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Solar Energy Resource Assessment in Minna, Nigeria: Influence of Sunshine Duration and Extraterrestrial Radiation

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Abstract

Accurate solar energy resource assessment is fundamental for the efficient planning, design, and deployment of photovoltaic (PV) systems, particularly in tropical regions where atmospheric conditions strongly influence solar irradiance. This study evaluated the influence of sunshine duration and extraterrestrial radiation on solar energy potential in Minna, Nigeria, using ten years (2015–2024) of meteorological data. The analysis focused on the relationships among global solar radiation, sunshine duration, extraterrestrial radiation, and clearness index to characterize the site's solar resource availability. The results indicate an annual mean global solar radiation (={H}) of approximately 18–19 $MJ \cdot m^{-2} \cdot day^{-1}$ (equivalent to about 5.0–5.3 $kWh \cdot m^{-2} \cdot day^{-1}$), with maximum values occurring during the dry season (~21 $MJ \cdot m^{-2} \cdot day^{-1}$) and minimum values during the wet season (~14–15 $MJ \cdot m^{-2} \cdot day^{-1}$). Despite these seasonal variations, the observed solar radiation consistently exceeded the minimum operational threshold required for efficient PV electricity generation throughout the year. Statistical analysis revealed a strong positive correlation between sunshine duration and the clearness index (R^2 = 0.89), demonstrating the significant influence of sunshine hours on atmospheric transmissivity. In contrast, the weak relationship between extraterrestrial radiation (={H}$_o$) and measured global solar radiation (={H}) ($R^2 \approx 0.04$) indicates that atmospheric factors, including cloud cover, humidity, and dust aerosols, predominantly regulate surface solar radiation. The estimated annual PV electricity yield of 1,400–1,800 kWh/kWp further confirms Minna's high solar energy potential. These findings underscore the importance of climate-responsive PV system design, incorporating seasonal variability, hybrid energy integration, and effective dust mitigation strategies to maximize long-term energy efficiency, reliability, and sustainability.

Keywords
Sunshine duration,
Extraterrestrial radiation,
Clearness index,
Photovoltaic,
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1. Introduction

The increasing global demand for energy, driven by rapid population growth, urbanization, and industrial development, has intensified concerns over the sustainability of conventional fossil fuel resources and their associated environmental impacts. The continued dependence on fossil fuels contributes significantly to greenhouse gas emissions and climate change, thereby necessitating the transition to cleaner and more sustainable energy sources (IEA, 2022). Among the various renewable energy options, solar energy has gained considerable attention due to its abundance, environmental friendliness, and suitability for decentralized electricity generation, particularly in developing countries.

Nigeria is endowed with substantial solar energy resources because of its location within the tropical region, receiving an average solar radiation ranging from approximately 3.5 to 7.0 kWh m^{-2} day^{-1} depending on geographical location and season. Despite this significant potential, the utilization of solar energy in the country remains relatively low compared to its available resource base (Agbo *et al.*, 2021). One of the major challenges to effective solar energy development is the limited availability of reliable site-specific solar resource assessments required for photovoltaic (PV) system design, energy planning, and policy formulation.

Solar radiation reaching the Earth's surface is influenced by both astronomical and atmospheric factors. Extraterrestrial radiation represents the maximum solar energy available at the top of the atmosphere and is determined primarily by the Earth–Sun geometry (Soneye, 2021). However, the amount of solar radiation that ultimately reaches the surface is significantly modified by atmospheric conditions such as cloud cover, water vapour, aerosols, and dust particles. Sunshine duration serves as an important indicator of atmospheric transparency and has been widely employed in solar radiation studies because of its strong relationship with the amount of solar energy received at the ground surface (Soneye, 2021). The interaction among sunshine duration, extraterrestrial radiation, global solar radiation, and clearness index provides valuable information for assessing solar energy availability and understanding seasonal variations in solar resources (Badescu, 2008; Duffie & Beckman, 2013).

Minna, located in North Central Nigeria within the Guinea Savannah ecological zone, experiences distinct wet and dry seasons that strongly influence sunshine duration, cloud cover, and solar radiation availability. The dry season is generally characterized by clearer skies and higher solar radiation levels, whereas the wet season is associated with increased cloudiness and reduced solar energy availability. Although several studies have investigated solar radiation characteristics in different parts of Nigeria, limited attention has been given to understanding the combined influence of sunshine duration and extraterrestrial radiation on the solar energy potential of Minna using recent long-term data.

