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Development of Winter Season Optimal Tilt Angle Model for Fixed Tilted Plane PV Installation in Akwa Ibom State, Nigeria

Akpan Ikoedem Ekpenyong¹, Umoren Mfonobong Anthony^{2*}, and Idorenyin Markson³

^{1,2} Department of Electrical/Electronic and Computer Engineering, University of Uyo, Akwa Ibom, Nigeria

³ Department of Mechanical Engineering, University of Uyo, Akwa Ibom, Nigeria

*Corresponding Author: umoren_m.anthony@yahoo.com

Abstract

In this paper, a polynomial model is developed for determining the winter season optimal tilt angle for fixed-tilt PV installations in Uyo metropolis, Akwa state of Nigeria. Satellite-derived NASA SSE solar radiation data was used in the study and the simulation was done using PVSyst software. The polynomial model is given as $WTF(\beta) = -0.00013(\beta^2) + 0.00643(\beta) + 0.99991$; where $WTF(\beta)$ is the winter average transposition factor and β is the tilt angle in degrees. The model has prediction accuracy of 99.92% with root mean square error of 0.001267 and optimal winter season tilt angle of 24.73°. Furthermore, the study also did the comparison of the effect of using seasonal or yearly fixed tilt and seasonally adjusted tilt angle for the PV panel. The results show that the greatest yearly average transposition factor is obtained when the tilt angle is optimally adjusted to suit the Winter months during the Winter and to suit the Summer months during the Summer seasons.

Keywords: Photovoltaic; Irradiation; Tilt Angle; Azimuth Angle; Transposition; Transposition Factor; Optimal Tilt Angle; Fixed Tilted Plane; Winter Optimal Tilt Angle.

1. Introduction

Photovoltaic (PV) devices traps and converts energy from sunlight into electric energy. In order to intercept the most sunlight, a PV panel must be positioned so that the sun's rays arrive at the panel perpendicular to its surface [1, 2]. When a PV panel is not aimed directly at the sun, it does not intercept as much light as it can. Consequently, it does not produce as much power as it can.

Generally, solar radiation includes both a direct component and a diffuse component made up from reflections off clouds, moisture vapour and other particulates within the sky [1,2]. Similarly, the satellite-derived National Aeronautics and Space Administration Surface meteorology and Solar Energy (NASA SSE) solar radiation data consist of the global horizontal irradiance and the direct irradiance on the horizontal plane [3,4,5,6]. Basically, global horizontal radiation consists of the direct and diffuse radiation components as measured incident on a flat horizontal plane. It is therefore the sum of the direct horizontal and diffuse horizontal values [7].

In practice, irradiation incident on the inclined plane of PV array is normally used to compute the PV energy potential [8]. In many cases PV modules are installed on tilted planes, in that case, the irradiance on a tilted plane need to be estimated. Transposition can be defined as the determination of the irradiation on an inclined plane, from the horizontal irradiation data [9,10,1]. PVsyst has two models for transposition, which are Perez model and Hay's model. The Perez transposition model is used in this study.

In many cases, photovoltaic (PV) power systems modules are installed on either fixed tilted planes or tracking receivers. Prediction of the global irradiation incident on such tilted surfaces is essential in evaluating the solar potentials and performance of PV power systems [9]. Studies have shown that the best way to collect maximum daily solar energy is to use tracking systems. Alternatively, for fixed tilted panels, the optimal tilt angle must be identified based on yearly average, monthly average, or seasonal average solar irradiation data. In this paper, the model for computing the seasonal optimal tilt angle for the Winter season is developed. The study is based on PV installation at Ibom E-library located at IBB Avenue, Uyo, Nigeria at latitude of 5.015197 and longitude of 7.913180.

