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Development of MATLAB-Based Model for Solar Radiation Prediction and Photovoltaic Panel Tilt Optimization Angle for Maiduguri Region, Nigeria

Muhammad M. HAMIDU

Department of Mechanical Engineering, University of Maiduguri, Maiduguri, Nigeria

muhammadhamidu@unimaid.edu.ng

Abstract

This study presents a MATLAB-developed computational model for estimating the optimum solar photovoltaic (PV) tilt angle and tilted for harnessing solar radiation for Maiduguri, Nigeria, using measured data from the Nigerian Meteorological Agency (NiMet). The study tackles the lack of tilt angle optimization frameworks and region-specific MATLAB-based solar radiation models for Maiduguri's semi-arid climate, which restricts the effectiveness of PV system design and implementation. The objectives of this work are to create a MATLAB-based simulation for estimating the best tilt and solar radiation, validate the model using actual NiMet data, and assess seasonal variations and energy gains that tilt optimization could provide. Solar geometry equations and the concepts of isotropic sky radiation were used to implement the model in MATLAB. The model calculated the corresponding tilted radiation, clearness index, and energy gain after processing monthly global horizontal irradiance data. The statistical results show that the modeled values are in good agreement with the measured data. The Mean Bias Error (0.183 kWh/m²/day) is very small, indicating minimal deviation between the two sets of values. The Root Mean Square Error (0.256 kWh/m²/day) is also low, suggesting that the overall difference between modeled and measured values is minor compared to the average daily solar radiation. The Coefficient of Determination ($R^2 = 0.627$) shows that the model explains about 63% of the variation in the measured data, which is considered an acceptable level of accuracy in solar radiation modeling. According to the MATLAB results, the ideal tilt angles ranged from 10.6° during the rainy season to 21.8° during the dry season, with an average yearly energy gain of 3.9% when compared to horizontal surfaces. The results validate the model's dependability in semi-arid climates and are consistent with earlier research conducted in northern Nigeria. The research revealed that the MATLAB-based model can improve Maiduguri PV system performance and effectively improve solar energy estimation. Future studies should include dust attenuation and anisotropic radiation models for increased accuracy during the Harmattan period, and the model should be incorporated into HOMER Pro and AI-driven optimization tools.

Keywords: *Solar radiation, MATLAB model, optimum tilt angle, Maiduguri, PV system optimization.*

1.0 Introduction

Solar energy remains one of the most sustainable and abundant renewable resources available for addressing the increasing global energy demand and climate challenges. The effectiveness of photovoltaic (PV) systems largely depends on accurate estimation of solar radiation and proper determination of panel orientation, particularly the tilt angle. The tilt angle governs the amount of incident solar energy received by PV modules and, therefore, directly influences energy yield and system performance [1]. In Nigeria, frequent grid instability and limited electricity access make solar energy deployment a strategic necessity, especially across the northern regions where high solar potential exists [2]. Maiduguri is located at latitude 11.83° N and longitude 13.15° E, it lies within the Sahelian climatic zone characterized by high direct beam radiation and frequent dust occurrences. The city records an average daily solar irradiance exceeding 6.5 kWh/m², offering exceptional potential for PV applications. However, the absence of localized and validated solar radiation models for Maiduguri's semi-arid atmosphere restricts system optimization and investment confidence.

Previous Nigerian studies on solar energy, such as Abdullahi *et al.* [3] for Kano and Augustine and Nnabuchi (2010) for southeastern regions, developed empirical correlations for tilt-angle estimation. While these models provided valuable insights, they relied primarily on generalized relationships and lacked integration with measured meteorological data specific to the Maiduguri region. Similarly, regional studies by Hassan *et al.* [4] and Nwokolo et al. [5] employed regression or Angström–Prescott models, but none incorporated real NiMet datasets into MATLAB-based computational environments. Recent advances in solar modeling have introduced hybrid and intelligent systems for tilt angle optimization. For example, Zhou *et al.* [6] used a machine learning-based approach for PV tilt prediction, while Adebayo *et al.* [7] applied AI optimization to tropical climates. Beyond Nigeria, works such as Ouf *et al.* [8] in Egypt and Li *et al.* [9] in northern China demonstrated that region-specific modeling significantly improves radiation estimation accuracy under semi-arid and dusty conditions. However, these frameworks have not yet been localized for the West African Sahel. This study bridges that gap by developing a MATLAB-based computational model for solar radiation and optimum tilt angle estimation tailored to Maiduguri solar radiation. The model integrates ground-measured NiMet data with validated solar geometry equations to produce reliable monthly irradiance and tilt angle values. It also evaluates seasonal energy gains achievable through tilt angle optimization, which has not been extensively quantified for this region.

