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Statistical Analysis and Estimation of Wind Speed Characteristics and Energy Potential for Power Generation in Forcados, South Southern, Nigeria.

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Abstract

This study examines the wind speed characteristics and potential for wind energy generation in Forcados, ***Nigeria.*** *Aiming to assess the viability of utilizing wind power for electricity generation in the area. Wind speed data collected from the Nigeria Meteorology Agency in Lagos, measured at heights of 10 meters and 50 meters, were analyzed between 2009 and 2019. The Weibull distribution function was applied to evaluate the wind energy potential. The results indicate that the mid-wet season, specifically July and August, exhibited the highest potential for wind energy harvest, while the onset of the dry season, specifically December, showed the lowest yield. The wind speed characteristics were analysed to estimate the wind energy potential, revealing high values for both the Weibull shape and scale parameters. These findings indicate the availability of favourable wind speeds and the consistently windy nature of Forcados. Furthermore, the monthly and annual mean wind speeds recorded exceeded the minimum values (3.0–4.0 m/s) required for most wind turbines to operate. The wind profile and its characteristics establish Forcados as a suitable location for wind power generation. Consequently, there is significant potential for wind power generation in Forcados and its surrounding areas*

1. Introduction

The role energy plays in human endeavours cannot be overemphasized; in all aspects, energy is a major requirement for both urban, suburban and rural needs to provide the necessities of life. Apart from hydropower and solar energy sources, Wind energy is currently the most economical renewable energy source; its usage flexibility and ability to be used as a decentralized energy form make it applicable in areas where it is technically and economically feasible. The main setback to the use of wind as electricity generation is that, wind is intermittent and periodical. However, wind power is one of the most promising and cheap renewable energy sources [1].

Wind energy has grown above an average of thirty per cent annually in the past five years and it is estimated that the market could reach about 60,000 MW of power worldwide shortly [1]. A total of six thousand five hundred MegaWatts (6500 MW) of wind energy generating capacity was added to the grid worldwide in 2001 bringing the sum of wind power capacity in the globe to twenty-four thousand MegaWatts (24000 MW). This is enough to meet the energy demand of more than 10 million households. Europe installed 4500 MW during 2001, India passed 1500 MW of the total installed wind power capacity in 2001 [2].

Wind energy has been getting a lot of interest from developed and developing countries because of the focus on renewable energies. Despite the Power deficit and epileptic power supply which are setbacks to the socio-economic development of any economy as evident in Nigeria, quite a number of studies have been carried out on wind energy resources and yet wind energy potential in Nigeria has not been exploited for power generation. However, potential wind power that Nigeria possesses in some parts may offer possible solutions to electricity generation, water pumping and windmills. The efficient use of wind energy requires a comprehensive knowledge of its potential at a location. Determination of wind energy potential for a selected location is made by studying detailed knowledge of the wind characteristics, such as wind speed, wind direction, wind power, availability etc. [3,4].