There has been several works on optimal tilt angle for winter season. In India, Nahar [11] arrived at optimal tilt angle during winter season, (October to March) as $\phi + 15^\circ$, where ϕ is the latitude of the location. Hottel [12] disclosed $\phi + 20^\circ$ as the optimal tilt angle during winter season whereas Lof and Taybout, [13] reported $\phi + (10^\circ-30^\circ)$. In South Africa, Chinnery [14] as well as Kern and Harris [15] reported winter optimal tilt angle as $\phi + 10^\circ$. Equally, Heywood [16] gave winter optimal tilt angle as $\phi - 10^\circ$, whereas Yellott [17] gave $\phi \pm 20^\circ$, Lewis [18] gave $\phi \pm 5^\circ$ and Lunde [19] gave $\phi \pm 15^\circ$. Finally, in Turkey, Ertekin, Evrendilek and Kulcu reported winter (December to February) optimal tilt angle as $\phi + 8.14^\circ$. From the available literatures, there are obvious disparities among the reported values or models for computing the winter season's optimal tilt angle for flat plane PV modules.

The focus in this paper is to determine the optimal tilt angle for a specific PV site in Akwa Ibom state. The seasonally fixed optimal tilt allows for selection of one optimal tilt angle for a given season and fixing the tilt angle of the PV panel at that season's optimal tilt angle all the year. On the other hand, the adjustable seasonal model allows the tilt angle of the PV panels to be adjusted twice a year based on the optimal tilt angles of the two seasons, namely; winter and summer. Furthermore, the study also did comparison of the seasonally adjusted, seasonally fixed and yearly fixed flat PV modules with respect to their yearly average transposition factors.

2. Methodology

Generally, (H_T) the total radiation incident on PV panel tilted at an angle β to the horizontal plane is the summation of direct-beam (H_{Tb}), diffused radiations (H_{Td}) and ground reflected radiations (H_{Tr}) on the tilted panel:

$$H_T = H_{Tb} + H_{Td} + H_{Tr} \quad (1)$$

In practice, available (H) monthly average daily global solar radiation incident on the horizontal plane (KWh/m^2) is decomposed and then transposed to the tilted plane of the PV module to obtain the (H_T) global solar radiation incident on the tilted plane. Different tilt angle (β) gives different values for H_T . Optimal tilt angle (β_{opt}) is the tilt angle at which the global radiation on the tilted plane (H_T) is at its maximum. This corresponds to the tilt angle at which the transposition factor (TF) is also at its maximum, where transposition factor (TF) is the ratio of (H_T) the global irradiation on

tilted plane to (H) the global irradiation on horizontal plane:

$$\text{Transposition Factor (TF)} = \frac{\text{Global Irradiation on Tilted Plane}}{\text{Global Irradiation on Horizontal Plane}} = \frac{H_T}{H} \quad (2)$$

The methodology adopted in the paper is presented as follows:

Step 1: Obtain (H) the monthly average daily global solar radiation incident on the horizontal plane.

In this paper, 22-year average satellite-derived NASA SSE solar radiation data of monthly average daily global solar radiation incident on the horizontal plane is downloaded from NASA website for the selected site located in Uyo Akwa Ibom state, at latitude of 5.015197 and longitude of 7.913180. Specifically, PVSyst simulation software is used to download the NASA SSE solar radiation data of monthly average daily global solar radiation incident on the horizontal plane. The data is stored in the meteorological file of PVSyst.

Step 2: Select a tilt angle β and then decompose and transpose the H unto the inclined plane tilted at an angle of β to the horizontal.

Again, PVSyst is also used to decompose (H) the global solar radiation incident on the horizontal plane into its beam (H_b) and diffused (H_d) components. Furthermore, the PVSyst is used to transpose the decomposed (H) to the tilted plane for different tilt angle (β) so as to obtain the H_T

Step 3: Compute the transposition factor (TF) for each of the winter months (October to December and January to March) the given tilt angle, β .

Both H and H_T are exported from the PVSyst to Microsoft Excel for each winter month and the given tilt angle.

Step 4: Repeat step 2 and step three for different tilt angles.

