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Article

Techno-economic assessment of commercial wind turbines for electricity generation in Nigeria

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ABSTRACT

The main aim of the present paper is to examine the wind energy potential, as well as the performance and economic sustainability, based on mean monthly wind speed data collected from the Nigerian Meteorological Agency (NIMET) and previous scientific studies. In this study, the Weibull distribution function is used to analyze the characteristics of the wind resources of 32 locations in Nigeria. Besides, intensity of turbulence, wind power density (WPD), annual energy production (AEP), capacity factor (CF), cost of energy (COE), and payback period (PBP) were evaluated for six commercial Enercon wind turbines (E53/800, E82/2000, E70/2300, E82/2300, E82/3000, and E101/3000). Results showed considerable differences between seasons and across space. Jos and Obudu were found to possess significant wind energy potential, with mean wind speeds above 8.0 m/s and WPD greater than 300 W/m^2. In contrast, Delta, Edo, Bauchi, and Abia had very low wind energy potentials, having WPDs less than 10 W/m^2. The seasonal analysis indicated that about 80% of the selected regions had high wind energy potential during the rainy season, resulting in greater energy generation capacity and improved turbine performance. In terms of energy production and cost per unit generated, the Enercon E101/3000 was shown to perform better than other turbine types, generating the greatest annual energy while recording the lowest cost per unit. The minimum energy cost of about 0.014 USD kWh^{-1} and the shortest payback period of 1.40 years were observed in Jos, while the maximum energy cost per unit and payback period were recorded in Bauchi. Based on these results, Jos and Obudu appear to be the best candidates for installing large-scale wind farms in Nigeria.

1. Introduction

Climate change is a major problem facing the entire world due to the high emissions of greenhouse gases resulting mainly from the consumption of fossil fuels, including coal, oil, and natural gas. This leads to rising global temperatures, causing changes in weather patterns and extreme weather conditions. The shift to renewable energy sources such as wind power has become essential to addressing climate change, helping to mitigate greenhouse gas emissions [1]. Renewable energy sources are important for reducing greenhouse gas emissions and climate change [2]. Wind energy is a sustainable energy source that does not produce any form of emissions, such as greenhouse gases, among other things. Wind energy is a renewable energy source that converts the kinetic energy of the wind into electrical energy [3]. In this regard, wind turbines are used to convert the kinetic energy of the wind into electrical energy. Wind turbines can be utilized for generating electricity for homes, schools, and health centers. In addition to this, wind energy can be of great importance in fulfilling the needs of electricity while sustaining development. Wind power can be a reliable source of electricity, especially in areas lacking traditional energy sources [4]. Over the past few years, the costs of wind power have continued to fall significantly, making it an attractive energy option [5].

1.1 Literature review related to energy situations in Nigeria

The generation of electricity is an essential activity in residential, commercial, and industrial applications. Electricity generation is essential for socio-economic development in Nigeria. The demand for electricity in Nigeria continues to rise as a result of population growth exceeding 200 million and a growing economy [6,7]. As the largest economy in Africa, there is an increasing demand for electricity as a result of growing industrial, commercial, and residential use. According to Ben-Iwo et al. [8], crude oil has been the main source of primary energy in Nigeria, accounting for more than 80 percent of Nigeria's total energy demand. Additionaly, the government has recently been encouraging renewable energy technologies [9, 10]. Although electricity use has increased by about 8% per year on average, there is not enough electricity supply in Nigeria because the national electricity access rate is about 60%, while in rural areas it ranges between 10% and 50% according to Ogbonna et al. [10], Ibrahim et al. [11], Emodi and Yusuf [12] and Oyedepo [13]. The Nigerian Electricity Regulatory Commission (NERC) is responsible for regulating the production, transmission, and distribution of electricity. Among the reforms implemented by the authority was the privatization of the electricity sector in 2013. However, these reforms failed to address the challenges facing the sector, such as inadequate infrastructure, insufficient generation, weak transmission and distribution, and power outages according to previous studies [13-18].

Generally, Nigeria has an installed electricity generation capacity of about 12.5 GW; however, only about 60% of that capacity is utilized owing to outdated facilities, poor maintenance, fuel shortages, and inadequate investment [14]. This capacity does not meet the national demand, which is estimated at around 30 GW. Gas-powered plants account for most of the electricity generated, while hydro and renewables account for a small share. Besides, the electrical distribution process is also limited, as it is characterized by more than 50% technical and commercial losses, attributed mostly to electricity theft, sabotage, and poor maintenance [12,13]. This decreases electricity availability, especially in rural areas, and affects economic development through limiting business activity and growth [13,19]. Moreover, electricity tariffs in Nigeria are administered by the Nigerian Electricity Regulatory Authority (NERC), and these tariffs vary according to the classification of the consumer and the distribution company that supplies each consumer with electricity [20]. Following the implementation of the service-based tariff policy in 2020, tariffs were raised in response to the increased cost of electricity production. The residential tariffs range between ₦23 ($0.06) and ₦62 ($0.16) per kilowatt hour, depending upon service classification. Commercial and industrial tariffs depend on electricity use, supply voltage, and service agreements with DisCos. While tariff reform was expected to improve cost recovery and the sustainability of the electricity industry, electricity tariffs have become a source of public discontent as the electricity supply remains unreliable. Higher tariffs are generally linked with poor investments, aging infrastructure, inefficiency, and high electricity generation and transmission costs. In conclusion, the country still faces the dual task of meeting the growing demand for electricity supplies in the country, as well as improving the affordability, availability, and reliability of electricity supplies. These are important issues that need to be resolved for the country to achieve sustainable economic development.

1.2 Literature review related to wind energy potential in Nigeria

Nigeria is the most populous country in Africa and has experienced rapid economic growth recently. The energy demand in the country has been on the increase due to population growth and industrialization. On the other hand, there have not been enough supplies of electricity, with many of the people in the country lacking access to electricity. In view of this problem, renewable energy sources such as wind energy have attracted attention in Nigeria recently. Wind energy refers to a renewable energy source that has gained popularity in Africa recently. Indeed, North African nations (Morocco, Egypt, and Tunisia) have dominated the market of wind energy in Africa [21,22], with Southern and Eastern African nations likely to set up wind farms to generate electricity soon [23]. On the other hand, Central African and West African nations have been slow in developing wind farms. It is against this background that this review of literature has sought to analyze wind energy in Nigeria.

Wind energy potential is plentiful in Nigeria, especially within the northern parts of the country. According to the National Renewable Energy and Energy Efficiency Policy (NREEEP) of 2015, the total amount of wind energy available in Nigeria is estimated at more than 53,000 MW. It is about five times the total installed electricity capacity of Nigeria currently. Furthermore, the northern part of Nigeria is blessed with large expanses of land, making it ideal for wind energy production. The region receives strong winds throughout the year. Particularly during the dry season, which occurs between November and March, the region experiences strong winds. A study conducted by the Nigerian Meteorological Agency (NiMet) has shown that wind speeds in the northern regions of Nigeria range between 4 and 10 m/s. Additionally, some wind energy projects have been initiated in Nigeria to utilize the available source of energy. Some of these projects include the construction of the Katsina Wind Farm, which generates 10 MW. This wind energy project consists of 37 wind turbines and is capable of producing 37,000 MWh of energy per year, thereby supplying electricity to about 300,000 homes annually. Other wind energy projects include the Lafiagi Wind Farm in Kwara State with an output of 1.2 MW and the Rimi Wind Farm in Katsina State with an output of 500 kW. However, despite being small compared to the potential for wind energy in Nigeria, these wind energy projects show great promise in Nigeria.

Besides the northern region, other parts of Nigeria, such as the coastal region, have the capacity for the production of wind energy. This is because the coastal area experiences sea breezes, which can be used to produce wind energy. According to the estimate of NREEEP, the coastal region of Nigeria has a potential for the production of more than 6,000 MW of wind energy. There have been several research studies carried out on the wind energy potential of Nigeria, and the findings have been impressive [24-47]. For instance, Ajayi et al. [24] studied the wind energy potential of Gusau, northwest Nigeria, through measured wind speed data and Weibull analysis. They found that the wind energy potential at Gusau is amongst the highest in Nigeria, with enough wind resources to sustain medium-scale wind energy generation and grid-connected electricity production. Fagbenle et al. [25] analyzed the wind energy potential of two sites in northeastern Nigeria, based on long-term wind speed data and Weibull distribution analysis. They found out that both sites have good wind properties, with one site having high wind power density and being appropriate for commercial wind energy exploitation. Ohunakin [26] conducted an assessment of wind characteristics and energy potential of Uyo, south Nigeria. From the study, there was a low average wind speed, making the area appropriate for the application of small-scale wind power, like water pumping and battery charging. Adaramola et al. [27] performed a study on the economic viability of electricity generation from wind energy conversion systems in north central Nigeria. Their findings revealed that the region has sufficient wind resources to generate electricity, which would be economically feasible under favorable investment conditions. Adaramola and Oyewola [28] evaluated the performance of various wind turbines at selected sites in Oyo State, southwestern Nigeria. The results demonstrated that the performance of wind turbines highly relies on local wind characteristics since low-wind-speed turbines yield better energy output. Ohunakin et al. [29] investigated the appropriateness of wind energy conversion systems for electricity production at seven selected sites in Nigeria. The results revealed considerable regional differences in wind energy resources, with northern sites having considerably greater wind energy potential compared to southern sites. Ajayi et al. [30] analyzed the wind energy resource potential at Jos City, Plateau State, Nigeria, for electricity generation. It found that the city of Jos is characterized by relatively high wind speeds and wind power density, which makes it a suitable location for wind energy applications. Ohunakin [31] studied the wind resources at six high-altitude sites in Nigeria. It found that high altitudes have a stronger and more stable wind regime.

Ohunakin and Akinnawonu [32] explored the wind energy potential and economic feasibility of wind power generation in Jos, Plateau State. They proved that wind energy utilization in Jos is technically feasible and economically viable when compared to many other places in Nigeria. Oyedepo et al. [33] estimated the wind speed characteristics and wind energy potential at three different locations in southeastern Nigeria. The study revealed low to moderate wind speeds, which means that the region is suitable for small-scale wind energy use rather than big commercial wind farms. Moreover, the economic feasibility of a wind-powered water pumping system in southern Nigeria was investigated by Paul et al. [34]. The results indicated that wind-powered water pumping can be a cost-efficient and environmentally sustainable alternative for rural areas without any access to electricity. Amoo [35] assessed the wind energy potential at two different sites in southwestern Nigeria using statistical wind analysis. The results have shown that there are moderate wind energy resources available for small-scale wind energy applications, but not for large-scale wind energy generation facilities. Nze-Esiaga and Okogbue [36] analyzed the potential of wind energy in five regions in southwestern Nigeria. The results showed that there were significant geographical differences in the potential of wind resources, which were higher for coastal regions than for inland regions. Ajayi et al. [37] provided a review of previous research studies on wind energy in Nigeria and carried out a case study of wind electricity generation cost in southwestern Nigeria. They concluded that northern Nigeria had the highest wind energy potential in the country, whereas technological development would make wind energy economically viable. Okeniyi et al. [38] analyzed the wind energy potential and wind characteristics in Akure, southwestern Nigeria, using an econometric method. The results showed relatively low wind energy potential; however, the role of favorable energy policy and technological development in improving wind energy exploitation was emphasized.

Ayodele et al. [39] carried out the evaluation of wind power utilization and economic analysis of wind turbines at fifteen locations, which were representative of six geopolitical zones in Nigeria. The results showed that high wind energy potential and low electricity generation costs were recorded in northern Nigeria compared to southern locations. Akinsanola et al. [40] assessed the wind energy potential in Koluama, Bayelsa State, Nigeria. The study found that although wind speeds were relatively low, small wind turbines could ensure sufficient and stable electricity generation for isolated communities. Udo et al. [41] examined the wind power potential of selected coastal cities of Nigeria. The results showed that coastal zones have stronger wind resources compared to inland zones and are more suitable for wind energy production. Audu et al. [42] analyzed the wind speed pattern and wind energy potential in Makurdi (north-central Nigeria). The results of the study showed moderate wind potential, which could be used for electricity generation and other renewable energy applications on a small scale. Peter et al. [44] evaluated five probability density functions in terms of their suitability in characterizing wind speed distributions in some chosen Nigerian cities. It was shown that Weibull density functions give a better representation of wind conditions to perform a reliable evaluation of wind-energy generation.

Okakwu et al. [45] carried out a comparison between different numerical methods of calculating Weibull parameters and assessing wind energy conversion system efficiency in Nigeria. The results showed that the choice of Weibull parameter calculation methods significantly affects predictions of wind energy intensity and power generation. Komolafe et al. [46] assessed the potential of wind energy generation in Omu-Aran, Nigeria, using Weibull and Rayleigh statistical models. It was found that the Weibull model gives a more accurate wind resource assessment, and that existing wind resources can be used mainly for small-scale wind energy. Generally, Nigeria is endowed with a huge amount of wind energy resources, especially in the northern part of the country. Wind energy resources in Nigeria are abundant and can play an important role in meeting Nigeria's energy needs. However, the wind energy sector in developing countries such as Nigeria faces various constraints. Some of these constraints have been pointed out by some scientists in previous studies [48,49].

1.3 Research aims

In this study, a techno-economic investigation into the potential of onshore wind energy in 31 locations in Nigeria is carried out, providing a fillip to the research into wind resource assessment in the region. While there exist numerous opportunities for harnessing the vast amounts of wind energy in Nigeria, there have not been adequate investigations into these potentials in relation to their economic efficiency. In this regard, the current study employs cutting-edge methods to conduct analysis of wind speeds and energy potentials through the application of power law and Weibull distribution models for wind speed frequency and wind Weibull parameter estimations. Whereas past studies have concentrated on assessing wind resources at lower hub heights, the current study analyzes wind power generation potential at higher hub heights. Additionally, the study conducts a comprehensive economic evaluation of six wind turbines to establish their technical viability and economic feasibility depending on wind regimes. These results provide useful insights that can be applied in optimizing wind resource assessment and ensuring an effective deployment of wind turbine generators for the purposes of Nigeria's renewable energy objectives and power demands. Moreover, the study presents a methodological approach for making decisions regarding initial stages of investment planning in wind farms within West Africa. Special attention is paid to such aspects as annual wind regime, dry and rainy wind seasons, and turbulence index in the areas with abundant wind energy resources. As a result, the main novelty of this research consists of conducting a thorough techno-economic evaluation of onshore wind farms in Nigeria, paying special attention to the cost of electricity at present value.

