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# IMPACT OF THE OPTIMAL TILT ANGLE ON THE SOLAR PHOTOVOLTAIC ARRAY SIZE AND COST FOR A 100 KWH SOLAR POWER SYSTEM IN IMO STATE

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## *ABSTRACT*

In this paper the impact of adjusting the optimal tilt angle of solar photovoltaic (PV) modules on monthly bases was studied and compared to that of the annually-fixed optimal tilt angle. PVSyst software was used to determine the optimal tilt angle for each month for a given case study site in Imo state in Nigeria. Mathematical models for computing the required PV array power to meet the daily energy demand of 100 kWh were presented. Addition parameters considered in the study were the PV array number of modules as well as PV array area and cost. For the case study 100 kWh daily energy demand, the selected PV module had a peak power rating of 100W, with a unit cost of N 18,000 and with dimensions that gave an area of 0.65945m^2. The results showed that there is about 4 % (annual average) reduction in the required PV array power when the monthly adjustment of the optimal tilt angle is used. December had the highest percentage reduction in the required PV array power. The reduction in the PV array power resulted in the corresponding reduction in the number of PV modules needed to provide the required power, as well as a reduction in PV array area and cost.

**Contribution/Originality:** This study is one of the very few studies which have investigated the impact of the optimal tilt angle on the solar photovoltaic array size and cost for the solar power system in Imo state, Nigeria.

## 1. INTRODUCTION

In recent year, there is growing adoption of solar photovoltaic power across Nigeria (Bala *et al.*, 2008; Melodi and Famakin, 2011; Akinboro *et al.*, 2012; Azodo, 2014; Ohunakin *et al.*, 2014; Byrne *et al.*, 2017; Dike *et al.*, 2017; Saka *et al.*, 2017). This has become necessary as the national electric power grid has failed to meet the daily demand of the greater majority of the nation's population (Alawiye, 2011; Etukudor *et al.*, 2015; Rapu *et al.*, 2015; Audu *et al.*, 2017). Moreover, the negative health and environmental implications of using diesel and fossil fuel have also encouraged the adoption of PV power across Nigeria (Dieu-Hang *et al.*, 2017; Sangroya and Nayak, 2017). Furthermore, the sustained drop in the cost of solar panels and their accessories has also facilitated the increasing installation of solar powers in homes and office buildings (Babatunde, 2007; Jäger-Waldau, 2007).

One major drawback in the adoption of the solar power system is the initial investment cost (Dahlke, 2011; Feron, 2016; Alsharif, 2017). As such, this paper presents mathematical expressions and sample numerical computations to demonstrate the reduction in the PV array power, the number of modules, PV array area, and cost when a monthly adjusted optimal tilt angle of the solar module is implemented instead of the current practice of yearly-fixed optimal tilt angle. The good thing about the monthly adjustment is that it can easily be done manually. It does not require complex and expensive sun=tracking mechanism.

The paper presents the description of how to use PVsyst to obtain the optimal tilt angle for each month based on the monthly average daily peak sun hour. Also, the essential mathematical expressions for computing the PV array power, size and cost are presented. Sample numerical example was also presented for a solar power system that has 100 kWh daily energy demand.

## 2. METHODOLOGY

The site is a location in Owerri Imo state with coordinates of 5.512 (latitude) and 7.041 (longitude). The dataset for the global solar radiation on the horizontal plane was obtained from the NASA website (NASA, 2018). The radiation data were loaded into the PVSyst. The PVSyst software was then used to determine the solar radiation on a tilted plane. Particularly, the optimal tilt angle for each month of the year was noted as well as the yearly fixed optimal tilt angle.

The monthly optimal tilt angles were obtained using the project site meteorological window in PVSyst to manually adjust the tilt angle for the site meteorological data until the maximum tilted plane global radiation is observed for the given month. Importantly, radiation data for each tilt angle was exported to Microsoft Excel where the global radiation on a tilted plane was compared for each month for the various tilt angle. Through the use of trend line on the dataset, the optimal tilt angle was obtained for each of the months.

