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Assessing the Performance of 100 kW Solar PV Power-plants Through I-V Characterization & Validation of Tilted Irradiance Calculation Compared to an Hourly Model

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Abstract **-** The requisite hourly solar radiation data for solar energy system design evaluation and performance studies is generally not available for a number of sites especially in remote locations. As such accurate determination of hourly solar radiation data, is important both at horizontal; surfaces and inclined surfaces.

A model to estimate global solar radiation using temperature and sunshine hour data has been developed. We use here the tilted radiation calculation algorithm which is common to all application models (i.e. on-grid, off-grid and water pumping applications) Out of which we are used it for on-grid application. It is used to calculate solar radiation in the plane of the PV array, as a function of its orientation, given monthly mean daily solar radiation on a horizontal surface.

These predicted hourly solar radiation data values are compared with measured hourly values to test the accuracy of the models. The total solar radiation on the inclined surfaces and vertical surfaces for different orientations, have also been estimated.

The estimated values are found to be in close agreement with measured values. The method presented can be used to estimate hourly, global, diffuse solar radiation for horizontal surfaces and total solar radiation on inclined and vertical surfaces at different orientations with greater accuracy for any location. This tells us the power generation capacity rated of power plant with the actual power generation capacity of the plant.

Keywords- *Solar Energy, Solar isolation, Hourly Solar Radiation, Diffuse Solar Radiation, Fill Factor, Declination*

I. INTRODUCTION

The world-wide demand for solar electric power systems has grown gradually from last (10-15) years. For a large number of applications, PV technology is simply the least-cost option. Solar cells (PV cell) can be treated as a dependent current source in parallel with a diode. When there is not sufficient light is present to produce any current, the solar cell behaves like a normal diode having same characteristics as that of normal diode.

As the amount of incident light intensity increases, current is produced by the solar cell. Estimation of hourly/daily values of diffused and global solar radiation data is required for the design and performance calculation of solar energy systems.

Photovoltaic (PV) power generation systems can mitigate effectively environmental issues such as the green house effect and air pollution. PV power generation systems have one big problem that the amount of electric power generated by PV module is always changing with weather conditions, i.e., irradiation.

Therefore, validation of tilted irradiance calculation compared with an hourly model is requires to compute the actual power generation capability of existing plant with the standard PV generation systems.

This paper is used to specify the kind of system under consideration, and calculate the monthly energy load & also computes the annual solar radiation on the tilted PV array for any array orientation, using monthly values of solar radiation on a horizontal surface

To characterize a photovoltaic system before evaluating its cost and energy performance, some values are suggested for component sizing (e.g. "Nominal PV array power"). Suggested or estimated values are based on input parameters and can be used as a first step in the analysis and are not necessarily the optimum values.

A flowchart of the algorithms is shown in Figure 6. The basics of solar energy & site location are covered in Section 1 & 1.1. Table 2 describes the tilted radiation calculation algorithm. It is used to calculate solar radiation in the plane of the PV array, as a function of its orientation, given monthly mean daily solar radiation on a horizontal surface.

Another Section presents the photovoltaic array model, which calculates PV array energy production given ambient temperature and available solar radiation. Then different application models are used to evaluate the interaction of the various components of the PV system and predict how much energy can be expected from the PV system on an annual basis.

II. EXPERIMENTAL

India lies in the sunny regions of the world. Most parts of India receive 4–7 kWh (kilowatt-hour) of solar radiation per square meter per day with 250–300 sunny days in a year.

SITE DESCRIPTION

Rajgarh is located at western part of Madhya Pradesh. Rajgarh District extends between the parallels of latitude 23^0 27' 12" North and 24^0 17' 20" North and between the meridians of longitude 76^0 11' 15" and 77^0 14' East. Geographical parameters shown in fig (1)

- Project location:-Village Jaitpurakalan, Vikas Khand Khilchipur, Rajgarh District, MP, India.
- Plant established: - July, 1998
- Electricity generation: - From October, 1999
- Design company: -Tata BP Solar India Ltd.
- Plant capacity: - 100 kW peak at STC
- Land area: - 1 acre
- Total project cost: Rs 370 lac (Central Govt: Rs 200 lac & State Govt: Rs 170 lac)
- Nominal peak power: - 75W
- Nominal peak voltage: - 12V
- Peak operating voltage: - 17V
- Highest generation duration: -Month of Feb, March & April.