2. Material and methods

2.1 Study area and data

Wind speed in Nigeria is highly variable and depends on many factors such as location, topography, and air masses. In general, there is higher wind speed along the coastal areas compared with inland areas. Another type of wind that prevails in Nigeria is the Harmattan wind, which occurs mostly in the northern parts of the country from November to March. These winds have dry and dusty conditions and may have a considerable influence on air quality. In the rainy season, which lasts from April to October, the speed of the wind is low. Usually, the maximum values of wind speed occur during the dry season, mainly along the coast. The average value of wind speed in Nigeria changes from 2 meters per second (m/s) to 6 m/s. In this study, monthly wind speed values at 10 m height at 32 selected locations (Table 1) are used for evaluating the wind power potential. For this study, wind data recorded at 32 sites, as shown in Table 1, were utilized. Wind data for Bauchi, Edo, Delta, Abia, Jigawa, and Yobe were gathered from the Nigerian Meteorological Agency (NIMET). However, wind data for the remaining sites, including Enugu, Gboko, Ogoja, Nsukka, Ilorin, Udi, Ikwo, Otukpo, Makurdi, Afikpo, Obudu, Abuja, Lafia, Koluama, Jos, Uyo, Abeokuta, Akure, Ibadan, Ikeja, Oshogbo, Iseyin, Shaki, Lagos Island Marine, and Ondo, were obtained from Refs. [24–47]. The mean monthly wind speed data of the selected locations is illustrated in Figure 1.

2.2 Wind speed distribution

The Weibull distribution is one of the most important distributions for wind speed parameters in studying wind potential and producing wind energy. Variation of wind speed can be expressed by two main functions: (a) probability density function and (b) cumulative distribution function. The probability density function ($f(v)$) expresses the proportion of the probability for which the wind speed is v. It can be expressed using Eq. (1) [48, 49].

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

The cumulative distribution of the speed v is defined as the proportion of time for which the wind speed is less than or equal to the speed v. Therefore, the cumulative distribution $F(v)$ is the integral of the probability density function, which is shown in Eq. (2) [49, 50].

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

The Weibull distribution was used to analyze wind speed characteristics and estimate wind energy density in this study. A comparative study of several approaches to estimating the values of the shape (k) and scale (c) parameters of the Weibull function has been proposed [51]. The maximum likelihood approach turned out to be the most appropriate method [52-54]. Therefore, the maximum likelihood method is used to determine Weibull parameters ($\boldsymbol{k}$ (Eq. (3)) and $\boldsymbol{c}$ (Eq. (4))) in the present work [54].

$$k = \left[\left(\frac{\sum_{i=1}^{n} v_i^k ln(v_i)}{\sum_{i=1}^{n} v_i}\right) - \left(\frac{\sum_{i=1}^{n} ln(v_i)}{n}\right)\right]^{-1} \quad (3)$$

$$c = \left(\frac{\sum_{i=1}^{n} ln(v_i)}{n}\right)^{1/k} \quad (4)$$

In this study, the EasyFit software was used with a CPU (Intel Xeon E5-16XX, octa-core, 64GB RAM, 64-bit operating system) to obtain the distribution function parameters.

Table 1. Geographic coordinates of the selected locations

LN	Location	Coordinates		Al [m]	PR
		Lat. [°N]	Long [°E]		
1	Enugu	7.55	6.46	192	2009–2018
2	Gboko	9.00	7.34	215	2009–2018
3	Ogoja	8.80	6.65	70	2009–2018
4	Nsukka	7.37	6.84	423	2009–2018
5	Ilorin	8.50	4.54	320	2009–2018
6	Udi	7.39	6.48	437	2009–2018
7	Ikwo	8.20	6.07	50	2009–2018
8	Otukpo	8.14	7.20	97	2009–2018
9	Makurdi	8.52	7.73	104	2009–2018
10	Afikpo	7.95	5.89	92	2009–2018
11	Obudu	9.06	6.40	1050	2009–2018
12	Abuja	9.25	6.93	476	2009–2018
13	Lafia	8.49	8.52	179	2009–2018
14	Koluama	4.47	5.77	6	1984-2013
15	Bauchi	10.31	9.84	616	2008-2017
16	Edo	6.63	5.93	232	2008-2017
17	Delta	5.70	5.93	21	2008-2017
18	Abia	5.45	7.52	129	2008-2017
19	Jigawa	12.23	9.56	373	2008-2017
20	Yobe	12.29	11.44	349	2008-2017
21	Jos	9.52	8.45	1217	1971–2007
22	Uyo	5.30	7.55	38	1986-2007
23	Abeokuta	7.10	3.20	101	1961-2011
24	Akure	7.17	5.18	375	1961-2011
25	Ibadan	7.26	3.54	227	1961-2011
26	Ikeja	6.35	3.20	39	1961-2011
27	Oshogbo	7.47	4.29	302	1961-2011
28	Iseyin	7.58	3.36	330	1987-2007
29	Shaki	8.40	3.23	457	1987-2007
31	Lagos Island	6.26	3.25	2	1978-2010
32	Ondo	7.06	4.5	287	1978-2010

Lat.: Latitude; Long: Longitude; Al: Altitude; PR: Period records; LN: Location number

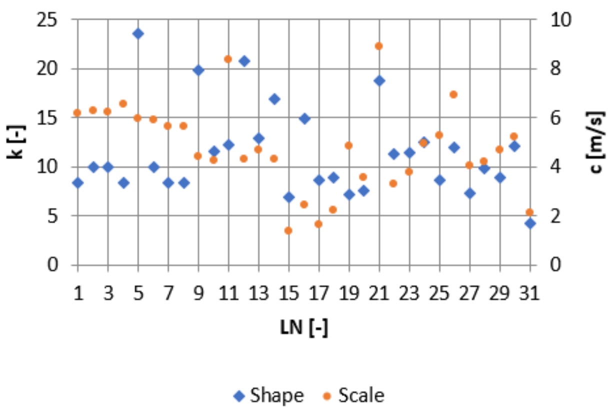

Figure 1. Annual value of Weibull parameters for all selected locations at 10m height

2.3 Wind potential estimation

The key parameters that are used to estimate wind energy potential to develop a wind farm are mean wind speed, wind turbulence index, wind power density, and the power law exponent. The above parameters have been calculated using the average of wind speed, power density, wind rose, power law exponent, and the wind turbulence index (turbulence intensity) at all sites with respect to season and time period. The formula for calculating the wind turbulence index ($\boldsymbol{I_n}$) has been provided in Eq. (5) [55-57].

$$I_n = \frac{\sigma}{v_m} \tag{5}$$

$$v_m = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{6}$$

$$\sigma = \left[\frac{1}{n-1}\sum_{i=1}^{n}(v_i - v_m)\right]^{1/2} \tag{7}$$

where $\boldsymbol{v_m}$ is the mean wind speed in m/s, $\boldsymbol{\sigma}$ is the standard deviation of the wind, $\boldsymbol{n}$ is the number of data observations, and v_i is the wind speed in time stage i.
Moreover, the model applied for estimating the average wind power density ($\overline{WPD}$) is expressed in Eq. (8) [54].

$$\overline{WPD} = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{8}$$

$$\rho = \frac{P}{RT} \tag{9}$$

where ρ is the air density, P, R, and T are the average air pressure, gas constant, and temperature, respectively, Γ is Gamma function and it defined in Eq. (6) [54].

$$\Gamma(x) = \int_0^{\infty} t^{x-1} exp(-t)\, dt \tag{10}$$

2.4 Wind profile vertical

The vertical wind profile can be stated as per Eq. (11). This model is also referred to as the power law. Power law plays a vital role in determining the wind speed at the heights needed by wind turbines. Power law can be formulated as: [58, 59].

$$\frac{v}{v_{10}} = \left(\frac{z}{z_{10}}\right)^{\alpha} \tag{11}$$

Where v_{10} is the wind speed at the original height z_{10} ($z_{10} = 10m$) and v is the wind speed at the wind turbine hub height (z).
Moreover, the power exponent (α) can be estimated using Eq. (12) [59].

$$\alpha = \frac{0.37 - 0.088 ln(v_{10})}{1 - 0.088 ln(z_{10}/10)} \tag{12}$$

2.5 Categorization of wind energy resources

Average wind energy resources are used to estimate potential wind resources at a specific location. Table 2 gives information on the expression of wind power density, wind speeds, and wind classes for estimating wind resources.

2.6 Evaluating commercial wind turbines' performance characteristics data

Many types of wind turbines are available for installation on the market, ranging from different designs to different performance standards [60]. It is essential to conduct thorough research to determine which performs best for installation. In general, the capacity factor is applied in selecting the appropriate turbine. The higher the capacity factor, the more attractive the turbine becomes, as there is a relationship between turbine performance and wind speed. This means that if the power factor is proven to be high (effective), the turbine will be considered effective for the chosen location. However, if the turbine is deemed inefficient, a new turbine will be selected through an iterative process [61].

Table 2. Wind energy resource classification at 10m height [60]

WRC	WC	WS [m/s]	WPD [W/m²]
Poor	1	3.5–5.6	50–200
Marginal	2	5.6–6.4	200–300
Moderate	3	6.4–7.0	300–400
Good	4	7.0–7.5	400–500
Excellent	5	7.5–8.0	500–600
Excellent	6	8.0–8.8	600–800
Excellent	7	Above 8.8	Above 800

WRC: Wind resource category; WS: Wind speed ; WC: Wind class

Eq. (13) can be used in the calculation of the power produced by the wind turbines [59]. Furthermore, it is possible to determine the power curve of wind turbines using the hyperbolic equation as shown in equation (14) [59].

$$E_{wt} = \sum_{i=1}^{n} P_{wt(i)}\, t \tag{13}$$

$$P_{wt(i)} = \begin{cases} P_r \frac{v_i^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} (v_{ci} \le v_i \le v_r) \\ \frac{1}{2}\rho A C_p v_r^2 (v_r \le v_i \le v_{co}) \\ 0 \quad (v_i \le v_{ci} and v_i \ge v_{co}) \end{cases} \tag{14}$$

Where E_{wt} is the total output power generated, t is the time in hours for the period being considered, v_i is the vector of the possible wind speed at a particular site, $P_{wt(i)}$ is the vector of the corresponding power output by the wind turbine (W), P_r is the rated power of the wind turbine (W), v_{ci} is the cut-in wind speed (m/s), v_r is the rated wind speed (m/s), and v_{co} is the cut-out wind speed (m/s). C_p is the coefficient of performance of the turbine (Eq. (15)), which depends on the tip speed ratio and the pitch angle.

$$C_p = 2\frac{P_r}{\rho A v_r^3} \tag{15}$$

Besides, the capacity factor CF can be estimated through Eq (16) [59].

$$CF = \frac{E_{wt}}{8760 P_R} \tag{16}$$

2.7 Rotor design for effective results

After selecting the most suitable turbine, rotor design parameters are determined to maximize power generation during turbine operation by utilizing the available wind. Many parameters determine the power generated by a wind turbine. They include the number of blades, the diameter of the rotor, the rotation speed of the rotor, the airfoil shape, the blade angle, and the angle of attack. According to González-Hernández and Salas-Cabrera [62], an increase in the number of blades results in the maximum power coefficient that is almost equal to the Betz limit. To optimize the annual energy yield from a low-speed wind turbine, the blade twist angle must take into consideration this objective. The best design of a wind turbine generator can be attained by focusing on the design (rated) since this will give the values of the cut-in and cut-off wind speed as well as the tip speed ratio and blade numbers. The determination of the average value of wind speed in the wind speed distribution is equivalent to the optimum angle of attack and helps obtain the twist angle needed for maximum annual energy production. Furthermore, the airfoil used by the rotor to give a lift-to-drag ratio is also determined. MATLAB code is implemented to analyze the performance of the horizontal shaft of the wind turbine through the blade elements theory and momentum theory. The major calculations involved in this program include determination of the coefficients such as moment coefficient ($\boldsymbol{C_q}$), angle of attack (α), relative angle (φ), twist angle (β), drag coefficient ($\boldsymbol{C_L}$), lift coefficient ($\boldsymbol{C_D}$), axial interference coefficient (G), tangential interference coefficient (E), local tip speed ratio (λ), local torque coefficient ($\boldsymbol{m_r}$), Prandtl efficiency (η_b), and power coefficient (C_p). This procedure is performed to maximize the output power through modification of the rotor's main aerodynamic parameter and hub height to ensure that the rotor always runs at maximum drag/lift coefficient ratio (C_L/C_D). The mathematical equations for blade element theory and momentum theory can be found in Red [63]. Table 3 lists the different types of wind turbines utilized to evaluate their suitability for selected locations in Nigeria. Figure A1 (Appendix) illustrates the power curves and power coefficient (C_p) of the selected wind turbines.

2.8 Economic Analysis

Several factors contribute to energy generation using wind power in the region. The cost of wind energy production varies from region to region, depending on technological, economic, social, and political environments and prevailing trends in energy markets. The cost per kilowatt-hour analysis (in USD) includes the cost of capital and interest, as well as the cost of operation and maintenance. The capital cost depends on the rate of interest and the repayment of the loans taken. The investment cost includes the wind power generation system, installation, land lease cost, grid connection cost, planning cost, and licensing cost. Eq. (17) defines the cost of energy (COE) in USD/kWh [58].

Table 3. Specification of the selected wind turbines (Manufacturer: Enercon; number of blade=3 blades)

Model	D [m]	P_r [kW]	WS [m/s]			h [m]	Max C_p
			v_r	v_{co}	v_{ci}		
E53/800	52.9	800	12.5	34	2.0	73	0.49
E82/2000	82	2000	12.5	34	2.0	108	0.50
E70/2300	71	2300	15.0	34	2.0	113	0.50
E82/2300	82	2300	12.0	34	2.0	98	0.50
E82/3000	82	3000	16.0	34	2.0	84	0.48
E101/3050	101	3000	13.0	25	2.0	74	0.48
D: Diameter; Max: Maximum; h: Hub Height							

$$COE = \frac{(r_d+0.025)C_{ICC}}{E_{wt}} \quad (17)$$

$$r_d = \frac{DR}{1-(1+DR)^{-n}} \quad (18)$$

$$C_{ICC} = B_C + H_C + B_C + PS_C + NC_C + LSS_C + BS_C + GB_C + E_C + YS_C + MF_C + PaR_c + HaC_C + EC_C + NC_C + AaI_C + F_C + T_C \quad (19)$$

Blade cost (B_C)

$$B_C = 3.8118\left(\frac{D}{4}\right)^{2.5025} + 0.5582\left(\frac{D}{4}\right)^{2} - 955.24 \quad (20)$$

Hub cost (H_C)

$$H_C = 0.5881\left(\frac{D}{2}\right)^{2.9158} + 24141 \quad (21)$$

Pith-system cost (PS_C)

$$PS_C = 0.4802\left(\frac{D}{2}\right)^{2.6578} \quad (22)$$

Nose-cone cost (NC_C)

$$NC_C = 103\left(\frac{D}{2}\right) - 2899 \quad (23)$$

Low-speed-shaft cost (LSS_C)

$$LSS_C = 0.1\left(\frac{D}{2}\right)^{2.887} \quad (24)$$

Bearing-system cost (BS_C)

$$BS_C = \left(\frac{D}{2}\right)^{2.5}(0.0043R - 0.011) \quad (25)$$

Gear-box cost (GB_C)

$$GB_C = 16.45(P_r)^{1.249} \quad (26)$$

Electronics cost (E_C)

$$E_C = 79(P_r) \quad (27)$$

Yaw-system cost (YS_C)

$$YS_C = 0.0678\left(\frac{D}{2}\right)^{2.964} \quad (28)$$

Main-frame cost (MF_C)

$$MF_C = 9.489\left(\frac{D}{2}\right)^{1.953} \quad (29)$$

Platform-and-railing cost (PaR_c)

$$PaR_c = 2.5397\left(\frac{D}{2}\right)^{1.953} \quad (30)$$

Hydraulic-and cooling cost (HaC_C)

$$HaC_C = 12(P_r) \quad (31)$$

Electrical-connection cost (EC_C)

$$EC_C = 40(P_r) \quad (32)$$

Nacelle-cover cost (NC_C)

$$NC_C = 11.537(P_r) + 3849.7 \quad (33)$$

Assembly-and-installation cost (AaI_C)

$$AaI_C = 1.965\left(\frac{D}{2}\right)(h)^{1.1736} \quad (34)$$

Foundation cost (F_C)

$$F_C = 303.24\left(\frac{\pi D^2}{4}\right)(h)^{0.4037} \quad (35)$$

Tower cost (T_C)

$$T_C = 0.596\left(\frac{\pi D^2}{4}\right)(h) - 2121 \quad (36)$$

Where C_{ICC} is initial capital cost and DR is the discount rate.

