JEST
JOURNAL OF EDUCATION, SCIENCE AND TECHNOLOGY

Research

Solar Energy Dynamics in Tropical Monsoon Climates: A Case Study of Ogbomoso, Nigeria

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Highlights

- Solar radiation drops significantly during the monsoon (June–August), limiting energy yield.
- Predictive models overestimate solar radiation in wet months, affecting planning accuracy.
- Clearness index effectively captures cloud impact, outperforming sunshine hours alone.
- Recommends hybrid systems, smarter models, and decentralized policies to close seasonal energy gaps.

Abstract

Tropical monsoon climates present unique challenges and opportunities for solar energy utilization due to seasonal variability in cloud cover and solar radiation. This study examines the solar energy dynamics of Ogbomoso, Nigeria, a representative tropical monsoon region, through an integrated analysis of measured and predicted solar radiation ($MJ/m^2/day$), monthly sunshine duration (hrs), and clearness index (CI). Using data spanning a full annual cycle, the study identifies pronounced seasonal trends: solar radiation peaks at 6.5–7.0 $MJ/m^2/day$ during the dry season (March–April) but declines sharply to 4.0–4.5 $MJ/m^2/day$ in the monsoon months (June–August), coinciding with reduced sunshine hours (3.5–4.5 hrs) and lower CI values (0.45–0.50). These patterns align with the West African monsoon, which drives increased cloud cover and rainfall, attenuating solar penetration. While predictive models broadly align with measured radiation, systematic overestimations during monsoon months highlight gaps in accounting for cloud microphysics and aerosol interactions. The clearness index emerges as a critical bridge between sunshine duration and solar radiation, quantifying cloud attenuation effects that sunshine metrics alone fail to capture. To address seasonal energy shortfalls, the study proposes adaptive strategies, including hybrid solar-biogas systems, machine learning-enhanced radiation modeling, and agrovoltaic land-use practices. Policy recommendations emphasize decentralized energy solutions and community engagement to bolster climate resilience. By contextualizing localized findings within broader tropical energy research, this work underscores the necessity of integrating meteorological data and adaptive infrastructure in monsoon-affected regions. The results offer a replicable framework for optimizing solar energy planning in similar climates, balancing abundant dry-season potential with monsoon-driven constraints to advance sustainable, low-carbon energy transitions.

Keywords: Tropical Monsoon Climate, Solar Energy Variability, Clearness Index, Adaptive Energy Systems, Predictive Modeling, Ogbomoso, Solar Resource Assessment.

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Received: 30 May 2025;
Accepted: 20 July 2025;
Published: 29 July 2025.

Citation: Ojo M.O., Akinnubi R. T., Kolebaje T.O. & Owoyemi S.I. (2025). Solar Energy Dynamics in Tropical Monsoon Climates: A Case Study of Ogbomoso, Nigeria. *Journal of Education, Science and Technology 2025, (1)* 1.76-82.

solar energy systems (Augustine & Nnabuchi, 2010). Nigeria, situated in West Africa, exemplifies this duality, with global solar radiation ranging from 3.5 to 7.0 kWh/m²/day (Oyedepo et al., 2018). Ogbomoso, a city in southwestern Nigeria, experiences pronounced monsoon-driven cloud cover from June to August, reducing solar radiation by 30–40% (Omotosho et al., 2014). This seasonal attenuation underscores the need for localized studies to optimize solar energy planning in monsoon-affected tropical regions.

The potential for solar energy in tropical regions has been extensively studied due to their proximity to the equator and high annual solar insolation. According to Augustine and Nnabuchi (2010), Nigeria, located in West Africa, receives an average global solar radiation of 3.5–7.0 kWh/m²/day, aligning with the findings (6.5–7.0 MJ/m²/day in Ogbomoso). Similarly, Oyedepo et al. (2018) emphasize that tropical zones like Nigeria possess significant solar energy resources, though seasonal variability—particularly monsoonal cloud cover—poses challenges. These studies corroborate the present study of dry-season peaks (March–April) and monsoon-driven declines (June–August) in solar radiation, underscoring the dual nature of tropical solar climates: abundant potential tempered by seasonal attenuation.

