A Statistical Analysis of Wind Energy Potential in Ibadan, Nigeria, Based on Weibull Distribution Function.

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ABSTRACT

Modeling of wind speed variation is an essential requirement in the estimation of the wind energy potential for a typical site. In this paper, the wind energy potential in Ibadan (Lat. 7.43^{0}N; Long. 3.9^{0}E; Alt. 227.2m) is statistically analyzed using daily wind speed data for 10 years (1995-2004) obtained from the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. The daily, monthly, seasonal, and yearly wind speed probability density distributions are modeled using Weibull Distribution Function. The measured annual mean wind speed in Ibadan is 2.75 ms^{-1}, while mean wind speed and the power density predicted by the Weibull probability density function are 2.947 m/s and 15.484 Wm^{-2}, respectively. Ibadan can be classified as a low wind energy region. The coefficient of determination (R^2) between the actual wind speeds and the Weibull predicted values ranged between 0.475 - 0.792. The Weibull distribution function can be used with acceptable accuracy for prediction of wind energy output required for preliminary design and assessment of wind power plants.

(Keywords: Ibadan, wind speed, renewable energy, Weibull distribution function, statistical modeling)

INTRODUCTION

Nigeria is richly endowed with both fossil energy resources such as crude oil, natural gas, coal, and renewable energy resources like solar, wind, biomass, biogas, etc. For many decades, fossil fuels and firewood (conventional energy resources) have continually remained the major energy sources which account over 90% of the national energy consumption (Akinbami et al., 2001). However, in recent times, there has been a continual decline in supply of conventional energy due to the depletion of the national reserve while the demand has continued to increase resulting in energy crisis with incessant power outages. The environmental pollution and health hazards associated with the use of fossil fuels are another driving force towards the global switch to renewable energy.

Presently in Nigeria, the Government is committed to the task of finding a long-term solution to the energy crisis through the adoption of the Renewable Energy Master Plan (REMP) with a target of increasing the present 5,000 MW generation capacity to 16,000 MW by the year 2015 through the exploration of renewable energy resources (Iloeje, 2002). In order to realize this goal, the exploration of wind energy resource is one of the key elements of this master plan. Wind energy is among the potential alternatives as renewable clean energy. At present, the share of wind energy in the national energy consumption has remained on the lower end with no commercial wind power plants connected to the national grid, while natural gas, hydroelectricity, fuelwood, and petroleum products constitute 5.22, 3.05, 50.45 and 41.28% share, respectively (Akinbami, 2001). Only a few number of stand-alone wind power plants have been 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 (Energy Commission of Nigeria, 1997).

Generally, the wind energy is characterized by a high variability both in space and time. It is therefore very important to describe the variation in wind speeds for optimizing the design of the systems in order to reduce energy-generating costs (Akpinar and Akpinar, 2004). 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 (Shabbaneh and Hasan, 1997; Mayhoub and Azzam, 1997; Riahy and Abedi, 2008; Cellura et al., 2008; Seguro and Lambert, 2000; Lun and Lam, 2000; Bivona et al., 2003; Jangamshetti and Rau, 2001; Akpinar and Akpinar, 2004).

Similarly, a number of studies have been carried out on the assessment wind speed characteristics in some locations in Nigeria (Ojosu and Salawu, 1990a and 1990b; Adekoya and Adewale, 1992; Anyanwu and Iwuagwu, 1995; Agbaka, 1987; Igbokwe and Omekara, 2002; Medugu and Malgwi, 2005; Ngala et.al, 2007; Oriaku et al., 2007). In these studies, the wind speed variability has been modeled using different analytical tools such as: statistical models including Weibull and Rayleigh distribution functions; stochastic simulation; seasonal autoregressive integrated moving average model; linear and multiple regression models; and artificial neural network models.

In statistical modeling of the wind speed variation, much consideration has been given to the Weibull two-parameter (shape parameter *k* and scale parameter *c*) function because it has been found to fit a wide collection of wind data (Akpinar and Akpinar, 2004). However, there is no study in the literature about the wind energy potential for Ibadan, 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 Ibadan, Nigeria.