A wind energy system is an investment that earns money. Economic analysis involves examining the profitability and feasibility of a wind energy installation in a given location. Payback analysis involves comparing earnings and expenditures to find out how much time it will take to recover the initial investment made. The simple payback period (SPP) can be calculated using Eq. (37) [64].

$$SPP = \frac{C_{ICC}}{E_{wt}P_e} \quad (37)$$

where P_e is the price of electricity ($/kWh).

In this study, the economic evaluation was conducted on the assumption that the lifetime of the wind turbine is 20 years and it operates at a discount rate of 10%. These values were assumed based on a previous study concerning the technical and economic evaluations of wind systems in Nigeria [65].

Besides, it was assumed that annual operation and maintenance costs would account for 2.5% of the initial capital expenditure, which includes the maintenance and servicing costs during the life of the turbine according to Attabo et al. [65]. Moreover, the electricity selling price was set to be 0.07 USD/kWh, which is equal to the average tariff approved for end users of electricity in Nigeria for the year 2024, according to the Nigerian Electricity Regulatory Commission (NERC) [66].

3. Results

3.1 Annual characteristics of the wind potential

As shown in Figure 1, the Weibull distribution shape parameter (k) indicates the reliability or randomness of wind speeds within a region. The higher the value of k, the more stable the wind regime in the location, whereas low values represent a high level of randomness in the behavior of the wind in that region. From the above results, some regions with high values of k include Ilorin (k=23.63), Makurdi (k=19.89), and Jos (k=18.78). The high levels of k values in these regions imply that the wind speed in these locations is relatively stable and not very random. Moreover, the scale factor in the Weibull (c) model is a measure of the characteristic wind speed of a given location and is directly related to the wind energy potential of the area. Larger-scale parameter values suggest a strong wind regime. Based on the findings, Obudu (8.36), Jos (8.88), Ilorin (5.97), and Enugu (6.19) have high scale parameter values that denote strong and energetic wind regimes. Conversely, sites like Delta (1.65), Edo (2.46), and Abia (2.20) have low scale values, suggesting weak wind regimes.

Moreover, the average wind speeds show a pattern similar to the Weibull shape factor pattern, with both factors determining the average strength of the wind system, as shown in Figure 2. Mean wind speeds were high in Jos (8.63 m/s), Obudu (8.02 m/s), Ikeja (6.65 m/s), and Enugu (5.85 m/s), hence the presence of abundant wind energies. Such places are better suited for the harnessing of wind energy, as it is directly proportional to the cube of the wind speed. On the other hand, mean wind speeds are low at places like Edo (2.38 m/s), Delta (1.56 m/s), and Ondo (1.93 m/s). Wind power density (WPD) gives the most direct measure of useful wind power because it includes both wind speed and air density. The findings (Figure 2) revealed an extremely large variability between locations. Jos (400.58 W/m^2) and Obudu (326 W/m^2) can be identified as locations with the best wind energy. These locations reveal that there is a high level of potential for wind energy utilization in Nigeria. Some locations, like Ilorin (123.20 W/m^2), Abeokuta (29.67 W/m^2), and Yobe (24.73 W/m^2), had moderate WPDs and, therefore, can accommodate wind energy of a small-to-medium scale. On the other hand, Delta (2.47 W/m^2), Edo (8.45 W/m^2), and Abia (5.89 W/m^2) had very low WPDs.

3.2 Seasonal regime of the wind potential at the locations

Differences in the seasonal behavior of wind energy availability at selected sites are shown during the dry period (January to March, and October to December) compared to the rainy period (April to September). With regards to the sustainability and planning of renewable energy, it is important to understand that these results are significant in providing an understanding of the temporal dependability and spatial practicability of wind resources.

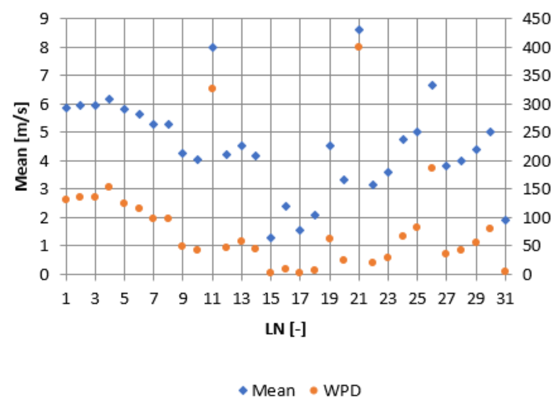

Figure 2. Mean and WPD values for all selected locations at 10m height

Concerning wind regime characteristics, an analysis of the Weibull scale parameter (c), which depicts the characteristic wind speed of a site, indicates a marked rise for all the sites during the rainy season, pointing to the potential for higher wind energy generation during this time of year, as shown in Figure 3. For instance, Enugu, where it rises from 6.079 m/s during the dry season to 6.276 m/s in the rainy season; Gboko, where it goes from 5.892 m/s to 6.558 m/s; Ogoja, where there is a rise from 5.892 to 6.545 m/s; Nsukka, where the value goes up from 6.441 to 6.621 m/s; and finally, Ikeja, where it goes from 6.770 to 7.089 m/s. This trend indicates the strengthening of regional atmospheric circulation patterns that facilitate the process of transferring kinetic energy within the lower atmosphere during the monsoon period. On the other hand, the k (Figure 3) follows a somewhat variable pattern, showing a slight rise at some locations (e.g., Ilorin: 5.863 to 6.046) and a slight decrease at others (Makurdi: 4.42 to 4.34).

Moreover, the mean wind speed provides additional support for wind resource enhancement during the wet season. The mean wind speed in Enugu rises from 5.66 m/s to 6.03 m/s, while that in Nsukka rises from 5.99 m/s to 6.35 m/s, from 5.59 m/s to 6.31 m/s in Gboko, and from 6.45 m/s to 6.84 m/s in Ikeja, as shown in Figure 4. Wind Power Density (WPD) can be considered the direct measure of energy that can be harvested from winds and is therefore the best way to measure its potential. WPD shows some significant differences from season to season as well as from region to region. WPD is an important parameter because it is the best direct measure of extractable wind energy potential. There is a distinct seasonal and spatial variation in the values of WPD recorded, as shown in Figure 4. During the rainy season, there is an increase in the values of WPD in most areas. For instance, in Enugu, the value of WPD rises from 122.35 W/m^2 to 138.23 W/m^2; in Nsukka, the value rises from 145.55 to 161.81 W/m^2; in Gboko, the value increases from 112.49 to 158.42 W/m^2; and in Ogoja, the WPD rises from 112.29 to 157.72 W/m^2. The above increases, which range from approximately 10% to 40%, represent the seasonal effect of enhanced monsoon activity and increased pressure gradient on the available wind energy resources. Ikeja has been observed to have an increase in its WPD value, rising from 171.68 W/m^2. As far as wind energy classification is concerned, the WPD values are usually classified into resource classes depending on their potential for generating energy.

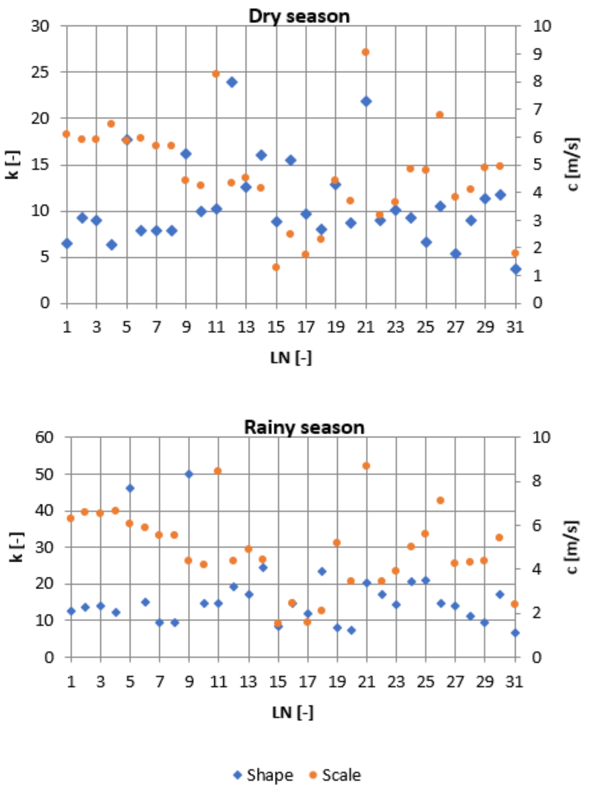

Figure 3. Seasonal value of Weibull parameters for all selected locations at 10m height

The Class 1 WPD values of less than 100 W/m^2 show poor wind energy resources; Class 2 (100-200 W/m^2) shows marginal to moderate wind energy potential. Class 3 (200-300 W/m^2) shows fairly good wind energy resources appropriate for small/medium wind energy applications. Class 4 (300-400 W/m^2) and higher show very good to excellent wind energy resources, which are useful for utility wind farms. Moreover, sites such as Jos and Obudu are in Class 4 to Class 5, showing their suitability for large-scale wind energy installations. Locations like Jos have exceptional wind potential characterized by WPD values of 427.42 W/m^2 in the dry season and 375.22 W/m^2 in the rainy season. Similarly, the Obudu site shows 309.61 W/m^2, which increases to 341.76 W/m^2. These sites are therefore ideal for wind energy projects. Areas with medium potential, which include Enugu (122-138 W/m^2), Nsukka (145-162 W/m^2), Ilorin (115-131 W/m^2), and Ikeja (172-201 W/m^2), fall into categories 2 to 3, meaning they have marginal to good wind resources.

This makes them inappropriate for large-scale wind farm development but suitable for decentralized renewable energy production systems, solar-wind hybrids, and rural electrification. The seasonal increase seen in these regions improves their viability during the rainy season, at which point the wind production will be maximized. On the contrary, low wind potential zones such as Bauchi (1.16–1.81 W/m^2), Delta (2.89–2.04 W/m^2), Edo (8.70–8.18 W/m^2), and Ondo (3.38–7.32 W/m^2) belong to Class 1, implying their poor suitability for wind energy harnessing. Although there might be some small seasonal changes, the value of WPD is too low for economically feasible wind energy production. Based on these findings, such regions should consider other renewable energy sources, namely solar photovoltaic systems. One of the most important links between dry and wet seasons is the overall improvement in wind energy intensity due to the wet season in about 80% of the stations analyzed. Such an improvement could vary from a slight increase of around 10-20% (for instance, in Ikeja and Nsukka) to a more significant augmentation above 40-60% (for example, in Gboko, Ogoja, and Ibadan). This observation is mainly attributed to stronger monsoon winds, active convection, and an unstable atmosphere. An exception is provided by Jos, where WPD slightly drops from 427.42 to 375.22 W/m^2.

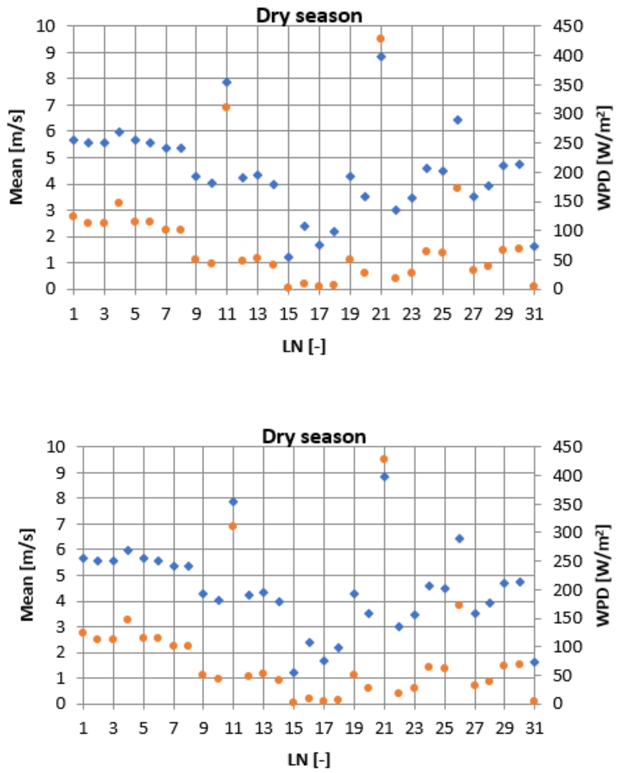

Figure 4. Seasonal value of Mean and WPD for all selected locations at 10m height

3.3 Technical viability results

Using the power law method (Eq. (11)), annual wind speed data observed at a height of 10 meters were estimated to fit the height of selected wind turbines (see Table 3). The estimated annual and seasonal wind speed data at different hub heights are shown in Figures A2-A4 as Appendix. Moreover, Figure 5 illustrates a comprehensive analysis of wind power in several locations in Nigeria through the application of six models of wind turbines from Enercon, which include the E53/800, E82/2000, E70/2300, E82/2300, E82/3000, and E101/3000. The results of this study are presented according to annual data, dry season data, and rainy season data. A simple first-order analysis of the turbine design specifications shows that there is an increase in diameter and power capacity from the smallest size (E53/800, D = 52.9 m, P = 800 kW) to the largest size (E101/3000, D = 101 m, P = 3000 kW). This increase is critically significant in the design because wind power generation is directly proportional to the swept rotor area (A ∝ D^2). Therefore, even small increases in diameter lead to large amounts of potential energy gain. Despite such an increase, all turbines maintain similar aerodynamic efficiency with maximum C_p values falling between 0.48 and 0.50. Therefore, the differences between them should arise from engineering design and not from superior aerodynamics. The spatial distribution of energy highlights a significant geographical disparity in the availability of wind resources. High-production areas such as Jos, Obudu, Nsukka, Ikeja, and Enugu tend to produce large amounts of power regardless of the class of turbines used. In this regard, the energy production for Jos is approximately 34.50 GWh using the E101/3000 turbine, while the corresponding figures for Obudu and Ikeja are 29.78 GWh and 18.85 GWh, respectively. These results indicate high-energy wind conditions, which can be influenced by factors such as the area's altitude and topography.