On the other hand, the optimal tilt for the annually-fixed tilted plane was computed using the expression (Anyanime *et al.*, 2016).

$$\beta_{ONN} = 3.7 + 0.69 \left| \emptyset \right| \qquad (1)$$

where Ø denotes the site latitude in degree. For the site with 5.512 latitude, the optimal tilt angle is 7.50328≈ 8° ≈ 8°. PVsyst was used to determine the solar radiation in Peak Sun Hours (PSH) for the monthly adjusted optimal tilt angles and the annually-fixed tilt angle for the selected study site and the results are given in Table 1.

**Table-1.** The solar radiation in Peak Sun Hours (PSH) for the monthly adjusted optimal tilt angles and the annually-fixed tilt angle for the selected study site.

| Month | Monthly Optimal tilt Angle (°) | PSH (h/day) On Horizontal Plane | PSH (h/day) On 8° Annually Fixed Tilted Plane | PSH (h/day) On Monthly Adjusted Optimally Tilted Plane |
|---|---|---|---|---|
| Jan | 33.2 | 5.53 | 5.88 | 6.38 |
| Feb | 25.5 | 5.79 | 6.05 | 6.29 |
| Mar | 10 | 5.32 | 5.38 | 5.38 |
| Apr | 0 | 5.09 | 5.00 | 5.09 |
| May | 0 | 4.72 | 4.55 | 4.72 |
| Jun | 0 | 4.31 | 4.11 | 4.31 |
| Jul | 0 | 3.85 | 3.69 | 3.85 |
| Aug | 0 | 3.77 | 3.68 | 3.77 |
| Sep | 0 | 3.94 | 3.93 | 3.94 |
| Oct | 15.8 | 4.27 | 4.36 | 4.39 |
| Nov | 29.7 | 4.84 | 5.10 | 5.40 |
| Dec | 36.2 | 5.29 | 5.67 | 6.29 |
| **Annual Average** | 8° | 4.73 | 4.79 | 4.98 |

## 3. SIZING OF THE SOLAR PV ARRAY

The PV array power output, $P_{OPV}$ for any given daily energy demand, $E_l$ in kWh is given as;

$$P_{OPV} = \frac{E_l}{(\eta_i)(\eta_c)(f_{dl})(PSH)} \qquad (2)$$

Where $\eta_i$ is the inverter efficiency ($\eta_i$ = 0.90), $\eta_c$ is the charge controller efficiency ($\eta_c$ =0.90), $f_{dl}$ are cumulative derating factors ($f_{dl} = 0.9$), PSH is the peak sunshine hours in hours/day.
Given that $E_l = 100\ kWh$ , the

$$P_{OPV} = \frac{100}{(0.9)\,(0.9)(0.9)\,(PSH)} = \frac{154.321}{PSH} \qquad (3)$$

The number of solar panels needed is $N_s$ where

$$N_s = \frac{P_{OPV}}{P_{pv}} = \frac{154.321}{P_{pv}\,(PSH)} \qquad (4)$$

Where $P_{pv}$ denotes the peak power rating of each PV module. In this study $P_{pv} = 100\ Watt$

$$N_s = \frac{P_{OPV}}{P_{pv}} = \frac{(154.321\,)1000}{100(PSH)} = \frac{1543.21}{PSH} \qquad (5)$$