MATERIALS AND METHODS

Wind Speed Data

The daily wind speed data used in this study was obtained from the meteorological station of International Institute of Tropical Agriculture (IITA), Ibadan (Latitude 7.43^{0}N; Longitude 3.9^{0}E; Altitude 227.2m), Nigeria, for the period of 1995 to 2004 (10 years). The wind speed data was measured continuously with a cup-generator anemometer at a hub height of 10m. The daily mean speeds were computed as the average of the speeds for each day.

Computation of Weibull Parameters of the Wind Speed

In statistical modeling of wind speed variation, the Weibull two-parameter (shape parameter *k* and scale parameter *c*) function has been widely applied by many researchers. The probability density function of the Weibull distribution is given as (Akpinar and Akpinar, 2004):

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

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, which have reference values in the units of wind speed.

The corresponding cumulative probability function of the Weibull distribution is given as (Seguro and Lambert, 2000; Akpinar and Akpinar, 2004):

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

where *F*(*v*) is the cumulative probability function of observing wind speed *v*.

The evaluation of the shape (k) and scale (c) parameters in the Weibull distribution function requires a good fit of Equation (2) to the recorded discrete cumulative frequency distribution. Equation (2) can be linearized by taking double natural logarithm of both sides of the equation, which gives:

$$\ln\{-\ln[1 - F(v)]\} = k\ln(v) - k\ln c \qquad \textbf{(3)}$$

Therefore, a plot of $\ln\{-\ln[1 - F(v)]\}$ versus $\ln(v)$ gives a straight line. The gradient of the line is *k* and the intercept with the y axis is $-k\ln c$. Generally, the k values range from 1.5 - 3.0 for most wind conditions (Akpinar and Akpinar, 2004). The mean value of the wind speed v_m can be defined in terms of the Weibull parameters *k* and *c* as:

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

where v_m is the mean value of the wind speed and $\Gamma(\ )$ is the gamma function of $(\ )$.

Estimation of Wind Power Density

The available power in the wind flowing at mean speed v_m through a wind rotor blade with sweep area A at any given site can be estimated as (Akpinar and Akpinar, 2004; Oriaku et.al., 2007):

$$P(v) = \frac{1}{2}\rho A {v_m}^3 \quad \textbf{(5)}$$

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

$$p(v) = \frac{P(v)}{A} = \frac{1}{2}\rho c^3\left(1+\frac{3}{k}\right) \quad \textbf{(6)}$$

where $P(v)$ is the wind power (W), $p(v)$ is the wind power density (W/m^2), ρ is the air density at the site = 1.21(kg/m^3), A is the swept area of the rotor blades (m^2), v_m is the wind speed at that location (m/s).

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, root mean square error (RMSE), and coefficient of efficiency (COE). These parameters were calculated based on the following equations:

$$R^2 = \frac{\sum_{i=1}^{N}(y_i - z)^2 - \sum_{i=1}^{N}(x_i - z)^2}{\sum_{i=1}^{N}(y_i - z)^2} \quad \textbf{(7)}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2\right]^{1/2} \quad \textbf{(8)}$$

$$COE = \frac{\sum_{i=1}^{N}(y_i - x_i)^2}{\sum_{i=1}^{N}(y_i - z)^2} \quad \textbf{(9)}$$

y_i is the i^{th} actual data, x_i is the i^{th} predicted data with the Weibull distribution, z is the mean of actual data, N is the number of observations.

RESULTS AND DISCUSSION

In this study, wind speed data for Ibadan, Nigeria, over a 10 year period from 1995 to 2004 measured by the International Institute of Tropical Agriculture (IITA) were analysed. The analyses were done using Microsoft Excel® and self developed Matlab® program. The Weibull distribution parameters in terms of k and c, mean power density and mean wind speed were determined for the weekly, monthly, seasonal and yearly variations.

Figure 1 shows the daily mean wind speed variation in Ibadan over the period of 10 years from 1995 – 2004, while the monthly mean wind speed values and standard deviations are presented in Table 1. It can be seen in Table 1 that the highest monthly wind speeds occur in the months of February (3.288 m/s), March (3.841 m/s), April (3.438 m/s) and May (3.174 m/s) for the whole year, while the minimum monthly wind speeds occur in the months of October (2.034 m/s) and November (2.029 m/s).

