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Optimum Angle of Inclination for a Fixed Stand-Alone Photovoltaic: A Review

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ABSTRACT. The optimum angle of tilt for PV system is very important for best performance in the generation of power and other related use of photovoltaic. This work, reviews the best angle of inclination for a stand-alone photovoltaic panel. The consideration of various studies has been looked at in line with some models. It was observed that the yearly fixed angle of tilt is close to or same as the latitude for a given location, although this may not be appropriate for use in other locations. The annual optimal angle of tilt of some locations were closely related in value i.e. 20.50^o, 20.50^o, 21.50^o, 20.20^o, 21.30^o and 22.40^o. The best electrical performance for the PV system was observed to be above 1598kWh/m^2 at20^o inclination facing south. Hencethe value of the optimum angle of tilt for best electrical performance of an array of stand-alone PV system could vary between 0^o and 90^o depending on the location latitude.
Keywords: Photovoltaic, solar power, solar radiation, optimum angle of tilt

1. Introduction

The generation and usage of electricity comes from fossil fuels which invariably has put the earth in a position to be dependent on these energy sources.Around the 18th and the early 19th century, electricity was basically used for lighting purpose. Today in our present world it is increasingly becoming difficult to live a healthy and better life without the availability of electricity. Presently, as put forward by world energy council, a large proportion of thepopulation of the world is without electricity provision[1]. It is worthy to note that solar energy occupies and will continue to play dominant role as one of the most important alternative sources of energy required both in rural and urban development. To have an accurate understanding of the distribution of radiation of solar energy in a given environment is of great interest[21]. One very vital need of the world today is energy requirement. The capacity to meet this ever increasing demand is another challenge on its own altogether. No meaningful development can take place wherever energy crisis exists. This is the bane of the developing world today.

The major disadvantage of fossil fuel usage is the challenge of greenhouse gases released to the climate. Fossil fuels at its present incremental usage faces depletion by the year 2060 [2], if a corresponding incremental use of other non-fossil fuel is not harnessed and equally put to use. This is very important to avoid global energy crisis.Solar energy is a renewable energy source and it is widely believed to bea sustainable energy solution base which is capable of ‘reducing friction’ restrictingthe wheelof technological development especially in developing economies. One efficient way to achieve maximum solar energy yield is by employing proper tiltangle. Optimum angle of tilt ensures that the incident solar radiation reaching the inclined surface of the photovoltaic cell is perpendicular to the surface of the solar cell. Therefore, inclining the solar panel atits best angleof inclination will bring about receiving highest amount of solar energy from the sun, and so resultto maximum yield of energy for the given array.

The solar radiation that is globally received on a surface that is inclined is characterised basically upon three separate components which include the beam, reflected, and diffused irradiance. Usually, the radiated beamthat falls on the inclined surface is dependent on the angle of zenith and the incidence angle of the solar radiation, while the combined component of the reflected and diffused part as received on the inclined surface are based on the angle of inclination ofthe given surface[3]. To calculate the component that is related to the beam radiation, the following equations becomes very handy:

$$I_{tb} = I_b \left(\frac{cos\theta_i}{cos\theta_z}\right) \quad (1)$$

$$\delta = 23.45 * \sin\left[\frac{2\pi(284+n)}{365}\right] \quad (2)$$

$$cos\theta_z = sin\varphi sin\delta cos\varphi cos\delta cos\omega \quad (3)$$

$$cos\theta_i = sin\delta sin\varphi cos\beta - sin\delta cos\varphi sin\beta cos\gamma + cos\delta cos\varphi cos\beta cos\omega + cos\delta sin\beta sin\gamma sin\omega + cos\delta sin\varphi sin\beta cos\gamma cos\omega \quad (4)$$

$$\omega = (solar\ time - 12) * 15\ degrees \quad (5)$$

Note that the solar time is determined by the using the following:

$$Solar\ time = standard\ time \pm 4(L_{st} - L_{loc}) + E \quad (6)$$

Where$E = 9.87sin2B - 7.53cosB - 1.5sinB\ (this\ is\ in\ minute)$(7)

