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Operability of Wind Energy Conversion Systems at Aiyetoro Coastal Area, Southwestern Nigeria

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Abstract: Nigeria's overdependence on non-renewable sources of energy has undermined economic growth for more than seven decades. Renewable energy generation promises an electric power supply of >60 gW. Although Nigeria has invested in hydropower as a source of electricity, there is a need to diversify into wind energy sources. This study examines the wind energy conversion systems potential at Ayetoro, Ondo state (latitude 6.1077997 °N and longitude 4.7721257 °E) using a year of data (June 2018 - May 2019) collected at 5 minutes interval. The data was collected from the Marine Science and Technology weather station, which used an Atmos 41 to record wind data at 5.5 m altitude. The wind speed data was adjusted to 50 and 90 m and fitted to the 2-factor Weibull distribution function. The wind directional frequency and operability of wind energy conversion systems were also calculated. About 62% of the wind blew from the South of the Atlantic Ocean. At 50 m altitude, the Weibull shape parameter (K) was 2.74, and the scale parameter (C) was 4.59 m/s. The wind power density peaked at 134.8 W/m^2. This wind power density can be classified as class 1 on the NREL wind power classification. The operating probability of a wind turbine with a shut-in speed of 3.5 m/s at 50 m altitude was 62%. Therefore, we conclude that the wind energy potential of the Aiyetoro Coast of the Atlantic Ocean is currently operable for small-scale, local applications but not commercializable for state or national energy distribution.

Keywords: Wind Power Density, Wind Energy Conversion Systems, Weibull Probability Distribution, Renewable Energy, South-Western Nigeria

1. Introduction

There is a significant deficiency in energy supply in Nigeria due to increasing population and economic activities [1]. This duo has caused an enormous energy deficit, with >40% of the nation's population without access to electricity [2]. Energy is fundamental to providing economic activities, health services, clean water, and good sanitation [3, 4]. This persistence of the energy crisis has weakened the industrialization process, which undermined economic growth and lowered living standards [5]. Currently, Nigeria depends significantly on non-renewable energy sources associated with environmental pollution. Adding renewable energy to the present energy supply would provide >60 gigawatts of power needed for economic growth without a

significant increase in environmental pollution [6].

There is increased awareness of the need for renewable energy sources in Nigeria due to the low socio-economic development attained through dependence on non-renewable energy resources [7]. Hydropower is currently the only renewable energy resource connected to the electricity grid in Nigeria [8]. However, the wind could be a viable, clean, eco-friendly, and sustainable energy source for power generation for the nation [9]. However, wind energy could be unreliable due to its intermittent and unstable nature [10]. According to the Nigerian Meteorological Agency (NIMET), wind speed in the southern part of Nigeria is generally weak except in coastal areas from Lagos through Ondo, Delta, Rivers, Bayelsa to Akwa Ibom state [9]. As a result, proper site analysis is needed to determine the wind energy generation of the conversion systems. In setting up a Wind Energy

Conversion System, assessing the potential and feasibility of wind power and wind speed is necessary [11]. For this assessment, the most practical method applicable is a distribution function.

The choice of wind speed distribution function influences the calculated outcome of the available wind energy or turbine performance at a chosen location [11]. Various probability density functions have been used in different studies to describe wind speed frequency distribution and classify the wind profile characteristics [12-15]. These include the gamma distribution function [16], normal and lognormal [17], Rayleigh [18], Weibull [19], and other statistical distributions. However, the Weibull function is more flexible and popularly applied. For instance, a study determined the best probability density function and concluded that the Weibull function provides the most reliable estimates [20].

Several numerical methods can be used to estimate Weibull parameters. The methods include the graphical method, maximum likelihood estimator method (MLE), moment method, etc. [21-24]. Elsewhere, Chang compared the performances of six numerical methods in Weibull estimation in three farms at different weather regions. He found that the MLE method of Weibull parameter estimation performed best [25]. This affirmation was buttressed by Tizgui et al. [26].

