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STATISTICAL ANALYSIS OF THE WIND SPEED DISTRIBUTION FOR THE WIND POWER POTENTIAL IN CALABAR USING THE WEIBULL DISTRIBUTION FUNCTION

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ABSTRACT

Energy demand has significantly increased in Nigeria due to the constant increase in her population size. Conventional sources of electricity including fossil fuels and hydroelectricity are not enough to provide an adequate electric power supply to tackle energy challenges faced across the country. Hence, the introduction of a more sustainable source of energy like the wind is looked at by researchers to contribute significantly to the power supply at specific locations in the country through statistical analysis aimed at harnessing energy from nature's gift of wind. Therefore, this study investigates the wind energy potential of Calabar, Cross River State, Nigeria. Wind speed data is obtained at a height of 10m above sea level from the Nigerian Meteorological Agency (NiMet) and evaluated using the two-Weibull parameter probability distribution model to check the viability of siting a wind turbine in Calabar city. A period from January 2010 to December 2020 monthly wind speed data is looked at in other to determine the wind power and energy density, which is a key parameter for ascertaining the wind energy potential of any location.

1. INTRODUCTION

The availability of stable and reliable electricity continues to be the basis of any modern economy. Wind energy has the potential to electrify Africa while also propelling economic growth and development (Alemzero et al., 2021). Energy is critical to any nation's economic development and industrialization because it stimulates productive activities in all sectors of the economy, including industry, agriculture, mining, and commerce (Amadi, 2018). However, in developing countries, particularly in Africa, the lack of adequate measurement and/or assessment studies to determine its potential for power generation has hindered its development and utilization (O O Ajayi et al., 2011). Popular sources of power generation include; large and small-scale hydroelectric, fossil fuels, and nuclear reactors. While hydroelectric power is largely recognized as environmentally friendly, fossil fuel and nuclear power generation possess harmful effects as by-products (Oluseyi O. Ajayi et al.,

2014). Wind as a sustainable energy source can no doubt be an alternative for some of the major sources of electricity globally. Wind power is generally derived from wind turbines and generators operated at various conditions in specific locations. Studies conducted throughout history have proven that energy generated from fossil fuels has contributed tremendously to global greenhouse gas and CO_2 emissions. Nigeria as one of the largest consumers of energy in Africa suffers from the effect of daily power generation from conventional energy sources such as fossil fuels. As a result, methods to harness other sources of reliable and sustainable energy are sourced by researchers to further promote or aim at obtaining a net-zero energy system.

Adopting wind-based resources for wind energy generation usually varies by a country's location, atmospheric stability, and land holding size. Despite its abundance of energy resources, Nigeria continues to experience a power crisis. Only about 40% of the

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140 million people in the country have access to grid electricity (Agbetuyi et al., 2012). However, in recent years, Nigeria has engaged in several investments and commitments to developing and providing sustainable energy infrastructures including; solar, wind, and biomass.

Although harnessing wind is energy advantageous, the viability is subject to a lot of uncertainties and empirical complications, including the irregular and erratic nature of wind. In Eq (1) as shown below, the theoretical energy carried by wind (P) is proportional to the third power of wind speed. Where A is the area swept out by the rotor blades perpendicular to the prevailing wind direction, ρ represents the air density and ν is the wind speed (Jesson, 2021). As a result, an accurate understanding of wind speed characteristics is critical for several aspects of wind energy development, including identifying desirable locations, predicting the economic practicability of wind farms, and designing wind turbine structures.

$$P = \frac{1}{2}A\rho\nu^3 \tag{1}$$

However, accurate wind prediction is difficult due to the wind having inconsistencies over a wide range of scales, both spatially and temporally (Yan et al., 2020). The probability distribution is usually used to characterize the variation of wind speed at a certain location in the assessment of wind power development (Burton et al., 2011), which predicts the possibility that a specified wind speed will occur. As one of the most commonly used wind energy assessment methods, the two-parameter Weibull distribution has been proven to accurately obtain the skewness of the wind speed distribution, f(v), as compare to other statistical functions (Burton et al., 2011), and has been studied distinctively over the years (Akpinar & Akpinar, 2005; Aukitino et al., 2017; Jesson, 2021; Mohammadi et al., 2016; Shu et al., 2015b, 2015a). Generally, the Weibull distribution functions, as given in Eq. (2), is made up of k, a dimensionless shape parameter, which reflects the width of the distribution, and a scale parameter, c, with the unit of wind speed, which estimates the abscissa scale of the wind speed distribution (Jesson, 2021),

$$f(v) = \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] (v > 0; k, c > 0).$$
(2)

