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Determination of Yearly Fixed Optimal Tilt Angle for Flat-Plate Photovoltaic Modules Based on Perez Transposition Model

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Abstract: In this paper, a method for the determination of the optimal tilt angle for yearly fixed flat-plate photovoltaic (PV) module at any given location is presented. The method is based on yearly global radiation incident on a horizontal plane as downloaded from NASA website. Futrthermore, PVSyst software that uses transposition model is used to generate the yearly global radiation incident on a tilted plane for various tilt angles, from 0° to 46°. The study is conducted for a health facility in Uyo, Akwa Ibom state, Nigeria with longitude of 7.860761, latitude of 5.011474 and elevation of 67.506 m. The optimal tilt angle is obtained from the quadratic trendline equation fitted to the graph of the transposition factor versus tilt angle. The result is that the optimal tilt angle for the yearly fixed flat-plate PV module at the selected Flocation is 9.71° which gives average yearly transposition factor 1.0105. Essential, the results indicate that about additional 1.05% of solar radiation will be captured per year by tilting the PV module at optimal tilt angle of 9.71°. At any other tilt angle less solar radiation will be captured per year.

Keywords: Optimal Tilt Angle, Global Solar Radiation, PVSyst Software, Transposition Factor, Yearly Fixed Tile Angle, Solar Power System

1. Introduction

At various steps in the design or simulation, as well as performance evaluation of photovoltaic (PV) power system, accurate solar radiation data are necessary. In flat-plate PV power systems, the PV modules are generally installed on either fixed tilted planes or tracking receivers [1-4]. However, in most cases, the fixed tilted plane is used because of lower cost of installation and maintenance. Nevertheless, data on solar radiation are generally provided for horizontal planes [5-8]. In this wise, algorithms and mathematical models are used to transpose the available solar radiation data on horizontal plane to the solar radiation on the tilted plane. Such mathematical models are referred to as transposition model [9-12].

Total or global radiation incident on a tilted plane consists of three components: beam radiation, diffuse radiation and reflected radiation from the ground [13-18]. In order to determine the global radiation incident on a tilted plane, PVsyst software offers two transposition models, namely Hay's model and Perez model [19, 20]. The two models differ by the way they determine the diffuse component of the radiation incident on a tilted plane. In the Hay model, the diffuse irradiance is divided into an isotropic contribution, and a "circumsolar" part, which is proportional to the beam component [21-25]. On the other hand, Perez-Ineichen model introduces the "horizon band" as a third diffuse component [19, 26]. It divides the sky into sectors, and parameterizes the transformations of the circumsolar and the horizon band according to correlations established on the basis of data of several dozen of measurement sites, distributed all over the world.

By default, the earlier versions of PVsyst software was using the Hay model. However, recent works of Pierre Ineichen [27-29] came to the conclusion that the Perez model is slightly better in any case, even with synthetic data. Therefore with the version 6, the Perez model is proposed as default.

Studies have shown that different tilt angles give different solar radiation values on the tilted plane. As such, PV power system designers are always interested in determining the tilt angle that gives the highest solar radiation value on the tilted plane. Such angle is referred to as the optimal tilt angle [30-32]. Also, studies have shown that the optimal tilt angle varies with the location of the site. Particularly, the optimal tilt angle has been related to the latitude of the location of the PV module [33-36]. The optimal tilt angle varies also with time. Different hours in a year have optimal tilt angle that may differ from that of other. Also, when considered in terms of average solar radiation on daily or monthly basis, the optimal tilt angle also is not the same for different days and different months in a year.

In any case, in this paper, the focus is on the method for determination of optimal tilt for flat plate PV modules that are installed on fixed tilted planes for a whole year. The study will use the meteorological data from NASA portal [37]. Particularly, the yearly global radiation incident on a horizontal plane is downloaded from the NASA portal in PVSyst software. The Perez transposition model is used in the in PVSyst software to transpose the yearly global radiation incident on a horizontal plane to yearly global radiation incident on the tilted plane. The transposition factor model is then derived alone with the optimal tilt angle for yearly fixed tilted PV module and the yearly optimal transposition factor.

