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Wind Speed Data Analysis and Assessment of Wind Energy Potential of Abeokuta and Ijebu-Ode, Ogun State, Southwestern Nigeria

Waliu O. Mufutau*, Olumayowa A. Idowu, Rufus A. Jokojeje, James Taiwo

Department of Electrical/Electronic Engineering, School of Engineering, Moshood Abiola Polytechnic, Abeokuta, Ogun State, Nigeria

Abstract The results of wind data analysis carried out to determine wind energy potential of Abeokuta and Ijebu-Ode, Ogun state, Nigeria is presented in this work. Fifteen years (2000 to 2014) monthly mean wind speed data at a height of 10 m obtained for the two sites was subjected to the 2-parameter Weibull statistical model. Power densities at extrapolated heights were found for Abeokuta and Ijebu-Ode and are classified according to Bastille-Pacific Northwest Laboratory Classification Scheme. The result showed that average monthly mean wind speed at height 10m for Abeokuta ranges between 2.90 and 4.0 m/s, while for Ijebu-Ode, it ranges from 2.8 to 4.2 m/s. Seasonally, the mean wind speed for Abeokuta ranges from 3.5 m/s (for dry) to 3.3 m/s (for wet), while for Ijebu-Ode it ranges between 3.6 m/s (dry) to 3.5 m/s (wet). The wind power density and Energy density were found to respectively range between 14.94 to 39.20 W/m^2 and 130.86 to 343.39 kWh/m^2 for Abeokuta and 13.00 to 44.61W/m^2 and 113.87 to 390.78 kWh/m^2 for Ijebu-Ode respectively. The respective mean annual values of the most probable wind speed and wind speed carrying maximum energy were gotten to be respectively 3.5 m/s and 4.4 m/s for Abeokuta and 3.8 m/s and 4.4 m/s for Ijebu-Ode. Based on extrapolated wind power density values for the two sites and in accordance with wind power classification scheme, the study concludes that wind speed characteristics viable for power generation can be assessed at heights higher than 350m above ground level.

Keywords Wind Power, Wind Speed, Power Density, Renewable energy, Weibull-Distribution

1. Introduction

Nigeria, like many other developing countries is being faced with challenge of inadequacy of power supply. Presently the generation capacity of Nigeria national grid stands at a value of 6803MW out of total installed capacity of about 12,000 MW [15]. With estimation population of about 180million, there is no doubt about the fact that Nigeria remains on the top spot of list of countries with poor energy use per capital. The reason for this is not far-fetched. Undoubtedly, the poor power supply can be traced to inadequate generation which itself is a consequent of over dependent of the Nigerian power generation system on Hydro and thermal means. Seasonal fluctuation in water availability cannot guarantee steady supply also irregularities in supply of gas also contribute to low power generation. Power supply is a key factor for economic growth as most small and Medium Enterprises (SMEs) as well as large scale industries rely greatly on constant of power supply. The concern over the production of adequate and sustainable electricity to drive economic developments is global issue. The conventional sources of fossil fuel burning have been able to produce surplus energy production, but its finite nature is a concern for the future. Employing environment friendly and non-toxic sources of energy production has gained wide acceptance across the globe, this is because these sources which include Wind, Solar, and Hydro are non-depletable and so contain sustainable potentials for electricity generation [2]. For improved economy situation through steady availability of power supply, there is need to diversify the source through which power is generated. One area that attention is being shifted to is renewable energy. The most commonly used renewable source of energy is wind. The use of wind energy as a form of renewable energy gained momentum in the 80s and 90s and there are now thousands of wind turbines operating all over the world [1, 14]. The interest in wind energy is growing worldwide because of its environmental benefit, freely availability, pollution free nature low maintenance costs and advancement of its technology, which is highly competitive with conventional energy technology. Today wind energy can be harnessed for grid and non-grid electricity generation, water pumping, irrigation, milling etc. However, this energy sources has not been fully exploited mainly due to the relatively high costs associated with the energy conversion technologies [3, 19].

Many studies have been carried out on wind resource assessment around the world to determine the potentialities of local sites for wind power/electricity. Also, several studies on wind resource assessment have been done in Nigeria. Each one of these reports considered different sites and presented analyses to justify their results. This work assesses wind energy potentials of two selected sites- Abeokuta and Ijebu-Ode in Ogun state, Southwestern Nigeria. The analysis yields monthly, yearly and seasonal potentials for electricity generation.

2. Materials and Method

2.1. Equations and Mathematical Formulations

2-parameters Weibull statistical distribution is employed for the assessment being reported owing to its proven accuracy than that of the 3-parameters. It can be employed in describing and predicting the characteristics of prevailing wind profile over a place [4, 5, 10, 14 and 18]. The Probability Density Function *f*(*v*) and the corresponding Cumulative Density Function *F(v*) associated with the 2-parameter Weibull distribution are given by Equations 1 and 2 respectively [14].

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

Where, k is the dimensionless Weibull shape parameter, c (m/s) is the scale parameter.

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

k and c are the weibull distribution parameters that should be determined. This is done by solving for k and c in equations 3 and 4.

$$k = \left(\frac{\sigma}{Vm}\right)^{-1.09} \quad (3)$$

$$c = \frac{Vm}{\Gamma(1+1/k)} \quad (4)$$

Where, δ, standard deviation and V_m is mean wind speed.

The Mean monthly wind speed and standard deviation were obtained using equations 5 and 6 below.

$$Vm = \frac{1}{n}\sum_{i=1}^{n} Vi \quad (5)$$

$$\sigma = \frac{1}{n-1}\sum_{i=1}^{n}\{(Vi - Vm)^2\}^{1/2} \quad (6)$$

Were *Vi* is the individual velocity, *Vm* is the mean velocity and *n* is the number of measurement [9].

