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Wind Characteristics and Wind Energy Potential Assessment in Uyo, Nigeria

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Abstract: This study examines the wind power potential of Uyo, a capital city in the Niger Delta region of Nigeria. A 21 years data obtained from the Nigerian Meteorological agency (NIMET) were statistically analyzed using the Weibull and Rayleigh distribution functions. The result of the study showed that Uyo has a mean wind speed of 3.17 m sec^{-1} with a maximum value of 3.67 m sec^{-1} in April while the corresponding mean wind power density is approximately 19.91 W m^{-2} for the whole year, thereby making the selected site to fall under class 1 of the international system of wind classification. Further investigations, revealed a higher wind speed in the afternoon than morning period and the South-Westerly (SW) and Westerly (W) to be responsible for the high wind values recorded in the area. The Weibull model was also proved to represent the actual data better than Rayleigh.

Key words: Weibull distribution, Rayleigh distribution, wind power density, wind speed, wind potential, Uyo, Nigeria

INTRODUCTION

Nigeria is richly endowed with both fossil energy (conventional) and renewable energy resources. It is widely known that oil is the mainstay of Nigerian economy and the over dependence as a major energy source has put the nation in danger in view of the fast diminishing oil reserves, inadequate refining capacity and the general insecurity in Niger Delta (Ohunakin, 2010). However, the country's unstable policies have equally made oil susceptible to global energy dynamics. Due to the growing economic activities and alarming population, energy demand has been accelerating but has not been supported with equal investment in the provision of infrastructure to meet the mounting energy need (Ohunakin, 2010).

Global concerns such as environmental pollution and health hazards through anthropogenic emissions associated with the consumption of fossil fuels have been a major contributing factor toward the global transition to renewable energy. This has encouraged the role of renewable resources such as wind, solar and geothermal to be growing almost proportionally within other resources as their generating costs decrease (Gokcek *et al*., 2007).

According to Gokcek *et al.* (2007), renewable energy sources are inexhaustible, clean and free and offer many environmental and economical benefits in contrast to conventional energy sources (hard coal, lignite, oil and gas, etc.). In spite of the benefits of wind energy for economic, large scale electricity production in countries such as Germany, Spain, United State, India and Denmark, only a few number of stand-alone wind power plants installed in the early 1960s in some Northern states mainly to power water pumps (such as at Goronyo in Katsina state, Kedada in Bauchi states and Sayya Gidan-Gada village in Sokoto state) are still in existence (Ohunakin, 2010) though a proposed 10 MW capacity wind farm to be commissioned in 2011 is to be built in Katsina. Hence, contribution of wind energy to the total energy consumption in Nigeria has been very insignificant.

In recent times, numerous studies have been carried out to assess the wind speed characteristics and associated wind energy potentials in different parts of the world with similar studies carried out on the assessment of wind speed characteristics in some locations in Nigeria (Fadare, 2008).

However, there is no study in the literature about wind energy potential for Uyo, Nigeria. The main objectives of the present study are to model the wind speed variation using the Weibull distribution function and to predict the wind energy output of wind power systems for Uyo, Nigeria.

MATERIALS AND METHODS

Uyo (latitude 05.30'N, longitude 07.55'E) is the capital city of Akwa Ibom state located in Niger Delta region in the South-south geo-political zone of Nigeria. The area has an average elevation of 38 m and a topography that is mostly flat because the underlying geology of the state is predominantly coastal plain sediments.

The monthly wind speed data ranging from 1986-2007 period (21 years) was used in this study and was obtained from the Nigerian Meteorological agency (NIMET), Oshodi, Lagos, Nigeria. The wind speed data were recorded at a height of 10 m by a cup-generator anemometer at a weather station of NIMET in Uyo. The recorded wind speeds were computed as the average of the speed for each month.

