

Experimental Investigation of Solar Photovoltaic Tilt Angles for Maximum Energy Harvest in Kogi State, Nigeria

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Abstract

This study aimed to investigate the impact of tilt angles on solar radiation, current, voltage, and power output of a photovoltaic system, while also employing mathematical modeling to predict solar radiation. This study experimentally investigates the effect of tilt angle (0°, 7.8°, 22.8°, 37.8°, and 52.8°) on the performance of 10W polycrystalline solar panels in Kogi State, Nigeria, over a 12-month period (November 2023–October 2024). Solar radiation, current, and power output were measured at 20-minute intervals using data loggers, voltmeters, and ammeters. The study only investigates the effect of tilt angle and does not consider other factors that may impact solar panel efficiency, such as dust accumulation, temperature, or shading. Results show that optimal performance varies seasonally: lower angles (0°–7.8°) yielded higher radiation and power during peak dry seasons (e.g., November, 613.67 W/m² at 22.8°), while steeper angles (22.8°–37.8°) performed better in transitional months. The 7.8° tilt achieved the highest yearly average radiation, whereas the 0° tilt produced the highest average current (0.300 A) and power (4.51 W). These findings suggest that adjusting tilt angles seasonally can maximize solar energy efficiency in Kogi State, with 7.8° recommended as the best annual fixed tilt.

Keywords: Solar photovoltaic (PV) panels, tilt angle optimization, solar radiation, Kogi State, Nigeria.

1.0 Introduction

Accessibility to energy is fundamental to the socio-economic wellbeing especially of developing nations, However, a substantial percentage of the population experienced unreliable electricity, forcing reliance on costly and polluting fossil fuel generators [1], [2]. The country's power crisis stems from insufficient generation, grid inefficiencies, and policy inconsistencies, with renewable energy (RE) emerging as a viable solution [3], [4]. Solar energy, given Nigeria's high solar irradiation of (3.5–7 kWh/m²/day), offers significant potential, but its utilization remains suboptimal due to inadequate localized data and reliance on theoretical models [5], [6].

While national figures highlight Nigeria's solar potential, practical implementation at the state level faces challenges due to limited experimental data. Kogi State, for instance, has an estimated of 3,567.99 MW of harvestable solar power, yet existing solar data lacks critical parameters like beam radiation and tilt-angle-specific measurements [7]. Most studies rely heavily on simulations without experimental validation, resulting in uncertainties in design and efficiency of solar energy systems [8].

Abdullahi et al. [9] presented a mathematical model of solar radiation to analyze the impact of collector slope angles on the radiation received by a solar collector. The study determined the optimum tilt angle and other factors such as prediction of beam, diffuse, and clearness index on a solar collector. The results indicate that for maximum energy collection throughout the year, optimal angles should be fixed to the latitude of Kano Sloping the solar collector to the monthly optimum tilt angles leads 28.6 and 24.8% increment in radiation gains for December and January respectively

Rouholamini et al. [10] study, a mathematical model was employed to estimate total radiation on tilted surfaces and to compute the output energy of PV panels. The experimental setup consisted of 8 metal structures equipped with PV panels, offering the potential to rotate the panels at various azimuth angles. Mono-crystalline 80W LORENZ-LC80-12M solar panels were utilized in the study. Sensors were strategically installed to measure solar irradiance, wind speed, ambient temperature, and module temperature. The logged data from the experiment captured the electrical energy generation at tilt angles of 0°, 10°, 20°, 30°, 40°, and 50°. Based on the analysis, a monthly optimum tilt angle was proposed for Mahan, Kerman. A comparison between the results obtained from the mathematical model and the logged experimental data revealed a close match, particularly at tilt angles greater than 10 degrees. This research work underscores the importance of considering environmental factors, such as dust deposition, when calculating the optimal tilt angles for PV panels to achieve maximum electrical energy generation.

Mamun *et al.* [11] conducted experimental investigations, both indoor and outdoor, to observe variations in PV performance and electrical parameters at different tilt angles using Malaysian weather conditions. Two experimental modes were employed: varying module tilt under constant irradiation levels, and adjusting irradiation intensity at the optimal tilt set-up. In the former scheme, irradiation levels were kept constant at $750\text{W}/\text{m}^2$, while in the later, module tilt angles were varied from 0° to 80° using a single-axis tracker. Results revealed that under constant irradiation of $750\text{W}/\text{m}^2$, every 5° change in tilt angle led to a power drop of 209W indoors and 3.45W outdoors. Conversely, under the same conditions, efficiency decreased by 0.54% indoors and 0.76% outdoors. Moreover, with every $100\text{W}/\text{m}^2$ increase in irradiation, solar cell temperature rose by 7.52°C indoors and 5.67°C outdoors. The experimental investigation confirmed that the optimum tilt angle in Malaysian conditions is 15° , suggesting that orienting a PV module at this angle maximizes captured solar energy and enhances performance.