The mean value of the wind speed *v*m and standard deviation σ for the Weibull distribution can be estimated using equations 7 and 8 respectively [6, 14, 17, 21].

$$Vm = c\Gamma\left(1 + \frac{1}{k}\right) \quad (7)$$

$$\sigma = \sqrt{c^2\left\{\Gamma\left(1 + \frac{2}{k}\right) - \left[\Gamma\left(1 + \frac{1}{k}\right)\right]^2\right\}} \quad (8)$$

In addition to the mean wind speed, the other two significant wind speeds for wind energy estimation are the most probable wind speed (Vmp) and the wind speed carrying maximum energy (Vemax). They are expressed respectively as in equations 9 and 10.

$$Vmp = c\left(\frac{k-1}{k}\right)^{1/k} \quad (9)$$

$$Vemax = c\left(\frac{k+2}{k}\right)^{1/k} \quad (10)$$

The specific power (Pv) available in a cross-sectional area (A) perpendicular to the wind stream moving at a speed *Vm* and energy per unit area (Ed) are expressed by equations 11 and 12 respectively [8].

$$Pv = \frac{P}{A} = \frac{1}{2}\rho V m^3 \ (\text{Wm}^{-2}) \quad (11)$$

$$Ed = \frac{E}{A} = \frac{1}{2}\rho V m^3 \times T \ (\text{Whm}^{-2}) \quad (12)$$

Both the mean wind speed and power density are generally used to classify the wind energy resource [16].

Mostly, wind data are obtained at 10 m height and turbines hub heights are always above 10m. This necessitates the need for the wind profile characteristics to be determined at heights above 10m. This can be determined using equation 13 [6, 11, 13].

$$Vref = Vo\left(\frac{href}{ho}\right)^{\alpha} \quad (13)$$

Where V_{ref} = wind speed at reference height, V_0 = wind speed at 10 m height, h_{ref} = reference height, h_0=10 m height, α is the surface roughness coefficient that can be determined using equation 14 and is assumed to be 0.143 (or 1/7) in most cases [22].

$$\alpha = \frac{(0.37 - 0.088 \ln Vo)}{1 - 0.088 \ln\left(\frac{ho}{10}\right)} \quad (14)$$

2.2. Data Collection

Fifteen years (2000 -2014) monthly mean wind speed data of the selected sites- Abeokuta and Ijebu-Ode was obtained from the Nigerian Meteorological Agency (NIMET) Oshodi, Lagos. The data had been measured continuously by NIMET using three cup generator anemometer at a height of 10 m above ground level. The data was then analyzed using Weibull distribution to determine the monthly, seasonal and yearly wind potentials for power generation. The geographical description of the selected sites is presented in Table 1.

Table 1: Geographical Description of the selected sites

Stations	Latitude (N)°	Longitude (E)°	Elevation, (M)	Air Density, (Kgm^{-3})
Abeokuta	7.10	3.20	104	1.21
Ijebu-Ode	6.82	3.92	77	1.22

3. Results and Discussion

Analysis of the whole data spread revealed that the ranges of the sites' average monthly wind speeds lies between 1.1 m/s and 6.3 m/s over the period of consideration. The monthly, annual and seasonal average wind speeds for the two selected sites are respectively presented in Figures 1, 2 and 3. From the Figure 1 that monthly average wind speed for Abeokuta is highest and lowest in March and October respectively while, for Ijebu-Ode it is in February and October respectively. Monthly, the average wind speed values ranges between 2.9m/s and 4.0 m/s for Abeokuta and 2.8 and 4.2 m/s for Ijebu-Ode. Figure 2, however represents the annual average wind speed from 2000 to 2014. The annual average wind speed is observed to be highest in 2000 and lowest in 2007 for Abeokuta and however highest in 2010 and lowest in 2002 for Ijebu-Ode. The annual average wind speed values ranges between 2.2 and 5.1m/s for Abeokuta and between 2.3 and 4.5 m/s for Ijebu-ode. It can then be inferred that Abeokuta has higher annual average wind speed range than Ijebu-Ode.

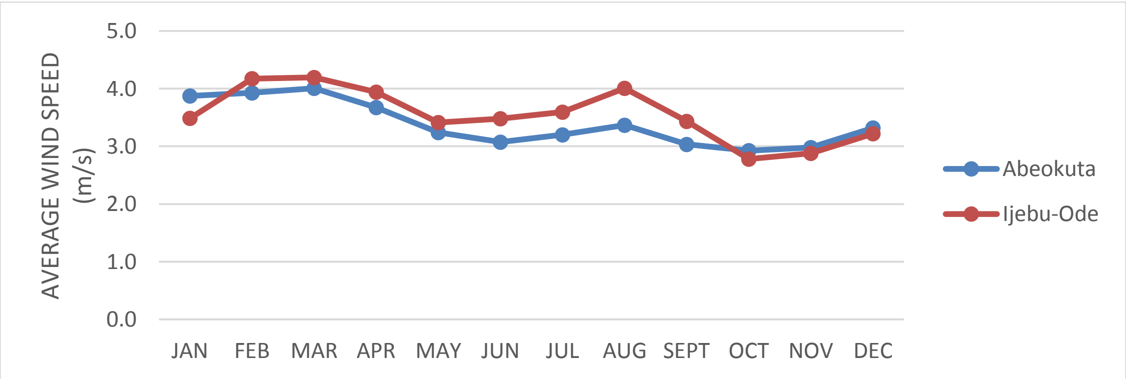

Figure 1: Monthly average wind speeds (at 10 m height) for Abeokuta and Ijebu-ode

