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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.

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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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locations. For instance, the Sahel and Guinea Savanna zones had the highest solar power, whereas Derived Savanna and Coastal zones had relatively low power. Based on the results, it was determined that the number of solar panels required in the sahel zone would be lower than those of the other zones.

Conclusion: It can be inferred from the results that the reception of maximum solar power is at the tilt angle of 45° in Sahel, Guinea, and Derived Savanah regions, and at 30° in the Coastal region. The results of this research will provide solar engineers with accurate information on the orientation and tilt of PV modules for efficient power generation.

Keywords: Optimum tilt angle; solar radiation; PV module; solar power; electricity; renewable energy.

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.

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:

$$H_g = H_b + H_s + H_r \quad (1)$$

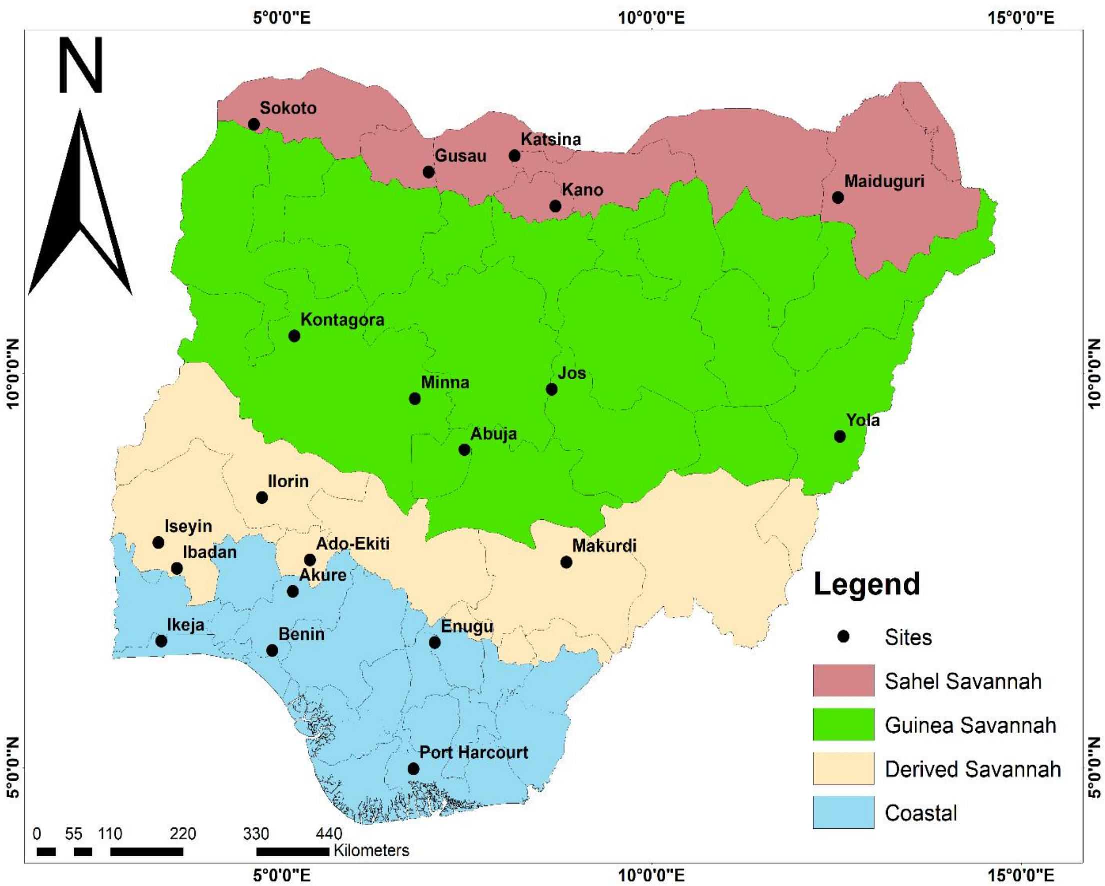

Fig. 1. Map of Nigeria showing the study locations

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.

$$E = A \times r \times H \times PR \qquad (2)$$

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:

$$r = \frac{electric\ power\ of\ one\ solar\ panel\ (KW)}{area\ of\ one\ panel} \qquad (3)$$

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:

$$H_b = (H_g - H_d)R_b \qquad (4)$$

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:

$$R_b = \frac{\cos(\varphi-\beta)cos\delta sin\omega_{ss}+\omega_{ss}\sin((\varphi-\beta)sin\delta}{cos\varphi cos\delta sin\omega_{ss}+\omega_{ss}sin\delta sin\delta} \qquad (5)$$

where φ is the latitude, β is the tilt angle, δ is the declination angle, and ω_{ss} is the sunset hour angle for the tilted surface.

