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INVESTIGATING THE OPTIMAL PHOTOVOLTAIC (PV) TILT ANGLE USING THE PHOTOVOLTAIC GEOGRAPHIC INFORMATION SYSTEM (PVGIS)

AUTHORS:
K. N. Ukoima[1,*], D. Efughu[2], O. C. Azubuike[3], and B. F. Akpiri[4]

AFFILIATIONS:
[1,2]Department of Electrical/Electronic Engineering, Michael Okpara University of Agriculture, Umudike, Nigeria.
[3]Department of Mechanical Engineering, Federal University of Technology, Owerri, Nigeria.
[4]Department of Electrical Engineering, Rivers State University.

***CORRESPONDING AUTHOR:**
Email: kelvin.ukoima@mouau.edu.ng

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Abstract
This work presents an investigation of the optimal tilt angles for mounting pv panels in South –South and South - East States in Nigeria when no tracking system exists using the photovoltaic geographic information system (PVGIS). Experiments were carried out to verify results obtained from the PVGIS database. The experimental set up consist of five PV panels each rated 10Watts inclined at five different angles including the optimal angle obtained from the PVGIS database. South-South Nigeria consists of six states (Rivers, Delta, Bayelsa, Edo, Cross-Rivers and Akwa-Ibom). South-East Nigeria consists of five states (Abia, Enugu, Imo, Ebonyi and Anambra). The optimal installation angle of selected cities within each of the States was identified. Results from experiments conducted showed that from January to April and September to December, the yearly optimal tilt angle (11^o for Port Harcourt, 12^o for Yenagoa, 11^o for Benin City, 10^o for Calabar, 11^o for Asaba and 10^o for Uyo) is suitable for use in the South – South while from January to April and September to December, the yearly optimal tilt angle (10^o for Umuahia, 11^o for Awka, 12^o for Enugu, 10^o for Owerri, and 11^o for Abakaliki) is suitable for use in the South – East. The horizontal plane (0^o) is suitable from May to August in both South – South and South – Eastern States. The untapped solar potential in the South – South was observed to be as high as 286.62kWh/m^2 for Port Harcourt and a low value of 19.34kWh/m^2 was recorded in Calabar when solar panels are not installed at the optimal angles. For the South –East, the untapped solar potential was observed to be as high as 222.11kWh/m2 for Umuahia and a lowest value of 21.31kWh/m2 was also recorded in Umuahia when solar panels were not installed at the optimal angles. Installing PV panels at the optimal tilt angle can improve the efficiency of solar energy generation, making it more cost-effective by maximizing the total amount of diffused and direct radiation.

1.0 INTRODUCTION
Solar energy is inexhaustible and one of the cleanest renewable sources of energy. The solar power in the form of irradiance trapped by the earth is $\approx 1.8 \times 10^{11}$ MW, which is far enough to solve all the present energy crisis in the world if it is used efficiently Lanjewar et al [1]. Figure 1 shows the estimated global renewable capacity growth estimates between 2019 and 2024 with solar energy harnessed from PV panels topping the chart. The off beam installation of Photovoltaic (PV) modules is a challenge to the optimal functioning of these PV panels despite the abundance of solar irradiation received in most African cities. The tilt angle of a PV panel has a huge influence on the panel performance. This is because this angle determines the amount of solar irradiance falling on the PV panel and subsequently the amount

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of electricity generated. Considering the different methods of effectively harnessing of solar energy, optimally installing of PV panels plays a significant function in enhancing the efficiency of power generation from a solar generation system. The position of the sun with respect to the earth makes the optimal tilt angle of solar panel vary from place to place throughout the earth. Variation can be either on a daily, monthly, or yearly basis [2]. Tilt angle is also affected by the location of the panels. Sun trackers (passive or active) are typically used to optimally harness solar energy. However, these tracking systems are expensive, requires maintenance and usually require electrical energy to operate them. When tracking systems cannot be afforded, manual orientation of the PV panels can be carried out for optimal performance. This can be done monthly, seasonally or yearly [3].

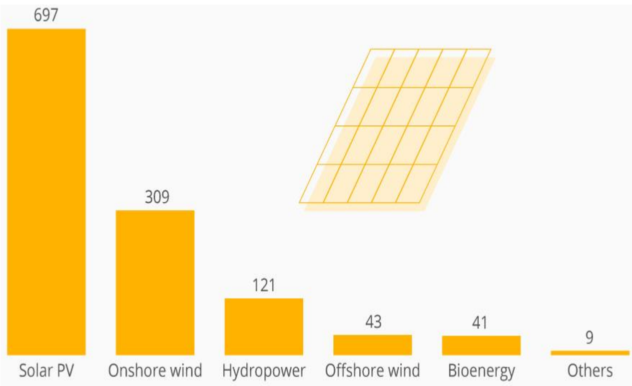

Figure 1: Global renewable capacity growth estimates between 2019 and 2024. [4]

It is therefore crucial to establish and maintain a solar panel's optimal tilt angle to guarantee highest energy generation. For finding the optimal tilt angle for a particular area, its latitude, climate condition, solar radiation characteristics, and utilization period plays an important role [5]. This work identifies optimal angles for the south – south and south east states in Nigeria noting the amount of solar irradiation obtainable at each city at these angles as well as estimating the deficit solar irradiation when PV modules are mounted on a horizontal plane.

Several research work has been conducted to find the optimal tilt angle. Jacobson and Jadhay [6] utilized a PV watts calculator to find solar panel output by varying tilt angle using the National renewable energy laboratory (NREL) PV watts calculator/global GATOR (Gas, Aerosol, Transport, Radiation) – GCMOM (General-Circulation, Mesoscale, and Ocean Model) meteorological station data for several countries around the world. Equation of optimal tilt angle as function of latitude as formulated. Ozbay et al [7] investigated the setting of PV panel manually at various angles and then this data is fed to the controller that calculates the output power and current in order to ascertain the optimal tilt angle using Raspberry pie microcontroller and python programming/real time data for BIlicek city, Turkey.

Kaddoura et al [8] formulated a MATLAB code in which solar radiation data from NASA is used as input which optimize tilt angle according to solar radiation for different cities in Saudi Arabia. Ashraf and Attia [9] computed the optimal PV tilt angle through an all-inclusive simulations carried out by starting from varying the tilt angle daily and then using one fixed tilt angle throughout the year. Their studies showed that adjusting the angle of tilt two times yearly at the computed optimal angles gives optimal results when compared to adjusting the panels daily. Zamora [10] studied the tilt angles in areas with low latitudes.

Agrawal et al [11] researched on means of increasing solar radiation by 18.4% for locations near the equator with focus on tilt angles. Liu [12] calculated the tilt angles in China using measured data. Umunnakwe [13] researched on the optimal tilt angle for a location in Egypt and found the angle to be 23.2° in Sharm El-Sheikkh, Egypt. Similarly, Karinka and Upadhyaya [14] computed the tilt angle and found that not changing the tilt angle monthly resulted in a 12.0% energy loss. Xu et al [15] proposed a way to find the optimal tilt angle in hilly areas, while Yadav et al [16] suggested a method for finding the optimal tilt angle when there are shadows from houses. Similar research on hilly locations can be found in [17 – 19]. Morad et al [20] used the Bernard-Menguy-Schwartz model to formulate a tilt angle model and is programmed using the EES (engineering equation solver) for different cities in Iraq.

The EES software used consist the programming structures of C and FORTRAN. In Nfaoui and El-Hami [21], MATLAB code is used to estimate the totality of the solar radiation on any inclined surface, from which optimal angle under which the maximum energy could be absorbed by the solar cells has been determined using MATLAB/ NASA data for Settat city in Morocco. In Salari et al [22], a MATLAB code was also developed to calculate the monthly average daily total solar radiation on a surface. The developed program calculates the optimum slope angles which correspond to the maximum amount of received irradiation for Yazd, Iran using Iranian Meteorological Organization total solar radiation data for the period of 1983–2012. Small solar panels were installed at various tilt angles and output power of the panels were

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calculated and confirmed through a solar radiation model.

From the experimental data, a second-order polynomial equation was determined to calculate the optimal tilt angle for Kitakyushu, Japan in Shu et al [23]. [24 – 25] used mathematical analysis to determine the optimal tilt angle for solar panels in Malaysia and Bangladesh on a monthly basis. The optimal tilt angle in Malaysia ranged from -17.16 degrees to 29.74 degrees. Experimental data from 2002 – 2003 was obtained from four (4) solar panels and radiation data from various weather stations, new energy and industrial technology development organization (NEDO) is utilized. The annual solar insolation on a fixed tilted surface was obtained in each location in the various cities in South Africa for all the feasible combinations of collector tilt angles. Confirmation is done using real time data from SolTrace software, pyranometers and pyrheliometers were used to obtain data in real time [26].

