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Assessment and Statistical Modelling of Large-Scale Wind and Solar Energy Resources for Sustainable Electricity Generation in Northern Nigeria

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ABSTRACT

This study assesses and statistically models large-scale wind and solar energy resources for sustainable electricity generation in Northern Nigeria. Monthly mean daily wind speed and solar radiation data (2015–2024) were obtained from National Aeronautics and Space Administration (NASA) and the Nigerian Meteorological Agency (NIMET) for selected states across the North Central, North East, and North West regions. Wind energy potential was analyzed using the Weibull probability distribution function, while solar energy estimation employed the Angström–Prescott model. Results show that Northern Nigeria possesses abundant renewable energy resources, with solar radiation remaining consistently high across all regions, averaging above 21 MJ/m²/day making it suitable for stable photovoltaic (PV) power generation. Wind resources exhibited greater spatial variability, with Plateau, Nasarawa, Borno, Yobe, Katsina, and Kebbi showing the highest potentials, peaking in the dry season. The models demonstrated strong predictive reliability, with calculated values closely matching measured data (differences within ±0.3 MJ/m²/day). The complementary seasonal patterns of wind and solar resources indicate that hybrid systems could ensure reliable, year-round electricity supply. These findings highlight the potential for strategic renewable energy deployment to address Nigeria's electricity deficit and advance its low-carbon energy transition.

Keywords: Wind Energy; Solar Radiation; Photovoltaic (PV); Renewable Energy Resources; Northern Nigeria; Weibull Distribution; Angström–Prescott Model; Hybrid Energy System; Power Generation; Statistical Modelling; Electricity Supply; Sustainable Energy.

1. Introduction

The world relies on fossil fuels for a lot of its industrial and technological activities that drive development. It is therefore necessary to meet the constant energy demand for growth and development. However, using too much fossil fuels cause environmental problems like global warming and speeds up the depletion of the limited fossil sources. Because of this, it became necessary to find alternative fuels that are easy to use, better for the environment, business-friendly, plentiful, and long-lasting [1]. Electricity is becoming increasingly necessary in Nigeria due to its expanding population. The nation is endowed with a wealth of renewable energy sources, such as hydropower, wind, and solar power, energy diversification is vital. According to [2], the country has a moderate amount of solar radiation, wind energy, biomass potential, and a large amount of uranium deposits that have not yet been measured [3]. Naturally, the country has not been connected to the current grid to meet its energy demands.

A new structure is suggested to enhance power generation, transmission, and distribution because the current one is defective. The decarbonization of Nigeria's electricity sector is seen to be largely dependent on public acceptance of nuclear power. Renewable energy adoption in Nigeria is being hampered by the absence of a clear legislative framework and incentives. Enforcing current energy regulations strictly is recommended in order to encourage sustainability and energy efficiency [4], [5], [6]. The need to harness renewable energy may assist in contributing to the reduction of carbon emissions globally and will also help to address Nigeria's electricity crisis.

1.1. Study Objectives

The objectives of this study are to:

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1) Assess the availability and variability of large-scale wind and solar energy resources across Northern Nigeria.

2) Apply statistical models such as the Weibull probability distribution for wind analysis and the Angström–Prescott model for solar radiation estimation.

3) Compare measured and calculated datasets to evaluate the reliability of the chosen models.

4) Identify states with the highest renewable energy potential suitable for utility-scale power generation.

5) Explore the complementary seasonal patterns of wind and solar resources for hybrid system development.

6) Provide scientific evidence that can guide policymakers and energy planners in deploying sustainable electricity solutions in Northern Nigeria.

2. Background Theory

2.1. Wind Speed Energy Potential

Wind energy potential can be achieved using Weibull distribution model which is employed in analyzing the wind data, where the wind speed data is the required parameter to determine the average wind speed.

2.1.1. Weibull Parameters

Weibull distribution function is a statistical algorithm used to describe wind speed variation in the study area and the probability density function with the corresponding cumulative distribution functions are used to characterize variations of wind velocity [7]. Two parameters of interest are dimensionless shaped parameter, *k* and scale parameter, *c*, which is used to determine the Weibull probability density function f (V) as expressed [2], [7]:

$$f(V) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^{k}\right] \quad (1)$$

where v is the average wind speed (m/s), with the help of the variance of the wind speed, the shape, *k*, and scale parameters, *c*, can be obtained using equations (2) and (3), [8] [7] respectively.

$$k = \left(\frac{\sigma}{V_m}\right)^{-1.086} \quad (2)$$

where σ is standard deviation

$$c = \frac{V_m k^{2.6674}}{0.184 + 0.816 k^{2.73855}} \quad (3)$$

where V_m is the mean wind speed.

