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ORIGINAL STUDY

Optimization of Photovoltaic Tilt Angles for Maximum Solar Energy Harvesting in a Tropical Savanna Region

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Abstract

The optimization of photovoltaic systems for sustainable energy generation is crucial for reducing reliance on fossil fuels and addressing the growing demand for electricity. In this study, we determined the optimum tilt angle for maximizing solar radiation capture in Kogi State, Nigeria, an area characterized as a tropical savanna region. Mathematical modeling using Excel and Matlab (ExMod and MatMod) are employed to analyze global, beam, and diffuse radiation components based on Nigerian Meteorological Agency (NiMET) data. Key parameters such as clearness index, daylight hours, and sunset angles were evaluated across five tilt angles (0°, 7.8°, 22.8°, 37.8°, and 52.8°). Results show that 7.8° (Kogi's latitude) is the optimal fixed tilt angle, balancing beam and diffuse radiation for year-round performance, while seasonal adjustments (e.g., 22.8° in dry months, 52.8° in wet months) further enhance energy yield. The clearness index peaks at 0.53 in the dry season (November—December) but drops to 0.33 in the rainy season (July—August), with stable daylight hours (11—12.4 h/day) ensuring consistent solar potential. The study recommends fixed 7.8° systems for cost-effective deployment and adjustable angles for seasonal optimization, providing critical insights for PV system design in tropical climates.

Keywords: Tilt angle, Photovoltaic, Solar radiation, Power output, ExMod, MatMod

1. Introduction

Energy and its associated environmental challenges are crucial elements in the sustainable development of a nation's society and economy. No country can achieve or maintain development without ensuring that a significant portion of its population has basic access to electricity [1,2]. It was also noted that energy needs by industries in developing countries such as Nigeria will continue to increase. Currently due to the increase in the industrial sector in the country. The pressure on resources is intensifying due to a large population, a low GDP, diminished competitiveness in the global market for Nigerians goods, and an ambition to elevate the living standards of its citizens by 2050 to match global progress, Hence developing countries such as Nigeria must optimize its industrial production processes to avoid squandering resources [3]. The significant energy supply shortage stems primarily from insufficient power generation from the limited operational hydro dams and the high distribution costs across the extensive 924, 000 km^2 land area of the nation [4,5]. Consequently, numerous households and industries have resorted to relying on fossil fuel generating plants, resulting in increased noise pollution and atmospheric emissions. Currently,

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between 60% and 70% of Nigeria's population lacks access to electricity. It's evident that unless the government takes steps to diversify energy sources across domestic, commercial, and industrial sectors and embraces available technologies to minimize energy wastage and cut costs, the ongoing power crisis in will persist [6,7]. While utilizing energy, various pressures are exerted on the natural environment. Some, like global warming, have global significance, while others, such as their effects on human health and local ecosystems, are localized to specific regions [8]. Solar energy stands out as a prime example of renewable energy, providing a means to generate clean, environmentally friendly power, pivotal in mitigating climate change. Solar energy technologies are pivotal in shaping trajectory, facilitating the production of clean, renewable and widely distributed energy sources [9–11] (see Table 1).

Recently, Yunus *et al.* [12] examined the significance of tilt angles and the process of determining the optimal tilt angle through various methodologies. They categorize past data analysis into mathematical model-based, experimental-based, simulation-base, or combinations thereof. Previous findings on PV system performance reveal contrasting outcomes when different techniques are employed to enhance output and reduce cost [13]. While experimental procedures, they are noted for their thoroughness, they are also acknowledged as time-consuming and requiring meticulous analysis. The study identifies monthly-based optimal tilt angles as more effective compared to other approaches, albeit at the expense of additional costs.

In previous study, Chang *et al.* [14] conducted an extensive research work across seven cities in Taiwan, employing advanced methods to optimize the efficiency of photovoltaic modules. To accurately predict solar radiation, they utilized the mathematical procedure of Julian dating, ensuring precise estimations of the sun's position at any given time and location. They integrated the particle-swarm optimization with nonlinear time-varying evolution (PSO-NTVE) to determine the optimal tilt angles for fixed south-facing PV modules. This approach involved exact parameter determination through matrix experiments with an orthogonal array, strategically designed to minimize the number of experiments while approximating the full factorial experiment's effect. To validate their findings, statistical error analysis was conducted to compare results obtained from the four PSO methods with experimental data. The simulation of electrical energy value from 231.12 kwh/m^2 for Taipei to 233.81 kwh/m^2 for Hengchun is higher than the measured values from 224.71 kwh/m^2 for Taichung to 228.47 kwh/m^2 for Hengchun by PV modules attributed to the inherent instability caused by climate change. The results show that the annual optimum tilt angle for Taipei area is 18.16°, for Taichung, 17.3°, for Tainan, 16.15°, for Kaosiung, 15.79°, for Henchung, 15.17°, and for Taitung, 15.94°. Hence, Photovoltaic modules should have their tilt angles adjusted according to the specific geographic locations where they are installed.

Furthermore, the Study of the effect of tilt angles and determination of monthly optimize titl angle for solar collector used in Kano State, Nigeria well presented by Abdulahi *et al.* [8]. They proposed the mathematical model of solar radiation to analyze the impact of collector slope angles on the radiation received by a solar collector. The optimum tilt angle and other factors such as prediction of beam, diffue, clearness index etc on a solar collector were determined. Two computer programs were developed to study the effects of solar collector slope angles and optimize them using Engineering Equation Solver (EES). The results indicate that for maximum energy collection throughout the year, optimal angles or fixed to latitude of Kano. Slopping the solar collector to the monthly optimum tilt angles leads to significant radiation gains, with increase of 28.6% and 24.8% in December and January, respectively.