A mathematical model was used in [27] for estimating the total (global) solar radiation on a tilted surface in Brunei, Darussalam. Comparison between mathematical model and simulation was done. Meteorological Department, Ministry of Communications, Brunei Darussalam. Just as in Yakup et al [27], a mathematical model was also used in Tang and Wu [28]. The Collares-Pereira and Rabl model was used for the estimation of diffuse-radiation, Klein and Hamilton model used for *R*b and *R*d using meteorological data for different cities in China. HOMER software was used in Sinha and Chandel [29] to calculate the global radiation on a photovoltaic panel using Hay, Davies, Klucher, and Reindl model which is used to calculate the optimal tilt angle. HOMER software was used and their data information obtained from weathering station in Hamirpur, NASA data from HOMER for Different sites in India was also used.

In Nigeria, limited studies has been conducted in this aspect. Also, no studies on determining the optimal tilt angle in Nigeria using PVGIS has been conducted. As such, this study can be considered to be novel with respect to the stated geographical zones. Few of the research works include determining the tilt angle for Enugu by Udoakah and Okpura [30] using a matlab program while Bala et. al [31] determined the tilt angle for Kano using two developed computer programs. Even when studies were conducted for some selected cities in Nigeria Ayodele et. al using mathematical equations, there has been no experimental validation to verify these claims. Generally, from the reviewed literatures, determining the optimal tilt angle was achieved either through mathematical computation or from a variety of softwares. In this work, we explore the potency of the PVGIS which was developed and is maintained by the Joint Research Centre (JRC) to investigate the optimal photovoltaic tilt angle in South – South and South – East Nigeria. Experiments are also conducted to validate the results obtained. The specific objectives are:

1. Analyze the data obtained from the PVGIS data base
2. Using the data in (1) above to determine the optimal tilt angles of PV panel installation.
3. Experimental validation of the angles in (2) above using solar panels.

A major contribution to knowledge from this study is the provision of technical recommendations of the optimal tilt angle schedule of panels for the South - South and South – East region of Nigeria which is possible to implement.

2.0 MATERIALS AND METHODS

2.1 Materials

The materials used in this study include the following;

Figure 2: Snap shot of the PVGIS system

2.1.1 The photovoltaic geographic information system (PVGIS)

The PVGIS is a map-based inventory of solar energy resources and assessment of the electricity generation from photovoltaic systems in Europe, Africa and southwest Asia as seen in Figure 2 [32-36]. Estimation of solar system performance can be carried out for any geographical location in the investigation area. The PVGIS irradiations considered in this work are the horizontal irradiation which is the monthly sum of the solar radiation energy that hits one square meter of a horizontal plane, measured in kWh/m^2; the global irradiation (optimal angle) which is the monthly sum of the solar radiation energy that hits one square meter of a plane facing in the direction of the equator, at the inclination angle that gives the highest annual irradiation, measured in kWh/m^2; and the global irradiation (selected angle) which is the monthly sum of the solar radiation energy that hits one square meter of a plane facing in the direction of the equator, at the inclination angle chosen by the user, measured in kWh/m^2 [37-41].

PVGIS calculates the direct, diffuse, and reflected components of clear-sky and real-sky global irradiance and/or irradiation for horizontal or inclined surfaces. It computes the total daily irradiation by integrating the irradiance values calculated at 15-minute intervals from sunrise to sunset, accounting for sky obstruction by local terrain features. The database is computed in three steps:

1. Computation of clear-sky global irradiation on a horizontal surface.
2. Calculation and spatial interpolation of the clear-sky index and computation of maps of global irradiation on a horizontal surface, and
3. Deriving the diffuse and beam components of the clear-sky index and computation of maps of global irradiation on inclined surfaces.

The calculator can suggest the optimal inclination /orientation of PV modules to maximize electricity production within a year, considering shadowing effects of neighboring terrain features. This, unquestionably is a powerful tool for solar power systems [42-44].

2.1.2 PV panels

The setup consisted of five solar panels inclined at different angles including the optimal angle obtained from PVGIS. Polycrystalline PV modules are used. The electrical power output of a solar PV panel is given in equation (1) as:

$$P = cf\left(\frac{g_t}{g_{t,stc}}\right)\left[1 + \gamma\left(t_c - t_{c,stc}\right)\right] \quad (1)$$

Where, c is rated capacity of the PV panel; f is PV panel derating factor; g_t is instantaneous radiation on the PV panel (kW m^{-2}); $g_{t,stc}$ is radiation on the PV panel at standard test condition (stc) (1 kW m^{-2}); γ is temperature coefficient of power (%/°C); t_c is instantaneous cell temperature (°C); $t_{c,stc}$ is cell temperature at stc (°C).

2.1.3 Digital ammeter and voltmeter

This is used to measure the current and voltage generated from the solar panels.

2.2 Methods

1. Determine the latitude and longitude of the state capitals of the various states under consideration. The state capitals were chosen for ease of carrying out experiments which includes accessibility of panels and other equipments. The states and their capitals are shown in Table 1 and Table 2.
2. Simulate the effect of varying tilt angles on the PVGIS software. The value of the tilt angle was changed from 0 to 90 degrees (with increments of 1 degree) to examine the system performance with various tilt angles.
3. Using the data obtained to determine the optimum tilt angle for the selected location.
4. Perform physical experiments using solar panels to validate the simulation results. Here, the energy generated from five PV panels each rated 10Watts inclined at five different angles including the optimal angle obtained from the PVGIS system is obtained. The data (measured current and voltage) was collected at an hourly basis from October 2021 to October 2022.

The energy obtained from the solar panels (E_p) per month is given in equation (2) as:

$$Ep = Power\ obtained\ (IV)\ x\ duration\ of\ sunshine\ x\ number\ of\ days \quad (2)$$

3.0 RESULTS AND DISCUSSION

3.1 PVGIS Results for the South – South Zone

Table 1: Optimal angles of South – South cities obtained from PVGIS

States	City(Capitals)	Latitude	Longitude	Optimal Angle
Rivers	Port Harcourt	4.8156° N	7.0498° E	11^0
Bayelsa	Yenagoa	4.9212° N	6.2748° E	12^0
Edo	Benin City	6.3350° N	5.6037° E	11^0
Cross-River	Calabar	4.9757° N	8.3417° E	10^0
Delta	Asaba	6.2059° N	6.6959° E	11^0
Akwa-Ibom	Uyo	5.0377° N	7.9128° E	10^0

Table 1 shows the tilt angles of the various South – South States in Nigeria under consideration at which solar energy can be optimally harnessed.

In Figure 3a, the irradiation on the horizontal and optimal planes, as well as a plane inclined at 45 degrees in Port Harcourt is shown. As observed in Figure 3a, from March to November, installing solar panels at 45 degrees is not optimal. However, an angle of 45 degrees shows highest irradiation levels of 222.76kWh/m2 for January and 201.13kWh/m2 for December and lowest value of 69.97kWh/m2 in November. The optimal inclination of 11 degree gives the highest value of 213.5kWh/m2 in January and a lowest value of 96.45kWh/m2 in July. Figure 3b show that 11° optimal angle produces the highest annual solar irradiance of 1756kWh/m2 while an angle of 45 degree produces 1469kWh/m2 of solar irradiance annually.

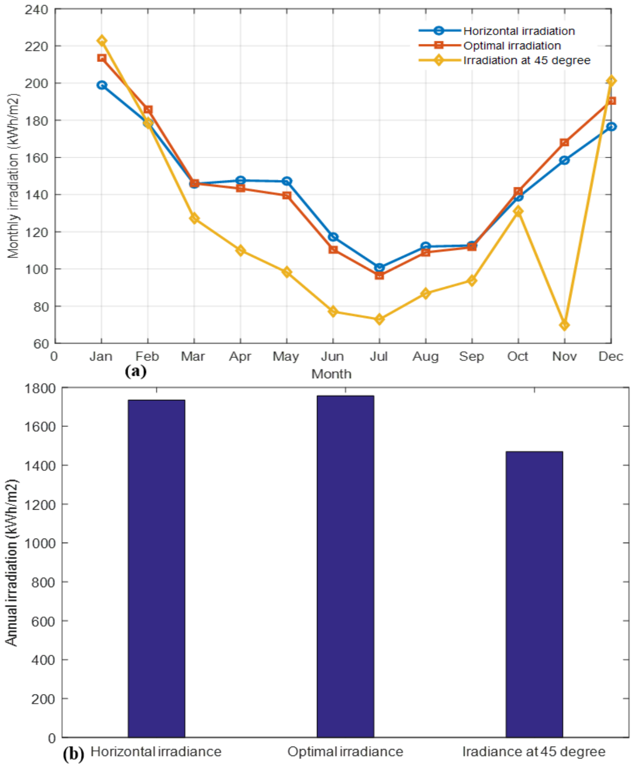

Figure 3: (a) Monthly irradiation on the horizontal plane, optimally inclined plane and plane at angle 45° in Port Harcourt, (b) annual horizontal, optimal and irradiance at 45° tilt angle in Port Harcourt

