Modeling and Variability Assessment of Global Solar Radiation in Gwagwalada, North-Central Nigeria: A Comparison of the Hargreaves-Samani and Angstrom-Prescott Models

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Abstract

Reliable estimates of global solar radiation are essential for the design, sizing, and performance evaluation of solar energy systems, particularly in regions where ground-based radiometric data are sparse. This study assessed the variability of global solar radiation and solar irradiance in Gwagwalada, a town in Nigeria's Federal Capital Territory (8.95°N, 7.08°E), using the Hargreaves-Samani and Angstrom-Prescott models. Monthly average maximum and minimum temperature, daylight hours, and measured global solar radiation and irradiance data spanning January 2020 to December 2022 were obtained from the Nigerian Meteorological Agency (NIMET). Model outputs were validated against measured radiation using mean bias error (MBE), root mean square error (RMSE), mean percentage error (MPE), and the coefficient of determination (R^2). The Hargreaves-Samani model showed a stronger association with measured radiation ($R^2 = 0.981$, RMSE = 1.100 MJ/m²/day, MBE = 0.999 MJ/m²/day) than the Angstrom-Prescott model ($R^2 = 0.902$, RMSE = 2.031 MJ/m²/day, MBE = 1.734 MJ/m²/day), indicating that a temperature-based estimation approach is more reliable than a sunshine-duration-based approach at this location. Global solar radiation was consistently higher during the dry season (November to March) and lower during the wet season (April to October), consistent with reduced cloud cover and lower atmospheric moisture in the dry months, with the annual peak occurring in February. Daily global solar radiation ranged from approximately 11.4 to 19.9 MJ/m²/day in the wet season and 17.4 to 21.8 MJ/m²/day in the dry season. These findings provide a quantitative basis for solar energy system planning in Gwagwalada and add to the limited body of location-specific solar radiation data available for North-Central Nigeria.

Keywords: Global solar radiation; Hargreaves-Samani model; Angstrom-Prescott model; solar irradiance; Gwagwalada; Nigeria

Introduction

Solar energy is one of the most viable alternatives to fossil fuels: the solar radiation intercepted by the Earth in a single year far exceeds total global fossil fuel reserves (Duffie & Beckman, 2013). Realizing this potential, however, depends on accurate, location-specific knowledge of the solar resource. The design and sizing of photovoltaic systems, the estimation of energy yield, and the prediction of thermal system performance all require reliable radiation data for the site in question (Duffie & Beckman, 2013), (Monteith & Unsworth, 2013). Where such data are unavailable or incomplete, system designs tend to be poorly matched to the actual resource, and performance estimates become unreliable.

Direct radiometric measurement remains limited across much of Nigeria because of the cost of maintaining calibrated pyranometer networks. Researchers have therefore relied on empirical models that estimate global solar radiation from more widely available meteorological variables such as temperature, sunshine duration, and relative humidity. The Angstrom-Prescott model, which relates radiation to sunshine duration, and the Hargreaves-Samani model, which relies only on maximum and minimum air temperature, are among the most widely applied of these approaches because of their comparatively low data requirements (Ayegba et al., 2017).

Several studies have examined solar radiation variability across Nigerian towns. Aweda et al. (Aweda et al., 2020) analyzed extraterrestrial radiation across six Nigerian stations, including Abuja, and reported clear north-south differences in irradiance linked to latitude and cloud cover. For Abuja specifically, Ugwu and Ugwuanyi (2011) applied the Hargreaves-Samani model to NIMET temperature data and found a high index of agreement (90%) between estimated and observed solar radiation, supporting the model's suitability for this climatic zone. Comparable model-validation work in other Nigerian cities, including a recent NIMET-based analysis of Owerri (Iheanyichukwu et al., 2024), has shown that empirical models can track measured radiation reasonably well, but that model choice materially affects accuracy, typically assessed using MBE, RMSE, and R^2 rather than visual agreement alone.

Despite this growing literature, Gwagwalada, a rapidly urbanizing town within the Federal Capital Territory, has not been the subject of a dedicated, multi-year radiation variability study. Existing FCT-focused work has generally used short observation windows of a few months, or has not directly compared multiple estimation models against measured data for the same location. This leaves a gap in the location-specific evidence needed to support solar energy planning in the area.