In this paper, the range of tilt angle (β) considered is 0° to 40° .

Step 5: Compute the average winter transposition factor (WTF) for each of the tilt angles

Now, let the transposition factor for the month j and tilt angle β be given as $TF_{(j)(\beta)}$ and the winter average transposition factor for the tilt angle β is given as $WTF_{(\beta)}$ where j = 1 for January, j = 2 for February, j = 3 for March, j = 4 for October, j = 5 for November and j = 6 for December. Then

$$WTF_{(\beta)} = \frac{\sum_{j=1}^{j=6} (TF_{(j)(\beta)})}{6} \quad (3)$$

Step 6: Plot the graph of average winter transposition factor ($WTF_{(\beta)}$) versus tilt angle (β)

Step 7: Fit a trend line curve on the graph of $WTF_{(\beta)}$ versus β . The trend line equation (of $WTF_{(\beta)}$ expressed in respect of β) gives the model for determining the optimal winter tilt angle, β_{opt} .

Step 8: Find the first derivative of the trend line equation of $WTF_{(\beta)}$ expressed in respect of β and then solve for β when the first derivative is set to zero. The value of β obtained is the optimal winter tilt angle for the location.

Importantly, step 5 can be used to compute the yearly average transposition factor

(YTF) and the average summer transposition factor (STF) for each of the tilt angles as follows:

Given that the transposition factor for the month j and tilt angle β is given as $TF_{(j)(\beta)}$ and the yearly average transposition factor (YTF) for the tilt angle β is given as $YTF_{(\beta)}$ where $j = 1$ for January, $j = 2$ for February, ... $j = 12$ for December, then

$$YTF_{(\beta)} = \frac{\sum_{j=1}^{j=12} (TF_{(j)(\beta)})}{12} \quad (4)$$

According to PVSyst, the summer months are April, May, June, July, August and September. Also, given that the transposition factor for the month j and tilt angle β is given as $TF_{(j)(\beta)}$ and the summer average transposition factor (STF) for the tilt angle β is given as $STF_{(\beta)}$ where $j = 1$ for April, $j = 2$ for May, ... $j = 6$ for September, then

$$STF_{(\beta)} = \frac{\sum_{j=1}^{j=6} (TF_{(j)(\beta)})}{6} \quad (5)$$

In order to demonstrate the benefit of the seasonally adjusted and yearly fixed PV, the yearly average transposition factor of the seasonally adjusted PV is compared to the yearly average transposition factor of the yearly fixed PV module. Generally, in Nigeria, ($\beta_{(summer)(opt)}$) the optimal summer tilt angle is zero; that is $\beta_{(summer)(opt)} = 0^\circ$. Furthermore, according to research findings in [20, 21] the optimal tilt angle for yearly fixed flat PV modules is given as

$$\beta_{(yearly)(opt)} = 3.7 + 0.69|\phi| \quad (7)$$

where ϕ is the local latitude in degrees and $\beta_{(yearly)(opt)}$ is the optimal yearly fixed tilt angle in degrees. Based on Eq. (7), the optimal tilt angle for yearly fixed PV at the selected site with latitude of 5.015197 is $\beta_{(yearly)(opt)} = 3.7 + 0.69|5.015197| = 7.16104 \approx 7^\circ$

Finally, step 1 to step 8 are employed to determine $WTF_{(\beta)}$, $YTF_{(\beta)}$ and $STF_{(\beta)}$ for the following three fixed tilt angles, namely: $\beta_{(summer)(opt)}$, $\beta_{(yearly)(opt)}$, $\beta_{(winter)(opt)}$ and for seasonally adjusted tilt angle.