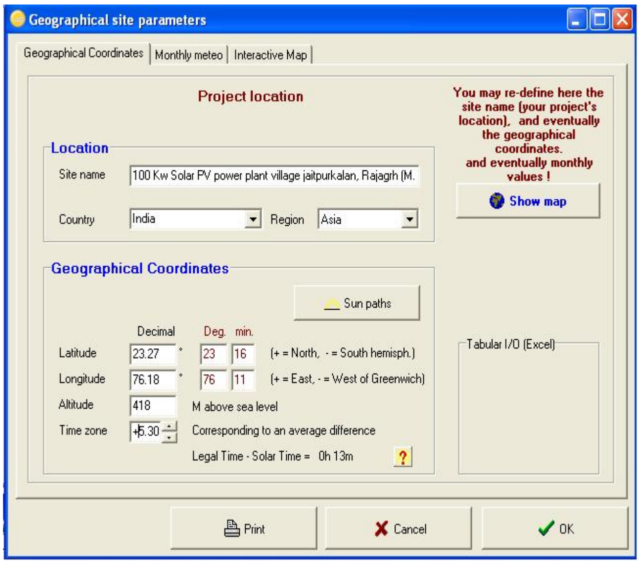

Fig. 2.1 Geographical parameters of site

SOLAR CELL

The basic structure of a cell model or solar cell is analogous to that of a photodiode, basically of silicon, intended to maximize the inclusion of photons from the sun light and minimize reflection from module surface.

When it receives an incident light falling to surface it act as a current source which increases in inverse proportion of the light incident upon it. The building block of PV array is the solar cell, which is basically a p-n junction semiconductor junction that directly converts light energy into electricity.

In an ideal cell, the total current I is equal to the current I_L generated by the photoelectric effect minus the diode current I_D, according to the equation:

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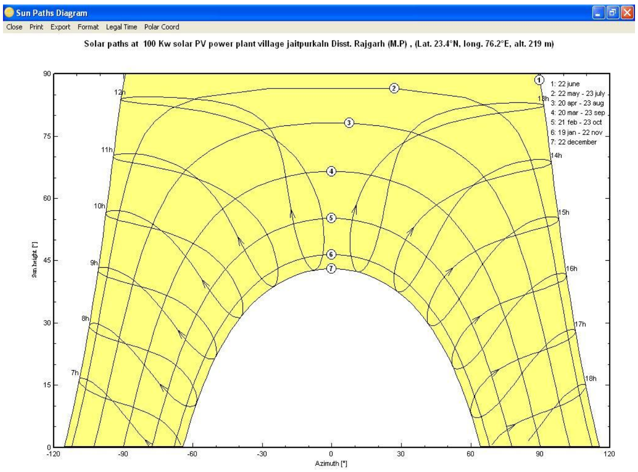

Fig 2.2 Sun Path Diagram for above mentioned Power plant

$$I = I_L - I_D \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$I = I_L - I_o\left(e^{\frac{qV}{kT}} - 1\right) \ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where,

I_o - Saturation current of the diode,

q - Elementary charge1.6x10-19 Coulombs,

k - Constant of value 1.38x10-23J/K,

T - Cell temperature in Kelvin,

V- Measured cell voltage

$$I = I_{pv} - I_o\left(e^{\frac{q(V+IR_S)}{nkT}} - 1\right) \ldots\ldots\ldots\ldots \quad (3)$$

$$I_{pv} = I_{pv}(T_1) + K_0(T - T_1) \ldots\ldots\ldots\ldots \quad (4)$$

$$I_{pv}(T_1) = I_{SC}(T_{1,nom})\frac{G}{G_{nom}} \ldots\ldots\ldots\ldots \quad (5)$$

$$K_o = \frac{I_{SC}(T_2) - I_{SC}(T_1)}{(T_2 - T_1)} \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

$$I_o = I_o(T_1) \times \left(\frac{T}{T_1}\right)^{\frac{3}{n}} e^{\frac{qVq(T_1)}{nk\left(\frac{1}{T} - \frac{1}{T_1}\right)}} \ldots\ldots\ldots \quad (7)$$

$$I_o(T_1) = \frac{I_{SC}(T_1)}{e^{\left(\frac{qV_{OC}(T_1)}{nkT_1} - 1\right)}} \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

The model includes the temperature dependence of photocurrent I and saturation current of the diode Io.