Using Weibull probability density function, wind power density, P_D (wind power unit will be computed from eqn. (4) [2].

$$P_D = \frac{P(V)}{A} = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (4)$$

where P (V) is the wind power (W), ρ is the air density at the site (typically 1.225kg/m^3), Γ is the gamma function.

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2.2. Solar Energy Potential

Angstrom – Type Model

In 1924, Angstrom presented a simple relationship to estimate the monthly-mean daily solar radiation from sunshine duration [9].

$$H = \left[\alpha + \frac{(1-\alpha)n}{N}\right] H_C \quad (5)$$

Where α is an empirical constant, n is the actual sunshine duration, N is the maximum possible sunshine. The ratio of n/N is the relative sunshine duration. H_C is the radiation transfer processes; the transfer processes could not be found until recently. Equation (5) could not be applied to sites with no radiation data, which is it disadvantage. To avoid this disadvantage, in 1940 Prescott then rearranged the correlation in a simpler form as;

$$H = \left[a + b\frac{n}{N}\right] H_0 \quad (6)$$

$$\bar{N} = \left(\frac{2}{15}\right) \cos^{-1}(-\tan\varphi \tan\delta) \quad (7)$$

$$a = -0.110 + 0.235\cos\varphi + 0.323\frac{n}{N} \quad (8)$$

$$b = 1.449 - 0.553\,\varphi - 0.694\frac{n}{N} \quad (9)$$

(a and a are the regression coefficient)

Equation (6) is called the revised angstrom approach or the Angstrom-Prescott approach. This approach only involves sunshine duration and thus, it is quite convenient for application. In reality Angstrom–Prescott has been the most popular approach to estimating global radiation from sunshine duration. It is important to emphasize that (a) and (b) which are empirical parameters are sensitive to local latitude, elevation and climate.

$$H_0 = \frac{24\times3600}{\pi} I_{sc}\left[1 + 0.033\cos\frac{360d}{36s}\right]\left(\cos\varphi\cos\delta\sin w_s + \frac{\pi}{180} w_s \sin\varphi\sin\delta\right) \quad (10)$$

H_0 is the extraterrestrial radiation (radiation intensity outside the earth's atmosphere) measured in mega joule per square meter per day (MJm^{-2} day^{-1}), d is the day of the year i.e., the Julian day calculated every 15th of each month.

$$w_s = \cos^{-1}(-\tan\varphi\tan\delta) \quad (11)$$

Where Ws is define as the sunset hour angle, φ and δ are the latitude and solar declination angle respectively, where δ is given by the relation;

$$\delta = 23.45\sin\left(360\frac{284+d}{36s}\right) \quad (12)$$

d is given by

$$d = INT\left(\frac{275\times M}{9}\right) - 1\times INT\left(\frac{M+9}{12}\right) + D - 30 \quad (13)$$

The expression for the Mean Bias Error (MBE) and Root Mean Square Error (RMSE) as stated by [10];

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$$RMSE = \left[\frac{\sum(H_{i,cal} - H_{i,measred})^2}{n}\right]^{\frac{1}{2}} \quad (14)$$

$$MBE = \left[\frac{\sum(H_{i,cal} - H_{i,measured})}{n}\right] \quad (15)$$

3. Material and Method

3.1. Study and Data Used

The study was based on random sampling techniques of some selected states in Northern Nigeria i.e., North Central (Benue, FCT-Abuja, Kogi, Kwara and Plateau) North East (Adamawa, Bauchi, Borno, Taraba and Yobe) and North West (Jigawa, Kano, Kaduna, Katsina and Kebbi) for Solar Energy Potential Estimation and for Wind Energy Potential Estimation the states used in North Central (Benue, Kogi, Kwara, Nasarawa and Plateau), North East (Adamawa, Bauchi Borno Taraba and Yobe) and Finally for North West (Jigawa, Kano, Katsina and Sokoto).

3.2. Data Collection

The data gathering process is developed as a diverse approach, embracing many sources and ways to acquire comprehensive information for a full analysis. In this study, Monthly mean daily wind speed data and the measured daily solar radiation data of the considered region is be obtained from National Aeronautics and Space Administration (NASA) Prediction and the Nigeria Meteorological Agency (NIMET) for the period spanning 2015 to 2024. These sources give significant insights into solar radiation patterns, establishing a framework for the technical examination of solar energy potential and wind energy potential within the Northern part of Nigeria.