3. Analysis of the Prediction Accuracy of the Model

Root Mean Square Error (RMSE) and Prediction Accuracy (PA) are used to characterize the prediction level of accuracy of the predictions made by the models. Expression for RMSE is given as:

$$RMSE = \sqrt{\left\{ \frac{1}{n} \sum_{i=1}^{i=n} |WTF_{(i)(actual)} - WTF_{(i)(predicted)}|^2 \right\}} \quad (8)$$

where:

$WTF_{(i)(actual)}$ is the actual solar radiation on tilted surface in KWh/m^2

$WTF_{(i)(predicted)}$ is the predicted solar irradiation on inclined plane in KWh/m^2

n is the number of data points; in this case, the number of tilt angles considered.

Then, the accuracy (PA in %) is given as:

$$PA = \left\{ 1 - \frac{1}{n} \sum_{i=1}^{i=n} \frac{|WTF_{(i)(actual)} - WTF_{(i)(predicted)}|}{WTF_{(i)(actual)}} \right\} * 100\% \quad (9)$$

4. Results and Discussion

Figure 1 is the PVSyst Meteorological Data Dialogue Box showing the monthly average global radiation on horizontal plane downloaded from NASA SSE website [22].

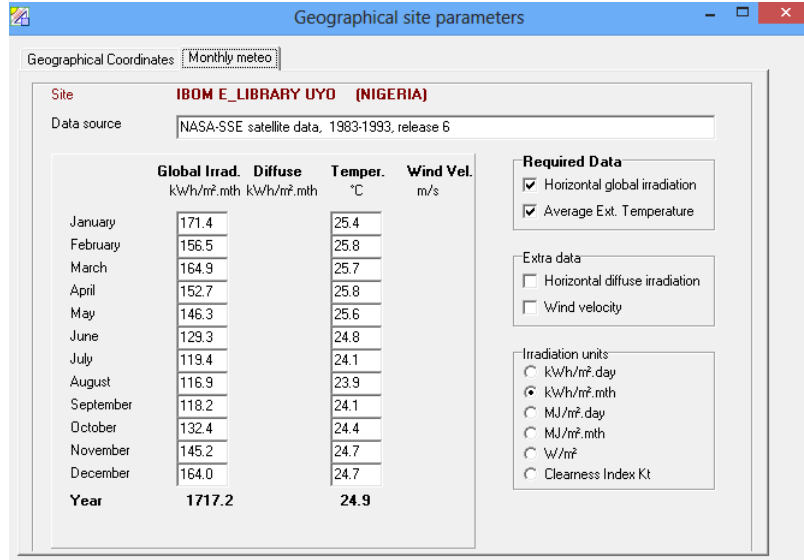


Figure 1: PVSyst Meteorological Data Dialogue Box For the monthly average global radiation on horizontal plane downloaded from NASA SSE website [14]

Table 1 gives the global irradiation on horizontal plane which has been decomposed and transposed onto a 7° inclined plane with albedo component of 0.20 or 20% for the winter months and summer months respectively. Fig. 2 shows the Winter months' monthly and winter average transposition factor at tilt angle of 7° and azimuth angle of 0° . According to Fig. 2, November has the highest transposition factor whereas October has the lowest transposition factor among the winter months. The tilt angle in this case is determined in PVSyst to suit the winter average solar irradiation data. Accordingly, the result in Fig. 2 shows that about 3 months (half of the winter months) have transposition factor above the winter average whereas another 3 months (half of the Winter months) have their transposition factors less than the Winter average transposition factor.

Similarly, Fig. 3 shows the summer months' monthly and Sumer average transposition factor at tilt angle at 7° and azimuth angle of 0° . According to Fig. 3, the highest transposition factor is in September whereas the lowest transposition factor among the summer months is in June. The tilt angle in this case is determined in PVSyst to suit the summer average solar irradiation data. Accordingly, the result in Fig. 3 shows that about 3 months (half of the summer months) have transposition factor above the summer average whereas another 3 months (half of the summer months) have their transposition factors less than the summer average transposition factor.