Terms used in equations are-

I - Current from solar cell

G - Isolation in W/m2.

T - Temp for which VI characteristics have to be found.

T1- Temperature for which characteristics is Known.

Isc - short circuit current

K_o - Increase in Amps/ Degree increase in Temp

q - Charge of an electron

Voc- Open circuit voltage

Expanding the equation gives the simplified circuit model shown below and the following associated equation, where n is the diode ideality factor (typically between 1 and 2), and R_S and R_{SH} represent the series and shunt resistances. The first stage is the handling of the incident irradiation form sun in the collector plane of solar module. It involves various examined models for estimation of transposition and diffused radiation (from global irradiation models).Without studying these models for global diffused radiation for comparison process, the actual plant models can have variation more than ten percent of some data used.

The physical structure and equivalent circuit are shown below in fig. 2.3.

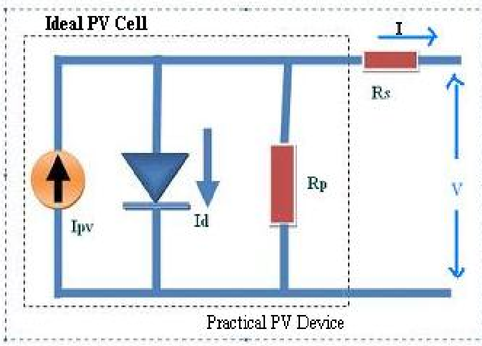

Fig. 2.3 Equivalent circuit of the PV cell.

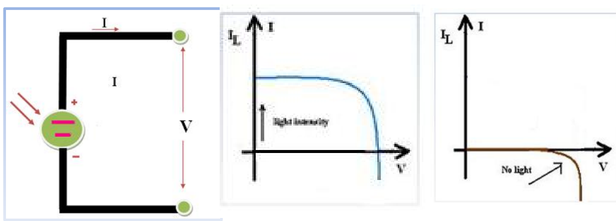

Fig. 2.4 Solar (PV) Cell & its V-I characteristics with light & no light condition

The VI characteristics curve of an energized PV cell has the curve characteristics shown in Figure 5 as the

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voltage across the measuring load is increased from zero to V_{oc}, various concert parameters for the PV cell can be determined from tested data, as described below.

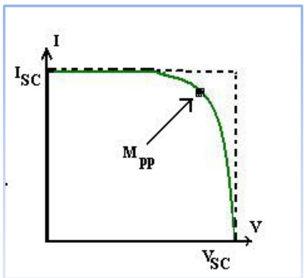

Fig. 2.5 V-I Curve of Energized PV cell.

DESCRIPTION OF PHOTOVOLTAIC SYSTEMS

The primary driving force in the Renewable market is the PV module. PV modules are specified on the performance basis of how much power module delivered under Standard Rating Testing Conditions of 1 kW per m² of sunlight and temperature of 25 °C of module. The generated power measured under STC is articulated in terms of "peak Watt" or WP supposed capacity.