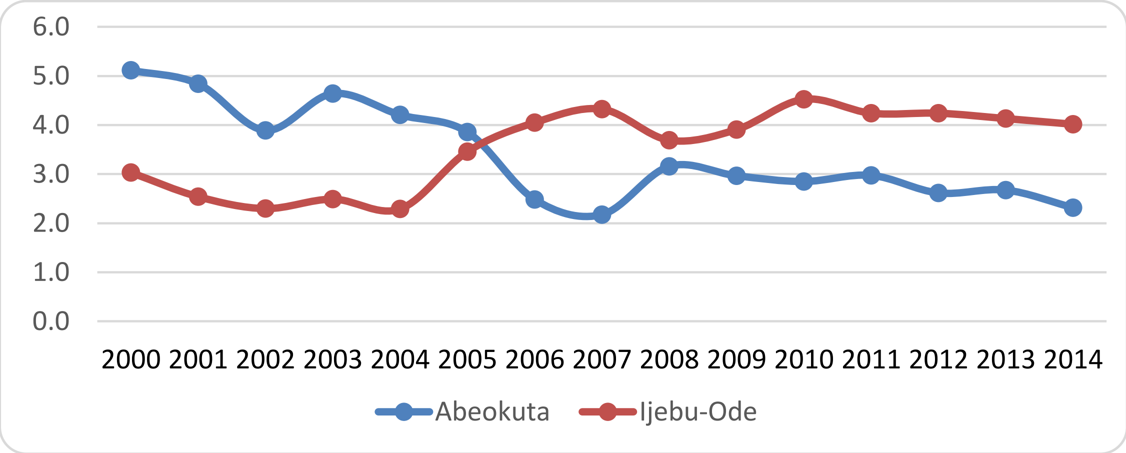

Figure 2: Annual average wind speeds (at 10 m height) for Abeokuta and Ijebu-ode for the period 2000 to 2014

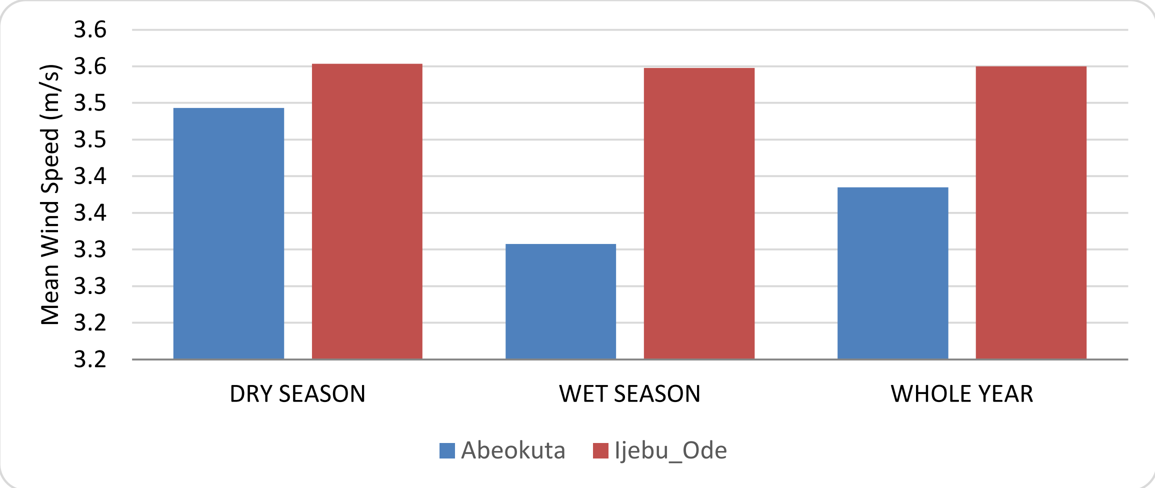

Figure 3: Seasonal average wind speeds (at 10 m height) for Abeokuta and Ijebu-ode

Seasonally, in Southern Nigeria, rainy season spans through March to July and then September to October while dry season spans through November to March and a short dry season in August, termed "August break'', As presented in Figure 3, Abeokuta site has a better magnitude of average wind speed profile in the dry season than in the wet, also from the same Figure Ijebu-Ode exhibits almost the same wind speed profile in the wet and dry season and as such it is safe to assume that its wind speed does not display seasonal variability. The mean measured data distribution between the dry and wet periods gave the range of mean wind speeds as 3.0 to 3.9 m/s and 2.9 to 4.0 m/s for Abeokuta, and 2.9 to 4.2 m/s and 2.8 to 4.2 m/s for Ijebu-Ode respectively.

Consequent upon evaluation of Equations 1, 2,3,4,6 and 11, Weibull parameters (c and k parameters), average mean speed, standard deviation and power density for Abeokuta and Ijebu-Ode obtained are presented respectively in Table 2 and 3 and the corresponding CDF and PDF plots for the seasons are shown in Figures 4 to 9.

Table 2a: Monthly and Seasonal Weibull Parameters for Abeokuta site at height of 10m

Months/Periods	Vm (ms^{-1})	δ (m/s)	k-shape	c-scale(m/s)	PD(Wm^{-2})
anuary	3.9	1.1	3.96	4.34	36.33
February	3.9	1.0	4.60	4.40	36.33
March	4.0	1.1	4.24	4.49	39.20
April	3.7	1.1	3.91	4.11	31.02
May	3.2	1.2	3.04	3.63	20.07
June	3.1	0.9	3.83	3.44	18.25
July	3.2	1.1	3.31	3.58	20.45

August	3.4	1.3	2.82	3.77	24.07
September	3.0	1.0	3.19	3.40	16.54
October	2.9	1.0	3.14	3.28	14.94
November	3.0	1.1	2.94	3.34	16.54
December	3.3	1.1	3.46	3.72	22.01
Dry Season	3.5	0.4	10.6	3.90	25.79
Wet Season	3.3	0.4	11.4	3.70	21.89
Whole Years	3.4	0.39	10.60	3.79	23.47