The feasibility study and assessments of wind energy resources across 15 locations in Nigeria have already been carried out [27]. The study stated that northern Nigeria is more attractive for the situation of wind turbines for electrical power generation. Also, a group studied the wind energy potential of offshore wind across African coastal regions [28]. They concluded that Western African coasts possess a fair wind resource potential. In another study, the wind energy potential assessment of ten selected sites in the southwestern region of Nigeria was carried out for a feasible, cost-benefit analysis of wind power generation [29]. Twenty-four years of wind speed data at 10 m height was obtained from the NIMET to classify the sites' wind profiles for electricity generation. The study concluded that Lagos and Oyo States sites were adequately suited for a large-scale generation with an average wind speed of 2.9 and 5.8 m/s, respectively.

To the best of our knowledge, no operating probability assessment had taken place at the Ayetoro coast, the longest coastline in West Africa. Therefore, this research assessed the possibility of installing wind energy conversion systems at Ayetoro, Ilaje Local Government Area of Ondo State, toward increasing the electrical power availability of the local government, state, or nation.

2. Methodology

Wind data was collected from the Department of Marine Science and Technology Akure's Aiyetoro weather station, located at latitude 6.1077997 °N and longitude 4.7721257 °E. Aiyetoro shares a boundary with Okitipupa Local Government to the North and the Atlantic Ocean to the South (Figure 1). It is one of the settlements in Ilaje Local government area (L.G.A) of Ondo State, Nigeria. The station used an AWS - Atmos 41 to record wind speed and direction at an interval of 5 minutes from June 2018 to May 2019.

Figure 1. Mapping the sampling location along Ayetoro seaside.

2.1. Wind Data Adjustment

The data used for this research was collected at an altitude of 5.5 m. Wind turbines used for commercial electricity generation require a high sweep area because the energy generated is directly related to the sweep area. Wind data collected needed to be extrapolated for higher altitudes and calculated using the log-law wind speed model given in equation (1).

$$V_2 = V_1 \cdot \frac{ln\left(\frac{h_2}{Z_0}\right)}{ln\left(\frac{h_1}{Z_0}\right)} \qquad (1)$$

where: V_2 = wind speed (m/s) at height h_2, V_1 = wind speed (m/s) at anemometer height, h_2 = new height (m), h_1 = Initial height (m), Z_0 = Surface roughness of station surroundings (μm).

2.2. Wind Classification

The national renewable energy laboratory of the USA grouped wind into classes based on wind power density. Wind power density is a preferred measure because of the cubic nonlinear dependence of wind power on wind speed [30].

Table 1. *Wind power classes measured at 50 m above the ground according to NREL wind energy-based classification.*

Wind power class	Resource potential	Wind power density (W·m⁻²)
1	Poor	0 – 200
2	Marginal	200 – 300
3	Fair	300 – 400
4	Good	500 – 600
5	Excellent	600 – 700
6	Outstanding	700 – 800
7	Superb	>800

2.3. Weibull Distribution

By calculating the probability of wind speed, it is possible to determine wind power potential accordingly [15]. The probability density function of the Weibull distribution is given by [31] as follows:

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

where F (v) is the probability of observing wind speed v, K is the dimensionless Weibull shape parameter, and C is the Weibull scale parameter that tells how windy a place is. According to [32], the maximum likelihood method is based on numerical iterations. Using numerical iteration, K can be estimated with the formula presented in Equation (3), while C can be calculated explicitly using equation (4).

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

$$C = \left[\frac{1}{N}\sum_{i=1}^{N} v_i^k\right]^{\frac{1}{k}} \qquad (4)$$

2.4. Wind Power Density

The wind power density can be perceived as the theoretical energy potential of a particular site, which varies in cube relation to the wind speed. As a result, an accurate wind speed estimation is essential for wind energy exploitation. The wind power density can be derived from the model:

$$Wind\ power\ density = \frac{1}{2}\rho v^3 F(v) \qquad (5)$$

where: ρ is the air density, v is the wind speed, and F (v) is its probability density function of wind data.

2.5. Wind Turbine Directional Frequency and Operability

Knowledge of wind direction enables wind turbines to be positioned appropriately to maximize the total amount of energy generated. A wind rose diagram can be used to identify the dominant direction of wind speed.