Key Contributions

1. Development of the first MATLAB-based solar radiation and tilt model specifically calibrated and validated for Maiduguri using NiMet data.
2. Integration of measured meteorological data with classical solar geometry and isotropic sky equations for region-specific radiation estimation.
3. Provision of a replicable computational framework that can be expanded into AI-driven optimization, IoT-based monitoring, and hybrid microgrid design suitable for northern Nigeria's energy landscape.

By contextualizing solar geometry to Maiduguri's semi-arid climate, this research contributes to more accurate PV design, improved energy yield prediction, and informed policy development for sustainable power systems in the Sahel region

2.0 Materials and Methods

2.1 Study Area

Maiduguri is located at latitude 11.83° N and longitude 13.15° E, approximately 354 meters above sea level, within the Sahelian region of northeastern Nigeria. The area experiences an extended dry season from October to April and a shorter wet season from May to September annually. Annual mean temperature of the study area ranges between 25°C and 38°C, and average daily solar irradiance is typically between 5.5 and 6.7 kWh/m²/day [10]. These climatic features, combined with frequent clear skies, make Maiduguri a representative location for semi-arid solar modeling and PV performance evaluation. Figure 1 presents the map of Nigeria, Borno State and Maiduguri (the study area) in specific.

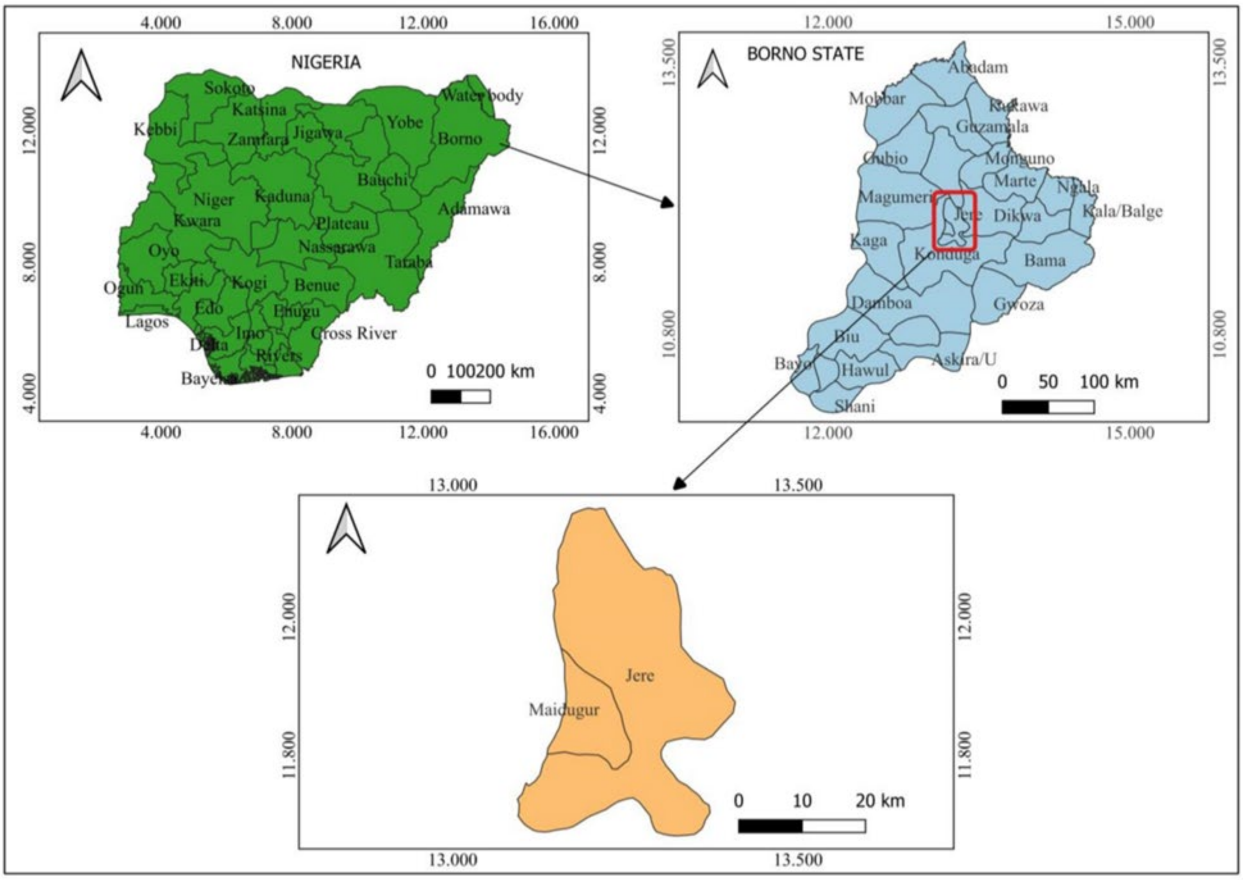

Figure 1. Map of the Study area Adopted from [11]