To bridge this gap, this study experimentally evaluates the performance of solar panels at five different tilt angles (0° , 7.8° , 22.8° , 37.8° , and 52.8°) over a 12-month period in Kogi State. The research aims to provide evidence-based guidance for solar system optimization in tropical environments like Nigeria. Data were collected and processed using standard solar radiation formulas, and Microsoft Excel was employed for the statistical analysis, including monthly and annual averaging of power outputs and comparison across tilt angles.

2.0 Materials and Method

2.1 Preparation of Materials

The materials used for this experiment include the following:

1. Solar Panel

A 10-watt photovoltaic solar panel was used to convert solar energy into electrical energy. The panel produces a direct current (DC) output with a nominal voltage and current suitable for small-scale experiments. It was selected due to its efficiency and ability to function under varying sunlight conditions.

Table 1: Specification of the Solar Photovoltaic Panel

S/N	MANUFACTURER	SUNLIGHT SOLAR
1	Panel type	Polycrystalline
2	Max power output (P_{\max})	10W
3	Current at P_{\max} (I_{mp})	0.58A
4	Voltage at P_{\max} (V_{mp})	17.5V
5	Short-Circuit Current (I_{sc})	0.62A
6	Open-Circuit Voltage (V_{oc})	21.5V
7	Output tolerance	$\pm 5\%$
8	Maximum System Voltage	DC 1000V
9	Maximum Series Fuse Rating	3A

2. Panel Stand

A metallic adjustable stand was used to support the solar panel at various tilt angles. The stand allows for angular adjustment to optimize solar capture during different times of the day. It is durable and stable enough to withstand outdoor environmental conditions.

3. Voltmeter

A digital voltmeter with a measurement range of $0\text{--}20\text{V}$ DC was used to measure the voltage output from the solar panel. It displays real-time voltage readings and is essential in monitoring the performance of the panel.

4. Ammeter

A digital ammeter was used to measure the amount of current generated by the solar panel. It supports measurements up to 10A DC and is also essential for performance analysis of the system.

5. Electronic Data Logger

A multi-channel electronic data logger was employed to automatically record voltage, current, and time-based values during the experiment. It stores data digitally and enables later transfer to analysis software for interpretation and visualization.

6. Excel Spreadsheet Tool

Microsoft Excel was used for data processing and analysis. Data exported from the logger was input into Excel where various charts, graphs, and summary statistics were created for interpretation of results.

7. Pyranometer

A pyranometer was used to measure solar radiation in watts per square meter (W/m^2). It served as a reference instrument during the calibration of the data logger, ensuring that recorded irradiance values were accurate and

reliable. The calibration process involved comparing readings from the data logger with those from the pyranometer under the same solar conditions. The average percentage deviation recorded during calibration was +4.5%, which was considered acceptable for the scope of this experimental study.

2.2 Experimental Setup

Five (5) Photovoltaic panels of 10W were mounted on solar stand at different tilt angles (0° , 7.8° , 22.8° , 37.8° , 52.8°), 0° was selected to test the performance at a horizontal flat surface 7.8° was the latitude of Kogi State, and 15 degree was added to the latitude to obtained 22.8° , 37.8° , and 52.8° . each panel was connected to a data logger for recording solar radiation, voltage, and current at an interval of 20 minutes for a period of twelve months. The data were taken thrice in a month including the mean day of each month (November, 2023 – October, 2024). An external battery (12V7.5Ah), and charge controller (12V/24V) were used to power the data loggers, and two PV panels were used to charge the battery.



Plate 1: Experimental setup

3.0 Results and Discussion

The experimental data reveal significant variations in solar radiation based on tilt angles and seasonal changes in Kogi State, Nigeria. The region experiences two major seasons: the rainy season (April to October) and the dry season (November to March). Each season exhibits distinct solar radiation patterns due to variations in cloud cover, atmospheric conditions, and the sun's position. The data clearly show that the most effective tilt angle shifts throughout the year in response to these seasonal transitions.