2. Determination of the Optimal Tilt Angle for Yearly Fixed Flat-Plate Photovoltaic Modules

Let G_{YH} be the total yearly global radiation on the horizontal plane and let $G_{YT(\beta)}$ be the total yearly global radiation on the titled plane at tilt angle β. Now, at tilt angle of zero, that is $\beta = \mathbf{o}^{\circ}$, $G_{YH} = G_{YT(0)}$. The yearly transposition factor at tilt angle β is denoted as $Tf_{Y(\beta)}$ where;

$$Tf_{Y(\beta)} = \frac{G_{YT(\beta)}}{G_{YH}} = \frac{G_{YT(\beta)}}{G_{YT(0)}} \quad (1)$$

The Perez transposition model is used in the PVSyst simulation software to generate the total yearly global radiation on the tilted plane, $G_{YT(\beta)}$ for various values of tilt angle, β; for $\beta \geq 0$. Assuming the value of the jth tilt angle is denoted as β_j and a total of n tilt angles are considered, then the yearly transposition factor at tilt angle β_j is denoted as $Tf_{Y(\beta_j)}$ where;

$$Tf_{Y(\beta_j)} = \frac{G_{YT(\beta_j)}}{G_{YH}}$$

$$= \frac{G_{YT(\beta_j)}}{G_{YT(0)}} \text{ for j= 0,1,2,…n-1} \quad (2)$$

The graph of $Tf_{Y(\beta_j)}$ versus β_j is plotted a quadratic trendline equation is fitted to the graph. The quadratic trendline equation is of the form:

$$Tf_{Y(\beta)} = A\ (\beta)^2 + D(\beta) + E \quad (3)$$

In order to obtain the yearly fixed optimal tilt angle, denoted as β_{Yopt}, the first derivative of the quadratic trendline equation is obtained as follows;

$$\frac{\partial(Tf_{Y(\beta)})}{\partial(\beta)} = 2(A)(\beta) + D \quad (4)$$

By equating the $\frac{\partial(Tf_{Y(\beta)})}{\partial(\beta)}$ to zero and solving for β, the yearly fixed optimal tilt angle, β_{Yopt} is obtained as;

$$\beta_{Yopt} = \beta = \frac{-D}{2(A)} \quad (5)$$

The yearly optimal transposition factor is denoted as Tf_{Yopt}, where;

$$Tf_{Yopt} = A\ \left(\beta_{Yopt}\right)^2 + D\left(\beta_{Yopt}\right) + E \quad (6)$$

3. Simulation Process, Results and Discussions

The study is conducted for PV modules located at on a health facility at Uyo, Akw Ibom state, Nigeria with longitude of 7.860761, latitude of 5.011474 and elevation of 67.506 m. The yearly global radiation incident on a horizontal plane (as shown in column 2 and column 5 of Table 1) is downloaded from NASA website into PVSyst meteorological directory. Then, PVSyst transposition model is set to Perez model, as shown in figure 1. The PVSyst software is then used to generate the yearly global radiation incident on a tilted plane for various tilt angles, from 0° to 46° (as shown in column 3 and column 6 of Table 1).

Table 1. *The Yearly Global Radiation Incident on A Horizontal and Yearly Global Radiation Incident on A Tilted Plane For Various Tilt Angles.*

Tilt Angle (°)	Yearly Global Radiation Incident On A Horizontal Plane	Yearly Global Radiation Incident On A Tilted Plane	Tilt Angle (°)	Yearly Global Radiation Incident On A Horizontal Plane	Yearly Global Radiation Incident On A Tilted Plane
0	1827.6	1827.6	24	1827.6	1806.6
2	1827.6	1835.2	26	1827.6	1793.9
4	1827.6	1841.1	28	1827.6	1779.5
6	1827.6	1845.3	30	1827.6	1763.6
8	1827.6	1847.8	32	1827.6	1745.9
10	1827.6	1848.5	34	1827.6	1726.7

