



## Assessment of Wind Energy Potential across Different Köppen Climatic Zones of Nigeria Using RETScreen Expert

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### ABSTRACT

The increasing demand for clean and sustainable energy has intensified the need to evaluate Nigeria's wind energy resources across different climatic regions. This study assessed the wind energy potential of selected stations within Nigeria's Köppen climatic zones using Weibull statistical modelling and the RETScreen (Renewable Energy Technologies Screen) Expert platform. Weibull shape and scale parameters were estimated to determine Wind Power Density (WPD) and extrapolated hub-height wind characteristics. The computed WPD values were subsequently used in RETScreen simulations to estimate Annual Energy Generation (AEG), Capacity Factor (CF), and Greenhouse Gas (GHG) reduction potential using the Vestas V90. The results revealed significant climatic variability in wind energy potential across Nigeria. Stations located within the northern arid and semi-arid climatic zones (BWh and BSh) generally exhibited stronger wind resources and better turbine performance than stations within the humid southern climatic zones. Baga recorded the highest WPD of 181.8 W/m<sup>2</sup>, corresponding to an AEG of 3220 MWh/year, CF of 18.38%, and GHG reduction potential of 3330 tCO<sub>2</sub>/year, indicating moderate suitability for wind power development. In contrast, Aba and Port Harcourt exhibited extremely low wind resource conditions that resulted in non-feasible turbine outputs. The climatic suitability ranking followed the order: *BWh* > *BSh* > *Aw* > *Am*, confirming northern Nigeria as the most promising region for utility-scale wind energy development. The study demonstrates that integrating Weibull modelling with RETScreen Expert provides a reliable approach for regional wind energy assessment and sustainable energy planning.

**Keywords:** Wind Energy Potential; Retscreen Expert; Weibull Distribution; Wind Power Density; Köppen Climatic Zones; Capacity Factor

### INTRODUCTION

The growing concerns over climate change, the gradual depletion of fossil fuel resources, environmental degradation, and global energy insecurity have intensified the shift towards renewable energy systems worldwide. This transition is driven by the urgent need to ensure long-term energy security while reducing the environmental consequences associated with fossil fuel utilization, particularly greenhouse gas emissions, air pollution, and climate change (Elkhatat & Al-Muhtaseb, 2024). Among the renewable energy sources such as wind, solar, hydropower, and biomass, wind energy has emerged as one of the fastest-growing sources of clean electricity generation due to its scalability, low greenhouse gas emissions, and declining installation costs (Bashiru et al., 2024). Recent global statistics from the Global Wind Energy Council (GWEC) indicate that approximately 165W of new wind power capacity was installed globally in 2025 up 40% on 2024 with over 138 countries now powering their economies with wind power. Global cumulative wind power capacity has now exceeded 1 TW, demonstrating the increasing importance of wind energy in the global electricity mix (GWEC, 2026).

The continued expansion of wind energy is strongly linked to international commitments toward decarbonization and sustainable development. The COP28 agreement emphasized the need to triple global renewable energy capacity by 2030, positioning wind energy as a major contributor to future low-carbon electricity systems (Izuchukwu, 2025). In addition, advancements in turbine technology, improved forecasting systems, grid integration techniques, and hybrid renewable energy systems have further enhanced the technical and economic viability of wind power generation worldwide

(Adeyinka et al., 2024). Consequently, both developed and developing nations are increasingly investing in wind resource assessment studies to identify suitable locations for large-scale and distributed wind energy deployment.

In Africa, the increasing electricity demand, low electrification rates in rural communities, and dependence on fossil-fuel-based power generation have stimulated growing interest in renewable energy development. Several African countries, including South Africa, Egypt, Morocco, and Kenya, have made significant progress in integrating wind energy into their national energy mix (Agoundedemba et al., 2023). However, despite possessing substantial wind resources, many Sub-Saharan African countries still face challenges related to inadequate wind resource characterization, insufficient technical assessment, limited investment, and poor energy infrastructure. These challenges are particularly pronounced in Nigeria, where electricity generation remains insufficient to meet the growing energy demands of the population and industrial sectors.

Nigeria has vast energy needs but persistent power shortages, prompting interest in diverse renewables. Despite abundant fossil and renewable resources, Nigeria's power sector remains inefficient and underpowered (Edeh & Okpo, 2026). The country's growing population, rapid urbanization, and industrial expansion continue to increase electricity demand beyond available generation capacity. As a result, there is an urgent need to diversify the national energy portfolio through the integration of sustainable and environmentally friendly renewable energy technologies such as wind energy. As Elkelay et al. (2024) noted, systemic issues like unreliable grid infrastructure and regulatory challenges have hindered even abundant resources such as wind from being harnessed

effectively. In practice, Nigeria's 13.5 GW of installed capacity (2021) is dominated by gas and hydro, with only about 10.2 MW of wind plant in Katsina (Dinneya-Onuoha, 2025). This gap between resource and production underscores the need to evaluate wind across Nigeria's varied climate zones for energy and economic potential.

Wind energy development in Nigeria has attracted increasing research attention over the past decade due to the country's diverse climatic and geographical conditions. Nigeria spans multiple climatic zones characterized by significant variations in atmospheric circulation patterns, temperature, surface roughness, humidity, and wind regimes (Akinsanola & Ogunjobi, 2014). Nigeria lies within latitudes 4°N and 14°N and longitudes 3°E and 15°E, and is characterized by distinct Köppens climate zones, including the warm desert (BWh) in the extreme northern fringe, warm semi-arid (BSh) across the sahel region, tropical savannah (Aw) dominating much of the central and southern inland areas, and tropical monsoon (Am) along the coastal zones, exhibiting varying climatic conditions (Igbawua et al., 2025). These climatic variations strongly influence wind speed distribution, wind power density, air density, turbulence characteristics, and overall wind energy potential across the country (Olayinka et al., 2019). The warm desert (BWh) and warm semi-arid (BSh) climatic zones in northern regions, have been reported to exhibit higher average wind speeds ranging from 4 to 7 m/s at a 10 m height, suggesting promising potential for utility-scale wind energy generation (Fagbenle et al., 2011; Aliyu et al., 2022).