While $B = \left(\frac{360}{364}\right) * (n - 81)$ (8)

To find the numerical quantity of the radiation (reflected) on the inclined surface, equation (9) is used:

$$I_{tr} = \frac{1}{2} * r_g * I * (1 - cos\beta) \quad (9)$$

Using different anisotropic and isotropic models the diffused component of the solar radiation can be estimated.
These models include:

The Hay Model's [4]

$$I_{td} = I_d\left[\frac{I - I_d}{I_{ext}}\frac{cos\theta_i}{cos\theta_z} + \left(\frac{1+cos\beta}{2}\right)\left(1 - \frac{I - I_d}{I_{ext}}\right)\right] \quad (10)$$

The Reindel's Model [5]

$$I_{td} = I_d\left[\left(1 - \frac{I_b}{I_{ext}}\right)\left(\frac{1+cos\beta}{2}\right) + \left(1 + \sqrt{\frac{I_b}{I}}sin^3\left(\frac{\beta}{2}\right)\right) + \frac{I_b}{I_{ext}}R_b\right] (11)$$

$$\text{where } R_b = \frac{\cos(\varphi-\beta)cos\delta sin\omega_{ss} + \omega_{ss}\sin(\varphi-\beta)sin\delta}{cos\varphi cos\delta sin\omega_{ss} + \omega_{ss}\, sin\varphi\, sin\delta} (12)$$

$$\text{while } \omega_{ss} = \min[cos^{-1}(-tan\varphi tan\delta),\ cos^{-1}(-\tan(\varphi-\beta)tan\delta)] (13)$$

The Muneer'sModel [6]

$$I_{td} = I_d\left[cos^2\left(\frac{\beta}{2}\right) + \frac{2b}{\pi}(3 + 2b)(sin\beta - cos\beta - \pi sin^2\left(\frac{\beta}{2}\right))\right] (14)$$

where $b = Radiance\ distribution\ index$

The Bugler's Model [7]

$$I_{td} = \left[\left(I_d - 0.05 * \frac{I_{td}}{cos\theta_z}\right) * \frac{1}{2}(1 + cos\beta)\right] + 0.05 I_{tb} cos\theta (15)$$

The Castro and Jimenez's Model [8]

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$$I_{td} = \frac{1}{2} * 0.2 I_d * (1 + cos\beta) \quad (16)$$

The Ma and Iqal Model [9]

$$I_{td} = I_d \left[\frac{I}{I_{ext}} \frac{cos\theta_i}{cos\theta_z} + \left[\left(1 - \frac{I}{I_{ext}}\right) \left(cos^2 \frac{\beta}{2}\right) \right] \right] (17)$$

The Perez et al's Model [10]

$$I_{td} = I_d \left[(1 - F_1) \left(\frac{1 + cos\beta}{2} \right) \right] \left(F_1 * \frac{a}{b} \right) (F_2 sin\beta) (18)$$

where $a, b = the\ circumsolar\ and\ horizontal\ solid\ angle$

$F_1, F_2 = the\ circumsolar\ and\ horizon\ brightness\ coefficient$

The Klucher's Model [11]

$$I_{td} = 0.5 I_d (1 + cos\beta) \left(1 + F sin^3 \left(\frac{\beta}{2} \right) \right) (1 + F cos^2\theta_i\, sin^3\theta_z) (19)$$

where $F = 1 - (\frac{I_d}{I})^2$

The Steven et al's Model [12]

$$I_{td} = I_d \left[\left(\frac{I_b}{I_{ext}} R_b \right) + \left(1 - \frac{I_b}{I_{ext}} \right) \left(\frac{1 + cos\beta}{2} \right) \left(1 + \sqrt{\frac{I_b}{I_g}} sin^3 \left(\frac{\beta}{2} \right) \right) \right] (20)$$