Fig. 4 shows the plot of the Winter months' transposition factors for different tilt angles. The winter months' average transposition factor plots is fitted with a quadratic model which is given as:

$$WTF_{(\beta)} = -0.00013\beta^2 + 0.00643\beta + 0.99991 \quad (6)$$

where $WTF_{(\beta)}$ is the winter average transposition factor and β is the tilt angle in degrees.

Fig. 5 shows the Summer Season Transposition Factor Versus Tilt Angle.

Table 1: Sample Winter Months Data on the Global Irradiation on Horizontal Plane Decomposed and Transposed onto a 7° Tilted Plane With Albedo Component of 0.20 or 20%.

Plane: Tilt 7°; Azimuth 0°; Albedo 0.20			
(a)		(b)	
Winter Months	Winter Months Transposition Factor	Summer Months	Summer Months Transposition Factor
Dec	1.0595	Apr	0.9830
Jan	1.0345	May	0.9665
Nov	1.0097	Jun	0.9613
Feb	1.0189	Jul	0.9681
Oct	1.0448	Aug	0.9829
Mar	1.0640	Sep	0.9983
Winter Average	1.0386	Summer Average	0.9767

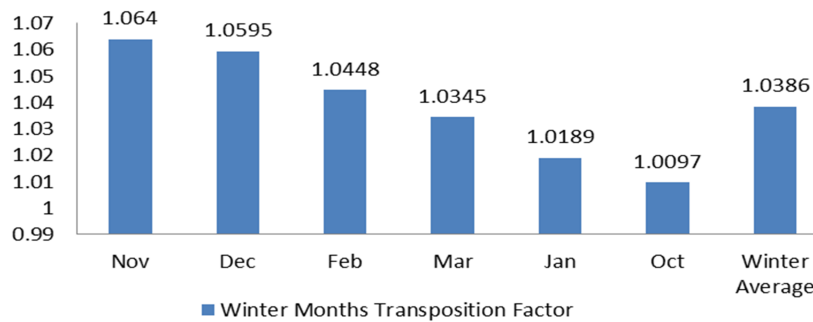


Figure 2: The Winter Months Transposition Factor At Tilt Angle of 7 Degree

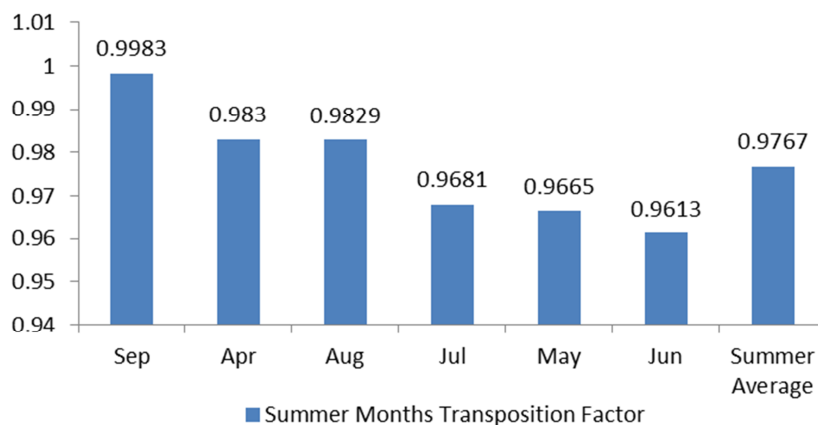


Figure 3: The Summer Months Transposition Factor at Tilt Angle of 7 Degree

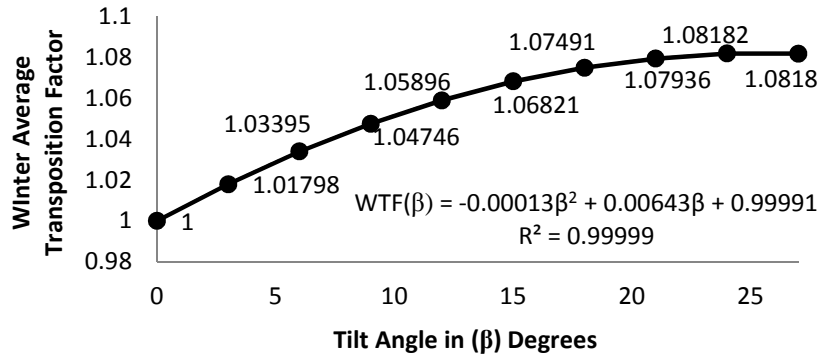


Figure 4: Winter Season Transposition Factor Versus Tilt Angle.