In contrast, areas with low production, including Bauchi, Makurdi, Afekepo, Abuja, Delta, and Edo, continue to produce relatively small amounts of power, with annual production levels ranging from 1-6 GWh depending on the class of turbines used. Bauchi State represents the worst case with low energy production levels estimated between 0.03 and 0.20 GWh. Concerning power generation capacity, there is clearly a power generation hierarchy for different wind turbines in different locations and seasons (i.e. E101/3000 > E82/3000 ≈ E70/2300 ≈ E82/2300 > E82/2000 > E53/800). The reason why the E101/3000 wind turbines always perform better in producing power than any other wind turbine is due to their larger rotor diameter and higher output capacity (101 meters and 3 megawatts, respectively).

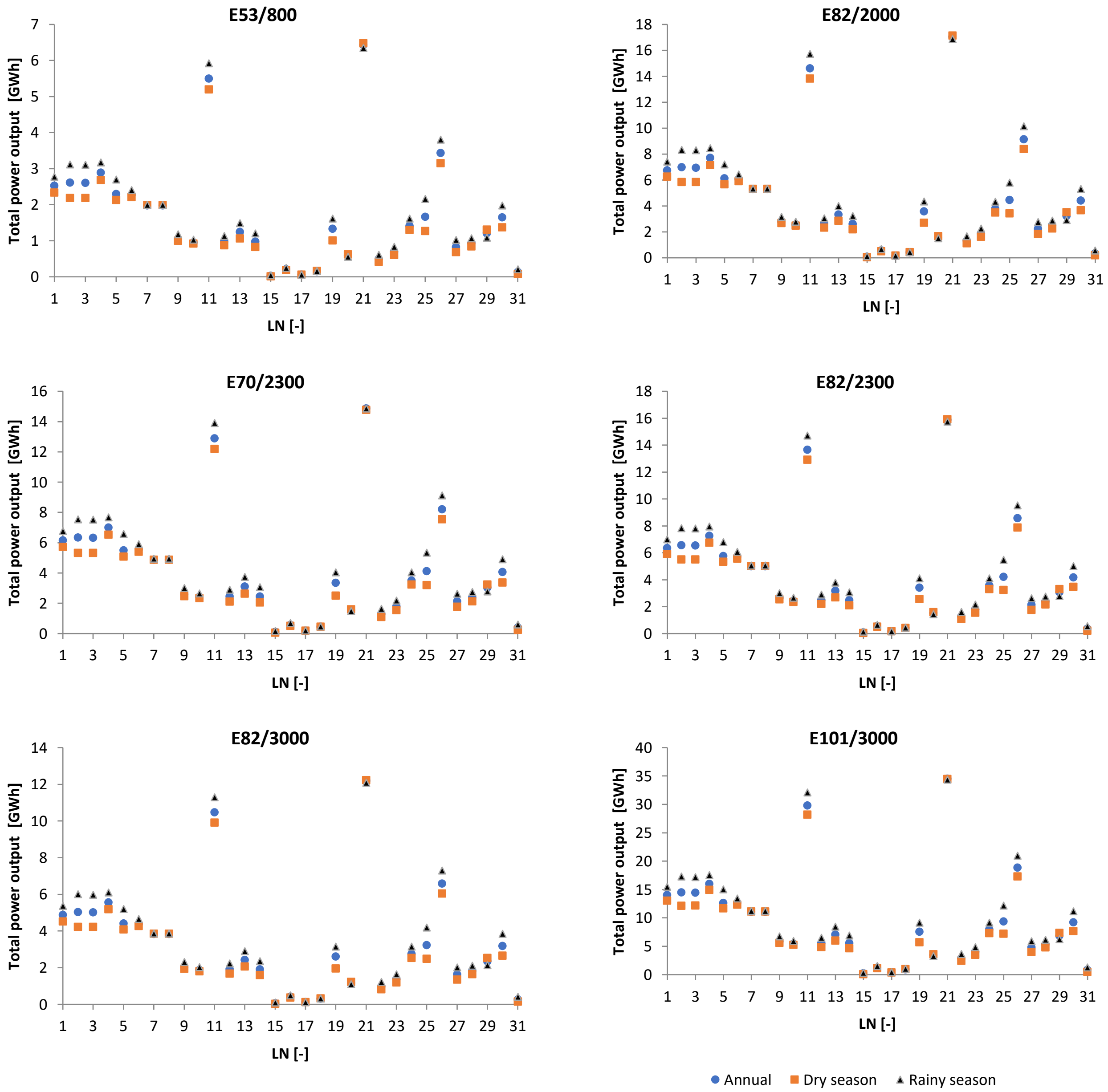

Figure 5. Total power output of selected wind turbines under annual and seasonal wind regimes in Nigeria

This turbine performs very well in areas with strong winds because power production increases as a function of wind speed distribution. In Jos, for example, annual power production is 34.50 GWh, while E53/800 produces only 6.43 GWh, a difference of about 5.4 times in efficiency. Moreover, the impact of seasonality on the dynamics of the wind power system was also discussed. In most cases, production levels during the rainy season are somewhat higher than during the dry season, which may mean that wind power generation is more suitable in these months due to better wind dynamics or weather conditions. For example, the E101/3000 located in Nsukka produces 14.93 GWh during the dry season and 17.56 GWh during the rainy season. Therefore, the seasonal difference is approximately 17.6%. The same trend can be observed for Ikeja (from 17.32 to 20.94 GWh) and Enugu (from 13.05 to 15.47 GWh). Meanwhile, in areas with strong winds, such as Jos and Obudu, seasonal variations are very low (<5%). On the other hand, areas with less wind show relatively small amounts of output along with relatively high rates of variability. In this case, Makurdi shows an average output of 5.85 GWh (E101/3000) rising to 6.76 GWh during the rainy season, which represents about 15.6 percent of the seasonal variance. Furthermore, Bauchi shows minimal generation regardless of the turbine used, with the highest recorded output being only 0.34 GWh (rainy season, E101/3000).

Besides, the capacity factors are a more reliable way to evaluate the performance of wind turbines because they standardize electricity production by comparing it to the turbine's rated power. The capacity factor (CF) is essentially the ratio of actual power produced to the maximum potential power that could have been produced if the turbine had been operating at full capacity all year round. Table 4 shows the capacity factors of the six Enercon wind turbine types per year, during the dry season, and during the rainy season for the selected locations in Nigeria. From the results shown, there is considerable variation in the wind turbine capacity factors as a result of the wind energy available at different locations. The highest capacity factors during the year are recorded at Jos (94.29–94.76%), Obudu (77.92–84.74%), Nsukka (54.43%), Gboko (50.76%), and Ogoja (50.65%). This means that these locations have the best wind resources for electricity production. On the other hand, lower capacity factors are recorded in locations with poorer wind resources. The Enercon E53/800 wind turbines record the highest capacity factors as a result of having lower rated power and wind speed than the other two turbine types; hence, it is more suited for the wind conditions at the selected locations. Table 4 shows the symbol (*) to indicate that the wind turbine type is not appropriate for installation in the specific location, as the energy produced is very small based on the existing wind resource.

Table 4. Annual, dry-season, and rainy-season capacity factors (%) of the selected Enercon wind turbines at the investigated locations in Nigeria

Location	Annual						Dry season						Rainy season					
	M# 1	M# 2	M# 3	M# 4	M# 5	M# 6	M# 1	M# 2	M# 3	M# 4	M# 5	M# 6	M# 1	M# 2	M# 3	M# 4	M# 5	M# 6
Enugu	49.6	13.1	1.9	15.2	0.6	3.9	47.0	19.1	4.3	21.3	1.7	7.4	53.0	5.8	0.3	7.3	*	0.9
Gboko	50.8	9.5	1.0	11.4	0.2	2.3	44.8	5.8	0.7	6.9	0.2	1.6	57.4	8.4	0.4	10.7	*	1.2
Ogoja	50.6	9.4	0.9	11.3	0.2	2.3	44.9	6.7	0.8	7.9	0.2	1.9	57.2	7.7	0.3	9.8	*	1.0
Nsukka	54.4	21.5	3.2	24.7	1.0	6.5	51.7	28.7	6.9	31.5	2.8	11.8	58.0	12.9	0.8	15.9	0.1	2.2
Ilorin	46.4	*	*	0.1	0.0	*	44.1	0.2	*	0.3	*	*	51.9	*	*	*	*	*
Udi	46.1	5.3	0.5	6.4	0.1	1.3	45.2	10.2	1.6	11.8	0.5	3.3	47.9	1.3	0.0	1.7	*	0.1
Ikwo	41.8	5.7	0.8	6.6	0.3	1.7	42.0	7.4	1.2	8.5	0.4	2.4	42.1	4.1	0.5	4.9	0.1	1.1
Otukpo	41.8	5.7	0.8	6.6	0.3	1.7	42.0	7.4	1.2	8.5	0.4	2.4	42.1	4.1	0.5	4.9	0.1	1.1
Makurdi	26.6	*	*	*	*	*	25.9	*	*	*	*	*	29.1	*	*	*	*	*
Afikpo	25.0	*	*	*	*	*	24.4	0.1	*	0.2	*	*	26.5	*	*	*	*	*
Obudu	84.7	77.9	11.4	81.7	2.1	31.6	81.5	73.2	14.2	76.9	3.4	32.8	89.1	84.9	9.7	88.1	1.2	32.6
Abuja	25.6	*	*	*	*	*	23.4	*	*	*	*	*	28.3	*	*	*	*	*
Lafia	30.3	*	*	0.1	*	*	27.0	*	*	*	*	*	34.3	*	*	*	*	*
Koluama	25.4	*	*	*	*	*	22.5	*	*	*	*	*	29.5	*	*	*	*	*
Bauchi	1.4	*	*	*	*	*	0.5	*	*	*	*	*	2.4	*	*	*	*	*
Edo	8.1	*	*	*	*	*	7.5	*	*	*	*	*	9.2	*	*	*	*	*
Delta	2.8	*	*	*	*	*	2.9	*	*	*	*	*	2.8	*	*	*	*	*
Abia	6.4	*	*	*	*	*	6.5	*	*	*	*	*	6.6	*	*	*	*	*
Jigawa	31.7	3.0	0.6	3.5	0.2	1.1	26.0	*	*	*	*	*	36.3	3.7	0.6	4.2	0.2	1.1
Yobe	17.6	0.2	*	0.2	*	*	18.3	0.1	*	0.1	*	*	16.9	0.2	*	0.3	*	*
Jos	94.3	92.6	8.3	94.8	0.6	40.6	94.8	93.8	4.9	95.9	0.3	36.4	93.5	93.5	6.7	95.4	0.4	35.4
Uyo	15.5	*	*	*	*	*	13.7	*	*	*	*	*	18.2	*	*	*	*	*
Abeokuta	20.0	*	*	*	*	*	18.0	*	*	*	*	*	22.8	*	*	*	*	*
Akure	33.0	0.2	*	0.3	*	*	31.1	0.9	0.1	1.1	*	0.2	36.3	*	*	*	*	*
Ibadan	37.0	3.0	0.4	3.6	0.1	0.9	30.7	3.6	0.8	4.1	0.3	1.4	44.6	*	*	0.1	*	*
Ikeja	61.3	19.0	1.2	23.4	0.2	3.4	57.8	17.3	1.5	20.9	0.4	3.9	65.8	22.0	0.8	27.9	0.1	2.7
Oshogbo	22.6	0.7	0.1	0.8	*	0.3	19.6	2.0	0.6	2.2	0.2	0.9	26.3	*	*	*	*	*
Iseyin	24.7	0.2	*	0.2	*	*	22.8	0.2	*	0.3	*	0.1	27.1	0.1	*	0.2	*	*
Shaki	29.5	0.8	0.1	1.0	*	0.2	31.3	0.3	*	0.4	*	*	27.4	0.5	*	0.6	*	0.1
Lagos Island	36.8	0.5	*	0.7	*	0.1	32.3	0.3	*	0.3	*	*	41.9	0.2	*	0.2	*	*
Ondo	5.5	*	*		*	*	3.4	*	*	*	*	*	8.0	*	*	*	*	*
Enugu	49.6	13.1	1.9	15.2	0.6	3.9	47.0	19.1	4.3	21.3	1.7	7.4	53.0	5.8	0.3	7.3	*	0.9
Gboko	50.8	9.5	1.0	11.4	0.2	2.3	44.8	5.8	0.7	6.9	0.2	1.6	57.4	8.4	0.4	10.7	*	1.2

M#1: E53/800; M#2: E82/2000; M#3: E70/2300; M#4: E82/2300; M#5: E82/3000; M#6: E101/3000
* The turbine is not suitable for the site due to negligible energy production

Besides, the relatively high capacity factors achieved in some sites are due to the relatively high wind speed estimates attained at the corresponding turbine hub heights using the power-law extrapolation (see Eq. (11)). For increased clarity, the annual and seasonal extrapolated wind speeds at the hub heights have been provided in Figures A2-A4 (Appendix). From these figures, it can be observed that the hub heights at sites like Jos and Obudu attain wind speeds close to the rated wind speed for several turbine models; thus, the turbines run close to their rated power for a considerable part of the year, resulting in increased annual energy generation and capacity factors. It should be noted that an examination of the calculated power factors showed that they were all less than 100% (theoretically, the maximum value).

3.4 Economic sustainability results

The results of calculating the equivalent energy cost (Figure 6) provide a reliable measure for assessing the financial efficiency of wind energy projects being considered in different locations and turbine types. The fact that the cost of energy production is expressed through the monetary cost of producing each kilowatt-hour of energy means that smaller numbers represent higher economic efficiency and greater financial attractiveness for an investment project. It can be noted that there is considerable variation among the calculated values both in terms of geographic space and different seasons. In particular, the smallest COE values are observed at those sites where wind energy production is highest, and the capacity factor is high. Analysis of the yearly cost of energy indicates that the minimum yearly cost of energy occurs in Jos; here, the E101/3000 turbine produces a COE of about 0.0140 USD/kWh while the other two turbines, namely E82/2000 and E82/2300, produce COE values of about 0.0214 USD/kWh and 0.0253 USD/kWh, respectively. On the other hand, Obudu also shows great economic viability because of its COE values ranging between 0.0162 and 0.0493 USD/kWh.