Tilt Angle (°)	Yearly Global Radiation Incident On A Horizontal Plane	Yearly Global Radiation Incident On A Tilted Plane	Tilt Angle (°)	Yearly Global Radiation Incident On A Horizontal Plane	Yearly Global Radiation Incident On A Tilted Plane
12	1827.6	1847.6	36	1827.6	1706.2
14	1827.6	1845	38	1827.6	1684.2
16	1827.6	1840.7	40	1827.6	1660.8
18	1827.6	1834.7	42	1827.6	1636
20	1827.6	1827.1	44	1827.6	1609.7
22	1827.6	1817.7	46	1827.6	1582

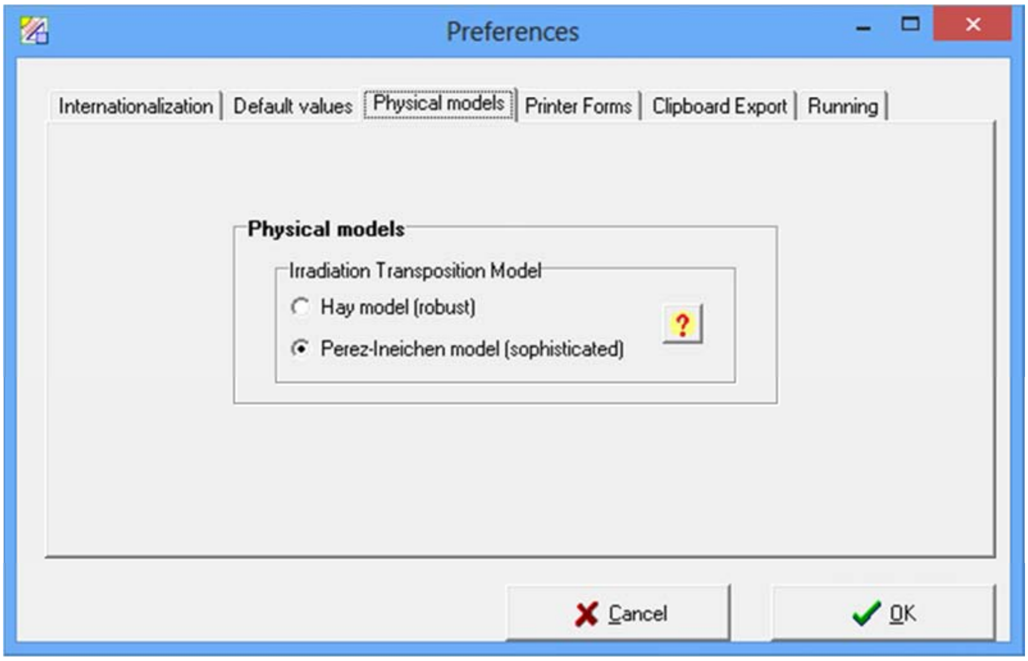

Figure 1. *The PVSyst Setting for The Transposition Model.*

From the data in Table 2 and the yearly transposition factors in Table 2, it appears that the maximum yearly global radiation incident on a tilted plane is obtained at tilt angle of 10° and the maximum yearly transposition factor of 1.0114 also occurred at the tilt angle of 10°. However, the optimal tilt angle is greater of equal to this apparent maximum yearly transposition factor.