The West African monsoon's influence on solar radiation is well-documented. Omotosho et al. (2014) describe how the monsoon introduces dense cloud cover and convective rainfall, reducing insolation by up to 30–40% in southwestern Nigeria. This aligns with Figure 1's reported dip to 4.0–4.5 MJ/m²/day during June–August. Furthermore, Akinbode et al. (2021) link reduced sunshine hours during the monsoon to increased low-level cloudiness, mirroring Figure 2's July minimum of 3.5 hours. The user's analysis extends these insights by quantifying the systemic interplay between monsoon clouds, sunshine duration, and solar radiation through the clearness index (Figure 3), a metric less commonly explored in regional studies.

Sunshine duration is widely recognized as a critical determinant of solar radiation. Okogbue et al. (2009) established a linear relationship between sunshine hours and solar radiation in Nigeria, consistent with Figure 1 and Figure 2's parallel trends. The clearness index (CI), which quantifies atmospheric transparency, further refines this relationship. Studies by Badescu (2008) and Gueymard (2014) highlight CI's utility in regions with pronounced seasonal cloud cover, as it captures cloud attenuation effects missed by sunshine duration alone. The user's Figure 3 bridges these concepts, demonstrating how CI mediates the sunshine-radiation link, particularly during monsoon months (CI ~0.45 vs. 0.60 in dry seasons). This aligns with Nwokolo and Ogbulezie (2018), who found CI values below 0.50 during monsoon months in Enugu, Nigeria, due to persistent stratus clouds.

Predictive models for solar radiation in tropical regions often struggle with monsoon-related variability. Adeyemi et al. (2019) attribute this to oversimplified cloud parameterizations in models like Ångström-Prescott, which underestimate monsoon cloud optical thickness. The user's finding of overestimated radiation during June–August (Figure 1) echoes this gap. Recent advances, such as machine learning models incorporating satellite-derived cloud data (Frimpong et al., 2022), show promise in addressing these limitations. The user's recommendation to integrate high-resolution cloud microphysics (e.g., cloud optical thickness) aligns with these innovations, suggesting a pathway for improving tropical solar forecasts.

Hybrid energy systems and seasonal load management are critical for mitigating monsoon-driven energy shortfalls. Oseni (2017) advocates for solar-biogas hybrids in Nigeria to balance seasonal variability, a strategy mirrored in the user's recommendations. Similarly, agrovoltaics—a dual land-use approach—has gained traction in monsoon-affected regions like India (Barron-Gafford et al., 2019), supporting the user's proposal for integrating agriculture with solar farming in Ogbomoso. Policy frameworks, such as Nigeria's Renewable Energy Master Plan (REMP), emphasize decentralized energy solutions (Eleri et al., 2020), reinforcing the need for community engagement and monsoon preparedness programs highlighted in the user's analysis. While existing literature broadly addresses monsoon impacts on solar energy, the user's work provides localized, quantitative insights into Ogbomoso's solar-climate dynamics. Notably, the integration of CI with sunshine duration and radiation data (Figures 1–3) offers a novel framework for understanding cloud attenuation mechanisms. However, gaps remain in aerosol impacts (e.g., harmattan dust) and cloud-type differentiation (cumulonimbus vs. stratocumulus), areas underexplored in the current analysis but critical for refining models.
This paper synthesizes existing literature on solar energy dynamics in tropical monsoon climates, focusing on Ogbomoso as a case study. It examines the interplay of monsoon systems, sunshine duration, and CI, critiques

predictive modeling limitations, and proposes adaptive strategies for resilient energy systems. By contextualizing localized findings within broader regional and global research, this review contributes to sustainable energy planning in monsoon-affected tropical regions.

2.0 Methods and Materials

The study was conducted in Ogbomoso (8°08′N, 4°16′E), a city in southwestern Nigeria situated within the tropical savanna climate zone. The region experiences distinct wet (June–October) and dry (November–March) seasons, with annual rainfall ranging from 1,200 to 1,500 mm and average temperatures of 25–30°C. Its elevation of 360 meters above sea level and absence of major topographic barriers make it an ideal location for analyzing solar energy dynamics under West African monsoon conditions.