This is due to the exceptionally low costs associated with the production of electricity as a result of the abundant wind energy resources available here, which leads to increased production and, therefore, spread of the cost over larger amounts of energy. Conversely, the maximum yearly COE values are found in Bauchi. This region has a COE of about 2.36 and 9.86 USD/kWh for E101/3000 and E53/800 turbines, respectively. Other regions having relatively high COE values include Delta, Ondo, Edo, and Abia. Further evidence that climatic factors have an impact on the economics of the project can be derived from the seasonal analysis. Specifically, during the dry season, the lowest values of the minimum COE will also occur in high-wind regions, including Jos and Obudu. The E101/3000 has the following dry season COE values in these two locations: 0.0140 USD/kWh for Jos and 0.0171 USD/kWh for Obudu. On the other hand, the maximum value of the COE during the dry season will again occur in Bauchi. Specifically, the following values have been obtained for the respective turbines: E53/800 has a COE of approximately 12.14 USD/kWh, while E70/2300 has a COE of around 11.72 USD/kWh. Clearly, these values are hundreds of times higher than those obtained in Jos, demonstrating how significantly bad wind resources may affect economics. During the rainy season, there is relatively higher economic efficiency than during the dry season. With high availability of wind, more energy can be generated, thus cutting down the costs of energy generation. During the rainy season in Enugu, the COE for the E101/3000 drops from 0.1323 USD/kWh to 0.1116 USD/kWh. In the same way, similar drops are experienced in Nsukka, Gboko, Ogoja, Akure, Ibadan, and Lagos Island. During the rainy season, the lowest COE still occurs in Jos and Obudu, whereby the COE in Jos drops to about 0.0141 USD/kWh, while that of Obudu is 0.0150 USD/kWh. However, the highest COE still occurs in Bauchi during the rainy season, at a drop in price from the dry season, ranging between 1.42 USD/kWh and 5.48 USD/kWh. The lowest energy cost per season and location is consistently achieved by the E101/3000 turbine, which is the most economical turbine used in this study. For instance, the yearly COE for the E101/3000 is approximately 0.0140 USD/kWh in Jos, 0.0162 USD/kWh in Obudu, 0.0256 USD/kWh in Ikeja, 0.0302 USD/kWh in Nsukka, and 0.0334 USD/kWh in Gboko.

All these values are much lower when compared to the smaller E53/800, which achieves an annual COE value of 0.0398 USD/kWh in Jos, 0.0466 USD/kWh in Obudu, 0.0746 USD/kWh in Ikeja, and 0.0887 USD/kWh in Nsukka. This better economic performance is due to the large size and higher energy generation capacity of the E101/3000. One of the significant trends that arise from the findings is the correlation of energy production with the COE. Places that had the highest amount of energy produced and capacity factor, for example, Jos, Obudu, Nsukka, Gboko, Ogoja, and Ikeja, invariably recorded low COE levels. On the other hand, places like Bauchi, Delta, Edo, Ondo, and Abia, which have low wind energy resources, invariably have high COE levels. The above trends clearly indicate that the economic viability of wind energy projects is directly determined by wind resource quality. In terms of economic sustainability, it is possible to conclude that the analysis results unambiguously group all locations into three different classes. First, there are highly economically sustainable locations, such as Jos and Obudu, characterized by the annual COE lower than 0.05 USD/kWh regardless of the turbine used. These costs make wind power economically comparable to conventional forms of electricity production, which makes these locations highly attractive from the standpoint of investments. Next, there are moderately economically viable locations, including Nsukka, Gboko, Ogoja, Enugu, Ikeja, Akure, and Ibadan, characterized by COE falling within the interval of 0.03 to 0.15 USD/kWh, depending on the type of the turbine. However, despite their high economic attractiveness in general, these locations might become even more appealing if large turbines, especially E101/3000, are used. Finally, there are economically marginal or unviable locations, including Bauchi, Delta, Edo, Ondo, and Abia, where COE may exceed 1 USD/kWh or even reach nearly 10 USD/kWh.

Based on the results of the COE analysis conducted, it can be concluded that Jos and Obudu appear to be the most economically sustainable sites for wind power production, while the most efficient turbines are E101/3000 in all cases. For example, the minimal COE for the year was recorded at about 0.014 USD/kWh in the case of Jos with the E101/3000 turbine, while the maximum COE equaled approximately 9.86 USD/kWh (Bauchi with E53/800). The same applies to the dry and rainy seasons as well. These results support the opinion that economic sustainability depends significantly on the quality of wind resources and the type of turbines used. Consequently, the further development of wind power plants should take into consideration high wind resource areas and large capacity turbines. Moreover, one of the most significant criteria for assessing the economic viability of a renewable energy scheme is the payback period (PBP).

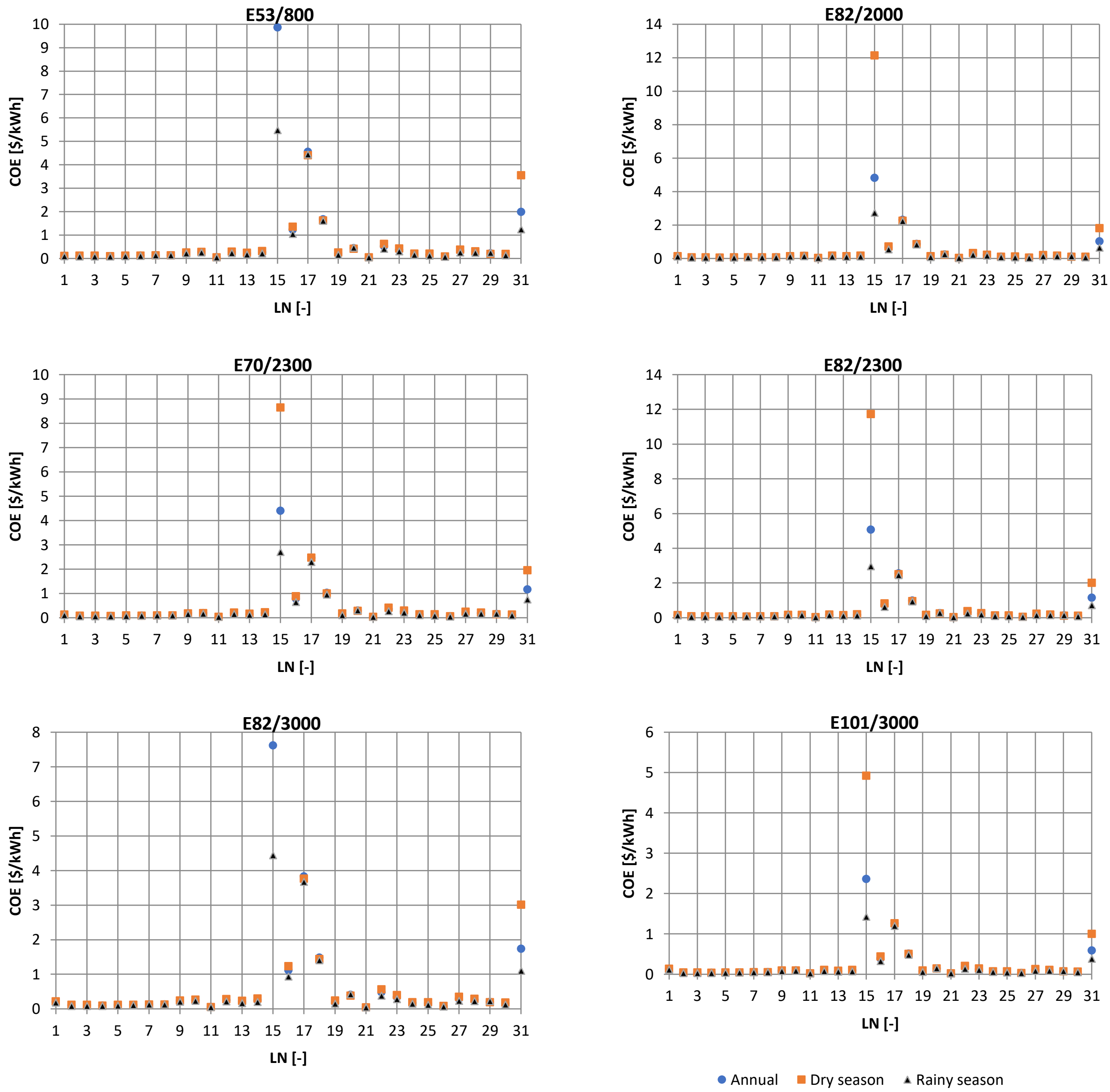

Figure 6. Economic sustainability assessment based on cost of energy

This criterion denotes the time taken for the accumulated income obtained from power generation to cover the initial capital cost of project implementation. A shorter payback period implies a quicker return on investment, lower risk, and greater economic benefits. On the other hand, a longer payback period implies poor returns and high risks for the investors. As shown in Figure 7, payback periods vary significantly depending on the specific site and wind turbine design. The findings show clear variations in the economic potential of the sites annually. The shortest annual payback period is seen in Jos, where the E101/3000 turbine gives a payback period of about 1.40 years, followed by the E82/2000 (2.14 years), E82/2300 (2.53 years), E70/2300 (2.98 years), E82/3000 (3.79 years), and E53/800 (3.98 years). Similar to Jos, Obudu also shows extremely good economics as the annual payback period ranges from 4.47 years (E53/800) to 1.62 years (E101/3000).

This is due to short payback periods, indicating very good economics as a result of the availability of abundant wind power production and high-capacity factors. However, in Bauchi, the maximum annual payback period ranges from 235.85 years (E101/3000) to 986.21 years (E53/800). Therefore, based on these long periods, wind energy projects are not currently economically viable at this location. Ondo, Delta, Edo, and Abia also have similar values. From the dry season analysis, the effects of seasonal variations on wind project economics are seen. In this regard, the shortest dry season payback period is still observed for Jos since it is characterized by a payback period of about 1.40 years using the E101/3000 turbine, followed by Obudu with a payback period of 1.71 years. This is because the wind resources in these areas do not vary much even during seasons, hence maintaining favorable economics throughout the year.

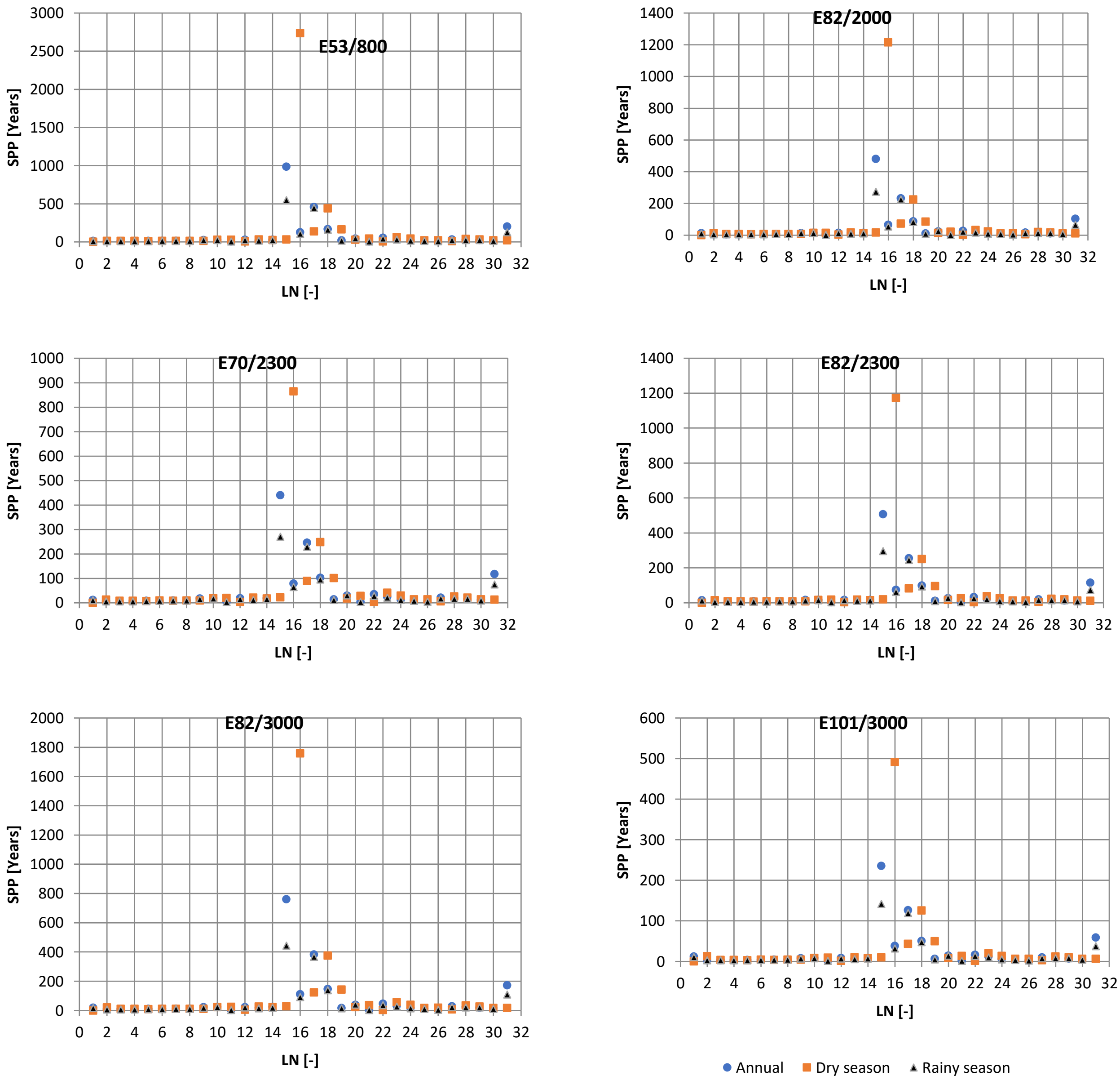

Figure 7. Economic sustainability assessment based on payback period

On the other hand, the longest dry season payback period is still observed in Bauchi since the payback period here becomes very high at approximately 491.43 years (E101/3000) and 2733.79 years (E53/800). This is caused by the reduction in energy production since low wind speeds result in lower power output, but with unchanged fixed costs. Generally, in most areas, payback periods for dry seasons become higher compared to annual ones because there will be fewer wind speeds, hence low power generation. For instance, the payback periods for the E101/3000 turbine in Enugu, Gboko, and Ogoja become 3.03, 3.98, and 3.27 years, respectively, compared to annual ones of 12.29, 3.34, and 3.35 years. The rainy season usually displays better economic performance because of higher production from wind turbines. The shortest payback period within the rainy season is seen in Jos, where the E101/3000 turbine generates an estimated period of about 1.41 years, while Obudu follows close at 1.51 years and Nsukka at 2.75 years. This clearly shows a quick recovery of investments with good economics. The longest payback period during the rainy season still occurs in Bauchi, where the E53/800 turbine generates an estimated payback period of approximately 547.96 years, while the E101/3000 turbine produces a period of 142.12 years. Although the figures appear lower compared to the returns of the dry season, they are still much higher than economically acceptable rates. Concerning economic sustainability, the results clearly reveal that Jos and Obudu are the best locations to consider for establishing wind farms. This is due to exceptionally rapid recovery periods, enormous amounts of generated power, and the good power factor recorded within the aforementioned sites. They are the best sites for wind energy generation, considering that there is a potential for attracting private investors and sustained operations. Furthermore, the E101/3000 wind turbine configuration is the most sustainable technology economically among the others that have been evaluated. The average annual payback period is approximately 1.40 years in Joss, reaching a value of 235.85 years in Bauchi, thus outperforming all other turbines. This is due to its superiority in energy extraction and lower levelized electricity costs. Economic sustainability is highly dependent on both the type of turbine used and the wind conditions in the selected location. In this study, the lowest payback time was observed to be 1.40 years (Jos, E101/3000), while the highest was above 2733 years (Bauchi, E53/800) during the dry season.

