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OPTIMAL TILT ANGLE FOR GETTING MAXIMUM ENERGY PRODUCED BY PV PANEL BY UTILIZING CLEAR SKY AND ARRAY PERFORMANCE MODELS

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ABSTRACT

In this paper, we analysed and implement clear sky and array performance models to achieve maximum electrical energy produced from the photovoltaic (PV) panel. The selected models just not only include location dependent parameters but also include environmental factors such as Linke Turbidity (include aerosols, absorption due to assorted gases, Rayleigh scattering), cloud cover, albedo, perceptible water vapour. 250 W PV panel was used as a reference to check the output electrical energy in a given location by inputting the latitude and longitude of a location. It is concluded that 27° facing south is the optimized tilt angle for every locations having latitude at north direction and longitude at east direction. By taking the example of location Nagpur India (21.14° N, 79.08° E), a difference of only 0.35 % is reported when comparing the computed electrical energy with actual electrical energy that have been acquired by using pyranometers, pyrheliometers and illuminance meters installed by the National Renewable Energy Laboratory (NREL). So, a good approximation of electrical energy can be computed by combining clear sky and array performance models.

Keywords: solar radiation, irradiance, beam radiation, diffuse radiation, ground reflected radiation, tilt angle, electrical energy

Quantity designations and abbreviations:

θ_z is the zenith angle;
E_{ext} is the extra-terrestrial solar irradiance;
λ is the latitude of location;
H is the altitude of location in feet's;
δ is the declination angle;
w is the hour angle;
d is the day of the year;
L_{std} is the standard meridian of local time;
L_{oc} is the actual longitude of location;
AM is the air mass;
E_{bh} is the beam component at horizontal surface;
I_b is the beam component at tilted surface;
E_n is the direct normal irradiance;
a is the angle of incidence;
γ_{sun} is the solar azimuth;
θ_{sun} is the solar zenith angle;
γ is the panel azimuth;
β is the panel tilt;
K_n is the direct beam transmittance;
K_{nc} is the maximum clear sky value;
$I_{d,sky}$ is the computed diffuse radiation on tilled surface;
P_{dc} is the DC power.

1. INTRODUCTION

Solar energy is an emerging, clean and safe source of electrical energy. The PV module directly converts light energy into electrical energy. In actu-

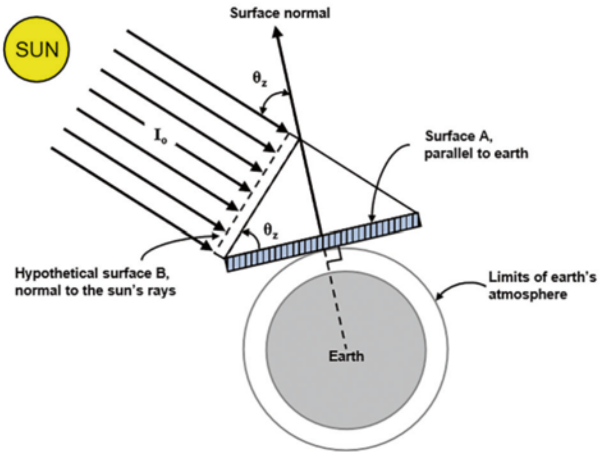

Fig. 1. Extra-terrestrial Radiation on horizontal surface (*Source*: www.powerfromthesun.net/Book)

al, the solar irradiation which exists above the atmosphere of the earth has more intensity than radiations reaches on the earth's surface [1]. The losses are owing to various atmospheric gases, clouds and various ecological effects. The incident solar insolation on earth could generate 1 kW/m^2, if it can convert competently [2]. Solar radiation and sunshine illuminance statistics are necessary for engineers and architects for planning and designing energy-efficient buildings [3]. For extracting maximum electrical outputs from the PV panel, the extent of solar irradiation incident on a particular region and time interval of peak sun shine hours are very important. Solar irradiation at every locality on the earth may depend on different parameters such as attitude, latitude, longitude, geographical location and humidity [4].