While numerous studies have explored PV tilt angle optimization for maximizing solar energy capture, most existing models and recommendations are derived from temperate or arid climatic conditions, with limited applicability to tropical savanna environments such as those in Nigeria. The variability in cloud cover, atmospheric turbidity, and seasonal radiation patterns in tropical regions significantly affect the performance of PV systems, yet these local climatic dynamics are often oversimplified or overlooked in global tilt-angle models. Furthermore, there is a lack of region-specific optimization frameworks that integrate both beam and diffuse radiation components alongside seasonal variations in daylight duration. In the context of Kogi State, Nigeria, a region with unique latitude, rainfall patterns, and clearness index fluctuations, comprehensive empirical validation and modeling of optimal tilt angles remain scarce. This study addresses this gap by developing and comparing mathematical models (ExMod and MatMod) to determine precise tilt configurations for maximizing solar radiation capture throughout the year in a tropical savanna setting.

Table 1. List of the materials used.

S/N	Items	Specification	Function
1	Excel	Spreadsheet tool	Analyzes and processes collected solar radiation data.
2	MATLAB	Computational tool	Performs advanced analysis and modeling of solar radiation data.

Consequently, the objective of the current research is to determine the missing solar radiation data for the tropical savanna region of Kogi State, assess the effect of tilt angle, and optimize the performance of the photovoltaic system.

2. Materials and Methods

2.1. Materials

The following materials were used to conduct the experiments.

2.2. Mathematical modeling of solar radiation

2.2.1. Prediction of monthly average diffuse and beam components on horizontal surfaces

To evaluate solar collector performance, it is crucial to separate the beam and diffuse components of solar radiation. Since these data are often unavailable, correlations described by Rabl [15] can be used to predict these components from the measured global radiation. The splitting of global radiation into its beam and diffuse parts is essential, as stated by. The parameter includes.

a. Solar Declination

The solar declination δ, is given by:

$$\delta = 23.45 * \sin\left[\frac{360^0(284+N)}{365}\right] \tag{1}$$

b. Daylight Hours (N)

The number of daylight hours is calculated using: [16]

$$N = \frac{2}{15}\cos^{-1}(-\tan\varnothing \tan\delta) \tag{2}$$

- Monthly Average Clearness Index (KT)

$$K_T = \frac{H}{H_D} \tag{3}$$

H: Monthly average global radiation on a horizontal surface.

- H_0: Monthly average extraterrestrial radiation.

c. Clearness Index Radiation (KT)

$$K_T = \frac{H}{H_0} \tag{4}$$

d. Ratio of Monthly Diffuse Radiation (RB)

For the northern hemisphere, this ratio is given by: [16]

$$R_B = \frac{\cos(\varnothing-\beta)\cos\delta\cos\omega + \sin(\varnothing-\beta)\sin\delta}{\cos\omega\cos\varnothing\cos\delta + \sin\varnothing\sin\delta} \tag{5}$$

e. Sunset Hour Angle (ws)

The sunset hour angle can be calculated as: [16]

$$w_s = \cos^{-1}(-\tan(\varnothing-\beta)\tan\delta) \tag{6}$$

f. Monthly Mean Solar Radiation on Tilted Surface (H_T)

The monthly mean solar radiation on an unshaded tilted surface is expressed as: [16]

$$H_T = H\left(1-\frac{H_D}{H}\right)R_B + H_D\left(\frac{1+\cos\beta}{2}\right) + H\rho_G\left(\frac{1-\cos\beta)}{2}\right) \tag{7}$$

Here

- H_D Monthly diffuse radiation.
- H: Monthly global radiation.
- ρ_G: Ground reflectance.

g. Ratio of Monthly Diffuse Radiation (HD/HH)

The ratio of monthly diffuse to mean global radiation is given by

$$\frac{H_D}{H} = 0.775 + 0.00606(w_s-90) - [0.505 + 0.00455(w_s-90)]\cos(115K_T-103) \tag{8}$$

h. Monthly Average Beam Component (H_B)

The monthly average beam component can be calculated as:

$$H_b = H - H_D \tag{9}$$

- Intraarterial radiation is given by

$$H_O = \frac{86400G_{SC}}{\pi}\left(1+0.033\cos\frac{360N}{365}\right)\left(\cos\delta\cos\varphi\sin\omega_s + \frac{\pi\omega_s}{}\sin\varphi\sin\delta\right) \tag{10}$$

2.2.2. Modelling procedure in matlab application software

MATLAB 2021 offers a robust platform for modeling various physical and engineering processes. The modeling procedures generally involve formulating mathematical equations or algorithms that describe the system being studied. These equations are then implemented as code in MATLAB, utilizing its extensive library of mathematical functions and visualization tools. Figs. 1 and 2 present the modeling flowcharts used in this study.