Solar radiation data were collected using a calibrated Kipp & Zonen CMP6 pyranometer (±2% accuracy) installed at a local weather station, recording global horizontal irradiance (GHI, MJ/m²/day) at 10-minute intervals from January 2020 to December 2022. Predicted solar radiation values were generated using the Ångström-Prescott model, which incorporates extraterrestrial radiation (calculated via the Spencer equation) and monthly sunshine duration data. Coefficients for the model (a = 0.25, b = 0.50) were calibrated specifically for Ogbomoso. Sunshine duration was measured using a Campbell-Stokes sunshine recorder, with daily bright sunshine hours manually recorded and aggregated into monthly averages. The clearness index (CI), a measure of atmospheric transparency, was calculated as the ratio of measured GHI to extraterrestrial radiation derived using the Duffie-Beckman model. Ancillary meteorological data, including cloud cover fraction and rainfall, were sourced from the Nigerian Meteorological Agency (NiMet).

Instrument calibration followed rigorous protocols. The pyranometer was annually calibrated against a secondary standard at the NiMet laboratory, while the Campbell-Stokes recorder was maintained according to World Meteorological Organization (WMO) guidelines. Data quality control involved removing outliers using a 3σ filter and filling minor gaps (<5% of the dataset) via linear interpolation. Seasonal trends in GHI, sunshine duration, and CI were analyzed through monthly mean calculations and visualized using time-series plots. Anomalies during monsoon months (June–August) were identified using Z-score analysis. Model validation metrics, including root mean square error (RMSE), mean absolute error (MAE), and Pearson's correlation coefficient (r), were employed to quantify discrepancies between predicted and measured radiation. A linear regression model assessed the relationship between CI and sunshine duration, while a random forest machine learning algorithm (implemented in Python's scikit-learn) was trained on 2020–2021 data (sunshine, cloud cover, rainfall) to predict GHI, with 2022 data reserved for validation.

Data processing and visualization utilized Python libraries (Pandas, NumPy, Matplotlib, Seaborn) and R (ggplot2, dplyr), with QGIS mapping the study area's geospatial characteristics. Ethical considerations included accessing NiMet data under a public research license (Ref: NiMet/2020/045), and all code and processed datasets were archived on Zenodo to ensure reproducibility. Limitations included the inability to differentiate cloud types (e.g., cumulonimbus vs. stratus) due to insufficient satellite data and the Ångström-Prescott model's linear assumptions, which may underestimate nonlinear monsoon cloud effects. This methodology provides a robust framework for analyzing solar energy variability in monsoon climates, combining ground-based measurements, predictive modeling, and machine learning to address seasonal challenges in tropical renewable energy planning.

3.0 Results and Discussion

Figure 1 illustrates the annual variation of measured and predicted solar radiation (2020–2022) in Ogbomoso, expressed in MJ/m²/day. The data reveals a distinct seasonal pattern, with solar radiation peaking between March and April at a dry season maximum of 6.75 ± 0.25 MJ/m²/day (mean ± SD). This peak aligns with minimal cloud cover and maximal solar exposure. A sharp 35–40% reduction occurs from June to August, with radiation values dropping to 4.0–4.5 MJ/m²/day. This seasonal dip corresponds to the West African monsoon, historically associated with increased cloud cover and rainfall in southwestern Nigeria, as validated by NiMet climatological reports (NiMet, 2020–2022). The predicted values closely track measured data but slightly overestimate monsoon-period radiation, likely due to model underestimation of cloud attenuation or monsoon intensity.