Several studies have investigated wind energy potential across various locations of Nigeria using statistical models, Weibull probability distribution functions, and wind power density analysis. Issa et al. (2025) surveyed wind data across all 36 states and confirmed that only the far north (northwest and northeast) have moderate winds, while most southern states have low (<3 m/s) winds. Attabo et al. (2023) assessed the wind energy potential and economic viability of selected coastal and offshore locations in Nigeria using Weibull statistics and techno-economic analysis. The study found that offshore sites, particularly Offshore-02 and Offshore-04, exhibited higher mean wind speeds and wind power densities, making them more suitable for offshore wind farm development than coastal locations. The authors further reported that the Vestas V117-4.0 MW turbine provided the best economic performance, with low levelized cost of electricity and favorable payback periods for offshore installations. Similarly, Akpootu et al. (2022) investigated the wind power potential of Warri and Port Harcourt in Nigeria's coastal region using 31 years (1980–2010) of measured wind speed data and the two-parameter Weibull distribution model. The study found that Warri exhibited slightly higher mean wind speed and wind power density than Port Harcourt, indicating better prospects for wind energy generation in the area. The authors further showed that the Weibull model effectively described the wind speed distribution, with strong correlations between measured wind speed and wind power density in both locations. Wawo et al. (2023) used RETScreen Expert to model a 3 MW wind farm in Wudil, Kano (a semi-arid BSh site), finding a mean wind of 3.1 m/s that would yield about 7,884 MWh/year. Along Nigeria's coast, Ameh et al. (2023) analyzed offshore vs. onshore sites and reported that offshore locations (Atlantic coast) possess roughly four times the wind potential of coastal sites, corresponding to "Class IIIb" wind conditions. They estimated levelized costs as low as \$0.04/kWh offshore, with payback periods under 6 years for large (60 MW) farms. In the coastal monsoon zone (Rivers State), Uzunmwangho et al. (2021) performed a

RETScreen feasibility study for Bonny Island, finding that a 30 MW wind farm could generate ~89,684 MWh/year at a cost of ~\$0.10/kWh, concluding the project economically viable. The literature indicate that northern sites have the best wind speeds and yields (Wawo et al., 2023; Issa et al., 2025) while specialized projects demonstrate that with appropriate siting and technology, Nigerian wind projects can be financially attractive (Ameh et al., 2023). Abu Ajrah and Sumsudeen (2025) assessed the feasibility of offshore wind energy development in Bahrain using RETScreen software integrated with geospatial and multi-criteria evaluation techniques. The study identified suitable offshore locations capable of generating significant electricity output, with the potential to contribute substantially to Bahrain's renewable energy targets and reduce dependence on fossil fuels. Their findings demonstrated that RETScreen is an effective tool for evaluating the technical and energy performance of offshore wind projects under varying environmental conditions, thereby supporting renewable energy planning and sustainable energy transition strategies in arid coastal regions. Kassem et al. (2023) evaluated the feasibility of wind energy development in Libya using RETScreen Expert by analyzing the technical, economic, and environmental performance of selected wind farm locations. The study reported that several Libyan regions possess favorable wind characteristics suitable for utility-scale electricity generation, with significant potential for carbon emission reduction and improved energy diversification. Their findings further demonstrated that RETScreen Expert provides a reliable platform for assessing wind energy projects and supporting renewable energy planning in arid and semi-arid environments.

Hence, many previous studies focused on isolated locations and did not comprehensively compare wind energy potential across the major climatic zones of the country using a unified assessment framework. Furthermore, limited studies have integrated advanced renewable energy feasibility tools such as RETScreen Expert into climatic-based wind resource assessment in Nigeria.

RETScreen Expert is a widely recognized clean energy management software developed for evaluating the technical, environmental, and economic feasibility of renewable energy projects (Natural Resources Canada, 2024). The software incorporates global meteorological datasets from NASA and other sources to estimate renewable energy outputs based on site-specific inputs such as wind speed, turbine specifications, and hub height (RETScreen Expert, 2023). RETScreen's analytical framework allows users to perform energy modeling, financial analysis, sensitivity testing, and greenhouse gas emission reduction assessments. For wind energy projects, it can simulate turbine performance and estimate annual energy generation under varying climatic conditions (Nwozor et al., 2021).

Therefore, this study assesses the wind energy potential across different climatic zones of Nigeria using RETScreen Expert. The study specifically evaluates wind characteristics and energy generation potential across selected locations representing the BWh, BSh, Aw, and Am climatic zones of Nigeria. The findings provide valuable insights into the spatial distribution of wind resources and contribute to renewable energy planning, policy formulation, and sustainable wind energy development in Nigeria.

## MATERIALS AND METHODS

### Study Framework

This study adopts a Weibull-based probabilistic wind energy assessment framework to evaluate wind energy potential

across selected stations within Nigeria’s Köppen climatic zones using RETScreen Expert. The methodology integrates measured wind speed analysis, Weibull statistical modelling, vertical wind speed extrapolation, and RETScreen-based energy simulation.

Unlike deterministic approaches based solely on mean wind speed, the Weibull probabilistic framework captures the variability and stochastic nature of wind regimes, thereby providing more realistic estimation of wind energy potential, particularly in low-wind environments.

**Study Area and Data Collection**

This study was conducted across selected locations distributed across the four Köppen climatic zones of Nigeria:

- i. warm desert climate (BWh) – Sahel climate
- ii. warm semi-arid climate (BSh) – Sudan/Savannah climate
- iii. tropical savannah climate (Aw) – Derived Savannah climate
- iv. tropical monsoon climate (Am) – Tropical monsoon/coastal climate

The BWh and BSh climatic zones are predominantly located within the northern region of Nigeria and are generally characterized by low rainfall, high temperature, sparse vegetation, and relatively stronger wind regimes due to the influence of the Sahara and Sahel atmospheric systems. The Aw climatic zone covers much of the central and southern inland regions and is characterized by distinct wet and dry seasons, while the Am climatic zone occurs mainly along the southern coastal belt with high humidity, heavy rainfall, and relatively lower wind speeds (Peel et al., 2007; Kottek et al., 2006).