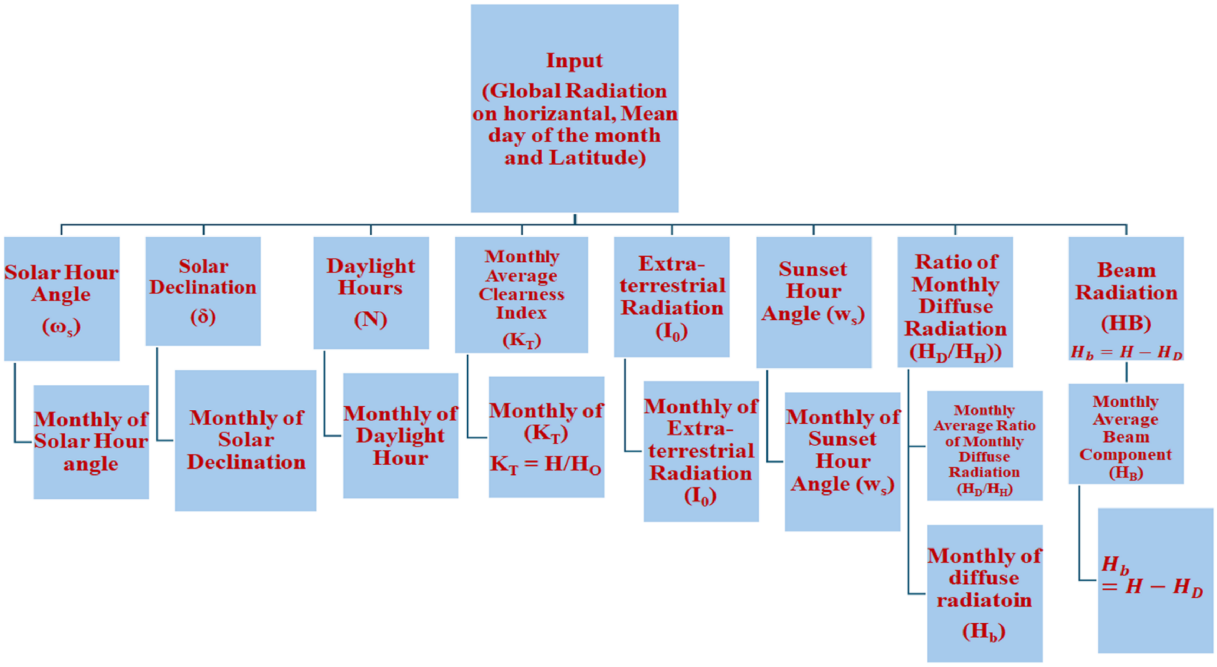

Fig. 1. Modelling flow chart.

3. Results and Discussion

3.1. Monthly average daylight hours

Results indicate a near-regular pattern in daylight times from year to year, ranging between 11 and 12.4 h per day. This consistency is advantageous for the design of photovoltaic systems as a consistent source of power during the year [17]. The region also shows no significant difference in the daylight hour throughout the year, as shown in Fig. 3. The length of the days tends to be longer during the months of April

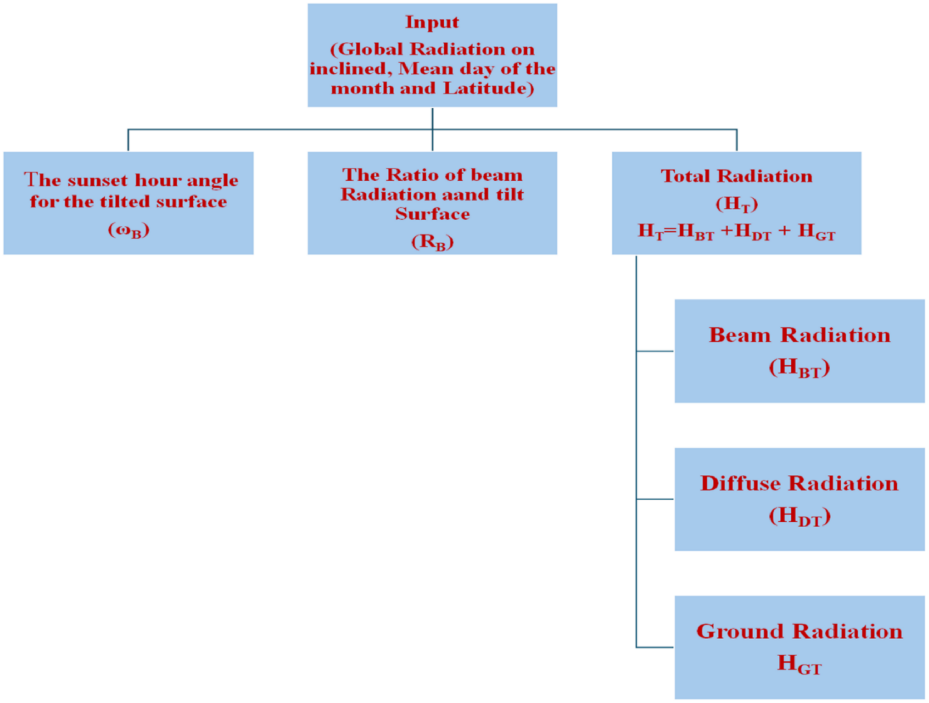

Fig. 2. Modelling flow chart.

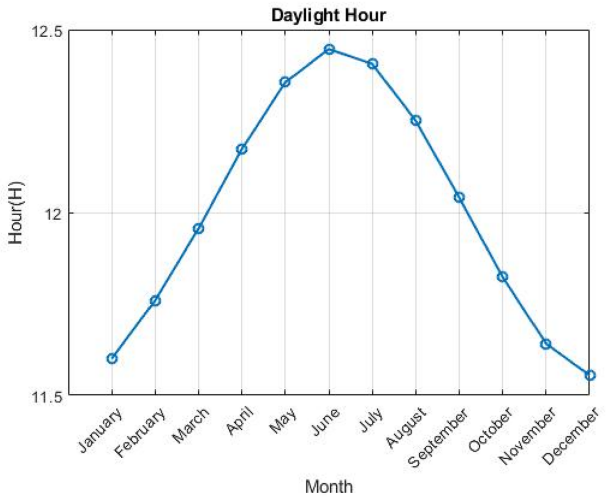

Fig. 3. Monthly average daylight hours.

through September with the highest in June (12.4 h) and this corresponds to wet and warm season. However, the difference is not significant and the annual average daylight hour is 12.00.