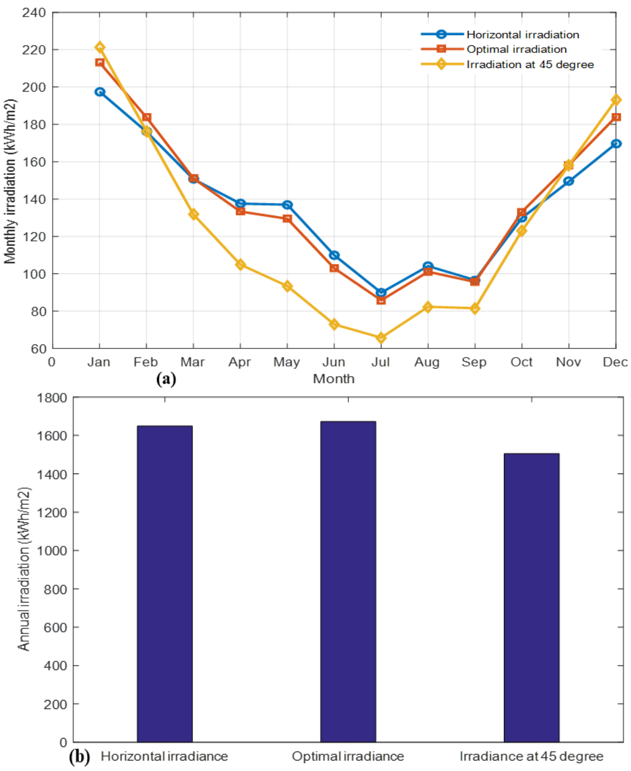

Figure 4: (a) Monthly irradiation on the horizontal plane, optimally inclined plane and plane at angle 45° in Yenagoa, (b) annual horizontal, optimal and irradiance at 45° tilt angle in Yenagoa

Figure 4a shows the irradiation on the horizontal and optimal planes, as well as a pane inclined at 45 degrees in Yenagoa. As observed in figure 4b, from March to September, installing solar panels at 45 degrees is not optimal. However, an angle of 45 degrees shows highest irradiation levels of 221.14kWh/m2 for January and 193.06kWh/m2 for December and lowest value of 65.767kWh/m2 in July. The optimal inclination of 12 degree gives the highest value of 213.12kWh/m2 in January and a lowest value of 85.81kWh/m2 in July. Figure 4b show that 12 degree optimal angle produces the highest annual solar irradiance of 1671.62kWh/m2 while an angle of 45 degree produces 1504.68kWh/m2 of solar irradiance annually.

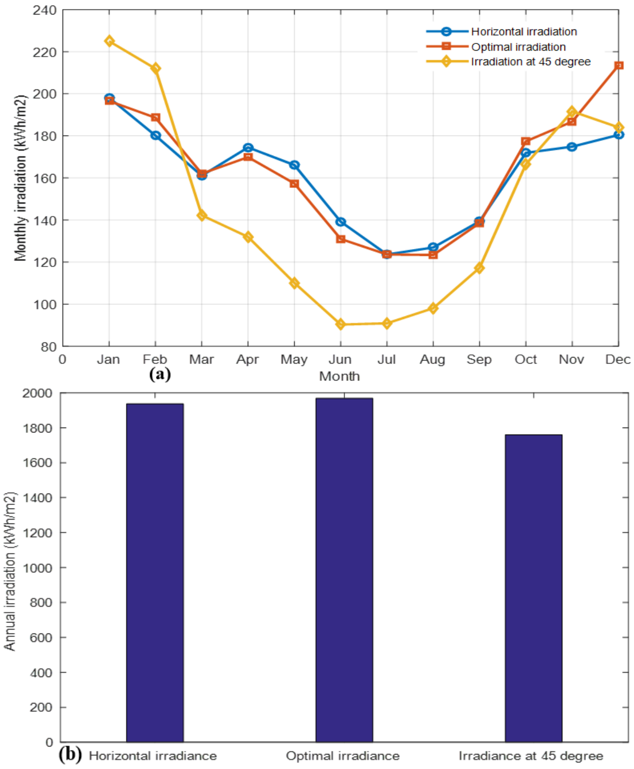

Figure 5: (a) Monthly irradiation on the horizontal plane, optimally inclined plane and plane at angle 45° in Benin City, (b) annual horizontal, optimal and irradiance at 45° tilt angle in Benin City

For Benin City, Figure 5a and 5b shows the irradiation on the horizontal and optimal planes, as well as a pane inclined at 45 degrees. As observed in figure 5a, from March to September, installing solar panels at 45 degrees is not optimal. However, an angle of 45 degrees shows highest irradiation levels of 224.9kWh/m2 for January and 211.93kWh/m2 for February and lowest value of 90.28kWh/m2 in June. The optimal inclination of 11 degree gives the highest value of 213.51kWh/m2 in December and a lowest value of 123.38kWh/m2 in August. Figure 5b show that 11 degree optimal angle produces the highest annual solar irradiance of 1968.64kWh/m2 while an angle of 45 degree produces 1759.86kWh/m2 of solar irradiance annually.

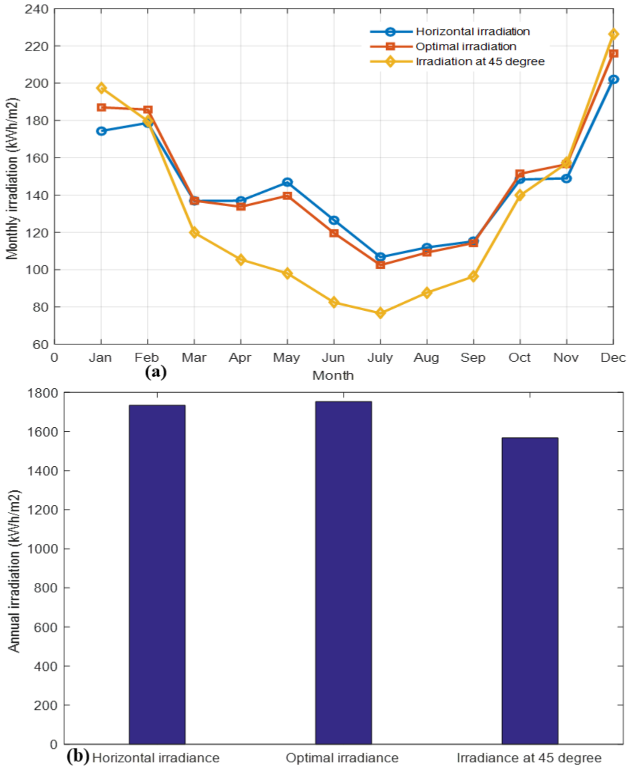

Figure 6: (a) Monthly irradiation on the horizontal plane, optimally inclined plane and plane at angle 45° in Calabar, (b) annual horizontal, optimal and irradiance at 45° tilt angle in Calabar

As observed in Figure 6a, from March to September, installing solar panels at 45 degrees is not optimal in Calabar. However, an angle of 45 degrees shows highest irradiation levels of 197.53kWh/m2 for January and 226.16kWh/m2 for December and lowest value of 76.59kWh/m2 in July. The optimal inclination of 10 degree gives the highest value of 216.07kWh/m2 in December and a lowest value of 102.44kWh/m2 in July. Figure 6b show that 10 degree optimal angle produces the highest annual solar irradiance of 1752.81kWh/m2 while an angle of 45 degree produces 1566.75kWh/m2 of solar irradiance annually.

In Asaba, from March to September, installing solar panels at 45 degrees is not optimal. This is shown in Figure 7a. However, an angle of 45 degrees shows highest irradiation levels of 213.79kWh/m2 for January and 232.41kWh/m2 for December and lowest value of 92.61kWh/m2 in June. The optimal inclination of 10 degree gives the highest value of 220.05kWh/m2 in December and a lowest value of 129.88kWh/m2 in June. Figure 7b show that 10 degree optimal angle produces the highest annual solar irradiance of 2006.83kWh/m2 while an angle of 45 degree produces 1790.47kWh/m2 of solar irradiance annually.