Several research works have been carried out both within and outside Nigeria to explore the prospect of wind energy potential; which can be used as an alternative energy resource. Some of these researches include the work of [5], who carried out wind energy measurements in Galati County, Romania. The hourly, monthly and annual wind speed data used for the analysis were measured at 10m height AGL from two different meteorological stations of the national network. These include Galati County measurement station number 3-GL3 and station 5-GL5. The Weibull and Rayleigh distribution models were applied respectively for the estimation of the average wind speed and the power density for both data from the stations. they observed from the result that the GL3 site has an average wind speed of 5.44m/s while the GL5 site has an average wind speed of 5.41m/s, both sites having a power density of $260.36w/m^2$and $361.w/m^2$ respectively. It was concluded that the difference in the power potential could be as a result of the different wind speed distribution at both sites. [6], carried out similar analysis in Nigeria, they perform wind power analysis of the coastal and non-coastal sites in Akwa Ibom state. The sites include; Eket, which is a coastal region at latitude $4^{\circ}33^{'}N$ and longitude $7^{\circ}58^{'}E$ and Uyo a non-coastal region at latitude $5^{\circ}18^{'}53.7^{''}N$ and longitude$7^{\circ}59^{'}39.29^{''}E$, the monthly and yearly wind speed data for the analysis were measured at 10m height for a period of 4 years (2010 to 2013) from the Nigeria meteorological agency (MIMET). The Weibull distribution function was used for the analysis, from the analysis; Eket has a higher average wind speed of 6.7m/s when compared to Uyo which has an average wind speed of 4.3m/s. The resulting wind power densities for both Eket and Uyo are $181.19w/m^2$ and $48.86w/m^2$ respectively. They concluded that Eket that is a coastal area is more viable for commercial wind potential production than Uyo, which is a non-coastal area. [7] investigated wind energy prospects for generation of power in University of Benin. In their investigation, Wind data was collected from National Centre for Energy and Environment for a period of one year at 10m height. 2- parameter Weibull probability density function was employed in their analysis, the highest mean wind speed of 1.975m/s was observed to occur in March and the lowest monthly mean speed of 0.977m/s occurred in November. The annual mean wind speed was 1.496m/s while the annual mean power density based on Weibull distribution function was 2.692W/m^2. In conclusion, they recommended that the institution can tap on the available wind power potential.

2. Materials and Method

Forcados is a small oil-rich town in Burutu Local Government Area of Delta State, Nigeria. It is most noted for the forcados river, which is a major navigable channel of the Niger Delta. The river starts about 20 miles (32km) downstream from Aboh and flows through zones of freshwater swamps and coastal sand ridges before completing its 198km course to the bight of Benin. The town is at lat. 5.35886 and long. 5.43827 and at a mean altitude of 7.0 m above sea level. Monthly and daily wind speed values for Forcados were measured at 10 m height by a cup-generator anemometer obtained from the Nigeria Meteorology (NIMET) Agency. The data spanned 10 years (2009 to

2019), and the wind speed data were used to estimate the wind energy potentials of Forcado. Figure 1 shows the google earth view of the measurement environment.

Figure 1. Google map of the investigated environment

2.1 Estimation of wind characteristics

Wind speed is one of the most essential characteristics in wind generation of power [8]. In effect, the variations of wind speed in both time and space are determined by many factors like geographic and weather conditions. Wind speed being a random parameter can be measured, and then the measured wind speed data are typically analyzed using statistical methods.

Wind can also vary with geographical locations, time of day, season, and height above the earth's surface, weather, and local landforms [8]. Proper knowledge of the wind characteristics of an area can help optimize wind turbine design, develop wind-measuring techniques, and select wind farm sites [8].

Different mathematical models and distribution functions such as normal, lognormal, Weibull, Reyleigh, and several others have been applied in analyzing wind speed data. However, the Weibull probability distribution function parameters are more acceptable than the parameters of other distribution functions because the Weibull distribution function gives a better fit for wind speed data [9, 10]. Many researchers have been able to carry out analysis of wind characteristics using Weibull distribution parameters [5, 6]. In this study, the Weibull distribution model was employed in analyzing the wind speed data. In characterizing the variations of wind velocity, the probability density function and the corresponding cumulative distribution functions of the Weibull distribution model are used.

The Weibull probability density function f (V) is expressed as [11]

$$f(V) = \left(\frac{K}{C}\right)\left(\frac{V}{C}\right)^{K-1} \exp\left[-\left(\frac{V}{C}\right)^{K}\right], \text{ (K>0, C>0, V>0)} \quad (1)$$

Where K and C are Weibull shape and scale parameters respective, the shape parameter is dimensionless and it shows peakedness of the wind distribution while the scale parameter in m/s shows the windiness of the wind location, and V is the speed of the wind in m/s.