This study addresses that gap using three years of NIMET-derived temperature, daylight, and radiation data (January 2020 to December 2022) to estimate global solar radiation in Gwagwalada with both the Hargreaves-Samani and Angstrom-Prescott models, and by comparing both model outputs against the corresponding measured radiation record. The specific objectives are to (i) estimate the variability of global solar radiation in Gwagwalada using the two models, (ii) evaluate the accuracy of each model against measured radiation, and (iii) characterize the daily and monthly variability of solar irradiance across the three-year period. The results are intended to support more reliable solar energy system design in Gwagwalada and to add to the broader dataset of location-specific solar radiation evidence for North-Central Nigeria.

Methods

Study area: Gwagwalada is a town in Nigeria's Federal Capital Territory, located at latitude 8.95°N and longitude 7.08°E, approximately 30 km southwest of Abuja. The area has a tropical savannah climate with a dry season from November to March and a wet season from April to October.

Data source: Secondary meteorological data were obtained from the Nigerian Meteorological Agency (NIMET), comprising average monthly maximum and minimum air temperature, daylight hours, solar declination, and measured global solar radiation and irradiance for the period January 2020 to December 2022. Measured radiation values in the NIMET record are obtained using standard pyranometers at NIMET-operated stations. All calculations and graphical analysis were performed in Microsoft Excel.

Estimation models: Two empirical models were used to estimate global solar radiation, both requiring only temperature and astronomical inputs, which makes them suitable for locations such as Gwagwalada where direct radiometric records are limited.

Hargreaves-Samani model: $R_s = K\_Rs\ (T\_max - T\_min)^{0.5} \times R_a$
where R_s is estimated solar radiation, T_max and T_min are maximum and minimum air temperature (°C), R_a is extraterrestrial radiation, and K_Rs is an empirical adjustment coefficient (0.16 for interior regions, 0.19 for coastal regions) (Hargreaves & Samani, 1985). A value of 0.16 was used, as Gwagwalada is an inland location.

Angstrom-Prescott model: $R_s = R_a\ (0.281 + 0.414 \times S/S_0)$
where S is measured sunshine duration and S_0 is the maximum possible daylight hours.

Derivation of extraterrestrial radiation: Extraterrestrial radiation (R_a) was calculated from solar declination, the inverse relative Earth-Sun distance, and the sunset hour angle, following the standard FAO-56 procedure (Allen et al., 1998), using the site latitude and day of year.

Model validation: Model performance was evaluated against measured global solar radiation using four statistical indicators, consistent with standard practice in comparable empirical solar radiation studies (Iheanyichukwu et al., 2024):
• Mean Bias Error (MBE) — indicates systematic over- or under-estimation
• Root Mean Square Error (RMSE) — indicates the overall magnitude of estimation error
• Mean Percentage Error (MPE) — expresses error as a percentage of measured values
• Coefficient of determination (R^2) — indicates the strength of linear association between estimated and measured values
Lower MBE, RMSE, and MPE, and higher R^2, indicate better model performance.

Results and Discussion
Temperature and radiation patterns: Monthly maximum temperature in Gwagwalada peaked toward the end of the dry season (February to March) and was lowest during the wet season (July to August), consistent with the reduced cloud cover and lower atmospheric moisture that characterize the dry months in North-Central Nigeria. Both estimation models and the measured radiation record followed the same broad seasonal pattern: global solar radiation was higher from November to March and lower from April to October, with the annual peak occurring in February.

Model comparison: Table 1 summarizes the validation statistics comparing each model's output against measured global solar radiation across the three-year record. The statistics are based on the 36 of 36 monthly values that could be reliably extracted from the source record at the time of writing.

Table 1.

Model performance against measured global solar radiation, Gwagwalada, 2020–2022 (n = 36 months)

Model	**n**	MBE (MJ/m²/day)	**RMSE (MJ/m²/day)**	**MPE (%)**	**R**	**R^2**
Hargreaves-Samani	36	0.999	1.100	6.26	0.991	0.981
Angstrom-Prescott	36	1.734	2.031	11.18	0.949	0.902

The Hargreaves-Samani model showed a substantially stronger association with measured radiation (R^2 = 0.981) than the Angstrom-Prescott model (R^2 = 0.902), together with lower bias and lower overall error. Both models produced a positive MBE, pointing to a general tendency toward slight overestimation relative to the measured record, but this tendency was larger and more variable for the Angstrom-Prescott model. For Gwagwalada, a temperature-based approach therefore appears to reproduce the measured radiation regime more reliably than a sunshine-duration-based approach, at least over the period examined.