Table 2b: Annual Weibull Parameters for Abeokuta site at height of 10m

Years	Vm (ms^{-1})	δ (m/s)	k-shape	c-scale (m/s)	PD(Wm^{-2})
2000	5.1	0.43	15.02	5.73	81.04
2001	4.8	0.55	10.70	5.42	68.67
2002	3.9	0.92	4.80	4.36	35.66
2003	4.6	0.67	8.24	5.20	60.50
2004	4.2	0.83	5.86	4.71	45.09
2005	3.9	0.60	7.55	4.32	34.75
2006	2.5	1.33	2.00	2.78	9.27
2007	2.2	0.50	4.99	2.44	6.22
2008	3.2	0.32	12.00	3.54	19.06
2009	3.0	0.29	12.75	3.32	15.80
2010	2.9	0.36	9.45	3.19	14.01
2011	3.0	0.41	8.59	3.33	15.93
2012	2.6	0.18	18.49	2.93	10.84
2013	2.7	0.40	7.93	3.00	11.58
2014	2.3	0.41	6.67	2.59	7.52

Table 3a: Monthly and Seasonal Weibull Parameters for Ijebu-Ode site at height of 10m

Months/Season	Vm(ms^{-1})	δ (m/s)	k-shape	c-scale (m/s)	PD (Wm^{-2})
January	3.5	0.8	5.0	3.9	224.64
February	4.2	1.0	4.7	4.7	385.22
March	4.2	1.1	4.5	4.7	390.78
April	3.9	1.0	4.4	4.4	324.15
May	3.4	0.7	5.3	3.8	210.76
June	3.5	0.9	4.4	3.9	223.36
July	3.6	0.8	4.9	4.0	245.90
August	4.0	1.2	3.6	4.5	340.89
September	3.4	1.0	4.0	3.8	214.49
October	2.8	0.8	3.9	3.1	113.87
November	2.9	0.7	4.3	3.2	126.60
December	3.2	0.8	4.4	3.6	176.94
Dry Season	3.6	0.5	7.8	4.0	237.78
Wet Season	3.5	0.4	9.6	4.0	236.63
Whole Years	3.6	0.6	6.7	4.0	269.80

Table 3b: Yearly Weibull Parameters for Ijebu-Ode site at height of 10m

Years	Vm(ms^{-1})	δ (m/s)	k-shape	c-scale (m/s)	PD (Wm^{-2})
2000	5.1	0.43	15.02	5.73	17.03
2001	4.8	0.55	10.70	5.42	10.02
2002	3.9	0.92	4.80	4.36	7.42
2003	4.6	0.67	8.24	5.20	9.44
2004	4.2	0.83	5.86	4.71	7.34
2005	3.9	0.60	7.55	4.32	25.23

2006	2.5	1.33	2.00	2.78	40.52
2007	2.2	0.50	4.99	2.44	49.35
2008	3.2	0.32	12.00	3.54	30.69
2009	3.0	0.29	12.75	3.32	36.42
2010	2.9	0.36	9.45	3.19	56.52
2011	3.0	0.41	8.59	3.33	46.55
2012	2.6	0.18	18.49	2.93	46.55
2013	2.7	0.40	7.93	3.00	43.08
2014	2.3	0.41	6.67	2.59	39.53

