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Assessments of Wind-Energy Potential of Four Nigeria States for Sustainable Development

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ABSTRACT

Growing worldwide energy demands and concerns about climate change have made the shift to renewable energy sources, especially wind energy, essential for sustainable development. However, despite Nigeria's richness of wind resources, there is scanty evaluations of wind properties (temporal and spatial characteristics of wind direction and speed), which are necessary for the siting of wind generation infrastructure. This research assessed the potential, trends, and variability of wind speed and direction to identify regions in Nigeria that would support higher wind power density and be appropriate for the installation of wind energy conversion systems aimed at electricity generation for sustainable development across four states: Abuja, Sokoto, Jigawa, and Ebonyi. Daily wind speed and direction data spanning from 1982 to 2023 for these selected locations were sourced from NASA's MERRA-2 archives, recorded at heights of 10 and 50 meters. The daily measurements were compiled into monthly averages and analyzed using the 2-parameter Weibull distribution test. The results indicated the average wind speeds at a hub height of 10 m were 3.83, 2.59, 3.06, and 3.98 m/s respectively for Abuja, Ebonyi, Jigawa, and Sokoto. At a hub height of 50 m, the wind power density was measured at 286.6 W/m² for Abuja (marginal - power class 2), 165.9 W/m² for Jigawa (poor - power class 1), 301.8 W/m² for Sokoto (fair - power class 3), all oriented in the ENE direction, and 99.3 W/m² for Ebonyi (poor - power class 1), directed towards the NNE. Moreover, the annual wind energy production reached 1980, 1390, and 2003 MWh/a for Abuja, Jigawa, and Sokoto, respectively, all in the ENE direction, while Ebonyi recorded the highest production of 495 MWh/a in the SSW direction. This suggests that Sokoto has the greatest potential for wind energy, followed closely by Abuja, whereas Ebonyi shows the least wind energy potential and is not capable of supporting an independent wind power system.

Keywords:
Wind Energy,
Wind Power Density,
Weibull Distribution,
Sustainable Development.

INTRODUCTION

As the global community progresses towards cleaner and more sustainable energy solutions, wind energy has emerged as one of the most promising substitutes for fossil fuels. In a nation like Nigeria – abundant in natural resources yet still facing challenges with energy access and reliability – pursuing renewable energy sources is not merely a choice; it is essential. Although solar energy has garnered significant attention, wind energy remains largely untapped, despite the fact that various regions in the country demonstrate considerable potential for effective harnessing.

This research examines the wind-energy potential in four carefully selected states in Nigeria: Abuja (FCT), Sokoto, Jigawa, and Ebonyi. These areas were chosen to represent a range of climatic zones, topographical characteristics, and regional energy requirements. From the arid and breezy northern plains of Sokoto to the more humid and diverse landscape of Ebonyi in the southeast, each state presents distinct conditions that could impact the feasibility of wind energy.

Wind energy is an abundant, clean, cost-effective, environmentally friendly, advanced, and limitless source of energy (Rehman & Ahmad, 2004). For over 3,000 years, humans have harnessed wind power. It was historically utilized as a mechanical power source for milling grain or pumping water until the early 20th century. As industrialization began, fossil fuel engines and the electrical grid replaced the inconsistent wind energy source with a more dependable electricity option

(Ackermann & Söder, 2002). A key characteristic of wind energy is its high variability in both time and space. Therefore, when setting up wind energy conversion systems, two important considerations must be factored in: assessing wind conditions and characterizing wind patterns at different sites (Garcia et al., 1998). Additionally, wind energy can be generated on-site using small wind turbines or larger turbines for utility-scale applications. Wind power categories are established to classify wind as a renewable resource, based on average wind speeds.

The adoption of wind energy as a renewable resource has received significant global focus due to its potential to mitigate climate change, lessen dependence on fossil fuels, and promote sustainable development. In Nigeria, the increasing demand for energy and ongoing electricity shortages have led to explorations of alternative energy sources, including wind (Ohunakin & Akinnawonu, 2012; Fagbenle et al., 2011).

The progress in wind energy has been remarkable globally, especially in nations like Germany, China, and the United States, where it plays a significant role in supporting national electricity networks (GWEC, 2023). Innovations in technology have enhanced the efficiency of wind turbines and refined site selection methods, enabling better forecasts of wind potential through the use of statistical and geospatial analysis tools (Manwell et al., 2010).

In Nigeria, evaluations of wind energy have mainly concentrated on the northern and central areas because of their elevated average wind speeds. Researchers like Fagbenle et al. (2011); Ohunakin & Akinnawonu, (2012) assessed the wind energy potential in Maiduguri, Potiskum, and Jos concluding that the regions possess robust wind resources, rendering them highly appropriate for wind turbine installations leading to power generation on a small to medium scale. Nze-Esiaga and Okogbue (2014) examined 51 years of wind data from five cities in southwestern Nigeria and discovered that wind speeds and power densities differ depending on the location, with Ikeja demonstrating the greatest potential.

Attabo et al. (2023) examined the potential for wind energy and the economic viability of establishing wind farms along Nigeria's coast and in offshore locations and revealed that offshore areas possess considerably greater wind power potential compared to coastal regions. In a similar vein, Adekoya and Adewale (1992) carried out one of the first extensive investigations into wind energy in Nigeria, pointing out that Sokoto and Katsina show considerable potential according to Weibull distribution modeling.

Probability density functions, especially the Weibull and Rayleigh distributions, are commonly used to model wind-speed characteristics for estimating energy potential (Carta et al., 2009). These models allow researchers to calculate key parameters including wind power density, capacity factor, and wind speed frequency distribution, which are vital metrics for the design and implementation of wind energy systems.

The advancement of renewable energy, particularly through wind power, is essential for meeting the United Nations Sustainable Development Goals (SDGs), specifically SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) (UN, 2015). In Nigeria, wind energy has the potential to enhance current energy systems, boost rural electrification, decrease greenhouse gas emissions, and aid in economic diversification (Aliyu et al., 2015).