The Koronaski's Model [13]

$$I_{td} = \frac{1}{2} I_d * (1 + cos\beta) \quad (21)$$

The Liu and Jordan's Model [14]

$$I_{td} = I_d * \left(1 + cos \frac{\beta}{2} \right) \quad (22)$$

The Badescu's Model [15]

$$I_{td} = I_d \left[\left(\frac{3 + cos\, 2\beta}{4} \right) \right] \quad (23)$$

The Tian's Model [16]

$$I_{td} = I_d \left(1 - \frac{\beta}{180} \right) \quad (24)$$

For a tilted plane, the total hourly solar irradiance is given by;

$$I_{tg,i} = I_{tb,i} + I_{tr,i} + I_{td,i} \quad (25)$$

The values of $I_{tg,i}, I_{tb,i}, I_{tr,i}\ and\ I_{td,i}$ can be determined by applying the equations listed above while taking the values of $i$to be between 1 and 8760, for a calendar year.

1.1 Direct and Diffused component

The global radiation G_β, that is incident on a surface inclined at a given angle of tilt is categorised by certain distinct classifications, namely:

(i) The component that is direct (beam)B_β which is the direct irradiation that falls on the surface that is tilted.
(ii) The component that is diffused, D_β, and
(iii) The component that is reflected, R_β describes the reflected radiation.

Hence;

$$G_\beta = B_\beta + D_\beta + R_\beta \quad (26)$$

A further study as outlined by[10] indicates that the diffused component comprises of an isotropic diffuse component,$D_{\beta,iso}$ circumsolar diffuse component $D_{\beta,cs}$ and a horizon brightening component,$D_{\beta,hb}$. Therefore, equation 26 becomes

$$G_\beta = B_\beta + (D_{\beta,iso} + D_{\beta,cs} + D_{\beta,hb}) + R_\beta \quad (27)$$

The determination of the component, B_β is completely geometrical. This is revealed by the expression:

$$B_\beta = B_N cos\theta_i = \frac{B}{cos\theta_z} cos\theta_i = B r_b \quad (28)$$

Where $B_{N,}$ represents direct beam,$B,$ represents direct horizontal solar irradiance, $\theta_z,$ equals solar zenith angle
$\theta_i,$ equals the beam radiation incidence angle on an inclined surface.
and$r_b = \max\left(0, \frac{cos\theta_i}{cos\theta_z}\right)$ [20], represents the factor for conversion.
The models, some of whose expressions have earlier been stated are those applied to determine the diffuse radiation falling on a surface that is tilted. These models can eitherbe isotropic or anisotropic. Those that are isotropic, have the assumption that the intensity of any given radiation is usually similar [20]. This implies that the diffuse radiation that reaches the inclined surface is a function of a part of the sky it is opened to. For the Anisotropic,it assumes that part of the sky taken as diffuse is a combination of radiation for both circumsolar region (i.e. sky near the solar disc) and those of the isotropics [20].

2.Brief overview on Tilt Angle

The difference in performance observed in photovoltaic output is mostly expressed by the period of experimentation, angle of tilt, orientation factor and the location latitude. This implies that power production of the solar panel is a direct proportion to the efficiency of the photovoltaic [17]. The angle of tilt of the photovoltaic is very vital at improving the overall efficiency of the solar panel array system.

Installation of some solar panel integrates the use of tracking systems that is designed to move along with the Sun as it travels across the horizon with respect to the earth's movement. These installations have been proven to produce a greater energy yields when they are compared with the fixed stand-alone counterpart [18,19]. It has however been agreed on, that these Sun tracking devices are very expensive and normally will require consistent maintenance to keep them functioning optimally. Hence the need to consciously optimize all parameter needed on the solar panel to provide maximum yield of energy when a stand-alone configuration is being considered.