The yearly variation of the wind speed is presented in Table 1 and Figure 2. It can be seen that the highest wind speed of 4.363 m/s occurs in the year 1996, while the minimum wind speed of 1.429 m/s occurs in the year 2002. The overall yearly mean wind speed in Ibadan is found to be 2.748 m/s (Table 1). The wind speed data were arranged in the frequency distribution format. A typical example for the month of February for the whole year is illustrated in Table 2. The wind speed is grouped into ten classes (bins), as given in the first column of Table 2.

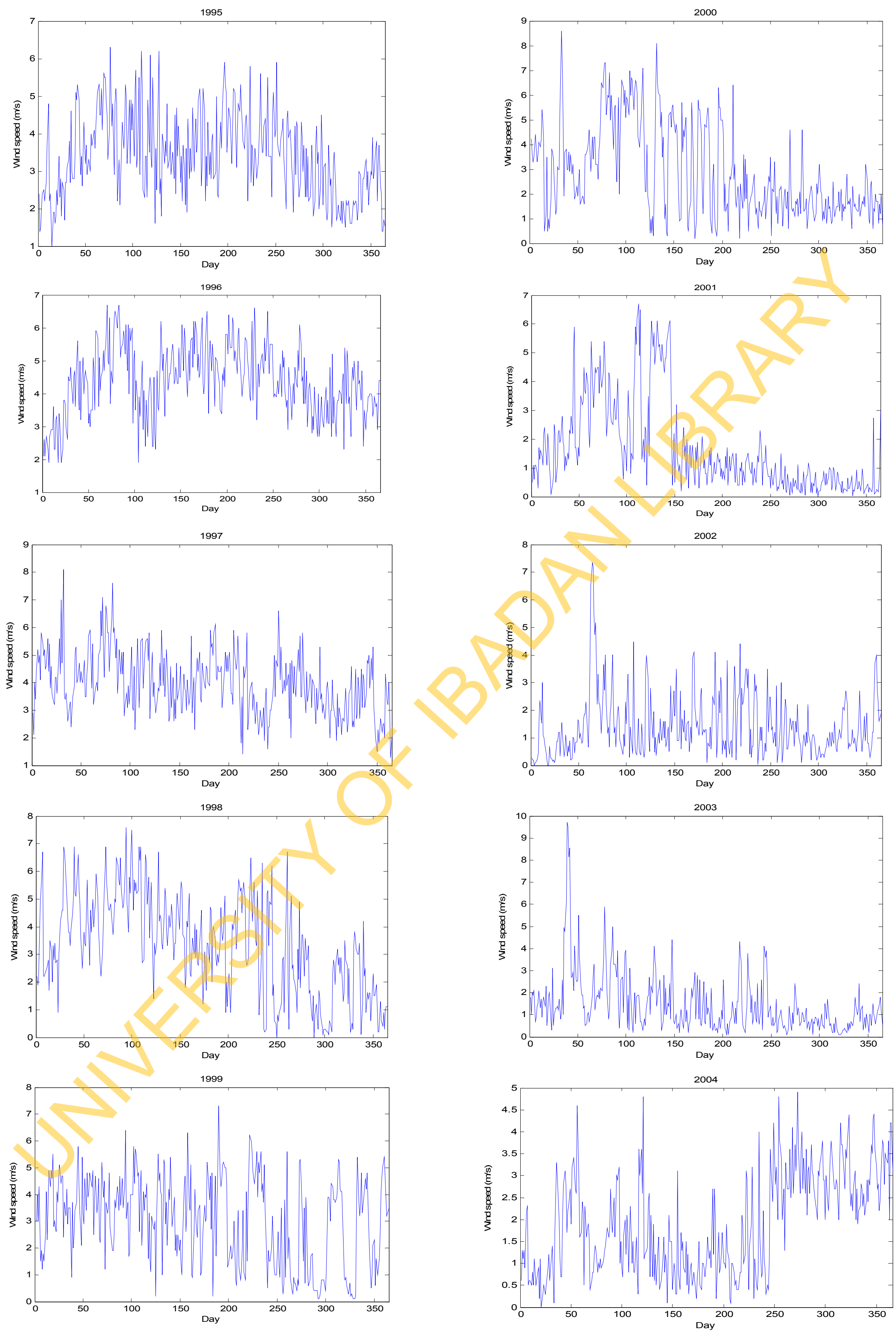

Figure 1: Daily Mean Actual Wind Speed Variation in Ibadan Between 1995 and 2004.

Table 1: Monthly Mean Actual Wind Speeds and Standard Deviations in Ibadan from 1995 to 2004.

Month	Parameters	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Whole year
January	v_m	2.352	2.977	4.474	3.474	3.471	3.058	1.345	0.652	1.426	0.816	2.405
	δ	0.739	0.818	0.985	1.606	1.203	1.358	0.698	0.719	0.611	0.504	1.564
February	v_m	3.643	4.321	4.132	4.400	3.696	3.203	2.614	1.011	3.522	2.338	3.288
	δ	0.766	0.845	1.164	1.106	1.069	1.611	1.304	0.540	2.698	0.998	1.649
March	v_m	4.332	5.397	5.174	4.807	3.552	4.810	3.629	2.891	2.419	1.403	3.841
	δ	1.012	0.861	1.143	1.123	1.034	1.412	0.972	1.881	1.290	0.579	1.698
April	v_m	4.113	4.023	4.227	5.390	3.743	5.340	2.837	1.261	1.537	1.910	3.438
	δ	1.140	1.129	1.049	1.219	1.348	1.427	1.803	1.043	1.123	1.068	1.880