4. Results and Discussion

4.1. Wind Energy

Figure 1(a), This region's wind speeds are moderate overall, with Plateau and Nasarawa showing the highest values. There is a clear seasonal cycle peaks mostly occur in January - February and November - December, with a noticeable dip in September - October. Benue: Starts high in January (5.60 m/s), gradually declines to a low in October (3.37 m/s), then rises again toward December. Kogi: Generally low-to-moderate winds all year, with the lowest in November (2.91 m/s) one of the lowest monthly values for the region.

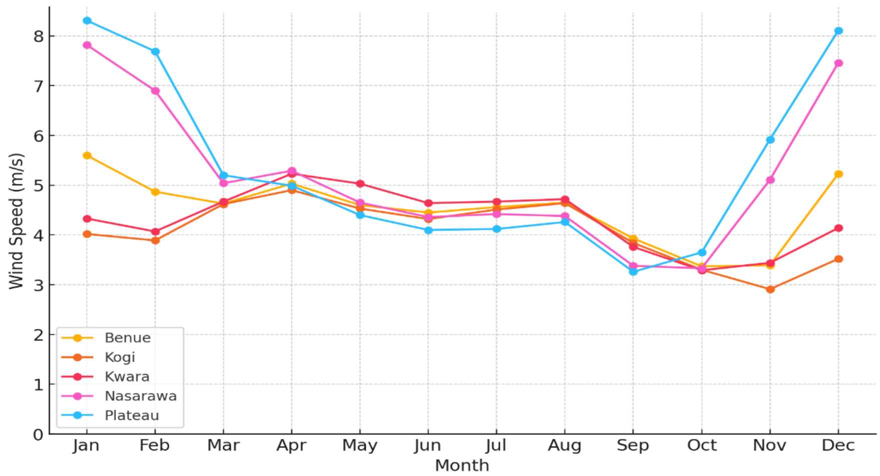

Figure 1(a). Average Monthly Wind Speeds for North Central

Kwara: Stable winds around 4–5 m/s most of the year, but dips in September - October before recovering in December. Nasarawa: Very strong winds in January (7.82 m/s) and December (7.46 m/s), dipping below 3.5 m/s in September - October. Plateau: The windiest state in the region peaks in January (8.31 m/s) and December (8.11 m/s), and even during the low months, winds stay above 3 m/s.

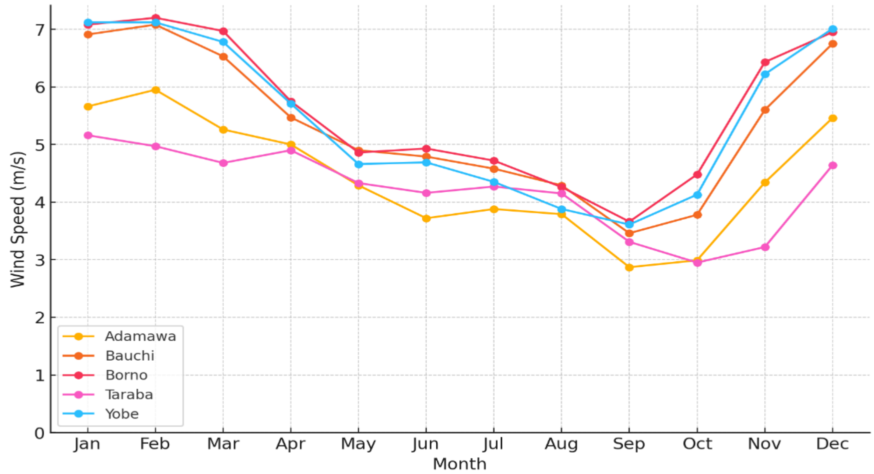

Figure 1(b). Average Monthly Wind Speeds for North East

Figure 1(b) shows one of the windiest parts in Nigeria, especially Borno and Yobe. Almost all states here show high values in January - March and November - December, with a pronounced low around September - October. Adamawa: Peaks at 5.95 m/s in February, lowest in September (2.87 m/s), Bauchi: High in January - March (above 6.5 m/s), drops to 3.46 m/s in September, then recovers, Borno: Strong winds year-round, reaching 7.20 m/s in February, only dipping slightly mid-year, Taraba: Consistently the lowest in this region, hovering around 4–5 m/s most months, with a September low of 3.31 m/s, and Yobe: Very windy in Jan–Feb (7.12 m/s both months), maintains strong winds into November - December.