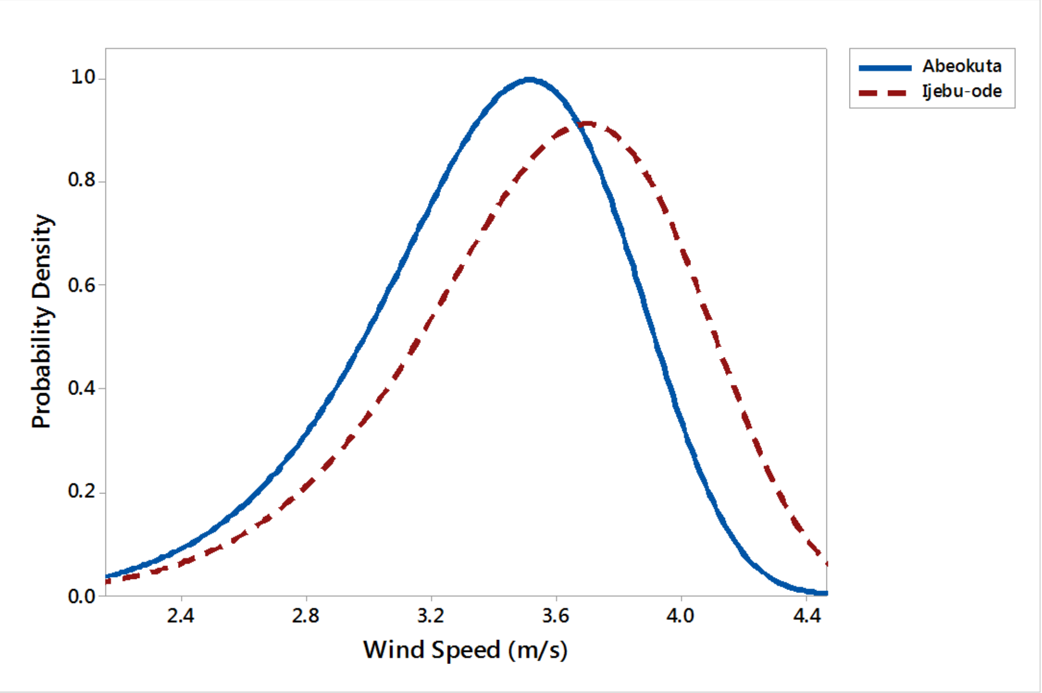

Figure 4: Probability Density Function for Whole Years at Height of 10m

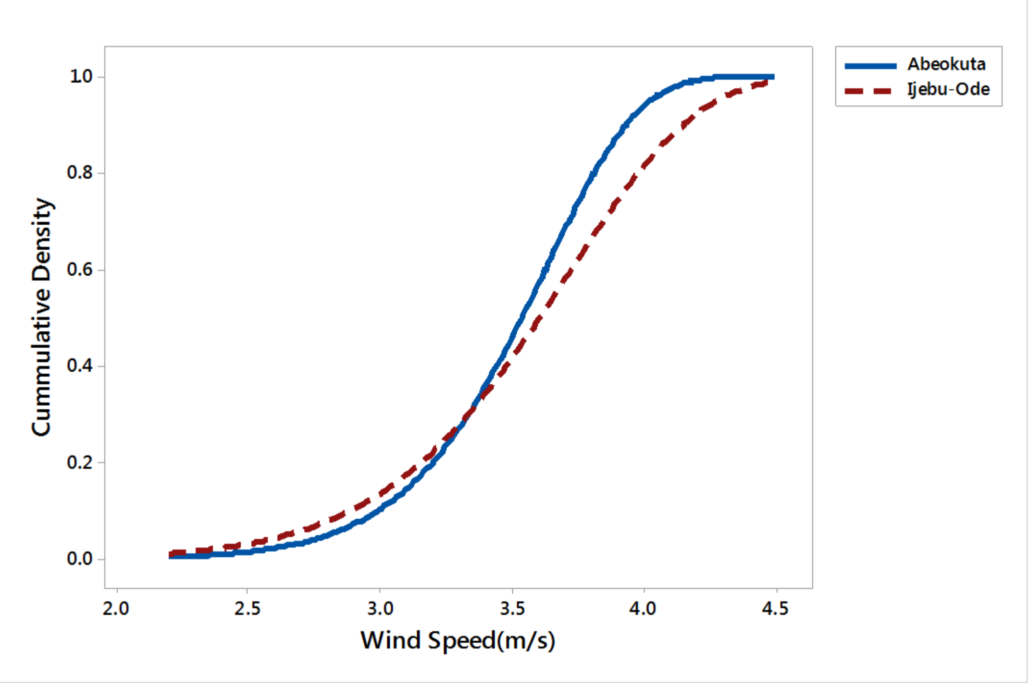

Figure 5: Cumulative Distribution Function for whole years at Height of 10m

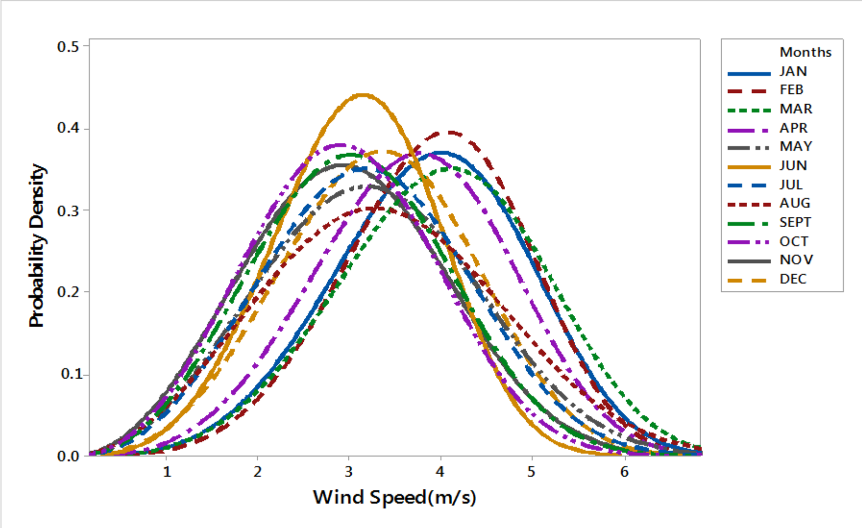

Figure 6: Probability Density Function for Whole Years at Height of 10m for Abeokuta.

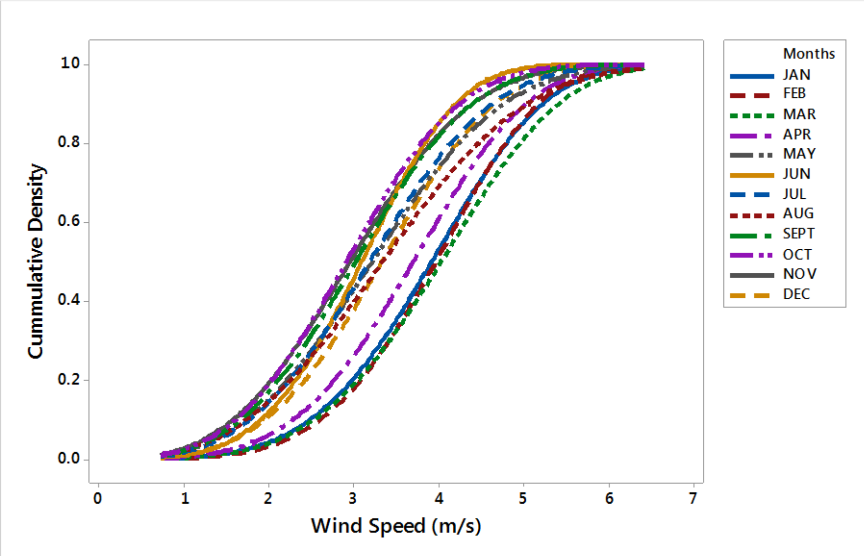

*Figure **7:** Cumulative Distribution Function for whole years at Height of 10m for Abeokuta.*