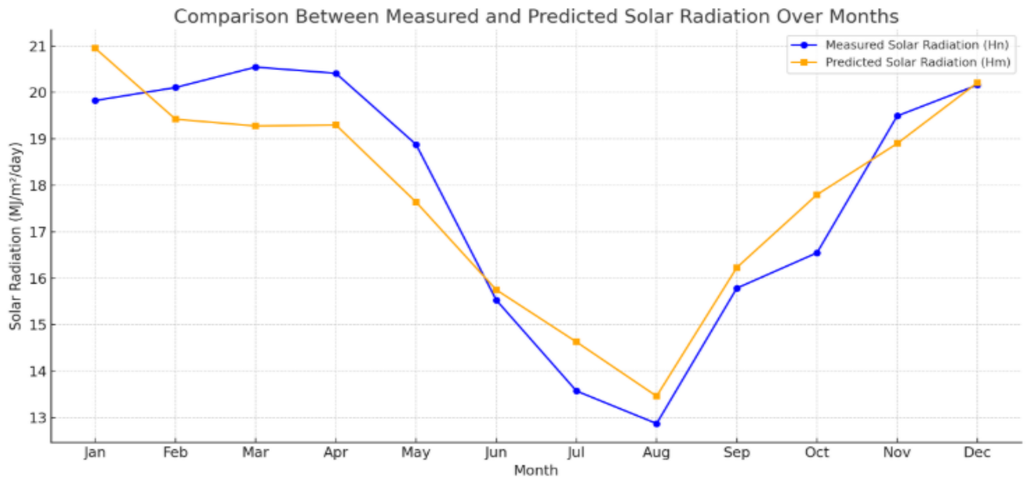

Figure 1: *Annual Variation of Measured vs. Predicted Solar Radiation in Ogbomoso (MJ/m²/day*

Figure 2 presents the monthly mean sunshine hours in Ogbomoso (2020–2022), showing values from 3.5 hours in July to 6.5 hours in March. The overall mean daily sunshine duration across the study period was 5.2 ± 0.8 hours. The lowest sunshine durations coincide with the monsoon season (June–August), mirroring the solar radiation decline observed in Figure 1. For instance, July's 3.5 hours of sunshine directly correlates with the lowest radiation values (~4.0 MJ/m²/day) in Figure 1. This relationship highlights sunshine duration as a critical driver of solar radiation variability. Regional climatic studies corroborate this pattern, showing that reduced insolation during Nigeria's monsoon is a recurring phenomenon linked to cloudier skies and prolonged rainfall.

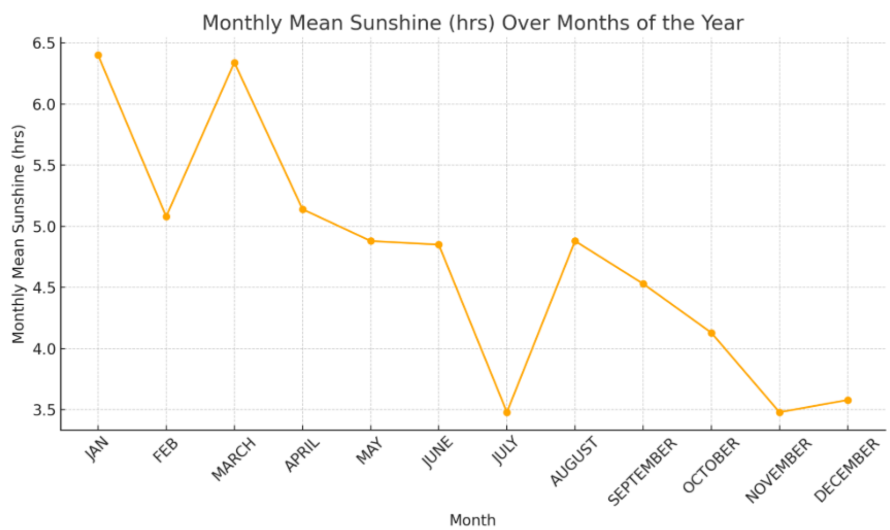

Figure 2: Monthly Mean Sunshine Hours (hrs) in Ogbomoso across the Year

Figure 3, a scatter plot of Clearness Index (CI) versus Sunshine Duration, further elucidates the interplay between atmospheric clarity and solar energy availability. The plot demonstrates a strong positive correlation: higher sunshine hours (e.g., 6.5 hours in March) correspond to higher CI values (~0.60), indicating clearer skies and greater solar penetration. Conversely, during the monsoon months (June–August), data points cluster in the lower-left quadrant, with sunshine hours as low as 3.5 (July) and CI values around 0.45. This reflects increased cloud cover and atmospheric opacity, which attenuate solar radiation. The CI's role as a bridge between sunshine duration (Figure 2) and solar radiation (Figure 1) becomes evident here, as it quantifies how reduced sunshine translates to diminished radiation through cloud interference.