The declination angle for a particular day, δ, was calculated using:

$$\delta = \frac{23.45\pi}{180} sin\left(\frac{2\pi(284+n)}{36\ 5}\right) \qquad (6)$$

where n is the nth day of the year.

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

$$\omega_{ss} = \arccos[-\tan\varphi tan\delta] \qquad (7)$$

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:

$$H_s = \frac{1}{2}H_d(1+cos\beta)[1+Fsin^3\left(\frac{\beta}{2}\right)](1+ Fcos^2\theta sin^3\theta_z) \qquad (8)$$

where H_s is the sky-diffuse radiation, H_d is the daily diffuse solar radiation on horizontal surface, β is tilt angle, θ_z is the solar zenith angle, θ is solar incidence angle on tilted plane, and F is a modulating function.

The modulating function was obtained using:

$$F = 1 - ({}^{H_d}/_{H})^2 \qquad (9)$$

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

The solar incidence angle θ on an inclined plane is given by [21]:

$$\theta = cos^{-1}[sin\delta\sin(\varphi-\beta) + cos\delta cos(\varphi - \beta cos\omega] \qquad (10)$$

The solar zenith angle θ_z is given by [22]:

$$\theta_z = cos^{-1}[sin\delta\sin\varphi + cos\delta cos\varphi cos\omega] = sin\omega \qquad (11)$$

where ω 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:

$$H_r = \sum_i^{day}[\frac{1}{2}I\rho(1 - cos\beta)][1 + sin^2\left(\frac{\theta_\Delta}{2}\right)](|cos\Delta|) \quad (12)$$

where Δ is the azimuth of the tilted surface with respect to that of the sun, θ_Δ is the solar azimuth angle, ρ is the albedo, β 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 their 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 zones and 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.

Meanwhile, in April and May, the solar power was distinctly higher in the Sahel and Guinea Savanna zones than in the Coastal and Derived Savanna zones, similar to the observations in January and March. Besides, Sahel zone had a different pattern from other zones in April and June, which may be as a result of wind stilling due to the decrease in wind speed in recent years [29,30]. Additionally, there was alternating high and low solar power in the Coastal and Derived Savanna zones, similar to the observation in January–March. Meanwhile, in May, the solar power increased in the Coastal and Sahel zones in 2014 and 2016, whereas an opposite trend was observed in the Guinea Savana zone. In addition, the solar power in May steadily increased in the Derived Savanna zone, reaching its peak in 2016 and afterwards decreasing. Meanwhile, the solar power was higher in the Coastal zone than in the Guinea Savanna zone in 2014, with a peak observed in the Coastal zone and a dip in the Guinea Savanna zone. Furthermore, the Coastal zone had a higher solar power than the Derived Savanna zone in May 2016. In June, there were dips in the solar power in all the zones in 2014, except in Sahel where it increased. The apparent difference in the pattern of the solar power in Sahel zone from other zones may be attributed to interannual variabilities in rainfall regime and cloud cover in recent years [31]. Additionally, the solar power was higher in the Coastal zone than in the Guinea and Derived Savanna zones in 2015.