4. Discussion

This study provides a comprehensive technical and economic assessment of wind energy potential in various climatic zones in Nigeria by applying Weibull distribution statistics and evaluating the performance of six types of commercial wind turbines designed by Enercon. This research shows that there is a great deal of variation in the characteristics of wind energy in terms of performance and economy. Moreover, Weibull parameter analysis also revealed tremendous variation in the wind regime characteristics between cities in Nigeria. Very high Weibull shape factors noted for Ilorin (23.63), Makurdi (19.89), and Jos (18.78) show stability and less variability in wind speed distribution. As explained by Seguro and Lambert [67], large Weibull shape factors represent reliable wind conditions and hence increase accuracy in wind energy forecasting. Also, Akpinar and Akpinar [68] showed that wind conditions characterized by a Weibull shape factor greater than 5 represented favorable wind energy resource conditions. Large values for the Weibull scale parameter found in Jos (8.88 m/s), Obudu (8.36 m/s), and Enugu (6.19 m/s) suggest a very strong wind regime and a significant amount of available kinetic energy. This observation is comparable with the earlier research carried out in other mountainous and elevated areas in Africa where wind speeds are enhanced topographically [69,70].

Besides, the mean wind speed assessment revealed Jos (8.63 m/s), Obudu (8.02 m/s), Ikeja (6.65 m/s), and Enugu (5.85 m/s) to be the most suitable sites for wind energy harnessing. Similar values of wind speeds have been found in wind farms located in South Africa, Morocco, Egypt, and Ethiopia [71,72]. Sites like Delta, Edo, and Ondo showed lower average wind speeds of less than 2.5 m/s and are thus not suitable for wind energy projects. Moreover, the wind energy intensity results are evidence of the spatial variability of wind energy in Nigeria. The annual WPD was found to be about 400.58 W/m^2 in Jos, while Obudu registered WPD levels of around 326 W/m^2. The WPD results are characteristic of Wind Power Classes 4-5, implying that these areas can be exploited for commercial-scale wind farms. Such values of WPD have been previously established in successful areas for wind energy generation in northern China, Spain, and parts of the United States [73-76]. The high WPD levels in both Obudu and Jos are mainly attributed to wind speed enhancement as a result of altitude, low surface roughness, and favorable atmospheric circulation conditions. The relatively low levels of WPD in Delta, Edo, Abia, and Bauchi regions are consistent with the findings by Adaramola et al. [28] and Ohunakin et al. [29], indicating the lack of wind energy potential in lowland areas of southern Nigeria. The analysis of the seasons showed that wind power resources tend to become better during the rainy season for about 80% of the analyzed areas. It can be seen from the increase in Weibull scale values, the increase in wind speed, and also an increase in wind power density. For instance, WPD changed from 122.35 to 138.23 W/m^2 in Enugu, from 145.55 to 161.81 W/m^2 in Nsukka, and from 112.49 to 158.42 W/m^2 in Gboko. Such positive changes during the rainy season may be attributed to the development of monsoon circulation and pressure gradients. Similar trends in wind energy have been observed in West Africa, where there is a significant role of monsoons in wind power energy development due to the climatic conditions of the region [73,74]. One of the exceptions was Jos, where there was some reduction of WPD during the rainy season.

The turbine performance assessment showed that energy production is largely dependent on the wind resource quality as well as the characteristics of the turbines. Out of all turbines assessed, the best-performing turbine was the Enercon E101/3000 with respect to annual energy production. The annual energy produced was 34.50 GWh at Jos, 29.78 GWh at Obudu, 18.85 GWh at Ikeja, and 16.01 GWh at Nsukka. This outstanding performance can be attributed to the large rotor diameter (101 m), high swept area, and better capacity of harvesting kinetic energy in low-moderate winds. The results are consistent with the work done by Hau [75] and Burton et al. [76]. These studies reported that a larger rotor diameter increases energy harvest ability, especially for moderate wind sites. The obtained hierarchy of wind turbine efficiency conforms to the general tendency E101/3000 > E82/3000 ≈ E82/2300 ≈ E70/2300 > E82/2000 > E53/800. The described trend clearly shows the importance of rotor swept area in the process of wind energy utilization.

The economic sustainability analysis highlighted a significant correlation between wind resource quality and profit potential. The lowest annual cost of energy (COE) was found for E101/3000 turbines installed in Jos (0.014 USD/kWh), while Obudu registered the second-lowest COE value (0.016 USD/kWh). Ikeja came in third place (0.026 USD/kWh) and Nsukka fourth (0.030 USD/kWh). According to the International Renewable Energy Agency [77], the cost of wind energy worldwide is situated within the range of 0.033 and 0.06 USD/kWh. Meanwhile, the COE in places where wind resources were relatively poor, including Bauchi, Delta, Edo, and Ondo, was very high (up to 9.86 USD/kWh in Bauchi). In addition, the payback period test helped to verify the economic viability of sites with higher resources. For instance, the lowest payback period on an annual basis was recorded at Jos with the use of E101/3000 (1.40 years), then Obudu (1.62 years). Such low payback periods suggest that the projects will be economically sustainable and highly appealing for investments. Similar low payback periods were reported for highly windy locations such as China, Spain, and Germany [78,79]. Conversely, payback periods of more than 900 years recorded at Bauchi signify that the production of electricity through wind projects in areas with weak resources is not economically feasible.

5. Limitations and future work

The current study has some limitations that should be considered when interpreting the results.

First, one of the limitations of this research is that the wind speed data that are available for analysis are monthly means obtained at various observation periods because of data availability reasons. Moreover, differences in observation periods may cause uncertainties related to interannual climate variability, making it difficult to make direct comparisons of wind conditions at the studied sites. Therefore, harmonized hourly or sub-hourly wind speeds data from consistent observation periods should be used in future studies to increase the accuracy and comparability of wind resource assessment results.

Second, the current study was conducted using available climate data. The lack of data on short-term wind speed changes did not allow for the assessment of additional wind characteristics such as turbulence intensity.

Third, the capacity factor was calculated based on monthly averages of wind speed. Because monthly averages of wind speed mitigate natural fluctuations in wind speed, and because the relationship between wind speed and wind turbine output is not linear, the calculated capacity factor will be exaggerated compared to those using high-frequency measurements of wind speed.

In the future, work will focus on obtaining and analyzing high-frequency wind speed data (for instance, data collected at 10-minute intervals). Such data can be used to accurately calculate turbulence intensity, capacity factors, and to gain a better understanding of wind resources and wind turbine performance. In the future, longer data collection intervals and data from more locations can be used for analysis.

6. Conclusion

This study conducted an extensive assessment of the technical and economic viability of wind energy projects at various locations in Nigeria through the use of Weibull distribution techniques as well as Enercon turbine models of six types. The outcome shows significant variations among the selected sites in terms of wind availability, turbine efficiency, and economic viability. The analysis shows that Jos and Obudu have the highest potential for wind energy production due to their average wind speeds of more than 8m/s and wind power density of more than 300W/m2. On the other hand, places such as Bauchi, Delta, Edo, Ondo, and Abia had low winds and wind power density, making them economically unviable. According to the results of seasonal analysis, about 80% of the sampled sites have an improved availability of wind power during the rainy season, leading to better power generation, better capacity factors, lower energy costs, and a faster payback period. These results indicate that seasonal variation should be taken into consideration when making plans for wind power. Out of the six different configurations of the wind turbines evaluated, the Enercon E101/3000 performed better in terms of economic and technical parameters because of its high rotor diameter and better power generation capacity. This turbine produced the highest amount of power and recorded the lowest energy cost among all other wind turbines at all the sites. Therefore, the E101/3000 is suggested as the best turbine configuration for future utility-scale projects in Nigeria. Economic analysis showed that wind energy plants could be very profitable where the conditions were ideal. The lowest cost of energy was obtained in Jos (0.014 USD/kWh), while the fastest payback period amounted to about 1.40 years. These figures suggest high investment attractiveness and the long-term economic viability of the projects. At the same time, it is possible to conclude that wind energy projects' economic feasibility is largely determined by wind characteristics at particular locations. The study provided useful data for developing national renewable energy policies and demonstrated substantial potential for the implementation of wind energy technology in Nigeria. Further research needs to include wind resources monitoring, assessing offshore wind generation opportunities, installing hybrid renewable energy systems, and improving capacity factor calculation methodology in accordance with international engineering practice.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere. All survey participants provided informed consent prior to participation, and the anonymity and confidentiality of all respondents were strictly maintained throughout the research process.

Data availability statement

The manuscript contains all the data. However, additional data will be provided by the corresponding author upon reasonable request.

Conflict of interest

The authors declare no potential conflict of interest.

References

[1] Owusu, P. A., & Asumadu-Sarkodie, S. (2016). A review of renewable energy sources, sustainability issues and climate change mitigation. Cogent Engineering, 3(1), 1167990. https://doi.org/10.1080/23311916.2016.1167990

[2] Sims, R. E. (2004). Renewable energy: a response to climate change. Solar energy, 76(1-3), 9-17. https://doi.org/10.1016/S0038-092X(03)00101-4

[3] Dehghani-Sanij, A. R., Al-Haq, A., Bastian, J., Luehr, G., Nathwani, J., Dusseault, M. B., & Leonenko, Y. (2022). Assessment of current developments and future prospects of wind energy in Canada. Sustainable Energy Technologies and Assessments, 50, 101819. https://doi.org/10.1016/j.seta.2021.101819

[4] Alsharif, M. H., Kim, J., & Kim, J. H. (2018). Opportunities and challenges of solar and wind energy in South Korea: A review. Sustainability, 10(6), 1822. https://doi.org/10.3390/su10061822

[5] Kumar, Y., Ringenberg, J., Depuru, S. S., Devabhaktuni, V. K., Lee, J. W., Nikolaidis, E., ... & Afjeh, A. (2016). Wind energy: Trends and enabling technologies. Renewable and Sustainable Energy Reviews, 53, 209-224. https://doi.org/10.1016/j.rser.2015.07.200

[6] Shaaban, M., & Petinrin, J. O. (2014). Renewable energy potentials in Nigeria: Meeting rural energy needs. Renewable and sustainable energy reviews, 29, 72-84. https://doi.org/10.1016/j.rser.2013.08.078

[7] Jack, J. T. B., & Jack, B. (2022). Nigeria's Energy Crisis and the Sustainability Question. Social and Health Sciences, 20(1 and 2), 19-pages.

[8] Ben-Iwo, J., Manovic, V., & Longhurst, P. (2016). Biomass resources and biofuels potential for the production of transportation fuels in Nigeria. Renewable and sustainable energy reviews, 63, 172-192. https://doi.org/10.1016/j.rser.2016.05.050

[9] Ohunakin, O. S., Ojolo, S. J., & Ajayi, O. O. (2011). Small hydropower (SHP) development in Nigeria: An assessment. Renewable and Sustainable Energy Reviews, 15(4), 2006-2013. https://doi.org/10.1016/j.rser.2011.01.003

[10] Ogbonna, K. S., Ibenta, S. N., Chris-Ejiogu, U. G., & Atsanan, A. N. (2019). Public debt services and Nigerian economic growth: 1970-2017. European Academic Research, 6(10), 22-34.
[11] Ibrahim, I. D., Hamam, Y., Alayli, Y., Jamiru, T., Sadiku, E. R., Kupolati, W. K., ... & Eze, A. A. (2021). A review on Africa energy supply through renewable energy production: Nigeria, Cameroon, Ghana and South Africa as a case study. Energy Strategy Reviews, 38, 100740. https://doi.org/10.1016/j.esr.2021.100740
[12] Emodi, N. V., & Yusuf, S. D. (2015). Improving electricity access in Nigeria: obstacles and the way forward. International Journal of Energy Economics and Policy, 5(1), 335-351.
[13] Oyedepo, S. O. (2012). Energy and sustainable development in Nigeria: the way forward. Energy, Sustainability and Society, 2(1), 1-17. https://doi.org/10.1186/2192-0567-2-15
[14] Onochie, U. P., Egware, H. O., & Eyakwanor, T. O. (2015). The Nigeria electric power sector (opportunities and challenges). Journal of Multidisciplinary Engineering Science and Technology, 2(4), 494-502.
[15] Joseph, I. O. (2014). Issues and challenges in the Privatized Power Sector in Nigeria. Journal of sustainable development studies, 6(1).
[16] Nwokoye, E. S., Dimnwobi, S. K., Ekesiobi, C. S., & Obegolu, C. C. (2017). Power infrastructure and electricity in Nigeria: Policy considerations for economic welfare. KIU Journal of Humanities, 2(1), 5-17. https://doi.org/10.58709/kiujhu.v2i1.100.5-17
[17] Adenikinju, A. F. (2003). Electric infrastructure failures in Nigeria: a survey-based analysis of the costs and adjustment responses. Energy policy, 31(14), 1519-1530. https://doi.org/10.1016/S0301-4215(02)00208-2
[18] Okafor, E. E. (2008). Development crisis of power supply and implications for industrial sector in Nigeria. Studies of Tribes and Tribals, 6(2), 83-92.
[19] Igwe, P. A., Amaugo, A. N., Ogundana, O. M., Egere, O. M., & Anigbo, J. A. (2019). Factors affecting the investment climate, SMEs productivity and entrepreneurship in Nigeria. European Journal of Sustainable Development, 7(1), 182-200. https://doi.org/10.14207/ejsd.2018.v7n1p182
[20] Babatunde, O., Buraimoh, E., Tinuoye, O., Ayegbusi, C., Davidson, I., & Ighravwe, D. E. (2023). Electricity sector assessment in Nigeria: the post-liberation era. Cogent Engineering, 10(1), 2157536. https://doi.org/10.1080/23311916.2022.2157536
[21] Adedipe, O., Abolarin, M. S., & Mamman, R. O. (2018, September). A review of onshore and offshore wind energy potential in Nigeria. In IOP conference series: materials science and engineering (Vol. 413, No. 1, p. 012039). IOP Publishing. https://doi.org/10.1088/1757-899X/413/1/012039
[22] Ibrahiem, D. M., & Hanafy, S. A. (2021). Do energy security and environmental quality contribute to renewable energy? The role of trade openness and energy use in North African countries. Renewable Energy, 179, 667-678. https://doi.org/10.1016/j.renene.2021.07.019
[23] Kayizzi-Mugerwa, S., Shimeles, A., Lusigi, A., & Moummi, A. (Eds.). (2016). Inclusive growth in Africa: Policies, practice, and lessons learnt. Taylor & Francis. ISBN 9780815358114
[24] Ajayi, O. O., Fagbenle, R. O., Katende, J., Okeniyi, J. O., & Omotosho, O. A. (2010). Wind energy potential for power generation of a local site in Gusau, Nigeria. International Journal of Energy for a Clean Environment, 11(1-4). https://doi.org/10.1615/InterJEnerCleanEnv.2011003309
[25] Fagbenle, R. O., Katende, J., Ajayi, O. O., & Okeniyi, J. O. (2011). Assessment of wind energy potential of two sites in North-East, Nigeria. Renewable energy, 36(4), 1277-1283. https://doi.org/10.1016/j.renene.2010.10.003
[26] Ohunakin, O. S. (2011). Wind Characteristics and wind Energy Potential Assessment in Uyo, Nigeria. J. Eng. Applied Sci, 6(2), 141-146.
[27] Adaramola, M. S., Paul, S. S., & Oyedepo, S. O. (2011). Assessment of electricity generation and energy cost of wind energy conversion systems in north-central Nigeria. Energy Conversion and Management, 52(12), 3363-3368. https://doi.org/10.1016/j.enconman.2011.07.007
[28] Adaramola, M. S., & Oyewola, O. M. (2011). Evaluating the performance of wind turbines in selected locations in Oyo state, Nigeria. Renewable Energy, 36(12), 3297-3304. https://doi.org/10.1016/j.renene.2011.04.029
[29] Ohunakin, O. S., Adaramola, M. S., & Oyewola, O. M. (2011). Wind energy evaluation for electricity generation using WECS in seven selected locations in Nigeria. Applied energy, 88(9), 3197-3206. https://doi.org/10.1016/j.apenergy.2011.03.022
[30] Ajayi, O. O., Fagbenle, R. O., Katende, J., & Okeniyi, J. O. (2011). Availability of wind energy resource potential for power generation at Jos, Nigeria. Frontiers in Energy, 5(4), 376-385. https://doi.org/10.1007/s11708-011-0167-5
[31] Ohunakin, O. S. (2011). Wind resource evaluation in six selected high altitude locations in Nigeria. Renewable Energy, 36(12), 3273-3281. https://doi.org/10.1016/j.renene.2011.04.026
[32] Ohunakin, O. S., & Akinnawonu, O. O. (2012). Assessment of wind energy potential and the economics of wind power generation in Jos, Plateau State, Nigeria. Energy for sustainable Development, 16(1), 78-83. https://doi.org/10.1016/j.esd.2011.10.004
[33] Oyedepo, S. O., Adaramola, M. S., & Paul, S. S. (2012). Analysis of wind speed data and wind energy potential in three selected locations in south-east Nigeria. International journal of energy and environmental engineering, 3(1), 1-11. https://doi.org/10.1186/2251-6832-3-7
[34] Paul, S. S., Oyedepo, S. O., & Adaramola, M. S. (2012). Economic assessment of water pumping systems using wind energy conversion systems in the