We also considered the consequences of several environmental parameters such as air mass, Linke turbidity (include aerosols, Rayleigh scattering and absorption due to assorted gases), cloud cover, albedo, perceptible water vapour and atmospheric turbidity (smoke, dust, water droplets), and location dependent parameters such as zenith angle, solar azimuth angle and elevation on PV panel. As a reference, 250W PV panel is selected for receiving the data of electrical power in a given location. It is valuable to measure the outcome of orientation and tilt of the PV panel to capitalize solar radiations incident on it. Solar irradiance on the tilted surface is a combination of a direct (beam), diffuse and ground reflected radiations [5]. On the other hand, it is quite difficult to purchase and install illuminance meters, sensors and pyranometers at every tilted angle and orientation to gather all of the requisite data. Because the measurement using those equipment is very expensive, therefore a model-based methodology has been adopted to evaluate the electrical energy of PV panel.

Previously, the optimal tilt angle of PV panel was calculated for some specific area [6–9]. The novel idea for this research is proposed by reviewing the various reports on this issue. The purpose of this approach is to combine several clear sky and array performance models to predict different solar irradiation components at an earth's location. The focal aim of this work is to implement optimized clear sky and array performance models of high prediction accuracy in MATLAB to compute electrical energy for locations on hourly, monthly and yearly basis and corresponding outcomes have been presented in the graphical form. A comparison has also been done to relate our results with actual data available in NREL.

2. MODELLING PROCESS

2.1. Extra-terrestrial Solar Irradiance (ESI):

The radiation above the atmospheric surface of earth as shown in Fig. 1 is known as *ESI*. It is the intensity of the sun at the top of the earth's atmosphere. It can be computed as:

$$E_{ext} = E_{SC} \cdot \left(1 + 0.033 \cdot \cos\left(\frac{360n}{365}\right)\right), \qquad (1)$$

where $E_{SC} = 1367\,\mathrm{wm}^{-2}$, n is the Julian day.

The ESI on horizontal surface could be computed as:

$$E_{h\_ext} = E_{ext} \cdot \cos\theta_z. \qquad (2)$$

2.2. Global Horizontal Irradiance (*GHI*):

GHI is the complete amount of solar irradiation above the earth's horizontal surface to the ground level. It has a significant impact on PV installation and contains direct normal irradiance (*DNI*) and diffuse horizontal irradiance (*DHI*). Pyranometer is usually used to compute *GHI* which has a hemispherical (180°) view angle. Kasten мodel could be used for computation of *GHI* [11].

$$GHI = C_{g1} \cdot E_{ext} \cdot \cos\theta_z \times$$
$$\times\, e^{(-C_{g2} \cdot AM \cdot (f_{h1} + f_{h2}(TL-1)))} \cdot e^{(0.01 \cdot AM^{1.8})}, \qquad (3)$$

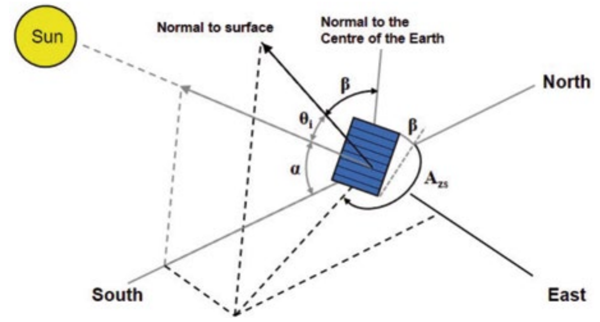

Fig. 2. Elevation, Zenith and Azimuth and incidence angle (*Source:* www.itacanet.org/the-sun-as-a-source-of-energy)

where *TL* is the Linke turbidity, which is equal to 2 in this case,

$$C_{g1} = 5.09e^{-5} \cdot h + 0.868, \quad (4)$$

$$C_{g2} = 3.92e^{-5} \cdot h + 0.0387, \quad (5)$$

$$f_{h1} = e^{(-h/8000)}, f_{h2} = e^{(-h/1250)},$$

$$\cos\theta_z = \cos\cos\ \cos w + \sin\lambda \sin\delta, \quad (6)$$

where $\delta = \sin^{-1}\left(\sin\left(23.45^o\right)\sin\left(\frac{360}{365}(d-81)\right)\right)$, (7)

$$w[degrees] = 15(Solar\,Time[h] - 12), \quad (8)$$

$$Solar\,Time = Clock\,Time + \left(\frac{1}{15}\right)(L_{std} - L_{oc}) + E, \quad (9)$$

$$E = 0.165\sin 2B - 0.126\cos B - 0.025\sin B, \quad (10)$$

$B = \frac{360(n-1)}{364}$, and n is the any day of the year.