In November 2023, the radiation levels are relatively high across all tilt angles. The 22.8° tilt captures the highest radiation, reaching 613.67 kW/m^2 , indicating its effectiveness in this month. The 37.8° tilt also performs well, with 606 kW/m^2 , although slightly less than 22.8° .

In December, radiation values decrease compared to November. Despite the drop, the 22.8° and 37.8° tilt angles continue to capture significant solar radiation, recording 589 kW/m^2 and 599 kW/m^2 respectively. The 22.8° tilt remains the most efficient, although slightly reduced from the previous month.

January records a further reduction in radiation values. The 22.8° tilt continues to provide the highest value at 543 kW/m^2 , but all tilt angles experience a general decline. This trend indicates that optimal tilt angles may shift with seasonal variations.

In February, radiation values slightly increase. The 22.8° tilt remains the most effective, maintaining its consistency across the early part of the year. Notably, the 7.8° tilt also shows an improvement, suggesting that lower tilt angles may become more favorable as the months progress.

March introduces a shift in performance. Lower tilt angles begin to outperform higher ones. The 0° tilt records 532 kW/m^2 , and the 7.8° tilt records 536 kW/m^2 , indicating better performance than the steeper angles. This shift may be attributed to the sun's position near the equinox.

In April, the 7.8° tilt provides the highest radiation at 526 kW/m^2 , followed by the 0° tilt with 492 kW/m^2 . In contrast, the 22.8° and 37.8° tilts drop significantly to 398 kW/m^2 and 324 kW/m^2 respectively, further supporting the need to adjust tilt angles seasonally.

May continues this trend, with the 0° tilt performing best at 489 kW/m^2 . The higher tilt angles, particularly 22.8° and 37.8° , yield considerably lower radiation values, highlighting a clear shift in the most effective tilt angle.

In June, radiation values reach their lowest for the year. Despite this, the 0° tilt remains the most effective, while the performance of steeper angles declines further due to the high sun position and shorter path lengths.

July and August follow with similarly low radiation levels. Again, the 0° tilt outperforms all others, reinforcing the trend that flatter angles are more efficient during mid-year months. In September, radiation levels begin to rise. Both the 0° and 7.8° tilts perform similarly, with the 0° tilt having a slight edge. This signals a transition back to more favorable solar conditions.

October records some of the highest radiation values for the year. The 22.8° tilt captures the most radiation at 511.00 kW/m^2 , suggesting its increasing effectiveness toward the end of the year.

Finally, the yearly average data shows that the 7.8° tilt has the highest average radiation, followed closely by the 0° tilt. Although the 22.8° tilt performs well in specific months (e.g., November and October), its overall average is lower, indicating that a dynamic tilt strategy may be more effective than a fixed-angle approach.

Overall, the data support the conclusion that lower tilt angles (0° – 7.8°) are more effective during mid-year months, while steeper angles (22.8° – 37.8°) perform better at the beginning and end of the year. These findings underscore the importance of seasonal adjustment for optimal solar energy harvesting.