For the operation of wind turbines, two important wind speed parameters are considered: the cut-in and cut-out speeds. The cut-in speed is the minimum wind speed required to generate usable power, whereas the cut-out wind speed is the speed at which turbines will shut down to prevent damage. Most wind turbines have a cut-in speed between 3-4 m/s, while the cut-out speed is about 25 m/s [33].

The formula for the operating probability of wind turbines can be given as follows:

$$P(v_1 < v < v_2) = exp\left[-\left(\frac{v_1}{c}\right)^K\right] - exp\left[-\left(\frac{v_2}{c}\right)^K\right] \qquad (6)$$

where P is the operating probability, V_1 = shut-in speed (m/s), V_2 = shut out speed (m/s).

Once the Weibull parameters are determined, the most probable wind speed (V_{mp}) and wind speed carrying maximum energy ($V_{max.\ E}$) can be derived. The most probable wind speed is the peak of a probability distribution function. A wind turbine system operates with maximum efficiency at its rated wind speed. Therefore, it is required that the wind turbine's rated wind speed should be as close to the wind speed carrying maximum energy as possible to maximize energy output.

Both factors can be given by Equations (7) and (8), respectively.

$$v_{mp} = C\left(1 - \frac{1}{k}\right)^{1/k} \qquad (7)$$

$$v_{max.E} = C\left(1 - \frac{2}{K}\right)^{1/k} \qquad (8)$$

3. Results and Discussion

3.1. Wind Speed Variation

The mean wind speed variation with altitude at the sampling location is shown in Figure 2. We observed a mean wind speed of 3.06 m/s at the anemometer height. Wind speeds at an altitude of 90 m are approximately 4.16 m/s.
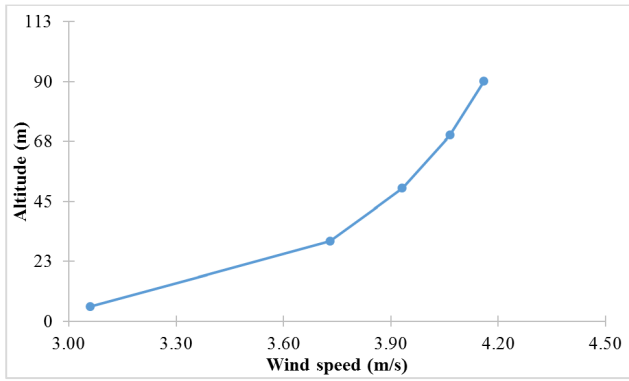
Figure 2. *Wind speed variation with height at Ayetoro meteorological station.*

3.2. Wind direction

With the wind direction data obtained from the

anemometer, the wind direction at the sample location was derived as presented in Figure 3. The wind from the South predominates, contributing >60%, 44% of which range 3.6 – 5.7 m/s, while 26% fall between 2.1 and 3.6 m/s. This wing was blowing directly from the Atlantic Ocean.