Therefore, this study aims to evaluate the influence of sunshine duration and extraterrestrial radiation on solar energy potential in Minna, Nigeria, using meteorological data covering the period 2015–2024.

The specific objectives of the study are to:

1. Determine the monthly and seasonal variations of sunshine duration, maximum possible sunshine duration, and relative sunshine duration in Minna.

2. Examine the relationship between relative sunshine duration and clearness index in order to assess atmospheric transparency and solar energy availability.
3. Analyze the seasonal variations of extraterrestrial radiation and global solar radiation and evaluate their relationship.
4. Assess the solar energy potential of Minna and discuss its implications for photovoltaic energy generation and deployment.

The findings of this study are expected to provide useful information for solar resource assessment, photovoltaic system planning, and renewable energy development in Minna and other locations with similar climatic characteristics in Nigeria.

2. Methodology

2.1. Study Area

The study was conducted in Minna, North Central Nigeria, located at approximately 9.6°N latitude and 6.5°E longitude (Figure 1). The area lies within the tropical savannah climate zone according to the Köppen–Geiger classification, characterized by distinct wet (April–October) and dry (November–March) seasons (Peel, Finlayson, & McMahon, 2007). The wet season is marked by high humidity and frequent rainfall, while the dry season experiences lower humidity, clear skies, and higher solar insolation (NiMet, 2021). This climatic setting makes Minna a suitable location for assessing solar energy potential in relation to sunshine duration and extraterrestrial radiation