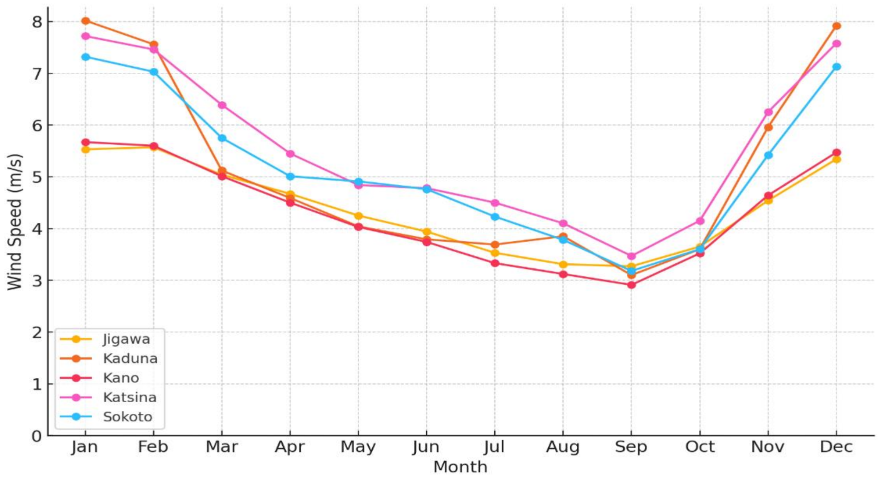

Figure 1(c). Average Monthly Wind Speeds for North West

Figure 1(c), has some of the highest wind peaks in Nigeria, especially Kaduna and Katsina. Like other regions, winds peak in dry months and are weakest in August - October. Jigawa: Starts at 5.53 m/s in January, gradually falls to 3.27 m/s in September, then climbs again, Kaduna: The standout in this region is 8.02 m/s in January, still high in December (7.92 m/s), but dips to 3.10 m/s in September, Kano: Moderate winds, 5.67 m/s in January, lowest in

September (2.91 m/s), Katsina: High winds above 7 m/s in Jan - Feb, and still above 6 m/s in November - December are great wind energy potential and Sokoto: Peaks at 7.32 m/s in January, drops to 3.18 m/s in September, then rebounds strongly.

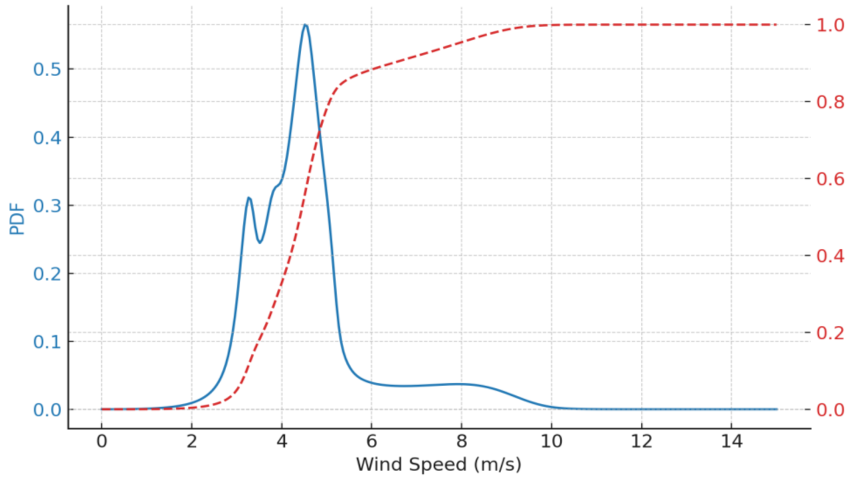

Figure 2(a). Probability Density Function and Cumulative Distribution Function for North Central

Figure 2(a), The Probability Density Function (PDF) peaks around 4.5 - 5 m/s, meaning this is the most frequently occurring wind speed range in the zone. The curve is moderately broad, showing that wind speeds vary, with a reasonable spread from 2 to 8 m/s. The right tail (winds >8 m/s) is present but not heavy high winds are less frequent here. The Cumulative Distribution Function (CDF) passes 50% (median) at roughly 4.7 m/s, meaning half the time, wind speed is below this level, and half the time it is above. About 80% of the time, wind speeds are below ~6 m/s and above 8 m/s, wind availability is only about 10–15% of the time.