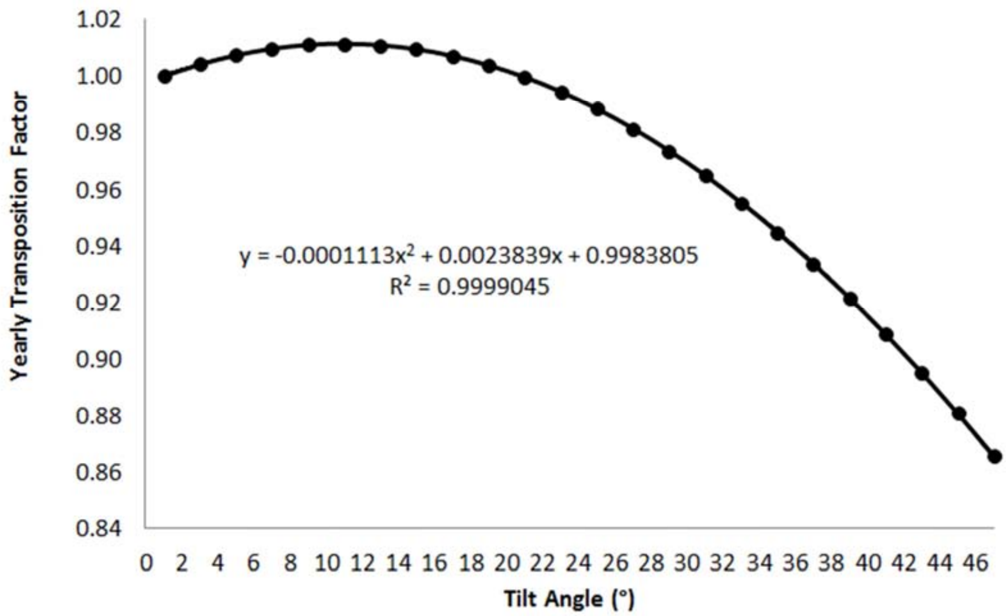

Figure 2. *The Graph of Yearly Transposition Factor, $Tf_{Y(\beta)}$ versus Tilt Angle, β (°).*

Table 2. *Yearly Transposition Factor for Various Tilt Angles.*

Tilt Angle (°)	Yearly Transposition Factor	Tilt Angle (°)	Yearly Transposition Factor
0	1	24	0.9885
2	1.0042	26	0.9816
4	1.0074	28	0.9737
6	1.0097	30	0.965
8	1.0111	32	0.9553
10	1.0114	34	0.9448
12	1.0109	36	0.9336
14	1.0095	38	0.9215
16	1.0072	40	0.9087
18	1.0039	42	0.8952
20	0.9997	44	0.8808
22	0.9946	46	0.8656

The optimal tilt angle is obtained from the trendline equation fitted to the graph of yearly transposition factor, $Tf_{y(\beta)}$ versus tilt angle, β (°) as shown in Figure 2. From figure 2, the trendline equation is given as;

$$Tf_{Y(\beta)} = -0.0001113\,\beta^2 + 0.0021613\,\beta + 1.00 \quad (7)$$

The first derivative of the trendline equation is given as;

$$\frac{\partial(Tf_{Y(\beta)})}{\partial(\beta)} = -0.0002226\,\beta + 0.0021613 \quad (8)$$

By setting $\frac{\partial(Tf_{Y(\beta)})}{\partial(\beta)} = 0$ and solving for β the optimal tilt angle for the yearly fixed flat-plate PV module is obtained as;

$$\beta_{Yopt} = \frac{-0.0021613}{2(-0.0001113)} = 9.71 \quad (9)$$

The yearly transposition factor at the optimal tilt angle for the yearly fixed flat-plate PV module is obtained as follows;

$$Tf_{Yopt} = -0.0001113\left(\beta_{Yopt}\right)^2 + 0.0021613\left(\beta_{Yopt}\right) + 1.00 \quad (10)$$

$$Tf_{Yopt} = -0.0001113\,(9.71)^2 + 0.0021613\,(9.71) + 1.00 = 1.0105$$

For the a health facility at Uyo, with longitude of 7.860761, latitude of 5.011474 and elevation of 67.506 m the optimal tilt angle for the yearly fixed flat-plate PV module is 9.71° and the average yearly transposition factor at the optimal tilt angle is 1.0105. This means that about additional 1.05% of solar radiation will be captured per year by tilting the PV module at optimal tilt angle of 9.71°. At any other tilt angle less solar radiation will be captured per year.

4. Conclusion

The method for determining the optimal tilt angle for the yearly fixed flat-plate PV module at any given location is presented. A sample health facility in Uyo, Akwa Ibom state, Nigeria with longitude of 7.860761, latitude of 5.011474 and elevation of 67.506 m is used to demonstrate the applicability of the method. In all, the optimal tilt angle for the yearly fixed flat-plate PV module at the selected location is determined along with the average yearly transposition factor at the optimal tilt angle.

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