PHOTOVOLTAIC ENERGY MODEL FLOWCHART

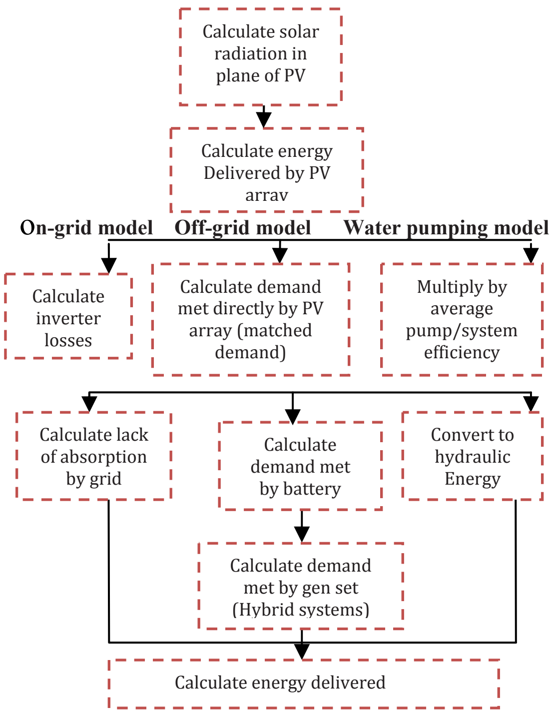

Fig. 2.6 Photovoltaic Energy Model Flowchart

Module Characteristics for Standard Technologies

PV module type	η_r (%)	NOCT (°C)	βp (%/°C)
Mono-Si	13.0	45	0.40
Poly-Si	11.0	45	0.40
a-Si	5.0	50	0.11
CdTe	7.0	46	0.24
CIS	7.5	47	0.46

Table 2.1 PV Module Characteristics for Standard Technologies

Where NOCT is the Nominal Operating Cell Temperature, η_r is the PV module efficiency; β*p is* the temperature coefficient for module efficiency

SOLAR ENERGY CALCULATION

Declination

The declination is the angular position of the sun at solar noon, with respect to the plane of the equator. Its value in degrees is given by equation:

$$\delta = 23.45\, Sin\left(2\pi \frac{284+n}{365}\right) \ldots\ldots\ldots. (9)$$

Where n is the day of year (i.e. n =1 for January 1, n = 32 for February 1, etc.). Declination varies between -23.45° on December 21 and+23.45° on June 21.

Maximum Power (P_{max}), Current at P_{max} (I_{mp}), Voltage at P_{max} (V_{mp}) For PV Cell

The power generated by the PV cell in Watts can be calculated with the help of VI curve of PV cell and by equation which gives relation between voltage, current & Power i.e. P=VI. The maximum value for power is in between I_{SC} and V_{OC} points, whereas the power will be zero at these points. The voltage and current at this point are denoted as V_{MP} and I_{MP} respectively and these points are maximum power point of PV cell.

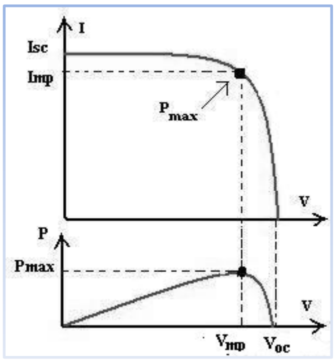

Fig. 2.8 Maximum Power for a V-I curve

Fill Factor (FF)

The Fill Factor (FF) is fundamentally a measure of superiority of PV cell. It is premeditated by comparing the theoretical power (PT) to maximum power generated and would be output at both the open circuit voltage and short circuit current together. FF can also be interpreted graphically as shown in Figure 9

$$FF = \frac{Pmax}{P_T} = \frac{Imp.\,Vmp}{Isc\ \ Voc}\ldots\ldots\ldots \quad (10)$$

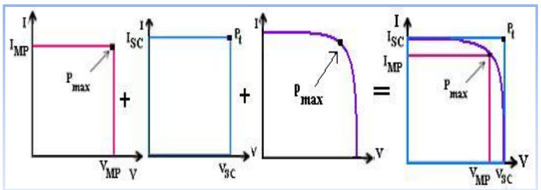

Fig. 2.9 Fill Factor from the I-V curve

A greater value of fill factor is advantageous, and is consistent with V-I curve which is more likely to be square. Characteristic fill factors value is range from 0.51 to 0.85. It can also be represented in percentage form.

Temperature Measurement Considerations

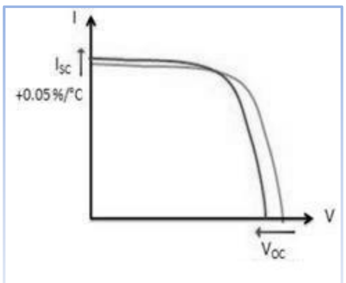

Fig. 2.10 Temperature Effect on a V-I curve

The material used to make solar cells, like other semiconductors materials, are susceptible to temperature. Figure 10, shows the temperature effect on a V-I curve. When a solar cell is exposing to solar irradiation as result of which temperature is increase, I_{sc} increases to some extent, while V_{oc} decreases more significantly.