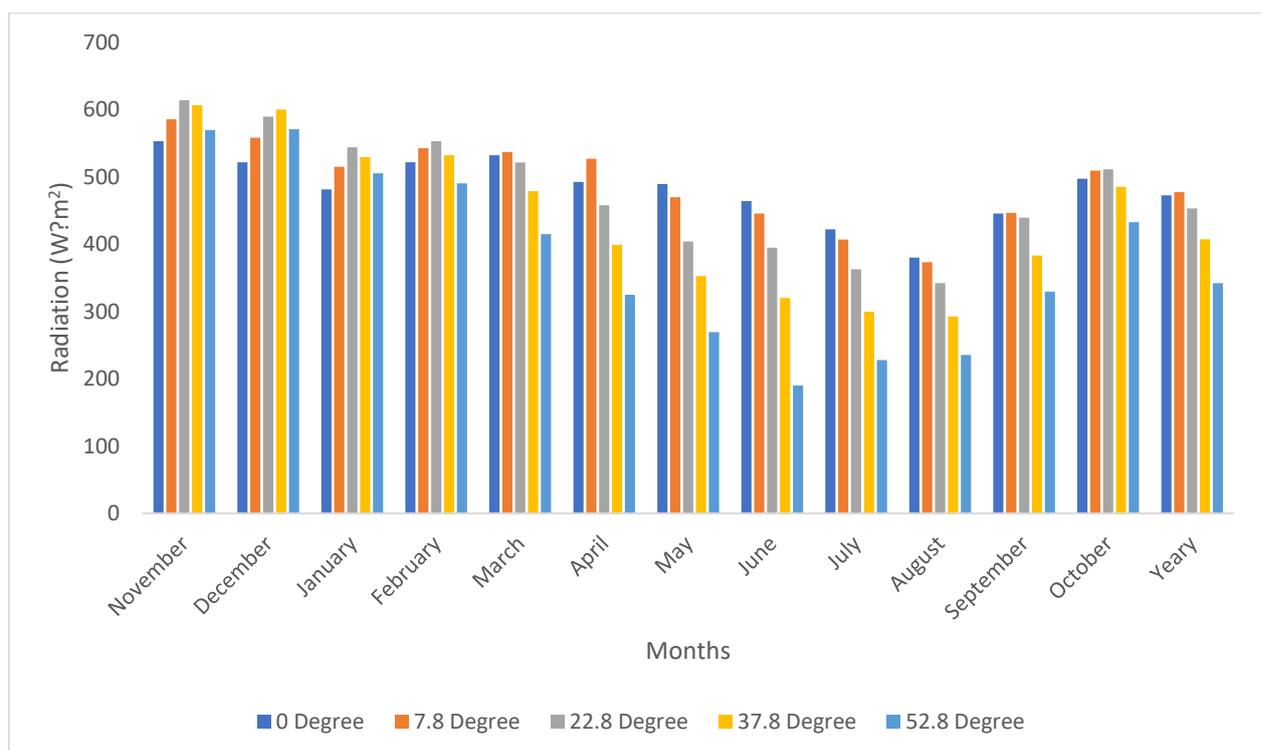


Figure 1: Radiation against month graph from November, 2023 to October, 2024

The analysis also highlights the impact of seasonal changes on solar radiation. During the dry season (November to March), clearer skies and higher solar intensity contribute to higher radiation values, particularly benefiting higher tilt angles like 22.8° . Conversely, the rainy season (April to October) is marked by increased cloud cover and shorter sunlight hours, which reduce overall radiation. In this period, lower tilt angles (0° and 7.8°) consistently outperform the steeper ones, likely due to the sun's more vertical path and diffuse light scattering. This seasonal insight emphasizes the importance of adapting tilt angles based on the local climate calendar.

3.1 Effect of Current at Different Tilt Angles

The current generated by the photovoltaic system is directly influenced by the solar radiation received by the panel. As radiation decreases with increasing tilt angles, the corresponding current values also show a downward trend. At 0° tilt angle, the current remains fairly stable throughout the year, with a yearly average of 0.300 A . In

November, the current is 0.320 A, corresponding to the high radiation value at this time of the year. At 7.8°, the current increases slightly, reaching 0.341 A in November and maintaining a yearly average of 0.302 A. This slight increase in current is due to the higher radiation captured at this angle in certain months. For 22.8°, the current in November is 0.343 A, with a yearly average of 0.289 A. The current values begin to decrease as the tilt angle moves beyond the optimal range for solar radiation capture. At 37.8°, the current continues to drop, with 0.311 A in November and a yearly average of 0.266 A. By the time the tilt angle reaches 52.8°, the current is significantly lower, at 0.306 A in November and 0.255 A on average over the year. The results clearly show that higher current values are achieved at lower tilt angles, corresponding with the higher radiation values at those angles.