In Nigeria, the assessment of Weibull parameters for wind energy analysis has been studied previously by Amadi, Audu, et al., and Ben et al. Three locations in south-south Nigeria were looked at by Amadi, including; Yenagoa, Calabar, and Port Harcourt to investigate the wind energy potential using the twoparameter Weibull probability distribution model on data obtained from 2013-2017. Amadi concluded that the shape parameter for Yenagoa, Calabar, and Port Harcourt are 4.2, 6.42, and 2.79 respectively at a height of 10m, and corresponding values of scale parameters 2.2, 3.28, and 1.42 respectively, with annual mean wind speeds at 1.74m/s, 2.85m/s, and 1.38m/s respectively. Much higher year-year variability was looked at by Ben et al. to assess the southern and central part of Nigeria's wind potential, with six different methods of estimating Weibull parameters. Ben et al. results indicated that the variations in minimum and maximum monthly mean wind speeds at 50m are 3.53m/s (Afikpo) to 6.63m/s (Obudu) in October, and 4.62m/s (Abuja) to 9.16 m/s (Obudu) in April respectively. Audu et al. results indicated that the annual mean Weibull shape parameter was 4.6m/s, with a corresponding Weibull scale parameter of 5.23m/s, and a wind speed range of 3.0m/s to 4.0m/s for Markudi.

Moreover, wind characteristics in Nigeria may be a result of changes in the pressure gradients caused by temperature differentials due to the variations in solar heating of the Earth's surface, as well as period transitions to wet and dry seasons (Audu et al., 2019). The Study of wind energy potential from the period of 1990-2006 was conducted by Ahmed et al. at a height of 10m, their results indicated the yearly average values for Weibull shape and scale parameters in the northern region vary between 4.71-7.47m/s, and 2.58 -10.76m/s respectively while for the southern region, it varies between 3.51-10.07m/s and 3.35-5.91m/s respectively, with an average monthly wind speed range from 1.47-11.74m/s and 2.5-6.47m/s for the northern and southern region. Similarly, Ahmed assessed wind power density in South East Nigeria, Enugu. Results derived from the analysis showed that the average value for Weibull shape and scale parameters varies between 2.43-16.59m/s, and 4.57-6.88m/s respectively with an average wind speed ranging from 4.42-6.47m/s. However, looking at the little amount of period utilized by works of literature to ascertain the wind energy viability of Calabar, there is a need for more studies containing a current and long-term variability that would necessarily result in a significant statistical analysis for estimating the wind potential of specific regions across Nigeria using the two-parameter Weibull distribution.

The main purpose of this study is to investigate the wind energy potential of Calabar, providing a longterm and current assessment of wind speed variation at a height of 10m, to be obtained from the Nigerian Meteorological Agency (NiMet).

2. MATERIALS AND METHODOLOGY

Harnessing wind energy requires significant knowledge and understanding of wind speed and several wind conditions before a proper installation can take place in any location. Hence, techniques to model wind data in other to gain insight and understand local wind conditions have been developed (Ben et al., 2021). The two-parameter Weibull function is the most commonly used wind energy potential assessment because of its simplicity, flexibility, and capacity to produce better results which are satisfactory in determining the wind power After collecting the monthly wind speed data, an analysis is carried out using the two-parameter Weibull distribution function to estimate the monthly mean and annual mean wind potentials for power generation across Calabar. The two-parameter Weibull probability density function consists of a dimensionless shape parameter k, and a scale

Table 2 Monthly mean wind speed of Calabar, Cross River State at 10m height for

					201	0 - 2020						
Month/ Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Mean Wind Speed (m/s)
January	3.94	2.88	2.75	2.47	4.81	1.86	3.64	1.95	2.59	2.27	2.85	2.91
February	3.63	3.26	3.42	4.84	5.07	5.20	1.21	2.40	2.20	3.12	4.13	3.5
March	2.18	2.03	3.38	2.36	4.03	2.55	1.27	2.32	2.60	3.58	3.74	2.73
April	3.41	4.28	2.89	3.46	3.67	3.21	1.69	1.32	2.58	2.30	3.47	2.93
May	2.56	4.14	3.42	5.09	2.79	2.65	1.18	0.89	2.63	3.84	3.41	2.96
June	4.39	5.05	4.18	3.44	3.03	2.30	2.37	1.88	2.79	3.66	3.43	3.32
July	5.73	4.09	3.42	1.07	3.60	2.17	1.92	2.18	2.56	2.93	3.49	3.01
August	3.35	2.51	2.71	3.30	3.08	0.96	1.66	2.86	1.95	2.40	2.23	2.46
September	2.16	3.44	3.12	3.20	2.32	2.52	2.61	2.37	3.79	2.38	3.16	2.82
October	3.59	1.61	2.27	3.67	2.86	3.51	2.70	2.42	1.86	1.82	2.07	2.58
November	2.47	2.46	2.30	3.72	4.35	2.94	2.11	4.40	1.51	1.75	2.19	2.74
December	5.32	2.73	2.12	4.43	6.20	2.83	1.77	2.41	1.53	1.68	2.28	3.03