For a particular set of atmospheric conditions, rise in temperatures result in a decline maximum power output P_{max}. Since the V-I curve will fluctuate according to rise or fall in temperature, it is advantageous to record the conditions under which the V-I curve was conducted. Temperature of surrounding can be measured using sensors such as thermistors or thermocouples & RTD's

Solar hour angle and sunset hour angle

The solar hour angle is the angular displacement of the sun east or west of the local meridian; morning negative, afternoon positive. The solar hour angle is equal to zero at solar noon and varies by 15 degrees per hour from solar noon. For example at 7 a.m. (solar time2) the hour angle is equal to –75° (7 a.m. is five hours from noon; five times 15 is equal to 75, with a negative sign because it is morning).

The sunset hour angle ωs is the solar hour angle corresponding to the time when the sun sets. It is given by the following equation:

$$cos\omega_s = -tan\emptyset tan\delta\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

Where δ is the declination, calculated through equation (1), and ø is the latitude of the site.

The angle of incidence θz is the zenith angle of the Sun,

$$\cos\theta_z = \sin\emptyset\sin\delta + \cos\emptyset\cos\delta\cos\omega\ldots\ldots \quad (12)$$

rd is the ratio of the diffuse radiation flux falling on the tilted surface to that falling on horizontal surface, assuming that the sky is an isotropic source of diffuse radiation,

$$r_d = \frac{(1+\cos\propto)}{2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

Assuming that the reflection of the beam on the ground is isotropic and the reflectivity is ρ the tilt factor for reflected radiation is

$$r_r = \frac{\rho(1-\cos\alpha)}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

The hourly tilt factor for site on south facing surface has been estimated and shown in table 2.2.

Extraterrestrial radiation and clearness index

Solar radiation outside the earth's atmosphere is called extraterrestrial radiation. Daily extraterrestrial radiation on a horizontal surface, Hø, can be computed for day n from the following equation:

$$H_o = \frac{86400 G_{sc}}{\pi}\left(1 + 0.033\cos\left(2\pi\frac{n}{365}\right)\right)(\cos\emptyset\cos\delta\sin\omega_s + \omega_s\sin\emptyset\sin\delta) \ldots\ldots (15)$$

Where G_{SC} is the solar constant equal to 1,367 W/m2, and all other variables have the same meaning as before. Before reaching the surface of the earth, radiation from the sun is attenuated by the atmosphere and the clouds. The ratio of solar radiation at the surface of the earth to extraterrestrial radiation is called the clearness index. Thus the monthly average clearness index $\overline{K_T}$ is defined as:

$$\overline{K_T} = \frac{\bar{H}}{H_0} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

Where $\bar{H}$ is the monthly average daily solar radiation on a horizontal surface and H_o is the monthly average extraterrestrial daily solar radiation on a horizontal surface. K_T values depend on the location and the time of year considered; they are usually between 0.3 (for very overcast climates) and 0.8 (for very sunny locations).

STC: Standard Test Conditions

The Standard Test Conditions for the measurement of PV modules is to put them in a flash tester which has been calibrated to deliver the equivalent of 1000 W/m^2 of solar radiation intensity, hold a cell temperature of 25'C (77'F), & assume an airmass of 1.5. This test gives them their STC ratings. They are defined as:

- 25°C – Nominal Module temperature,
- 1000 W/m² - solar Irradiance (global when in outdoor conditions).
- Air Mass 1.5 – STC (vertical air mass at the sea level).

For Concentrating solar PV module, the suggested irradiance is specified in terms of Direct Normal Incident value of solar radiation In Indian subcontinent Until March 2013, it was usually 800 or 850 W/m^2.
The present convention for STC has fixed it at 1000 W/m².