Calculation of wind power density: The estimation of the wind power density is an important factor when assessing the wind potential of a location as it indicates how much energy per unit of time and swept area of the blades is available at the selected area for conversion to electricity by a wind turbine (Fyrippis *et al*., 2010). In the study of Akpinar and Akpinar (2004), Oriaku *et al.* (2007) and Jowder (2009), it is expressed as:

$$P(v) = \frac{1}{2}\rho A v_m^3 \quad (1)$$

While the power of the wind per unit area is:

$$P(v) = \frac{1}{2}\rho v_m^3 \quad (2)$$

The wind power density (wind power per unit area) based on the Weibull probability density function can be calculated as:

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

Where:

P(v) = Wind power (W)
p(v) = Wind power density (W m^{-2})
ρ = Air density at the site (1.21 kg m^{-3})
A = Sweep area of the rotor blades (m^2)

Weibull and Rayleigh distribution function: According to Gokcek *et al.* (2007), the Weibull distribution function which is a special case of generalized gamma distribution for wind speed is expressed as:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (4)$$

While the corresponding cumulative probability function is given by:

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^2 \uparrow k\right] \quad (5)$$

Rayleigh distribution function is similar to the Weibull distribution with the exception that the shape parameter (k) is given a constant value of 2. Its distribution is given by Akpinar and Akpinar (2004):

$$f(v) = \left(\frac{2}{c}\right)\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)\right]^2 \quad (6)$$

Where:

f(v) = Probability of observing wind speed (v)
k = Dimensionless Weibull shape parameter
c = Weibull scale parameter (m sec^{-1})
F(v) = Cumulative probability function of the observing wind speed (v)

Weibull shape and scale parameters (k and c) can be determined using several methods, some of which include; Weibull probability plotting paper, Standard deviation method, Moment method, Maximum likelihood method and Energy pattern factor method (Fyrippis *et al*., 2010). In this study, the Standard deviation method given by Jowder (2009) and Ogba and Utang (2009) is used:

$$k = \left(\frac{\delta}{v_m}\right)^{-1.086} \quad (1 \le k \le 10) \quad (7)$$

$$c = \frac{v_m}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (8)$$

Where:

δ = Standard deviation
v_m = Average wind speed (m sec^{-1})
Γ (x) = Gamma function of (x)

$$v_m = \frac{1}{n}\sum_{i=1}^{n} v_i \quad (9)$$

$$\delta^2 = \frac{1}{n-1}\sum_{i=1}^{n}(v_i - v_m)^2 \quad (10)$$

$$\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}dt \quad (11)$$

From Eq. 8, k and c are related by:

$$v_m = c\Gamma\left(1+\frac{1}{k}\right) \quad (12)$$

Prediction performance of the Weibull distribution model: The prediction accuracy of the model in the estimation of the wind speeds with respect to the actual values were evaluated based on the correlation coefficient (R^2), Chi-square (χ^2), Root Mean Square Error (RMSE) and Coefficient of Efficiency (COE). These parameters were calculated based on the following equations (Akpinar and Akpinar, 2004):

$$R^2 = \frac{\Sigma_{i=1}^{N}(y_i - [Z])^2 - \Sigma_{i=1}^{N}(x_i - [Z])^2}{\Sigma_{i=1}^{N}(y_i) - [Z]^2} \quad (13)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}[(y_i) - x_i)^2\right]^{\frac{1}{2}} \quad (14)$$

$$\chi^2 = \frac{\Sigma_{i=1}^{N}[(y_i) - x_i)^2}{N - n} \quad (15)$$

$$COE = \frac{\sum_{i=1}^{N}(y_i - x_i)^2}{\sum_{i=1}^{N}(y_i - Z)^2} \quad (16)$$

Where:

y_i = ith actual data
x_i = ith predicted data with the Weibull distribution
z = Mean of actual data
N = Number of observations
n = Number of constants

Hence, the best distribution function can be selected according to the highest value of R^2 and the lowest values of RMSE and χ^2 (Akpinar and Akpinar, 2004).

RESULTS AND DISCUSSION

The Weibull parameters in terms of c and k, mean power density, mean wind speed, wind energy and error analyses were estimated using the combination of Microsoft Excel and self developed Matlab programme with Mathwork-Matlab 7.6.0 (R2008a).