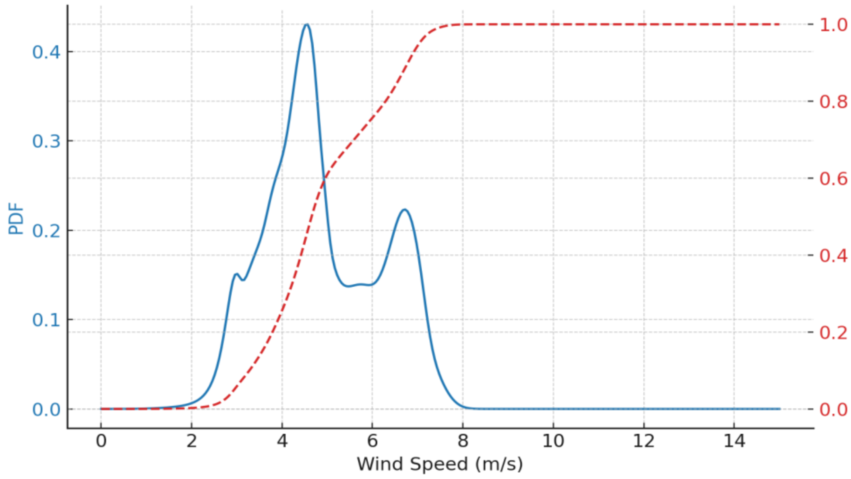

Figure 2(b). Probability Density Function and Cumulative Distribution Function for North East

Figure 2(b), The Probability Density Function (PDF) peak is shifted right compared to North Central, around 5.5 - 6 m/s, showing a higher most probable wind speed. The curve is slightly narrower than North Central, meaning wind speeds are more consistent. The right tail is longer, indicating that strong winds (>8 m/s) occur more often than in North Central, regards to the Cumulative Distribution Function (CDF) curve, The median wind speed is ~5.7 m/s, higher than North Central. About 70% of the time, wind speeds are below 6.8 m/s meaning high winds are more common here and winds above 8 m/s are available roughly 20 - 25% of the time.

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Figure 2(c), The PDF peak is between 5 - 5.5 m/s, slightly less than North East but higher than North Central. The spread is fairly wide, meaning wind speeds vary from calm to strong more than in North East and the right tail is longer than North Central's but shorter than North East's strong winds are present but not as frequent as in North East. The Cumulative Pattern median wind speed is ~5.4 m/s, 75% of the time, wind speeds are below 6.7 m/s and about 18–20% of the time, wind speeds exceed 8 m/s.

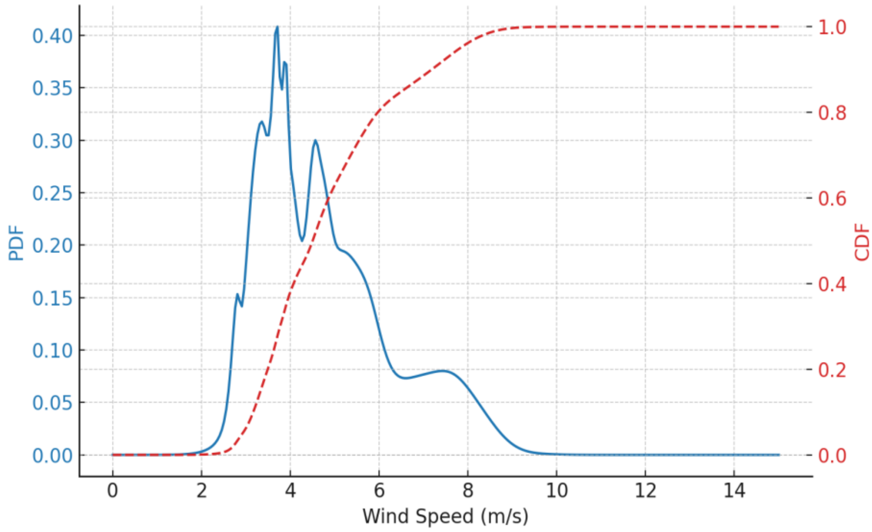

Figure 2(c). Probability Density Function and Cumulative Distribution Function for North West

Figure 3(a) shows that In the North Central Zone, Plateau and Nasarawa dominate with peaks in January (Plateau > 350 W/m², Nasarawa ~ 301 W/m²). Benue starts high (~ 117 W/m²) in January, dips mid-year, and recovers in December (~ 110 W/m²). Kogi and Kwara remain lower and steadier, peaking modestly (~60–74 W/m²). All states drop sharply May–September, with September–October values often < 35 W/m².

