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Evaluation of Wind Energy Potential for Electricity Generation at Three Selected Locations In Nigeria

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Abstract

This study investigates the wind speed characteristics and wind potential of three selected cities in Nigeria using daily wind speed data for 3 years obtained from Nigerian Meteorological Agency (NIMET). The results obtained show that the annual mean wind speeds at a height of 10m for Jos, Asaba, and Warri are 13.68m/s, 3.65m/s and 3.18m/s respectively. The annual mean power densities based on Weibull distribution function are 341.90W/m², 51.82W/m², and 50.91 W/m² respectively. Thus, the mean annual values of the most probable wind speed are 12.49m/s, 3.16m/s, and 1.82m/s for Jos, Asaba and Warri respectively while the annual wind speeds carrying maximum energy are respectively 19.63m/s, 5.48m/s, and 6.02m/s.

Keywords: Wind energy potential, Evaluation, Electricity, Weibull distribution

Nomenclature

A Swept area of the rotor blades (m^2)
c Scale factor (m/s)
c_o Scale factor at the measurement height h_o (m/s)
$c(h)$ Scale factor at the turbine hub height h (m/s)
E_D Mean energy density(kWh/m^2)
$f(v)$ Probability density function
$F(v)$ Cumulative distribution function
k Shape factor
k_0 Shape factor at the measurement height h_o.
$k(h)$ Shape factor at the turbine hub height h
P_D Wind power density(W/m^2)
P_V Wind power (W)
V Wind speed at the turbine hub height h (m/s)
v_E Wind speed carrying maximum energy(m/s)
v_m Mean wind speed(m/s)
v_o Wind speed at the measurement height h_o (m/s)
v_p Most probable wind speed (m/s)
σ Standard deviation
α,β Surface roughness coefficient
ρ Air density (kg/m^3)
Γ( ) Gamma function of ( )

1.0 Introduction

In recent years, the world has been inundated with the quest to reduce effect of environmental degradation caused by conventional energy resources and more importantly, the dire need to meet the growing energy demand of the global

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population. These have motivated a genuine research attention in the use of renewable energy resources which are friendlier to the environment than the conventional energy resources.

Wind energy, as a renewable energy resource is free, and clean, inexhaustible, stands out as most valuable and promising choice. Due to its many advantages, wind energy has also become the fastest growing renewable resource of energy in both developed and developing countries. For example, wind energy is widely used to produce electricity in countries like China, USA, Germany, Spain, India UK, Italy and France. Interestingly, the global cumulative installed capacity of wind power had increased sharply from 6,100 MW in 1996 to about 282,587 MW in 2012 [1]. The increasing energy demand, the rapidly depleting fossil fuel reserves and the environmental problems associated with the use of fossil fuel have necessitated the development of alternative energy resources like wind energy for electricity generation in Nigeria.

Prior studies, however, have shown that the effective utilization of wind energy at a typical location requires sound knowledge of the wind characteristics and accurate wind data analysis. For example, the choice of wind turbine design must be based on the average wind velocity at a selected wind turbine installation site [2]. Prior studies have also shown that the wind flow patterns are influenced by terrains, vegetation and water bodies. The focus of this study is, therefore, to evaluate the wind energy potential in three selected locations in Nigeria. It is hopeful that this information will be helpful to the government and any organization in making an informed decision with regard to investment in wind energy resource in these parts of Nigeria.

2.0 Methodology

The data employed for the study were daily wind speed obtained from the Nigerian Metrological Agency, Oshodi, Lagos State, Nigeria covering the period from 2008 to 2010. Data were recorded employing the continuous use of cup-generator anemometers at a height of 10m.

2.1 Frequency Distribution and Site Wind Speed Parameters

There are several continuous mathematical functions called probability density functions that can be used to describe and analyse wind resource data. In wind power studies, according to Chang et al.,[3], the Weibull and Rayleigh probability density functions are commonly used and widely adopted. This study therefore employs the 2-parameter Weibull distribution, since the Rayleigh distribution is only a sub-set of it. In addition, the Weibull parameters at a known height can be used to estimate wind parameters at another height [4].

In Weibull distribution, the variation in wind velocity is characterized by 2-parameter function, the probability density function and the cumulative distribution function. The probability density function *f*(v) indicates the probability of the wind at a given velocity v, while the cumulative distribution function *F*(v) of the velocity v gives the probability that the wind velocity is equal to or lower than v, or within a given wind speed range. The Weibull probability density function *f*(v) and the cumulative distribution function*F*(v) are given by equations (1)&(2) as used in [5].