This pattern is broadly consistent with model comparison work elsewhere in Nigeria, where the relative performance of temperature-based and sunshine-based models depends on local climate and data quality rather than following a fixed hierarchy (Isikwue et al., 2013), (Iheanyichukwu et al., 2024). Site-specific validation, rather than an assumption that a model's performance transfers directly from one location to another, is therefore necessary before either model is adopted for design purposes in a new location.

Seasonal and daily irradiance variability: Daily solar irradiance ranged from approximately 11.4 to 19.9 MJ/m²/day during the wet season (April to October) and from approximately 17.4 to 21.8 MJ/m²/day during the dry season (November to March). The wet season shows a wider spread between its lowest and highest daily values, reflecting the greater day-to-day variability introduced by intermittent cloud cover, while the dry season maintains a narrower, consistently higher band. This asymmetry has a direct practical implication: solar energy systems in Gwagwalada should be sized with sufficient tolerance, or paired with adequate storage, to accommodate the sharper short-term dips in irradiance that occur during the wet season, rather than being sized around wet-season averages alone.

Interpretation: Taken together, these results show that global solar radiation in Gwagwalada is seasonally predictable at the monthly scale, and considerably more variable at the daily scale, particularly during the wet season. The stronger performance of the Hargreaves-Samani model suggests it is the more suitable of the two for radiation estimation at this location when only temperature records are available.

Limitations

The study relies on a single measurement network operated by NIMET rather than an independently calibrated reference instrument, so any systematic bias in the source instrumentation would carry through to the validation statistics reported here. This limitation does not affect the qualitative seasonal pattern reported, which is consistent across the full three-year record, but it does affect the precision of the quantitative validation statistics and should be resolved before the results are used for engineering design purposes.

Conclusion

This study assessed the variability of global solar radiation and solar irradiance in Gwagwalada, North-Central Nigeria, using three years of NIMET meteorological data (2020–2022) and two empirical estimation models. Global solar radiation followed a clear seasonal pattern, higher during the dry season (November to March) and lower during the wet season (April to October), with the annual peak occurring in February. Daily irradiance was more variable in the wet season, ranging from roughly 11.4 to 19.9 $MJ/m^2/day$, compared with a narrower, consistently higher band of about 17.4 to 21.8 $MJ/m^2/day$ in the dry season.

Comparison against measured radiation showed that the Hargreaves-Samani model provided a substantially closer fit than the Angstrom-Prescott model ($R^2 = 0.981$ versus 0.902), indicating that a temperature-based approach is more reliable than a sunshine-duration-based approach for estimating global solar radiation at this location. This finding offers a practical, quantitative basis for engineers and system designers working on solar energy projects in Gwagwalada, and it contributes location-specific evidence to a Nigerian solar radiation literature that remains sparse outside a handful of well-studied cities.

Future work should extend the comparison to additional empirical and machine-learning-based models, cross-check the ground-based record against satellite-derived products such as NASA POWER (Zhang et al., 2007), and incorporate direct ground-based radiometric measurement where feasible to reduce reliance on secondary data alone.

Declarations

Ethics approval and consent to participate: Not applicable (this study utilized secondary meteorological reanalysis data from the Nigerian Meteorological Agency and involved no human or animal subjects).

Consent for publication: Not applicable (no individual person's identifying data is included in this manuscript).

Competing interests: The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability: The meteorological datasets generated and analyzed during this study are derived from the Nigerian Meteorological Agency (NiMet) archives. Restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly open. However, processed monthly aggregated datasets and model calculation sheets are available from the corresponding author upon reasonable request and with permission from NiMet.

Author contributions: Okwuchukwu Praise Ezego: Conceptualization, Methodology, Software, Data Curation, Formal Analysis, Writing – Original Draft Preparation. Ogorchukwu Emmanuel Ochem: Methodology, Validation, Writing – Review & Editing, Supervision.

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