Mean wind speed: It can be observed from Fig. 1 that the windiest months were March to May with mean wind speed of 3.59, 3.67 and 3.49 m sec^{-1}, respectively while the calmest month was December with a mean wind speed of 2.56 m sec^{-1} for the study period ranging from 1986-2007. The average mean wind speed from calculation based on data in Table 1 is 3.17 m sec^{-1}. Hence, this speed will not be economically viable for wind power generation since, the minimum year round wind speed required is 5.36 m sec^{-1} (Asiegbu and Iwuoha, 2007). The trend of the graph (Fig. 1) reveals that high values were recorded from February to May and September followed afterwards by a decrease from June to August and a significant reduction taking place from October to January. The high values were due to the influence of South-Westerly (SW) and Westerly (W) prevailing winds between March and October while the low values were the result of the North-Easterly (NE), Easterly (E) and North-Westerly (NW) winds sweeping across the Niger Delta region during these periods each year.

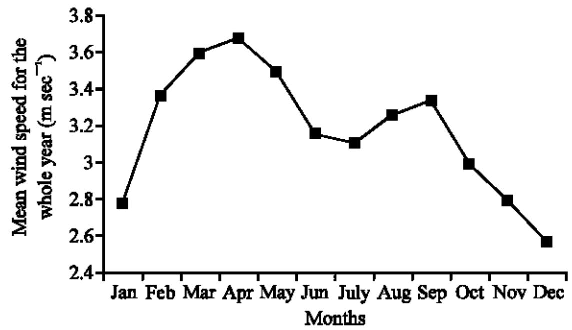

Fig. 1: Variation of mean wind speed for the whole year at 10 m height

Table 1: Whole year mean wind speed and power density based on actual and Weibull

Months	Mean wind speed (m sec^{-1})	Actual power density (W m^{-2})	Weibull power density (W m^{-2})
Jan	2.77	12.88	15.35
Feb	3.36	22.99	24.33
Mar	3.59	28.00	29.84
Apr	3.67	29.94	34.78
May	3.49	25.73	28.89
Jun	3.15	18.95	20.58
Jul	3.10	17.94	21.24
Aug	3.25	20.81	23.77
Sep	3.33	22.31	23.94
Oct	2.99	16.10	17.35
Nov	2.79	13.15	14.36
Dec	2.56	10.17	10.99
Average	3.170833333	19.91416667	22.11833333

Speed between 5.5 and 7.9 m sec^{-1} are rare in this region but occur occasionally during the onset of heavy rainfall or thundering activities (Ogba and Utang, 2009). At the same altitude, light air (0.3-1.5 m sec^{-1}) and light breeze (1.6-3.3 m sec^{-1}) are characteristics of NE, E and NW prevailing winds while gentle breeze (3.4-5.4 m sec^{-1}) is a representative of SW and W, prevailing winds.

The sudden rise noticed in September could be attributed to the thermal convection caused by the decrease in temperature during the rainy season thus, making the momentum of the higher altitude air (upper air)

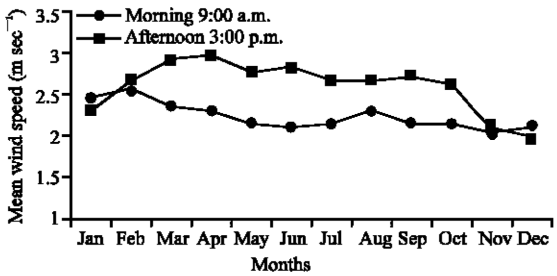

Fig. 2: Mean wind speed at 9:00 and 15:00 h of the day for the whole year from 1981-2007 at 10 m height