The optical thickness of the earth's atmosphere can be represented by *AM* which can be derived as follows:

$$AM = \frac{1}{\cos\theta_z}, AM =$$

= 1 means that the Sun is overhead. (11)

2.3. Beam radiation Model for Horizontal and Tilted Surface

Beam component at horizontal (E_{bh}) and beam component at tilted surface (I_b) [12] can be computed as:

$$E_{bh} = E_n . \cos\theta_z, \quad (12)$$

$$I_b = E_n . \cos a, \quad (13)$$

where E_n is the direct normal irradiance, a is the angle of incidence and computed as:

$$a = \arccos\begin{bmatrix}\sin_{sun}\cos(\gamma - \gamma_{sun})\sin\beta + \\ +\cos_{sun}\cos\beta\end{bmatrix}, \quad (14)$$

where

$$\gamma_{sun} = \arccos\left(\frac{\sin\cos - \sin\cos cosw}{cos(90-\theta_z)}\right). \quad (15)$$

Fig. 2 shows the angular picture of Elevation, Zenith and Azimuth angles.

2.4. Direct Normal Irradiance Model

It is total amount of solar irradiation realized per unit area by the plane surface that is placed perpendicular to the sun rays. Pyrheliometer is usually used for the measurement of *DNI*. It can also be computed by *DISC* Model [13] as:

$$E_n = K_n . E_{ext}, \quad (16)$$

where K_n is the direct beam transmittance,

$$\Delta K_n = K_{nc} - K_n, \quad (17)$$

K_{nc} is the maximum clear sky value, ΔK_n is the disappearance of transmittance value from its corresponding maximum values K_{nc}. Clear Bird model [14] is used to compute K_{nc} value, which is given below:

$$K_{nc} = 0.866 - 0.122\,AM + 0.0121\,AM^2 + $$
$$+ 0.000653\,AM^3 + 0.000014\,AM^4. \quad (18)$$

Least square regression analysis is used to compute ΔK_n:

$$\Delta K_n = a + be^{(cAM)}. \quad (19)$$

The coefficients $a, b, \text{and}\, c$ can only be known if we know clearness value K_t [15] and it strongly depends on cloud cover (*CC*).

$$K_t = \frac{GHI}{E_{h\_ext}}. \quad (20)$$

If K_t < 0.60 (cloudy conditions), a=0.512–1.56.K_t+ +2.286.$K_t^2 - 2.222.K_t^3$, $b = 0.370 + 0.962.K_t$, and $c = -0.280 + 0.932.K_t - 2.048.K_t^2$.

If K_t > 0.60 (mostly clear conditions), $a = -5.743 + 21.77.K_t - 27.49.K_t^2 + 11.56.K_t^3$, $b = 41.40 - 118.5.K_t + 66.05.K_t^2 + 31.90.K_t^3$, $c = -47.01 + 184.2.K_t - 222.0.K_t^2 + 73.81.K_t^3$.

When ΔK_n and K_{nc} are known, then *DNI* (E_n) and beam radiation incident on tilted surface can be easily computable as: $I_b = E_n \cdot \cos\ \alpha$.

2.5. Diffuse Radiation Model

DHI is the terrestrial diffused or scattered irradiance by the atmosphere received on a horizontal. *DHI* is normally measured with a pyranometer, however, in this case the direct light of the sun is blocked in order to remove the beam component of the radiation.

Diffuse radiations on tilted surface can be categorized into:

- Isotropic diffuse radiation;
- Circumsolar radiation;
- Horizon brightening.

Klucher Model [16] covers all the three parameters as discussed above, so that the computed diffuse radiation on tilled surface as:

$$I_{d,sky} = I_d \begin{bmatrix} (1 - A_i).\left(\dfrac{1+\cos(\beta)}{2}\right)\times \\ \times 1 + Fsin^3\left(\dfrac{\beta}{2}\right) + A_i R_b \end{bmatrix}, \qquad (21)$$

where I_d is the hourly diffuse horizontal radiation,

$R_b = \dfrac{I_b}{E_{bh}}$, $A_i = \dfrac{E_{bh}}{E_{h\_ext}}$, $F = \dfrac{E_{bh}}{GHI}$.

2.5. Ground Reflected Radiation Model

Lui and Jordan's assumption [17] concluded that the constant coefficient of albedo could be added to GHI to realize ground reflected irradiation on PV panel

$$R_h = 0.2 \cdot G_h. \qquad (22)$$

2.6. Array Incidence Plane Model

A fundamental step in calculating PV performance is determining the irradiance incident on the plane of the array (*POA*) as a function of time. This *POA* irradiance is dependent upon several factors, including array orientation, beam, diffuse and ground reflected radiation. These factors are incorporated through the use of the Perez algorithm [18]

$$I_{poa} = I_b + I_{d,sky} + I_{d,ground}, \qquad (23)$$

where $I_{d,ground} = 0.2$ default value.