The wind speed frequency and Weibull distribution curve at the anemometer height and 50 m altitude are shown in Figures 3 and 4. At 5.5 m, the predominant wind was blowing at 4 – 5 m/s, and wind speeds above 5 m/s were under 28% of the total. Comparatively, wind speeds above 5 m/s were about 52% of the total windblown. The total wind power density at 5 m altitude was 29.03 W/m^2 which increased to 61.63 W/m^2 at 50 m altitudes. The scale factor recorded throughout the year at 5 m altitude is 3.57 m/s which increased to 4.59 m/s at 50 m altitudes. However, the shape factor did not have a significant increase from 2.74.
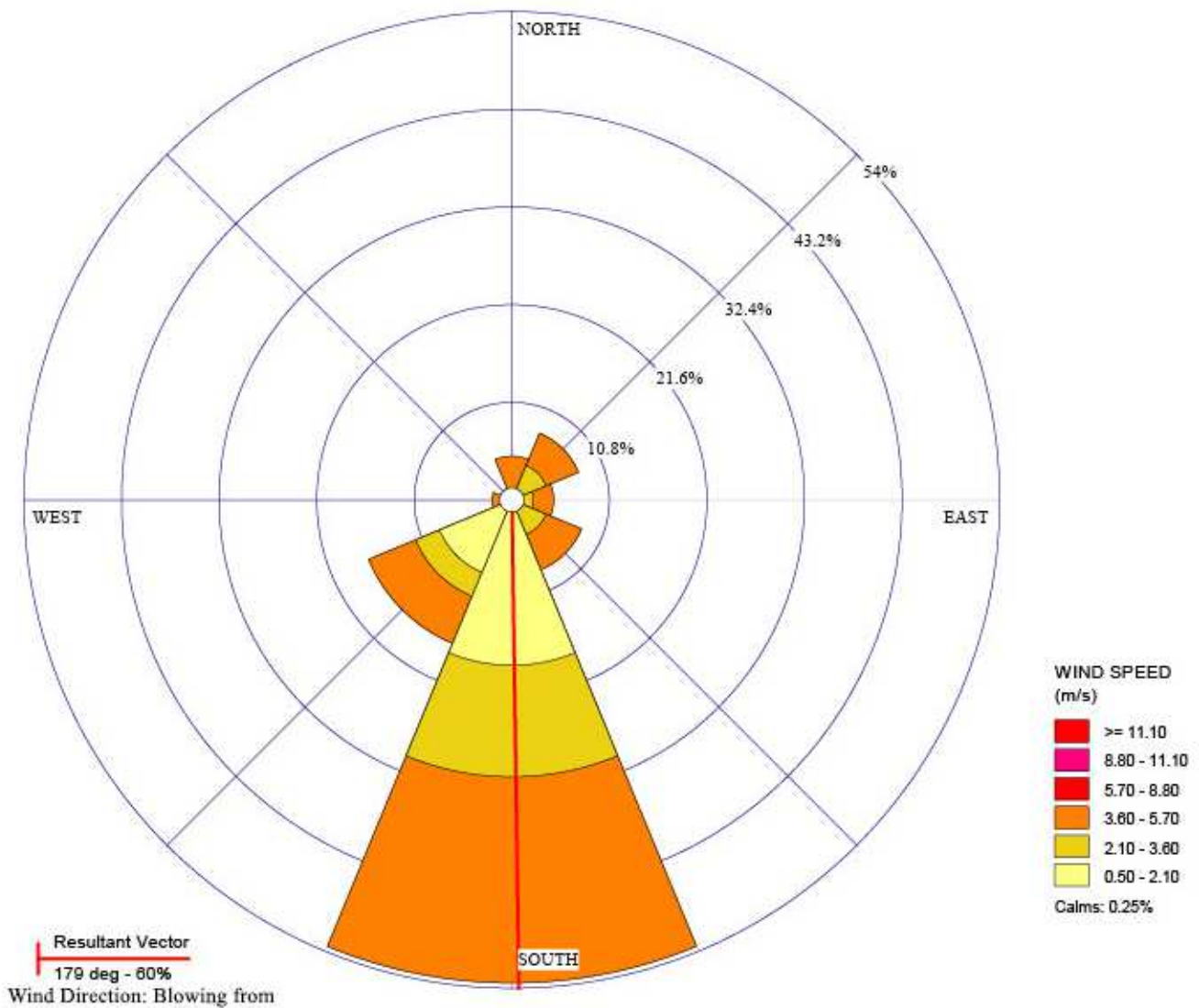