The cumulative distribution of Weibul distribution function is given as [11]

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

The Weibull shape parameter, k was computed using the expression [9].

$$K = \left(\frac{\sigma}{V_m}\right)^{-1.086} \quad (3)$$

With σ as the standard deviation, V_m is the mean wind speed

The scale parameter (c) of Weibull distribution function was estimated using the expression in [11].

$$C = \frac{V_{mK}{}^{2.6674}}{0.814+0.816K^{2.73855}} \quad (4)$$

Equation (5) [13] was used to calculate the most feasible wind speed (V_{mf})

$$V_{mF} = C\left(\frac{K-1}{K}\right)^{\frac{1}{K}} \quad (5)$$

The wind speed carrying maximum energy was evaluated using the expression [13].

$$V_{mE} = C\left(\frac{K+2}{K}\right)^{\frac{1}{K}} \quad (6)$$

Wind power density is a comprehensive index in valuing the wind resource at a particular site. It is the available wind power in airflow through a perpendicular cross-sectional unit area in a given time period. The classes of wind power density at two standard wind measurement heights considered in this study are 10 m and 50 m. Some of wind resource assessments utilize 50 m towers with sensors installed at intermediate levels such as 10 m and 20 m. The wind power per unit area, P_D (power density) can be calculated from the Weibull probability density function as [13].

$$P_D = \frac{P(V)}{A} = \frac{1}{2}\rho C^3 \Gamma\left(1 + \frac{3}{K}\right) \quad (7)$$

P(V) is the wind power, Γ is the gamma function, ρ is the air density and it is typically given as 1.225 kg/m^3. The mean wind energy density, E_D is calculated for a desired period of time, T by the relation in [12]

$$E_D = \frac{1}{2}\rho C^3 \Gamma\left(1 + \frac{3}{K}\right) T \quad (8)$$

3. Results and Discussion

It can be observed from the mean monthly variation of wind speed in Fig. 2 that the wind speeds at 10 m and 50 m, both presented similar shapes with peak wind speed values of 4.50 and 5.78 m/s respectively in August and July. The lowest values of wind speed in the area are 3.20 m/s at 10 m in December and 4.15 m/s at 50 m in the month of January. This may be a result of changes in the pressure gradient triggered by temperature differentials due to the differential solar heating of the Earth's surface [14]. July to September are the transition periods from the rainy to dry season in the region when the sky is getting free from cloud activities and water droplets. High solar radiation reaches the Earth's surface during this period, leading to high temperature, and hence high wind speed. This is because solar energy is converted into a form of wind energy, due to the uneven heating of the Earth's surface by the Sun [9].

On the other hand, the lowest wind speed in December for the 10 m wind speed data and January for the 50 m wind speed data is due to the onset of dry season when the sky is relatively full of harmattan dust. Most of the incoming solar radiations are scattered and some are reflected into space, this results in low temperatures which leads to low wind speed, [11] also observed a similar trend in Port Harcourt in the Niger Delta region. The maximum wind power production from the wind energy system in Focados can be observed to be at the rainy season months (June to September) as shown in Figure 3, with the peak values in the months of July and August at 50 m and 10 m heights respectively. The minimum power was obtained during the dry season months (October to January) with the lowest power in December at both 10 m and 50 m heights.