2.7. Module Cover Model

Given the total *POA* irradiance incident on the module cover, *PV Watts* applies an *AOI* correction to adjust the direct beam irradiance for incidence angles greater than 50 degrees to account the reflections losses. The correction uses the Sandia PV Array Performance Model polynomial correction, with coefficients for glass.

$$f = b_0 + b_1 a + b_2 a^2 + b_3 a^3 + b_4 a^4 + b_5 a^5. \qquad (24)$$

Coefficients b_0, b_1, b_2, b_3, b_4 *and* b_5 are module cover Polynomial coefficients:

$b_0 = 1.0$, $b_1 = -2.438 \cdot 10^{-3}$, $b_2 = 3.103 \cdot 10^{-4}$, $b_3 = -1.246 \cdot 10^{-5}$, $b_4 = 2.112 \cdot 10^{-7}$, $b_5 = -1.359 \cdot 10^{-9}$,

$$I_{tr} = I_{poa} - (1 - f) E_n \cdot \cos. \qquad (25)$$

2.8. Power Computation Model

PV Watts module has been approached to compute electrical power that is an edition of *PVFORM* version prototypes [19]. DC power through an array can be calculated by providing panel's rated power, *POA* irradiance and cell temperature.

$$P_{dc} = \frac{I_{tr}}{1000} P_{dc0}\left(1 + \gamma\left(T_{cell} - T_{ref}\right)\right),$$

if

$$I_{tr} > 125\ Wm^{-2}. \qquad (26)$$

$$P_{dc} = \frac{0.008 I_{tr}^{\ 2}}{1000} P_{dc0}\left(1 + \gamma\left(T_{cell} - T_{ref}\right)\right),$$

if

$$I_{tr} < 125\,\mathrm{Wm}^{-2}. \qquad (27)$$

Here γ is the temperature coefficient fixed at –0.5 %/° C which is assumed for crystalline sil-

Table 1. Purpose of Choosing Models

Model	Purpose	Reason
Kasten	GHI	Environmental factors e.g. Air Mass (AM) and Linke Turbidity (include Aerosols, absorption due to assorted gases and Rayleigh scattering) and location dependent parameters like Zenith Angle (z), Elevation (h).
DISC	DNI	Covers air mass, cloud cover, albedo, perceptible water vapour and atmospheric turbidity (dust, smoke and water droplets).
Klucher	Diffuse Radiations	Circumsolar Radiation, Isotropic diffuse radiation and Horizon brightening
Perez algorithm	Module Cover	Merges beam, diffuse and ground reflected radiation
Power Computation	Power output	Include all module parameters

icon PV module, T_{ref} = 25 °C, T_{cell} is the cell temperature, and P_{dc0} is the nominal module power equal to 250 W.

2.9. Block Diagram of Modelling Process

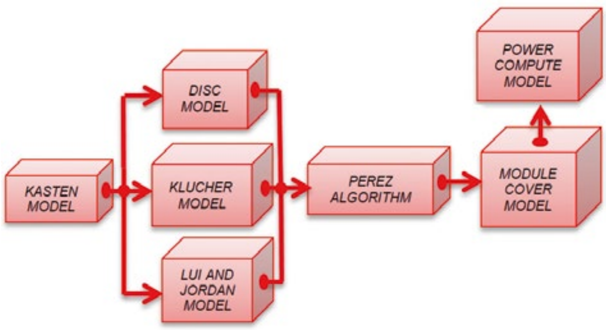

Fig. 3. Block diagram of modelling procedure

3. MODELS SELECTION AND SIMULATION TOOL

Fig. 3 and Table 1 display the modelling process, purpose and reasons for selecting the models for implementation. We have implemented the entire process in MATLAB. A Guided User Interface (*GUI)* of the system is presented in Fig. 4.

4. RESULTS AND DISCUSSIONS

In our process, the result can be computed by keeping the panel azimuth fixed at 180° while the tilt of the panel is varied. Fig. 5 summarizes average energy/month and average energy/year with variable tilt angle of panel and at fixed Panel's azimuth 180° facing south and shows its graphical representation.