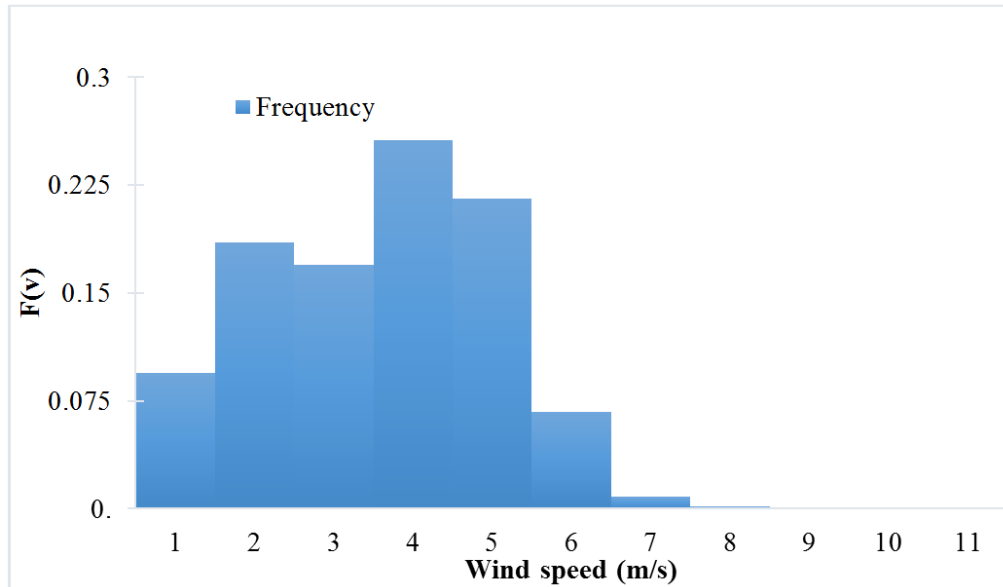***Figure 3.*** *Wind rose plot of wind direction at Ayetoro Meteorological Station.*

Figure 4. Wind speed probability distribution function at 5 m altitude.

K = 2.74
C = 3.57 m/s
Wind power density = 29.03 W/m^2.

The variation of the shape factor (K) and the Scale factor (C) is represented in Figure 5. C was lowest around December, with speeds of 3.06 m/s, and greatest in June and August, reaching a peak of 5.89 m/s in both months.
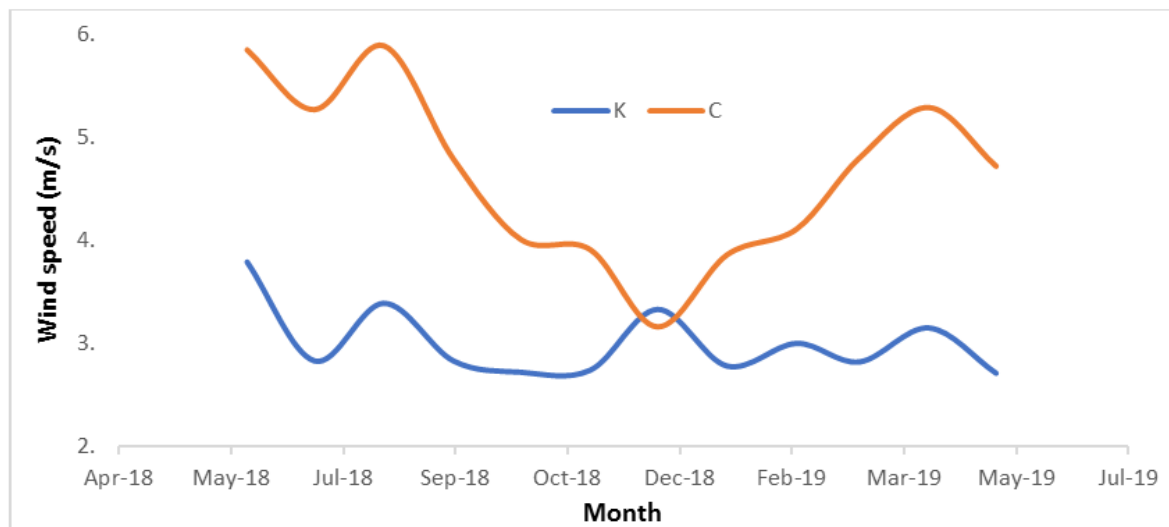

Figure 5. Weibull shape and scale parameters at 50 m altitude.