Nigeria lies within the tropical region of West Africa between latitudes 4°N and 14°N and longitudes 3°E and 15°E, and exhibits diverse climatic conditions influenced by atmospheric circulation, topography, proximity to the Atlantic Ocean, and the seasonal movement of the Inter-Tropical Discontinuity (ITD) (Ayoade, 2008; Nigerian Meteorological Agency [NiMet], 2023). These climatic variations significantly influence wind speed characteristics, air density, temperature distribution, and wind energy availability across different regions of the country.

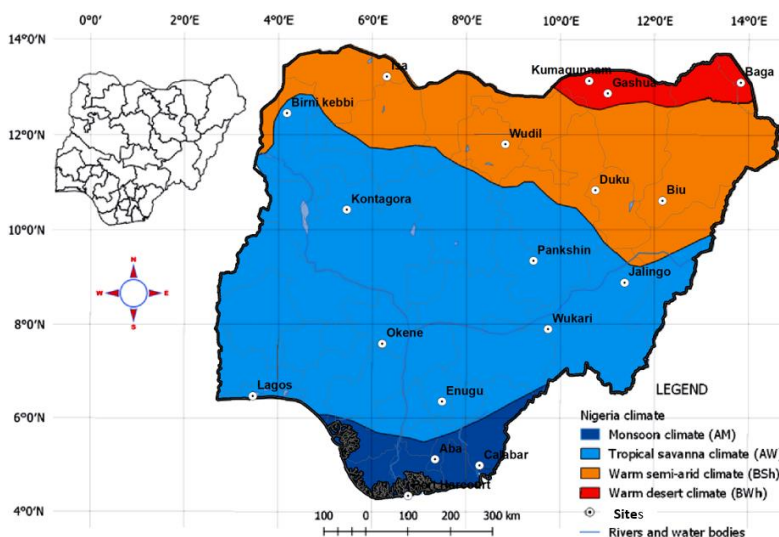


Figure 1: Map of Nigeria Showing Locations under Study Based On Köppens Climate Classification

Fifteen locations distributed across the selected climatic zones were considered in this study as shown in Figure 1. The geographical coordinates of the selected stations are presented in Table 1. The stations were selected to ensure adequate

spatial representation of the different climatic conditions across Nigeria and to enable comparative assessment of wind energy potential under varying atmospheric environments.

**Table 1: Geographical and Climatic Characteristics of Study Locations**

Site	Location	State	Climatic Zone	Latitude (°N)	Longitude (°E)	Elevation (m)
1	Baga	Borno	BWh	13.11	13.87	283.78
2	Gashua	Yobe	BWh	12.88	11.04	341.72
3	Kumagunnam	Yobe	BWh	13.15	10.64	349.50
4	Biu	Borno	BSh	10.60	12.20	456.32
5	Duku	Gombe	BSh	10.82	10.77	431.06
6	Wudil	Kano	BSh	11.80	8.85	480.7
7	Isa	Sokoto	BSh	13.24	6.33	334.26
8	Birnin-Kebbi	Kebbi	Aw	12.46	4.20	238.05
9	Pankshin	Plateau	Aw	9.32	9.45	712.32
10	Kontagora	Niger	Aw	10.41	5.47	268.48
11	Okene	Kogi	Aw	7.56	6.23	280.34
12	Enugu	Enugu	Aw	6.33	7.50	107.54
13	Lagos	Lagos	Aw	6.45	3.47	12.43
14	Wukari	Taraba	Aw	7.87	9.76	166.35

Site	Location	State	Climatic Zone	Latitude (°N)	Longitude (°E)	Elevation (m)
15	Jalingo	Taraba	Aw	8.86	11.39	285.62
16	Aba	Abia	Am	5.10	7.35	60.61
17	Calabar	Cross River	Am	4.97	8.30	34.68
18	Port-Harcourt	Rivers	Am	4.33	6.78	18.00

Meteorological data used in this study were obtained from the NASA database through the RETScreen Expert climate database system. The climatic variables extracted included monthly mean wind speed, air temperature, relative humidity, and atmospheric pressure for each selected location. The use of NASA climate data within RETScreen Expert provides standardized and globally validated meteorological datasets suitable for renewable energy assessment (Natural Resources Canada, 2024).

The wind speed data obtained from RETScreen are referenced at the standard meteorological height of 10 m above ground level. To obtain a more realistic assessment of wind energy generation potential for modern utility-scale wind turbines, the wind speeds were subsequently extrapolated to a hub height of 100 m using the power law model. The selection of 100 m hub height was based on its widespread application in contemporary wind energy systems and its suitability for utility-scale electricity generation studies (Manwell et al., 2023; Ahmed et al., 2024).

### Wind Speed Extrapolation

Wind speed varies with height above the ground surface due to changes in surface roughness, terrain characteristics, and atmospheric stability. In wind energy studies, wind measurements obtained at standard meteorological heights are usually extrapolated to turbine hub heights in order to provide a more realistic estimation of the available wind energy resource (Manwell et al., 2023). Since the wind speed data obtained from RETScreen Expert are referenced at a standard height of 10 m above ground level, the wind speeds were extrapolated to a hub height of 100 m for subsequent analysis. An extrapolation height of 100 m was adopted in this study because it represents a commonly used hub height for modern onshore wind turbines and provides a realistic basis for regional wind energy assessment (Wang et al., 2024). At higher elevations, wind speeds are generally stronger and more stable due to reduced ground friction effects, thereby improving the accuracy of wind power estimation and turbine performance evaluation.

The extrapolation of wind speed from 10 m to 100 m was carried out using the power law model, which is widely applied in wind resource assessment because of its simplicity and suitability for locations with limited vertical wind profile measurements (Ahmed et al., 2024). The power law relationship is expressed in equation (1) as:

$$v_2 = v_1 \left( \frac{z_2}{z_1} \right)^\alpha \quad (1)$$

where,  $v_2$  is the extrapolated wind speed (m/s),  $v_1$  is the wind speed at the reference height (m/s),  $z_2$  is the desired hub height (100 m),  $z_1$  is the reference measurement height (10 m) and  $\alpha$  is the wind shear exponent.