Let the area of each PV module be $A_{pv}$ and the total area of the PV array be $A_{AR}$, then

$$A_{AR} = (A_{pv})N_s = 1543.21\left(\frac{A_{pv}}{PSH}\right) \qquad (6)$$

Let the cost of each PV module be $C_{pv}$ and the total cost of the PV array be $C_{AR}$, then

$$C_{AR} = (C_{pv})N_s = 1543.21\left(\frac{C_{pv}}{PSH}\right) \qquad (7)$$

## 4. RESULTS AND DISCUSSION

The PV module parameters and cost were used to compute the PV array power output, the number of solar panels needed, the total area of the PV array and the total cost of the PV array for the annually-fixed optimal tilt angle and the monthly adjusted optimal tilt angle. The selected PV module has a peak power rating of 100W, with a unit cost of ₦ 18,000 and with dimensions that gave an area of 0.65945$m^2$. The results for the PV array output power for the annually fixed optimal tilt angle and for the monthly adjusted optimal tilt angle are given in Table 2. Based on the results in Table 2, there is about 4 % (annual average) reduction in the required PV array power when the monthly adjustment of the optimal tilt angle is used. December had the highest percentage reduction in the required PV array power.

**Table-2.** Comparison of the output power for the annually fixed optimal tilt angle and for the monthly adjusted optimal tilt angle.

| Month | Output Power (kW) for the Annually Fixed Optimal Tilt Angle | Output Power (kW) for the Monthly Adjusted Optimal Tilt Angle | Percentage Reduction in output power demand |
|---|---|---|---|
| Jan | 26.24507 | 24.18824 | 7.8 |
| Feb | 25.5076 | 24.53434 | 3.8 |
| Mar | 28.5842 | 28.8842 | 0.8 |
| Apr | 30.8642 | 30.31847 | 1.8 |
| May | 33.9167 | 32.69513 | 3.6 |
| Jun | 37.54769 | 35.80534 | 4.6 |
| Jul | 41.82141 | 40.08338 | 4.2 |
| Aug | 41.93505 | 40.93395 | 2.4 |
| Sep | 39.26743 | 39.16777 | 0.3 |
| Oct | 35.39472 | 35.15285 | 0.7 |
| Nov | 30.25902 | 28.57796 | 5.6 |
| Dec | 27.21711 | 24.53434 | 9.9 |
| **Annual Average** | 32.26223 | 30.96225 | 4.0 |