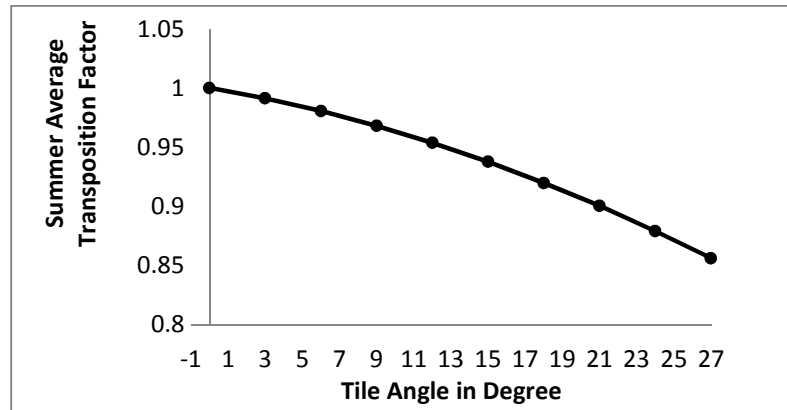


Figure 5: Summer Season Transposition Factor Versus Tilt Angle.

Table 2a: The Winter Months' and Winter Average Seasonal Transposition Factor for Different Tilt Angles

Tilt Angle in degrees	0°	3°	6°	9°	12°	15°	18°	21°	24°	27°	30°
Jan	1	1.02684	1.05193	1.07410	1.09393	1.11144	1.12602	1.13827	1.14819	1.15578	1.15344
Feb	1	1.01661	1.03067	1.04217	1.05176	1.05943	1.06454	1.06709	1.06709	1.06518	1.06582
Mar	1	1.00546	1.00910	1.01031	1.00970	1.00667	1.00121	0.99394	0.98484	0.97332	0.97756
Oct	1	1.00906	1.01662	1.02190	1.02568	1.02719	1.02644	1.02341	1.01964	1.01284	1.01511
Nov	1	1.02066	1.03926	1.05579	1.07025	1.08196	1.09160	1.09917	1.10468	1.10744	1.10675
Dec	1	1.02927	1.05610	1.08049	1.10244	1.12256	1.13963	1.15427	1.16646	1.17622	1.17317
Winter Average Transposition Factor <i>WTF</i> (β)	1	1.01798	1.03395	1.04746	1.05896	1.06821	1.07491	1.07936	1.08182	1.08180	1.08197

Table 2b: The Summer Months' and Summer Average Seasonal Transposition Factor for Different Tilt Angles

Tilt Angle in degrees	0	3	6	9	12	15	18	21	24	27
Apr	1	0.99411	0.98625	0.97577	0.96398	0.95023	0.93386	0.91683	0.89718	0.87557
May	1	0.98701	0.97198	0.95489	0.93575	0.91524	0.89337	0.86945	0.84347	0.81682
Jun	1	0.98453	0.96752	0.94818	0.92807	0.90565	0.88167	0.85615	0.82908	0.80046
Jul	1	0.98743	0.97318	0.95725	0.93881	0.91953	0.89774	0.87511	0.84996	0.82397
Aug	1	0.99401	0.98546	0.97605	0.96493	0.95210	0.93670	0.92045	0.90248	0.88281
Sep	1	1.00085	0.99915	0.99577	0.99069	0.98393	0.97462	0.96447	0.95178	0.93739
SUMMER AVERAGE	1	0.99132	0.98059	0.96799	0.95371	0.93778	0.91966	0.90041	0.87899	0.85617