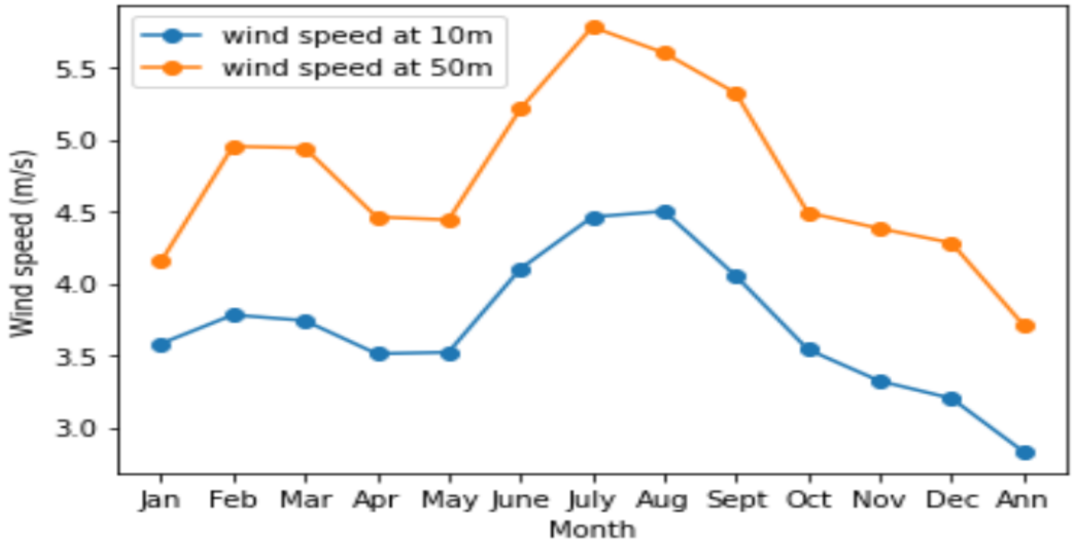


Figure 2. Monthly mean daily wind speed variations in Focados at 10 m and 50 m

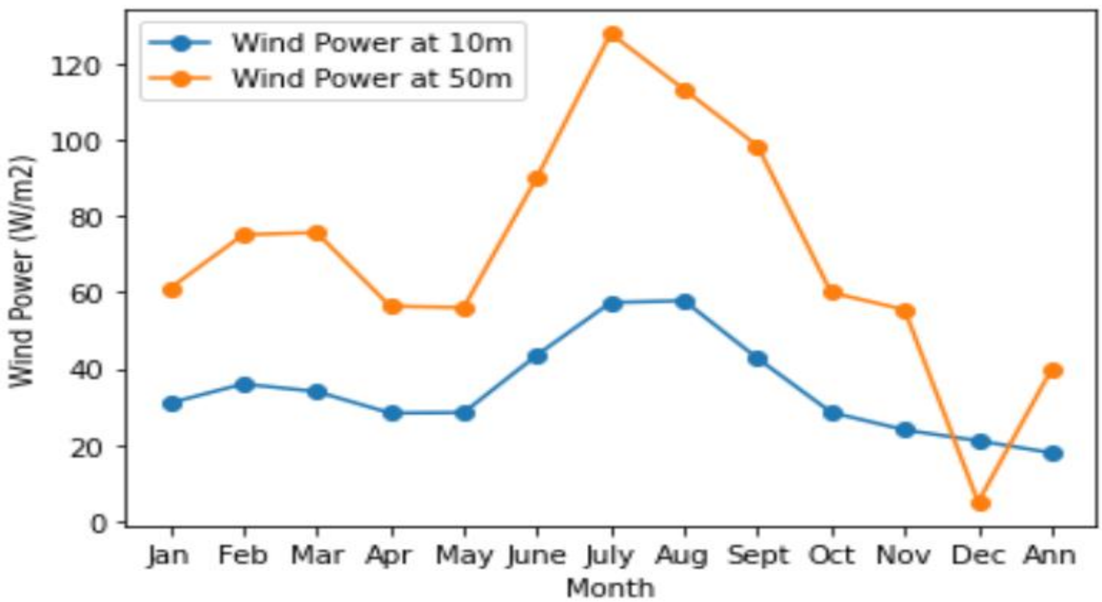


Figure 3. Monthly wind power variations in Focados at 10 m and 50 m

The annual mean wind speed for the period under investigation was 2.83 m/s at 10 m height and 3.71 ms-1 at 50 m height (Tables 1 and 2). This implies that Forcados is a moderate wind speed region. Interestingly, the wind speed within the range values of 2.5–6.5 ms-1 was reported for the southern region of Nigeria [12]. According to [15, 16], the values of most wind turbines start turning operation and generating electricity at wind speeds of about 3.0–4.0 m/s. The monthly and annual mean wind speed obtained in this work, therefore, implies that Forcados and its environs have great potential for generation of electricity using wind power.