The wind shear exponent ( $\alpha$ ) accounts for the influence of terrain roughness and atmospheric conditions on the vertical variation of wind speed. In this study, a standard wind shear exponent value of 0.143 or 1/7, also known as the one-seventh power law exponent, was adopted. This value is commonly used for open terrain conditions and has been widely applied in regional wind energy assessments in Nigeria and other developing regions with similar climatic characteristics (Fatigun et al., 2017).

The extrapolated wind speed values at 100 m were subsequently used for Weibull parameter estimation, wind power density analysis, RETScreen energy simulation, and techno-economic evaluation of wind energy potential across the selected climatic zones of Nigeria.

### Weibull Distribution Analysis

The Weibull probability distribution function is one of the most widely used statistical models for wind resource assessment due to its flexibility and effectiveness in describing wind speed characteristics over a given location (Manwell et al., 2023). In wind energy studies, the Weibull distribution is commonly applied to evaluate wind speed frequency distribution, wind energy availability, and turbine performance under varying atmospheric conditions (Akdağ & Dinler, 2021). Its application provides a reliable basis for estimating wind energy potential and comparing the wind characteristics of different regions.

In this study, the Weibull distribution model was employed to analyze the wind speed characteristics of the selected locations across the four Köppen climatic zones of Nigeria at an extrapolated hub height of 100 m. The Weibull probability density function (PDF) is expressed as Köse (2025):

$$f(v) = \frac{k}{c} \left( \frac{v}{c} \right)^{k-1} \exp \left[ - \left( \frac{v}{c} \right)^k \right] \quad (2)$$

While the cumulative distribution function (CDF) is given as:

$$F(v) = 1 - \exp \left[ - \left( \frac{v}{c} \right)^k \right] \quad (3)$$

Where,  $f(v)$  is the Weibull probability density function,  $F(v)$  cumulative distribution function,  $v$  is the wind speed (m/s),  $k$  is the Weibull shape parameter and  $c$  is the Weibull scale parameter (m/s).

The Weibull shape parameter,  $k$  describes the degree of wind speed variability and atmospheric stability within a location. Higher values of  $k$  indicate more stable and uniform wind regimes, whereas lower values signify greater wind speed fluctuations (Ahmed et al., 2024). The Weibull scale parameter,  $c$  represents the characteristic wind speed of a location and is directly related to the wind energy potential of the site. Locations with higher  $c$  values generally possess stronger wind resources suitable for electricity generation.

The Weibull parameters were estimated using the standard deviation method due to its computational simplicity and wide application in regional wind energy studies (Akdağ & Dinler, 2021). The shape and scale parameters were calculated using Equations (4) and (5), respectively:

$$k = \left( \frac{\sigma}{v_m} \right)^{-1.086} \quad (4)$$

$$c = \frac{v_m}{\Gamma \left( 1 + \frac{1}{k} \right)} \quad (5)$$

Where,  $v_m$  mean wind speed (m/s),  $\sigma$  is the standard deviation of wind speed,  $\Gamma$  is the Gamma function expressed as (Parajuli, 2016).

$$\Gamma(x) = \int_0^\infty \exp(-t) t^{x-1} dx \quad (6)$$

Equations (7) and (8) can be used to calculate the values of mean wind speed and standard deviation respectively (Alavi, 2015):

$$v = \frac{1}{n} \sum_{i=1}^n v_i \quad (7)$$

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (v_i - v)^2} \quad (8)$$

$v$  And  $\sigma$  can be expressed in terms of Weibull distribution function as equations (9) and (10) respectively:

$$v = \int_0^{\infty} v f_w(v) dv = c \Gamma \left( 1 + \frac{1}{k} \right) \quad (9)$$

$$\sigma = \sqrt{c^2 \left[ \Gamma \left( 1 + \frac{2}{k} \right) - \Gamma \left( 1 + \frac{1}{k} \right)^2 \right]} \quad (10)$$

The estimated Weibull parameters were subsequently used for wind power density estimation and comparative evaluation of wind energy potential across the four climatic zones of Nigeria. The Weibull analysis also provided useful insights into the spatial variability and consistency of wind regimes within the study area.

### Wind Power Density

Wind Power Density (WPD) is one of the most important parameters used in wind resource assessment because it provides a direct measure of the mean annual wind power per unit swept area of a wind turbine (Teimourain et al., 2022). Unlike wind speed alone, wind power density accounts for both wind speed magnitude and air density, thereby providing a more reliable indicator of the energy generation capability of a location (Manwell et al., 2023). According to equation (11), the relationship is derived as (Alavi, 2015; Teimourain et al., 2022):

$$WPD = \frac{P}{A} = \frac{1}{2} \rho v^3 = \frac{1}{2} \rho \frac{1}{2} \rho c^3 \Gamma \left( 1 + \frac{3}{k} \right) \quad (11)$$

where,  $P$  is power watts and  $A$  is the swept area in  $m^2$ ,  $v^3$  is the wind speed cubed in  $m/s$ ,  $\rho$  is the standard air density at sea level ( $kg/m^3$ ).  $P$  is power watts and  $A$  is the swept area in  $m^2$ . Wind power density is computed in Watt per square meter ( $\frac{W}{m^2}$ ). Higher WPD values generally indicate greater suitability for wind energy development and utility-scale electricity generation. The WPD analysis also provided a basis for identifying regions with the highest wind energy potential and for assessing the influence of climatic variability on wind resource distribution across Nigeria.

The air density values used in this study were obtained from the meteorological parameters extracted from RETScreen Expert. Since air density varies with atmospheric pressure, temperature, and altitude, its inclusion improves the reliability and accuracy of wind energy estimation across different climatic zones (Ahmed et al., 2024).

The estimated WPD values at 100 m were used to evaluate and compare the wind energy potential of the selected locations across Nigeria's Köppen climatic zones. Locations with higher WPD values were considered more suitable for utility-scale wind power generation, while areas with relatively lower WPD values were considered more appropriate for small-scale or hybrid renewable energy applications.