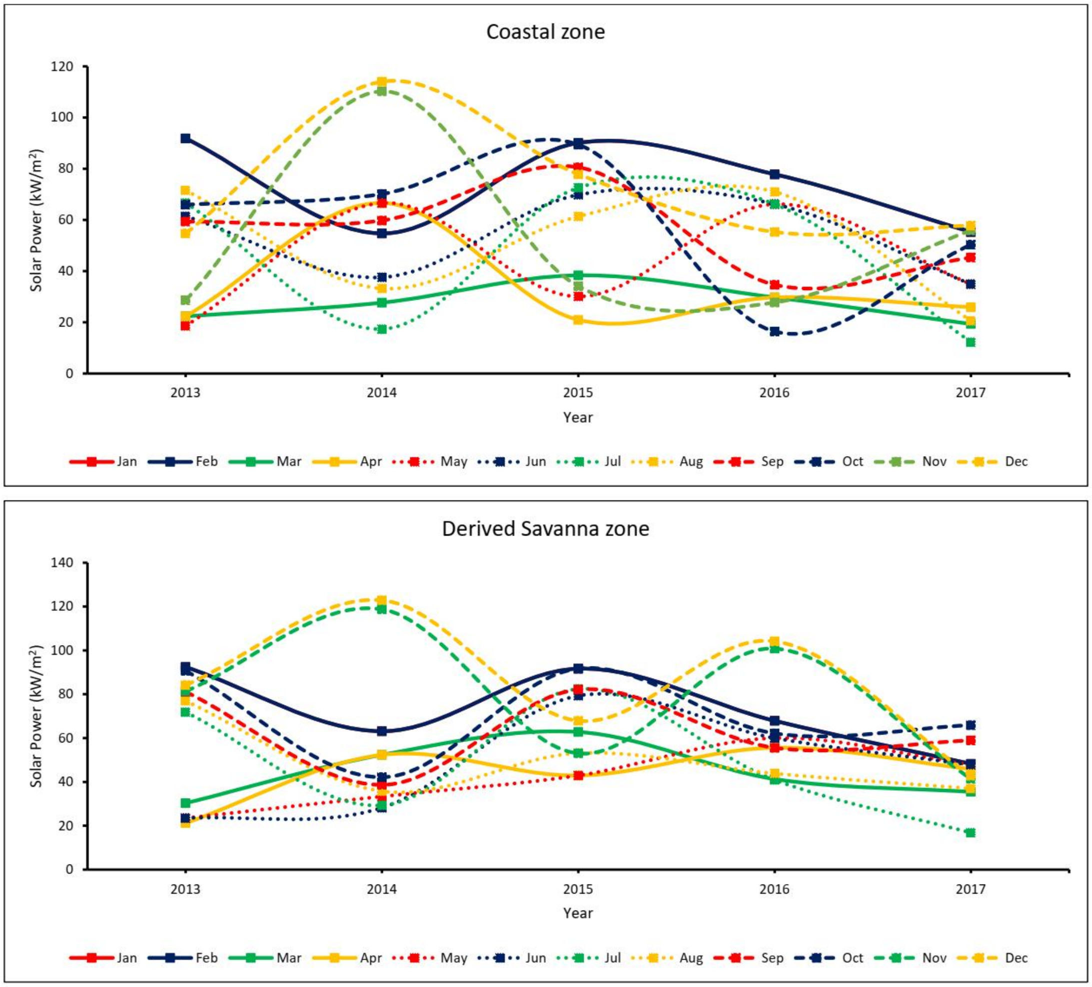

Fig. 2. Interannual variations of monthly mean solar power in coastal and derived Savanna zones from 2013 to 2017

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 2014 in the Coastal and Derived Savanna zones, whereas the dips were not noticeable in the Sahel and Guinea Savanna zones. In August, the solar power was highest in the Coastal zone in 2016, whereas it was lowest in the Sahel zone in 2015 and 2016. This may be associated with extreme weather events. In September, Sahel, Guinea Savanna, and Coastal zones had alternating solar power, suggesting that the solar power may increase and decrease at two-year intervals. Furthermore, the Sahel zone had a decreased solar power in September 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 an increase in solar power in December 2013, whereas the other zones had decreases in solar power. Besides, the solar power began to increase in 2017 in the Coastal zone while the decreasing trend continued in the other zones. Similar to the observation in November, the Guinea Savanna zone had the highest solar power in December.

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.