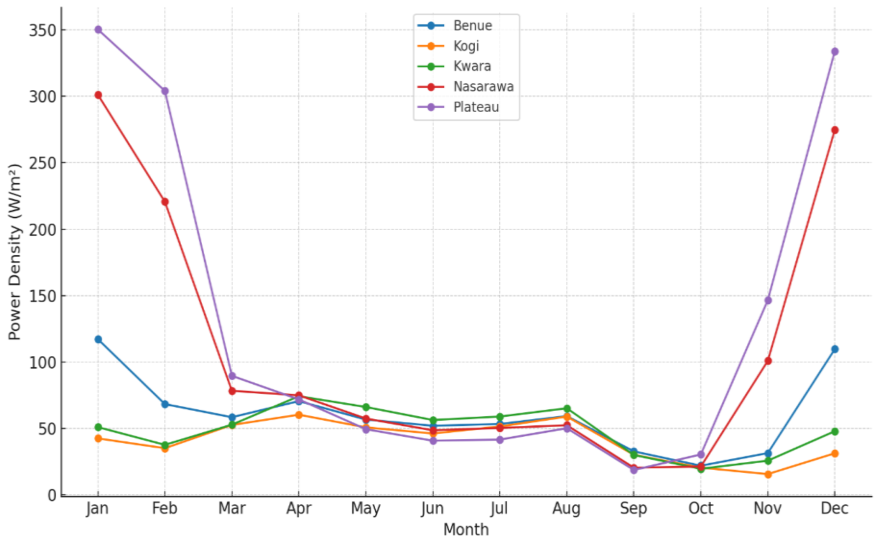

Figure 3(a). Power Density (W/m^2) North Central

North East: Borno, Bauchi, and Yobe lead, exceeding 200 W/m² in the dry season (Jan–Mar, Nov–Dec). Adamawa peaks in February (~ 125 W/m²) but drops to ~ 14 W/m² in September. Taraba stays mostly < 90 W/m² except in January. A clear May– September decline is observed.

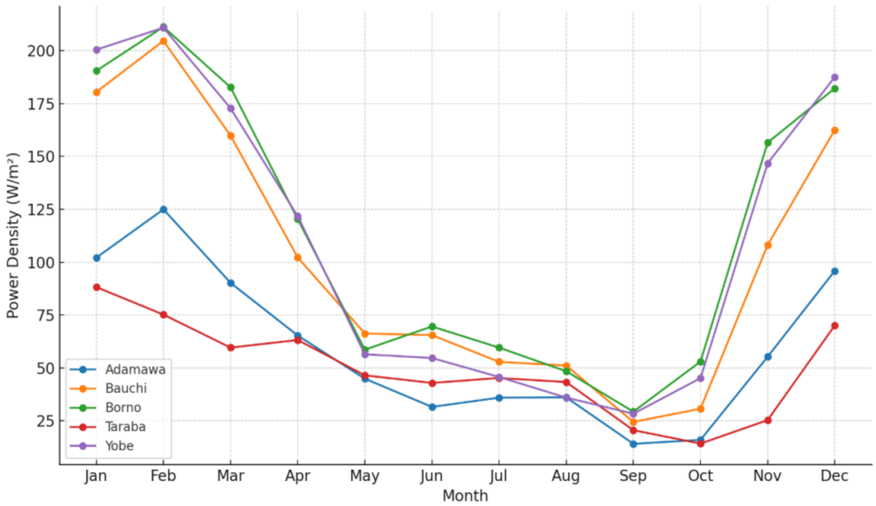

Figure 3(b). Power Density (W/m^2) North East

North West: Kaduna (~ 307 W/m²) and Katsina (~ 272 W/m²) dominate early in the year and in December. Sokoto also performs strongly in January (228 W/m²) and December (218 W/m²). Kano and Jigawa are consistently lowest, rarely exceeding 105 W/m². September–October are weakest across all states, with some values < 20 W/m².

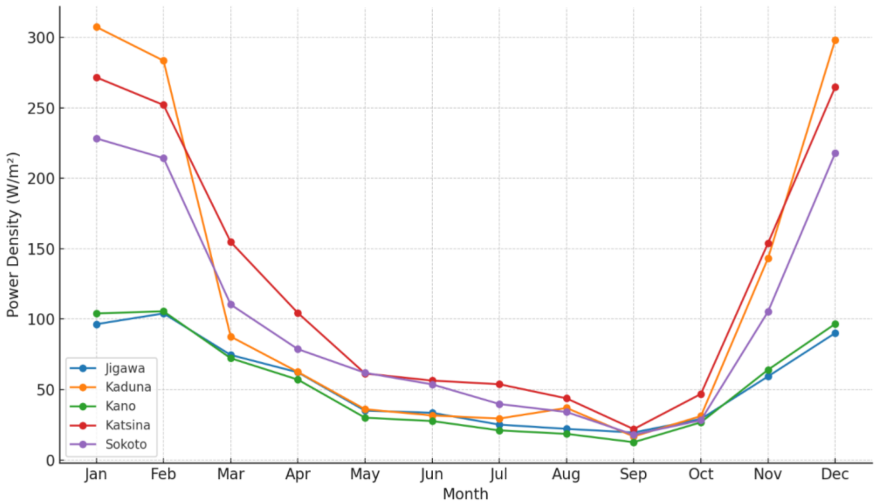

Figure 3(c). Power Density (W/m^2) North West

4.2. Solar Energy Potential

Figure 4(a) shows a combined Measured and Calculated Monthly Global Solar Radiation for North central, both datasets show small seasonal variation (~4–5 MJ/m²/day). Calculated values slightly smooth out short-term dips seen in measured data. The Energy Potential, with average radiation above 21 MJ/m²/day year-round, North Central can sustain stable PV electricity generation. This region can produce consistent output without heavy reliance on hybrid systems only minimal storage may be needed for evening loads.