3.2. Clearness index

The clearness index (Kt) is a measure of atmospheric clarity, calculated as the ratio of actual global solar radiation to extraterrestrial radiation at the top of the atmosphere [18]. It varies between 0 (completely overcast skies) and 1 (perfectly clear skies). The monthly clearness index values, situated at a latitude of 7.8°, highlight significant seasonal variations influenced by the region's tropical climate.

In this study, the clearness index is highest during the dry season, with values peaking in November (0.5316) and December (0.5227). These months mark the end of the rainy season and the onset of the harmattan, characterized by minimal cloud cover and clear skies. The values for January (0.4675) and February (0.4729), while slightly lower, still indicate favorable solar conditions. The reduction in these months could be attributed to harmattan dust, which scatters solar radiation and reduces clarity slightly. Overall, this period provides the best conditions for solar energy generation, dominated by beam radiation with minimal atmospheric interference [19].

As Kogi State transitions from the dry season to the rainy season, the clearness index gradually declines. The value in March (0.4529) signifies increased atmospheric moisture and cloud cover. The trend continues in April (0.4213) and May (0.4191), with cloud cover becoming more persistent. By June (0.4036), the clearness index approaches the threshold for cloudy conditions. This gradual decline signifies a transition from dominance of beam radiation to a greater dependence on diffuse radiation, as clouds begin to scatter and reflect incoming solar radiation [20]. The clearness index reaches its lowest values in July (0.3668) and August (0.3278), reflecting the peak of the rainy season. During this period, thick cloud cover and frequent rainfall significantly reduce atmospheric clarity. Beam radiation is minimal, and solar energy is almost entirely dependent on diffuse radiation. The dominance of diffuse radiation poses challenges for photovoltaic systems, requiring careful consideration of system design, such as steeper tilt angles to capture scattered light. The clearness index begins to recover in September (0.3787) and continues improving in October (0.4443). These months mark the gradual retreat of the rainy season, with decreasing cloud cover and increasing solar radiation. The improving clearness index reflects a transition back to favorable conditions for solar energy generation. By October, the beam radiation component becomes more prominent, signaling the approach of the dry season.

The clearness index results for Kogi State reveal a clear seasonal cycle as shown in Fig. 4. During the dry season, with high clearness index values, photovoltaic systems can rely on beam radiation, which is more effectively captured with moderate tilt angles (e.g., 7.8°, corresponding to latitude). In the rainy season, however, the dominance of diffuse radiation requires design adaptations, such as steeper tilt angles to maximize energy capture. Adjustable systems could enhance efficiency by accommodating seasonal variations, but for simplicity and cost-effectiveness, fixed systems can be optimized for the dry season, which offers the best energy generation potential.

The sunset hour angle (ω_s) is an important factor in solar energy studies, as it determines the length of daylight hours and influences the amount of solar energy received at a specific location [21]. It represents the angular distance of the sun from the meridian at sunset and is calculated based on the latitude of the location and the solar declination angle for the day. For Kogi State, Nigeria, which lies at a latitude of approximately 7.8°, the results reveal a clear seasonal pattern in the sunset hour angle, ranging from 86.66° in December to 93.35° in June.

During the dry season, which spans from November to February, the sunset hour angle starts at 86.66° in December and gradually increases to 88.19° in February. This period is marked by shorter daylight hours as the sun moves farther south. Although the days are brief, the skies are typically clear, which enhances solar energy generation. These shorter days often bring cooler temperatures and minimal cloud cover, making the dry season an ideal time for solar power systems. As the region transitions into the wet

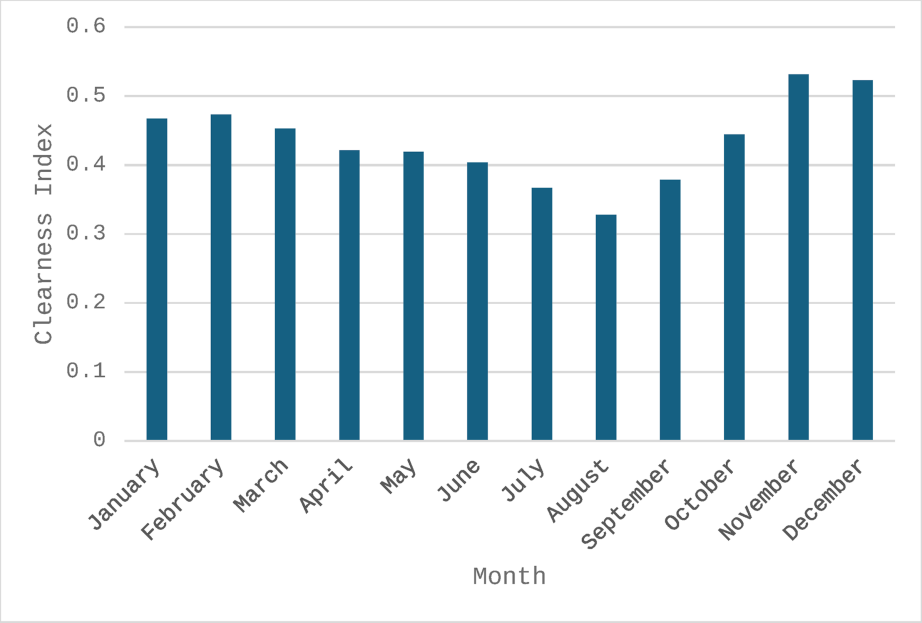

Fig. 4. Result of clearness index.