Fig. 6 shows the actual and predicted yearly transposition factor as a function of the tilt angle. The model in Eq. (6) has prediction accuracy of 99.92% and RMSE of 0.001267. The slope of the quadratic trend line polynomial model of Eq. 6 is given as:

$$\frac{\partial(WTF_{(\beta)})}{\partial\beta} = -0.00026\beta + 0.00643 \quad (7)$$

The optimal tilt angle, β_{opt} is the tilt angle at which the slope in Eq. (7) is zero, that is, when $\frac{\partial(WTF_{(\beta)})}{\partial\beta} = 0$. Hence,

$$\beta_{opt} = \frac{0.00643}{0.00026} = 24.73 \quad (8)$$

The optimal tilt angle from Eq. (3) is computed as $\beta_{opt} = 3.7 + 0.69 |\phi| = 3.7 + 0.69 |5.015| = 7.17^\circ \approx 7^\circ$

From Eq. (8), the optimal tilt angle for the Winter season is $\beta_{opt} = 24.73 \approx 25^\circ$ and the transposition factor is 1.083. With respect to the latitude of the site, The $\beta_{opt} = 5.015197 + 19.714803 \approx \phi + 20^\circ$ which is the results reported by Hottel [12].

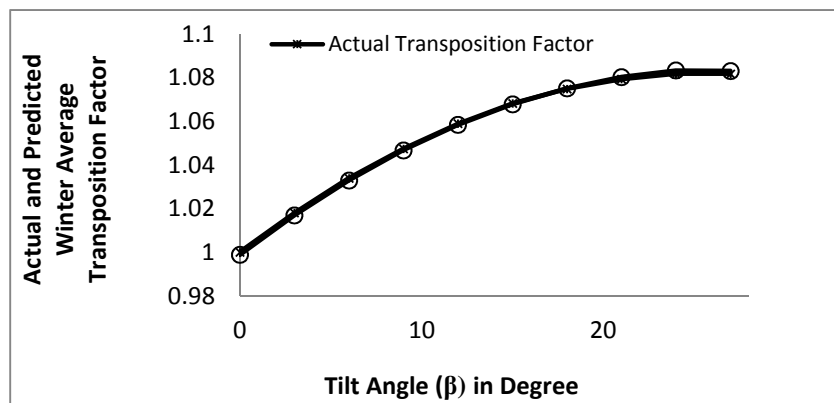


Figure 6: Actual and Predicted Winter Season Transposition Factor Versus Tilt Angle

Finally, Table 3 shows the comparison of the effect of using seasonally fixed tilt, yearly fixed tilt and seasonally adjusted tilt angle for the PV panel. When optimally tilted for summer average transposition factor, the average yearly transposition factor is 1 (as

shown in column 2 last row of Table 3). When optimally tilted for winter average transposition factor, the average yearly transposition factor is less than 1 (as shown in column 3 last row of table 3) but the winter Average transposition factor is greater than 1. When optimally tilted for the yearly average transposition factor, the average yearly transposition factor is greater than 1 (as shown in column 4 last row of Table 3). However, the greatest yearly average transposition factor is obtained when the tilt angle is optimally adjusted during the winter and summer seasons (as shown in column 5 last row of table 3). Essentially, simple adjustment of the tilt angle twice in a year to optimally align with the optimal tilt angle for the two seasons will significantly affect the yearly solar radiation captured by the PV power plant. In all, from the last row in table 3, the yearly fixed tilt will give about 0.76% that is, $(1.007629-1)*100\%$ increase in solar radiation captured on tilted plane. On the other hand, the seasonally adjusted PV will give about 4.59% $(1.045891-1)*100\%$ increase in solar radiation captured on tilted plane.