### RETScreen Analysis

The technical and economic performance of wind energy generation across the climatic zones of Nigeria was evaluated using RETScreen Expert, a clean energy management software developed by Natural Resources Canada for renewable energy feasibility assessment. The software integrates climatic databases, energy production models, financial analysis tools, and greenhouse gas (GHG) emission evaluation within a unified platform, thereby making it suitable for wind energy project assessment under varying environmental conditions (Natural Resources Canada, 2024). The extrapolated wind speed data at 100 m, together with the monthly mean air temperature and atmospheric pressure obtained from the RETScreen climate database, were used as input parameters for the simulation. The software was subsequently used to estimate the technical performance of

wind energy projects across the different Köppen climatic zones of Nigeria.

The technical analysis focused on the estimation of annual energy generation and capacity factor. The Annual Energy Generation (AEG) represents the total amount of electrical energy expected from the wind turbine system within one year under the prevailing wind conditions of a location (Manwell et al., 2023). It is estimated using equation (12) (Astaneh, 2016):

$$AEG = P \times CF \times 8760 \quad (12)$$

Where,  $AEG$  is the annual energy generation (kWh/year),  $P$  is the rated power of the wind turbine (kW),  $CF$  is the capacity factor, 8760 is the total number of hours in one year.

The Capacity Factor (CF) is an important performance indicator that expresses the ratio of the actual energy generated by a wind turbine to the maximum possible energy output if the turbine operates continuously at rated capacity throughout the year (Manwell et al., 2023). It is expressed in equation (13) as:

$$CF = \frac{E_{actual}}{E_{rated}} \quad (13)$$

Where,  $CF$  is the capacity factor,  $E_{actual}$  is the actual annual energy generated (kWh),  $E_{rated}$  is the maximum possible annual energy output at rated capacity (kWh).

Higher capacity factor values generally indicate stronger and more reliable wind resources suitable for electricity generation (Manwell et al., 2023). Higher capacity factor values indicate better wind resource availability and improved turbine performance.

Greenhouse gas (GHG) reduction potential measures the amount of carbon emissions avoided when wind energy replaces fossil fuel-based electricity generation. Higher AEG and CF generally lead to greater GHG reduction because more clean electricity is produced consistently (Aljudaya et al., 2024). CF indicates turbine efficiency, while AEG represents the total annual electricity generated from available wind resources. Therefore, stations with stronger wind regimes and higher wind power density usually achieve higher environmental benefits. This highlights the important role of wind energy in climate change mitigation and sustainable energy development. Recent global reports show that wind energy continues to contribute significantly to carbon emission reduction and global decarbonization efforts (International Renewable Energy Agency [IRENA], 2025).

## RESULTS AND DISCUSSION

### Spatial Distribution of Meteorological Parameters across Nigeria's Köppen Climatic Zones

The spatial distribution of the mean annual meteorological parameters across the selected stations revealed clear climatic variability consistent with Nigeria's Köppen climatic classification (see Table 2). The warm desert climate (BWh) stations, comprising Baga, Gashua, and Kumagunnam, recorded the highest mean annual wind speeds ranging from 3.90 to 4.76 m/s, accompanied by relatively high air temperatures (27.71–29.43 °C), lower atmospheric pressure values (97.04–97.73 kPa), and very low relative humidity levels (28.83–34.52%). In contrast, the tropical monsoon climate (Am), represented by Aba, Calabar, and Port Harcourt, exhibited the lowest wind speeds (2.05–3.23 m/s) but recorded the highest atmospheric pressure (100.39–101.08 kPa) and relative humidity values exceeding 85%, reflecting the strong maritime influence of the Atlantic Ocean and persistent moisture-laden air masses. The warm semi-arid climate (BSh) displayed moderate wind speeds and intermediate humidity conditions, while the tropical savannah climate (Aw) exhibited wider variability due to differences in

elevation, vegetation cover, and regional atmospheric circulation. For instance, Pankshin recorded relatively lower air temperature and atmospheric pressure owing to its elevated terrain characteristics, whereas Lagos exhibited comparatively higher wind speed and atmospheric pressure due to coastal and urban influences. The progressive decrease in wind speed from the northern desert regions toward the southern coastal areas demonstrates the significant influence of climatic systems, surface roughness, atmospheric moisture content, and regional pressure gradients on wind energy distribution across Nigeria. This goes further to indicate that drier northern climates favor stronger and more stable wind

regimes because of reduced aerodynamic drag and lower atmospheric moisture, whereas humid southern regions experience weaker wind flow associated with dense vegetation cover, high humidity, and increased atmospheric stability (Obioha, et al., 2025). These findings further confirm that Köppen climatic classification provides an effective framework for comparative wind resource assessment and climate-sensitive renewable energy planning across Nigeria, thereby reinforcing the major novelty of the present study. Similar climatic influences on wind energy variability across tropical and subtropical regions have been reported in recent renewable energy studies (Jimoh & Chetty, 2026).

**Table 2. Mean Annual Meteorological Parameters at 10 m Height across the Selected Stations within Nigeria's Köppen Climatic Zones**

Station	Mean Wind Speed (m/s)	Annual Temperature (°C)	Mean Annual Air Atmospheric (kPa)	Annual Pressure	Mean Relative (%)	Annual Humidity	Air Density (kgm <sup>3</sup> )	Köppen Climatic Zone
Baga	4.76	29.43	97.73		28.83		1.125	
Gashua	3.9	27.74	97.12		34.52		1.124	BWh
Kumagunnam	4.03	27.71	97.04		32.20		1.124	
Biu	3.74	26.46	95.88		48.71		1.115	
Duku	3.43	26.31	96.15		48.85		1.119	BSh
Wudil	2.47	25.68	95.64		45.61		1.115	
Isa	3.94	27.58	97.23		39.02		1.126	
Birnin Kebbi	2.94	27.59	98.28		47.55		1.138	
Pankshin	3.22	24.36	93.18		58.75		1.091	
Kontagora	2.74	26.01	97.98		64.75		1.141	
Okene	2.68	25.62	97.88		73.92		1.141	Aw
Enugu	2.62	25.22	99.84		82.76		1.166	
Lagos	3.71	26.52	100.96		83.86		1.174	
Wukari	2.88	25.46	99.13		74.80		1.156	
Jalingo	2.91	25.97	97.78		64.82		1.139	
Aba	2.1	25.35	100.39		85.83		1.172	
Calabar	3.23	25.98	100.68		85.16		1.173	Am
Port Harcourt	2.05	26.73	101.08		86.15		1.174	