2.2 Data Collection and Pre-processing

Monthly mean daily global horizontal irradiance (GHI) data for Maiduguri were obtained from the Nigerian Meteorological Agency (NiMet. The raw data, initially recorded in megajoules per square meter per day (MJ/m²/day), were converted into kilowatt-hours per square meter per day (kWh/m²/day) using the standard relationship [12] and then Equation 1 was obtained after the conversion:

$$1 \text{ MJ/m}^2\text{/day} = 0.2778 \text{ kWh/m}^2\text{/day} \quad (1)$$

Data quality checks were performed before model implementation. Missing or anomalous values were detected using a two-step procedure:

1. Monthly GHI values deviating more than ±2 standard deviations from the mean were flagged.
2. Missing or flagged values were replaced using neighboring monthly averages to preserve trend continuity.

This preprocessing ensured data consistency and avoided bias in model validation.

2.3 Solar Radiation and Tilt Modeling

The MATLAB model was developed based on fundamental solar geometry relationships and isotropic sky radiation assumptions, following Duffie and Beckman [1] and Liu and Jordan [13] methods. The key computational equations used include: Solar Declination, Extraterrestrial Radiation on Horizontal Surface, Sunset Hour Angle, Clearness Index, Optimum Tilt Angle and Tilted Solar Radiation.

1. **The Solar Declination (δ) was calculated using Equation 2** [1. 13]

$$\delta = 23.45^{o} \times \sin\left(\frac{360}{365}(284+n)\right) \tag{2}$$

where n is the day of the year.

2. **Sunset Hour Angle (ω_s)** was calculated using Equation 3 [1. 13]

$$\omega_s = cos^{-1}(-\tan\emptyset \times \tan\delta) \tag{3}$$

where $\emptyset$ is latitude.

3. **Extraterrestrial Radiation on Horizontal Surface (H_0)** was calculated using Equation 4 [1. 13]:

$$H_o = \frac{24 \times 3600}{\pi} \times G_s \times \left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right] \times \left[cos\emptyset\, cos\,\delta \sin\omega_s + \frac{\pi\omega_s}{180} sin\emptyset sin\omega_s\right] \tag{4}$$

where $G_s = 1367\, w/m^2$

4. **Clearness Index (K_t)** was determined using Equation 5[1. 13]:

$$K_t = \frac{H}{H_o} \tag{5}$$

where H is the measured horizontal solar radiation.

5. **Optimum Tilt Angle** (β_{opt} was calculated using Equation 6 [1. 13]

$$\beta_{opt} = \begin{cases} \emptyset + 10^{0} & (Dry\ season:\ October - March) \\ 0.9 \times \emptyset & (Wet\ season:\ April - septepter) \end{cases} \tag{6}$$

6. **Tilted Solar Radiation (H_t)** was calculated using Equation 7 [1. 13]

$$H_b\, R_b + H_d\left(\frac{1+\cos\beta_{opt}}{2}\right) + H_{pg}\left(\frac{1-\cos\beta_{opt}}{2}\right) \tag{7}$$

where H_b and H_d are beam and diffuse radiation component respectively, pg = 0.2 is ground reflectance, and R_b is the tilt factor calculate using solar geometry from Duffie and Beckman [1].

2.4 Model Implementation in MATLAB

The simulation workflow in MATLAB was designed to ensure reproducibility and computational efficiency. The algorithm followed these main steps as summarize in Figure 2.

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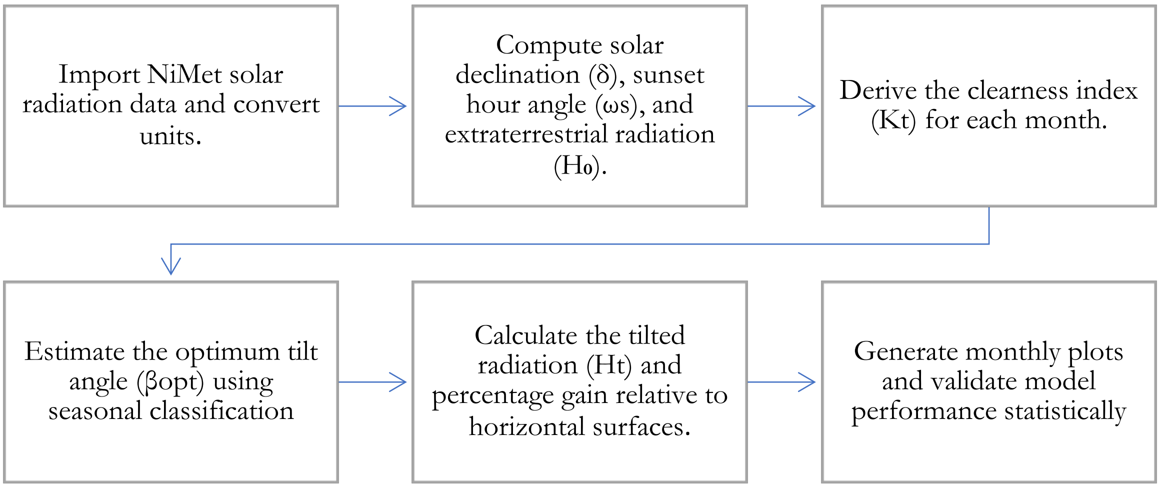