southern part of Nigeria. Energy Exploration & Exploitation, 30(1), 1-17. https://doi.org/10.1260/0144-5987.30.1.1

[35] Amoo, O. M. (2012). Evaluation of the wind energy potential of two south west sites in Nigeria. Frontiers in Energy, 6(3), 237-246. https://doi.org/10.1007/s11708-012-0201-2

[36] Nze-Esiaga, N., & Okogbue, E. C. (2014). Assessment of wind energy potential as a power generation source in five locations of South Western Nigeria. Journal of Power and Energy Engineering, 2(05), 1. https://doi.org/10.4236/jpee.2014.25001

[37] Ajayi, O. O., Fagbenle, R. O., Katende, J., Ndambuki, J. M., Omole, D. O., & Badejo, A. A. (2014). Wind energy study and energy cost of wind electricity generation in Nigeria: Past and recent results and a case study for South West Nigeria. Energies, 7(12), 8508-8534. https://doi.org/10.3390/en7128508

[38] Okeniyi, J. O., Moses, I. F., & Okeniyi, E. T. (2015). Wind characteristics and energy potential assessment in Akure, South West Nigeria: econometrics and policy implications. International Journal of Ambient Energy, 36(6), 282-300. https://doi.org/10.1080/01430750.2013.864586

[39] Ayodele, T. R., Ogunjuyigbe, A. S. O., & Amusan, T. O. (2016). Wind power utilization assessment and economic analysis of wind turbines across fifteen locations in the six geographical zones of Nigeria. Journal of cleaner production, 129, 341-349. https://doi.org/10.1016/j.jclepro.2016.04.060

[40] Akinsanola, A. A., Ogunjobi, K. O., Abolude, A. T., Sarris, S. C., & Ladipo, K. O. (2017). Assessment of wind energy potential for small communities in South-South Nigeria: Case study of Koluama, Bayelsa State. J. Fundam. Renew. Energy Appl, 7(02). https://doi.org/10.4172/2090-4541.1000227

[41] Udo, N. A., Oluleye, A., & Ishola, K. A. (2017). Investigation of wind power potential over some selected coastal cities in Nigeria. Innovative Energy & Research, 6(01), 2576-1463.

[42] Audu, M. O., Terwase, A. S., & Isikwue, B. C. (2019). Investigation of wind speed characteristics and its energy potential in Makurdi, north central, Nigeria. SN Applied Sciences, 1(2), 1-6. https://doi.org/10.1007/s42452-019-0189-x

[43] Ben, U. C., Akpan, A. E., Mbonu, C. C., & Ufuafuonye, C. H. (2021). Integrated technical analysis of wind speed data for wind energy potential assessment in parts of southern and central Nigeria. Cleaner Engineering and Technology, 2, 100049. https://doi.org/10.1016/j.clet.2021.100049

[44] Peter, J. M., Mohammed, M., Bello, A. A., Burari, F. W., & Tijjani, A. (2022). Goodness of fit test for wind energy potential using five probability density functions for some selected cities in Nigeria. Fudma journal of sciences, 6(1), 81-92.

[45] Okakwu, I., Akinyele, D., Olabode, O., Ajewole, T., Oluwasogo, E., & Oyedeji, A. (2023). Comparative Assessment of Numerical Techniques for Weibull Parameters' Estimation and the Performance of Wind Energy Conversion Systems in Nigeria. IIUM Engineering Journal, 24(1), 138-157. https://doi.org/10.31436/iiumej.v24i1.2611

[46] Komolafe, C. A., Fadare, D., Oladeji, L., & Gbadamosi, A. (2024). Evaluation of wind energy potential in omu aran, nigeria using weibull and rayleigh models. Green and Low-Carbon Economy, 2(2), 131-141. https://doi.org/10.33003/fjs-2022-0601-882

[47] Jimoh, S. T., & Chetty, N. (2026). Comparative analysis of wind speed probability distributions for wind energy potential in Southwestern Nigeria. Discover Energy, 6(1), 25. https://doi.org/10.1007/s43937-026-00135-6

[48] Sumair, M., Aized, T., Gardezi, S. A. R., Bhutta, M. M. A., Rehman, S. M. S., & Ur Rehman, S. U. (2021). Comparison of three probability distributions and techno-economic analysis of wind energy production along the coastal belt of Pakistan. Energy Exploration & Exploitation, 39(6), 2191-2213. https://doi.org/10.1177/0144598720931587

[49] Deep, S., Sarkar, A., Ghawat, M., & Rajak, M. K. (2020). Estimation of the wind energy potential for coastal locations in India using the Weibull model. Renewable energy, 161, 319-339. https://doi.org/10.1016/j.renene.2020.07.054

[50] El Khchine, Y., Sriti, M., & Elyamani, N. E. E. K. (2019). Evaluation of wind energy potential and trends in Morocco. Heliyon, 5(6). https://doi.org/10.1016/j.heliyon.2019.e01830

[51] Khahro, S. F., Tabbassum, K., Soomro, A. M., Dong, L., & Liao, X. (2014). Evaluation of wind power production prospective and Weibull parameter estimation methods for Babaurband, Sindh Pakistan. Energy conversion and Management, 78, 956-967. https://doi.org/10.1016/j.enconman.2013.06.062

[52] Kassem, Y., Camur, H., & Mosbah, A. A. S. (2024). Wind resource evaluation in Libya: a comparative study of ten numerical methods for the estimation of weibull parameters using multiple datasets. Engineering, Technology & Applied Science Research, 14(2), 13388-13397. https://doi.org/10.48084/etasr.6882

[53] Shoaib, M., Siddiqui, I., Rehman, S., Khan, S., & Alhems, L. M. (2019). Assessment of wind energy potential using wind energy conversion system. Journal of cleaner production, 216, 346-360. https://doi.org/10.1016/j.jclepro.2019.01.128

[54] Kassem, Y., Gokcekus, H., Camur, H., & Abdelnaby, A. H. A. (2022). Wind power generation scenarios in Lebanon. Engineering, Technology & Applied Science Research, 12(6), 9551-9559. https://doi.org/10.48084/etasr.5258

[55] Ren, G., Liu, J., Wan, J., Li, F., Guo, Y., & Yu, D. (2018). The analysis of turbulence intensity based on wind speed data in onshore wind farms. Renewable energy, 123, 756-766. https://doi.org/10.1016/j.renene.2018.02.080

[56] Li, F., Ren, G., & Lee, J. (2019). Multi-step wind speed prediction based on turbulence intensity and hybrid deep neural networks. Energy conversion and management, 186, 306-322. https://doi.org/10.1016/j.enconman.2019.02.045

[57] Arenas-López, J. P., & Badaoui, M. (2020). Stochastic modelling of wind speeds based on turbulence intensity. Renewable Energy, 155, 10-22. https://doi.org/10.1016/j.renene.2020.03.104
[58] Yadav, A. K., Yadav, V., Kumar, U., Ranjan, A., Kumar, T. S. V., Khargotra, R., ... & Singh, T. (2025). Analysis of wind power generation potential and wind turbine installation economics: A correlation-based approach. Results in Engineering, 25, 103743. https://doi.org/10.1016/j.rineng.2024.103743
[59] Alayat, M. M., Kassem, Y., & Çamur, H. (2018). Assessment of wind energy potential as a power generation source: A case study of eight selected locations in Northern Cyprus. Energies, 11(10), 2697. https://doi.org/10.3390/en11102697
[60] Irwanto, M., Gomesh, N., Mamat, M. R., & Yusoff, Y. M. (2014). Assessment of wind power generation potential in Perlis, Malaysia. Renewable and sustainable energy reviews, 38, 296-308. https://doi.org/10.1016/j.rser.2014.05.075
[61] Darwish, A. S., Shaaban, S., Marsillac, E., & Mahmood, N. M. (2019). A methodology for improving wind energy production in low wind speed regions, with a case study application in Iraq. Computers & Industrial Engineering, 127, 89-102. https://doi.org/10.1016/j.cie.2018.11.049
[62] González-Hernández, J. G., & Salas-Cabrera, R. (2021). Maximum power coefficient analysis in wind energy conversion systems: questioning, findings, and new perspective. Mathematical Problems in Engineering, 2021(1), 9932841.. https://doi.org/10.1155/2021/9932841
[63] Bakırcı, M., & Yılmaz, S. (2018). Theoretical and computational investigations of the optimal tip-speed ratio of horizontal-axis wind turbines. Engineering Science and Technology, an International Journal, 21(6), 1128-1142. https://doi.org/10.1016/j.jestch.2018.05.006
[64] Adeyeye, K. A., Ijumba, N., & Colton, J. S. (2021). A techno-economic model for wind energy costs analysis for low wind speed areas. Processes, 9(8), 1463. https://doi.org/10.3390/pr9081463
[65] Attabo, A. A., Ajayi, O. O., Oyedepo, S. O., & Afolalu, S. A. (2023). Assessment of the wind energy potential and economic viability of selected sites along Nigeria's coastal and offshore locations. Frontiers in Energy Research, 11, 1186095. https://doi.org/10.3389/fenrg.2023.1186095
[66] Nigerian Electricity Regulatory Commission (NERC). (2025). 2024 annual report & accounts. https://nerc.gov.ng/wp-content/uploads/2025/07/2024-Annual-Report-1.pdf
[67] Seguro, J. V., & Lambert, T. W. (2000). Modern estimation of the parameters of the Weibull wind speed distribution for wind energy analysis. Journal of wind engineering and industrial aerodynamics, 85(1), 75-84. https://doi.org/10.1016/S0167-6105(99)00122-1
[68] Akpinar, E. K., & Akpinar, S. (2005). An assessment on seasonal analysis of wind energy characteristics and wind turbine characteristics. Energy conversion and management, 46(11-12), 1848-1867. https://doi.org/10.1016/j.enconman.2004.08.012
[69] Ayodele, T. R., Jimoh, A. A., Munda, J. L., & Agee, J. T. (2013). A statistical analysis of wind distribution and wind power potential in the coastal region of South Africa. International Journal of Green Energy, 10(8), 814-834. https://doi.org/10.1080/15435075.2012.727112
[70] Ayodele, T. R., Jimoh, A. A., Munda, J. L., & Agee, J. T. (2014). Viability and economic analysis of wind energy resource for power generation in Johannesburg, South Africa. International Journal of Sustainable Energy, 33(2), 284-303. https://doi.org/10.1080/14786451.2012.762777
[71] Gualtieri, G. (2021). Reliability of ERA5 reanalysis data for wind resource assessment: A comparison against tall towers. Energies, 14(14), 4169. https://doi.org/10.3390/en14144169
[72] Shata, A. A., & Hanitsch, R. (2006). Evaluation of wind energy potential and electricity generation on the coast of Mediterranean Sea in Egypt. Renewable energy, 31(8), 1183-1202. https://doi.org/10.1016/j.renene.2005.06.015
[73] Nicholson, S. E. (2013). The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability. International Scholarly Research Notices, 2013(1), 453521. https://doi.org/10.1155/2013/453521
[74] Bloomfield, H. C., Wainwright, C. M., & Mitchell, N. (2022). Characterizing the variability and meteorological drivers of wind power and solar power generation over Africa. Meteorological Applications, 29(5), e2093. https://doi.org/10.1002/met.2093
[75] Hau, E., & Von Renouard, H. (2006). Wind turbines: fundamentals, technologies, application, economics. Berlin, Heidelberg: Springer Berlin Heidelberg.
[76] Burton, T., Jenkins, N., Sharpe, D., & Bossanyi, E. (2011). Wind energy handbook. John Wiley & Sons. ISBN: 9781119993926, 111999392X
[77] International Renewable Energy Agency. (2023). Renewable power generation costs in 2022. IRENA. https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022
[78] Saidur, R., Islam, M. R., Rahim, N. A., & Solangi, K. H. (2010). A review on global wind energy policy. Renewable and sustainable energy reviews, 14(7), 1744-1762. https://doi.org/10.1016/j.rser.2010.03.007
[79] Blanco, M. I. (2009). The economics of wind energy. Renewable and sustainable energy reviews, 13(6-7), 1372-1382.