May	v_m	3.484	4.561	3.871	4.103	3.226	3.655	4.219	1.496	1.943	1.184	3.174
	δ	0.982	0.866	0.810	1.008	1.338	2.275	1.792	0.885	1.055	0.613	1.685
June	v_m	3.530	5.133	3.977	3.250	3.193	3.127	1.300	1.657	1.223	0.893	2.728
	δ	0.936	0.774	0.825	1.026	1.391	1.849	0.678	0.934	0.817	0.578	1.676
July	v_m	4.036	5.023	4.523	3.365	3.042	3.107	1.026	1.474	0.826	1.145	2.757
	δ	0.930	0.779	0.929	1.297	1.793	1.912	0.377	1.149	0.614	0.629	1.850
August	v_m	3.894	4.910	3.087	3.803	3.613	1.781	1.007	1.853	1.645	1.297	2.689
	δ	0.886	0.828	0.942	1.780	1.738	0.752	0.468	1.266	1.190	0.974	1.702
September	v_m	3.723	4.370	4.267	2.303	1.667	1.883	0.645	1.353	0.963	3.130	2.431
	δ	0.879	0.669	0.930	1.771	1.394	0.897	0.429	0.891	0.921	0.878	1.643
October	v_m	2.961	3.884	3.555	1.513	1.555	1.810	0.453	0.868	0.810	2.936	2.034
	δ	0.785	0.882	0.768	1.354	1.549	0.817	0.303	0.536	0.433	0.544	1.445
November	v_m	2.137	3.830	3.097	2.133	2.463	1.517	0.519	1.133	0.513	2.950	2.029
	δ	0.556	0.798	0.766	1.113	1.916	0.515	0.275	0.640	0.408	0.659	1.367
December	v_m	2.607	3.919	3.210	1.426	3.058	1.587	0.520	1.448	1.016	3.119	2.191
	δ	0.713	0.619	1.119	0.951	1.466	0.573	0.669	0.917	0.487	0.683	1.372
Yearly	v_m	3.399	4.363	3.966	3.323	3.021	2.904	1.672	1.429	1.475	1.921	2.748
	δ	1.105	1.052	1.129	1.777	1.609	1.830	1.577	1.145	1.353	1.147	1.725

The range of wind speed in each class is given in the second column. The mean wind speeds are calculated for each speed class interval (the third column).