Figure 2. Flowchart of the MATLAB-based solar radiation modeling and validation process

This structure allows flexibility to modify parameters for other Nigerian cities or semi-arid regions with minimal changes in the input data file.

2.5 Statistical Validation and Model Reliability

The model's performance was validated against measured NiMet radiation data using three statistical indicators namely; Mean Bias Error, Root Mean Square Error, and Coefficient of Determination [14]:

1. **Mean Bias Error (MBE):**

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(H_{t,model,i} - H_{t,measured,i}) \tag{8}$$

2. **Root Mean Square Error (RMSE):**

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(H_{t,model,i} - H_{t,measured,i})^2} \tag{9}$$

3. **Coefficient of Determination (R²):**

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(H_{t,model,i} - H_{t,measured,i})^2}{\sum_{i=1}^{N}(H_{t,measured,i} - H_{t,model,i})^2} \tag{10}$$

These metrics comprehensive assess bias, error magnitude, and correlation strength, evidencing model validity.

2.6 Assumptions and Limitations

The model assumes that:

1. The **sky is isotropic,** meaning diffuse radiation is uniformly distributed. This assumption holds well in Maiduguri's clear-sky conditions but may cause slight overestimation during Harmattan months when dust particles scatter sunlight.
2. Monthly averages are representative of each period, which smooth's short-term fluctuations.
3. Ground reflectance **(**pg = 0.2) is constant, although it may vary with surface type.

Limitations include the absence of explicit **dust attenuation** and **anisotropic sky models.** These factors will be incorporated in future versions for improved accuracy during dusty and cloudy periods.

2.7 Reproducibility and Model Adaptation

The MATLAB code was designed to be modular, allowing users to modify parameters such as latitude, clearness index, or solar constants for different locations. With minimal data adjustment, the model can be adapted for other Nigerian or Sahelian cities, supporting regional renewable energy studies and hybrid system design.

3.0 Results and Discussion

3.1 Data Quality Assurance and Preprocessing

The NiMet solar radiation dataset for Maiduguri was carefully screened to ensure accuracy before modeling. Missing values were detected and corrected using linear interpolation, while anomalous entries outside ±2 standard deviations were removed to maintain consistency. After correction, monthly average global horizontal irradiance (GHI) values ranged between 5.2 and 6.6 kWh/m²/day, which is consistent with long-term radiation levels reported for northern Nigeria by Akpootu *et al.* [2] and Nwokolo *et al.* [5]. The smooth and consistent seasonal pattern observed (Figure 3) reflects the city's strong solar potential, dominated by clear skies and minimal cloud interference during most months. The reliability of the processed data provided a strong foundation for the MATLAB model's calibration and validation

