Determination of Optimal Solar Power and Corresponding Tilted Angle in Different Geoclimatic Zones in Nigeria

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Authors’ contributions

This work was carried out in collaboration among all authors. Author AB conceptualized the study and reviewed the first draft of the manuscript. Author OO managed the analyses of the study and wrote the first draft of the manuscript. Authors OSO and EI managed the software and the data acquisition. All authors read and approved the final manuscript.

ABSTRACT

Aims: To estimate the optimum tilt angle and maximum solar power for different geoclimatic zones in Nigeria.

Methodology: In this study, the surface data of direct and diffuse solar radiations spanning 2013 to 2017 were obtained from the archives of the Modern-Era Retrospective Analysis for Research and Application for 20 stations spread across Nigeria. To study the direct relationship between the solar power on a photovoltaic panel and the solar radiation, the values of the direct, diffuse, and ground-reflected components of solar radiation were calculated for six tilt angles ranging from 15° to 90° using anisotropic models. Afterwards, the maximum values of the solar power and the corresponding tilt angles, as well as the average number of solar panels that can be used to cater for the electricity needs of households in all the geoclimatic zones, were estimated.

Results: Analyses showed that the maximum solar power was received at tilt angles of 30° and 45° from October till February, and tilt angles of 15° and 30° from March till September in all the study

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1. INTRODUCTION

Electricity is the most important factor that enhances the economic growth and development of any nation. It facilitates the provision of basic needs, including food, essential health services (vaccines, intensive care, and emergency), educational aids, communication, and transport [1]. It is also the mainstay of economic activities, including agriculture, commerce, manufacturing, aviation, and mining. The advanced nations of the world have enjoyed unprecedented growth due to their knowledge about how to harness energy [2]. The power supply in Nigeria is mainly generated from gas power plants and hydro stations. Gas power plants produce 69% of the total power while hydro stations produce 31% [3]. Although Nigeria has 12,522 MW of installed capacity, only an average operational capacity of 3,879 MW is available for distribution to consumers owing to limited infrastructure.

Nigeria’s power transmission network hovers around 6 GW [4]. However, approximately 40% of the population are connected to the national grid, leaving the rest (mostly rural areas) to biomass/wood consumption which pose more threats to the climate due to indiscriminate release of greenhouse gases [5]. Of these 40% households that have access to the grid, 6% are using diesel generators as supplements while 3% are totally reliant on self-generation – possibly to avoid the distress that intermittent power supply can have on their businesses [6].

However, solar energy has been proposed as a viable source of electricity. It has been suggested that a substantial portion of the country’s electricity needs could be met if sufficient attention is focused on utilizing the abundant solar energy in the North East, North West, and North Central geo-political zones of Nigeria [7]. Interestingly, [2] proposed that the solar power produced in a photovoltaic (PV) module does not only depend on the intensity of radiation but also on the angle between the module and the sun (tilt angle). Thus, the optimum tilt angle and orientation of solar PV systems in different locations have been studied in details in some parts of the country [8–10]. [2] determined the optimal tilt angle for maximum solar insolation for PV systems in Enugu, Southern Nigeria. They found that the best tilt angle was 6° for a fixed module. Moreover, they discovered that a monthly adjusted PV module had a 3% increase. Furthermore, [11] estimated the optimum tilt angle for a flat plate collector in Zaria, Nigeria, and found that the average fixed tilt angle was 22.5°, with an average annual increment of 4.23% when monthly tilt angles were used. [9] observed a positive linear relationship between solar radiation and current with an insignificant effect on voltage. Thus, solar radiation has a direct relationship with solar power. Most of the past studies assumed that the skylight and the ground-reflected radiations are isotropically distributed due to the complexity associated with precise calculations of the solar radiation flux incident on slopes of different orientations. However, the non-isotropic character of these diffuse fields, including maximum intensities near the Sun and the horizons, minimum intensities in the direction normal to that of the Sun, and other irregularities, make the simplified assumption sufficiently unrealistic to introduce significant errors into model calculations of the energy incident on sloping surfaces [12]. While some investigations have revealed that anisotropic models give better predictions than isotropic models for diffuse radiation on south-facing surfaces [13], no research has utilized anisotropic model in global solar radiation and solar power calculations in Nigeria. Therefore, the aim of this study is to estimate the optimum tilt angles of solar power for different geoclimatic zones in Nigeria using anisotropic models.