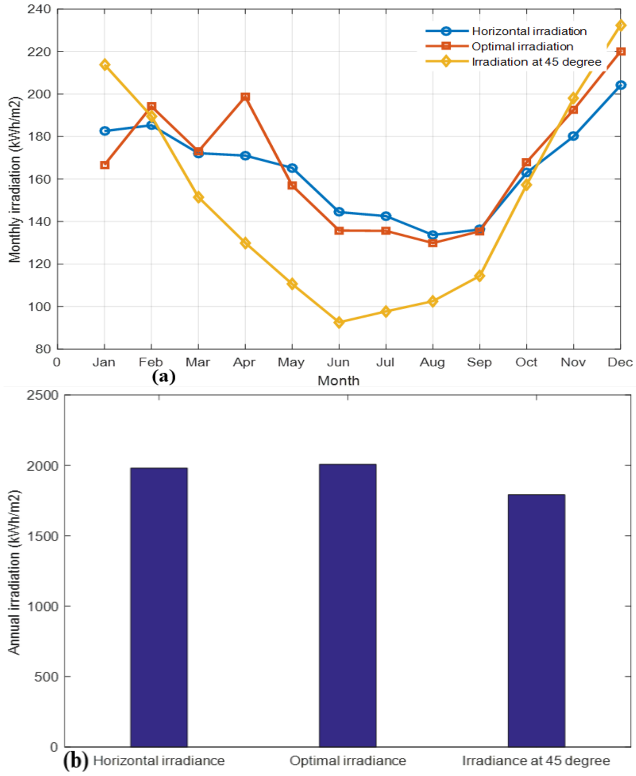

Figure 7: (a) Monthly irradiation on the horizontal plane, optimally inclined plane and plane at angle 45° in Asaba, (b) annual horizontal, optimal and irradiance at 45° tilt angle in Asaba

For Uyo, as observed in Figure 8a, from March to September, installing solar panels at 45 degrees is not optimal. However, an angle of 45 degrees shows highest irradiation levels of 236.8kWh/m2 for January and 212.26kWh/m2 for December and lowest value of 89.97kWh/m2 in July. The optimal inclination of 11 degree gives the highest value of 224.43kWh/m2 in January and a lowest value of 124.89kWh/m2 in July. Figure 8b show that 10 degree optimal angle produces the highest annual solar irradiance of 2000.25kWh/m2 while an angle of 45 degree produces 1773.19 kWh/m2 of solar irradiance annually.

Figure 9a shows the annual unused solar irradiance when solar panels are installed in 45 degree plane when compared with the optimal planes for the respective cities. Port Harcourt has the highest with 286.62kWh/m2 of untapped potential while Yenagoa recorded the lowest with 166.94kWh/m2 of unused irradiance. Figure 9b shows the annual unused solar irradiance when solar panels are installed horizontally when compared with the optimal planes for the respective cities. Benin City has the highest with 32.42kWh/m2 of untapped potential while Calabar recorded the lowest with 19.34kWh/m2 of unused irradiance.

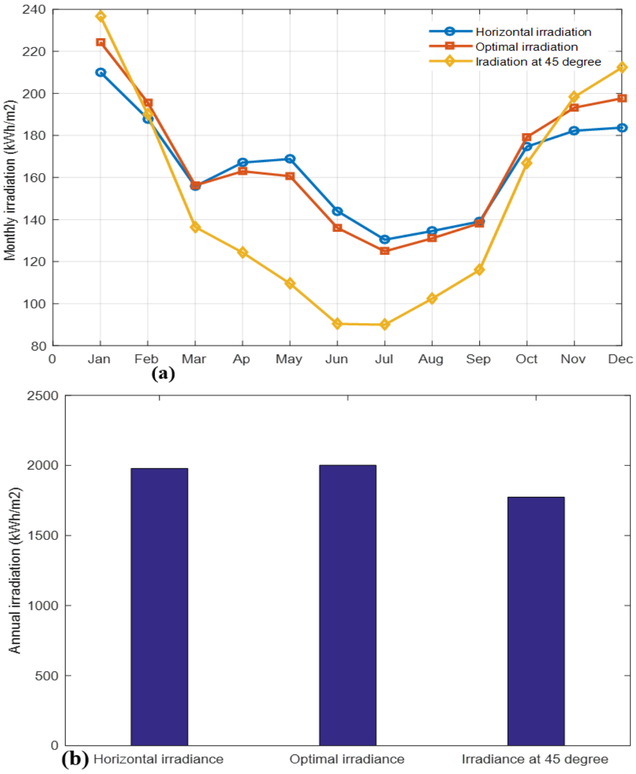

Figure 8: (a) Monthly irradiation on the horizontal plane, optimally inclined plane and plane at angle 45° in Uyo, (b) annual horizontal, optimal and irradiance at 45° tilt angle in Uyo

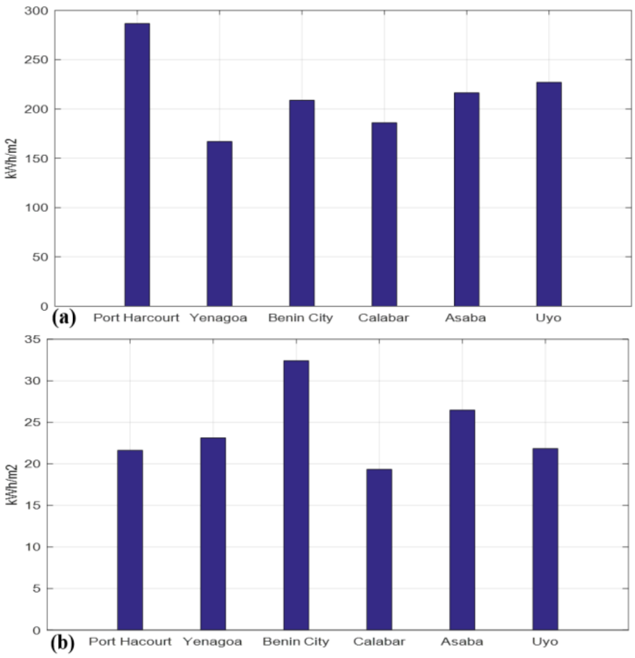

Figure 9: Annual unused solar radiation in South – South Nigeria when panels are installed at (a) 45°, (b) horizontal plane (0 degree)

3.2 PVGIS Results for the South – East Zone

Table 2: Optimal angles of South – East cities obtained from PVGIS

States	City(Capitals)	Latitude	Longitude	Optimal Angle
Abia	Umuahia	5.5250° N	7.4922° E	10^0
Anambra	Awka	6.2220° N	7.0821° E	11^0
Enugu	Enugu	6.4584° N	7.5464° E	12^0
Imo	Owerri	5.4891° N	7.0176° E	10^0
Ebonyi	Abakaliki	6.3231° N	8.1120° E	11^0

Table 2 shows the tilt angles of the various South – East States in Nigeria under consideration at which solar energy can be optimally harnessed.

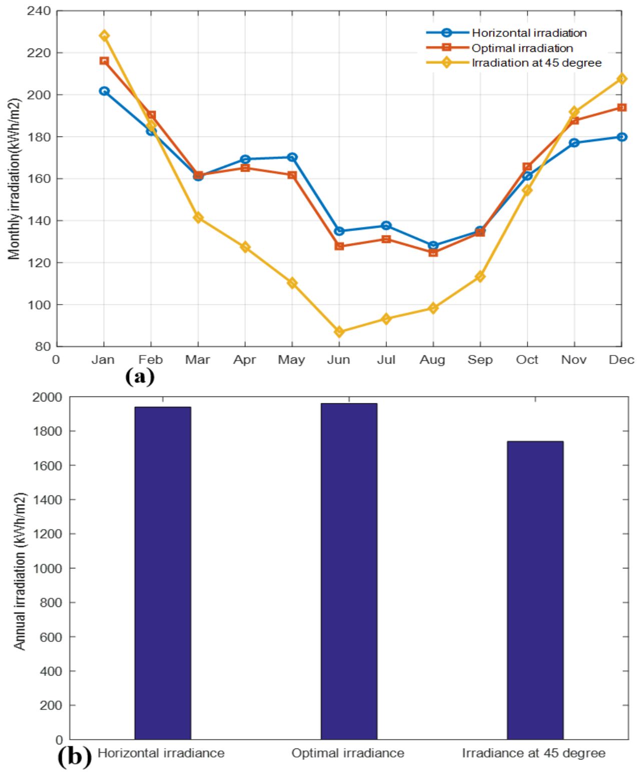

Figure 10: (a) Monthly irradiation on the horizontal plane, optimally inclined plane and plane at angle 45° in Umuahia, (b) annual horizontal, optimal and irradiance at 45° tilt angle in Umuahia

Figure 10a, from March to September, installing solar panels at 45 degrees is not optimal in Umuahia. However, 15, angle of 45 degrees shows highest irradiation levels of 228.13kWh/m2 for January and 207.71kWh/m2 for December and lowest value of 86.99kWh/m2 in June. The optimal inclination of 10 degree gives the highest value of 216.15kWh/m2 in January and a lowest value of 124.82kWh/m2 in August. Figure 10b show that 10 degree optimal angle produces the highest annual solar irradiance of 1960.76kWh/m2 while an angle of 45 degree produces 1738.65kWh/m2 of solar irradiance annually.