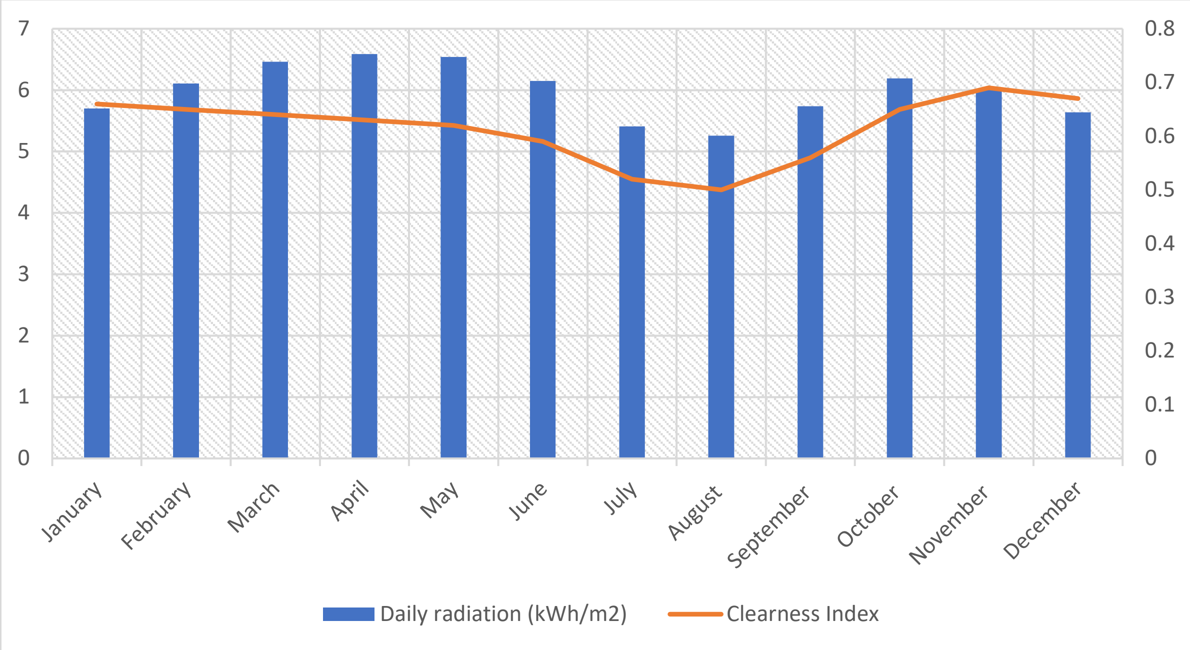

Figure 3: Preprocessed NiMet average monthly GHI dataset after anomaly correction and interpolation.

3.2 Computed Solar Geometry and Optimum Tilt Angles

The MATLAB-generated solar declination and sunset hour angles were used to determine monthly extraterrestrial radiation. Derived optimum tilt angles (β_{opt}) demonstrated a predictable seasonal variation pattern. As shown in Figure 4, values ranged from 10.6° during the wet months (April–September) to 21.8° during dry months (October–March). These values align closely with the theoretical relationship between latitude and solar declination for locations near 12° N. The results also compare well with findings from Abdullahi *et al.* [3] for Kano (20°–24°) and Akpootu *et al.* [2], who reported seasonal tilt changes between 9°–22° across northern Nigeria. This confirms that the MATLAB model correctly represents solar geometry for Maiduguri's semi-arid environment.

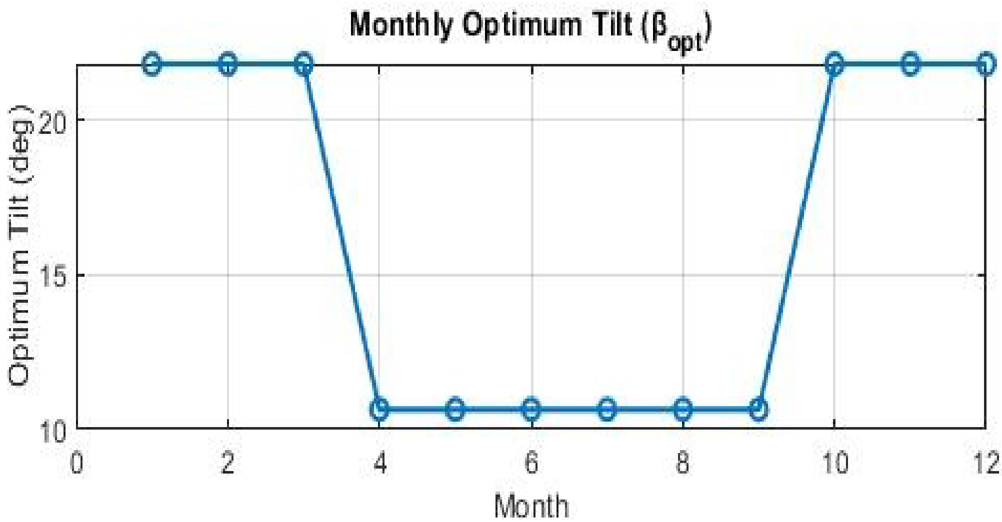

Figure 4: Monthly optimum tilt angle (β_{opt})) profile generated from solar geometry principles.

3.3 Comparison between Horizontal and Tilted Radiation

Figure 5 compares the monthly solar radiation received on horizontal and optimally tilted surfaces. The model shows that tilted surfaces capture consistently higher irradiance throughout the year, with the most notable difference during dry months dominated by beam radiation. The average energy gain from applying seasonal tilt adjustments was 3.9% per year, with peaks of approximately 6% during the dry season. These improvements are within the range (3–7%) reported by Elminir *et al.* [15] and El-Sebaii *et al.* [16] for other semi-arid locations. The

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results indicate that modest tilt adjustments can significantly enhance system performance without complex tracking mechanism.