Transposition Factors as function of the plane orientation/ Global/Diffuse reading

Month	Hor. global	Hor. diffuse	Extra-terrestrial	Clearness Index	Amb Temp	Wind velocity
Jan.	163.9	53.1	257.6	0.636	21.7	5.0
Feb.	179.0	47.5	257.7	0.695	21.7	5.6
Mar.	216.6	49.7	311.0	0.696	22.2	5.6
Apr.	221.3	57.3	317.1	0.698	22.5	6.1
May	224.7	61.9	331.1	0.679	23.8	6.1
June	199.5	67.4	318.7	0.626	26.4	4.1
July	187.2	73.4	328.9	0.569	27.6	3.6
Aug.	178.7	75.9	327.4	0.546	27.8	3.6
Sep.	179.2	70.2	306.3	0.585	28.0	3.1
Oct.	197.2	57.8	293.4	0.672	28.0	4.5
Nov.	171.6	49.2	256.1	0.670	26.4	5.0
Dec.	152.4	54.4	248.2	0.614	23.5	5.6
Year	2271.3 kWh/ m².mth	717.7 kWh/m ².mth	3553.5 kWh/m². mth	0.639	25.0 °C	4.8 m/s

Table 2.2 *Transposition Factors values of site*

Solar Radiation on a Tilted Surface

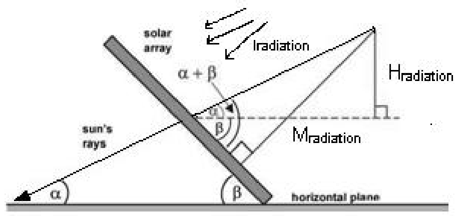

Fig. 2.11 Module tilt parameter with respect to solar radiation

The power generated by solar cell depends not only on the power enclosed in the solar radiation falling on PV module, but also on the inclination angle between the PV module and the sun. When the fascinating module and the sunlight are at right angles to each other, the power density (P_d) on the module surface is equal to that of power density of the sunlight (P_d is maximum when the PV module is at right angles to the sun).As the sun changes its position with respect to time, angle between the sun and a permanent module is changing, continually. The P_d on a permanent solar module is less than that of the incident light.

S.no	Elevation angle (∝)	Angle of module (β)	Incident Radiation (I_r)	Horizontal Radiation (H_r)	Module Radiation (M_r)
1	0^0	30^0	20	0	10
2	10^0	40^0	20	3.473	15.3209
3	20^0	50^0	20	6.8404	18.7939
4	30^0	60^0	20	10	19.9239
5	40^0	70^0	20	12.8558	18.7939
6	50^0	75^0	20	15.3209	16.383
7	60^0	50^0	20	17.3205	18.7997
8	65^0	45^0	20	18.1262	18.7939
9	70^0	40^0	20	18.7939	18.7939
10	50^0	45^0	20	15.3209	19.9239

Table 2.3 Values of module tilt with angle of elevation of sun

The equations relating $M_{rad.}$, $H_{rad.}$ and $I_{rad.}$ are:

$$H_{radiation} = I_{radiation} \sin \propto \ldots\ldots\ldots\ldots (17)$$

$$M_{radiation} = I_{radiation} \sin(\propto + \beta) \qquad (18)$$

Where
α is the angle of elevation ; and
β is the tilt angle of the module measured from the horizontal.

$$\propto = 90 - \varphi + \delta \ldots\ldots\ldots\ldots \ldots.(19)$$

Where φ is the latitude; and δ is the declination angle previously formulated above (9) from these equations a relationship between $M_{radiation}$ and $H_{radiation}$ can be determined as:

$$M_{radiation} = \frac{H_{radiation} \sin(\propto + \beta)}{\sin \propto} \ldots\ldots\ldots (20)$$

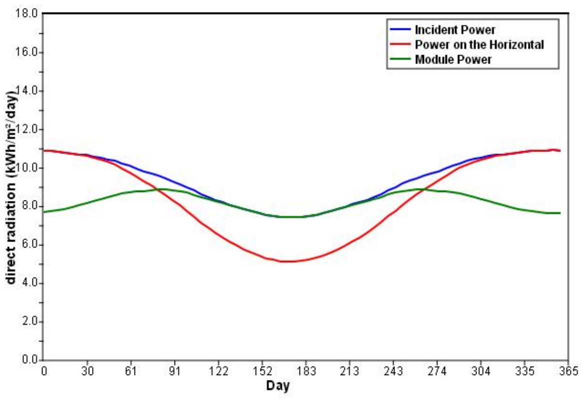

Fig. 2.12 Solar isolation as a function of Module Angle (Tilt) & latitude

The following active equations show the calculation of the incident and horizontal solar radiation and that on the module. The amount of solar radiation incident on a tilted module surface is the component of the incident solar radiation which is perpendicular to the module surface.

