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Statistical Analysis of Wind Energy Resource Potentials For Power Generation In Jos, Nigeria, Based On Weibull Distribution Function

By

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--ABSTRACT--

*Statistical analysis of wind speed data for Jos location in North Central, Nigeria was conducted based on monitored wind speed data, which was monitored at thirty minute interval using cup anemometer mounted at 10m height, for a period of three years (2008 – 2010). The measurement was conducted using automatic weather measuring instrument data logger model **Weather Link 5.7.1**. Assessment of wind energy resource potentials for the site was performed using Weibull probability distribution functions. It was discovered that the measured average monthly wind speed of Sokoto vary from 3.93 m/s in the month of September to 7.38m/s in the month of March for the whole years. While, monthly mean wind speed and monthly average power densities predicted by Weibull probability density function at same height were found to vary from 3.61 m/s to 6.91m/s and 51.92 W/m² to 309.04W/m², for same period. Furthermore, the statistical parameters obtained from the results has shown that the coefficient of determination R^2, χ^2 and $RMSE$, between the actual measured wind speeds and the Weibull predicted values were in agreement, with the best correlation fit found in the month of October and least correlation fit in the month of March, as can be seen from the highest values of R^2, and lowest values of χ^2 and $RMSE$ obtained for the month of October and March respectively (0.84 to 0.96, 0.087 to 0.019 and 0.074 to 0.013) respectively. This implies that Weibull distribution function can be use with acceptable accuracy for predicting of preliminary wind energy output for design and assessment of wind power applications.*

***KEYWORDS**: Statistical Analysis, Weibull distribution function. Mean wind speed, Wind power density, Weather link, Jos, Nigeria, Assessment, Resource potentials, and measurement.*

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NOMENCLATURE

A	Area (m²)
C	Weibull scale parameter or factor (m/s)
$F_{(v)}$	Cumulative distribution function
$f_{(v)}$	Probability distribution function
h	height (m)
K	Weibull shape parameter or factor
N	Number of observations
n	Number of constant
P	Power from the wind (W/m2)
P/A	Power density
R^2	Correlation coefficient
RMSE	Root mean square error
v	Wind speed (m/s)
v_m	Mean wind speed (m/s)

v_{mp} Most probable wind speed

v_{MaxE} Wind speed carrying Max Energy

x_i ith measured value

y_i ith calculated value

Whole year Average three year's data

Greek symbols

ρ Air density (kg/m3)

σ Standard deviation

$\Gamma(x)$ Gamma function of x

χ^2 Chi- square

I. INTRODUCTION

The role of energy as a basic element of any economic development is well establishes and electric energy is an important index of a country`s economic and technological progress [1]. The relationship between development of any nation and its energy per capita is linear in nature; therefore, energy is being seen as one of the fundamental devices to derive any nation from developing to developed or from stable to more stable position [2]. Energy is not only prime agent for generation of wealth but a significant factor in economic development and the driving force for industrialization of any society [3,4]. A major portion of world`s electricity energy requirement has been supplied by thermal and hydro power plants even thought the present non-renewable energy sources have been causing negative effects (global warming, ozone layer depletion, acid rain etc) on the atmosphere [5]. Nigeria is blessed with energy sources from ranging from fossil fuels, nuclear and renewable sources; yet Nigerian energy industry is probably one of the most inefficient in meeting the needs of its customers globally [6]. The increasing global energy demand and the adverse effects of non-renewable fossil fuels on environment had motivated considerable research attention in wide range of engineering application of renewable sources such as solar, geothermal, and wind [7]. Renewable energy sources are inexhaustible, clean and free and offer many environmental and economical benefits in contrast to conventional energy sources.

Wind energy is one of the fastest growing renewable sources of energy in both developed and developing countries with total available wind power surrounding the earth being in the order of 10^{11}GW, which is several times more than the current global energy consumption [7]. The wind energy market is growing in hasty ascending manner worldwide with an installed capacity of 17.4GW in 2000 reaching up to 236GW by end of 2011 with annual average growth of 1.2% [8]. The ability to accurately assess renewable energy resources is an essential prerequisite to integrating renewable energy technologies into the energy supply portfolio of any community [9]. In Nigeria several research efforts were made in order to assess wind energy resource potentials such as [10,11,12,13,14,15,16,17,18], most of these research assessment efforts were based on daily average wind speed data obtained from weather monitoring agencies such as Nigerian Meteorological Agency (NIMET), International Institute of Tropical Agriculture (IITA) and even satellite data like NASA, which are associated with approximations. The aim of this paper is to assess the wind energy potentials for Jos location, in North central-Nigeria using 30 minute interval wind speed data obtained from field measurement for power generation using statistical Weibull distribution density function.