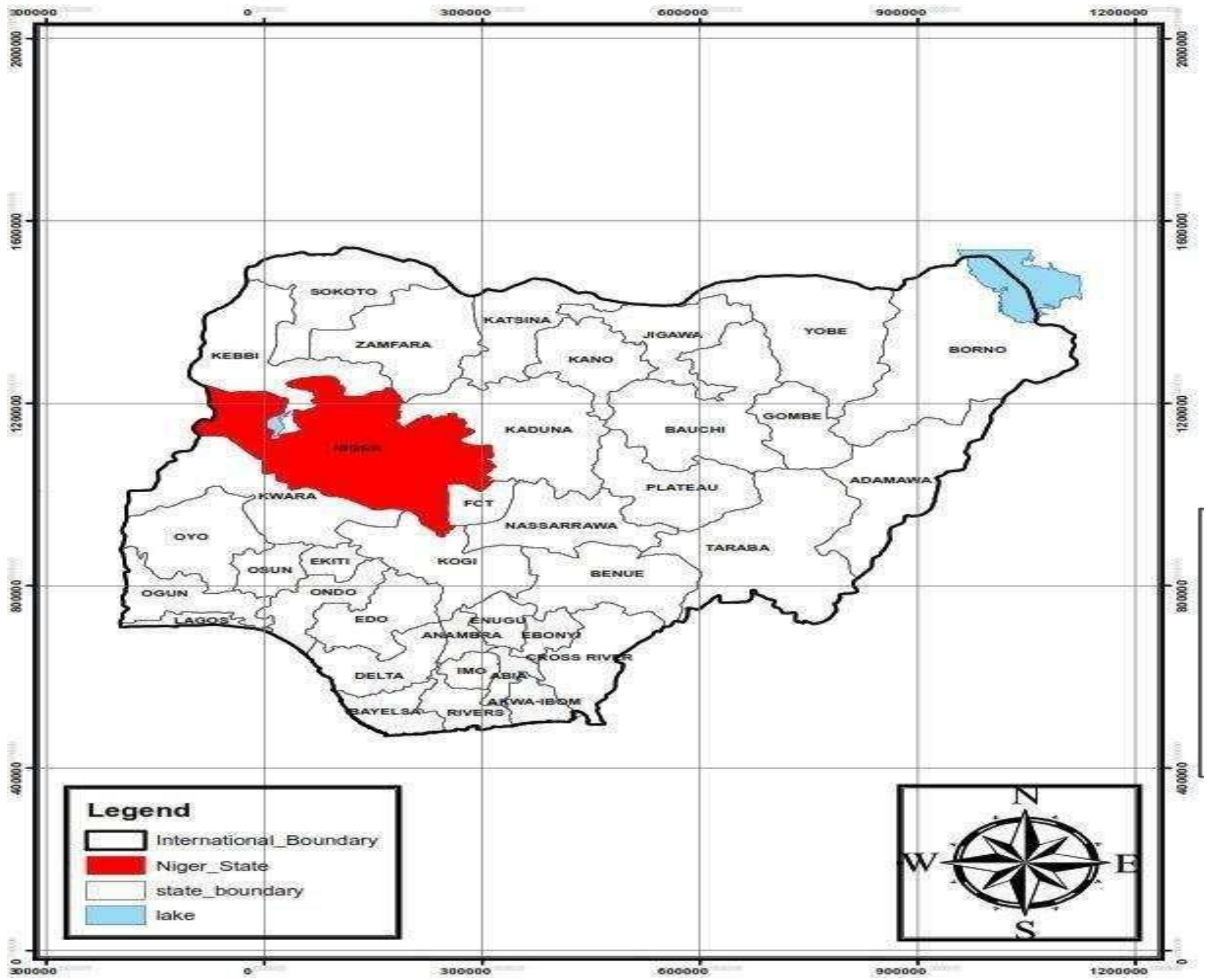

Figure 1: Map of Nigeria showing Niger State with Minna as the study location.

2.2 Data Collection

This study utilized both measured meteorological data and computed solar radiation parameters spanning 2015–2024:

1. Measured Meteorological Data

• Monthly global solar radiation (H) and sunshine duration (n) were obtained from the Nigerian Meteorological Agency (NiMet) station in Abuja.

2. Calculated Parameters

• Maximum Possible Sunshine Duration (N): Computed from solar geometry relations based on site latitude (∅), solar declination (δ), and sunset hour angle (ω_s):

$$N = \frac{2}{15}\omega_s \quad (1)$$

where ω_s is the sunset hour angle (°), given as:

$$W_s = \cos^{-1}(-\tan\phi\tan\delta)$$

(2)

(Duffie & Beckman, 2013).

• Extraterrestrial Radiation (H_0): Calculated using astronomical equations involving solar constant (Isc), latitude (∅), declination (δ), and ω_s (Duffie & Beckman, 2013; Iqbal, 1983):

$$H_0 = (\frac{24}{\pi})I_{sc}[1 + 0.033\cos(\frac{360n}{365})] \times [\cos\phi\cos\delta\sin\omega_s + (\frac{2\pi\omega_s}{360})\sin\phi\sin\delta] \quad (3)$$

Where:

I_{sc} – the solar constant,

∅ – the latitude

δ - the solar declination angle

W_s – the sunset hour angle

The expressions for I_{sc}, δ and ω_s are given by same Iqbal as:

I_{sc} = 1367 Wm^{-2}

Equations for the solar declination angle (δ) and the sunset hour angle (ω_s) are given as

$$\delta = 23.45\sin\left[\frac{360(284 + d_n)}{365}\right] (°) \quad (4)$$

$$W_s = \cos^{-1}(-\tan\phi\tan\delta) \quad (5)$$

Clearness Index (K_T): The clearness index (K_T) was calculated as the ratio of measured global solar radiation to extraterrestrial radiation, expressed as:

$$K_T = \frac{H}{H_o} \quad (6)$$

where H is the global solar radiation, and H_o is the estimated extraterrestrial radiation. The clearness index provides a measure of atmospheric transparency and solar energy availability (Gueymard, 2004).

2.3 Data Analysis

Meteorological and solar radiation parameters (sunshine duration *n*, maximum possible sunshine duration *N*, extraterrestrial radiation H_o, and global solar radiation *H*) were analysed using descriptive statistics to compute monthly means and assess variability (Wilks, 2011). Seasonal patterns were examined by classifying data into dry (November–March) and wet (April–October) seasons, following the climatic regime of North Central Nigeria (Olaniran & Sumner, 1989).

Relationships among parameters were assessed through correlation and regression techniques. The clearness index ($K_T = H/H_o$) and sunshine duration ratio (*n/N*) were derived to evaluate atmospheric transparency and solar availability (Liu & Jordan, 1960). Linear correlation coefficients were calculated to quantify associations, while regression models ($Y = a + bX + \varepsilon$) were applied to test the predictive capacity of sunshine duration ratio and extraterrestrial radiation for estimating global solar radiation (Gujarati & Porter, 2009; Duffie & Beckman, 2013).