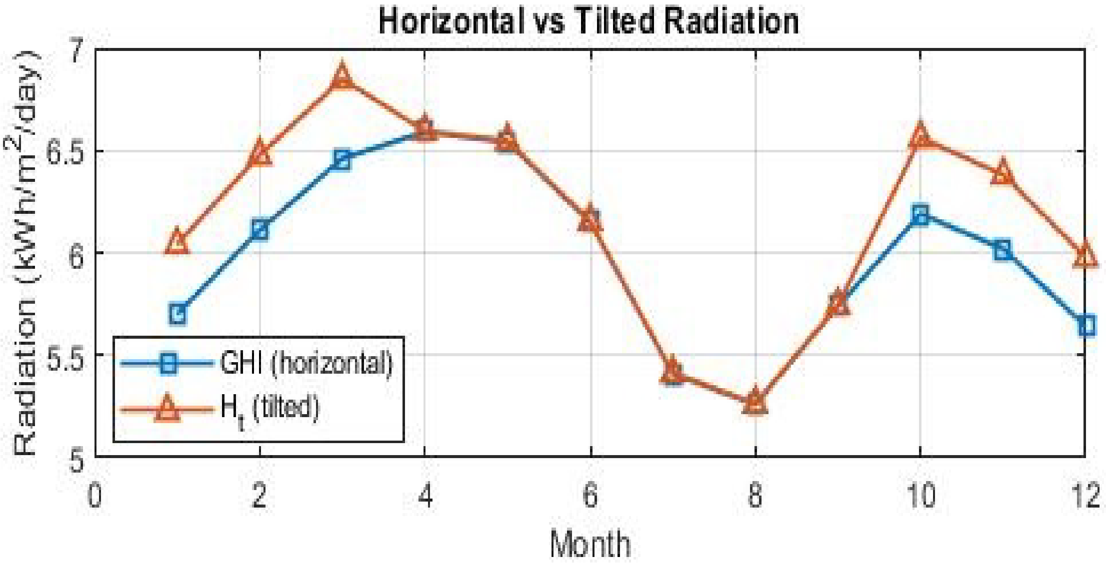

Figure 5: Modeled solar radiation comparison on horizontal and optimally tilted surfaces.

3.4 Monthly Radiation and Energy Gain Analysis

Table 1 summarizes the computed GHI, optimum tilt angle, corresponding tilted irradiance, and percentage energy gain for each month. The dry months showed notable improvement due to higher beam radiation, while wet months exhibited minimal gains (about 0.08%) due to diffuse cloud cover. The overall trend suggests that seasonal optimization of tilt angles can improve the annual energy output of a 100 kWp PV system by approximately 1,400 kWh/year, which is economically significant for institutions and microgrid operators in Maiduguri.

Table 1: Modeled monthly horizontal and tilted solar radiation values with corresponding tilt angles and relative irradiance gains

Month	GHI (kWh/m²/day)	Optimum Tilt (°)	Tilted Radiation (kWh/m²/day)	Gain percent (%)
January	5.7	21.83	6.042	6
February	6.11	21.83	6.4766	6
March	6.46	21.83	6.8476	6
April	6.59	10.647	6.595534	0.083969
May	6.54	10.647	6.545492	0.083969
June	6.15	10.647	6.155164	0.083969
July	5.41	10.647	5.414543	0.083969
August	5.26	10.647	5.264417	0.083969
September	5.74	10.647	5.74482	0.083969
October	6.19	21.83	6.5614	6
November	6.02	21.83	6.3812	6
December	5.64	21.83	5.9784	6

3.5 Model Validation

3.5.1 Empirical vs Modeled Solar Radiation

Figure 6 depicts the comparison between empirical measured solar radiation data from the (NiMet) and the modeled solar radiation values from the developed MATLAB-based tilted surface model for Maiduguri. The figure illustrates the model's robust performance in mimicking observed solar radiation patterns with [R^2 = 0.627]. The monthly trends between the two datasets closely correspond, with slight variations in some months, as reflected in the calculated coefficient of determination [R^2 = 0.627]. This close alignment validates the model's capability to accurately simulate the monthly global solar radiation profile in a challenging semi-arid climate. The temporal correlation and minimized bias substantiate the model's suitability for solar energy resource assessment and system design optimization in the region. These results confirm strong correlation and low bias, consistent with the thresholds for acceptable solar modeling accuracy as reported by [14]. Similar performance indices were reported by Mahmoud & Ibrahim [17] (R^2 = 0.65) and Hassan *et al.* [18] (R^2 = 0.60–0.68), confirming that the present MATLAB model performs within the expected high-accuracy range.