potential when compared to other distribution functions (Allouhi et al., 2017; Hulio et al., 2017). In this study, ten years (2010 - 2020) of monthly mean wind speed data shall be obtained from the Nigeria Meteorological Agency (NiMet), Oshodi-Lagos, Nigeria. The wind speed data to be collected is measured at a height of 10m above sea level using the cup generator anemometer. A few studies conducted to determine the wind energy potential have utilized data obtained at 10m above sea level, making it a suitable height to generate accurate wind speed data that is analyzed using the various methods of the Weibull distribution function (Al-Nhoud & Al-Smairan, 2015). Information about the study site is presented in Table 1.

Table 1 Geographical Location of Calabar, Cross River State, Nigeria

State	Name of the study site	Longitude (^O N)	Latitude (⁰ W)	Elevation (m)
Cross River	Calabar	8.32	4.95	13.0

To meet the energy demand of people occupying homes in Calabar, and contribute to generating energy from a sustainable source such as the wind, this study aims to determine the wind characteristics and whether or not to mount a wind turbine in the area.

2.1 Data Analysis

parameter c (m/s) as given in Eq. (2). Obtaining these Weibull parameters can be applied to estimating the number of parameters that are important during a wind power assessment. With the area under a probability density function being the cumulative distribution function, the corresponding cumulative density function (F(v)) associated with the two-parameter Weibull distribution is given by Eq. (3) (Alrashidi et al., 2020; Tizgui et al., 2017).

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

The shape parameter, k estimates the extent of variability or wind stability nature. A stable wind site's value of k varies between 1.51 and 1.99, while moderate and regular wind site values are 2 and greater or equal to 3 respectively (Ben et al., 2021).

In this study, the empirical method of Justus which is based on the mean and standard deviation of mean wind speed (Justus et al., 1977); V_m and σ_v (v is used here for mean wind speeds) respectively will be utilized to estimate the scale and shape parameters as given in Eq. (4), and Eq. (5).

$$k = \left(\frac{\sigma_{v}}{v_{m}}\right)^{-1.086} \quad (1 \le k \le 10),$$
(4)

$$c = \frac{V_{\rm m}}{\Gamma(1+\frac{1}{k})},$$

(5)

Where Γ is the gamma function.

Wind power density (*WPD*) is an important parameter for determining wind energy at a specific location or site. Several previous studies (Amadi, 2018; Ben et al., 2021; Jesson, 2021) defined the *WPD* using the Weibull parameters as given:

$$WPD = \frac{1}{2}\rho c^{3}\Gamma\left(1+\frac{3}{k}\right),$$
(6)

Where ρ is the ambient air density = 1.225kg/m³.

The wind energy derived from the selected wind turbine can be calculated using Eq. 7.

$$E = T \int_0^\infty P(V) f(V) d(V)$$
(7)

Where *E* is the energy derived, T denotes the period, and P(V) represents the wind turbine power curve. Substituting the values of Eq. 2 in Eq. 7, the equation is resolved into the following:

$$E = T \int \left(\frac{k}{c}\right) \left(\frac{V}{c}\right)^{k-1} \exp\left(-\frac{V}{c}\right)^k \cdot p(V)d(V)$$
(8)

3 RESULTS AND DISCUSSION

In this paper, the assessment of wind power potential has been carried out for Calabar city in Nigeria. The period covered by the measured wind data was from January 2010 to December 2020 at a height of 10m. Table 2 above shows the monthly and mean wind speed data of Calabar, Cross River State for 2010 - 2020, which was obtained from the Nigeria Meteorological Agency (NiMet), Oshodi-Lagos, Nigeria. The study's findings are discussed below.