Finally, results were compared with earlier studies conducted in Nigeria and other tropical regions (Falayi *et al.*, 2008; Okundamiya & Nzeako, 2011) to contextualize findings and validate observed trends.

3. Results and Discussion

3.1. Analysis of Measured Sunshine Duration (n) and Maximum Possible Sunshine Duration (N)

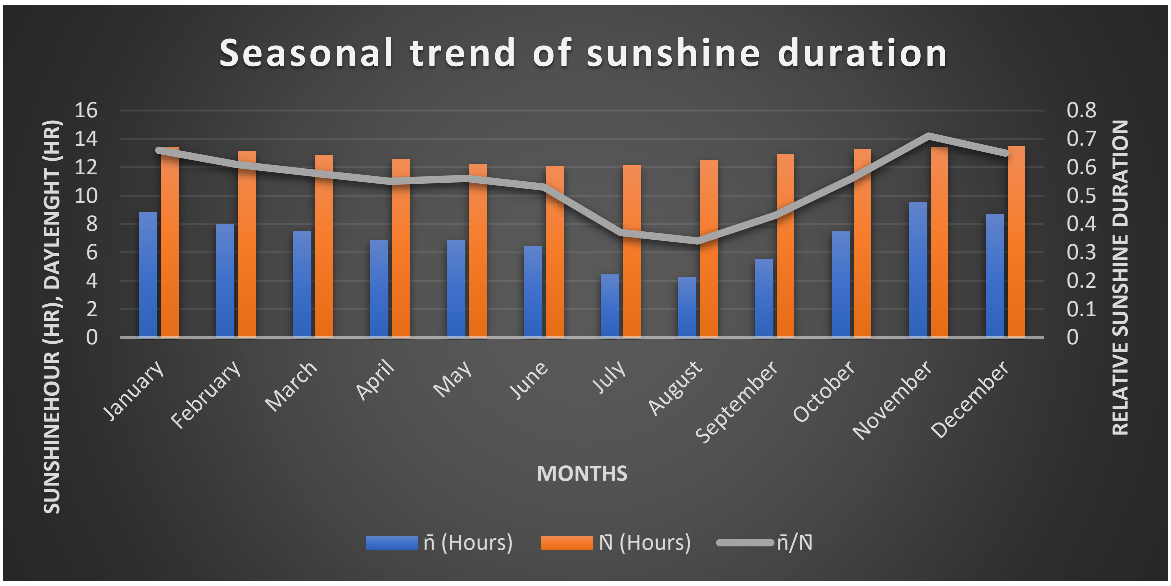

Figure 2: Monthly Mean Day Lenght (n), Sunshine Hour (N) and Relative Sunshine Hour ($\frac{n}{N}$) for Minna (2015-2024)

Figure 2 shows that the maximum possible sunshine duration (N) in Minna remains nearly constant (12.0–13.5 hours), reflecting the minimal seasonal variation typical of tropical latitudes. In contrast, measured sunshine duration (n) exhibits strong seasonality, peaking at 9.5 hours in November (dry season) and declining to 4.2 hours in August (wet season). The relative sunshine hour (n/N) ranged from 0.71 to 0.34, indicating the dominant influence of cloud cover, rainfall, and aerosols associated with the West African monsoon. These findings agree with previous studies across Nigeria and North Africa that highlighted the strong role of atmospheric conditions in modulating surface solar availability (Trabea & Shaltout, 2000; Ohunakin *et al.*, 2014).

3.2. Relationship between sunshine duration and clearness index (K_T)

The relationship between relative sunshine duration (n/N) and clearness index (K_T) shown in Figure 3, demonstrates a strong linear correlation (K_T = 1.476(n/N) – 0.242; R^2 = 0.89). This indicates that sunshine duration explains nearly 90% of K_T variability, making it a reliable predictor of atmospheric transparency and transmissivity. Higher n/N values during the dry season corresponded with higher K_T (0.55–0.65), while the wet season was associated with lower values (0.40–0.50), consistent with seasonal atmospheric turbidity. The results align with the classical Angström–Prescott model and confirm findings from other tropical regions (Falayi *et al.*, 2008; Yaro *et al.*, 2018).