According to [22] in their comparative approach for tilt angle optimization, to achieve maximum radiation on the tilted surface, they observed for a range of tilt angles to be between 0° and 90° while the photovoltaic is south facing. According to their findings, the angle varies upward at winter period and can attain a highest value of 62°.

In the case of [23], they discover that for Chennai, the seansonal optimal angle of tilt is lower when compared with that of other locations during winter, spring and autumn season which is same for Nagpur during summer for its seasonal optimum angle of tilt. The result of their work further stressed that Solar modulesthatfaces the South usually give the highest value ofelectrical power for all angles selected and emphasizing that a tilt angle taken to be 30° produced highest recorded power.

[20] discovered that the monthly best tilt is not similar for other stations. Also the seasonal best inclination is not the same for different stations, whilethe annual best tilt as observed is almost similar to the latitude of the given location. It was further discovered that majority of diffuse radiation models yielded similar optimum angle of tilt.

According to [24], result for the angle of best tilt for solar collector carried out in Taiwan have a positive value while ensuring the surface faces south but have a negative value when the surface faces north during summer ranging from the months ofMay, June and July. The annual optimal angle of tilt based on their work for places likeTaitung,Kaohsiung,Tainan, Taichung, Hualien and Taipei were respectively given as20.50^o,20.50^o,21.50^o, 20.20^o, 21.30^o and 22.40^o.According to [25], it was discovered that the best tilt angle was around 20◦ when facing south, and was able to provide over 1598kWh/m^2. Their finding shows the angle of inclination of a surfaceis closely associated with the latitude of the location. For [2],it wasobserved from their results that the best energy yield from the photovoltaic waswhen the inclination angle is between 15 and 25^o.

3. Conclusion

The best angle of inclination for a stand-alone photovoltaic panel from other studies have been reviewed. In the consideration various studies were looked at in line with some models. A number of the study revealed that optimum tilt angle occurs when $\beta = \varphi - \delta$ at the time when γ=0˚, i.e. from the months of September-March and when γ=180˚ between the months of April-August. These yielded better electrical performance when compared with when the tilt angle is $\beta = 0$˚, the latitude of the location, $\beta=\varphi$or when $\beta = \varphi + \delta$. For some of the models, the angle of tilt in summer is in the range of 0˚-30˚ while in winter period it is between 50˚-70˚. Hence the following conclusions are to be considered.

• To be able to harvest highest solar radiation, proper angle of tilt for locations in the northern hemisphere should be considered with the array facing south.

• It observed that the yearly fixed angle of inclination is close to or equal to the latitude that represent the location, but this may not be appropriate in other locations.

•That the value of the optimum angle of tilt could vary between 0˚ and 90˚.

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Nomenclature

B_N = Beam (direct)
B = direct (horizontal) solar irradiance.
θ_z = solar zenith angle.
G_β=the global incident solar radiation
B_β = direct irradiation that falls on the surface that is tilted.
D_β= diffuse solar irradiance.
R_β = reflected component of the radiation.
Lst = the standard longitude
Lloc = the longitude of the given location
θi = the surface incidence angle
δ = the angle of declination
ω = the hour angle
β = the angle of inclination
γ = the angle of orientation
φ = it islatitude of study area
n =day number of the year, taking January 1^{st} as 1
Ib = radiation (beam) on a given surface that is horizontal
I = radiation (global)on a given surface that is horizontal
Id = radiation (diffuse)on a given surface that is horizontal
Itg = radiation(total)on a given surface
Itd = radiation(diffuse)on a given surface
Itb = radiation(beam)on a given surface
Itr = radiation(reflected)on a given surface
Itb,i = radiation (beam) for a given i_{th} hour
Itr,i = radiation(reflected) for a givenith hour
Itd,i = radiation(diffusion)for a given i_{th}hour
Itg,i= radiation(global) for a given i_{th}hour

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