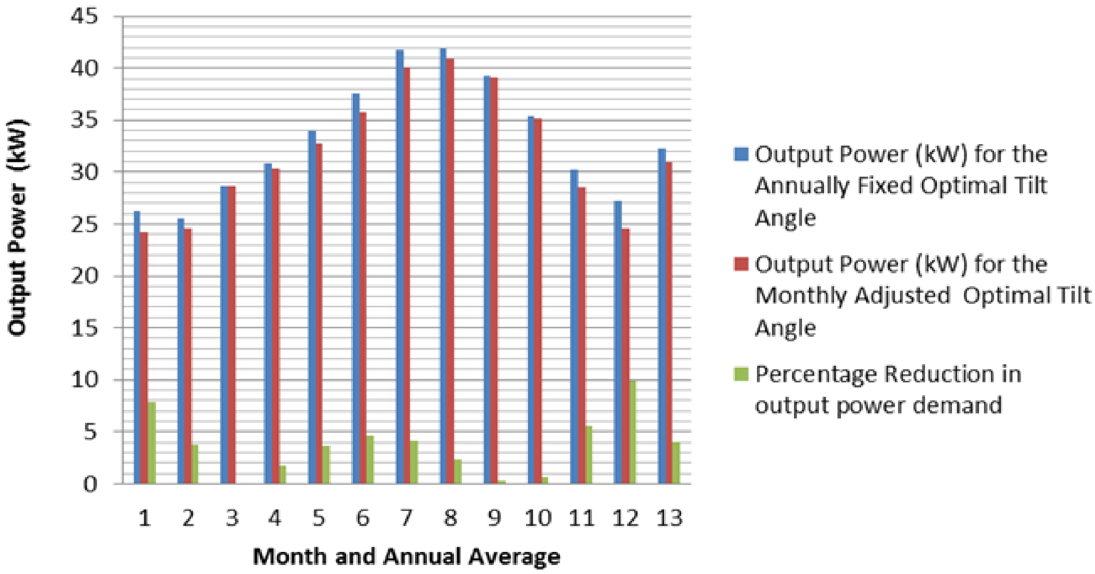


**Figure-1.** Output Power (kW) and percentage reduction in power due to monthly adjustment of the optimal tilt angle.

The implication of the reduction in the PV array power is that there is a corresponding reduction in the number of PV modules needed to provide the required power. Accordingly, Table 3 shows that there is also 4 % annual average reduction in the number of PV module when the monthly adjustment of the optimal tilt angle was used. Again December had the highest percentage reduction in the number of PV modules. Furthermore, there was also the corresponding reduction in PV array area and cost as shown in Table 4 and Table 5 respectively.

**Table-3.** Comparison of the number of solar panels needed for the annually fixed optimal tilt angle and for the monthly adjusted optimal tilt angle.

| Month | Number of Solar Panels Needed for the Annually Fixed Optimal Tilt Angle | Number of Solar Panels Needed for the Monthly Adjusted Optimal Tilt Angle | Percentage Reduction in the number of solar panels |
|---|---|---|---|
| Jan | 263 | 242 | 8.0 |
| Feb | 256 | 246 | 3.9 |
| Mar | 287 | 287 | 0.0 |
| Apr | 309 | 304 | 1.6 |
| May | 340 | 327 | 3.8 |
| Jun | 376 | 359 | 4.5 |
| Jul | 419 | 401 | 4.3 |
| Aug | 420 | 410 | 2.4 |
| Sep | 393 | 392 | 0.3 |
| Oct | 354 | 352 | 0.6 |
| Nov | 303 | 286 | 5.6 |
| Dec | 273 | 246 | 9.9 |
| **Annual Average** | 323 | 310 | 4.0 |

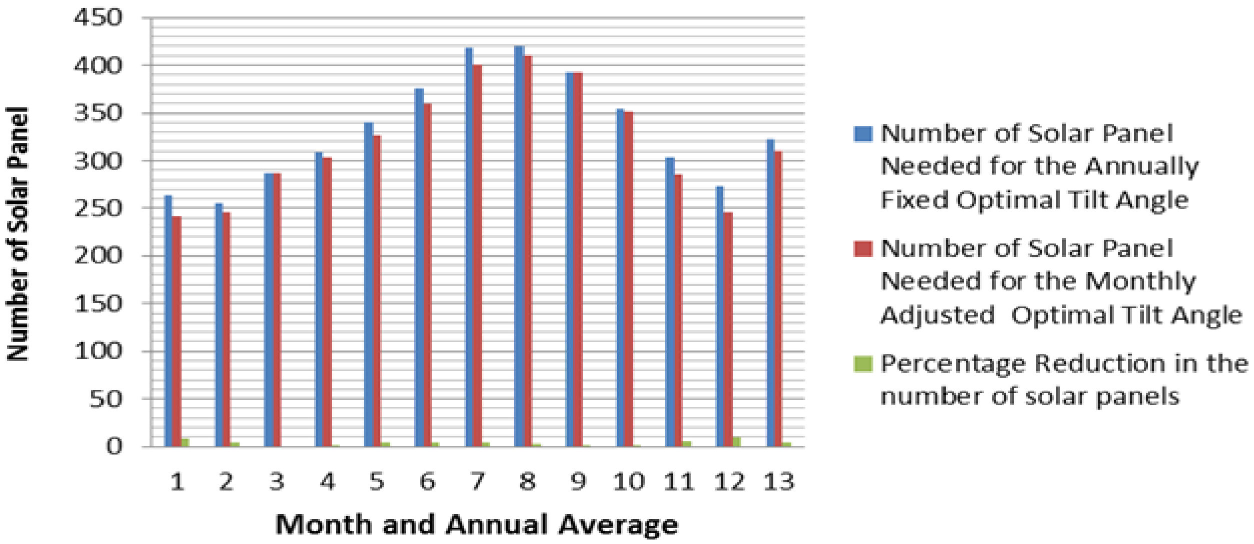


**Figure-2.** Comparison of the number of solar panels needed for the annually fixed optimal tilt angle and the monthly adjusted optimal tilt angle.