The monthly mean Weibull shape parameter, k ranges from 6.04 to 7.35 with an annual mean value of 3.57 at 10 m height as seen in Table 1. Similarly, in Table 2 at 50 m height, the monthly mean Weibull shape parameter k was presented. K ranges from 5.32 to 9.18 with an annual mean value of 3.69. The high value of k is an indication of data spread in the normal distribution and good uniformity with a relatively small scatter exhibited by the data spread. The increase in the scale parameter from 6.76 to 8.39 at 10 m may be attributed to the wind regime exhibiting a more clustered distribution around a specific mean value. This, in turn, necessitates a higher k value for certifying the probability of observing different wind speeds at a particular site [12].

Table 1. Monthly mean wind speed characteristics and wind potential at 10 m in Focados.

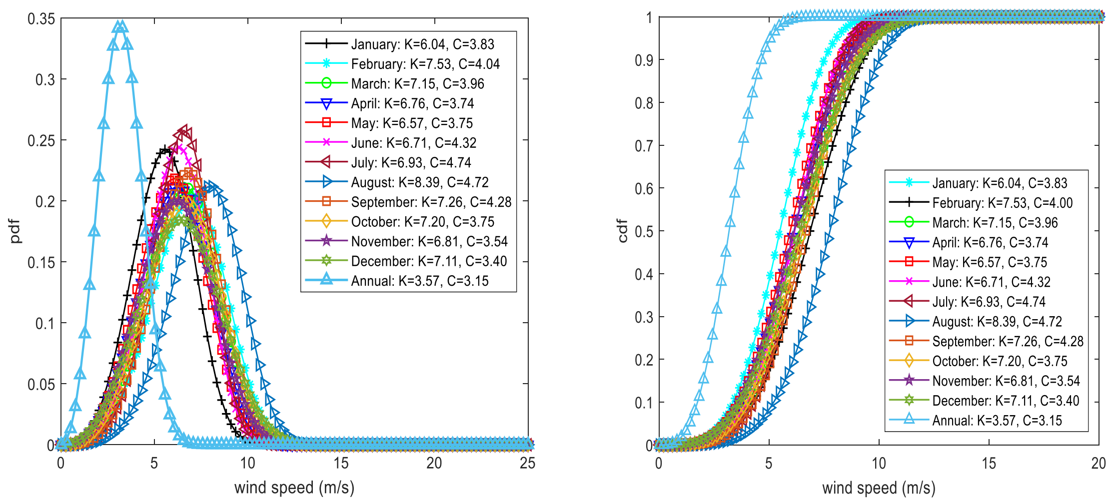
Month	Vm(m/s)	SD	K	C(m/s)	V_F(m/s)	V_E(m/s)	P_D(W/m^2)	E_D(kWh/m^2)
Jan	3.58	0.68	6.04	3.83	3.73	4.04	31.00	23.00
Feb	3.78	0.63	7.35	4.00	3.92	4.14	36.00	25.06
March	3.74	0.61	7.15	3.96	3.90	4.12	34.00	25.30
April	3.51	0.60	6.76	3.74	3.65	3.90	28.37	20.40
May	3.52	0.62	6.57	3.75	3.66	3.91	28.51	20.52
June	4.10	0.70	6.71	4.32	4.22	4.51	43.60	32.74
July	4.45	0.75	6.93	4.74	4.64	4.94	57.36	42.06
Aug	4.50	0.64	8.39	4.72	4.65	4,86	57.82	42.72
Sept	4.05	0.66	7.26	4.28	4.20	4.45	42.71	31.00
Oct	3.54	0.57	7.20	3.75	3.68	3.90	28.56	21.58
Nov	3.32	0.57	6.81	3.54	3.46	3.70	23.95	17.86
Dec	3.20	0.52	7.11	3.40	3.32	3.52	21.12	15.77
Annual	2.83	0.88	3.57	3.15	2.90	3.64	17.94	13.35

Table 2. Monthly mean wind speed characteristics and wind potential at 50 m in Focados