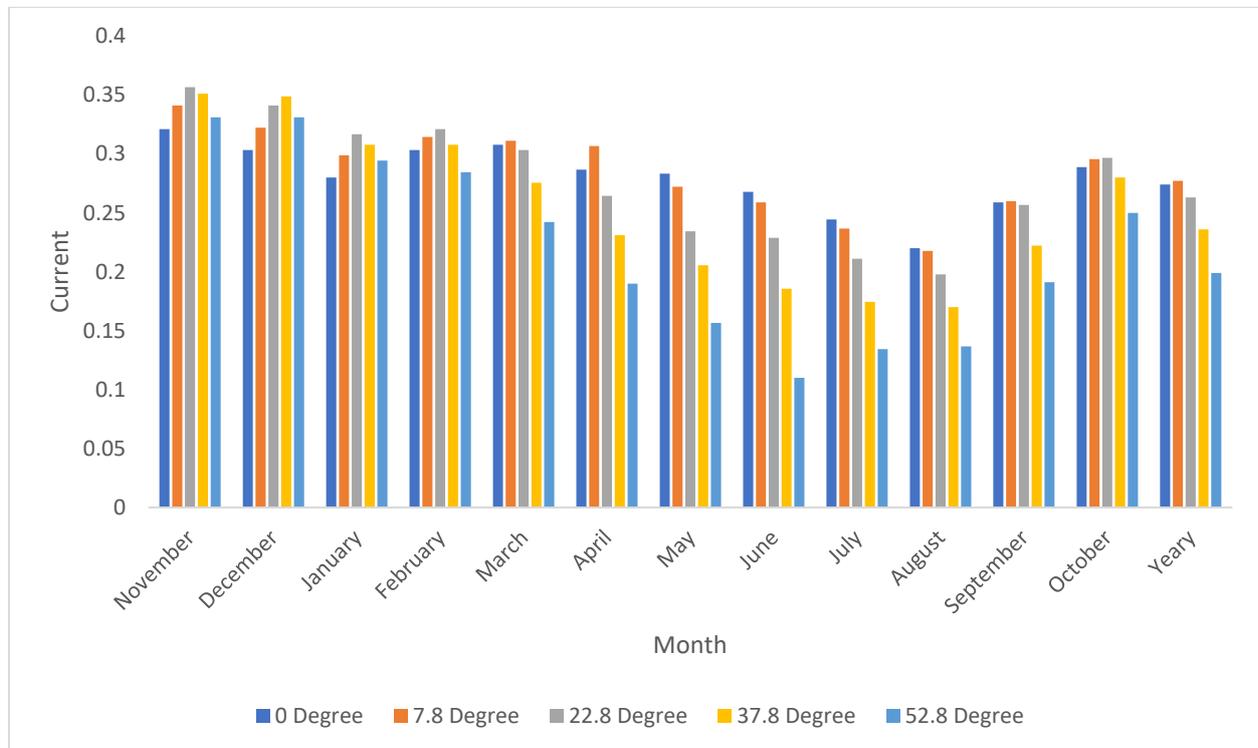


Figure 2: Experimental Current (A) against Month result from November, 2023 to October, 2024

3.2 Effect of Power at different Tilt Angles

The power output of the photovoltaic system is a function of both current and voltage. Since the voltage remains relatively constant throughout the measurements, the power output is primarily influenced by the current, which in turn depends on the incident solar radiation.

At a 0° tilt angle, the power output is relatively high due to higher current values, particularly in mid-year months. In November, the power output is 5.29 W, with a yearly average of 4.51 W. At 7.8°, the power output in November is slightly higher at 5.61 W, and the yearly average is 4.55 W. This slight improvement is due to increased current generation at this angle during certain parts of the year.

For a 22.8° tilt, the power output in November is 5.67 W, though the yearly average drops to 4.24 W, indicating that while this angle performs well in specific months (e.g., November and October), it is less consistent throughout the year. As the tilt angle increases further, the power output begins to decline. At 37.8°, the power in November is 5.14 W, with a yearly average of 3.65 W. By 52.8°, the power drops significantly to 4.93 W in November and only 3.28 W on average over the year.

These results show that power output follows the same trend as radiation and current, with higher values observed at lower tilt angles. The reduction in power at steeper angles is largely attributed to the decrease in both radiation exposure and current generation.

This highlights the importance of optimizing tilt angles for solar panel installations in Kogi State, Nigeria. The findings suggest that solar system designers and users should prioritize tilt angles between 0° and 22.8° to achieve maximum energy output. Considering the climatic and seasonal conditions in the region, implementing adjustable or optimized fixed-tilt systems within this range can significantly improve the overall efficiency and return on investment for solar energy systems.