season, the sunset hour angle steadily increases, starting from 89.67° in March and reaching 92.67° in May. The longer daylight hours during this period are a result of the sun's apparent movement northward. However, as the wet season begins, the presence of increased atmospheric moisture and cloud cover reduces the clarity of the skies, slightly impacting the efficiency of solar energy capture. The peak of the wet season, which occurs from June to August, coincides with the maximum sunset hour angle of 93.35° in June. This period has the longest daylight hours of the year, but the frequent cloud cover and heavy rainfall significantly limit the amount of direct solar radiation that can be harnessed. Although July and August maintain relatively high sunset hour angles of 93.04° and 91.88°, respectively, the dominance of diffuse radiation during these months presents challenges for solar energy systems, which need to be designed to capture scattered sunlight effectively [22].

As the rainy season begins to retreat, the sunset hour angle gradually decreases from 90.30° in September to 87.31° in November. This transition marks the return of shorter daylight hours as the sun moves southward. By this time, the atmospheric conditions also improve, with reduced cloud cover and clearer skies, making the later months of the year ideal for solar energy generation. The result of sunset hour angle is presented in Fig. 5. The combination of clear skies and moderate daylight duration during this period creates optimal conditions for photovoltaic systems. The findings on the sunset hour angle for Kogi State highlight the seasonal variations in daylight duration. While longer daylight hours in June provide extended opportunities for solar energy capture, the effectiveness of photovoltaic systems also depends on atmospheric clarity. Designing solar systems for this region requires a balance between capturing the maximum sunlight during the wet season and optimizing performance during the dry season when conditions are more favorable. This emphasizes the importance of incorporating seasonal adjustments, such as tilt angle modifications, to ensure consistent energy generation throughout the year [23].

3.3. Prediction of solar radiation at horizontal surface

The solar radiation modeling utilized ExMod and MatMod, with NiMET's global horizontal surface radiation data as inputs. Both models had similar performances, as evidenced by the MATLAB and Excel outputs.

The agreement between MATLAB and Excel outputs validates the correctness of both modeling tools. The very good agreement between them further underscores the robustness of the computational approach. Fig. 6 presents the MatMod Beam and Diffuse Radiation tilt at Horizontal surface. The models well reconstructed missing solar radiation data and provided accurate predictions for beam and diffuse radiation.

The 0° tilt angle, or flat orientation, achieved the lowest total efficiency for every month. While it

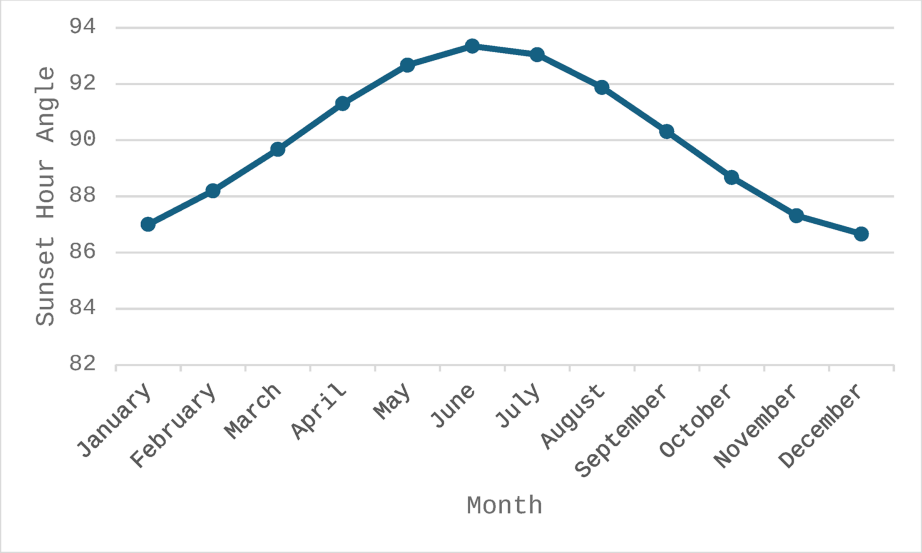

Fig. 5. Result of sunset hour angle.

absorbed moderate levels of beam radiation over the dry period, its lack of adjustment for the sun's changing altitude by the year saw it lose astronomical amounts of energy. The planar orientation proved particularly inefficient throughout the wet season, where diffuse and beam levels of radiation both fell below their respective levels when absorbed by tilting panels. This reinforces optimal tilt angles being necessary to take full advantage of solar energy yields. The ExMod Beam and Diffuse Radiation tilt at Horizontal surface is presented in Fig. 7.