The fourth column gives the frequency of occurrence of each speed class. The probability density distribution of the actual data for the month is presented in the fifth column, while the sixth column gives predicted value for the Weibull distribution function.

The corresponding cumulative distribution densities for the actual data and Weibull function are given in seventh and eight columns respectively. The monthly wind speed probability density distribution and the corresponding cumulative probability distribution for the whole year are shown in Figures 3 and 4, respectively.

The Weibull distribution parameters (k and c) were calculated using the measured wind speed data based on Equation 3 and the model prediction performance parameters (R^2, RMSE and COE) were calculated based on Equations 7, 8 and 9, respectively.

The monthly Weibull distribution parameters for the whole year and the model performance parameters are shown in Table 3. It can be seen that the shape parameter (k) varies between 1.017 and 1.610, while the scale parameter (c) ranges from 1.017 to 3.595 m/s (Table 3).

Table 2: Typical Probability Density and Cumulative Density Distributions of the Measured Wind Speed for February of the Whole Year and the Calculated Values from Weibull Distribution Function.

n	v_i	$v_{m,i}$	f_i	Probability density distribution		Cumulative Probability distribution	
				$f_A(v_i)$	$f_W(v_i)$	$F_A(v_i)$	$F_W(v_i)$
1	0 - 1	0.5	25	0.088	0.197	0.088	0.197
2	1 - 2	1.5	45	0.159	0.208	0.247	0.404
3	2 - 3	2.5	53	0.187	0.175	0.435	0.579
4	3 - 4	3.5	80	0.283	0.135	0.717	0.714
5	4 - 5	4.5	47	0.166	0.099	0.883	0.813
6	5 - 6	5.5	23	0.081	0.069	0.965	0.882
7	6 - 7	6.5	3	0.011	0.047	0.975	0.929
8	7 - 8	7.5	1	0.004	0.031	0.979	0.960
9	8 - 9	8.5	4	0.014	0.020	0.993	0.980
10	9 - 10	9.5	2	0.007	0.013	1.000	0.993

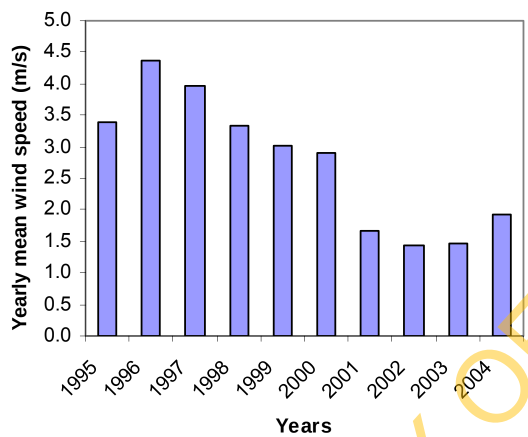

Figure 2: Yearly Mean Wind Speed Variation in Ibadan Between 1995 and 2004.

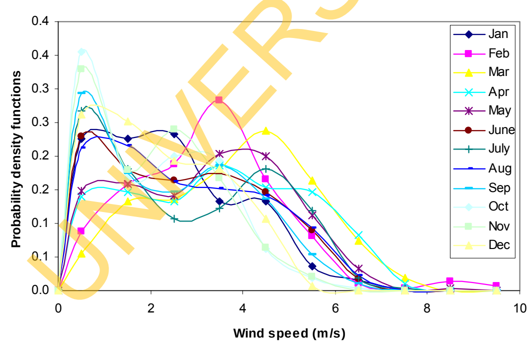

Figure 3: Monthly Wind Speed Probability Density Distributions in Ibadan for the Whole Year.

Ahigh variation in scale parameter was observed compared with that of shape parameter. Akpinar and Akpinar (2004) has been reported a same observation for the wind speed distribution analysis for Agin-Elazig, Turkey.

The model prediction performance parameters (R^2, RMSE and COE) for the monthly wind speed distributions range from 0.489 to 0.792, 0.057 to 0.076 and 0.102 to 0.615 respectively. The comparison between the actual probability distribution of wind speed for the whole year and Weibull approximations is shown in Figure 5.