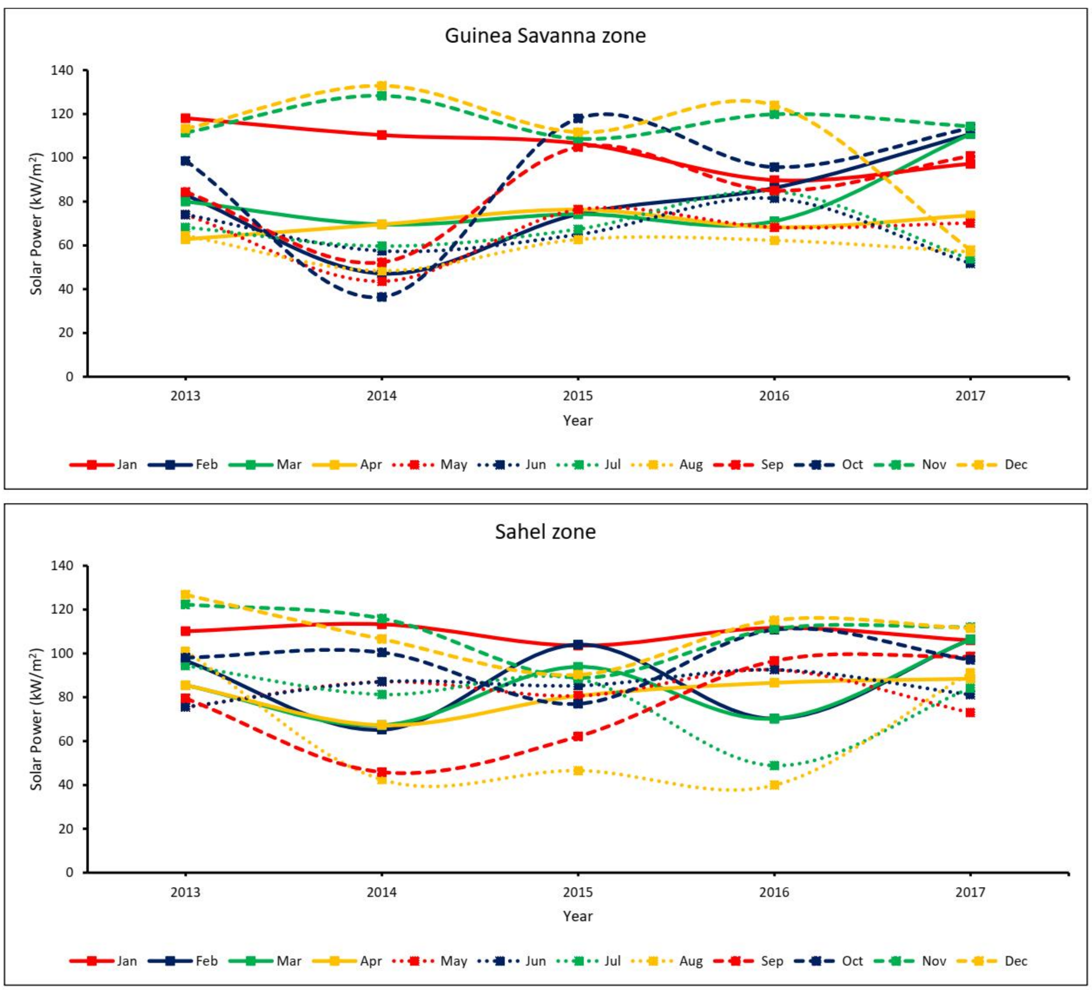

Fig. 3. Interannual variations of monthly mean solar power in Guinea Savanna and Sahel zones from 2013 to 2017

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 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 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.

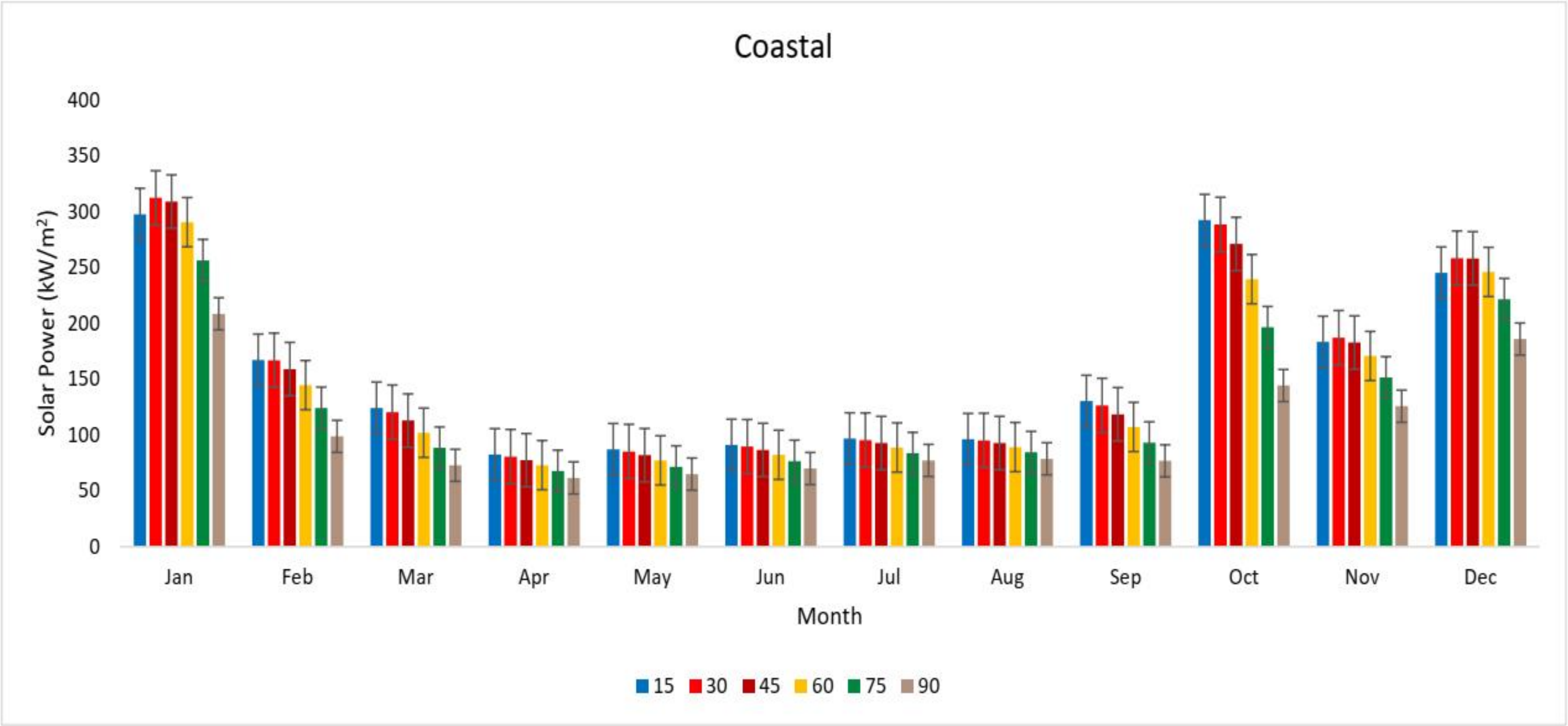

Fig. 4. Monthly mean solar power in coastal zone at different tilted angles from 2013 to 2017