However, significant hurdles such as insufficient funding, fragile infrastructure, regulatory and policy obstacles, little financial commitment, ineffective grid integration and inadequate technical knowledge obstructs the broad adoption of wind technologies (Amadi et al., 2024). Incorporating wind energy into Nigeria's energy mix requires robust policy backing, enhanced infrastructure, and active cooperation between the government and private sector participants.

While several studies have examined the wind energy potential in northern Nigeria, there is still a notable lack of thorough evaluations in other states with different climatic and geographical characteristics. Additionally, previous assessments have not extensively used long-term datasets or satellite-based measurements. Hence, this study aims to fill this gap by assessing the wind energy potential of four Nigerian states through a combination of long-term wind data, statistical modeling, and sustainability metrics.

MATERIALS AND METHODS

Description of Study Area

Nigeria, located in West Africa, is notable for its varied climate and geographical features. It lies between latitudes 4°N and 14°N of the equator, and longitudes 3°E and 15°E of the Greenwich meridian, covering an area of 923,768 km^2. The country shares its borders with Benin Republic to the west and Cameroon to the east, while Chad and Niger are to the north, and the Gulf of Guinea is situated to the south. The southern region of Nigeria is characterized by consistent humidity, significant cloud cover, and lower levels of solar radiation, whereas the northern region experiences a drier climate with well-defined wet and dry seasons. Different areas across the country receive vastly different amounts of rainfall. The Sahel region in the north necessitates irrigation due to its more pronounced dry season, which features high solar radiation and aerosols, while the Niger Delta region in the south thrives with lush greenery owing to its heavy cloud coverage and rainfall. The landscape is comprised of plains, plateaus, and mountains, with the Jos Plateau at the center and the Adamawa Plateau in the northeast being particularly prominent. The coastal plains and mangrove swamps in the southwest enhance the country's rich biodiversity. Weather patterns are influenced, and seasonal monsoons are enhanced by the interplay between the Atlantic Ocean, the Gulf of Guinea, and Nigeria's southern coastline. These interactions affect the nation's ecology, agricultural practices, and lifestyle. Nigeria is organized into thirty-six (36) states, along with Abuja as the Federal Capital Territory (Igbawua et al., 2024).

Figure 1 is the map of Nigeria showing the digital elevation model of the research locations and surrounding areas marked as sample sites, and Table 1 shows the meteorological station descriptions at the chosen locations.

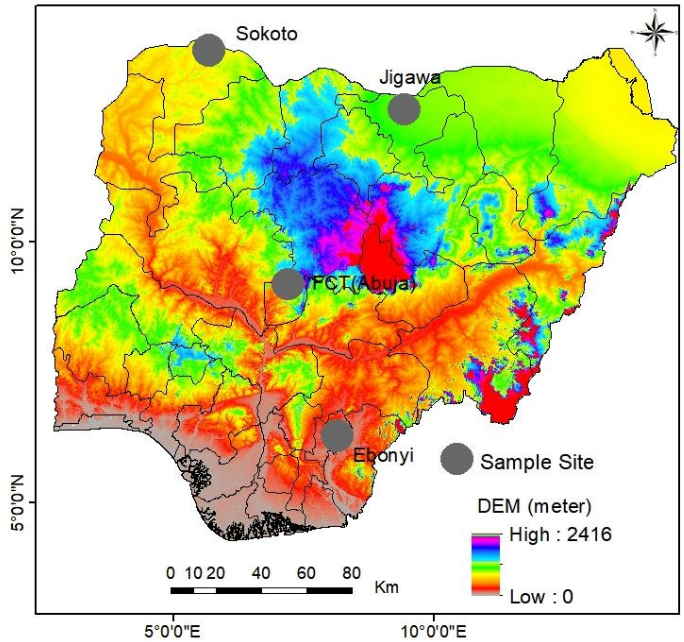

Figure 1: The map of Nigeria showing the digital Elevation Model of the research locations and surrounding areas

Table 1: Meteorological station descriptions at the chosen locations

State	Duration of wind data	Latitude (ºN)	Longitude (ºE)	Air Density (kg.m^{-3})	Altitude (m)
Abuja	1982 – 2023	9.07	7.48	1.225	840
Sokoto	1982 – 2023	13.04	5.14	1.215	305
Jigawa	1982 – 2023	12.22	9.56	1.220	439
Ebonyi	1982 – 2023	6.33	8.11	1.228	172

Abuja Research Area

The capital city of Abuja is located in central Nigeria, north of where the Niger and Benue rivers meet, covering a land area of about 8000 km². The region's geography is marked by two prominent rock formations: Aso rock, situated to the east of the city, and Zuma rock, which serves as the starting point for the Federal Capital Territory. Due to its elevation and tropical positioning, Abuja enjoys a temperate climate with two distinct seasons: the rainy season, which lasts from April to October, where temperatures can soar to 40 °C in May and rainfall varies between 305 to 762 mm, and the dry season, which occurs from November to March, bringing cooler temperatures down to 12 °C accompanied by dry winds. The area boasts fertile agricultural land, primarily growing maize and tubers, attributable to its ample rainfall, rich soil, and location within the Guinea-Savanna vegetation zone (Abubakar, 2014).

Sokoto Research Area

Sokoto is the northernmost district in Nigeria, adjacent to the Sahara Desert. With an estimated population of around 3.2 million people. Sokoto is surrounded by sand dunes and isolated hills. The region experiences an average temperature of 34.5˚C and receives between 300 and 800 mm of rainfall each year. Nigeria has never recorded daytime temperatures exceeding 45°C, even during the dry season. The dominant wind in this area is the Harmattan, or North-East Trade wind, which carries Sahara dust across the landscape during times of low air pollution. Due to its inland location and its role as a transitional area between the arid Sahara and the humid tropics of Africa, Northern Nigeria experiences the lowest rainfall globally. The Sahel is particularly susceptible to fluctuations in solar radiation and sea surface temperatures in the southern Pacific, referred to as El Niño, which impact the African monsoon. Historically, the Sahel has endured numerous periods of drought (Adegboyega et al., 2016).