3.4. Effect of tilt angles on solar radiation

During the dry season months, from November to March, beam radiation, which is the direct component of solar radiation, showed higher values due to clearer atmospheric conditions. In contrast, a declining trend was observed during the wet season, from April to October, as increased cloud cover reduced the amount of solar radiation, as illustrated in Fig. 8. The average beam radiation in the year was found to be 52.88% and the month with higher beam radiation was found

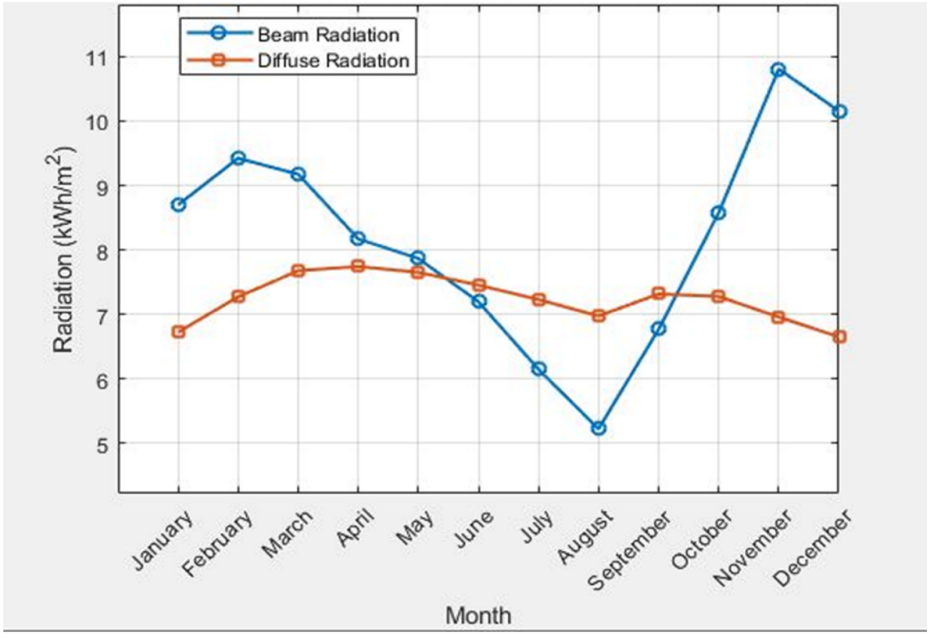

Fig. 6. MatMod beam and diffuse radiation tilt at horizontal surface.

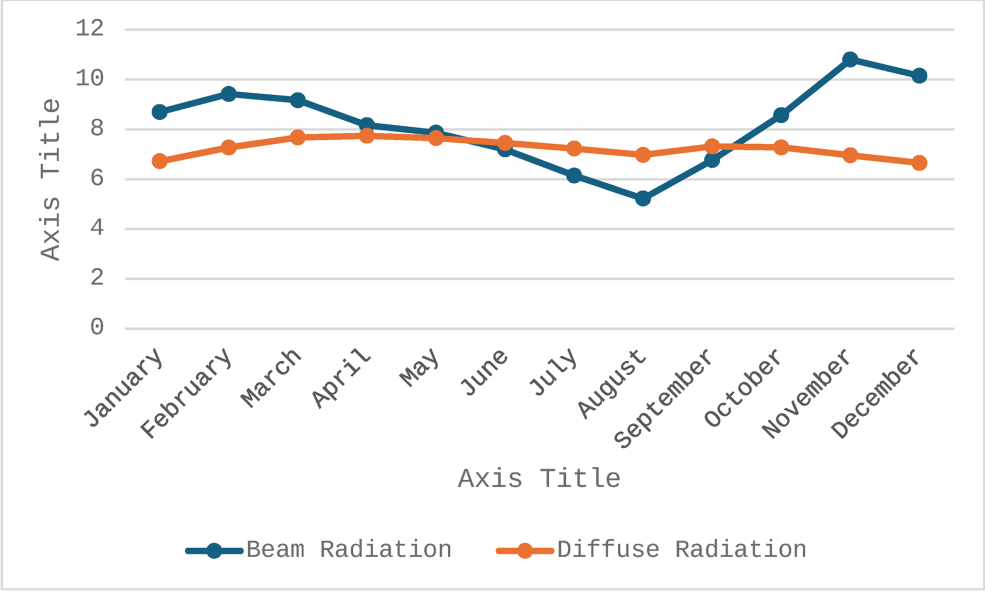

Fig. 7. ExMod beam and diffuse radiation tilt at horizontal surface.

to be at the month of November. In order hand, diffuse radiation was much higher in the wet season, because of cloud and atmospheric particle scattering effects. This inverse correlation between beam and diffuse radiation indicates seasonal variation in solar energy potential in Kogi State. The yearly average of diffuse radiation was found to be 47.12%. Tilt angle of a photovoltaic (PV) system is a significant parameter which decides the intensity of solar radiation received. Tilt angles studied in this research were 0°, 7.8°, 22.8°, 37.8°, and 52.8°. The performance of every tilt angle was taken for different months depending on beam radiation, diffuse radiation, and total global radiation [24]. It has been seen from the results that tilt angle plays a dominant role in receiving solar radiation and is seasonal-dependent, particularly for the climatic condition of Kogi State.

The 7.8° tilt angle, which corresponds to the latitude of Kogi State, registered the maximum amount of total solar radiation throughout the year. The angle places the solar panels near right angles to the sun's rays, thus guaranteeing maximum radiation absorption. During the dry and wet seasons, the 7.8° tilt had a good balanced performance for beam and diffuse