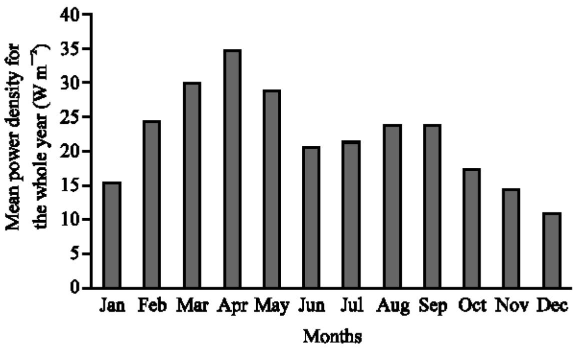

Fig. 3: Variation of mean power density for the whole year at 10 m height

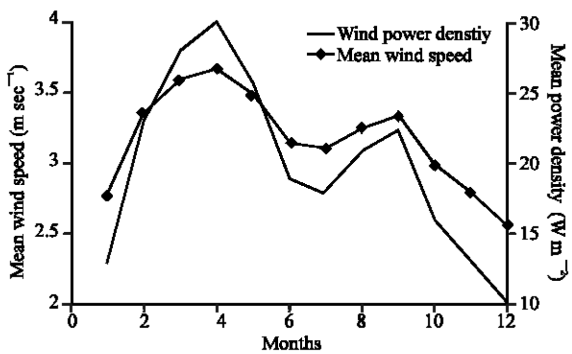

Fig. 4: Comparison of monthly mean wind speed and mean power density

to be transmitted to the lower and surface layers. Figure 2 further supports Fig. 1, going by the monthly trend of the graph, it can be seen from Fig. 2 that there is a general increase in wind speed in the afternoon (15:00 h) than morning (9:00 h), this could be the result of:

- High temperature stratification experienced in the afternoon and dry season (November to April)
- Vertical exchange in momentum more prominent in the afternoon mostly during the rainy season (May to October), Thereby causing an increase of wind speed as a result of thermal convection

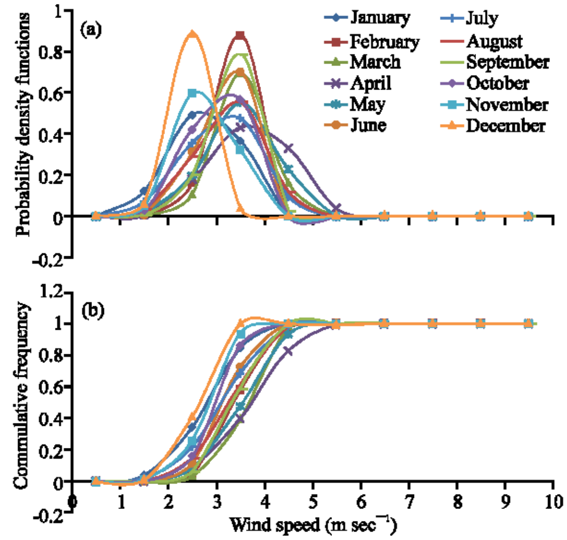

Fig. 5: Monthly wind speed; a) probability density; b) cumulative probability density distributions derived from the measured data fo Uyo for whole year at 10 m height

Wind power density analysis: The mean power density shown in Fig. 3 recorded a similar trend with the mean wind speed (Fig. 4) but each having different rates of change; careful study of Eq. 1 and 2, reveals that wind power density is proportional to the cube of wind speed hence, a small variation in wind speed will lead to a significant variation in wind power density.

The gradual increase in trend from January to April with a peak of 34.78 W m^{-2} in April could be linked to the general rise in solar radiation associated with dry season. The decreasing trend noticed from May to December is due to the drop in temperature during the rainy season. However, the sudden rise experienced in August and September within the rainy period could be attributed to thermal convection resulting from low temperature causing the upper air momentum to be transferred to lower layers. The lowest value ranged between 10.17 and 10.99 W m^{-2} in December and the average mean power density calculated for the whole year considered was approximately 19.91 and 22.12 W m^{-2} for the actual and Weibull power densities, respectively.

Probability density functions: Figure 5a, b shows the probability density and cumulative distributions respectively for each month, derived from the available time series data of Uyo for the whole year. It can be observed from the graphs that all the curves gave similar drift of the monthly wind speeds for the two distributions. Figure 6a, b shows the Weibull and Rayleigh approximations fitted to the actual probability density

Table 2: Comparison of actual probability distribution of wind speeds with Weibull and Rayleigh approximations for whole year

	f (v)				
Wind speed (m sec^{-1})	Actual data	Weibull data	Rayleigh data	COE W	COE R
1	0	8.61E-06	0.009935	0.000183	0.001061
2	0.095238095	0.015174	0.059398	0.011392	0.031195
3	0.666666667	0.052611	0.012064	0.224482	0.041103
4	0.19047619	0.08223	0.126353	0.12178	0.018891
5	0.047619048	0.004672	0.026879	4.65E-06	0.002397
6	0	1.00E-10	0.002603	0.00027	0.000259
7	0	1.55E-23	0.000312	0.00027	0.002442
8	0	1.13E-45	2.37E-05	0.00027	0.003872
9	0	5.73E-81	1.16E-06	0.00027	0.004359
10	0	4.50E-134	3.64E-08	0.00027	0.004476
Summation	-	0.154696	0.237568	0.359194	0.110054
RMSE	-	0.124377	0.154132	0.430676	2.158642
χ^2	-	0.019337	0.029696	-	-
R^2	-	0.841809002	0.556592166	-	-