4.1. Comparison of Computed Electrical Energy with Actual Energy

In this section, we have made a comparison of the computed results from our software with the actual data (http://pvwatts.nrel.gov/India/pvwatts.php). We have selected the specification given below:

Location: Nagpur India,
Latitude = 21.14° N,
Longitude= 79.08° E,
Tilt of panel = 27°,
Panel Azimuth =180°.

Table 2 compares computed and actual monthly and yearly average energy with the optimal tilt angle of the panel which is 27° and at fixed Panel's azimuth 180° facing south. Fig. 6 displays the graphical comparison between computed and actual yearly average energy.

The difference of Output Electrical Energy between Computed and Actual Energy is little greater in the months of July, August and September. This difference is because of the monsoon season from July to September.

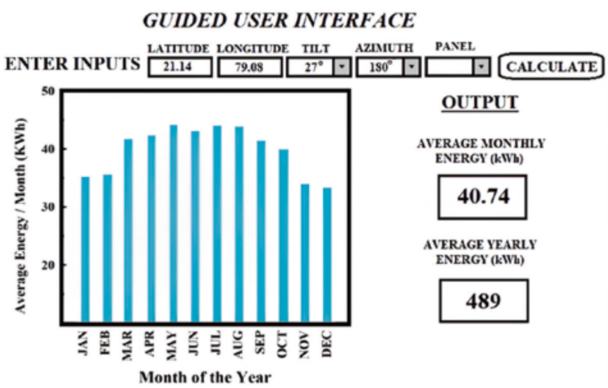

Fig. 4. Guided user interface of the system

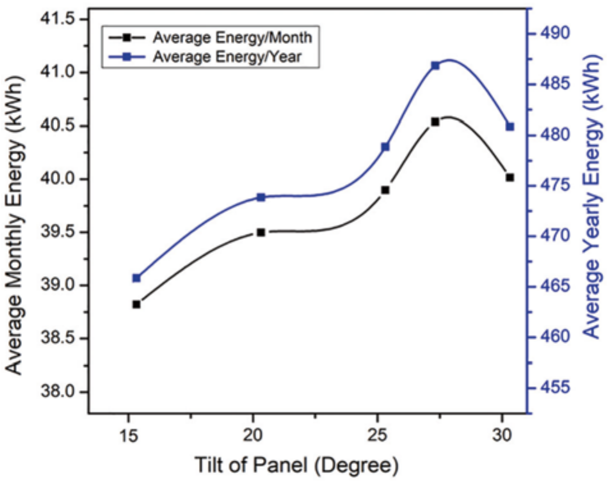

Fig. 5. Average monthly and yearly energy on the variable tilt angle of the panel

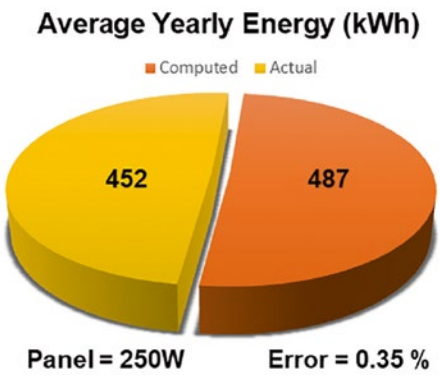

Fig. 6. Computed and actual yearly average energy with an optimal tilt angle of 27°

5. CONCLUSIONS

This work is focusing to compute optimal tilt angle of PV panel for getting maximum amount of energy produce per month and per year for every locations having latitude at north direction and longitude at east direction. The selected clear sky and array performance models include various environmental location and module dependent parameters. Evaluation has been done by comparing actual energy with computed energy for location Nagpur India (21.14° N, 79.08° E) at 27° tilt and we found difference of only 0.35 % has been recorded between actual and computed electrical energy. It is concluded that 27° facing south is the optimal tilt angle for generating maximum electrical energy. We can conclude from current work that the clear sky and array performance models are much known and easy to use without installing expensive sensors like pyranometer and pyrheliometers to get the data of solar irradiance.

Table 2. Computed and Actual Average Energy

Month	Computed Average Energy (kWh)	Actual Average Energy (kWh)
JAN	40.4	41.7
FEB	38.1	38.5
MAR	44.0	43.8
APR	42.2	39.6
MAY	41.3	38
JUN	38.1	32.3
JUL	40.2	30.2
AUG	42	30.2
SEP	42	36.5
OCT	44.1	41.7
NOV	37.4	39.6
DEC	37	39.6

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