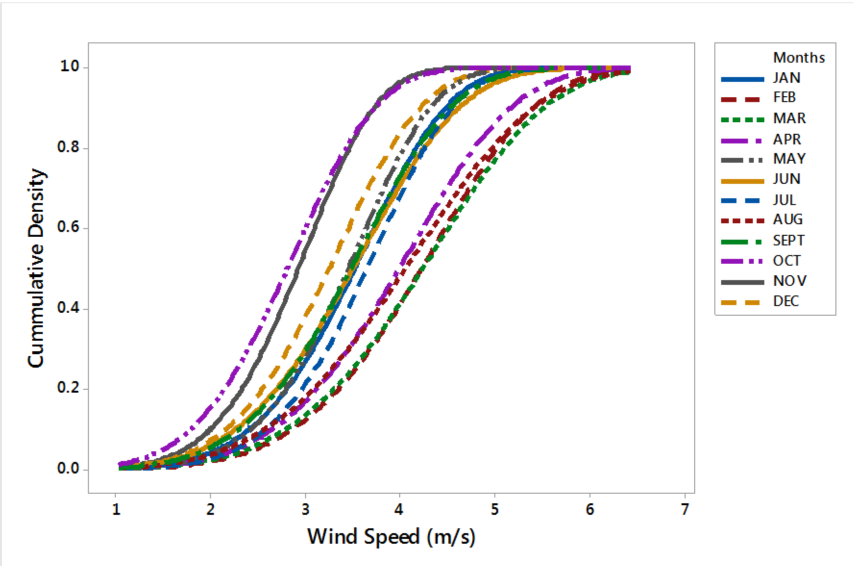

Figure 8: Cumulative Density Function for Whole Years at Height of 10m for Ijebu-ode

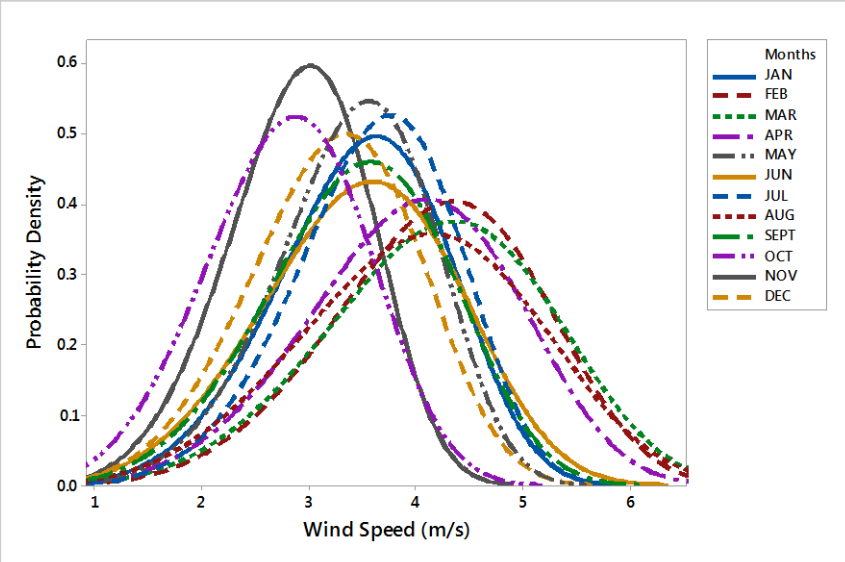

Figure 9: Probability Density Function for Whole Years at Height of 10m for Ijebu-ode

From the Figures, the wind profiles for monthly and annual data series follow the same cumulative distribution pattern. These curves pattern shows high level of agreement which what has been reported in literatures on similar studies [2, 7, 14, 20]. The observed difference in shapes of the CDF and PDF plots is as a result of the varying values of k and c.

Furthermore, the values of k and c from the analysis across all the stations range between $2.00 \leq k \leq 12.75$ and $2.44 \leq c \leq 5.73$, respectively. These high values of k and c ($k \geq 2$ and $c \geq 2$) indicate a data spread in a perfectly normal distribution [10], and also show that the data spread exhibits good uniformity with relatively small scatter. The scale parameter, c, further indicates how windy a location under consideration is, whereas the shape parameter, k, indicates how peaked the wind distribution is [17]. Thus, if the wind speeds tends to spike steeply at a certain value, the distribution will have a high k value.

Monthly and seasonal power densities are respectively presented in Table 2a and 2b for Abeokuta and 3a and 3b for Ijebu-ode. From the tables, it can be observed that that Ijebu-Ode has better monthly/seasonal wind power density range than Abeokuta. For Abeokuta, the monthly values of the wind power density ranges between 14.94 to 39.20 W/m^2 and seasonally, it ranges between 25.79(dry) to 21.89W/m^2 (wet). For Ijebu-Ode, monthly values of the wind power density ranges between 13.11 to 44.96 W/m^2 and seasonally, it ranges between 27.14(dry) to 27.01W/m^2 (wet). The Power density is less than 100W/m^2 at 10m above ground level in the two selected sites. These sites are classified as class 1 in line with the Battelle-Pacific Northwest Laboratory (PNL) classification scheme presented in Table 4 [16]. Based on this, the two selected sites are not fit for wind power generation at 10m height above ground level but can be utilized for domestic use such as production of community water supply, livestock watering, and farm irrigation by means of installing windmills.

Table 4: Battelle-Pacific Northwest Laboratory (PNL) classification scheme [16]

Wind power Class	Wind speed at 10m (m/s)	Wind Power Density at 10m (W/m^2)	Remarks
1	0 – 4.4	0 – 100	Poor
2	4.4 – 5.1	100 – 150	Marginal
3	5.1 – 5.6	150 – 200	Fair
4	5.6 – 6.0	200 – 250	Good
5	6.0 – 6.4	250 – 300	Excellent
6	6.4 – 7.0	300 - 400	Outstanding
7	7.0 – 9.5	400 -1000	Superb

Assessing a site's wind resources for power generation involves not only profiling the wind power potential but also evaluating two important wind speeds that will aid in the determination of the wind speed rating of a suitable wind turbine. These wind speeds are the most probable wind speed (Vmp) and the maximum energy carrying wind speed (Vemax) [14], evaluated using Equations 9 and 10. The results obtained are shown in Table

5. The plots of monthly, seasonal and whole year's values of these wind speeds are presented in Figure 10 and 11.

Table 5: Most probable wind speed (v_{mp}) and the wind speed carrying maximum energy (v_{emax}).