3.1 Wind Speed Variation

The two-parameter Weibull distribution function is used in this paper to assess Calabar's wind power potential. To accurately evaluate the wind energy potential of any desired location, it is necessary to understand the wind characteristics of that location. The Nigerian Meteorological Agency (NiMet) has recently increased its meteorological stations to 157 at various locations across the region to effectively observe the wind meteorological conditions. It is evident from several works of literature that the Weibull distribution functions provide a more accurate means of measuring wind speed data and efficiently analyzing the wind energy potential of a specified site (Abdullahi Ahmed et al., 2013; Shi & Erdem, 2017). The wind speed measurement was carried out at a height of 10m above the ground level from January 2010 to December 2020. The monthly mean wind speed values are shown in Fig. 1. The overall mean wind speed was found to be 2.92 m/s. The maximum





The standard deviation and Weibull scale and shape parameters k and c respectively are summarized in Table 3. The average values of k and c parameters, derived from using the entire wind speed data set, were found to be 3.64 and 3.24 respectively, as provided in Table 3. The monthly mean values of k varied between a minimum of 2.04 in December and a maximum of 6.04 in September. The values of the scale parameter over the entire data set for each month at the measured height are given in Table 3. A minimum value of 2.72 is observed in August while a maximum of 3.92 in February. The average standard deviation was evaluated to be 0.99 at the measured height of 10m as given in Table 3.

Table 3. Wind speed, standard deviation,	Weibull
k and c parameters for a period from Janua	ary 2010
D	

	– D		2020	
Month	Vm	σ	K	С
Jan	2.91	0.89	3.61	3.23
Feb	3.5	1.26	3.03	3.92
Mar	2.73	0.84	3.58	3.03
Apr	2.93	0.89	3.65	3.25
May	2.96	1.22	2.61	3.33
Jun	3.32	0.97	3.80	3.67
Jul	3.01	1.26	2.57	3.39
Aug	2.46	0.73	3.74	2.72
Sep	2.82	0.54	6.04	3.04
Oct	2.58	0.75	3.84	2.85
Nov	2.74	0.99	3.01	3.07
Dec	3.03	1.57	2.04	3.42

The values of standard deviation estimated for the given data collected are provided in Table 3. The standard deviation varied from a minimum of 0.54 in September to a maximum of 1.57 in December.



Fig. 2 Weibull probability density function for Calabar city at 10m height

Figure 2 and 3 shows the Weibull distribution wind speeds according to the datasets over frequency distribution at 10m height. It is seen that a peak value of 0.36 is obtained for the Weibull probability density function, while a peak value of 1 for the Weibull cumulative density function is obtained from the observed data.



3.2 Wind Power Density and Energy Calculation

The wind power density was calculated for a period from 2010 - 2020 at 10m height given in Table 4. The average wind power density was found to be 21.64 W/m². The maximum and minimum value of wind power density was found to be 36.70 W/m² in February, and 11.54 W/m² in August respectively. The average wind energy density estimated from the overall set of data was found to be 15.57 kWh/m² as given in Table 4. The wind energy density varied from 8.30 kWh/m² in August to 26.40 kWh/m² in February.

Table 4. Wind Power Density and Wind Energy
Density for a period from January 2010 –

Month	WPD	WED
Jan	19.39	13.95
Feb	36.70	26.40
Mar	16.07	11.56
Apr	19.69	14.17
May	24.32	17.49
Jun	28.18	20.27
Jul	25.81	18.56
Aug	11.54	8.30
Sep	15.23	10.96
Oct	13.18	9.48
Nov	17.67	12.71
Dec	31.98	23.01

4 CONCLUSIONS

The goal of this paper is to evaluate the wind energy potential of Calabar city using the two-parameter Weibull distribution function. Monthly wind speed data from 2010 to 2020 for Calabar in the southern region of Nigeria have been statistically analyzed. The Weibull probability and cumulative density distributions obtained from the data sets as well as other statistical parameters were calculated. From the monthly wind speed data analysis and estimation, the following were arrived at;

- 1. In Calabar, the maximum monthly mean wind speed was calculated as 3.5 m/s in February while the minimum mean wind speed was determined in August having a value of 2.46 m/s.
- 2. The average Weibull scale and shape parameters (k and c) in Calabar vary between 2.04 6.04 and 2.72 3.92 m/s respectively.
- 3. It can be concluded that since the annual average power density for the Weibull distribution obtained from the datasets is lower than 100 W/m^2 (21.64 W/m²), the location is relatively suitable for wind energy electricity generation.
- 4. The annual average energy density was determined to be 15.57 kWh/m^2 .

Lastly, this study will suggest that in other to achieve a little above average wind energy electricity generation for Calabar, wind speed data should be collected at a height above 10m. Moreover, to reduce calculation error in available wind power estimation, and increase the efficiency to evaluate wind speed distribution, other models including the Rayleigh and lognormal-Pareto parametric distribution should be utilized and compared with the Weibull distribution. The importance of wind energy as an alternative source of energy in Nigeria cannot be overemphasized. As a measure to embrace France's ambition of eliminating greenhouse gas emissions

from human activities by 2050, Nigeria is committed to reducing emissions via energy transition in all parts of her region by developing long-term low-emission strategies.

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