Research Area

Jigawa is located in the northwestern region of Nigeria. The census conducted in 2006 indicated that the population stands at 318,234 individuals. Jigawa State is bordered by Bauchi and Yobe States to the east and by Kano and Katsina to the west. To the north, Jigawa shares an international boundary with the Republic of Niger, creating a unique opportunity for cross-border commerce. The total land area of Jigawa State is around 23,154 km². Based on the Koppen climate classification, Jigawa State experiences a tropical wet and dry climate (tropical continental climate). The month of August sees the highest levels of rainfall, which predominantly occurs from May to September (Abaje et al., 2012). The rainy season is marked by moderate temperatures and significant humidity. The period from October to April is recognized as the "dry season," characterized by very low humidity and elevated temperatures. The greatest evaporation takes place during the dry season due to the intense Harmattan caused by the northeast trade wind during this time. The area's vegetation is classified as Sudan Savanna type, exhibiting characteristics and species found in both the Guinea and Sahel Savannas (Hassan et al., 2018).

Ebonyi Research Area

Ebonyi State is located in the southeastern region of Nigeria, and an analysis of its shapefile shows that its area spans 7,465 km². The population of Ebonyi State grew from approximately 1.0 million in 1991 to 2.1 million in 2006 (Census, 2006), and it surpassed 2.8 million by 2018. The analysis of the study's digital elevation model (DEM) indicated that the elevation varied between 10 and 282 meters above sea level, with the northern region having the highest elevation coverage (Zhang et al., 2013).

Source of Data

Wind speed and direction data, expressed in metres per second (m/s) and degrees (°) respectively, for Abuja, Sokoto, Jigawa, and Ebonyi States in Nigeria were sourced from the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), a reanalysis product developed by the National Aeronautics and Space Administration (NASA), obtained from https://power.larc.nasa.gov/data-access-viewer/. This dataset covers the timeframe from 1982 to 2023 and encompasses measurements taken at standard elevations of 10 and 50 metres above ground level. These data were used to assess the potential for wind energy in the chosen locations, examine the temporal trends and variability in wind speed and direction, and calculate wind power density using selected commercial wind turbine models.

Following data processing and statistical evaluations were conducted using MATLAB. The wind speed data were fitted to a two-parameter Weibull probability distribution to understand the wind regime. For each location, the Weibull shape (k) and scale (c) parameters were calculated. Monthly mean wind speeds were derived from hourly wind speed values, which formed the foundation for further statistical analyses and assessments of energy potential. The results are displayed and thoroughly discussed in the subsequent sections.

Robust Coefficient of variation (RCoV)

The robust coefficient of variation (RCoV) of the dataset, a statistically strong and resistant spread metric that is split by an average metric was calculated by dividing the median absolute deviation (MAD) by the median (Gunturu and Schlosser, 2012).

$$\mathrm{RCoV} = \frac{\mathrm{MAD}}{\mathrm{Median}} \times 100 \qquad (1)$$

Mathematical Analysis

Weibull parameters

The two-parameter Weibull distribution is employed in this research as it provides a more accurate fit for observed density probability distributions compared to other statistical models and has demonstrated a strong correlation with experimental data (Akdag and Güler, 2010; Fagbenle et al. 2011). The equations for the probability density function and the cumulative distribution function of the two-parameter Weibull are represented in equations 2 and 3 (Ohunakin & Akinnawonu, 2012).

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{k}} \qquad (2)$$

$$f(v) = 1 - exp[-(\tfrac{v}{c})^{k}] \qquad (3)$$

where k represents the dimensionless Weibull shape parameter, and c denotes the Weibull scale parameter (m/s). Ahmed and Hanitsch (2006) further explored four distinct approaches (equations 4 – 7) for estimating the Weibull parameters k and c. Nevertheless, this article computes the monthly and annual values of the shape and scale parameters using standard deviation methods, thereby linking the two Weibull function parameters k and c to the mean speed v_m and standard deviation σ according to Ouammi et al. (2010).

$$v_m = c\Gamma(1 + \tfrac{1}{k}) \qquad (4)$$

where

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt \qquad (5)$$

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \quad (1 \le k \le 10) \qquad (6)$$

$$c = \frac{v_m}{\Gamma(1 + \frac{1}{k})} \qquad (7)$$

Power law exponent

The power law exponent, typically represented by α, is an important factor utilized to estimate wind speeds at various altitudes based on measurements taken at a known reference height. This approach is frequently used in wind energy evaluations when wind data at hub heights (such as 50 m, 80 m, or 100 m) are lacking, yet information at a lower elevation (like 10 m) is available.

$$v = v_0\left(\frac{H}{H_0}\right)^{\alpha} \quad (8)$$

where v is the wind speed at the desired height H, v_0 is the wind speed at the reference height H_0, H is the desired height (m), H_0 is the reference height (m), and α is the power law exponent (dimensionless)

Wind Power Density

The WPD assessment can be conducted in two ways. One method relies on the power available in the wind, which is captured by the wind conversion system and directly estimated from the wind speed v (m/s), while the other method uses the two-parameter Weibull approach. These two methods are given as equations (9) and (10):

$$P(v) = \frac{1}{2}\rho c A v^3 \quad (9)$$

$$WPD = \frac{P(v)}{A} = \frac{1}{2}\rho c^3\left(1 + \frac{3}{k}\right) \quad (10)$$

where, $P(v)$ is the wind power (W), WPD is the wind power density (W/m^2) and ρ is the air density (kg/m^3) at the site.

Wind Power Classes

Wind power classifications, commonly used to represent wind resources, categorize different ranges of average wind speed corresponding to the annual average wind power density, as shown in table 2.

Table 2: Wind Power Classification at 50 m hub Height (Murty, 2010).

Wind power class	WPD(W/m2)	Wind speed(m/s)	Remark
1	≤200	≤5.6	Poor
2	≤300	≤6.4	Marginal
3	≤400	≤7.0	Fair
4	≤500	≤7.5	Good
5	≤600	≤8.0	Excellent
6	≤800	≤8.8	Outstanding
7	≤2000	≤11.9	Superb

RESULTS AND DISCUSSION

Wind Speed and Direction

Figure 2 is the windrose diagrams of the five research locations. The windrose diagram, created using the wind directions and wind speeds, offers helpful details about the available directional wind speed at various wind speed intervals as well as the predominant wind direction (Rehman and Al-Abbadi, 2008). Below is the yearly windrose according to time with the coloured bars showing where the wind is blowing from.