	Abeokuta Site		Ijebu-Ode Site	
PERIOD	**Vmp (m/s)**	**Vemax (m/s)**	**Vmp (m/s)**	**Vemax (m/s)**
January	4.1	4.9	3.8	4.2
February	4.2	4.8	4.5	5.1
March	4.2	5.0	4.5	5.2
April	3.8	4.7	4.2	4.9
May	3.2	4.4	3.7	4.1
June	3.2	3.9	3.7	4.3
July	3.3	4.2	3.9	4.4
August	3.3	4.7	4.1	5.2
September	3.1	4.1	3.6	4.3
October	2.9	3.9	2.9	3.5
November	3.0	4.1	3.1	3.6
December	3.4	4.3	3.4	4.0
Dry Season	3.6	4.6	3.9	4.4
Wet Season	3.4	4.3	3.8	4.4
Whole Year	3.5	4.4	3.8	4.4

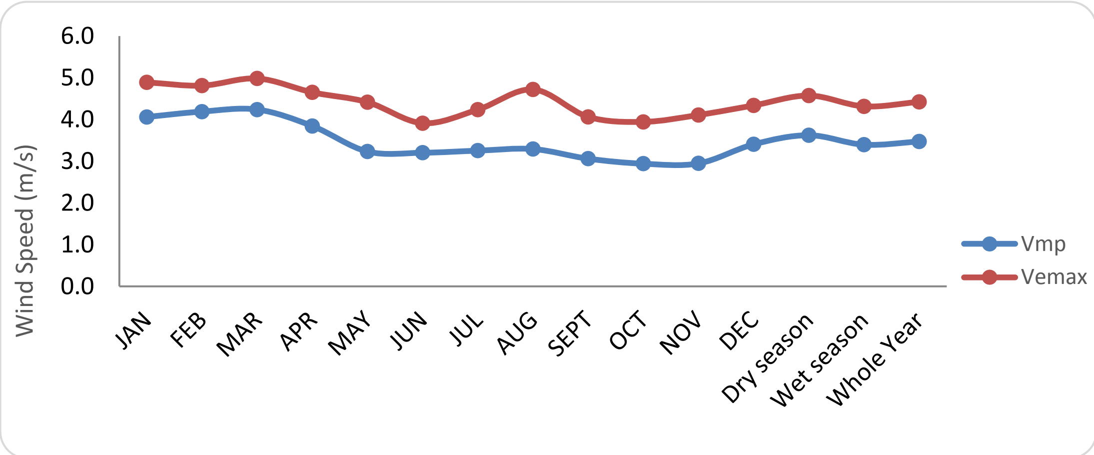

Figure 10: Plot showing the variation of the most probable wind speed (Vmp) and the wind speed carrying maximum energy (Vemax) for Abeokuta.

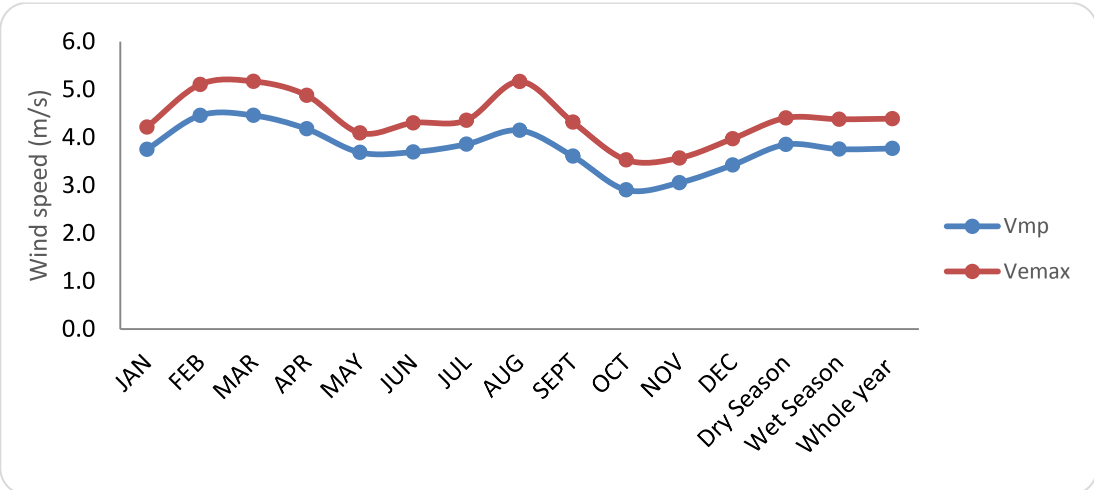

Figure 11: Plot showing the variation of the most probable wind speed (Vmp) and the wind speed carrying maximum energy (Vemax) for Ijebu-ode.

In this work, hilltops areas which abound in the two selected area were considered for potential wind-generated electricity. As such Vertical extrapolation was carried out on the wind speeds between 50 to 350 m AGL, in increments of 100m, in order to determine wind speeds at different heights above ground level using the expression of equation 13 together with equation 11 to compute extrapolated wind power densities [12]. The results obtained are presented using Figures 12 and 13 respectively for Abeokuta and Ijebu-Ode.

For Abeokuta site, at heights of 50 m and below, wind speed and power densities falls under class 1 of the wind classification scheme which is not suitable for generating electricity. At 150 m AGL, extrapolated wind speed and estimated power density in January, February and March fall under class 2, and other months fall under class 1. At 250m AGL, February and March fall into class 3, January falls under class 2, and class 1 in other months, while at 350m AGL January, February and March fall under class 3, April, august and December (slightly in case of December) fall under class 2 and other months under class 1. Considering the average wind power density for the whole year, heights at 50m, 150m and 250m AGL fall under class 1, however, at 350m height, average power density falls under the class 2 scheme.