The zonal average meteorological parameters in table 3 reveals a strong climatic influence on wind energy distribution across Nigeria's Köppen climatic zones. The warm desert climate (BWh) recorded the highest mean wind speed (4.23 m/s), highest temperature, and lowest relative humidity, indicating dry and unstable atmospheric conditions favorable for stronger wind circulation and enhanced wind energy potential. In contrast, the tropical monsoon climate (Am) exhibited the lowest wind speed (2.46 m/s) but the highest atmospheric pressure and humidity due to persistent maritime air masses from the Atlantic Ocean. The warm semi-arid (BSh) and tropical savannah (Aw) climates showed intermediate atmospheric characteristics representing transitional climatic conditions. Thus, the progressive

decrease in wind speed from northern to southern Nigeria highlights the important roles of atmospheric moisture, pressure gradients, surface roughness, and climatic circulation systems in controlling wind flow dynamics and renewable energy potential. These findings confirm that Köppen climatic classification provides an effective framework for climate-sensitive wind energy assessment and renewable energy planning in Nigeria (Jimoh & Chetty, 2026).

#### Spatial Variation of Measured Wind Speed across Stations and Climatic Zones of Nigeria

Figures 3 and 4 present the spatial distribution of measured mean wind speed at 10 m height across the selected stations and Köppen climatic zones of Nigeria.

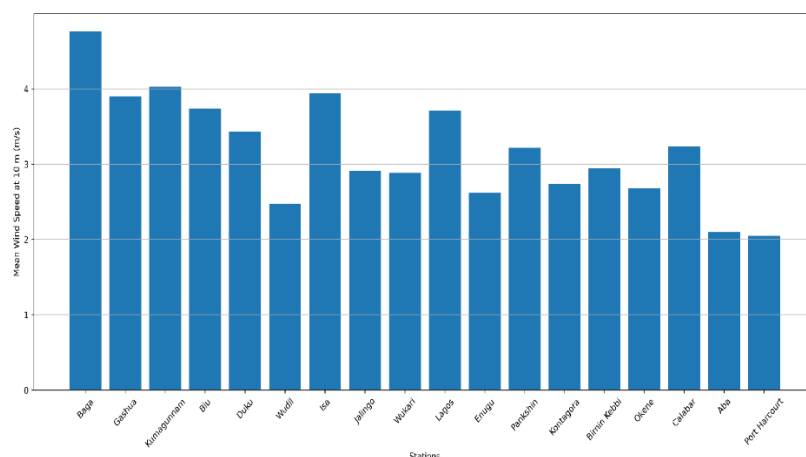


Figure 3: Station-Level Annual Mean Wind Speed across Nigeria’s Köppen Climatic Zones

At the station level (see figure 3), the highest measured mean wind speed was recorded at Baga (4.75 m/s), followed by Kumagunnam (4.03 m/s), Isa (3.94 m/s), and Gashua (3.90 m/s). These stations are located within the arid and semi-arid northern regions of Nigeria, particularly within the BWh and BSh climatic zones. In contrast, the lowest wind speeds were observed at Port Harcourt (2.05 m/s) and Aba (2.10 m/s), both located within the humid tropical coastal environment (Am zone). At the zonal scale in Figure 4, the BWh zone exhibited the highest mean wind speed (4.23 m/s), followed by BSh

(3.40 m/s), Aw (2.96 m/s), and Am (2.46 m/s). This north–south decreasing trend reflects the influence of atmospheric circulation, land-surface roughness, vegetation density, and moisture availability on near-surface wind behaviour. The stronger winds observed in the northern zones are associated with dry atmospheric conditions, sparse vegetation cover, and enhanced turbulent mixing, whereas the weaker winds in the southern coastal regions are linked to higher humidity, dense vegetation, and increased surface friction (Arya, 2001).

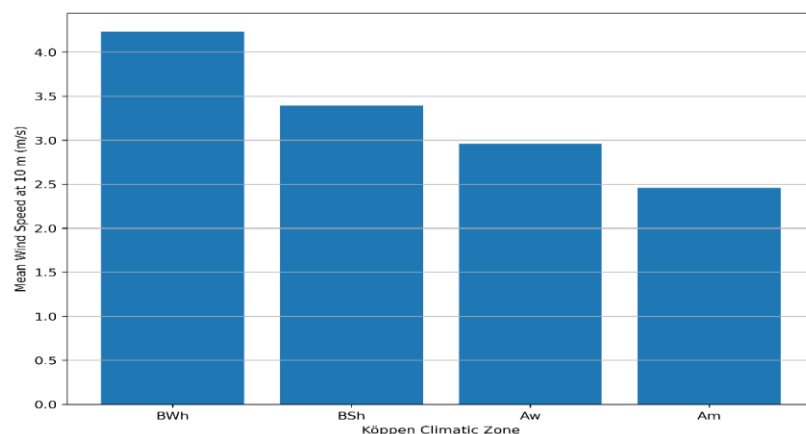


Figure 4: Comparative Zonal Mean Annual Wind Speed across Nigeria’s Köppen Climatic Zones

The results indicate that the BWh and BSh climatic zones possess comparatively higher wind energy potential and are therefore more suitable for utility-scale wind power development in Nigeria. Since wind power output varies with the cube of wind speed,  $P = \frac{1}{2} \rho A v^3$  even moderate increases in measured wind speed can substantially improve energy generation and project viability (Manwell et al., 2021).

**Monthly Wind Speed Variability across Climatic Zones**

The multi-panel plots in figure 5 illustrates clear seasonal and climatic influences on wind speed variation across Nigeria’s Köppen climatic zones. In BWh, wind speeds remained relatively high throughout the year, with stronger winds occurring during the dry season months and lower values during the peak rainy season. This pattern is mainly associated with Harmattan circulation and strong seasonal pressure gradients generated by dry continental air masses from the

Sahara region (Abdullahi & Limangba, 2026). BSh also showed noticeable seasonal changes, although with slightly lower wind intensity, reflecting its transitional nature between the dry northern region and the more humid central part of Nigeria. Stations such as Isa and Biu exhibited stronger fluctuations, indicating increased atmospheric turbulence and changing weather conditions across seasons.