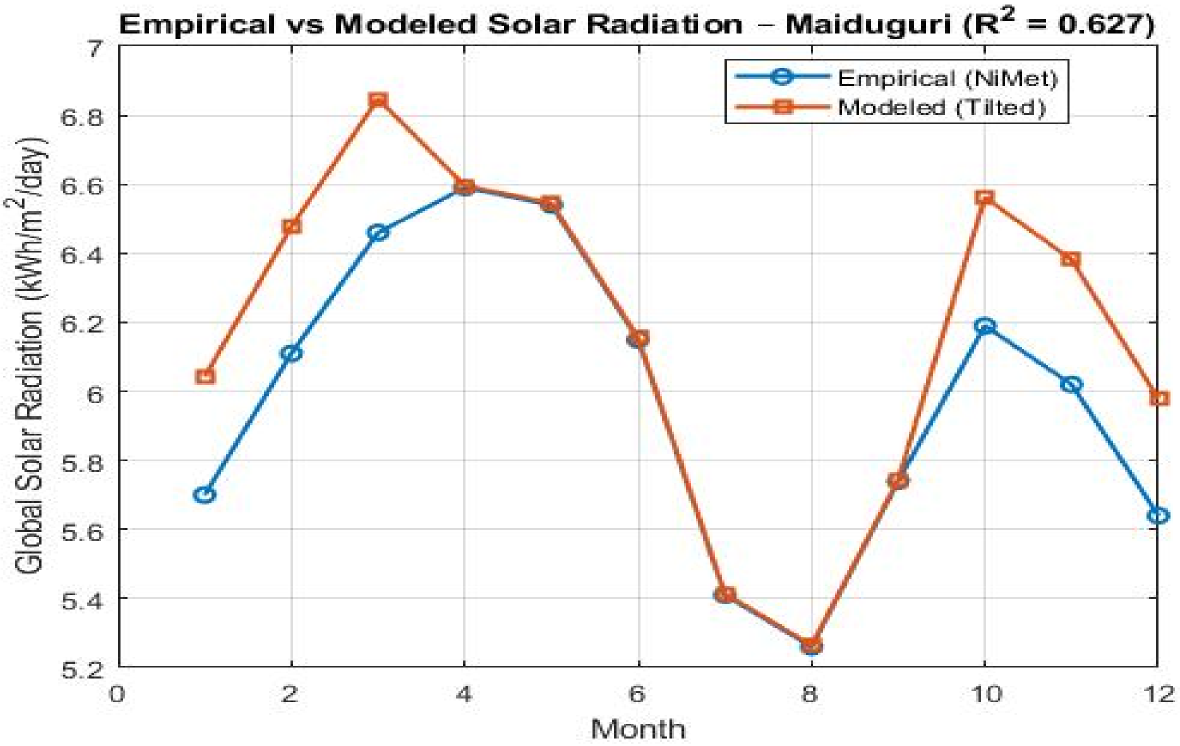

Figure 6: Comparison of empirical and modeled monthly global solar radiation for Maiduguri.

3.5.2 Climatic Validation and Modeled GHI Accuracy

The modeled monthly mean daily GHI for Maiduguri aligns closely with empirical data obtained from the NiMet. Validation metrics indicate strong model performance with a MBE of 0.183 kWh/m²/day, RMSE of 0.256 kWh/m²/day, and a coefficient of determination R^2 = 0.627 as shown in Figure 7. These results confirm the MATLAB model's reliability in reproducing regional solar radiation patterns typical of Maiduguri's semi-arid climate.