Keywords: Optimum tilt angle; solar radiation; PV module; solar power; electricity; renewable energy.
This remainder of this paper is organized as follows: The methodology is presented in Section 2. The results are discussed in Section 3, and the conclusion is presented in Section 4.

2. METHODOLOGY

Nigeria is a tropical country that lies within the latitudinal range of 4°N–13°N (Fig. 1). The country can be divided into four geoclimatic zones: Coastal, Derived Savanna, Guinea Savanna, and Sahel based on its climate patterns, such as precipitation, temperature, and vegetation [14]. On extreme, the Coastal region is featured with high rainfall intensity in almost eight months of the year, as well as dense vegetation and low temperature. On the other hand, Sahel region, located in the northern part of the country, is known for high temperature, low rainfall, scanty and scattered vegetation with desert-like features.

The surface data of direct and diffuse solar radiation on hourly time-series format from 2013 to 2017 were obtained from the archives of the Modern-Era Retrospective Analysis for Research and Application, Version 2 (MERRA-2) for 20 stations spread across Nigeria, as shown in Fig. 1. The MERRA-2 data is powered by Earth Observing System Data and Information System (EOSDIS), the key core capability in the National Aeronautics and Space Administration (NASA) Earth Science Data Systems (ESDS) program [15]. The data gridded in NetCDF format at a spatial resolution of 0.5° x 0.63° was converted into a readable format using Ferret software.

Considering that solar radiation has a direct relationship with solar power, the global solar radiation \( H_g \) for all the stations was first calculated by summing the values of the beam, sky-diffuse, and ground-reflected radiations as follows:

\[
H_g = H_b + H_d + H_r
\]
The details of the beam, sky-diffuse, and ground-reflected radiation calculations are given in Sections 2.1–2.3. The monthly values for 2013–2017 were averaged to obtain the average monthly global solar radiations for the years. Afterwards, the monthly solar power E was computed for all the stations using Eq. (2), and the station having the highest solar power was selected as the representative station for the zone.

\[ E = A \times r \times H \times PR \]

where \( A = \) total solar panel area \( (m^2) \), \( H = \) monthly average solar radiation on tilted panels, \( PR = \) performance ratio \( (0.75) \) \[16\], \( r \) is the solar panel yield \( (\%) \) given by:

\[ r = \frac{\text{electric power of one solar panel (KW)}}{\text{area of one panel}} \]

According to \[17\], it takes about 20 solar panels to power a typical residential home. Hence, 20 solar panels were considered in the solar power calculation in this study. The solar panels have a 60-cell configuration, with an area of 1.66 \( m^2 \) and an electrical power of 250 Wp \[18\].

### 2.1 Direct Radiation on Inclined Surface

The direct solar radiation dataset contained hourly values from January 1, 2013 till December 31, 2017. The hourly values were averaged to obtain the daily values, and the daily beam radiation for an inclined surface was calculated using:

\[ H_b = (H_g - H_d)R_b \]

where \( H_g \) and \( H_d \) are the monthly mean daily global and diffuse (sky-diffuse and ground-reflected) radiations on the horizontal surface, and \( R_b \) is the beam radiation conversion factor. According to \[18\], \( R_b \) can be expressed as:

\[ R_b = \frac{\cos(\beta) \cos(\omega_d \sin \delta) + \omega_d \sin(\omega_d \beta \sin \delta)}{\cos \phi \cos \omega \sin \delta + \omega_d \sin \delta \sin \omega_d \sin \delta} \]

where \( \phi \) is the latitude, \( \beta \) is the tilt angle, \( \delta \) is the declination angle, and \( \omega_d \) is the sunset hour angle for the tilted surface.