Aw displayed more irregular wind patterns due to variations in vegetation cover, elevation, and local atmospheric conditions. Coastal and elevated locations such as Lagos and Pankshin experienced relatively stronger winds because of sea-breeze influence and terrain effects. In contrast, Am recorded the weakest and most stable wind conditions, particularly in Aba and Port Harcourt, where high humidity, dense vegetation, and persistent maritime moisture reduced wind development. However, Calabar showed comparatively stronger mid-year winds due to enhanced coastal airflow interactions and localized convective activity.

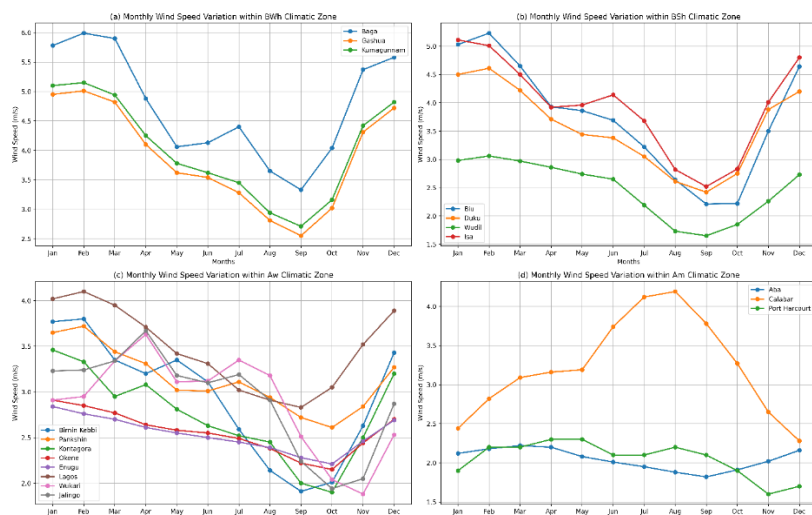


Figure 5: Monthly Wind Speed Variation across Climatic Zones

**Wind Speed Extrapolation and Weibull Distribution Characteristics**

The extrapolated wind speed results in table 4 revealed a consistent increase in wind speed from 10 m to 100 m height across all stations, reflecting the influence of vertical wind profile behavior and reduced surface friction within the atmospheric boundary layer.

The highest extrapolated wind speeds were observed in the northern BWh and BSh climatic zones, particularly at Baga (6.62 m/s), Kumagunnam (5.59 m/s), Isa (5.48 m/s), and Gashua (5.41 m/s), while the lowest values occurred in the humid Am zone at Port Harcourt (2.85 m/s) and Aba (2.92 m/s). The stronger winds in the northern regions are associated with low surface roughness, sparse vegetation, enhanced atmospheric mixing, and unstable boundary-layer conditions that favour efficient vertical momentum transfer. While, the lower wind speeds recorded in the southern coastal zones are linked to higher atmospheric moisture, dense vegetation cover, and stable atmospheric conditions that suppress turbulence and reduce wind acceleration with height (Arya, 2001).

The Weibull parameters further showed important differences in wind consistency and aerodynamic suitability for wind energy generation across the climatic zones. The Weibull shape parameter (*k*) ranged from 4.03 to 10.88, indicating generally stable wind regimes with varying turbulence intensity across the stations. Higher *k* values observed in stations such as Port Harcourt, Aba, and Enugu indicate more uniform wind flow and lower short-term variability, whereas relatively lower *k* values in stations such as Biu and Pankshin suggest greater turbulence and wind fluctuation. Similarly, the Weibull scale parameter (*c*) and wind power density (WPD) followed the spatial pattern of wind speed, with Baga recording the highest *c* value (7.14 m/s) and WPD (181.8 W/m<sup>2</sup>). Since wind power density varies with the cube of wind speed, the relatively high wind speeds in the BWh and BSh zones produced substantially greater wind energy potential than the humid southern regions. The findings indicate that northern Nigeria possesses more favorable atmospheric and aerodynamic conditions for utility-scale wind power development, while moderate wind regimes in parts of the Aw zone may support decentralized and hybrid renewable energy applications.

**Table 3: Wind Energy Result for Selected Sites**

Station	Mean Wind Speed 10 m (m/s)	Standard Deviation	Mean Wind Speed 100m (m/s)	Weibull k	Weibull c(m/s)	WPD (W/m <sup>2</sup> ) 100m
Baga	4.76	0.94	6.62	5.82	7.14	181.8
Gashua	3.9	0.85	5.41	5.21	5.88	101.97
Kumagunnam	4.03	0.88	5.59	5.24	6.08	112.3
Biu	3.74	1.03	5.19	4.03	5.72	95.98
Duku	3.43	0.73	4.77	5.39	5.17	68.68
Wudil	2.47	0.51	3.44	5.5	3.72	25.55
Isa	3.94	0.86	5.48	5.21	5.95	105.86
Birni kebbi	2.94	0.67	4.09	5.01	4.45	44.85
Pankshin	3.22	0.84	4.47	4.29	4.91	58.8
Kontagora	2.74	0.5	3.8	6.4	4.08	34.43
Okene	2.68	0.44	3.72	7.18	3.98	31.79
Enugu	2.62	0.42	3.64	7.23	3.88	30.19
Lagos	3.71	0.76	5.16	5.6	5.58	90.48
Wukari	2.88	0.54	4	6.2	4.31	40.89
Jalingo	2.91	0.55	4.05	6.15	4.36	41.78
Aba	2.1	0.31	2.92	7.86	3.1	15.57
Calabar	3.23	0.63	4.49	5.92	4.84	58.9
Port Harcourt	2.05	0.23	2.85	10.88	2.98	14.07