The wind rose diagrams for the five selected states–Abuja, Sokoto, Jigawa, and Ebonyi–highlight notable spatial variations in wind speed and direction across Nigeria. These differences are essential for assessing the potential for wind energy development in each area. Abuja experienced winds predominantly from the West-Southwest (WSW) to East-Southeast (ESE), with a strong tendency towards the Southwestern (SW) direction (Figure 2a). Wind speeds typically range from 2 to 4 m/s, with occasional peaks between 6 and 7 m/s, indicating suitability for small to medium-sized systems due to the moderate speeds and mixed directional flow. Sokoto has a robust wind pattern (Figure 2b), characterized by East-Northeast (ENE) winds most of the speed ranging from 3 to 6 m/s, and also with occasional speeds in the 7 to 9 m/s range. These consistent, high-speed winds make Sokoto an excellent candidate for utility-scale wind energy generation. Jigawa, with winds primarily coming from the Northeastern (NE) direction (Figure 2c) and speeds between 3 and 5 m/s, presents moderate to high potential for wind energy development, especially for mid-scale and off-grid applications, due to its steady and focused directional flow. On the contrary, Ebonyi in the southeast showed lower potential (Figure 2d), with winds from the Southwest (SW) and speeds mostly from 2 to 4 m/s, and few instances above 5 m/s. The combination of minimal

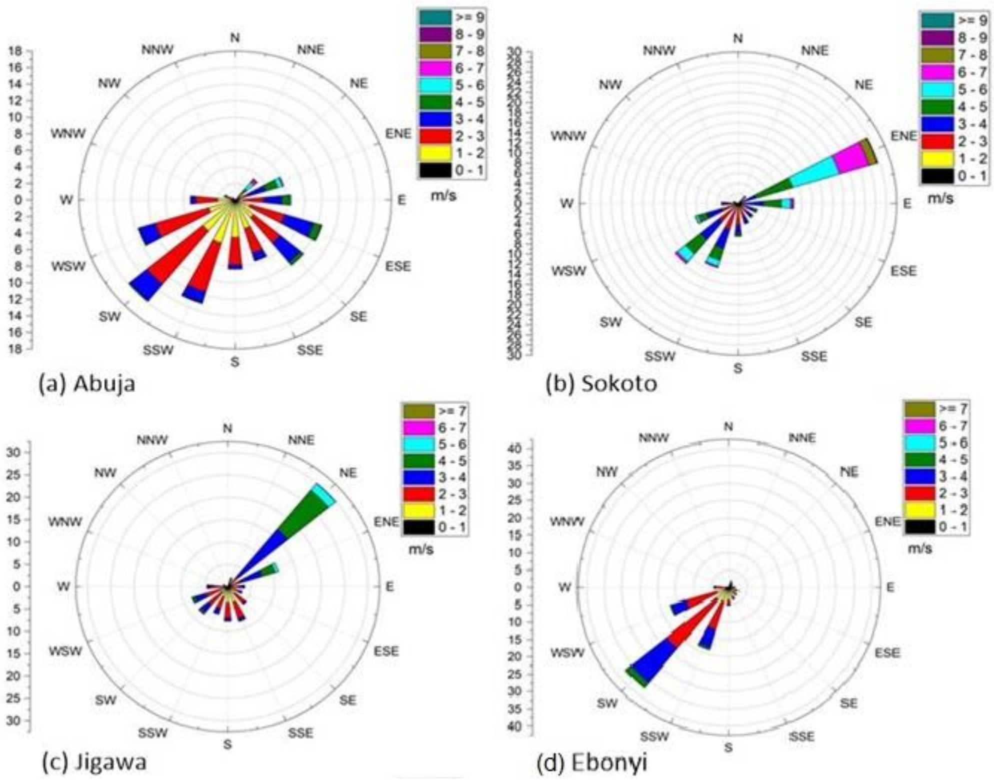

Figure 2: Wind rose diagram of the four research locations

Wind speeds and fluctuating directions indicates limited feasibility for large-scale initiatives; however, small-scale systems could be explored in rural hybrid energy setups. Adaramola & Oyewola (2011) observed that the yearly average wind speeds in Nigeria vary from approximately 2 to 9.5 m/s, and the pattern shows low speeds in the southern regions and that gradually rise to comparatively higher speeds in the northern areas.

Analysis of Regression Trends in Long-Term Temperature and Wind Speed

To gain a clearer understanding of the long-term climatic factors influencing the potential for wind energy, a regression analysis was performed on the temperature and wind speed data from 1982 to 2023 across four chosen states. The regression slopes, as can be seen in figure 3 suggests valuable insights into the trend and extent of changes in these variables over the years, with all observed trends being statistically significant at $p < 0.05$.