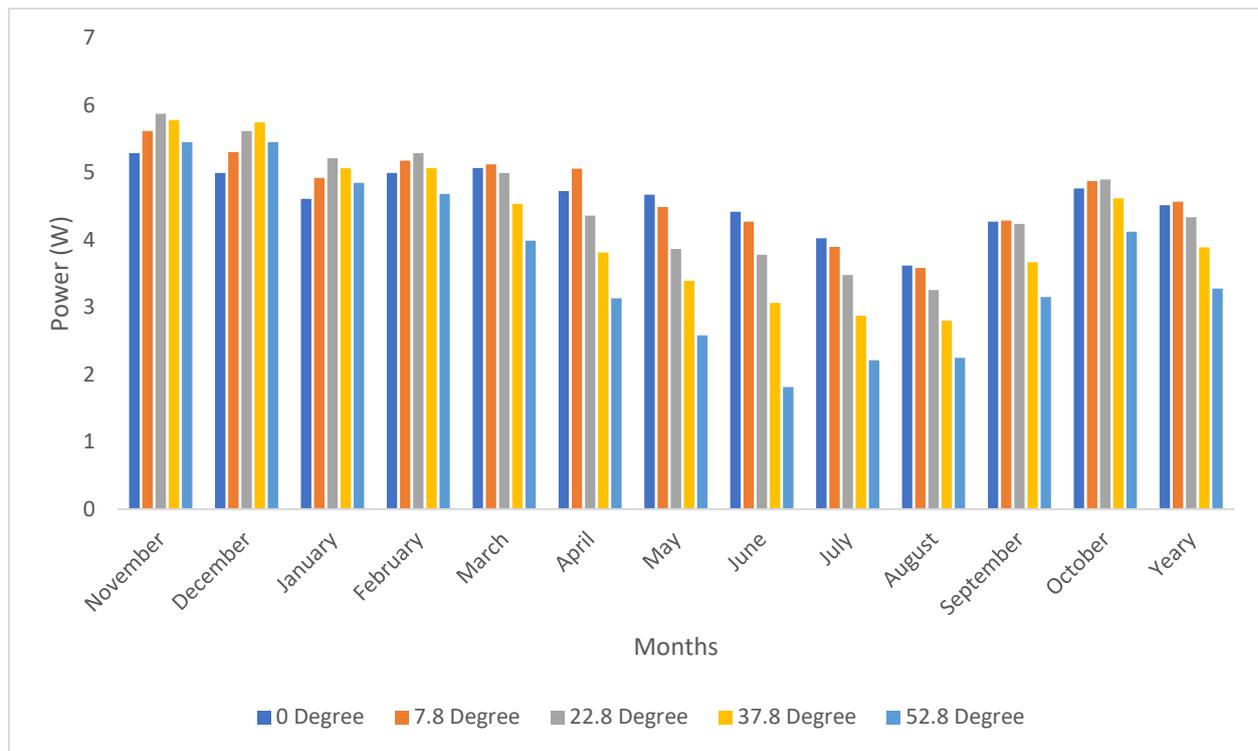


Figure 3: Power (W) against Month graph from November, 2023 to October, 2024

4.0 Conclusion

This study experimentally examined the effect of varying tilt angles (0° , 7.8° , 22.8° , 37.8° , and 52.8°) on the performance of 10W photovoltaic panels over a 12-month period in Kogi State, Nigeria. Results revealed that solar radiation, current, and power output varied with both tilt angle and seasonal changes. Notably, lower tilt angles (0° and 7.8°) performed better during the rainy season (April–October), while moderate tilt angles (22.8° – 37.8°) were more efficient in transitional dry months (November–March).

The 7.8° tilt angle recorded the highest average yearly solar radiation, while the 0° tilt yielded the highest average current (0.300 A) and power output (4.51 W). These findings indicate that adjusting panel tilt angles seasonally or adopting an optimized fixed angle can significantly improve the energy yield of small-scale solar installations in Nigeria's tropical climate.

More broadly, this study contributes to addressing the localized solar data gap in Kogi State, offering practical insight for the deployment of solar technologies in underserved areas. By optimizing tilt angles, system designers and solar developers can improve photovoltaic performance, thereby increasing access to clean electricity — especially in rural or off-grid communities. This has the potential to reduce dependence on fossil fuels, lower carbon emissions, and advance Nigeria's transition to renewable energy sources. From a policy standpoint, the study recommends that:

- Solar project developers in Kogi State adopt lower tilt angles (preferably 7.8°) as a baseline for fixed installations.
- Government and rural electrification agencies integrate tilt optimization strategies into off-grid solar programs.
- Technical standards and design guidelines for solar systems in Nigeria include location-specific tilt recommendations.

However, the study focuses solely on the effect of tilt angle. Other factors such as dust accumulation, temperature fluctuations, panel degradation, and shading were not considered, and these could influence real-world performance. Future research should investigate these additional parameters to provide a more comprehensive understanding of solar panel behavior in tropical environments.

Additionally, further studies could explore automated solar tracking systems or hybrid renewable energy models combining solar with battery storage or wind systems to enhance power availability and system resilience.

In conclusion, the study's findings have practical value for engineers, policymakers, and renewable energy stakeholders seeking to improve solar energy access and performance in Kogi State and similar regions across sub-Saharan Africa.

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