The monthly variations of the most probable wind speed and the wind speed carrying maximum energy are shown in Figure 6. Low probable wind speeds (2.21 – 2.79 m/s) were observed between October and February, with peak wind speeds of 4.2 and 4.13 m/s in June and August, respectively. This wind regime is similar to that observed in Koulouma Bayelsa, another coastal city in Nigeria [34]. There was a positive linear correlation of 0.95 between the most probable wind speed and the wind speed carrying maximum energy. The highest wind speed was 5.25 m/s, while the lowest wind

speed in December at 2.83 m/s.

3.3. Wind Power Density and Operability of Wind Turbines

The monthly wind power density is presented for 5.5 and 50 m altitude in Figures 7 and 8, respectively. The wind power density at 50 m altitude peaked at 134.8 W/m^2 in September and was lowest around March. At 5.5m, the power densities had a mean of 29.67 ± 5.25 W/m^2, with a range of 60.61 W/m^2.
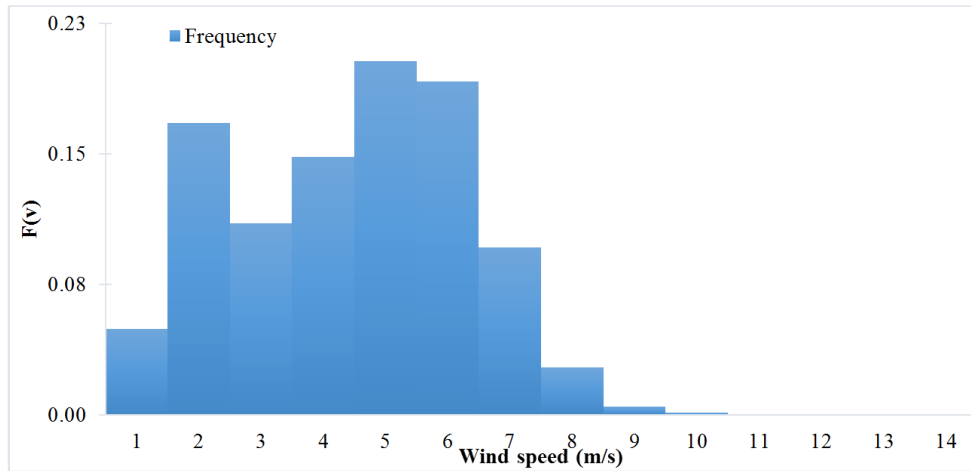
Figure 6. WInd speed probability density function at 50 m altitude.

K = 2.74
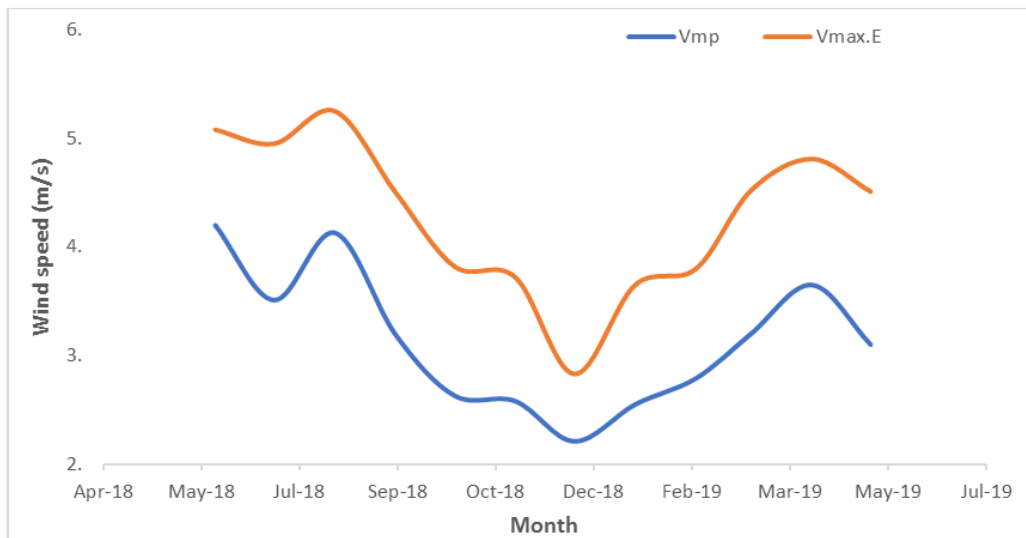C = 4.59 m/s
Wind power density = 61.63 W/m^2.