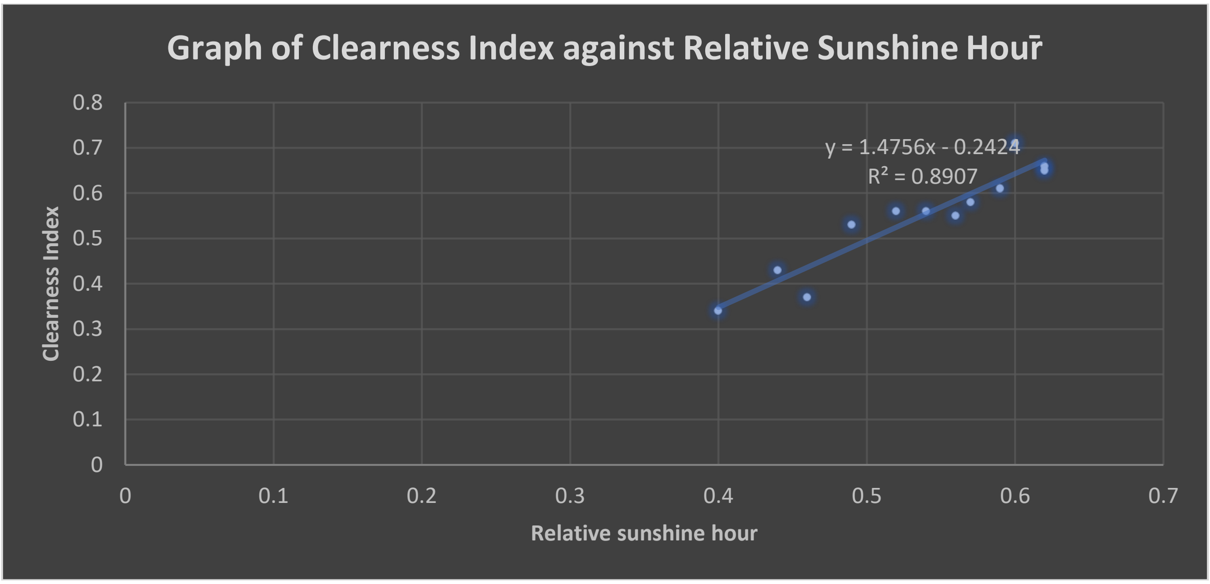

Figure 3: Relationship between relative sunshine duration ($\frac{n}{N}$) and clearness index (K_T).

3.3. Monthly Mean Variations of Extraterrestrial Radiation ($\overline{H}_o$) and Global Solar Radiation ($\overline{H}$)

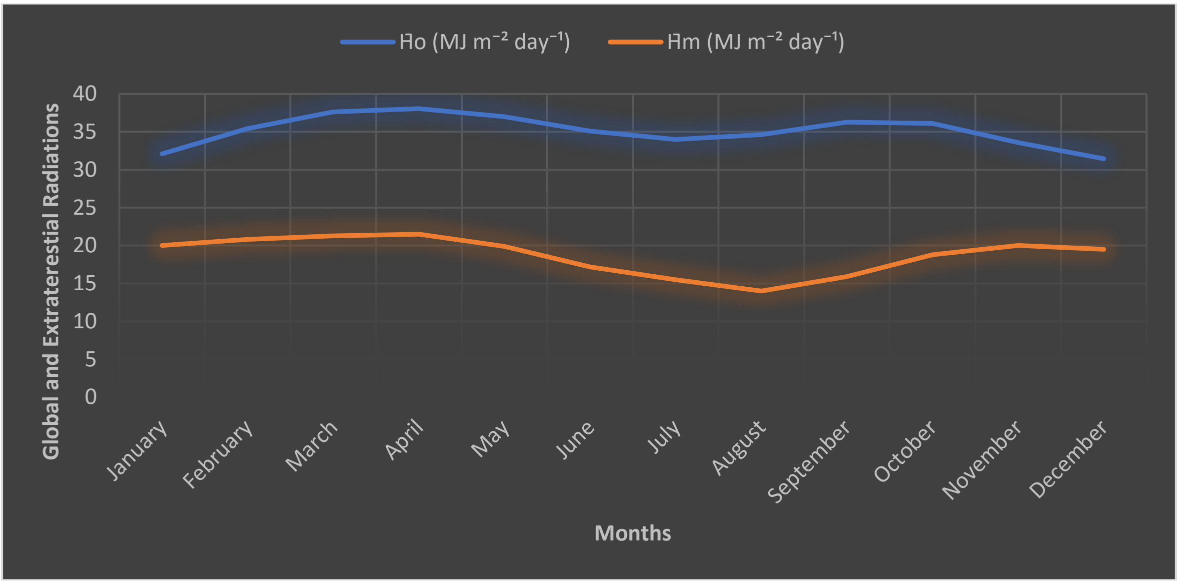

Figure 4: Seasonal variation of Global Solar Radiation and Extraterstial Radiation