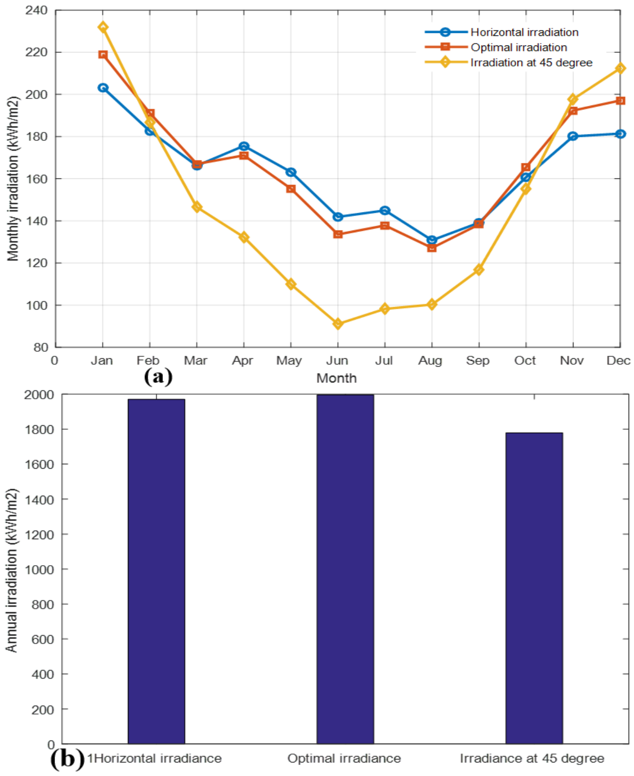

Figure 11: (a) Monthly irradiation on the horizontal plane, optimally inclined plane and plane at angle 45° in Awka, (b) annual horizontal, optimal and irradiance at 45° tilt angle in Awka

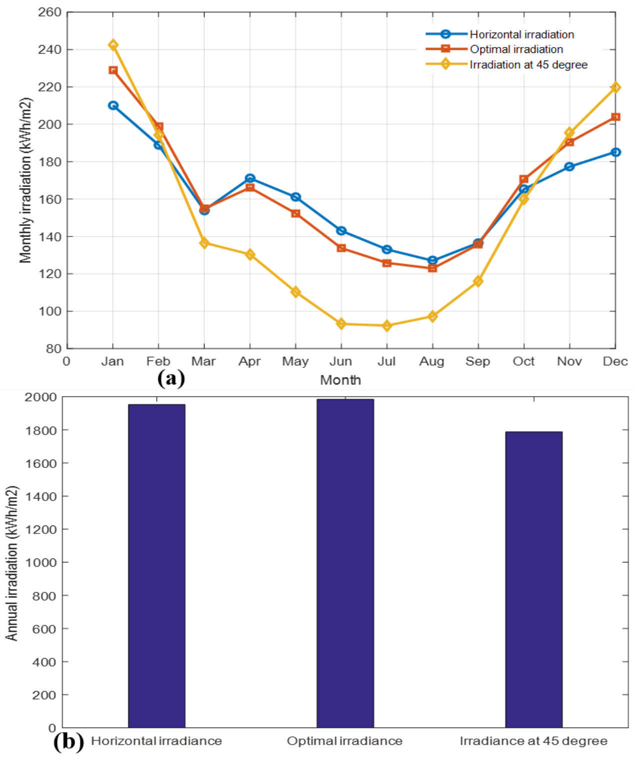

Figure 12: (a) Monthly irradiation on the horizontal plane, optimally inclined plane and plane at angle 45° in Enugu, (b) annual horizontal, optimal and irradiance at 45° tilt angle in Enugu

In Figure 11a, it can be observed that from March to September, installing solar panels at 45 degrees is not optimal. However, an angle of 45 degrees shows highest irradiation levels of 231.81kWh/m2 for January and 212.35kWh/m2 for December and lowest value of 91.08kWh/m2 in June. The optimal inclination of 11 degree gives the highest value of 219.06kWh/m2 in January and a lowest value of 127.17kWh/m2 in August. Figure 11b show that 11 degree optimal angle produces the highest annual solar irradiance of 1995.46kWh/m2 while an angle of 45 degree produces 1778.87kWh/m2 of solar irradiance annually.

Figure 12a shows that from March to September, installing solar panels at 45 degrees is not optimal in Enugu. However, an angle of 45 degrees shows highest irradiation levels of 242.45kWh/m2 for January and 219.56kWh/m2 for December and lowest value of 92.31kWh/m2 in July. The optimal inclination of 12 degree gives the highest value of 229.13kWh/m2 in January and a lowest value of 122.87kWh/m2 in August. Figure 12b show that 12 degree optimal angle produces the highest annual solar irradiance of 1984.58kWh/m2 while an angle of 45 degree produces 1787.51kWh/m2 of solar irradiance annually.

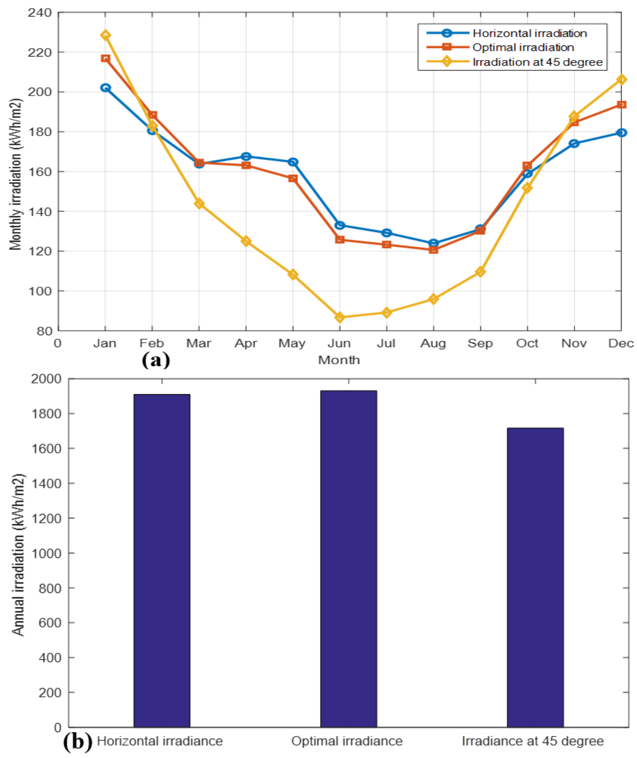

Figure 13: (a) Monthly irradiation on the horizontal plane, optimally inclined plane and plane at angle 45°

in Owerri, (b) annual horizontal, optimal and irradiance at 45° tilt angle in Owerri

In Owerri, from March to September, installing solar panels at 45 degrees is not optimal. This is shown in Figure 13a. However, an angle of 45 degrees shows highest irradiation levels of 228.48kWh/m2 for January and 206.39kWh/m2 for December and lowest value of 86.73kWh/m2 in June. The optimal inclination of 10 degree gives the highest value of 216.93kWh/m2 in January and a lowest value of 120.64kWh/m2 in August. Figure 13b show that 10 degree optimal angle produces the highest annual solar irradiance of 1930.69kWh/m2 while an angle of 45 degree produces 1716.15kWh/m2 of solar irradiance annually.

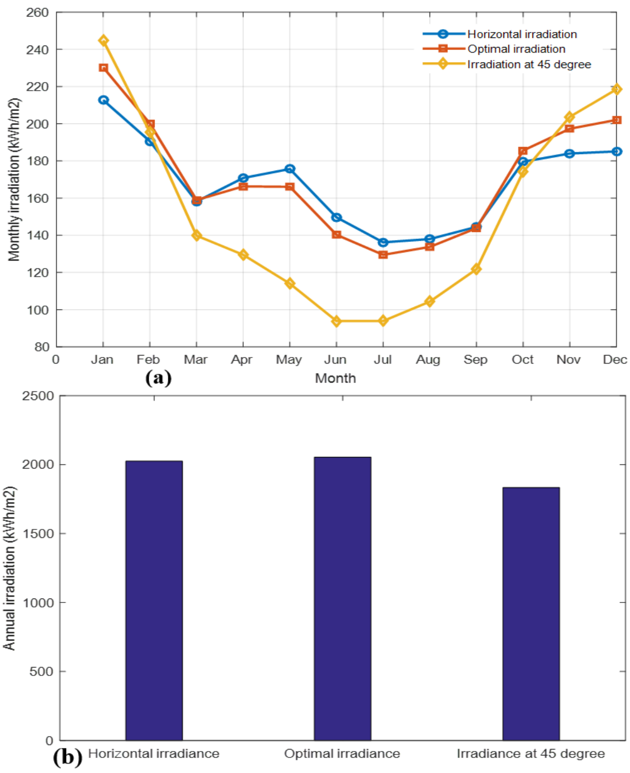

Figure 14: (a) Monthly irradiation on the horizontal plane, optimally inclined plane and plane at angle 45° in Abakiliki, (b) annual horizontal, optimal and irradiance at 45° tilt angle in Abakiliki

In Abakaliki, as observed in Figure 14a, from March to September, installing solar panels at 45 degrees is not optimal. However, an angle of 45 degrees shows highest irradiation levels of 244.78kWh/m2 for January and 218.5kWh/m2 for December and lowest value of 93.87kWh/m2 in June. The inclination of 11 degree gives the highest value of 230.3kWh/m2 in January and a lowest value of 129.48kWh/m2 in July. Figure 14b show that 11 degree optimal angle produces the highest annual solar irradiance of 2054kWh/m2 while an angle of 45 degree produces 1833.84kWh/m2 of solar irradiance annually.