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

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

Where c is the scale parameter andk is the shape parameter, kis a parameter that indicates the variability or stability of the wind. There are several methods of determining Weibull k and c parameters. In this study, the two parameters k and c are obtained using the mean wind speed standard deviation method [6].

$$k=\left(\frac{\sigma}{v_m}\right)^{-1.086} \quad (1\leq k\leq 10) \quad (3)$$

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

Where

v_m =mean wind speed

σ=Standard deviation,

v_m and σ can be calculated using equations (5) and (6) as stated in [7].

$$v_m = \frac{1}{n}\sum_{i=1}^{n} v_i \quad (5)$$

$$\sigma = \left[\frac{1}{n}\sum_{i=1}^{n}(v_i - v_m)^2\right]^{0.5} \quad (6)$$

In addition to the mean wind speed, there are two other wind speeds that are very useful to wind energy investors and assessors. These are the most probable wind speed $v_P$and wind speed carrying maximum energy v_E . v_E and $v_p$can be calculated using equations (7) and (8) as expressed in [8].

$$v_P = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \quad (7)$$

$$v_E = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \quad (8)$$

The most probable wind speed corresponds to the peak of the probability density function while the wind speed carrying the maximum energy can be used to estimate the wind turbine design or rated wind speed. Prior studies have shown that turbine system operate most efficiently at its rated wind speed. Therefore, it is desirable that the rated wind speed and the wind speed carrying maximum energy should be as close as possible [9].

2.2 Variation of Wind Speed with Height

The available wind data are measured at a height different from the wind turbine hub height in most cases. It should be noted that it is the wind speed at the turbine hub height that is of interest in wind power application. Therefore, the available wind speeds are extrapolated to the wind turbine hub height using by using equation (9) [5].

$$\frac{v}{v_o} = \left(\frac{h}{h_o}\right)^{\alpha} \quad (9)$$

Where v = wind speed at the hub height, h

v_o= wind speed at the measurement height, h_o

α = surface roughness coefficient

The surface roughness coefficient can be determined using equation (10) as stated in [10].

$$\alpha = \frac{(0.37 - 0.088\ln v_o)}{(1 - 0.088\ln\frac{h_o}{10})} \quad (10)$$

Since the boundary layer development and the effect of the ground are non-linear with respect to wind speed, the Weibull scale factor c(h) and the shape factor k(h) will vary as a function of height as represented by equations (11) and (12)as stated in [11].

$$c(h) = c_o\left(\frac{h}{h_o}\right)^{\beta} \quad (11)$$

$$k(h) = \frac{k_o\left[1 - 0.088\ln\left(\frac{h_o}{10}\right)\right]}{\left[1 - 0.088\ln\left(\frac{h}{10}\right)\right]} \quad (12)$$

Where $c_o$and $k_o$are the scale factor and shape factor respectively, at the measurement height h_oβ is the surface roughness coefficientand it can be determined by using equation (13) as stated in [10].

$$\beta = \frac{[0.37 - 0.088\ln c_o]}{\left[1 - 0.088\ln\left(\frac{h}{10}\right)\right]} \quad (13)$$

2.3 Estimation of Mean Wind Power Density and Energy Density

The mean wind power density which is defined as the wind power per unit area can be estimated by using equation (14).

$$P_D = \frac{P_v}{A} = \frac{\frac{1}{2}\rho A v_m^3}{A} = \frac{1}{2}\rho v_m^3 \qquad (14)$$

The mean wind speed and power density are generally used to classify the wind energy resource.

However, the wind power density (wind power per unit area) based on the Weibull probability density function can be calculated using equations (15) as stated in[12].

$$P_D = \frac{P_v}{A} = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \qquad (15)$$

The mean energy density E_D over a period of time T, is the product of the mean power density and the time T, and is given as:

$$E_D = \frac{1}{2}\rho c^3 T \Gamma\left(1 + \frac{3}{k}\right) \qquad (16)$$

3.0 Results and Discussion

3.1 Wind Speed Frequency Distribution

The annual probability density frequency and cumulative distribution of wind speed for the three locations obtained using the Weibull distribution function are shown in Figures 1 and 2. As expected, the peak of the density function of all the sites skewed towards the higher values of the mean wind speed (Figure 1). It should be remarked that the peak of the probability density function curve indicates the most frequent velocity. It can be observed from Figure 1 that the most frequent wind speeds expected in Jos, Asaba and Warri are about 12.5m/s, 4m/s and 2m/s respectively.