It can be seen that, the wind speeds less than 3 m/s were over estimated, while wind speeds between 3 and 7 m/s were under estimated and speeds above 7 m/s were adequately estimated by the Weibull approximation. The overall mean wind speed and the power density predicted by the Weibull probability density function for the whole year are 2.947 m/s and 15.484 Wm^{-2} respectively are given in Table 4, while the Weibull probability distributions of the wind speed for the whole year is shown in Figure 6.

Ibadan is located in the tropical rain forest having a climate with well-marked dry and rainy seasons (Njoku, 1963). In order to determine the Weibull parameters for the seasonal mean wind speed, the months are divided into two seasons identified as follows:

(a) Rain season: March to November.
(b) Dry season: December to February

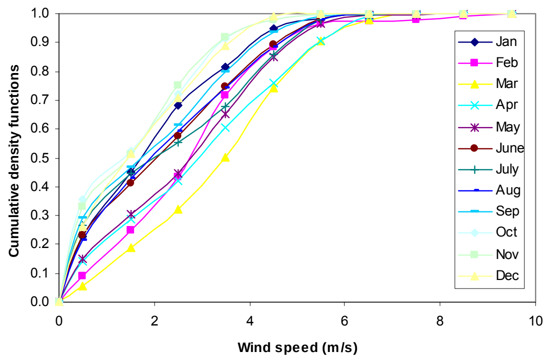

Figure 4: Monthly Cumulative Probability Distributions of Wind Speed in Ibadan, for the Whole Year.

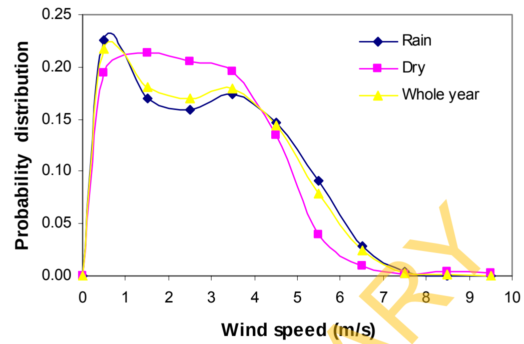

Figure 6: Seasonal Weibull Probability Distributions of Wind Speed in Ibadan.

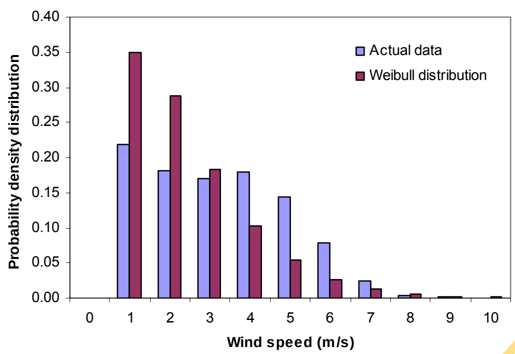

Figure 5: Comparison of Actual Wind Speed Probability Distribution for the Whole Year with Weibull Approximations.

Table 3: Monthly Weibull Shape Parameters, k and Scale Parameters, c Distribution and Performance Parameters in Ibadan (whole year).

	Weibull Parameters		Model Performance Parameters		
Month	**k**	**c(m/s)**	**R^2**	**RMSE**	**COE**
Jan	1.146	1.934	0.739	0.067	0.521
Feb	1.496	2.907	0.518	0.068	0.437
Mar	1.610	3.595	0.453	0.061	0.387
Apr	1.249	2.999	0.489	0.061	0.186
May	1.396	2.557	0.475	0.075	0.102
June	1.077	2.199	0.720	0.061	0.487
July	1.071	2.077	0.704	0.065	0.453
Aug	1.081	2.237	0.748	0.057	0.535
Sep	1.024	1.846	0.774	0.063	0.580
Oct	1.065	1.436	0.792	0.074	0.599
Nov	1.017	1.510	0.775	0.071	0.615
Dec	1.178	1.639	0.748	0.076	0.486

The Weibull distribution parameters, performance parameters, mean wind speed, and wind power density for the two seasons for the whole year are given in Table 4, while the Weibull probability distributions of the wind speed for the seasons is shown in Figure 6. The mean wind speed predicted by the Weibull probability density function for rain and dry seasons are 2.969 and 2.925 m/s, while the power density predicted are 15.834 and 15.140 Wm^{-2} respectively. The mean wind speed and wind energy availability was slightly higher during the rain season than the dry season.