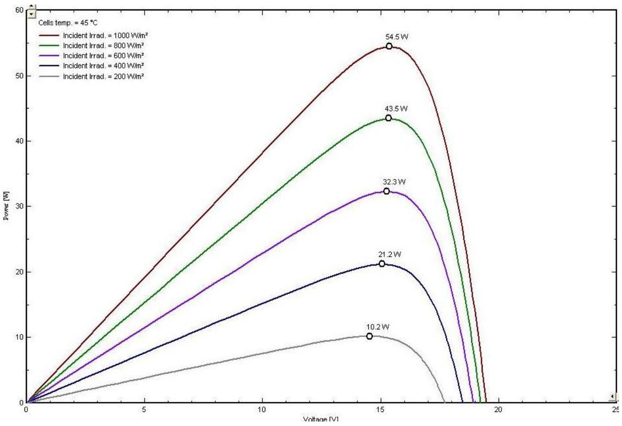

Fig. 2.13 PV graph curve parameter incident irradiance

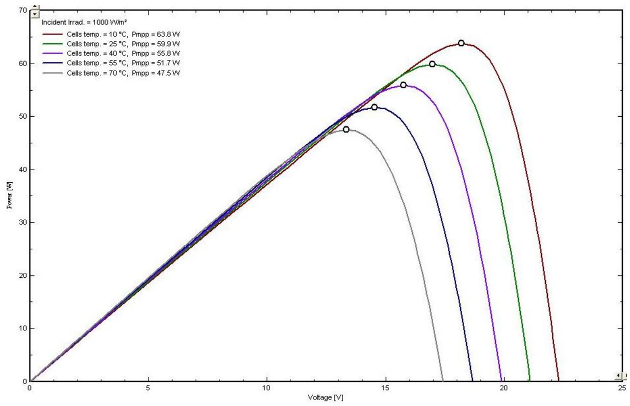

Fig. 2.14 PV graph according to module temperature

III. CONCLUSIONS

The global solar irradiance on horizontal surfaces has been measured. Software programs calculate solar irradiance of the monthly average and daily hourly solar irradiance on tilted surfaces from the global solar irradiance. The hourly diffuse solar radiation and the average monthly daily diffuse solar irradiance are estimated.

The solar radiation values for different tilt for the summer month may-June and winter month November-December From the obtained results, it may be concluded that the maximum hourly solar irradiance on a tilted surface facing south is 1152.97 Wm-2 in March and the minimum hourly solar radiation on a tilting surface facing south is 223.69 Wm-2 in December.

The tilt angle has a major impact on the solar radiation incident on a surface. For a fixed tilt angle, the maximum power over the course of a year is obtained when the tilt angle is equal to the latitude of the location. by a module that perfectly tracks the sun. Power on Horizontal is the solar radiation striking the ground and is what would be received for a module lying flat on the ground.

These values come due to latitude position for a particular region and inclination of PV module or module tilt to the solar radiation received in whole year in Wh/m^2day^1 without any shading of cloud. The PV Module Power is the solar energy striking a slanted module. The module inclination angle or tilt angle is measured from the horizontal plane.

The Incident Power is the solar radiation at right angles to the sun's rays and is what would be expected is regarded as maximum possible values at the particular region where PV plant is to be established. The module is implicit to be in front of south in the northern hemisphere and north in the southern hemisphere. For some tilt, the light is incident from the back of the module and in these cases the module power drops to 0. Partial shading effect of clouds consider negligible during calculation .

The value of the ground reflected element may be neglected compared to the beam and diffuse components. The maximum value t H is 29.25 (MJ/m^2day) during March. The minimum value of t H is 15.54 (MJ/m2 day) during January.

Also, the effective ratio of solar energy incident on a tilted surface to that on a horizontal surface and the monthly average clearness index for the months from August 2013 to December 2013 was estimated. The total day light which is available for power generation is very less, for this all necessary calculation is required. Through which better production capability is achieved & that is required.

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