Month	Vm(m/s)	SD	K	C(m/s)	V_F(m/s)	V_E(m/s)	P_D(W/m^2)	E_D(kWh/m^2)
Jan	4.15	0.84	6.18	4.83	4.70	5.07	61.00	45.38
Feb	4.95	0.64	9.18	5.16	5.09	5.28	75.13	52.30
March	4.94	0.68	8.60	5.18	5.10	5.32	75.68	58.31
April	4.46	0.66	8.00	4.70	4.62	4.84	56.39	40.60
May	4.44	0.67	7.84	4.69	4.61	4.84	56.02	40.33
June	5.21	0.70	7.80	5.50	5.40	5.68	90.24	60.34
July	5.78	0.90	5.83	6.17	6.00	6.54	127.88	95.14
Aug	5.60	0.70	7.54	5.93	5.82	6.14	113.21	99.11
Sept	5.32	0.71	6.78	5.66	5.54	5.91	98.39	73.21
Oct	4.49	0.64	6.38	4.80	4.68	5.03	59.98	43.90
Nov	4.38	0.60	6.38	4.67	4.54	4.90	55.47	41.23
Dec	4.28	0.69	5.32	2.09	2.02	2.25	5.03	3.74
Annual	3.71	1.11	3.69	4.11	3.81	4.72	39.85	29.65

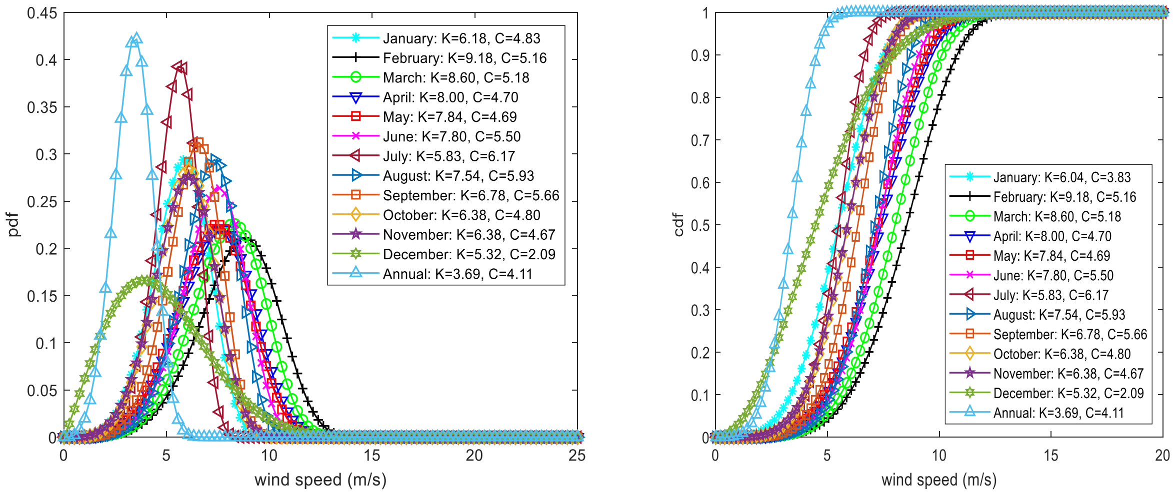
The Weibull scale parameter, denoted as c, exhibits a monthly range of 3.40 to 4.74 m/s at 10m, with an annual average of 3.15 m/s. At 50m, the range is 2.09 to 6.17 m/s, with an annual average of 4.11 m/s. The scale parameter, c, represents the predicted wind speed based on the Weibull shape parameter, k. A higher value of c indicates a windier location [9]. Notably, the maximum values of c occur in July, reaching 4.74 m/s and 6.17 m/s at 10m and 50m, respectively. This corresponds to the maximum mean wind speeds of 4.45 m/s and 5.78 m/s. Conversely, the minimum values of care observed in December at 3.40 m/s and 2.09 m/s, which align with the minimum mean wind speeds of 3.20 m/s and 4.28 m/s, respectively.