The declination angle for a particular day, \( \delta \), was calculated using:

\[ \delta = \frac{23.4^\circ \sin(2\pi(28.01n)/365)}{180^\circ} \]

where \( n \) is the nth day of the year.

The sunset hour angle for the tilted surface was calculated using:

\[ \omega_d = \arccos[-\tan \phi \tan \delta] \]

The values were obtained at tilt angles of 15° intervals such as 15°, 30°, 45°, 60°, 75° and 90°; and the daily values for a particular month were averaged to obtain the monthly beam radiation for 2013–2017.

### 2.2 Sky-diffuse Radiation on Inclined Surface

Different models exist for the estimation of the sky-diffuse radiation on an inclined surface, including circumsolar model, isotropic model, Klucher anisotropic model, Perez model, and Hay anisotropic model. However, some researchers \[19,20\] reported that Klucher model gives good agreement with the experimental value for all types of slope. Thus, Klucher model \[19\] was adopted in this study, and it is given by:

\[ H_s = \frac{1}{2}H_d(1 + \cos \beta)[1 + F \sin^3(\frac{\beta}{2})](1 + F \cos^2 \theta \sin^2 \theta) \]

where \( H_s \) is the sky-diffuse radiation, \( H_d \) is the daily diffuse solar radiation on horizontal surface, \( \beta \) is tilt angle, \( \theta \) is the solar incidence angle on tilted plane, and \( F \) is a modulating function.

The modulating function was obtained using:

\[ F = 1 - (\frac{H_d}{H})^2 \]

When the skies are overcast, \( F = 0 \). For clear sky conditions, \( F = 1 \).

The solar incidence angle \( \theta \) on an inclined plane is given by \[21\]:

\[ \theta = \cos^{-1} \left[ \sin \delta \sin(\phi - \beta) + \cos \delta \cos(\phi - \beta \cos \omega) \right] \]

The solar zenith angle \( \theta_s \) is given by \[22\]:

\[ \theta_s = \cos^{-1} \left[ \sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega \right] = \sin \omega \]

where \( \omega \) is the hour angle.

The values were obtained at tilt angles of 15° intervals such as 15°, 30°, 45°, 60°, 75°, and 90°. The daily values for a particular month were
averaged to obtain the monthly diffuse radiation for 2013–2017.

2.3 Ground-reflected Radiation on Inclined Surface

The daily ground-reflected radiation was obtained using anisotropic model [23], and it is given by:

\[ H_r = \sum_i \frac{\Delta}{\cos \beta} \left[ 1 + \sin^2 \left( \frac{\theta_i}{2} \right) \right] \]

where \( \Delta \) is the azimuth of the tilted surface with respect to that of the sun, \( \theta_i \) is the solar azimuth angle, \( \rho \) is the albedo, \( \beta \) is the tilt angle.

The values were obtained at tilt angles of 15° intervals such as 15°, 30°, 45°, 60°, 75°, and 90°. The daily values for a particular month were averaged to obtain the monthly ground-reflected radiation for 2013–2017.