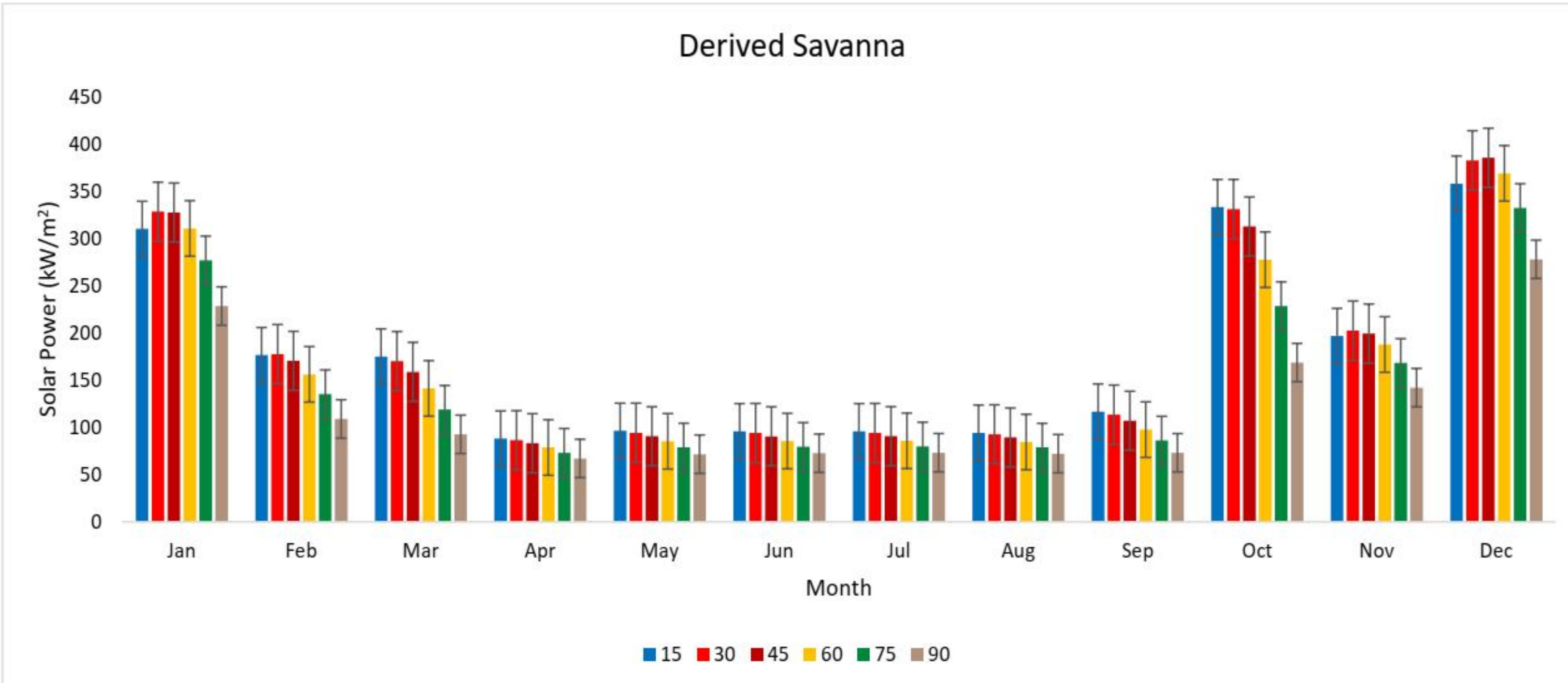

Fig. 5. Monthly mean solar power in Derived Savannah zone at different tilted angles from 2013 to 2017