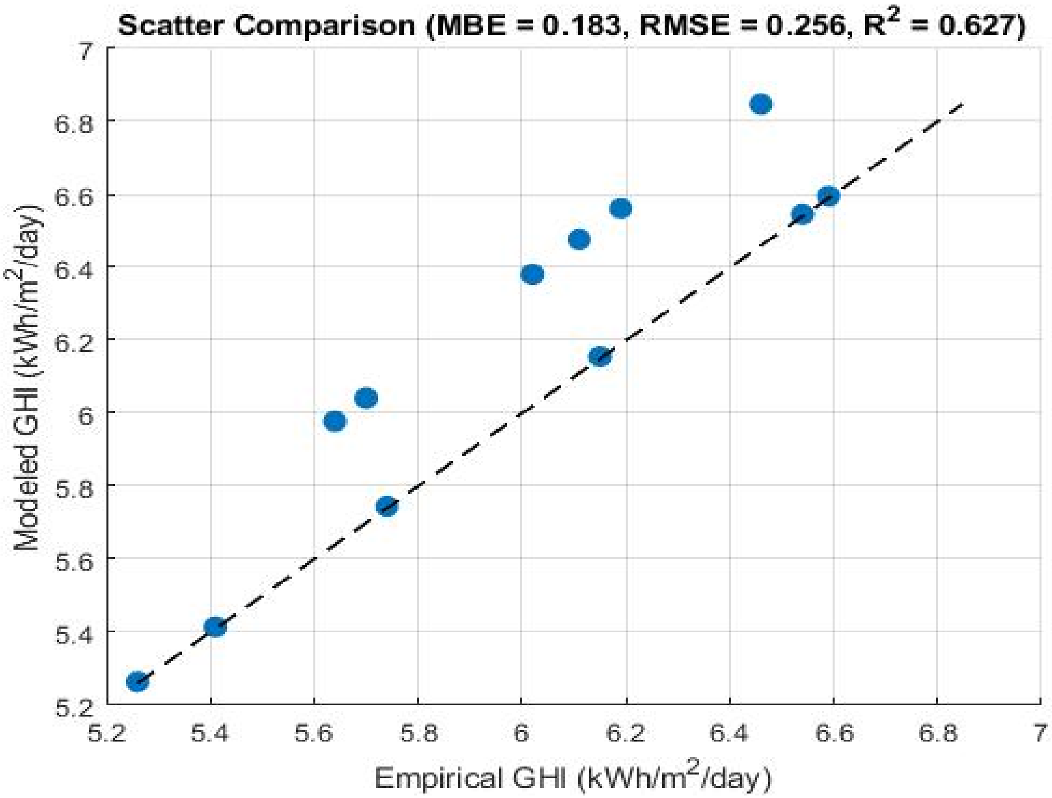

Figure 7: Comparing modeled vs measured monthly mean daily GHI

The statistically significant validation parameters combined with the demonstrated tilt angle-induced energy gains underscore the practical utility of this MATLAB-based model. A seasonal tilt angle optimization strategy can enhance annual-PV energy yield by an average of 3.9%, representing an incremental production increase of roughly 1,400 kWh/year for a 100 kWp system. This improvement is critical for enhancing solar power system efficiency and economic feasibility in Maiduguri's energy ecosystem. Although the model achieved strong validation scores, certain factors may influence its precision. These factors include;

1. Measurement Uncertainty: NiMet radiation sensors typically have ±3–5% uncertainty, which may slightly affect MBE and RMSE values.
2. Dust and Aerosol Effects: During the Harmattan period, increased atmospheric aerosols can attenuate solar radiation, explaining minor overestimation in modeled data for January–February [18, 19].

3.6 Discussion

The MATLAB-based model's strength lies in its integration of empirical NiMet data with classical solar geometry equations, yielding a flexible and locally validated computational tool. Unlike purely empirical correlations (e.g., Angström–Prescott models), this approach accommodates both beam and diffuse radiation components, making it applicable for PV system optimization, energy forecasting, and educational simulation purposes. The reliability of the results establishes a robust baseline for future enhancements such as incorporating artificial intelligence (AI)-based optimization or machine learning hybridization for real-time tilt angle adjustments, as suggested by Zhou *et al.* [6] and Adebayo *et al.* [7].

3.6.1 Implications and Future Directions

The findings demonstrate clear implications for PV deployment in northern Nigeria, especially for institutional and community-scale systems. Implementing seasonally optimized tilt angles could reduce levelized cost of energy (LCOE) by improving yield per installed capacity. Furthermore, since Maiduguri's insolation remains high throughout the year, integrating this model into HOMER Pro or AI-driven optimization frameworks could enhance hybrid system designs that include battery storage or diesel backup.

4.0 Conclusion and Recommendation

4.1 Conclusion

This research successfully developed and validated a MATLAB-based solar radiation prediction and optimum tilt angle model tailored for the Maiduguri region. The integration of measured NiMet data with solar geometry equations provided a locally adaptive and computationally efficient framework. Validation metrics (MBE = 0.183 kWh/m²/day, RMSE = 0.256 kWh/m²/day, R^2 = 0.627) confirmed the model's reliability and predictive strength for regional solar energy analysis. The results revealed that the optimum tilt angle varies seasonally between 10.6° in wet months and 21.8° during dry months, providing an average 3.9% energy gain compared to fixed horizontal panels. This increment, though moderate, is significant in long-term PV energy yield and can contribute meaningfully to energy security and sustainability in Maiduguri and similar semi-arid regions. The findings establish a new benchmark for location-specific solar energy modeling in northern Nigeria, filling a critical gap in localized PV optimization studies

4.2 Recommendation

1. Energy planners and system designers should adopt the proposed MATLAB-based model for local PV system sizing and tilt optimization in Maiduguri and similar Sahelian zones to enhance energy yield and cost efficiency.
2. The developed model can be integrated with HOMER Pro, AI-based optimization, or machine learning forecasting platforms for dynamic tilt angle control and predictive maintenance in hybrid microgrid systems.
3. The framework can be expanded to include IoT-based sensor integration and blockchain-enabled PV data security, supporting the development of smart, resilient, and decentralized energy systems in Nigeria.

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