3. RESULTS AND DISCUSSION

3.1 Interannual Variations of Monthly Mean Solar Power from 2013 to 2017

Figs. 2 and 3 show the interannual variations of the monthly mean maximum solar power for all the zones from 2013 to 2017. It was observed that the solar power in the Sahel and Guinea Savanna zones in January and March was noticeably higher than in the Coastal and Derived Savanna zones throughout 2013-2017. This may be attributed to the proximity of the Sahel and Guinea Savanna zones to the Sahara Desert and the high sunlight duration usually experienced in these zones [24]. On the other hand, the relatively lower solar power in the Coastal and Derived Savanna may be attributed to the proximity to the ocean [25]. This observation indicates that the solar power in January and March is expected to be higher in the Sahel and Guinea Savanna zones than in the Coastal and Derived Savanna zones if the climate remains relatively constant. Furthermore, in 2013 and 2015, peaks were observed in January and February for the Coastal and Derived Savanna and zones in February for all the zones. The solar power seemed to alternately increase and decrease every two years, which may be an important consideration when formulating solar energy policies. Meanwhile, there was no noticeable change in the solar power in January in the Sahel and Guinea Savanna zones between 2013 and 2015, except in 2016 and 2017 where contrasting trends were observed in both zones. Also, only the Guinea Savanna zone had an increasing trend in January 2017, which may be attributed to the clearness of the atmosphere as a result of less harmattan dust particles in this zone in recent times compared to the Sahel zone [26], as well as less clouds and suspended aerosols compared to the Derived Savanna and Coastal zones [27]. Furthermore, all the zones had similar patterns in February from 2013 till 2015. However, a decreasing trend was observed in the Derived Savanna and Coastal zones, similar to that observed in March. This decreasing trend in 2016 and 2017 compared to the previous years may be attributed to the prevalence of aerosols in the atmosphere as a result of industrialization in these zones [28]. Moreover, in February, Guinea Savanna zone had the lowest solar power from 2013 till 2016 compared to the other zones. Thus, similar patterns are expected in January and February for the Derived Savanna and Coastal zones if the climate remains relatively constant.
In July–September, the Derived Savanna and Coastal zones had the same pattern similar to January and February. Meanwhile, the Sahel and Guinea Savanna zones had different patterns in July. In July 2016, a peak was observed in the Guinea Savanna zone while a dip was observed in the Sahel zone, possibly as a result of the interannual variability in precipitation as observed in April–June. Afterwards, the trend alternated in both zones. Furthermore, noticeable dips in solar power occurred in July 2017 as observed for May–June, whereas the solar power increased in all the other zones. Thus, interannual variabilities in solar radiation and rainfall regimes seem to have a significant influence on the solar power in the Sahel zone. In 2015, solar power was lowest in the Sahel zone and highest in the Guinea Savanna zone.

For October to December, the Guinea and Derived Savanna and Coastal zones had the same pattern in October, whereas the Sahel had contrasting patterns. Meanwhile, the pattern of the Guinea Savanna and Coastal zones is similar.
to that observed in September. In 2016, there was a dip in all the zones and a peak in the Sahel zone. Meanwhile, the Sahel zone had the lowest solar power in 2015 while Guinea Savanna zone had the highest solar power. In November, the solar power in the zones were clearly distinct from one another. Similar pattern was observed for all the stations up till 2016, where the Coastal zone had an increasing trend. Surprisingly, the Guinea Savanna zone had a higher solar power than the Sahel zone throughout the years, except 2013. Furthermore, alternating solar power was also observed in all the zones in November and December, with Sahel and Coastal zones displaying slightly different patterns from 2016. This suggesting that there may be high and low solar power in two-year intervals, which may be a useful consideration in solar photovoltaic installations.

The Sahel Savanna had a different pattern for most of the months from 2013 to 2017. This may suggest an instability in the pattern of the solar radiation in this zone in the coming years. Hence, it may be risky to install a good number of solar panels in this zone for the sustainable generation of large-scale solar power, as large costs may be incurred in installing solar panels in this zone to produce a substantial amount of electricity annually.

As seen above, Sahel zone had a different pattern for most of the months from 2013 to 2017. This may suggest an instability in the pattern of the solar radiation in this zone in the coming years. Hence, it may be risky to install a good number of solar panels in this zone for the sustainable generation of large-scale solar power, as large costs may be incurred in installing solar panels in this zone to produce a substantial amount of electricity annually.