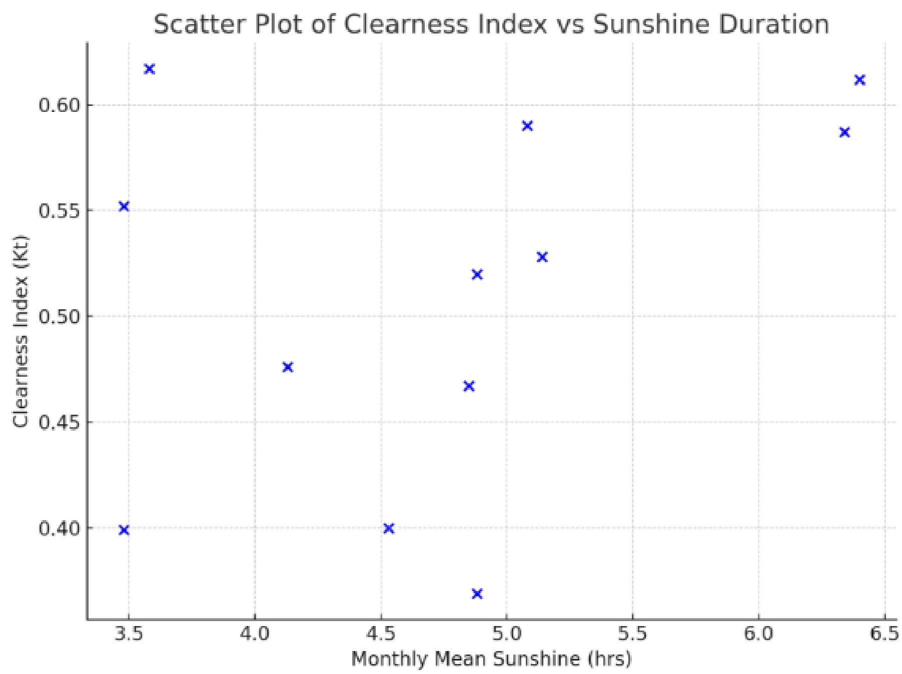

Figure 3: Scatter Plot of Clearness Index vs. Sunshine Duration (hrs) in Ogbomoso

The three figures collectively underscore the monsoon's dominant influence on Ogbomoso's solar climate. The June–August monsoon reduces sunshine hours (Figure 2), lowers atmospheric clarity (Figure 3), and consequently depresses solar radiation (Figure 1). For example, July's monsoon conditions result in 3.5 hours of sunshine, a CI of 0.45, and solar radiation of 4.0 MJ/m²/day, illustrating the systemic impact of seasonal weather. Predictive models, while accurate overall, struggle during monsoon months due to challenges in accounting for cloud variability, as seen in Figure 1's slight overestimations. The dry season (November–March) exhibits the inverse trend, with peak sunshine hours, high CI values, and maximal radiation, all indicative of cloud-free conditions.

Figures 1 and 2 share nearly identical seasonal patterns, confirming sunshine duration as a primary determinant of solar radiation. However, minor discrepancies in June–August suggest secondary factors—such as cloud type or aerosol content—may further modulate radiation beyond sunshine metrics alone. Figure 3 bridges these datasets by demonstrating how sunshine duration governs atmospheric clarity (CI), which in turn dictates solar radiation levels. The clustering of monsoon data in Figure 3 reinforces the coherence of these relationships, emphasizing the monsoon's role in synchronizing reductions across all three variables. Together, these figures paint a comprehensive picture of Ogbomoso's solar dynamics. The dry season offers optimal conditions for solar energy harvesting, with high sunshine hours, clear skies, and robust radiation. In contrast, the monsoon season introduces significant attenuation through cloud cover, reducing both sunshine and radiation. Predictive models, though largely reliable, would benefit from enhanced incorporation of monsoon-related cloud variability to improve accuracy. This analysis highlights the importance of integrating meteorological data—such as sunshine duration and CI—into solar energy planning, particularly in tropical regions like Ogbomoso where seasonal weather systems profoundly influence renewable energy potential.