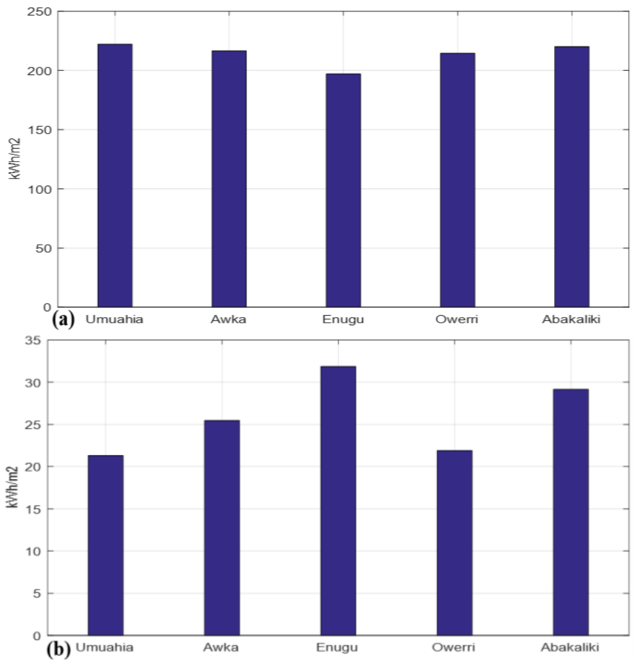

Figure 15: Annual unused solar radiation in South – East Nigeria when panels are installed at (a) 45°, (b) the horizontal plane (0°)

Figure 15a shows the annual unused solar irradiance when solar panels are installed in 45 degree plane when compared with the optimal planes for the respective cities. Umuahia has the highest with 222.11kWh/m^2 of untapped potential while Enugu recorded the lowest with 197.07kWh/m^2 of unused irradiance. In Figure 15b, the unused solar irradiance when solar panels are installed horizontally when compared with the optimal planes for the respective cities show that Enugu has the highest value of 31.86kWh/m^2 of untapped potential while Umuahia recorded the lowest with 21.31kWh/m^2 of unused irradiance.

3.3 Experimental Results

3.3.1 South – south

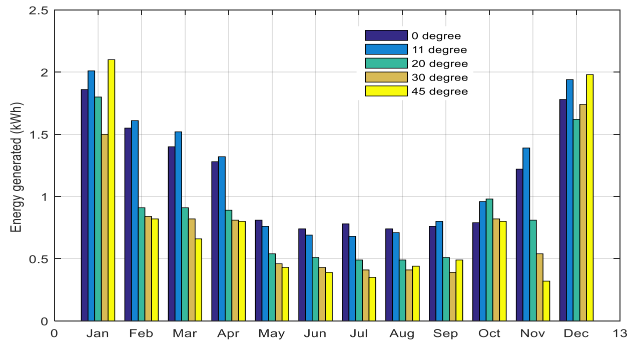

Figure 16: Experimental data of energy generated (kWh) from South – South (Port - Harcourt)

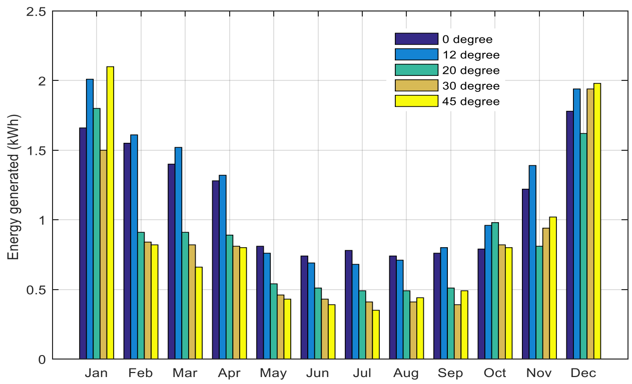

Figure 17: Experimental data of energy generated (kWh) from South – South (Yenagoa)

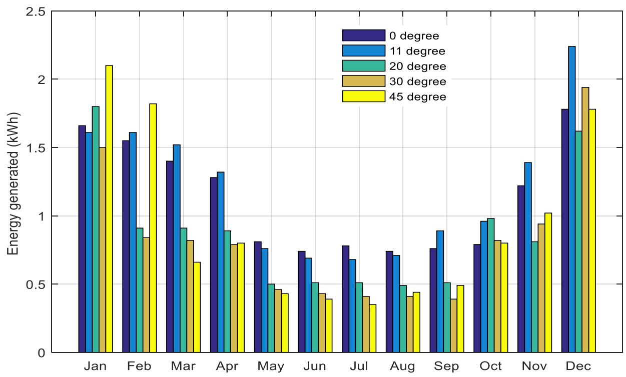

Figure 18: Experimental data of energy generated (kWh) from South – South (Benin city)

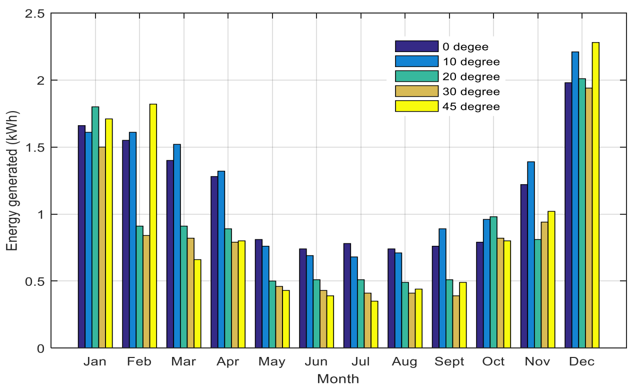

Figure 19: Experimental data of energy generated (kWh) from South – South (Calabar)

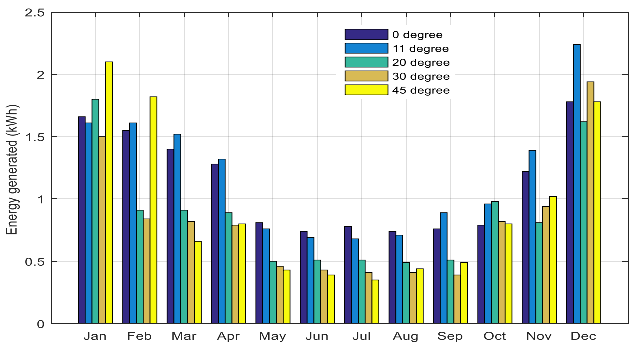

Figure 20: Experimental data of energy generated (kWh) from South – South (Asaba)

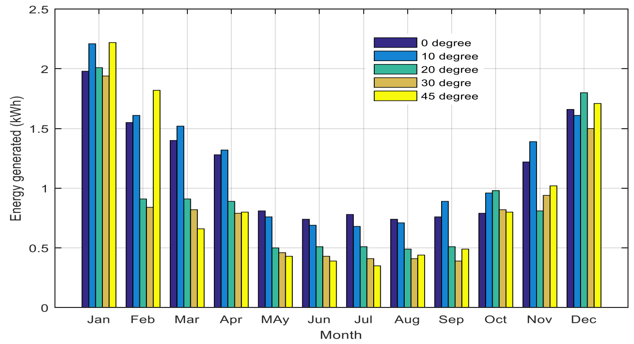

Figure 21: Experimental data of energy generated (kWh) from South – South (Uyo)

Figures 16 – 21 shows the results of the experiments conducted in the South – South zone. It was observed that the yearly (annual) optimal tilt angle obtained from the experiments corresponds with the annual tilt angle obtained from PVGIS when each component of the months were added for the various months within the year. It can also be seen that the optimal tilt angles obtained from PVGIS for the respective cities (11° for Port Harcourt, 12° for Yenagoa, 11° for Benin City, 10° for Calabar, 11° for Asaba and 10° for Uyo) is suitable from January to April and September to December while the horizontal plane (0°) is suitable from May to August.