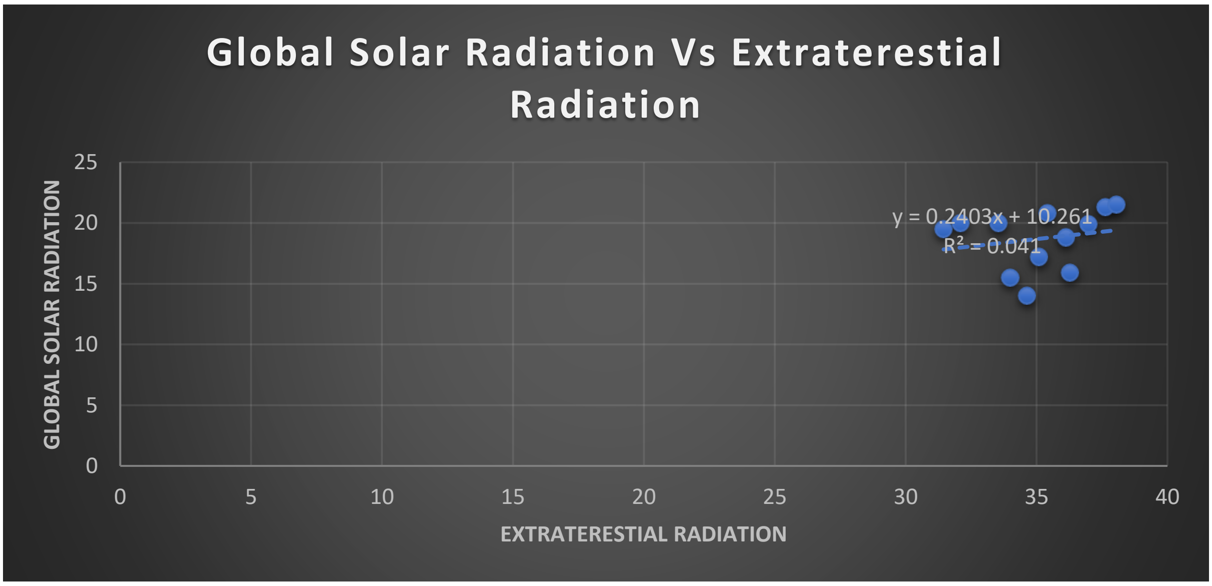

Figure 5: Relationship between Extraterrestial Solar Radiation and Global Solar Radiation of Minna (2015 - 2024).

Figure 4 shows that extraterrestrial radiation ($\overline{H}_o$) over the study location follows a distinct seasonal cycle, with maximum values (38.06 MJ m^{-2} day^{-1}) in April and a secondary peak in September (36.28 MJ m^{-2} day^{-1}), while minima (31.45 MJ m^{-2} day^{-1}) occur in December, reflecting solar declination and day length variations. Global solar radiation ($\overline{H}$), consistently lower than $\overline{H}_o$ due to atmospheric attenuation, peaks at 21.3 - 21.5 MJ m^{-2} day^{-1} in March–April under clearer skies and declines to 14.0–15.5 MJ m^{-2} day^{-1} in July–August during peak monsoon cloudiness, before partially recovering in October–November. The persistent $\overline{H}$, $\overline{H}_o$ gap highlights strong atmospheric modulation by clouds, aerosols, and humidity, leading to the loss of about 40–50% of incoming radiation. These results are consistent with recent findings across West Africa (Asamoah *et al.*, 2022; Sawadogo *et al.*, 2023; Agbor *et al.*, 2023; Clauzel *et al.*, 2024), underscoring the influence of monsoon circulation and aerosol loading on solar resource availability. Such seasonal variability provides valuable insight for photovoltaic deployment, indicating greater energy potential in the dry season and reduced availability during the wet season.