**Table-4**. Comparison of the PV array area for the annually fixed optimal tilt angle and the monthly adjusted optimal tilt angle.

| Month | PV Array Area ($m^2$.) for the Annually Fixed Optimal Tilt Angle | PV Array Area ($m^2$.) for the Monthly Adjusted Optimal Tilt Angle | Percentage Reduction in the number of solar panels |
|---|---|---|---|
| Jan | 173.4354 | 159.5869 | 8.0 |
| Feb | 168.8192 | 162.2247 | 3.9 |
| Mar | 189.2622 | 189.2622 | 0.0 |
| Apr | 203.7701 | 200.4728 | 1.6 |
| May | 224.213 | 215.6402 | 3.8 |
| Jun | 247.9532 | 236.7426 | 4.5 |
| Jul | 276.3096 | 264.4395 | 4.3 |
| Aug | 276.969 | 270.3745 | 2.4 |
| Sep | 259.1639 | 258.5044 | 0.3 |
| Oct | 233.4453 | 232.1264 | 0.6 |
| Nov | 199.8134 | 188.6027 | 5.6 |
| Dec | 180.0299 | 162.2247 | 9.9 |
| **Annual Average** | 213.0024 | 204.4295 | 4.0 |

**Table-5.** Comparison of the PV array cost for the annually fixed optimal tilt angle and for the monthly adjusted optimal tilt angle.

| Month | PV Array Cost in Naira for the Annually Fixed Optimal Tilt Angle | PV Array Cost in Naira for the Monthly Adjusted Optimal Tilt Angle | Percentage Reduction in the PV Array Cost |
|---|---|---|---|
| Jan | 4,734,000.0 | 4,356,000.0 | 8.0 |
| Feb | 4,608,000.0 | 4,428,000.0 | 3.9 |
| Mar | 5,166,000.0 | 5,166,000.0 | 0.0 |
| Apr | 5,562,000.0 | 5,472,000.0 | 1.6 |
| May | 6,120,000.0 | 5,886,000.0 | 3.8 |
| Jun | 6,768,000.0 | 6,462,000.0 | 4.5 |
| Jul | 7,542,000.0 | 7,218,000.0 | 4.3 |
| Aug | 7,560,000.0 | 7,380,000.0 | 2.4 |
| Sep | 7,074,000.0 | 7,056,000.0 | 0.3 |
| Oct | 6,372,000.0 | 6,336,000.0 | 0.6 |
| Nov | 5,454,000.0 | 5,148,000.0 | 5.6 |
| Dec | 4,914,000.0 | 4,428,000.0 | 9.9 |
| **Annual Average** | 5,814,000.0 | 5,580,000.0 | 4.0 |

## 5. CONCLUSION

A method of using PVSyst software to determine the monthly optimal tilt angle for solar power installation at any given location is presented. In addition, the effect of using annually fixed optimal tilt and monthly optimal tilt angles are studied and compared. In particular, the effect of the annual and monthly optimal tilt angles on PV array power, number of required modules, the area the PV array will occupy and he total cost of the array are presented. The mathematical equations for computing the listed parameters were presented and then used in a sample numerical example to demonstrate the applicability of the ideas presented in this paper. The results showed that adjusting the PV modules on monthly basis produces a significant improvement in the overall PV power system; there is a reduction in the required solar power to meet a given daily energy demand. Accordingly, there is also, reduction in the number of PV modules, PV array area and PV array cost when the tilt angle of the solar modules are adjusted optimally once every month.

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**Contributors/Acknowledgement:** All authors contributed equally to the conception and design of the study.

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