Appendix

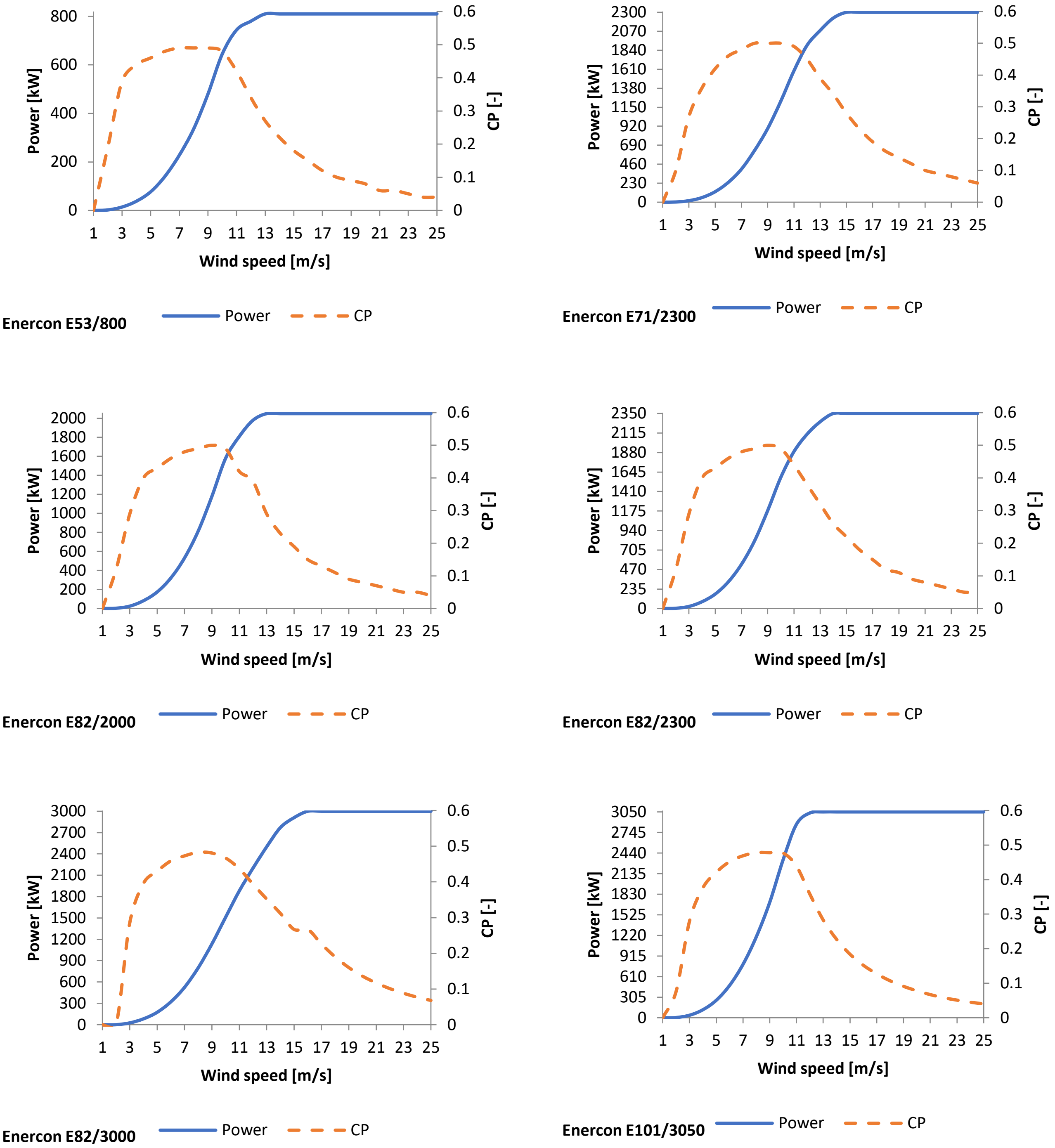

Figure A1. Power curves and power coefficient of the selected wind turbines

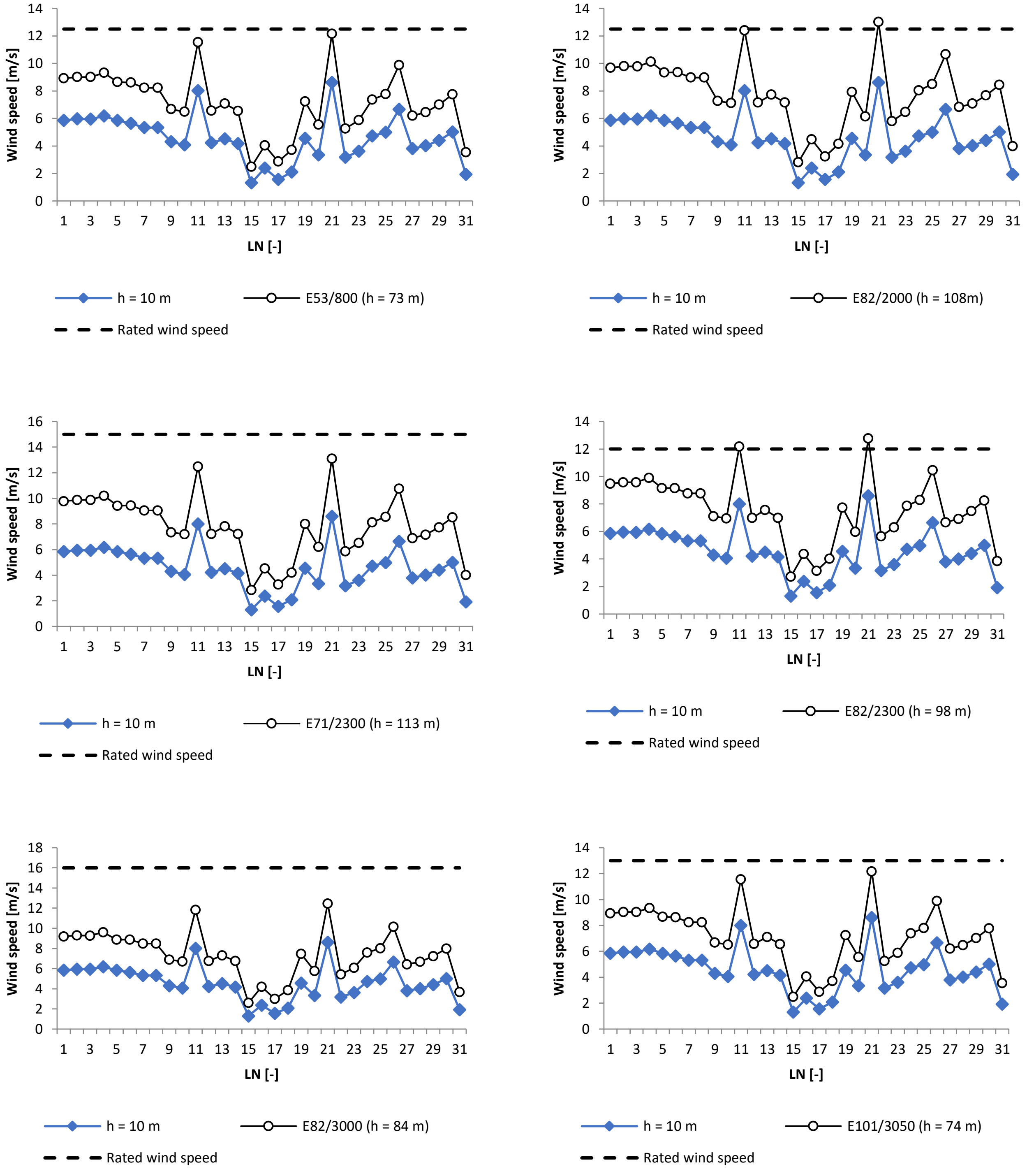

Figure A2. Annual wind speed value for all selected locations at various hub-height

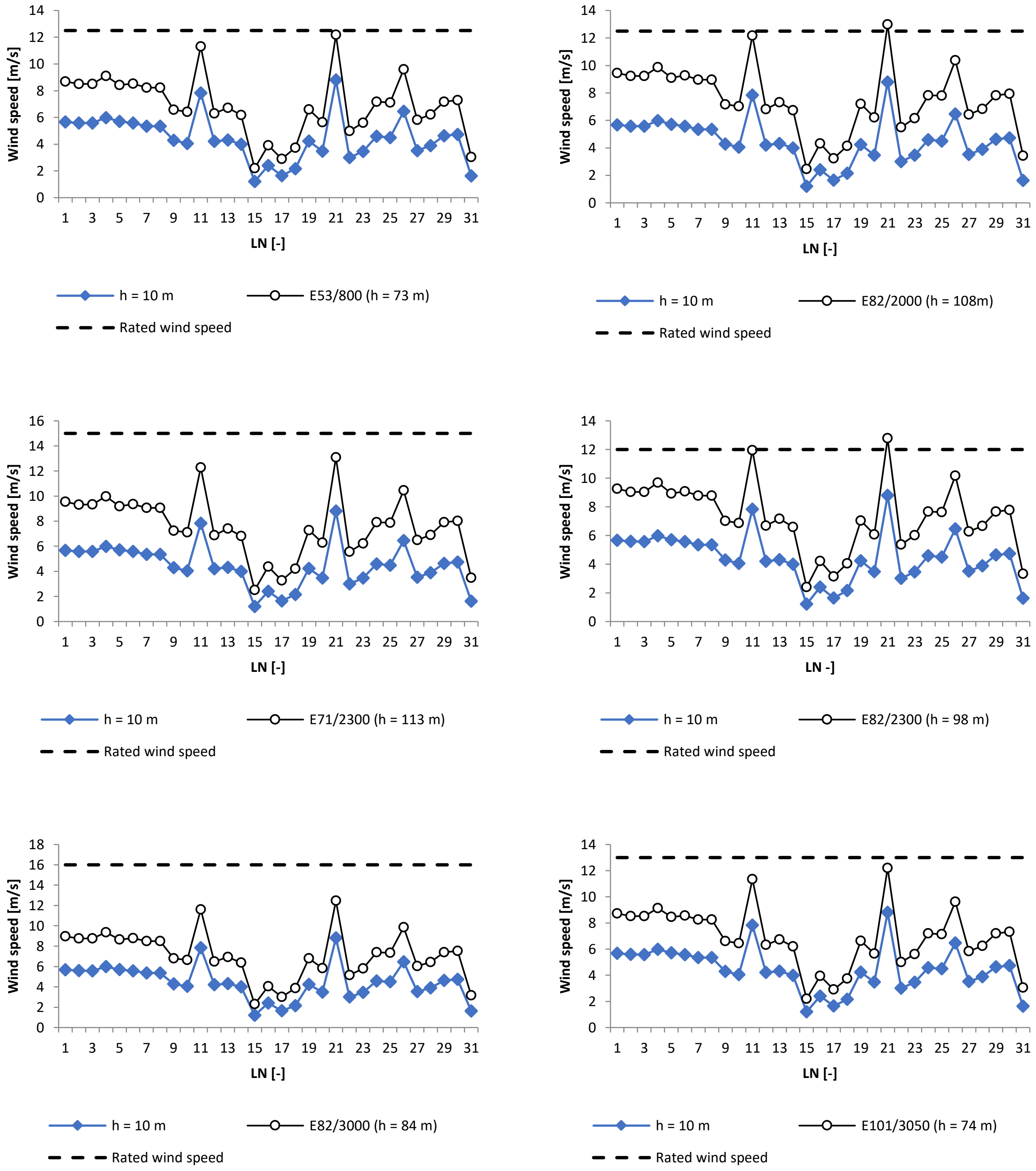

Figure A3. Annual wind speed value during dry season for all selected locations at various hub-height

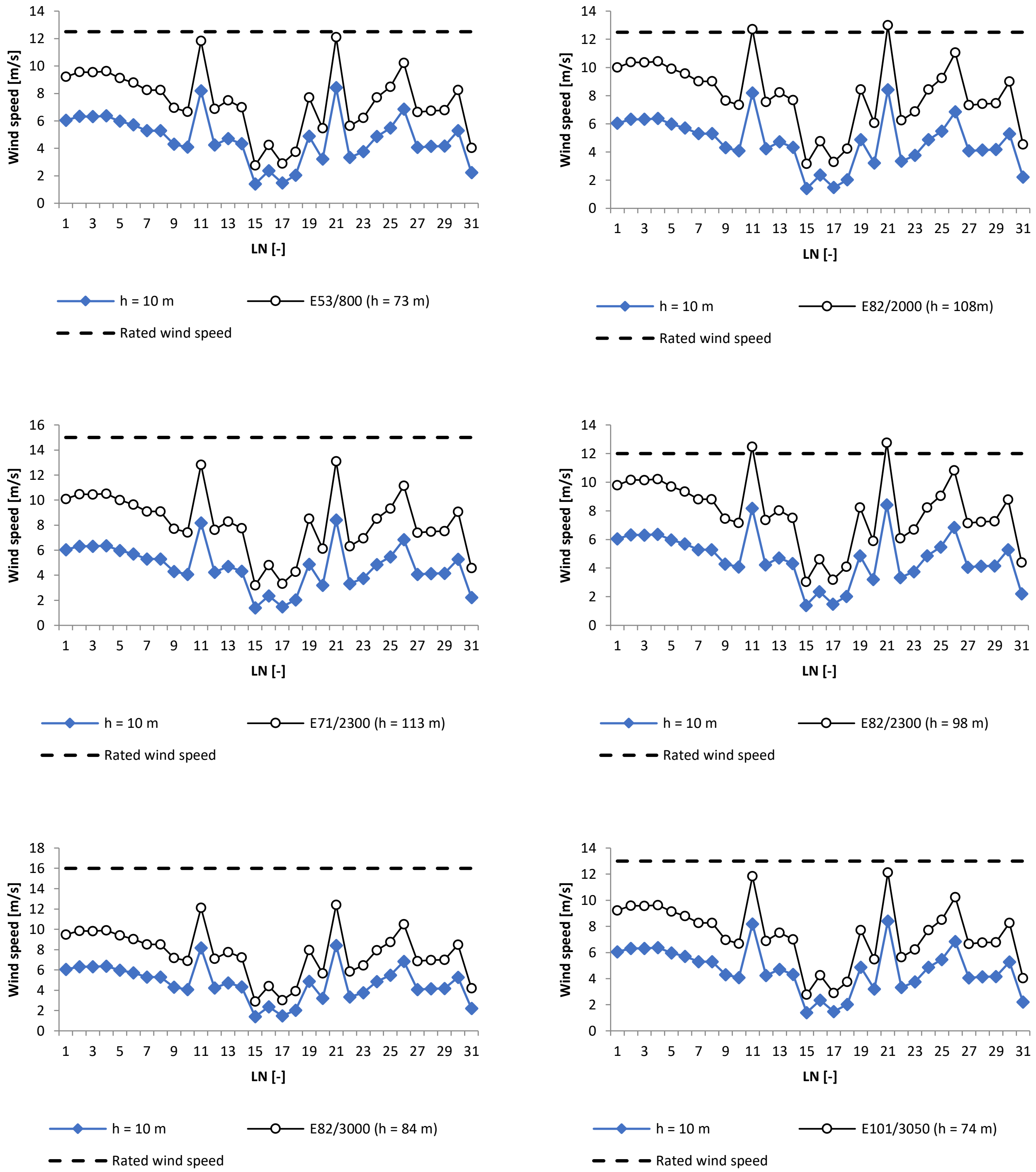

Figure A4. Annual wind speed value during rainy season for all selected locations at various hub-height