Table 3: Comparison of the Effect of Using Seasonally Fixed Tilt, Yearly Fixed Tilt and Seasonally Adjusted Tilt for the PV Panel.

	Fixed Tilt at $\beta_{(summer)(opt)} = 0^\circ$	Fixed Tilt at $\beta_{(winter)(opt)} = 25^\circ$	Fixed Tilt at $\beta_{(yearly)(opt)} = 7^\circ$	Adjusted Tilt for Summer $\beta = 0^\circ$ and for Winter $\beta = 25^\circ$
	Optimal for Summer Average Transposition Factor	Optimal for Winter Average Transposition Factor	Optimal for Yearly Average Transposition Factor	Adjusted Optimal for Both Winter and Summer Average Transposition Factor
Summer	1	0.864051	0.9767	1
Winter	1	1.084332	1.03856	1.084332
Yearly	1	0.973013	1.007629	1.045891

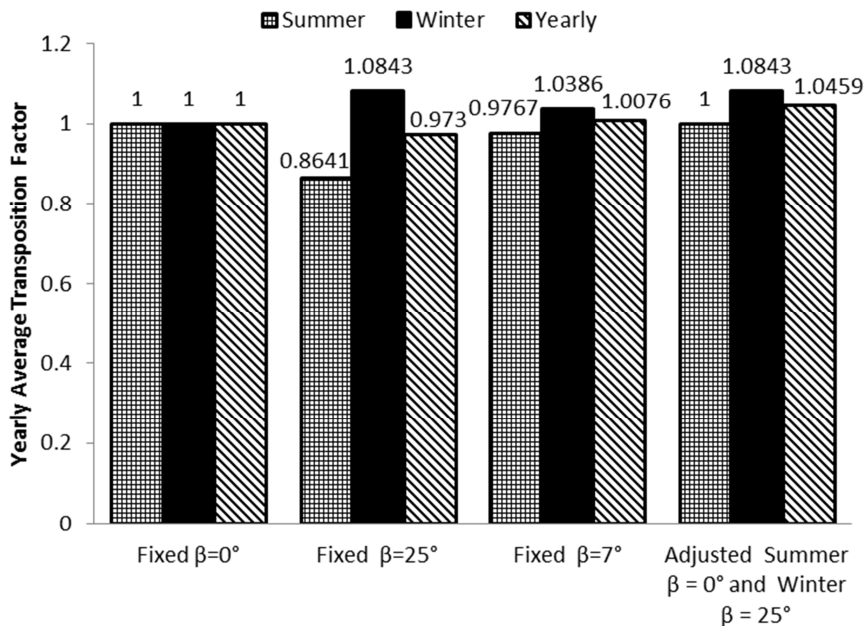


Figure 7: Effect of Fixed and Seasonally Adjusted Optimal Tilt Angle on Yearly Average Transposition Factor

5. Conclusion and Recommendation for Further Works

5.1. Conclusion

A site-specific Winter season's optimal tilt model is developed for PV power installation in Uyo Akwa Ibom state of Nigeria. NASA SSE solar radiation data and PVSyst simulation software are used to generate the average winter season's transposition factor used in the development of the model.

Furthermore, the study also did the comparison of the effect of using seasonal or yearly fixed tilt and seasonally adjusted tilt angle for the PV panel. The results show that the greatest yearly average transposition factor is obtained when the tilt angle is optimally adjusted to suit the Winter months during the Winter and to suit the Summer months during the Summer seasons. Essentially, simple adjustment of the tilt angle twice in a year to optimally align with the optimal tilt angle for the two seasons will significantly affect the yearly solar radiation captured by the PV power plant.

5.2. Recommendation for Further Works

In this paper, the Winter season optimal tilt angle model is considered. Further work is required to determine the monthly optimal tilt angle model and to determine the gain in energy output by applying the monthly rather than the seasonal optimal tilt angle.

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