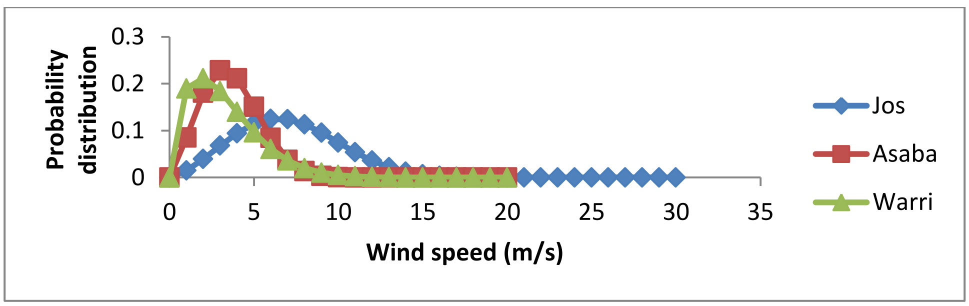

Figure 1: Annual probability distribution function

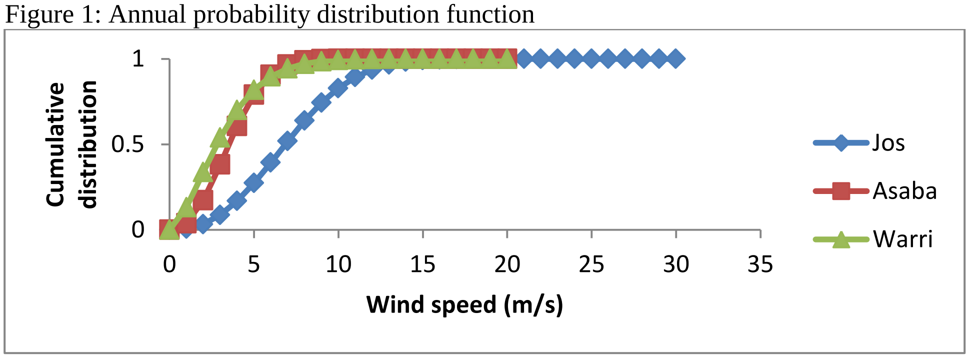

Figure 2: Annual cumulative density function

The cumulative probability distributions of the wind speed at all the study locations in Figure 2 shows a similar trend. For wind speeds greater than or equal to 2.5m/s cut-in windspeed (the minimum speed at which a turbine will generate usable power) for Jos, Asaba and Warri have frequencies of about 98.9%, 72.8%, and 55.8% respectively while the same locations respectively have frequencies of about 98.2%, 61.8% and 46.1% of 3m/s cut-in wind speed (the speed at which the turbine will shut down). According to Ojosu and Salawu [13] a wind turbine system with a design cut – in wind speed of 2.2 m/s can be used in the country for electricity generation. At this speed the three sites have frequencies of more than 90% as shown in Figure 2, which implies wind turbines that can be installed to generate electricity in the various locations.

3.2 Mean Wind Speed and Mean Power Density

The monthly variation of the mean wind speed characteristics (v_m, v_p, and v_E), mean power density (P_D), mean energy density, as well as annual values of these parameters at a height of 10m are presented in Tables 1, 2 and 3. The monthly mean wind speed varies between 9.93m/s in September and 17.99m/s in November for Jos site (Table 1). The monthly mean power density varies between 1261.12W/m^2 and 5383.76W/m^2. The annual mean power density for this location is 2498.99W/m^2.

For Asaba (Table 2), the monthly mean wind speed varies between 3.28m/s in May and 4.30m/s in February. The annual mean wind speed for this site is 3.65m/s and the annual mean power density is 51.82W/m^2 while for Warri site (Table 3), the minimum and maximum mean wind speeds are 2.02m/s and 3.91m/s in January and April respectively. The monthly mean power density varies between 15.61W/m^2 in January and 92.82W/m^2 in July.

Table 1: Characteristic speeds and mean power density in Jos at a height of 10m

	v_M (m/s)	k	c (m/s)	v_P (m/s)	v_E (m/s)	P_D (W/m^2)	E_D(kWh/m^2)
JAN	13.97	2.09	15.77	11.55	21.75	3057.8	2201.61
FEB	17.82	2.98	19.96	17.41	23.7	4881.14	3514.42
MAR	17.67	2.82	19.84	16.99	23.99	4918.42	3541.26
APR	14.28	3.04	15.98	14.02	18.87	2486.68	1790.41
MAY	11.9	2.66	13.39	11.22	16.52	1558.51	1122.13
JUN	10.2	1.94	11.5	7.93	16.55	1277.75	919.98
JUL	11.53	2.39	13.01	10.38	16.76	1529.64	1101.34
AUG	11.02	2.13	12.44	9.23	16.99	1475.82	1062.59
SEP	9.93	1.83	11.17	7.24	16.75	1261.12	908.01
OCT	11	1.79	12.36	7.81	18.83	1760.55	1267.6
NOV	17.99	2.66	20.24	16.96	24.98	5383.76	3876.3
DEC	16.87	3.33	18.8	16.89	21.65	3913.53	2817.74
ANN	**13.68**	**2.47**	**15.42**	**12.49**	**19.63**	**2498.99**	**24123.39**