### RETScreen-Based Evaluation of Wind Turbine Performance under Different Climatic Regimes

The RETScreen-based assessment revealed substantial climatic variability in wind energy potential across Nigeria's Köppen climatic zones. Table 4 reveals that stations located within the arid and semi-arid northern regions (BWh and BSh) consistently exhibited superior wind resource characteristics, higher Wind Power Density (WPD), greater Annual Energy Generation (AEG), and improved Capacity Factors (CF) compared to stations in the humid southern regions (Aw and Am). This confirms the strong influence of regional atmospheric circulation, surface roughness, and climatic conditions on wind energy availability across Nigeria. Similar spatial variability in Nigerian wind regimes has been reported in recent wind resource assessment studies (Nwachuku & Morka, 2024; Akporhonor et al., 2023). Among all stations investigated, Baga recorded the highest wind energy performance with a WPD of 181.8 W/m<sup>2</sup>, AEG of 3220 MWh/year, and CF of 18.38%, indicating moderate suitability for utility-scale wind energy deployment. Conversely, stations within the tropical monsoon climatic zone, particularly Aba and Port Harcourt, exhibited extremely low WPD values (<20 W/m<sup>2</sup>), resulting in non-computable AEG and CF outputs in RETScreen Expert. This suggests that the prevailing wind regimes within these humid coastal environments remain below the operational threshold

required for effective electricity generation using the selected Vestas V90. Similar limitations of wind energy development within southern coastal Nigeria have been highlighted in recent studies on tropical wind resource variability and coastal atmospheric conditions (Ajayi et al., 2024; Seidu et al., 2024). The results further established a strong positive relationship between WPD and turbine performance indicators, confirming that increases in wind speed substantially improve energy generation due to the cubic dependence of wind power on wind velocity (see equation 4).

The northern stations characterized by stronger and more persistent wind regimes produced significantly higher AEG and GHG reduction potentials compared to southern stations. The highest GHG reduction potential of 3330 tCO<sub>2</sub>/year was recorded at Baga, indicating the environmental significance of wind energy deployment in northern Nigeria for carbon emission mitigation and sustainable energy transition objectives. These findings align with global renewable energy transition trends emphasizing increased utilization of low-carbon energy technologies for climate change mitigation (IRENA, 2024; GWEC, 2026). The findings therefore provide important insights for renewable energy planning, regional energy diversification, and future atmospheric physics studies involving boundary-layer wind dynamics and climate-dependent renewable energy assessment across West Africa.

**Table 4: RETScreen-Based Wind Energy Performance Indicators for Selected Stations across Nigeria's Köppen Climatic Zones Using the WPD Resource Method**

Station	Climatic Zone	WPD (W/m <sup>2</sup> )	Annual Energy Generation, AEG (MWh/year)	Capacity Factor, CF (%)	GHG Reduction (tCO <sub>2</sub> /year)	Resource Suitability
Baga	Bwh	181.8	3,220	18.38	3,330	Moderate
Gashua	Bwh	101.97	1,643	9.37	2,648	Marginal
Kumagunnam	Bwh	112.3	1,851	10.56	2,738	Moderate
Biu	Bsh	95.98	1,526	8.71	2,597	Marginal
Duku	Bsh	68.68	982	5.60	2361.77	Marginal
Wudil	Bsh	25.55	186.16	1.06	2017.53	Poor
Isa	Bsh	105.86	1724.76	9.84	2683.10	Marginal
Birni kebbi	Aw	44.85	533.57	3.05	2167.81	Poor
Pankshin	Aw	58.8	777.44	4.44	2273.30	Poor
Kontagora	Aw	34.43	335.89	1.92	2082.30	Poor
Okene	Aw	31.79	284.66	1.62	2060.134	Poor
Enugu	Aw	30.19	262.32	1.50	2050.47	Poor
Lagos	Aw	90.48	1470.82	8.40	2573.25	Marginal
Wukari	Aw	40.89	455.45	2.60	2134.02	Poor
Jalingo	Aw	41.78	464.36	2.65	2137.87	Poor
Aba	Am	15.57	NF	NF	1936.99	Non-viable
Calabar	Am	58.9	819.96	4.68	2291.70	Poor
Port Harcourt	Am	14.07	NF	NF	1936.99	Non-viable

**Note:** NF = Not Feasible. RETScreen Expert did not generate meaningful Annual Energy Generation (AEG) and Capacity Factor (CF) outputs for stations with extremely low wind power density due to insufficient wind resource relative to turbine operational threshold.

### CONCLUSION

This study evaluated the wind energy potential of selected stations in major Köppen climatic zones of Nigeria using Weibull statistical modeling and RETScreen Expert simulation techniques. The estimation of WPD and RETScreen-based energy performance analysis offered a detailed understanding of the spatial variability of wind resources and turbine performance in contrasting climatic settings of Nigeria. The results show that climate clearly affects the availability of wind energy and the productivity of turbines. Stations in the northern arid and semi-arid climatic

zones (that is, BWh and BSh) consistently showed higher wind power density, higher annual energy generation, better capacity factors, and better greenhouse gas reduction potential compared to stations in the humid southern climatic zones (Aw and Am). Among all the studied stations, Baga has the highest wind energy potential with WPD of 181.8 W/m<sup>2</sup>, AEG of 3220 MWh/year, CF of 18.38% and GHG reduction potential of 3330 tCO<sub>2</sub>/year. While stations such as Aba and Port Harcourt showed very low WPD values which are not enough for a significant turbine energy generation with the selected Vestas V90. Moreover, the study revealed a strong

positive correlation between wind power density and turbine performance parameters, indicating that small variations in wind speed may have a high effect on energy production as wind power is dependent on the cube of the wind speed. The general hierarchy of climatic suitability obtained in this study was:

$BWh > BSh > Aw > Am$

This ranking confirms the dominance of northern Nigeria as the most promising region for utility scale wind energy deployment. The humid coastal region is largely unsuitable for conventional large-scale wind turbine applications without specialized low wind speed turbine technologies. The estimated GHG reduction potentials from a sustainability perspective, indicate the potential contribution of wind energy development to Nigeria's renewable energy transition and carbon emission mitigation goals. The study thus calls for region-specific wind energy planning strategies to account for climate variability, atmospheric conditions and local wind characteristics. The findings also provide useful information to policy makers, energy planners and renewable energy investors seeking to optimize wind energy deployment across different climatic zones of Nigeria.

Future studies should include the use of higher resolution measured wind data, offshore wind resource assessment and techno-economic analysis including levelized cost of electricity, net present value and hybrid renewable energy systems. Additionally, the application of low cut-in wind turbines specifically designed for weak wind regimes could improve wind energy feasibility within some southern coastal locations.

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