The monthly mean most probable wind speed, V_F ranges from 3.32 to 4.65 m/s with an annual mean value of 2.90 m/s (Table 1). At 50 m, V_F ranges from 2.02 to 6.00 m/s with an annual mean value of 3.81 m/s (Table 2). The annual mean wind speed carrying maximum energy, V_E was 3.64 m/s at 10 m and 4.72 m/s at 50m. It is usually greater than the wind speed, which is 2.83m/s at 10m and 3.71m/s at 50 m. In the estimation of wind turbine design, wind speed carrying maximum energy is very critical. Wind turbine system has been reported to operate well at its rated wind speed. Therefore, it is vital that the rated wind speed and the wind speed carrying maximum energy should be as close as possible [12]. Monthly mean wind power, P_D and energy densities, E_D are in proportional variation with the monthly mean wind speed (Tables 1 and 2). This is because of the dependence of wind power and energy on the wind speed. Thus, there is a correlating maximum wind power and energy density in July and August with the minimum in December corresponding to the mean wind speed. The highest power and energy densities are 57.82 W/ m^2 and 42.72kWh/m^2 at 10 m and 127.88 W/m^2 99.11kWh/m^2 while the least are 21.12W/m^2 and 15.77 kWh/m^2 at 10 m and 5.03 W/m^2 and 3.74 kWh/m^2 at 50 m respectively. The annual mean wind power and energy densities observed in this study are 17.94 W/ m^2 and 13.35 kWh/m^2 then 39.85 W/ m^2 and 29.65 kWh/m^2. Wind power density is a key factor in determining the electric power efficiency in using wind energy. The higher the power density, the higher the potential of the site to generate electric power. This shows that Forcados has a good prospect for wind energy resources. Interestingly, [14] observed a similar trend of results of wind speed characteristics, Weibull shape parameter, scale parameter, wind power and energy densities observed in this study. The wind speed in Forcados was classified using the wind power classification scheme developed by the Pacific Northwest National Laboratory (PNL). According to this scheme, the monthly average power density in Forcados mostly belongs to class 1 ($P_D \leq 100$), except for the months of July and August at 50 m where it falls into class 2 ($100 < P_D \leq 150$). However, the monthly mean power density consistently falls within the class 1 wind resource category of $P_D \leq 100$. Typically, the wind characteristics observed in Forcados indicate that it falls within a region in Nigeria that offers moderate potential for wind energy. The average wind speed recorded there slightly surpasses the minimum threshold (3.0 to 4.0 m/s) necessary for the operation of most wind turbine generators.



(a) (b)

Figure 4. Weibull wind speed probability distribution at 10 m height: (a) pdf (b) cdf



(a) (b)

Figure 5. Weibull wind speed probability distribution at 50 m height: (a) pdf (b) cdf

Figures 4 and 5 present the Weibull PDF and CDF distribution of the wind speed in the study areas. Thses distributions were plotted using the distribution parameters (shape and scale parameters) at 10 m and 50 m heights.

4. Conclusion

1. The monthly mean wind speed varies between 3.20 m/s in December and 4.50 m/s in July at 10 m and 4.28 m/s in December and 5.78 m/s in July at 50 m height.
2. At a height of 10 meters, the annual mean wind speed, most likely wind speed, and wind speed carrying the highest energy in Forcados are measured at 2.83, 2.90, and 3.64 m/s, respectively. Similarly, at a height of 50 meters, the corresponding values are recorded as 3.71, 3.81, and 4.72 m/s.
3. For Forcados, the annual mean Weibull shape parameter (k) was determined to be 3.57 at a height of 10 meters, while the annual mean Weibull scale parameter (c) was found to be 3.15m/s. At a height of 50 meters, the corresponding values were measured as 3.69 for k and 4.11 m/s for c.
4. Using the wind data analyzed in this study, the wind energy resource in Forcados, as per the PNL classification, can be categorized as class 1.
5. The wind speed observed in Forcados falls within the recommended range of 3.0–4.0 m/s, which is conducive for initiating electricity generation in most turbines. As a result, Forcados and its surrounding areas exhibit significant potential for wind power generation.
6. From the analysis, the 50 m height has more energy potential than the 10 m height in Forcados

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