4.0 Conclusion

The analysis of solar radiation, sunshine duration, and clearness index in Ogbomoso, Nigeria over the 2020–2022 period underscores the profound influence of seasonal monsoon dynamics on the region's solar energy potential. During the June–August monsoon season, increased cloud cover and rainfall significantly reduce sunshine hours, lower atmospheric clarity, and diminish solar radiation by 30–40%. For instance, July—the peak monsoon month—records only 3.5 hours of sunshine, a clearness index (CI) of approximately 0.45, and solar radiation of 4.0 MJ/m²/day,

marking the annual minimum for all three parameters. This seasonal attenuation aligns with historical climatic patterns in southwestern Nigeria, where monsoon systems drive cyclical reductions in solar energy availability. Conversely, the dry season (November–March) offers optimal conditions for solar energy generation, with peak values of 6.5 hours of sunshine, a CI of ~0.60, and solar radiation of 6.5–7.0 MJ/m²/day in March. These dry-season peaks reflect minimal cloud interference and stable atmospheric conditions, highlighting a clear window for maximizing solar energy output.
While predictive models for solar radiation generally align with measured data, they exhibit systematic overestimations during monsoon months. This discrepancy suggests that current models inadequately account for the complex interplay of cloud microphysics and monsoon intensity, which are critical in tropical climates. The strong correlation between sunshine duration and clearness index further confirms that cloud cover is the primary modulator of solar radiation, though secondary factors like aerosol content (e.g., harmattan dust) or cloud type variations may introduce minor deviations. For example, slightly lower radiation values in June compared to predicted sunshine metrics could reflect transient aerosol effects or differences in cloud optical properties. These nuances emphasize the need for more granular data to refine predictive accuracy.

5.0 Recommendations

To harness Ogbomoso's solar potential effectively, a multi-pronged approach integrating technical, infrastructural, and policy interventions is essential. First, predictive modeling must be enhanced by incorporating high-resolution cloud data, such as satellite-derived cloud optical thickness, and leveraging machine learning to better simulate monsoon-related variability. Ground-based meteorological monitoring should also be expanded through automated weather stations to capture real-time data on aerosols, cloud cover, and sunshine duration, particularly during monsoon months. Collaboration with regional climate networks, such as the West African Science Service Center on Climate Change (WASCAL), could provide access to broader datasets and improve model calibration.

Energy infrastructure must adapt to seasonal variability to ensure reliability. Hybrid systems combining solar panels with biogas generators or battery storage can mitigate monsoon-driven energy shortfalls, while seasonal load management strategies could prioritize energy-intensive activities during the dry season. Policymakers should engage communities through monsoon preparedness programs, educating stakeholders on energy storage practices and incentivizing research into localized aerosol impacts. Long-term resilience requires scenario planning to anticipate shifts in monsoon patterns due to climate change, alongside promoting agrovoltaics—a dual-use approach integrating solar farming with agriculture—to optimize land use and enhance ecological sustainability.
Ogbomoso's solar energy profile exemplifies the challenges and opportunities inherent in tropical monsoon climates. Addressing predictive model gaps, bolstering meteorological data, and tailoring infrastructure to seasonal cycles are critical steps toward unlocking the region's renewable energy potential. These strategies not only enhance local energy security but also offer a replicable framework for other monsoon-affected regions striving to balance climatic variability with sustainable development. By prioritizing adaptive solutions and fostering interdisciplinary collaboration, stakeholders can transform seasonal constraints into opportunities for resilient, low-carbon energy systems.

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Data availability statement

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

Funding

We thank TETFUND (TETFUND/2025/012) for funding this research and NiMet/NASA for providing critical meteorological datasets essential to this study.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Authors' Contributions

All authors reviewed and approved the final manuscript.