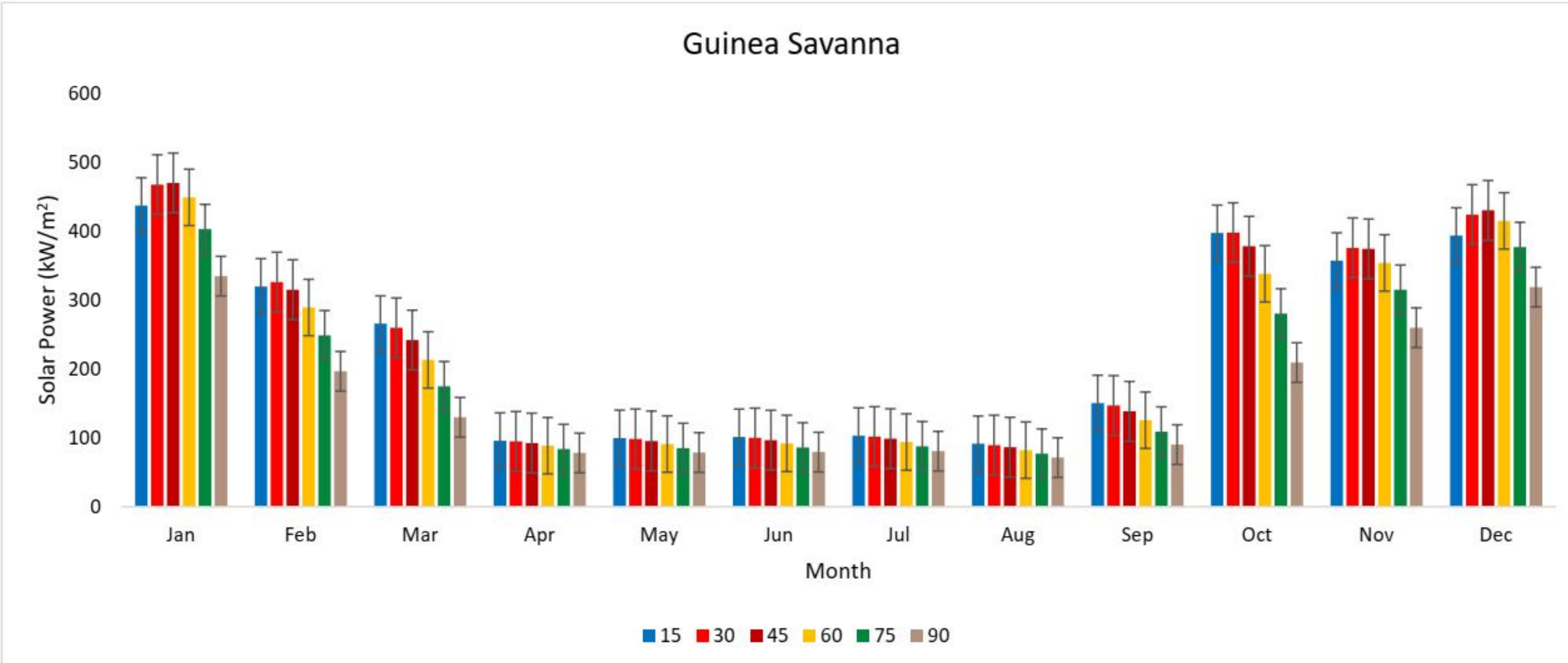

Fig. 6. Monthly mean solar power in Guinea Savanah zone at different tilted angles from 2013 to 2017

