time:		………………..		Time:	
	V	I	V	I	V	I			V	I
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
…..										

Peak Power	P_{max1}:		P_{max2}:		P_{max3}:				$P_{max\ n}$:	

$$\text{Energy Yield} = P_{\text{max1}} \times \Delta t_1 + P_{\text{max2}} \times \Delta t_2 + P_{\text{max3}} \times \Delta t_3 + \cdots + P_{\text{max n}} \times \Delta t_{\text{n}}$$

Table 2: Measurements when the PV module is under sun tracking condition when sun rays are perpendicular to the PV module surface

S. No.	Time period (Δt_1)		Time period (Δt_2)		Time period (Δt_3)		………………..		Time period (Δt_n)	
	Time:		Time:		Time:		………………..		Time:	
	V	*I*	*V*	*I*	*V*	*V*	*I*	*V*	*I*	*V*
1										
2										
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Peak Power	P_{max1}:		P_{max2}:		P_{max3}:				$P_{max\ n}$:	

$$\text{Energy Yield} = P_{\max 1} \times \Delta t_1 + P_{\max 2} \times \Delta t_2 + P_{\max 3} \times \Delta t_3 + \cdots + P_{\max\ n} \times \Delta t_n$$

Table 3: Measurement of solar irradiance

S. No.	IST	LAT	ω (°)	I_g (W/m^2)	I_d (W/m^2)	cos θ_z	I_{bn} (W/m^2)	r_d	r_r	I_T (W/m^2)	P_{max}	η	P_{max}
1													
2													
3													
4													
5													
6													

Precautions:

1. Level the pyranometer properly with the help of spirit level provided.
2. While taking readings, get the voltage readings sufficiently closer so that a smooth curve can be drawn. Also do the I-V data collection very fast so that within this period of time the variation in solar radiation is very small.
3. The measurements should be made fast and accurate.

Supplementary exercise:

1) What are advantages and disadvantages of fixed and sun tracking of modes of modules operation?
2) Find out the installed capacity of solar PV electricity generation and its contribution in overall electricity supply in India?
3) List the solar PV power plants across the globe, which are using sun tracking systems for energy gains?
4) What are the ranges of inflation and discount rates for current scenario?

References:

1. Hermann Weston A., ‘Quantifying Global Exergy Resources’, *Energy*, **31**, 1685–1702, 2006.
2. Prof. Sukhatme S. P. and Prof. Nayak J. K., *Solar Energy, Principles of Thermal Collection and Storage*, Tata McGraw-Hill Publishing Company Limited, New Delhi, India, 2008.
3. Green M. A., Solar cells: Operating principles, technology and system applications, Prentice-Hall Inc, Englewood Cliffs, NJ, USA, 1981.
4. Streetman Ben G., *Solid State electronic devices*, Prentice-Hall of India Pvt. Ltd., New Delhi 1995.
5. Barringer H. Paul, Barringer P.E. and Associates, ‘A Life Cycle Cost Summary’ *International Conference of Maintenance Societies (ICOMS -2003),* Perth, May 20-23, 2003.
6. Prof. Solanki C. S., ‘‘Solar Photovoltaics: Fundamentals, Technologies and applications’’ *Prentice Hall of India*, **2008**.