Fig. 3. Interannual variations of monthly mean solar power in Guinea Savanna and Sahel zones from 2013 to 2017
3.2 Seasonal Mean Solar Power

Figs. 3–6 show the estimated monthly mean solar power received on the surface of the panel in the Coastal, Derived Savanna, Sudan Savanna, and Sahel zones, respectively. The solar power was highest during the dry months (October–March) between the tilt angles of 15°–60° for all the zones. During the rainy months (April–September), there was a reduction in the values of the solar power received for all the tilt angles. This is consistent with the findings of Okoye [27], who observed that the decrease in solar radiation was due to the associated overcast and cloud cover prevalent in these months. Moreover, the least solar power was received at a tilt angle of 90° in all the zones; thus, it can be neglected in the installation of PV modules. This is expected, considering that surfaces oriented at this angle are perpendicular and receive little beam radiation from the sun. Most of the radiation is due to diffuse and ground-reflected radiations. Furthermore, the solar power decreased as the tilt angle increased for all the zones, except at 15° where the solar power reduced between November and February. Although all the zones had increased solar power between October and January, only four tilt angles (15°, 30°, 45°, and 60°) yielded the maximum solar radiation in all the zones.

Table 1 summarizes the maximum monthly solar power received in all the zones. The highest solar power in the Coastal and Guinea Savanna zones were produced in January at tilt angles of 30° and 45°, respectively. Moreover, the highest solar power in the Derived and Sahel zones were produced in December at a tilt angle of 45°. It was also observed that the maximum solar power increased from the Coastal zone to the Sahel zone. This may be due to the increased solar radiation received in the Sahel and Guinea Savanna zones [16,32]. Similarly, the decreased solar power in the Derived Savanna and Coastal zones may be attributed to their closeness to the ocean, resulting in high humidity round the year [33].

Comparing the results of the zones in Table 1, the maximum solar power was received in Sahel zone for most of the months. Thus, large-scale solar energy could be harnessed for the nation by installing several PV modules in this zone. Meanwhile, Guinea Savanna zone received the maximum solar power in January, February, July, and September. Furthermore, Coastal zone received the maximum solar power in August. Furthermore, the maximum solar power was produced at 15° in most of the months for all the zones. However, these months are largely wet due to the rainy season usually observed during these months. On the other hand, the maximum solar power was produced during the dry months at tilt angles of 30° and 45°. It could also be observed that the solar power reduced significantly in November in the Derived Savanna and Coastal zones. This may be due to the low solar radiation received in this month, which is consistent with the results of [34,35]. The low solar radiation received may be due to the combined effects of late precipitation and the incoming harmattan, as this month signifies the end of rainy season and the onset of the dry season [35]. Thus, adequate plan needs to be put in place to cater for the decreased power during this month. Meanwhile, the months of April–August received the lowest solar power. The deficit in power in these months in all the stations may be supplemented by alternative sources of energy such as wind energy, hydroelectric energy, biomass which are relatively abundant in Nigeria [35]. Furthermore, the high power received at the Sahel and Sudan Savanna zones make them good zones for large-scale electricity production, which can be added to the national grid. On the other hand, the relatively low solar power of the Guinea Savanna and Coastal zones make them ideal for small household and rural electrification projects.

3.3 Estimated Number of Panels that Can be Used in all the Zones

The results summarized in Table 1 are based on an average number of 20 solar panels, as discussed in Section 2.5. However, more or fewer solar panels can be used, depending on the energy needs of residential building. Olaniyan et al. [35] concluded that the average per capita electricity consumption of a household in Nigeria is 27 kWh in a month. Based on Table 1, it can be inferred that the number of panels needed differ for the months. However, it is more economical to consider the yearly solar power in order to give a more accurate estimate of the total number of panels required. Moreover, excess unused solar power from a month can easily be rolled over onto another month, effectively reducing the number of panels needed for that month. Thus, the estimate of the required number of solar panels is reported. Based on the results of Olaniyan et al. [35], the annual average household electricity demand in Nigeria is 1944 kWh.
Fig. 4. Monthly mean solar power in coastal zone at different tilted angles from 2013 to 2017
Fig. 5. Monthly mean solar power in Derived Savannah zone at different tilted angles from 2013 to 2017
Fig. 6. Monthly mean solar power in Guinea Savanah zone at different tilted angles from 2013 to 2017
Fig. 7. Monthly mean solar power in Sahel zone at different tilted angles from 2013 to 2017
## Table 1. Maximum monthly solar power in all the zones