The daily variations in the wind speed and energy characteristics were investigated in terms of the days of the week from Monday to Saturday for the whole year. The Weibull distribution parameters, predicted daily mean wind speed and wind power density for each day of the week for the whole year are given in Table 5. It can be seen in Table 5, that the shape parameter (k) varies between 0.795 and 0.901, while the scale parameter (c) ranges from 2.670 to 2.901 m/s.

The daily mean wind speed and power density predicted by the Weibull probability density function for each day of the week ranges from 2.870 to 3.225 m/s and 14.302 to 20.293 Wm^{-2} respectively. The maximum speed and power density occur on Tuesday, while the minimum values occur on Saturday.

Table 4: Seasonal Weibull Distribution Parameters, Performance Parameters, Mean Wind Speed, and Wind Power Density in Ibadan, between 1995 and 2004.

Season	k	c (m/s)	R^2	RMSE	COE	v_m (m/s)	Power density (Wm^{-2})
Rain	1.255	2.116	0.707	0.068	0.298	2.969	15.834
Dry	1.259	2.070	0.689	0.069	0.426	2.925	15.140
Whole year	1.274	2.100	0.718	0.068	0.335	2.947	15.484

CONCLUSIONS

The daily measured time series wind speed data for Ibadan, Nigeria have been analyzed statistically based on Weibull probability distribution function. The daily, monthly, seasonal and yearly Weibull probability distribution parameters, mean wind speeds and wind energy density availability for the location have been determined. Based on the analysis the following conclusions can be made:

(a) The actual mean yearly wind speed of 2.748 m/s for Ibadan shows the Ibadan is in a low wind speed region.

(b) The yearly wind power density value of 12.555 Wm^{-2} for the whole year indicates that Ibadan belongs to wind power class 1, since the density value is less than 100 Wm^{-2} (Akpinar and Akpinar, 2004) . Hence, wind power availability in Ibadan can only be used small stand-alone wind power systems, such as battery charging and for powering street light and water pumps.

(c) The mean yearly wind speed of 2.748 m/s for Ibadan shows the Ibadan is in a low wind speed region.

(d) The yearly wind power density value of 12.555 Wm^{-2} for the whole year indicates that the location belongs to wind power class 1, since the density value is less than 100 Wm^{-2} (Akpinar and Akpinar, 2004) . Hence, wind power availability in Ibadan can only be used small stand-alone wind power systems, such as battery charging and for powering street light and water pumps.

(e) The Weibull probability distribution scale parameters (c) are consistently higher in values and variability than the shape parameters (k) for the daily, monthly, seasonal and yearly distributions.

(f) The coefficient of determination (R^2) between the measured wind speed data and the Weibull distribution function ranges between 0.475 - 0.792. The Weibull distribution function can be used with acceptable accuracy for prediction of wind energy output required for preliminary design and assessment of wind power plants.

NOMENCLATURE

$f(v)$	probability of observing wind speed v,
k	dimensionless Weibull shape factor
c	Weibull scale parameter.
$F(v)$	cumulative distribution function of observing wind speed v.
v	wind speed (m/s)
v_m	mean value of the wind speed
$\Gamma(x)$	gamma function of (x).
$P(v)$	wind power (W)
$p(v)$	wind power density (W/m^2)
ρ	air density at the site = 1.21(kg/m^3)
A	swept area of the rotor blades (m^2)
R^2	correlation coefficient
RMSE	root mean square error
COE	coefficient of efficiency.
y_i	i^{th} actual wind speed data (m/s)

x_i — i^{th} predicted wind speed data with the Weibull distribution (m/s)

z — mean of actual wind speed data (m/s)

N — number of observations.

δ — standard deviation

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