Figure 5 illustrates the relationship between global solar radiation ($\overline{H}$) and extraterrestrial radiation ($\overline{H}_o$), revealing a weak positive linear association (R^2 = 0.041), with only ~4% of the variation in $\overline{H}$ explained by $\overline{H}_o$. Despite the narrow seasonal range of $\overline{H}_o$ (≈32–38 MJ m^{-2} day^{-1}), $\overline{H}$ fluctuates more widely (≈14–21 MJ m^{-2} day^{-1}), particularly during the wet season when cloud cover, humidity, and aerosols substantially attenuate radiation. This weak correlation contrasts with the theoretical dependence between the two variables and highlights the strong role of atmospheric modulation, consistent with earlier findings in West Africa that link monsoon circulation and Saharan dust intrusions to reduced surface insolation (Asamoah *et al.*, 2022; Sawadogo *et al.*, 2023; Clauzel *et al.*, 2024). The results suggest that astronomical parameters alone are insufficient for reliable prediction of surface radiation in tropical monsoon climates and that models incorporating sunshine duration, cloud fraction, aerosol loading, and humidity are necessary (Nwokolo & Ogbulezie, 2018).

Overall, the analysis underscores the need to account for regional atmospheric dynamics when assessing solar resource potential, reaffirming that while $\overline{H}_o$ sets the theoretical upper limit, surface availability is strongly controlled by local atmospheric processes.

3.4. Estimation of Solar Energy Potential and Recommendations for PV Deployment in Minna

The estimation of solar energy potential in Minna demonstrates a substantial resource for photovoltaic (PV) applications, with an annual mean global radiation of 18–19 MJ m^{-2} day^{-1} (≈5.0 – 5.3 kWh m^{-2} day^{-1}), comparable to values reported for other West African sites (Asamoah et al., 2022; Sawadogo et al., 2023). Peak values occur in the dry season (~21 MJ m^{-2} day^{-1}; 5.8 kWh m^{-2} day^{-1}), while minima (~14–15 MJ m^{-2} day^{-1}; 4.0 kWh m^{-2} day^{-1}) are observed in July–August, yet remain above the operational PV threshold of 3.5 kWh m^{-2} day^{-1} (Agbor et al., 2023).

The weak correlation between extraterrestrial and global radiation (R^2 ≈ 0.04) underscores the strong influence of atmospheric conditions particularly cloud cover, humidity, and dust on surface solar availability, consistent with regional evidence that monsoon circulation and Saharan dust intrusions significantly affect PV performance (Clauzel et al., 2024). To optimize deployment, strategies should include grid-connected PV for maximizing dry-season output, storage integration or hybridization with diesel/wind during rainy-season intermittency, and dust-mitigation measures to sustain panel efficiency. These findings affirm that Minna holds strong PV potential, but climate-informed system design and operational planning are essential for reliable long-term performance, aligning with recent West African studies emphasizing the importance of atmospheric variability in solar energy planning (Sawadogo *et al.*, 2023; Agbor *et al.*, 2023).

4. Conclusion

This study demonstrates that Minna, North Central Nigeria, has a strong solar energy potential, with annual mean global radiation of ~5.0 $kWh \cdot m^{-2} \cdot day^{-1}$ (≈1,825 $kWh \cdot m^{-2} \cdot yr^{-1}$), suitable for photovoltaic applications. Seasonal variability is evident, with higher values in the dry season (≈5.8 $kWh \cdot m^{-2} \cdot day^{-1}$) and lower but still viable levels during the wet season (≈4.0 $kWh \cdot m^{-2} \cdot day^{-1}$). Sunshine duration showed a strong correlation with clearness index (R^2 = 0.89), while the weak relationship between global and extraterrestrial radiation (R^2 ≈ 0.04) highlights the dominant role of atmospheric effects.

Expected PV yields of 1,400–1,800 kWh/kWp annually can be achieved with appropriate system design, incorporating grid integration, storage, hybridization, and dust mitigation. These results establish Minna as a promising hub for PV deployment and reinforce the need for climate-informed solar energy planning across West Africa (Asamoah *et al.*, 2022; Sawadogo *et al.*, 2023; Agbor *et al.*, 2023; Clauzel *et al.*, 2024).

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