Table 2: Characteristic speeds and mean power density in Asaba at a height of 10m

	v_M(m/s)	K	c (m/s)	v_P (m/s)	v_E (m/s)	P_D (W/m^2)	E_D (KWh/m^2)
JAN	3.75	2.92	4.20	3.64	5.03	46.10	33.19
FEB	4.30	2.69	4.84	4.07	5.95	73.07	52.61
MAR	3.86	2.53	4.35	3.57	5.47	55.04	39.63
APR	3.72	2.11	4.20	3.10	5.76	57.18	41.17
MAY	3.28	1.84	3.69	2.41	5.51	45.07	32.45
JUN	3.82	2.11	4.31	3.18	5.91	61.91	44.57
JUL	3.37	2.62	3.79	3.16	4.71	35.81	25.79
AUG	3.87	2.68	4.35	3.66	5.36	53.34	38.41
SEP	3.34	2.19	3.77	2.86	5.07	39.96	28.77
OCT	3.50	1.84	3.94	2.57	5.88	54.92	39.54
NOV	3.51	1.91	3.96	2.69	5.75	52.91	38.10
DEC	3.52	2.20	3.97	3.02	5.33	46.59	33.54
ANN	**3.65**	**2.30**	**4.12**	**3.16**	**5.48**	**51.82**	**447.77**

The annual most probable wind speed v_P for Jos, Asaba and Warri are 12.49m/s, 3.16m/s and 1.82m/s respectively while the annual wind speed carrying the maximum energy V_E are 19.63m/s, 5.48m/s and 6.02m/s respectively. The annual shape parameter for Jos, Asaba and Warri are 2.47, 2.30 and 1.55 respectively while the annual scale factor for Jos, Asaba and Warri are 15.42m/s, 4.12m/s and 3.54m/s respectively.

Table 3: Characteristic speeds and mean power density in Warri at a height of 10m

	v_M(m/s)	k	c(m/s)	v_P (m/s)	v_E (m/s)	P_D (W/m^2)	E_D (kWh/m^2)
JAN	2.02	1.38	2.21	0.87	4.23	15.61	11.24
FEB	3.03	1.40	3.32	1.34	6.29	51.85	37.33
MAR	3.29	1.55	3.66	1.87	6.25	56.64	40.78
APR	3.91	1.86	4.40	2.91	6.52	75.56	54.40
MAY	3.48	1.48	3.85	1.79	6.87	71.82	51.71
JUN	3.26	1.40	3.58	1.46	6.74	64.14	46.18
JUL	3.75	1.45	4.13	1.83	7.54	92.82	66.83
AUG	3.09	1.40	3.39	1.38	6.40	54.82	39.47
SEP	3.31	2.04	3.74	2.68	5.23	41.68	30.01
OCT	3.39	1.65	3.79	2.15	6.14	56.90	40.97
NOV	3.13	1.88	3.53	2.36	5.18	38.26	27.55
DEC	2.55	1.40	2.80	1.14	5.27	30.71	22.11
ANNUAL	**3.18**	**1.55**	**3.54**	**1.82**	**6.02**	**50.91**	**468.58**

The annual mean energy densities are 24123.39kWh/m^2, 447.77kWh/m^2 and 468.58kWh/m^2 for Jos, Asaba and Warri respectively. As earlier mentioned, the efficiency of a wind turbine is closely related to these parameters especially the wind speed carrying maximum energy v_E , which should be as close as possible to the design or rated wind speed of the wind turbine system.

4.0 Conclusion

In this study, investigation of the wind speed and wind power potential in three selected locations in Nigeria was carried out using the Weibull distribution function. The findings from this study can be summarized as follows:

The annual mean wind speeds for Jos, Asaba and Warri are 13.68m/s, 3.65m/s and 3.18m/s respectively. The annual values of the wind speed carrying maximum energy for these locations are respectively 19.63m/s, 5.48m/s and 6.02m/s while the most probable wind speeds are 12.49m/s, 3.16m/s and 1.82m/s respectively.

The mean annual values of the Weibull scale parameter, c is between 3.54m/s and 15.42m/s while the annual values of the shape parameter, k is between 1.55 and 2.47.

The annual mean power density for Jos, Asaba and Warri are 2498.99W/m^2, 51.82W/m^2 and 50.91W/m^2 respectively while the annual mean energy density are 24123.39kWh/m^2, 447.77kWh/m^2 and 468.58kWh/m^2 for Jos, Asaba and Warri respectively. Therefore, the proposed wind turbine, if installed in Jos would produce more power than in the other two locations.

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