Figure 4(b) shows the Seasonal patterns are identical, with calculated values sometimes 0.05–0.1 MJ/m²/day higher. Both datasets show moderate dips in winter months (~19–20 MJ/m²/day). The Energy Potential: has a high peak radiation (up to 26 MJ/m²/day) which makes this region excellent for utility-scale PV farms. However, in

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states like Bauchi and Adamawa, winter radiation drops enough to justify hybrid PV–wind systems or battery storage for constant supply.

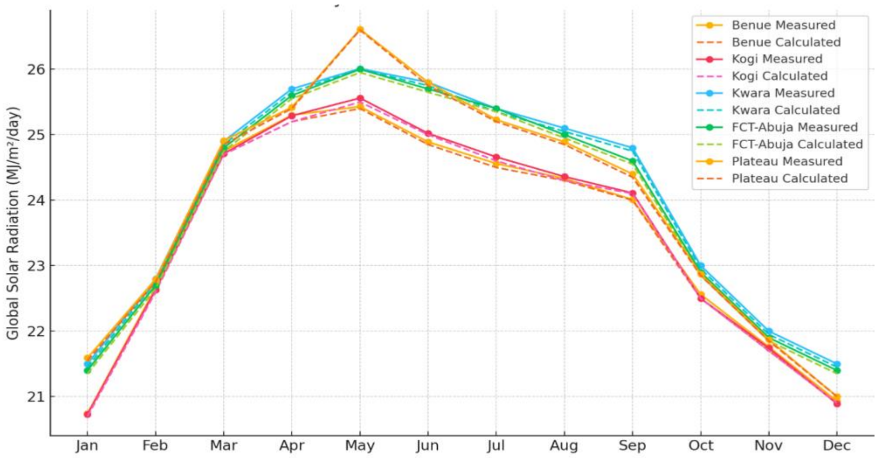

Figure 4(a). Monthly Global Solar Radiation for North Central

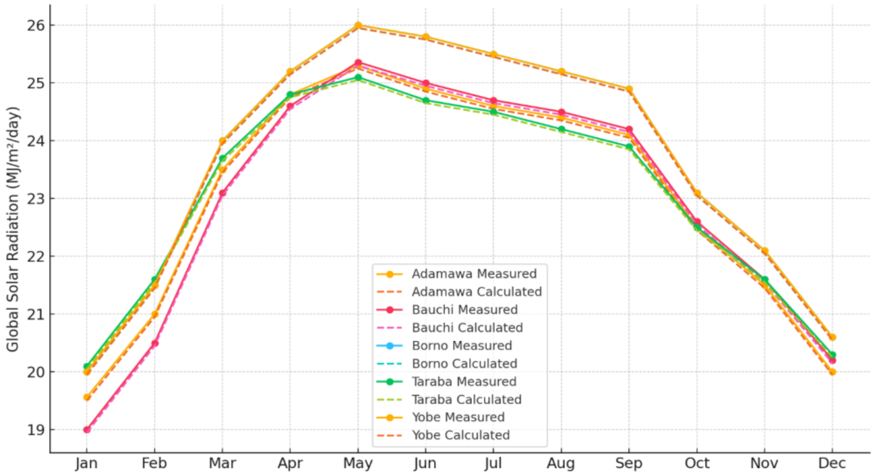

Figure 4(b). Monthly Global Solar Radiation for Northeast

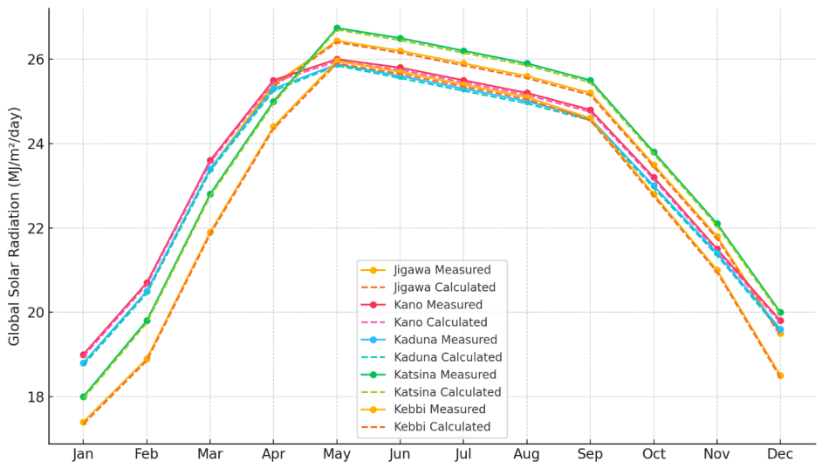

Figure 4(c). Monthly Global Solar Radiation for Northwest

Figure 4(c), the calculated values follow the same trend but appear slightly more consistent, removing small fluctuations in the measured dataset. This region shows the largest seasonal variation (~8–9 MJ/m²/day). The

Energy Potential of the Northwest Peaks in months of May–June which exceed 26.7 MJ/m²/day, the highest in Northern Nigeria, offering maximum PV generation potential. However, low months (December–January) can drop to 17–18 MJ/m²/day, reducing generation capacity by up to 35%. This high variability means wind hybridization and/or larger storage systems are essential for reliable year-round energy supply. Table 1, Based on the Data, Energy Potential in kWh was calculated say 1 MJ/m²/day ≈ 0.2778 kWh/m²/day, PV module efficiency ≈ 15% and Performance ratio ≈ 0.75.

Table 1. Combined Table: Peak and Minimum usable AC output (kWh/m²/day)

Region	Dataset	Peak Month & State	Peak Output	Lowest Month & State	Lowest Output
North Central	Measured	Plateau (May)	**0.831**	Benue/Kogi (Jan)	**0.647**
	Calculated	Plateau (May)	**0.831**	Benue/Kogi (Jan)	**0.647**
North East	Measured	Borno/Yobe (Apr)	**0.813**	Bauchi (Jan)	**0.594**
	Calculated	Borno/Yobe (Apr)	**0.811**	Bauchi (Jan)	**0.592**
North West	Measured	Katsina (May)	**0.835**	Kebbi (Dec)	**0.543**
	Calculated	Katsina (May)	**0.834**	Kebbi (Dec)	**0.542**

The General Comparison, for both the measured (H_m) and calculated (H_{cal}) datasets show very close agreement, which means that:

1) The solar radiation estimation model used in the study is reliable.
2) There is no major bias, based on calculated values which are usually within ±0.1–0.3 MJ/m²/day of measured data.
3) Seasonal trends (peak months, low months) are consistent between the two datasets.