Figure 7. Most probable wind speed and wind speed with maximum energy monthly variation.
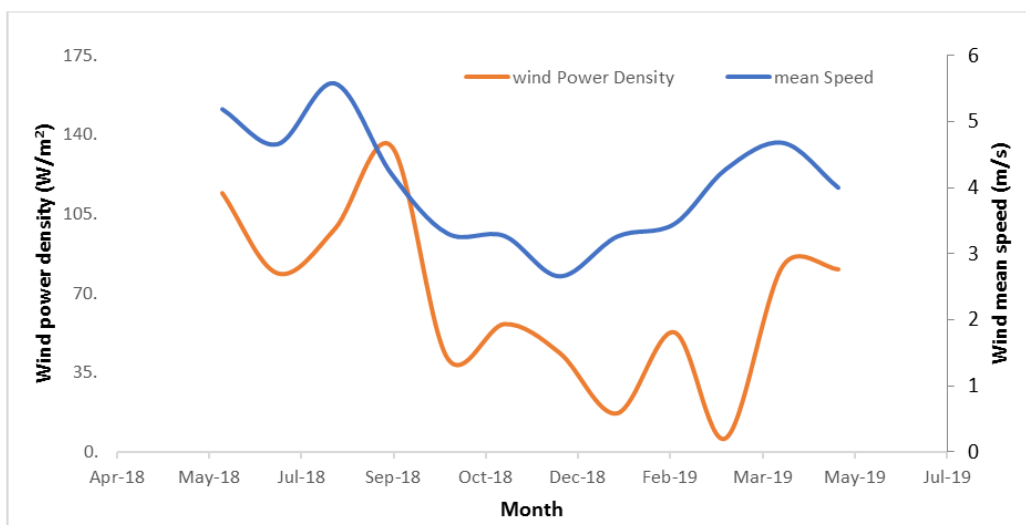

Figure 8. Variations in wind power density and monthly mean speed.

The average wind speed increased significantly with height, with a speed of 4.01 m/s observed at 90 m altitude. 70% of the wind was blowing from the South, with a resultant vector of 179°. More than 44% of the wind blowing from the Atlantic Ocean has speeds between 3.6 – 5.7 m/s at 50 m altitude. These values are satisfactory compared to the average shut-in speed of commercial utility wind turbines of 3.5 m/s. As displayed in Figures 4 and 6, the Weibull scale parameter estimated the wind of 4.59 m/s at 50 m, better than the 3.57 m/s at 5 m altitude. However, between October and February, i.e., the dry harmattan season of the Nigerian climate system, the most probable wind speeds for the period were below the shut-in speed of most commercial utility wind turbines. This occurrence was caused by the predominant wind blowing from the Northern region. This wind regime was explained elsewhere [35].

The rated wind speed of any prospective wind turbine should be within 3.5 – 5.08 m/s for appreciable efficiency. The wind power density at the station is classified as class 1 on the NREL wind power classification. Furthermore, the operating probability of wind turbines with a shut-in speed of 3.5 m/s at 50 m altitude is 62%.

4. Conclusion

The operating probability of wind energy conversion systems and wind power potential in the Ayetoro Coastal Region of Nigeria has been analyzed based on wind data from May 2018 to June 2019 using a 2-parameter Weibull distribution function. This study infers the following:

1. According to the NREL classification, the wind power density is classified as Class 1. This classification recommends that wind energy conversion system applications be for small-scale local energy needs.
2. 60% of the wind is blowing from the South, which is the direction of the Atlantic Ocean.
3. The operating probability of a wind turbine with a shut-in speed of 3.5 m/s is 62%
4. Low probable wind speeds (2.21-2.79 m/s) at 50 m altitude were observed between October and February, with peak wind speeds of 4.2 and 4.13 m/s in June and August, respectively.
5. Wind power density at 50 m altitude peaked at 134.8 W/m^2 in September and was lowest in March.

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