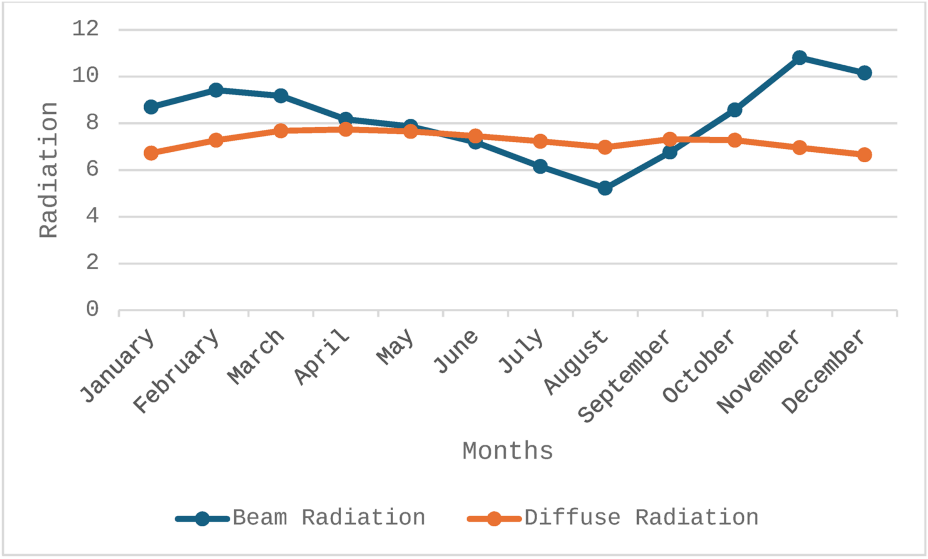

Fig. 8. Beam and diffuse radiation at latitude of 7.8 °.

radiation. This renders it the optimum choice for systems applied to year-round energy production. Uniformity in its performance means that an optimum tilt at 7.8° can minimize system complexity without compromising optimal energy production [25].

The 22.8° and 37.8° tilt angles had better performance during the dry season, particularly between November and March when the sun was at lower angles. During this time, beam radiation prevailed, since clear skies permitted free sunlight. Such angles effectively collected direct radiation and were thus well-suited for use in high energy output applications during the dry season [26]. During the wet season, their effectiveness decreased because they struggled to collect diffuse radiation. This trade-off indicates that such tilt angles are better suited for systems prioritizing energy optimization in dry seasons. Fig. 9 presents the ExMod Beam and Diffuse Radiation at 22.8° and while Fig. 10 presents at 37.8° tilt angles.

The 52.8° tilt angle performed better in the wet season (April to October) with an increase in more diffuse radiation when compared to the lower tilt angles. Cloud cover during the wet season scatters sunlight, which decreases beam radiation but increases diffuse radiation. Oblique sunlight impacts were less during the wet season because the elevated angle had increased

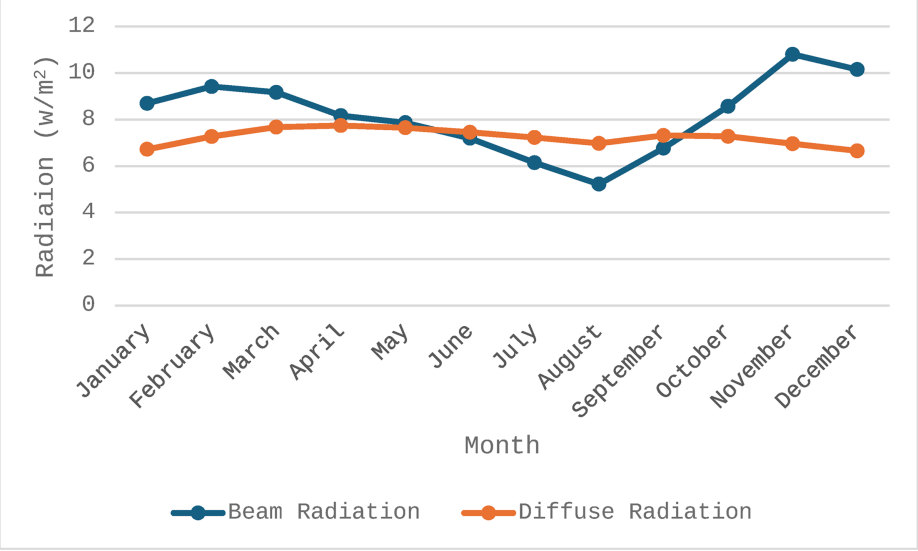

Fig. 9. ExMod Beam and diffuse radiation at 22.8° tilt angle.

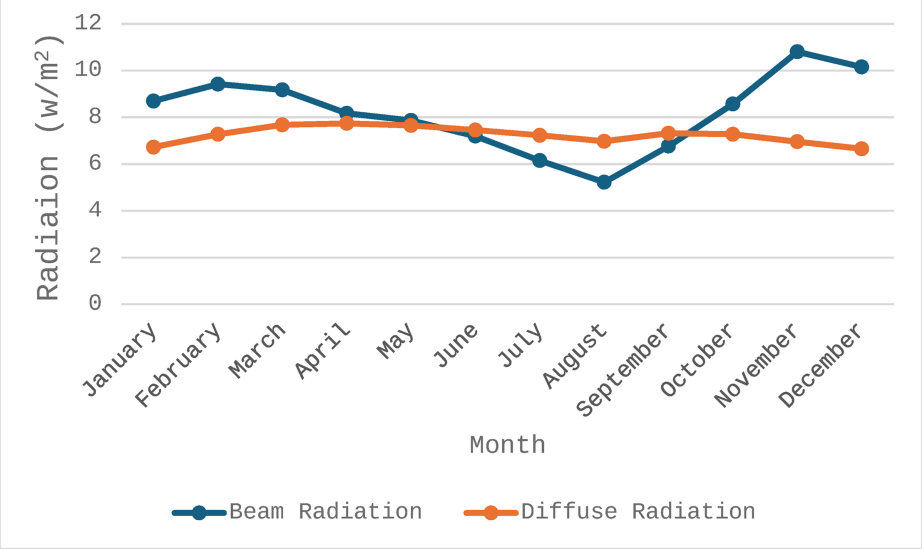

Fig. 10. ExMod Beam and diffuse radiation at 37.8° tilt angle.

scattered rays received. But the 52.8° tilt angle performed poorly during the dry season when there was prevailing direct sunlight. Fig. 11 presents the ExMod Beam and Diffuse Radiation at 52.8° and while Fig. 12 presents the MatMod tilt angles. This result suggests that high tilt angles may be optimally suited for systems that operate in diffused light conditions, such as during periods of extended cloud cover or in latitudes north of where this study took place [27].