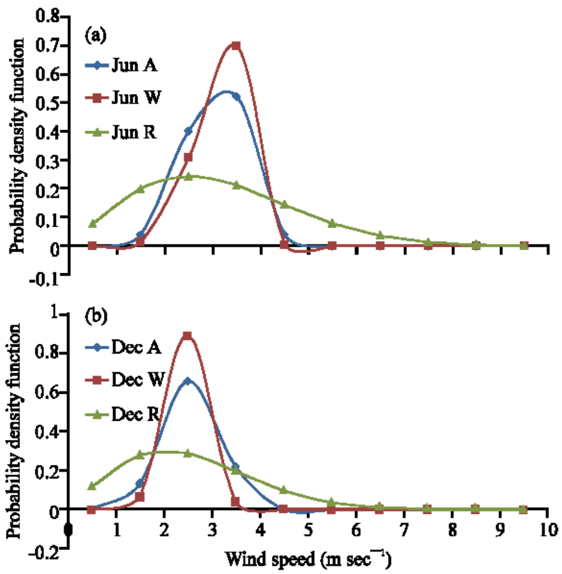

Fig. 6: Weibull and Rayleigh approximation of the actual probability distribution of wind speeds for; a) June (rainy season); b) December (dry season)

distribution of wind speeds for 2 selected months of June and December, existing under the SW and NE prevailing winds as a representative of the rainy and dry seasons respectively for the whole year.

The most frequent wind speeds for the months as observed from the two graphs is around 3.2 and 2.5 m sec^{-1}, respectively corresponding to the values that the peak of the distribution curves make with the horizontal axis thereby verifying the results of the analysis of mean wind speed earlier performed.

It can also be confirmed that the chances of obtaining wind speed >5.5 m sec^{-1} is rare in this region as previous discussed (Ogba and Utang, 2009). An error analysis was conducted using the Root Mean Square Error (RMSE) parameter, Chi-square (χ^2) test and correlation coefficient (R^2) in evaluating the performance of the two models adopted. A sample comparison of the two approximations (Weibull and Rayleigh) together with the actual probability distribution for the month of January of the whole year is shown in Table 2. The results show that values got for RMSE and Chai-square (χ^2) of the Weibull distribution are lower than that given by Rayleigh while the highest R^2 value was got through Weibull computation as compared to Rayleigh. The rest of the months showed similar pattern. In view of these reasons, Weibull approximations give the most accurate of the distributions.

CONCLUSION

The data made available for the research work spanned a length of 21 years, making an appreciably conclusive results to be safely drawn. However, the data gathered was collated on a monthly basis, thereby making diurnal wind pattern difficult; this calls for further studies because the non-analysis of the diurnal wind patterns could lead to significant under or overestimation of the wind energy potential of the location under study. Conversely, the following conclusion were drawn from the results of the assessment of wind characteristics and wind power potential in Uyo at 10 m height using Weibull and Rayleigh distributions.

The average mean wind speed for Uyo was calculated as 3.17 m sec^{-1} and the maximum value computed as 3.67 m sec^{-1} in the month of April for the whole year during the period under study. The prevailing winds in the area under study were predominantly South-Westerly, Westerly, North-Easterly, Easterly and North-Westerly. The high values of wind speeds were due to the South-Westerly and Westerly prevailing winds while the low values were the consequences of the Easterly, North-Easterly and North-Westerly winds blowing across the Niger Delta region. Weibull distribution function calculated for the location was found to represent the actual data better than Rayleigh distribution according to the judgement based on Chai-square (χ^2), RMSE and R^2. The average power densities calculated were 19.91 and 22.12 W m^{-2}, respectively for the actual data and Weibull distribution for the whole year with the highest under the actual data being 29.94 while the lowest is 10.17 W m^{-2} in the months of April and December, respectively. The study site fall under class 1 of the international system of wind classification and as such may only be adequate for non-connected electrical and mechanical applications like battery charging and water pumping.

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