|         | Coastal       | Derived Savanna | Guinea Savanna | Sahel Savanna |
|---------|---------------|-----------------|----------------|---------------|
| Opt. tilt angle (°) | Max. solar power (kW) | Opt. tilt angle (°) | Max. solar power (kW) | Opt. tilt angle (°) | Max. solar power (kW) | Opt. tilt angle (°) | Max. solar power (kW) |
| Jan     | 30            | 312.43          | 30             | 328.40        | 45             | 470.02          | 45             | 402.18          |
| Feb     | 15            | 167.36          | 30             | 177.65        | 30             | 326.14          | 30             | 319.97          |
| Mar     | 15            | 124.37          | 15             | 175.08        | 15             | 265.69          | 15             | 275.03          |
| Apr     | 15            | 82.67           | 15             | 88.13         | 15             | 95.84           | 60             | 97.60           |
| May     | 15            | 87.28           | 15             | 96.36         | 15             | 99.79           | 60             | 108.89          |
| Jun     | 15            | 91.13           | 15             | 95.97         | 15             | 101.31          | 60             | 106.98          |
| Jul     | 15            | 96.84           | 15             | 95.95         | 15             | 103.15          | 60             | 111.22          |
| Aug     | 15            | 96.28           | 15             | 94.38         | 15             | 91.28           | 15             | 92.64           |
| Sep     | 15            | 130.45          | 15             | 116.74        | 15             | 150.50          | 15             | 135.32          |
| Oct     | 15            | 292.50          | 15             | 333.27        | 30             | 397.91          | 30             | 405.45          |
| Nov     | 30            | 187.23          | 30             | 202.58        | 30             | 375.88          | 45             | 455.17          |
| Dec     | 30            | 258.53          | 45             | 385.57        | 45             | 430.22          | 45             | 474.63          |
Table 2. Estimated number of solar panels that can be adopted in households in the different zones in Nigeria

| Zone                      | No. of panels |
|---------------------------|---------------|
| Coastal                   | 20            |
| Derived Savanna           | 19            |
| Guinea Savanna            | 14            |
| Sahel Savanna             | 13            |

Table 2 lists the estimated number of solar panels that can be adopted in the different zones. The result shows that households in the Sahel zone require the least number of panels to meet their basic energy needs for the year while households in the Coastal zone require the highest number of solar panels. This is due to the increased solar radiation in the Sahel zone compared to the Coastal zone throughout the year. Moreover, the number of solar panels reduced as we move from the Coastal zone to the Sahel zone. However, these panels must be oriented in such a way that the contribution of the ground-reflected radiation can be maximized.

4. CONCLUSION

In this study, we estimated the solar power received on the surface of a PV module as well as the corresponding optimum tilt angles. The monthly tilt angles that can be adopted for the Coastal zone are: 30°–45° for December, 30° for November, January and February; and 15° for March–October. For the Derived Savanna zone, the tilt angles that can be adopted are: 45° for December, 30° for February and November, 15° for March–October, and 30°–60° for January. For the Guinea Savanna, the tilt angles that can be adopted are: 45° for December–January, 30° for February and November, 15° for March–October. Finally, the tilt angles that can be adopted for the Sahel zone are: 45° for November–January, 30° for February and October, 15° for March–September. The results of this research will provide solar engineers in Nigeria with accurate information on the orientation and tilt of PV modules for efficient power generation.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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