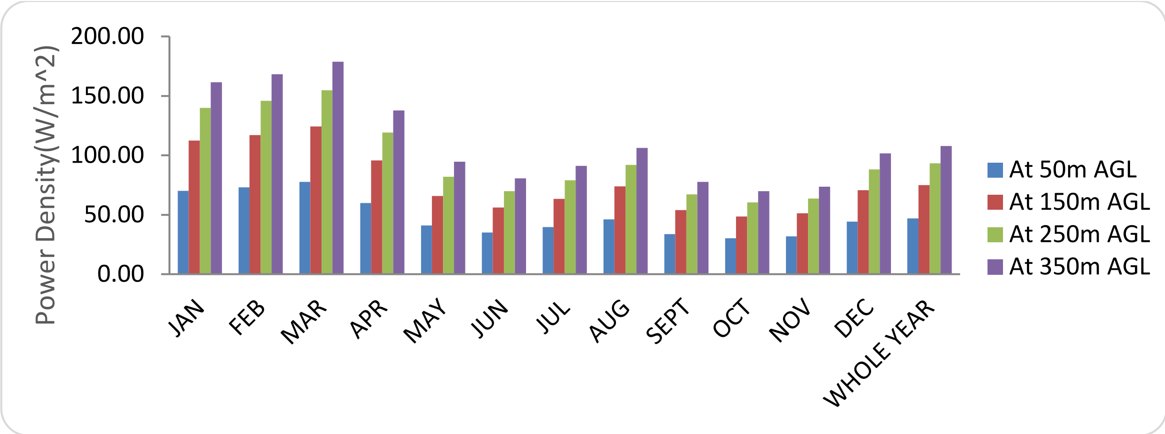

Figure 12: Monthly variation of power densities for the extrapolated mean wind speeds for Abeokuta

Similarly for Ijebu-ode site, at heights at 50 m and below, the wind speed and wind power densities can be classified into class 1 of the wind classification scheme which is not suitable for generating electricity., At 150 m AGL, extrapolated Wind speed and estimated power density in February, March and April fall under class 2, and other months fall under class 1. At 250m AGL, February, March and August fall under class 3; January, June, July & April, fall under class 2 and other months fall under class 1. At 350m AGL, February & March fall under class 4, April and August fall under class 3, January, May, June, July & September fall under class 2 and other months under class 1. Considering the average wind power density for the whole year, heights at 50m & 150m AGL fall under the class 1 and at 250m & 350m fall under class 2. Therefore, wind speed characteristics viable for power generation can be assessed on highlands and hilltops of height higher than 350m above ground level using taller wind turbines for both Abeokuta and Ijebu-ode sites.

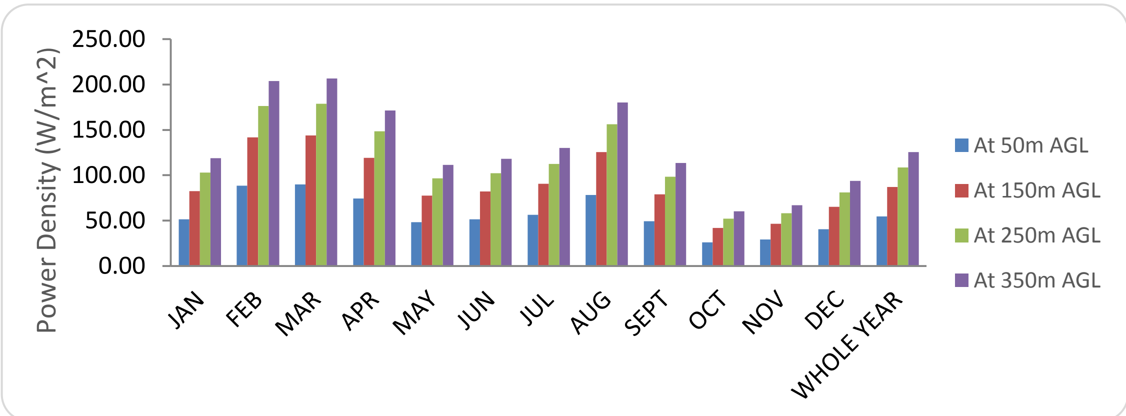

Figure 13: Plot showing the monthly variation of Power densities for the extrapolated means Wind speeds for Ijebu-Ode

Conclusion

The assessment of wind energy potential for power generation in two selected sites in Ogun State namely Abeokuta and Ijebu Ode, Nigeria was carried out and hereby reported. Fifteen (15) years of monthly mean wind data at 10-m height from the Nigeria Meteorological Department Oshodi, Nigeria was obtained and subjected to Weibull two-parameter to determine the potential of the sites' wind resources for power generation. The result of the analysis revealed that:

i. The values of k and c from the analysis across all the stations range between $2.00 \leq k \leq 12.75$ and $2.44 \leq c \leq 5.73$, respectively.
ii. That average monthly mean wind speed variation for Abeokuta range from 2.90 to 4.0 m/s, while for Ijebu-Ode, it range from 2.8 to 4.2 m/s. Seasonally, data variation between the dry and wet seasons revealed that, the mean wind speed variation for Abeokuta range from 3.5 m/s (for dry) to 3.3 m/s (for wet), while for Ijebu-Ode it range from 3.6 m/s (dry) to 3.5 m/s (wet).
iii. The wind power density and Energy density variation were found to range from 14.94 to 39.20 W/m^2 and 130.86 to 343.39 kWh/m^2 for Abeokuta and 13.00 to 44.61 W/m^2 and 113.87 to 390.78 kWh/m^2 for Ijebu-Ode respectively. It was further shown that the respective mean annual values of the most probable wind speed(Vmp) and wind speed carrying maximum energy (Vemax) are respectively 3.5 m/s and 4.4 m/s for Abeokuta and 3.8 m/s and 4.4 m/s for Ijebu-Ode.
iv. Abeokuta and Ijebu-Ode falls under class1 at 10m above ground level and as such not fit for wind power generation at that level.
v. The wind power densities viable for power generation can be assessed at heights higher than 350m above ground level for both Abeokuta and Ijebu-Ode.

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