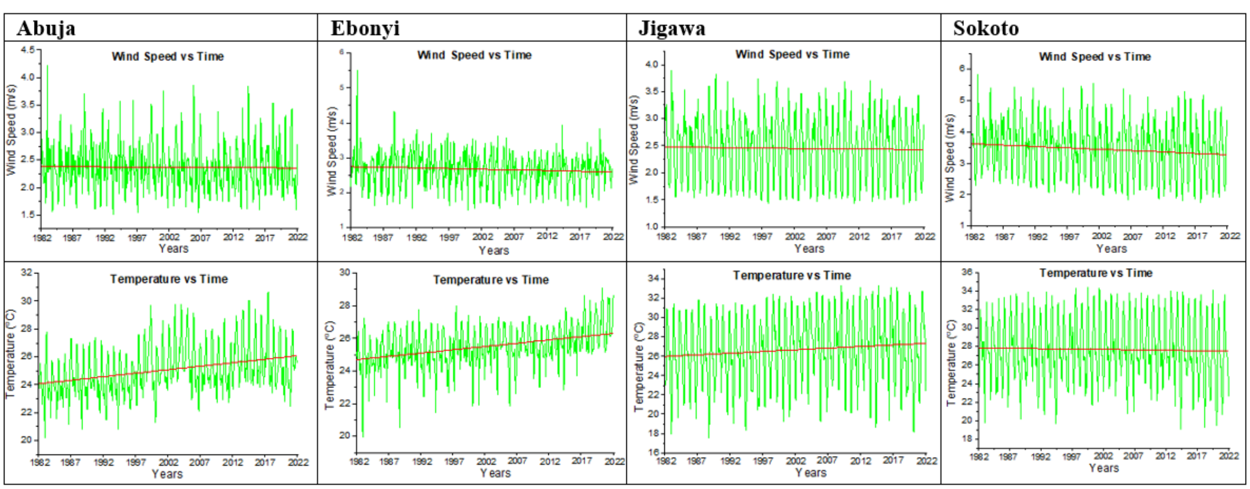

Figure 3: Temporal Variation of Wind speed and Temperature for 1982 – 2023

Figure 3 shows the temporal variability of wind speeds and temperature over the examined locations. In Abuja, wind speeds attained over 8 m/s in both 2000 and 2022, while the lowest recorded was 1.12 m/s in 1996 and 2016. The monthly averages at a height of 10 m range from 1.12 to 8.98 m/s, resulting in an overall average of 2.9 m/s. A long-term decreasing trend in wind speed was recorded (slope of -5.72e-05 m/s/year), whereas temperatures have shown a consistent increase (slope of 0.004 ^{o}C/year), the most pronounced among all studied location, suggesting that future wind systems will need to adjust to both changing wind patterns and rising temperatures. In Ebonyi, the highest wind speed recorded was 6.35 m/s in 2020, while the lowest was 0.95 m/s in both 1996 and 2017, with monthly speeds varying from 0.95 to 6.35 m/s, averaging 2.4 m/s. The state exhibits a declining trend in wind speed (slope of -2.95e-04 m/s/year) and rising temperatures (slope of 0.0032 ^{o}C/year), indicating limited standalone wind energy prospects, thus favouring solar or hybrid systems. Jigawa experienced a maximum wind speed of 6.7 m/s in 2015 and a minimum of 1.01 m/s in 1989, with speeds fluctuating between 1.01 and 6.7 m/s, yielding an average of 3.1 m/s. The wind trend reveals a moderate downward shift (slope of -9.65e-05 m/s/year) accompanied by an increasing temperature trend of 0.0027 ^{o}C/year, suggesting that there is still potential for wind energy development despite environmental changes. In Sokoto, wind peaked at 8.9 m/s in 2005, with a minimum of 1.01 m/s recorded in 2022. The monthly wind speeds range from 1.01 to 8.9 m/s, with an average of 4.1 m/s. Sokoto record the lowest in temperature trend (slope of -6.894e-04 ^{o}C/year), and showed the only decline in wind speed (slope of -6.85e-04 m/s/year), potentially affecting long-term wind energy efficiency. These trends have revealed the necessity for adaptive and climate-resilient solutions in wind energy planning across the various regions.

Robust Coefficient of Variation (RCoV)

The percentages of the wind relative coefficient of variation (RCoV) for wind speed in the five Nigerian states is presented in Table 3.

Table 3: Robust Coefficient of variation (RCoV) of wind speed in the research areas

State	Wind (RCoV) %
Sokoto	0.81586
Abuja	0.75818
Jigawa	0.74086
Ebonyi	0.61114

Table 3 shows that Sokoto has the highest RCoV at 0.81586, indicating considerable variations in wind speed, which may impact the reliability of wind power generation. In contrast, Ebonyi has the lowest RCoV at 0.61114, indicating more stable and consistent wind patterns, which are typically advantageous for reliable energy production. Abuja, and Jigawa have intermediate RCoV values that reflect various levels of wind variability. Generally, while elevated RCoV values might indicate the possibility of strong wind bursts, they also suggest greater unpredictability, making it crucial to balance both wind speed and stability when evaluating locations for wind energy development.

Wind Profile Analysis

The result of wind profile analysis for Abuja, Ebonyi, Jigawa, and Sokoto is presented in Table 4. It demonstrates significant spatial differences in wind energy potential, marked by variations in average wind speed and the power law exponent (α) at a height of 50 meters.

Table 4 reveals that Sokoto has the highest average wind speed of 5.754 m/s, followed by Abuja at 5.650 m/s, Jigawa at 4.992 m/s, and Ebonyi at 4.040 m/s. Jigawa features the highest average α value of 0.306, indicating a more stable wind regime, while Ebonyi, despite its lower wind speeds, has a relatively high α value of 0.276, reflecting less variability in wind flow. In most areas, the ENE direction consistently shows the greatest wind speeds—7.701 m/s in Abuja, 7.835 m/s in Sokoto, and 6.418 m/s in Jigawa—suggesting it is the best orientation for wind turbine installation. In contrast, Ebonyi registers the highest wind speeds in the NNE and SSW directions, with measurements of 5.409 m/s and 4.364 m/s, respectively.

Table 4: Wind Profile at a Reference Height of 50 m

Direction	Abuja		Ebonyi		Jigawa		Sokoto	
	α	WS (m/s)	α	WS (m/s)	α	WS (m/s)	α	WS (m/s)
N	NaN	NaN	0.268	4.160	NaN	NaN	NaN	NaN
NNE	0.263	6.491	0.256	5.409	0.317	6.385	0.251	6.5
ENE	0.260	7.701	0.231	4.054	0.321	6.418	0.246	7.835
E	0.267	6.642	0.226	3.617	0.295	4.614	0.252	6.595
ESE	0.252	4.283	0.219	3.039	0.304	3.774	0.236	4.446
SSE	0.253	3.613	0.236	2.656	0.316	3.554	0.234	3.932
S	0.245	3.582	0.274	2.938	0.312	3.521	0.234	4.049
SSW	0.210	4.734	0.285	4.364	0.287	3.895	0.209	4.941
WSW	0.217	4.819	0.286	4.263	0.274	4.340	0.216	4.995
W	0.246	4.293	0.282	3.550	0.289	4.176	0.243	4.596
WNW	0.259	3.909	0.267	2.924	0.284	4.066	0.252	4.460
NNW	0.270	4.984	0.202	1.690	0.304	5.393	0.252	5.969
Mean	0.243	5.650	0.276	4.040	0.306	4.992	0.233	5.754
Reference Height: 50 m								

Generally, the findings imply that while Ebonyi may necessitate careful site optimization due to its lower wind speeds, Sokoto, Abuja and Jigawa present strong prospects for wind energy development, especially when turbines are positioned to harness prevailing ENE winds for maximum energy uptake.