The study established a clear seasonal variation in beam and diffuse radiation. During the dry season, beam radiation was significantly higher due to clear weather conditions, accounting for most of the total global radiation. In contrast, diffuse radiation was minimal during this period. However, the situation reversed in the wet season, as beam radiation decreased with increased cloud cover, making diffuse radiation the dominant component. The 7.8° tilt angle provided a uniform capture of beam and diffuse radiation throughout the year, whereas steeper angles like 52.8° were better at capturing diffuse radiation in the wet season.

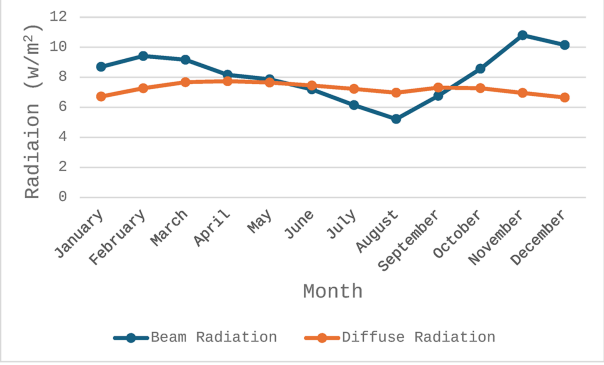

Fig. 11. ExMod Beam and diffuse radiation at 52.8° tilt angle.

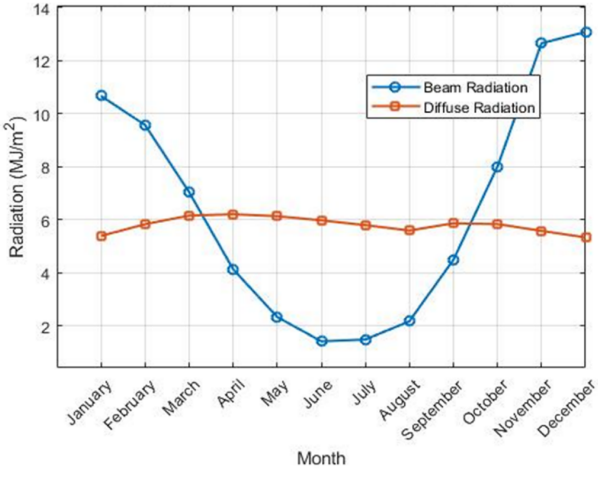

Fig. 12. MatMod Beam and diffuse radiation at 52.8° tilt angle.

The varying solar irradiation seasonally reflects the requirement for tilt maximization [28]. Employing adjustable tilt systems would serve to tilt the PV panels relative to the migrating position of the sun. For low-cost and low-maintenance systems, a fixed tilt angle of 7.8° is recommended since it offers high performance during all seasons. The analysis of tilt angles has significant implications for the design of photovoltaic systems. With the application of appropriate tilt angles based on seasonal priorities, system efficiency can be significantly enhanced. Fixed-angle systems at 7.8° offer simplicity and reliability for general applications. Conversely, adaptive systems may further optimize performance by reacting to seasonal change, albeit at higher complexity and cost. These outcomes are necessary to achieve the best solar energy systems in terms of highest energy output and least installation and maintenance cost [29,30].

4. Conclusion

The study focused on addressing the missing solar radiation data for Kogi State to enhance photovoltaic system performance. By using ExMod and MatMod models with global radiation data from NiMET, it analyzed beam and diffuse radiation components, daylight hours, clearness index, and the impact of tilt angles. The findings provided valuable insights for optimizing photovoltaic systems in the region, ensuring reliable and efficient energy generation. The results showed stable monthly average daylight hours ranging between 11 and 12.4 h, indicating predictable energy generation throughout the year. The clearness index analysis revealed higher values during the dry season, reflecting optimal solar conditions, and lower values during the wet season due to atmospheric conditions. This seasonal variation underscores the importance of considering weather patterns in photovoltaic system design. Furthermore, the study identified the optimal fixed tilt angle for Kogi State tropical savanna region as 7.8°, aligning with its latitude, which balanced beam and diffuse radiation for year-round performance. Alternative angles such as 22.8° and 37.8° performed better during the dry season, while the steeper 52.8° angle captured more diffuse radiation in the wet season. These findings emphasize the importance of tilt angle optimization, recommending fixed or adjustable systems based on application needs and budget constraints.

The current challenges are not limited to the variability of local weather patterns, particularly during the transitional months between seasons, making it challenging to achieve consistent model validation. Advanced solar monitoring equipment is essential. Additionally, field validation of the optimized tilt

angles may be limited by restricted access to physical PV installations for experimental verification. Future research should prioritize long-term experimental validation of the proposed tilt angles using installed PV systems equipped with real-time monitoring sensors. Incorporating machine learning algorithms and satellite-based solar data could further enhance predictive accuracy and automate seasonal adjustment modeling.

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Conflicts of interest

The authors don't have any financial or non-financial conflict of interest to declare.

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