This alignment increases confidence in using calculated data for locations without direct measurements, which is valuable for planning large-scale PV systems in remote Northern Nigeria.

5. Conclusion

This study has demonstrated that Northern Nigeria possesses abundant solar and wind energy resources that can be harnessed for large-scale electricity generation. Solar radiation is consistently high across all states, with peaks during the dry season and relatively minor spatial variation, making it a dependable resource throughout the region. Wind potential, while more location-specific, is significant in certain states particularly Plateau, Nasarawa, Borno, Yobe, Katsina, and Kebbi—offering opportunities for targeted wind power development. The statistical validation of the Angström–Prescott and Weibull models confirmed their suitability for resource estimation, with strong correlations and minimal errors. The complementary seasonal patterns of wind and solar provide a strong basis for hybrid renewable energy systems capable of delivering stable, year-round electricity.

5.1. Future Suggestions

1) Future studies should incorporate longer-term on-site measurements of wind speed and solar radiation to complement satellite and modeled data for higher accuracy.

2) There is a need to evaluate the economic feasibility of hybrid wind–solar systems in Northern Nigeria, including cost benefit analysis and life-cycle assessments.

3) Further research should explore the integration of renewable energy with storage technologies (e.g., batteries, hydrogen storage) to ensure continuous supply during low-resource periods.

4) Policy-focused studies should be conducted to assess the impact of regulatory frameworks, incentives, and grid infrastructure on renewable energy deployment.

5) Future work may extend this analysis to include other renewable resources such as biomass and small hydropower and clean energy to provide a more holistic renewable energy development strategy for Northern Nigeria.

Declarations

Source of Funding

This study received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Competing Interests Statement

The authors declare that they have no competing interests related to this work.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

Both the authors took part in literature review, analysis, and manuscript writing equally.

Availability of data and materials

Supplementary information is available from the authors upon reasonable request.

Institutional Review Board Statement

Not applicable for this study.

Informed Consent

Not applicable for this study.

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