Weibull Statistical Distribution

The measured wind speeds were analyzed using a 2-parameter Weibull model. Table 5 presents the Weibull scale parameter, *c* (m/s), the dimensionless Weibull shape parameter *k*, and the measured wind speeds for the four chosen locations.

The highest Weibull scale parameter of 8.414 m/s from the ENE direction was observed in Sokoto, followed closely by Abuja at 8.271 m/s, indicating a significant wind energy potential in this direction in northwestern and central Nigeria states. Conversely, Ebonyi registered the lowest value of 2.936 m/s from the SSE, reflecting weak and inconsistent wind patterns. An analysis of the Weibull shape parameter (k), which indicates the reliability of wind speed, revealed that Jigawa recorded the highest k values from NNE (7.969), ENE (6.599), and NNW (6.308). Abuja followed with values of 7.335 from NNE and 6.411 from ENE, suggesting a moderate level of wind consistency. In contrast, Ebonyi showed lower k values (ranging from 3.3 to 4.9), signifying greater variability, whereas Sokoto displayed moderate consistency from ENE (6.427) and NNE (5.752). This outcome indicates that Jigawa exhibits the most steady and dependable wind speeds, especially from the northeastern orientations (NNE, ENE, NNW), followed by Abuja and Sokoto. An analysis of average Weibull directional wind speeds shows that Sokoto (7.84 m/s) and Abuja (7.70 m/s) displayed the highest speeds coming from the ENE, followed by Jigawa (6.42 m/s) in the same direction and 6.39 m/s (NNE), while Ebonyi again reflected the least potential with a peak of 5.41 m/s in the NNE direction. These results reveal the geographical differences in wind characteristics, with the ENE direction generally presenting the most promising prospects for wind energy development in Nigeria, except in Ebonyi, where southwestern winds dominate but with lower strength. According to Nze-Esiaga and Okogbue (2014), the two parameters of the Weibull statistics were found to lie between $2.99 \leq k \leq 5.32$ and $3.02 \leq c \leq 8.57$, respectively for southwestern Nigeria.

Table 5: Weibull Statistical Parameters

Direction	Abuja			Ebonyi		
	c (m/s)	k	WS (m/s)	c (m/s)	k	WS (m/s)
N	-	-	-	-	-	4.160
NNE	6.922	7.335	6.491	5.968	3.993	5.409
ENE	8.271	6.411	7.701	4.502	3.556	4.054
E	7.386	4.513	6.742	4.015	3.580	3.617
ESE	4.737	3.830	4.283	3.377	3.500	3.039
SSE	3.980	4.108	3.613	2.936	3.851	2.656
S	3.951	4.008	3.582	3.274	3.324	2.938
SSW	5.24	3.775	4.734	4.768	4.726	4.364
WSW	5.264	4.749	4.819	4.651	4.846	4.263
W	4.681	4.893	4.293	3.916	4.012	3.550

WNW	4.303	4.153	3.909	3.188	4.890	2.924
NNW	5.459	4.538	4.984	-	-	1.690
Mean	6.324	4.756	5.650	4.472	4.028	4.040
	Jigawa			**Sokoto**		
	c (m/s)	**k**	**WS (m/s)**	**c (m/s)**	**k**	**WS (m/s)**
N	-	-	-	-	-	0
NNE	6.782	7.969	6.385	7.023	5.752	6.500
ENE	6.883	6.599	6.418	8.414	6.427	7.835
E	5.082	4.129	4.614	7.222	4.552	6.595
ESE	4.129	4.632	3.774	4.199	3.811	4.446
SSE	3.867	5.078	3.554	4.354	3.745	3.932
S	3.831	5.084	3.521	4.146	4.108	4.049
SSW	4.257	4.701	3.895	5.432	4.258	4.941
WSW	4.737	4.817	4.34	5.461	4.676	4.995
W	4.564	4.717	4.176	5.017	4.816	4.960
WNW	4.473	4.200	4.066	4.917	4.174	4.590
NNW	5.797	6.308	5.393	5.969	3.097	5.093
Mean	5.556	5.294	4.992	6.424	4.492	5.754

The Frequency of Wind

When evaluating wind resources and building wind farms, wind speed frequency—which reflects the frequency of wind speed in each direction—is a crucial statistic. The wind energy resources in wind farms can be described by wind speed frequency, which also influences the assessment of power generation and financial gains (Wang et al., 2021). Figure 4 is the frequency of wind obtained from the Weibull probability distribution function.

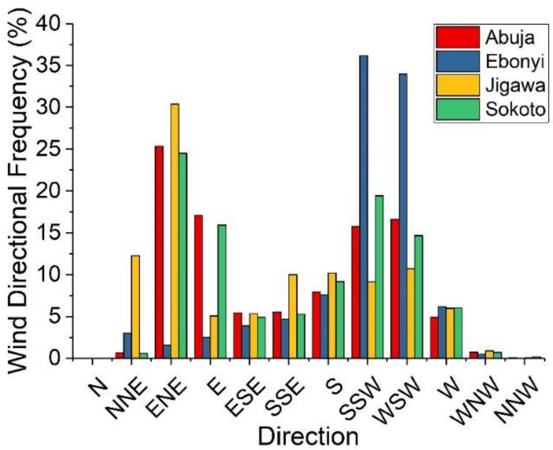

Figure 4: Frequency of Wind

Figure 4 shows the wind direction frequency for the study locations. Abuja experienced a bimodal wind system, with winds predominantly from ENE (25.35%), WSW (16.60%), and SSW (15.73%). Ebonyi's winds were largely dominated by SSW (36.19%) and WSW (33.96%), accounting for over 70% of occurrences. Jigawa indicated prevailing winds from ENE (30.39%) and NNE (12.26%), while Sokoto presented a mixed wind profile with ENE (24.52%) and SSW (19.42%), hinting at seasonal variations. This result compared favourably with that obtained by Nwachuku and Morka, 2024. Understanding these directional patterns is essential for enhancing turbine placement and design.