3.3.2 South – east

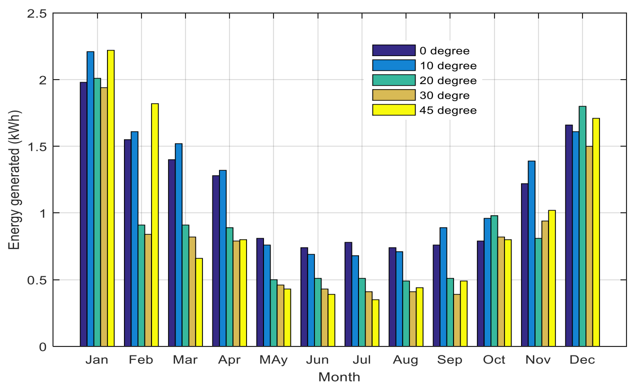

Figure 22: Experimental data of energy generated (kWh) from South – East (Umuahia)

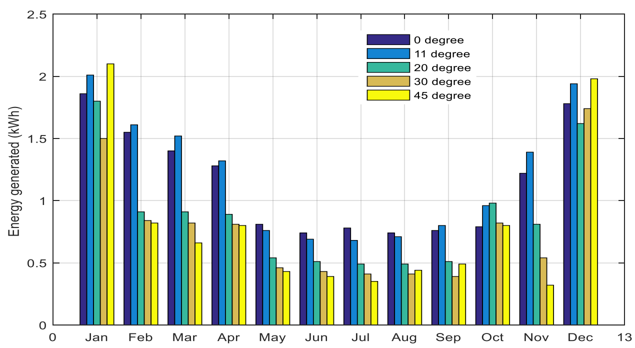

Figure 23: Experimental data of energy generated (kWh) from South – East (Awka)

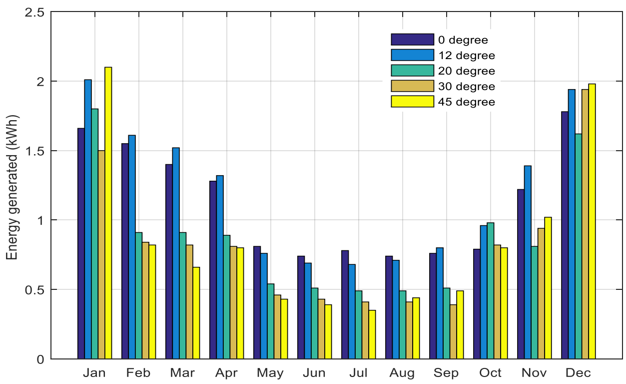

Figure 24: Experimental data of energy generated (kWh) from South – East (Enugu)

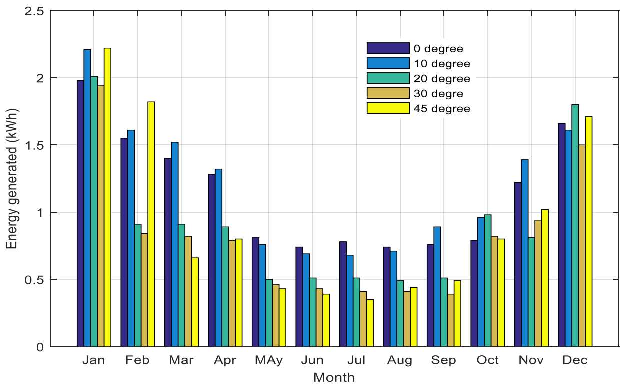

Figure 25: Experimental data of energy generated (kWh) from South – East (Owerri)

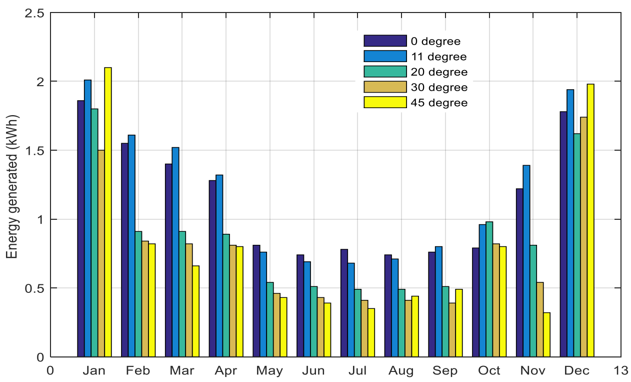

Figure 26: Experimental data of energy generated (kWh) from South – East (Abakaliki)

Similarly Figures 22 – 26 shows that the optimal tilt angles obtained from PVGIS for the respective cities (10^o for Umuahia, 11^o for Awka, 12^o for Enugu, 10^o for Owerri, and 11^o for Abakaliki) is suitable from January to April and September to December while the horizontal plane (0^o) is suitable from May to August.

4.0 CONCLUSION

In conclusion, we investigated the optimal photovoltaic tilt angle for the South – South and South – Eastern States in Nigeria. We obtained the yearly optimal tilt angle for the various states using the PVGIS. With the aid of experiments conducted using five 10Watts solar panels oriented at different angles, the monthly optimal tilt angle was obtained and shown graphically. The experimental results validated the results obtained from PVGIS (yearly optimal angle). Finally, recommendations for installing solar panels are given as:

1. For the South –South, 11^o for Port Harcourt, 12^o for Yenagoa, 11^o for Benin City, 10^o for Calabar, 11^o for Asaba and 10^o for Uyo is suitable from January to April and September to December while the horizontal plane (0^o) is suitable from May to August.
2. For the South –East, 10^o for Umuahia, 11^o for Awka, 12^o for Enugu, 10^o for Owerri, and 11^o for Abakaliki) is suitable from January to April and September to December while the horizontal plane (0^o) is suitable from May to August.

When panels are not installed optimally, the untapped solar irradiance can be as high as 286.62kWh/m^2 and 222.11kWh/m^2 as recorded in Port Harcourt and Umuahia respectively. Installing PV panels at the optimal tilt angle can improve the efficiency of solar energy generation, making it more cost-effective by maximizing the total amount of diffused and direct radiation. This leads to an increase in energy yield from the PV system and also helps in minimizing the effects of shading and dirt accumulation on the panels. By improving the efficiency of solar energy generation through the use of optimal tilt angles, Nigeria can further reduce reliance on non-renewable sources of energy and reduce carbon emissions. We recommend studies on optimal tilt angle determination to be extended to the states in all geographical zones in Nigeria. Also, the effect of the azimuth in the optimal orientation of PV panels in all the zones should be considered.

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REFERENCES

[1] Lanjewar, B. A., Wakchaure, N. S., Tete, P. R., and Joshi, S. S. "Determination of Optimum Tilt Angle of Solar Collectors for Solar Cities in Maharashtra", *India Tech-Chronicle*, 2016; 26, 94.

[2] Mamun, M., Sarkar, M., Parvez, M., Nahar, M., and Rana, M. "Determining the optimum

tilt angle and orientation for photovoltaic (PV) systems in Bangladesh", in: *Proceedings of the 2nd International Conference on Electrical & Electronic Engineering (ICEEE)*, IEEE, 2017, pp. 1–4

[3] Ayodele, T. R., Ogunjuyigbe, A. S., and Oladeji, S. "Determination of optimal tilt angles in some selected cities of Nigeria for maximum extractable solar energy", *Int. J. Renewable Energy Technology*, 2018; Vol. 9, No. 4

[4] IEA. "Market analysis and forecast", [https://ww w.iea.org/reports/renewables-2019](https://www.iea.org/reports/renewables-2019); Accessed 14th February, 2022

[5] Akhlaghi, S., Sangrody, H., Sarailoo, M., and Rezaeiahari, M. "Efficient operation of residential solar panels with determination of the optimal tilt angle and optimal intervals based on forecasting model", *Power Gener.*, 2017; 11, 1261.

[6] Jacobson, M. Z., and Jadhav. "World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels", *Sol. Energy*, 169, 55.

[7] Ozbay, H., Karafil, A., Onal, Y., and Kesler, H. "The Monitoring of Monthly, Seasonal and Yearly Optimum Tilt Angles by Raspberry Pi Card for Bilecik City, Turkey", *Energy Procedia*, 2017; 113, 311.

[8] Kaddoura, T., Ramli, M., and Al-Turki, Y. "On the estimation of the optimum tilt angle of PV panel in Saudi Arabia", *Renewable Sustainable Energy Rev.*, 2016; 65, 626.

[9] Ashraf, K. and Attia, E. "Estimation of optimal tilt angles for photovoltaic panels in Egypt with experimental verifications", *Nature*, 2023; [https:/ /doi.org/10.1038/s41598-023-30375-8](https://doi.org/10.1038/s41598-023-30375-8)

[10] Zamora, N. M. R. "Optimal tilt angle for solar photovoltaic modules on pitched rooftops: A case of low latitude equatorial region", *Sustain. Energy Technol. Assess.*, 2022; **50**, 101821. https:// doi. org/ 10. 1016/j. seta. 2021. 101821.