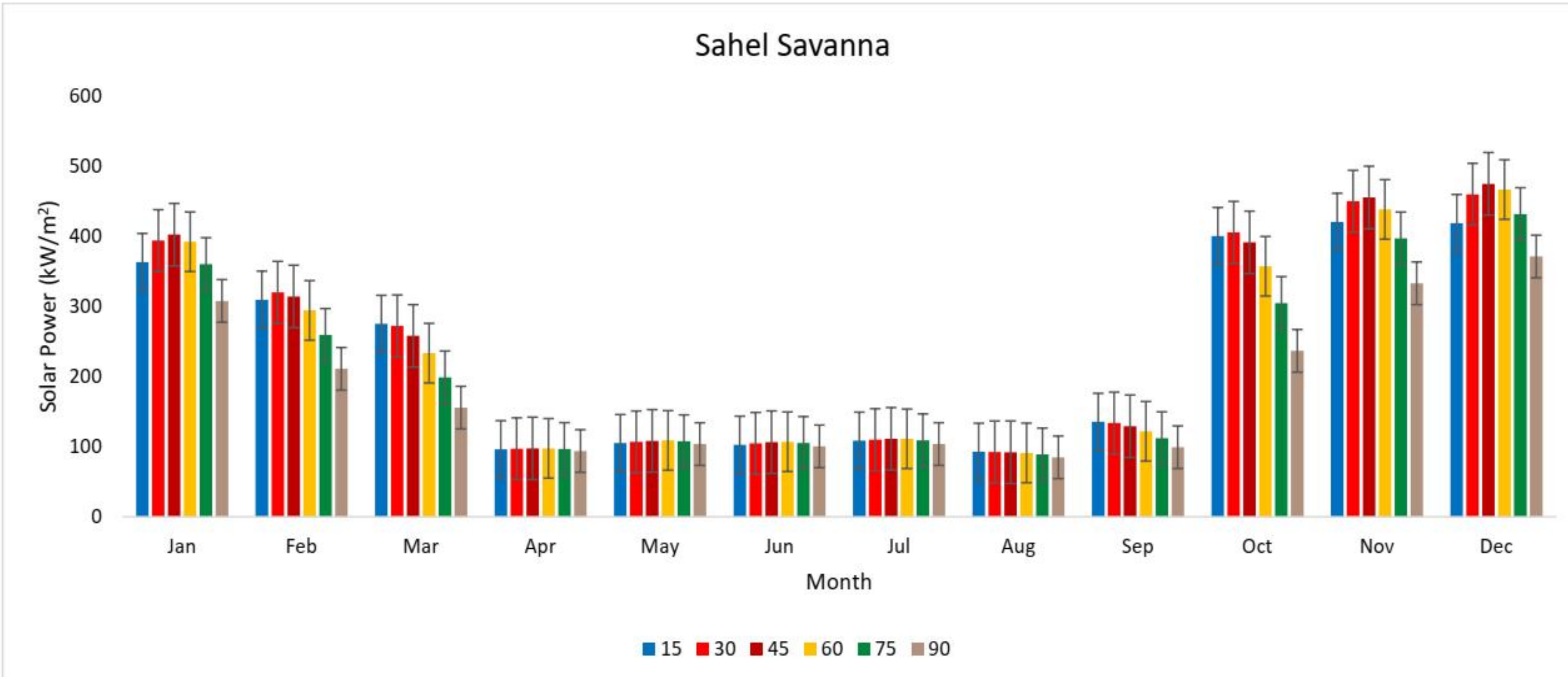

Fig. 7. Monthly mean solar power in Sahel zone at different tilted angles from 2013 to 2017

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

	Coastal	Derived Savanna	Guinea Savanna	Sahel Savanna
No. of panels	20	19	14	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.

REFERENCES

1. Oyedepo SO. Energy and sustainable development in Nigeria: The way forward. Energy, Sustain. Soc. 2012;2(15):1–11. DOI: 10.1186/2192
2. Udoakah Y, Okpura N. Determination of optimal tilt angle for maximum solar insolation for PV systems in Enugu-Southern Nigeria. Niger. J. Technol. 2015: 34(4):838. DOI: 10.4314/njt.v34i4.24
3. Igbokoyi AO, Iledare O. The role of natural gas in Nigeria power generation: Empirical analysis of challenges, constraints and opportunities. Soc. Pet. Eng.- SPE Niger. Annu. Int. Conf. Exhib. 2015;2008:1–13. DOI: 10.2118/178394-ms
4. Fernstrom E. The Nigerian power sector: A case study of power sector reform and the role of PPP background Nigeria; 2011.
5. Ohunakin SO. Energy utilization and renewable energy sources in Nigeria. J. Eng. Appl. Sci. 2010;5(2):171–177.
6. Giwa A, Alabi A, Yusuf A, Olukan T. A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria. Renew. Sustain. Energy Rev. 2017;69:620–641. DOI: 10.1016/j.rser.2016.11.160
7. Bugaje IM. Renewable energy for sustainable development in Africa: A review. Renew. Sustain. Energy Rev. 2006;10(6):603–612, DOI: 10.1016/j.rser.2004.11.002
8. Li DHW, Lam TNT. Determining the optimum tilt angle and orientation for solar energy collection based on measured solar radiance data. Int. J. Photoenergy. 2007: 1–9, 2007. DOI: 10.1155/2007/85402
9. Ajder A, Durusu A, Nakir I. Impact of climatic conditions on PV array's optimum tilt angle. European Journal of Science and Technology. 2018;13:84–90.
10. Ettah EB, Nwabueze J, Njah CN. The relationship between solar radiation and the efficiency of solar panels in Port Harcourt, Nigeria. Int. J. Appl. Sci. Technol. 2011;1(4):124–126.