Monthly Statistics of Wind Speed

An understanding of monthly variations in wind speed at various hub heights is essential for assessing the wind energy potential of a site. A comparative assessment of wind speed data at 10 m and 50 m above ground level, which are recognized reference heights for meteorological studies and wind energy evaluations, respectively is presented in figure 5.

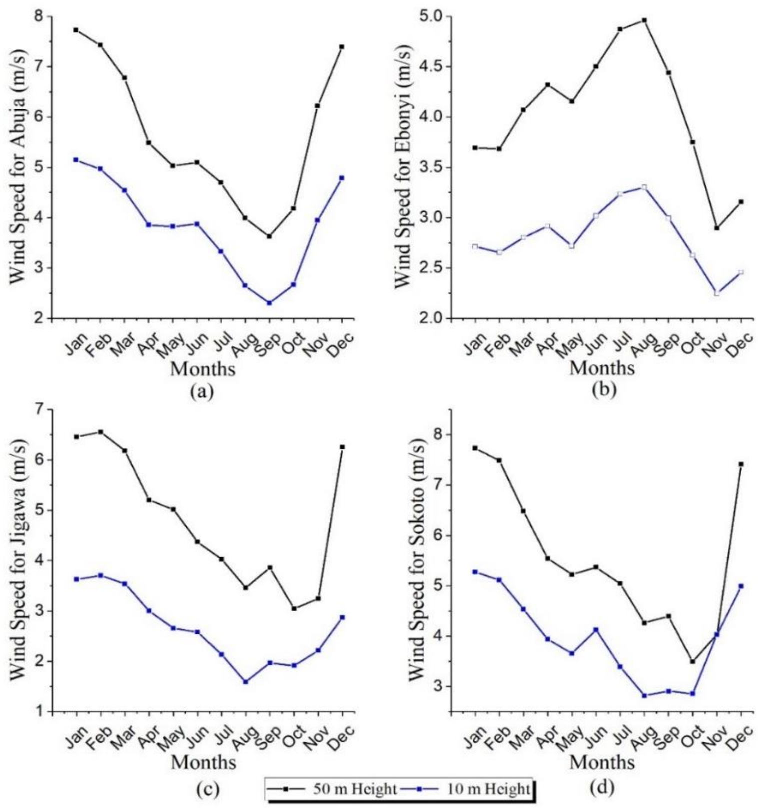

Figure 5: Monthly statistics of wind speed at hub height 50 m and 10 m

The monthly trends in wind speed across Abuja, Ebonyi, Jigawa, and Sokoto at elevations of 10 m and 50 m (figure 5) display distinct spatial and monthly variations. In Abuja (figure 5a), there is a clear seasonal pattern in wind speeds, peaking during the dry months of January and February and dropping significantly during the rainy season, particularly in August and September. At 50 m, wind speeds reached up to 7.7 m/s in January, whereas the average at 10 m was about 5.1 m/s, illustrating typical increase in wind velocity with height. In contrast, Ebonyi showcased the lowest wind speeds, exhibiting a relatively stable seasonal pattern. Monthly averages hovered between approximately 3.7 and 4.9 m/s at 50 m, and between 2.0 and 3.2 m/s at 10 m. This indicates limited opportunities for standalone wind energy generation, although such conditions could still support small-scale or hybrid systems. In Jigawa, wind speeds were moderate but exhibited more pronounced seasonal changes, peaking in February at 6.5 m/s (50 m) and declining in September. These seasonal fluctuations correspond to wider atmospheric shifts in northern Nigeria, like the Harmattan and rainy seasons. Sokoto stands out as the most promising location, as wind speeds frequently surpassed 7 m/s during the dry season, reaching nearly 8 m/s in December. Even at 10 m, wind speeds exceeded 5 m/s for much of the year, enhancing the efficiency of wind turbines. Across all regions, wind speeds at 50 m consistently surpassed those at 10 m, emphasizing the significance of elevation in wind energy collection. These observations feature Sokoto as the most practical state for wind energy development, while Jigawa and Abuja present moderate opportunities. Ebonyi may be more appropriate for hybrid systems where wind energy complements other renewable sources like solar power.

Wind Power Density

The directional distribution of wind power density (WPD) gives understanding to the locational differences in wind energy potential. Figure 6 displays the WPD values across twelve directional sectors for the four chosen states in Nigeria.