[11] Agrawal, M., Chhajed, P., and Chowdhury, A. "Performance analysis of photovoltaic module with reflector: Optimizing orientation with different tilt scenarios", *Renew. Energy*, 2022; **186**, 10–25. https:// doi. org/ 10. 1016/j. renene. 2021. 12. 149.

[12] Liu, Y. "Spatial estimation of the optimum PV tilt angles in China by incorporating ground with satellite data", *Renew. Energy*, 2022; **189**, 1249–1258. https:// doi. org/ 10. 1016/j. renene. 2022. 03. 072.

[13] Umunnakwe, A. "Modeling and estimation of the optimal tilt angle, maximum incident solar radiation, and global radiation index of the photovoltaic system", *Heliyon*, 2022; **8**(6), e09598. https:// doi. org/ 10. 1016/j. heliy on. 2022. e09598.

[14] Karinka, S., and Upadhyaya, V. "Concept of annual solar window and simple calculation for optimal monthly tilt angle to maximize solar power generation", *Mater. Proc.*, 2022; **52**, 2166–2171. https:// doi. org/ 10. 1016/j. matpr. 2021. 12. 594.

[15] Xu, L., Long, E., Wei, J., Cheng, Z., and Zheng, H. "A new approach to determine the optimum tilt angle and orientation of solar collectors in mountainous areas with high altitude", *Energy*, 2021; **237**, 121507. https:// doi. org/ 10. 1016/j. energy. 2021. 121507.

[16] Yadav, S., Hachem-Vermette, C., Panda, S. K., Tiwari, G. N., and Mohapatraa, S. S. "Determination of optimum tilt and azimuth angle of BiSPVT system along with its performance due to shadow of adjacent buildings", *Sol. Energy*, 2021; **215**, 206–219. https:// doi. org/ 10.1016/j. solen er. 2020. 12. 033.

[17] Awasthi, A. "Solar collector tilt angle optimization for solar power plant setup-able sites at Western Himalaya and correlation formulation", *J. Thermal Anal. Calorim.*, 2022; **147**, 11417–11431. https:// doi. org/ 10. 1007/ s10973- 022- 11345-0.

[18] Sharma, A., Ali Kallioğlu, M., Chauhan, A. A. R., Fekete, G., and Singh, T. "Correlation formulation for optimum tilt angle for maximizing the solar radiation on solar collector in the Western Himalayan region", *Case Stud. Thermal Eng.*, 2021; **26**, 101185. https:// doi.org/ 10. 1016/j. csite. 2021. 101185.

[19] Mansour, R. B., MateenKhan, M. A., Alsulaiman, F. A., and Mansour, R. B. "Optimizing the solar PV tilt angle to maximize the power output: A case study for Saudi Arabia", *EEE Access*, 2021; **9**, 15914–15928. https:// doi. org/ 10. 1109/ access. 2021. 30529 33.

[20] Morad, A., Al-Sayyab, A., and Abdulwahid, A. "Optimisation of tilted angles of a photovoltaic cell to determine the maximum generated electric power: A case study of some Iraqi cities", *Case Stud. Therm. Eng.*, 2018; 12, 484.

[21] Nfaoui, M., and El-Hami, K. “Optimal tilt angle and orientation for solar photovoltaic arrays: case of Settat city in Morocco”, *Int. J. Ambient Energy*, 2018; 41, 214.

[22] Salari, M., and Javaran, E. “Optimising the tilt angle for solar surfaces using different solar irradiation models in Yazd, Iran”, *Int. J. Ambient Energy*, 2018; 39, 323.

[23] Shu, N., Kameda, N., Kishida, Y., and Sonoda, H. “Experimental and theoretical study on the optimal tilt angle of photovoltaic panels”, *J. Asian Archit. Build.Eng.*, 2006; 5, 399.

[24] Mamun, M., Islam, M., Hasanuzzaman, M., and Jeyraj, S. “Effect of tilt angle on the performance and electrical parameters of a PV module: Comparative indoor and outdoor experimental investigation”, *Energy and Built Environment*, 2022; 3, 278–290, https://doi.org/10.1016/j.enbenv.2021.02.001

[25] Khan, T., Soudagar, M., Kanchan, M., Afzal, A., Banapurmath, N., Akram, N., Mane, S., and Shahapurkar, K. “Optimum location and influence of tilt angle on perfor- mance of solar PV panels”, *J. Therm. Anal. Calorim.*, 2020; 141, 511–532

[26] Le Roux, W. G. “Optimum tilt and azimuth angles for fixed solar collectors in South Africa using measured data”, *Renewable Energy*, 2016; 96, 603.

[27] Yakup, M., and Malik, A. “Optimum tilt angle and orientation for solar collector in Brunei Darussalam”, *Renewable Energy*, 2001; 24, 223.

[28] Tang, R., and Wu, T. “Optimal tilt-angles for solar collectors used in China”, *Applied Energy*, 2004; Volume 79, Issue 3, https://doi. org/10.1016/j.apenergy.2004.01.003.

[29] Sinha, S., and Chandel, S. “Review of software tools for hybrid renewable energy systems in 2016 7th India International Conf. on Power Electronics (IICPE)”, *IEEE*, 2016; Patiala, pp. 1–6.

[30] Udoakah, Y. N., and Okpura, N. I. “Determination Of Optimal Tilt Angle For Maximum Solar Insolation For Pv Systems In Enugu-Southern Nigeria”, *Nigerian Journal Of Technology (Nijotech)*, 2015; Vol. 34 No. 4, Pp. 838 – 843

[31] Bala, A., Saidu, B. A., Nura, M. M., Al-Dadah, R. K., and Mahmoud, S. “Optimum Tilt Angle for Solar Collectors used in Kano, Nigeria”, *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 2019.

[32] Dike, V. N., Nwofor, O. K., Chineke, T. C., and Okoro, U. K. “Climate change Mitigation through decentralized solar energy option in Nigeria”, *International Science Research Journal*, 2010; 2:27e33.

[33] Huld, T. A., Suri, M., Dunlop, E. D., and Micale F. “Estimating average daytime and daily temperature profile within Europe”, *Environmental Modelling and Software*, 2006; 21(12):1650e61.

[34] Huld, T., Lri, M., Kenny, R. P., and Dunlop, E. D. “Estimating PV performance over large geographical regions”, *Proceedings of the 31st IEEE photovoltaic specialists conference and exhibition*, 2005; vol. 3.

[35] Kerry, A., Lokman, H., and Shivan, S. “Photovoltaic tilt angle optimization”, *ICREN*, 2021; https://doi.org/10.1051/e3sconf/202123900019

[36] Huld, T., Lri, M., and Dunlop, E. D. “A GIS-based system for performance of solar energy systems over large geographical regions”, *Solar 2006 conference: renewable energy*, key to climate recovery, vol. 7, 2006.

[37] IEA. “Renewables for power generations: status and prospects”, *Paris: International Energy Agency*, http://www.iea.org/textbase/nppdf/free/2000/renewpower_2003

[38] Khasawneh, Q. A., Damra, Q. A., and Bany O. H. “Determining the Optimum Tilt Angle for Solar Applications in Northern Jordan.”, *Jordan Journal of Mechanical and Industrial Engineering*, 2015; vol. 9.

[39] Chineke, T. C., and Ezike, F. M. “Political will and collaboration for electric power reform through renewable energy in Africa”, *Energy Policy*, 2010; 38:678e84.

[40] PVGIS user manual. https://joint-research-centre.ec.europa.eu/pvgis-photovoltaic-geographical-information-system/getting-started-pvgis/pvgis-user-manual_en accessed Nov, 20, 2022

[41] Rundle, J. “The renewable energies unit activities report 2005”, European Commission; 2006. Publication N_ 004517. pp 40.

[42] Hassan, Q., Abbas, M. K., Abdulateef, A. M. A. J., and Mohamad, A. “Assessment the potential solar energy with the models for optimum tilt angles of maximum solar irradiance for Iraq”, *Case Stud. Chem. Environ. Eng.*, 2021; **4**, 100140. https:// doi. org/ 10. 1016/j. cscee.2021. 100140

[43] Solar, https://www.iea.org/topics/renewables/solar/ (accessed: March 2022).

[44] Súri, M., Huld T. A., Dunlop E. D., Albuisson M., and Wald L. “Online data and tools for estimation of solar electricity in Africa: the

PVGIS approach", *Proceedings from 21st European photovoltaic solar energy conference and exhibition*, October 2006, Dresden, Germany ([preprint]).