11. Eke AB. Prediction of optimum angle of inclination for flat plate solar collector in Zaria, Nigeria. Agric. Eng. Int. CIGR J. 2011;13(4).
12. Temps RC, Coulson KL. Solar radiation incident upon slopes of different orientations. Sol. Energy. 1977;19(1):179–184.
13. Noorian AM, Moradi I, Kamali GA. Evaluation of 12 models to estimate hourly diffuse irradiation on inclined surfaces. Renew. Energy. 2008;33(6):1406–1412.
DOI: 10.1016/j.renene.2007.06.027
14. Ojo OS, Adeyemi B. Estimation of solar radiation using air temperature and geographical coordinates over Nigeria. Pacific J. Sci. Technol. 2014;15(2).
15. Ojo OS, Adeyemi B, Ogolo EO. Assessments of the night-time and daytime radiative fluxes balance on seasonal timescale over West Africa. J. Atmos. Solar-Terrestrial Phys. 2019;191:105048.
DOI: 10.1016/j.jastp.2019.05.012
16. Markos FM, Sentian J. Potential of solar energy in Kota Kinabalu, Sabah: An estimate using a photovoltaic system model. J. Phys. Conf. Ser. 2016;710.
DOI: 10.1088/1742-6596/710/1/012032
17. Barrus E. Advanced innovative solar technologies for UNC-Chapel Hill: Examining the future status of emerging solar technologies in 2020 and 2025 for placement on the new football indoor practice facility. 2015;20.
18. El-Sebaii AA, Al-Hazmi FS, Al-Ghamdi AA, Yaghmour SS. Global, direct and diffuse solar radiation on horizontal and tilted surfaces in Jeddah, Saudi Arabia. Appl. Energy. 2010;87(2):568–576.
DOI: 10.1016/j.apenergy.2009.06.032
19. Pandey CK, Katiyar AK. A note on diffuse solar radiation on a tilted surface. Energy. 2009;34(11):1764–1769,
DOI: 10.1016/j.energy.2009.07.006
20. Khalil SA, Shaffie AM. A comparative study of total, direct and diffuse solar irradiance by using different models on horizontal and inclined surfaces for Cairo, Egypt. Renew. Sustain. Energy Rev. 2013;27:853–863.
DOI: 10.1016/j.rser.2013.06.038.
21. Iqbal M. An introduction to Solar Radiation. Elsevier; 2012.
22. Katiyar AK, Panday CK. Study of ground-reflected component and its contribution in diffuse solar radiation incident on inclined surfaces over India. Int. J. Energy Environ. 2010;1(3):547–554,
DOI: 10.1016/j.desal.2007.01.030
23. Audu MO, Isikwue BC, Eweh JE. Estimation of seasonal and annual albedo of the Earth's atmosphere over Kano, Nigeria. IOSR J. Appl. Phys. 2014;6:56–62.
DOI: 10.9790/4861-06515662
24. Falaiye OA, Aweda FO, Yakubu AT. Harmattan dust mass over Ilorin-A Guinea Savanna African city, FUTA J. Res. Sci. 2017;13:158–167.
25. Jagtap SS. Environmental characterization of the moist lowland savanna of Africa. in: Moist Savannas Africa Potentials Constraints Crop Prod. 1995;9–30.
26. Soneye OO, Ayoola MA, Ajao IA, Jegede OO. Diurnal and seasonal variations of the incoming solar radiation flux at a tropical station, Ile-Ife, Nigeria. Heliyon. 2019;5.
DOI: 10.1016/j.heliyon.2019.e01673
27. Kim D, Chin M, Remer LA, Diehl T, Bian H, Yu H, Brown ME, Stockwell WR, Role of surface wind and vegetation cover in multi-decadal variations of dust emission in the Sahara and Sahel, Atmos. Environ. 2017;148: 282–296.
DOI: 10.1016/j.atmosenv.2016.10.051
28. Lin C, Yang K, Huang J, Tang W, Qin J, Niu X, Chen Y, Chen D, Lu N, Fu R. Impacts of wind stilling on solar radiation variability in China, Sci. Rep. 2015;5:1– 7.
DOI: 10.1038/srep15135.
29. Nicholson SE. The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability, ISRN Meteorol. 2013;453521.
DOI: 10.1155/2013/453521
30. Ohunakin OS, Adaramola MS, Oyewola OM, Fagbenle RO. Solar energy applications and development in Nigeria: Drivers and barriers. Renew. Sustain. Energy Rev. 2014;32:294–301.
DOI: 10.1016/j.rser.2014.01.014
31. Olusanya J. Variation of rainfall and humidity in Nigeria. J. Environ. Earth Sci. 2014;4:29.
32. Lawin AE, Niyongendako N, Manirakiza C. Solar irradiance and temperature variability and projected trends analysis in Burundi. Climate. 2019;7(6):83.

DOI: 10.3390/cli7060083

33. Audu MO, Isikwue B. Survey of the reflectivity of the Earth's atmosphere over some selected cities in Nigeria. Int. Res. J. Pure Appl. Phys. 2015;3:54–64.
34. Shaaban M, Petinrin JO. Renewable energy potentials in Nigeria: Meeting rural energy needs. Renew. Sustain. Energy Rev. 2014;29:72-84.
35. Olaniyan K, McLellan BC, Ogata S, Tezuka T. Estimating residential electricity consumption in Nigeria to support energy transitions. Sustain. 2018;10(5).
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