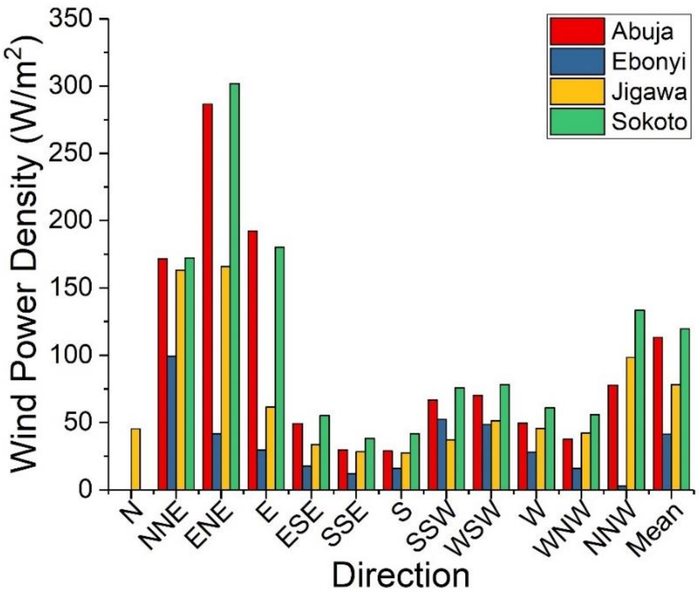

Figure 6: Wind power density at a hub height of 50 m

Figure 6 reveal significant variations in both the intensity and direction of wind power potential, which are vital for the strategic placement and orientation of wind energy systems. The predominant wind direction in Abuja is the east-northeast (ENE), where WPD peaks at 286.6 W/m², followed by east (E) and north-northeast (NNE) directions. The average WPD across all directions is 113.2 W/m², indicating a moderate to high potential for wind energy development, particularly when turbines are positioned to take advantage of the prevailing ENE winds. Conversely, Ebonyi showed a significantly lower wind energy profile, with a mean WPD of 41.4 W/m². The maximum WPD is found in the NNE direction (99.3 W/m²), with other directions contributing far less. This indicates limited potential for standalone wind systems, emphasizing the necessity for integrated renewable energy approaches, possibly merging wind with solar. Jigawa features a more even wind profile, with substantial contributions from both ENE (165.9 W/m²) and NNE (163.3 W/m²) directions. The total mean of 78.1 W/m² categorizes Jigawa as having moderate viability for wind energy. The steady performance of northeast winds suggests promising potential for small- to medium-scale installations. Sokoto offers the most promising location, with the highest mean WPD of 119.5 W/m². It records the highest single directional WPD at 301.8 W/m² in the ENE direction, along with consistently robust values in the E and NNE directions. The prevalence and strength of easterly winds bolster Sokoto's suitability for commercial wind farm initiatives. Adaramola & Oyewola (2011) observed that the annual wind power density fluctuates between 3.40 and 520 kW/m^2, with low values in the southern regions and gradual rise to comparatively higher WPDs in the north.

Annual Wind Energy Production

An investigation of annual wind energy output was done across the four typical sites to illustrate the regional wind resource potential and presented in table 6.

Table 6: Annual Wind Energy Production

Direction	Abuja					Ebonyi				
	OP (h/a)	Total [MWh/a]	0-5 [MWh/a]	5-10 [MWh/a]	10-15 [MWh/a]	OP [h/a]	Total [MWh/a]	0-5 [MWh/a]	5-10 [MWh/a]	10-15 [MWh/a]
N	--	--	--	--	--	2	--	--	--	--
NNE	60	31	31	--	--	260	88	7	80	1
ENE	2220	1980	7	1707	267	138	19	7	12	--
E	1494	956	18	843	95	218	20	11	9	--
ESE	474	74	23	51	--	339	17	14	2	--
SSE	484	41	28	13	--	411	11	11	--	--
S	694	57	39	18	--	665	30	26	4	--
SSW	1378	304	55	249	--	3170	495	170	325	--
WSW	1454	311	61	250	--	2975	426	171	255	--

W	430	62	25	37	--	540	44	31	13	--
WNW	63	7	4	3	--	42	1	1	--	--
NNW	8	2	2	--	--	1	--	--	--	--
Mean	8760	3825	260	3204	362	8760	1151	449	700	1
Capacity factor = 0.145						Capacity factor = 0.056				

	Jigawa					Sokoto				
Direction	**OP (h/a)**	**Total [MWh/a]**	**0-5 [MWh/a]**	**5-10 [MWh/a]**	**10-15 [MWh/a]**	**OP [h/a]**	**Total [MWh/a]**	**0-5 [MWh/a]**	**5-10 [MWh/a]**	**10-15 [MWh/a]**
N	--	--	--	--	--	--	--	--	--	--
NNE	1074	536	6	530	--	54	29	1	28	--
ENE	2662	1390	22	1368	--	2148	2003	6	1662	336
E	443	89	19	70	--	1396	830	18	755	56
ESE	467	45	30	16	--	429	76	19	56	--
SSE	874	67	58	9	--	461	54	24	30	--
S	893	66	58	8	--	802	100	44	55	--
SSW	800	86	51	36	--	1701	409	64	345	--
WSW	939	146	51	94	--	1282	309	48	261	--
W	524	72	30	41	--	405	73	20	54	--
WNW	77	10	4	6	--	71	12	3	9	--
NNW	7	2	2	--	--	12	5	5	--	--
Mean	8760	2509	329	2180	--	8760	3900	247	3260	392
Capacity factor = 0.14						Capacity factor = 0.147				

An assessment of yearly wind energy output across the four research sites indicated considerable spatial variability. Abuja reported an annual production of 3825 MWh/a with a capacity factor of 14.5%, and Sokoto at 3900 MWh/a with a capacity factor of 14.7%. Jigawa generated 2509 MWh/a with a capacity factor of 14%, while Ebonyi had the least production at 1151 MWh/a and a capacity factor of 5.6%. Across all locations, the predominant wind speed range of 5–10 m/s was responsible for the majority of energy production—Abuja (1304 MWh/a), Ebonyi (700 MWh/a), Jigawa (2180 MWh/a), and Sokoto (3260 MWh/a)—showing the important role of this wind regime in total output. A directional assessment further emphasized the significance of site-specific wind patterns: the ENE direction was identified as the main source of energy in Abuja (1980 MWh/a), 2220 h, Jigawa (1390 MWh/a, 2662 h), and Sokoto (2003 MWh/a, 2148 h), while SSW was the most effective in Ebonyi (495 MWh/a, 3190 h/a). Northern-facing directions (N, NNW) demonstrated minimal or no production at all locations, while eastern and southern directions tended to be more productive. Table 6 also reveals that ENE is the most efficient fixed direction and verifies the north's greater wind energy potential, driven by extended operational hours.

CONCLUSION

In conclusion, this study shows that the potential for wind energy varies considerably among the four chosen locations in Nigeria. Sokoto exhibited the greatest potential, followed by Abuja, while Ebonyi showed the least. The analysis revealed that the ENE wind direction delivers optimal power density for most sites, although Ebonyi had its peak in the NNE direction. Although the average wind power densities categorize most locations as poor to marginal in terms of wind power classes, the installation of taller turbines at a 100 m hub height could improve energy capture, despite financial limitations. To further refine and optimize the deployment, additional research should concentrate on high-resolution temporal analysis, terrain-informed micro-siting, and the integration of hybrid systems, particularly in low-potential areas like Ebonyi. Conducting environmental and socio-economic evaluations, along with developing supportive policies and financing models, will be crucial to fostering investment and ensuring sustainable growth. These results provide a data-driven basis for advancing Nigeria's wind energy sector within the framework of its broader renewable energy objectives.

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