II. THEORETICAL CONSIDERATION

For wind turbines applications, the wind speed at the hub height is of interest and in most a times different from height of measurement, therefore, the wind speeds had to be adjusted to the wind turbine hub height using the following power law expression [19];

$$\frac{U}{u_0} = \left(\frac{H}{H_o} \right)^{\alpha} \quad (1)$$

Where u is the wind speed at the required height H, u_0 is wind speed at the original height H_0 and α is the surface roughness coefficient and is assumed to be 0.143 (1/7) in the study.

2.1 Weibull Probability distribution function

Weibull distribution function is described by two parameters, The Shape factor K and scale factor C (m/s). Weibull distribution has probability density function and cumulative distribution functions of the two-parameter Weibull are expressed in to equation (2) and (3) respectively [10,16] as ;

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

$$F(v) = 1 - e^{-\left(\frac{v}{c}\right)^{k}} \quad (3)$$

Where k is dimensionless Weibull shape parameter and c is the Weibull scale parameter (m/s). Although there are various method discussed by [10] on the evaluation of Weibull parameters k and c, in this study the monthly and annual values of shape and scale parameters were computed using standard deviation methods so that the two parameters of Weibull functions k and c can be related to mean speed v_m and standard deviation σ by [15] as;

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \qquad (1 \le k \le 10) \quad (4)$$

$$C = \frac{v_m}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (5)$$

$$\Gamma(x) = \int_0^{\alpha} t^{x-1} e^{-t}\, dt \quad (6)$$

Which can be further expressed [20] as:

$$\Gamma(x) = \sqrt{2\pi x}\,(x)^{x-1} e^{-x}\left[1 + \frac{1}{12x} + \frac{1}{288x^2} - \frac{139}{51840x^3} + ...\right] \quad (7)$$

Where Γ is the gamma function, however Lysen used the following approximation to find *c*, as reported by [10]

$$\frac{c}{\overline{V}} = (0.568 + 0.433/k)^{-\frac{1}{k}}. \quad (8)$$

The two significant wind speeds for wind energy estimation are the most probable wind speed (v_{mp}) and the wind speed carrying maximum energy $(v_{\max E})$ which according to [14] can be expressed as:

$$v_{mp} = C\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \quad (9) \text{ and}$$

$$v_{\max E} = C\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \quad (10)$$

Respectively, Wind turbine system operates at its maximum efficiency at its design or rated wind speed and it would be essential the rated wind speed and the wind speed carrying maximum energy should be as close as possible.

2.2 Wind Power Density Function

The power of wind at speed (v) through a blade of sweep area (A) increases as the cube of its velocity and is given by $[19,21]$ as:

$$P(V)=\frac{1}{2}\rho A v_m^3 \qquad (11)$$

Where ρ is the mean air density at average atmospheric pressure at sea level and at room atmospheric temperature, which depends on altitude, air pressure and temperature $[21]$. While, the expected monthly or annual wind power density per unit area of a site based on a Weibull probability density function can be expressed as follows $[22]$

$$p(V)=\frac{P(V)}{A}=p_w=\frac{1}{2}\rho c^3\Gamma\left(1+\frac{3}{k}\right) \qquad (12)$$

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 (considered to be 1.22kg/m^3 in this study), and A is the swept area of the rotor blades (m^2) and C is the Weibull scale parameter (m/s) and is given by:

$$c=\frac{v_m}{\Gamma\left(1+\frac{1}{k}\right)} \qquad (13)$$

2.3 Evaluation of Wind Energy

The daily, monthly and yearly extractable mean wind energy are evaluated using the following equations $[16]$:

$$\bar{E}_j = 24\times 10^{-3}\ \bar{P}_T\,(KWh/m2) \qquad (14)$$

$$\bar{E}_{jm} = 24\times 10^{-3}\ d\bar{P}_T\,(KWh/m2) \qquad (15)$$

$$\bar{E}_y = \sum_{n=1}^{n=12}\bar{E}_{jm}(KWh/m2/year) \qquad (16)$$

Where $\bar{p}_T = p(V)$ in (W/m^2) and d is number of days in the corresponding month considered.

2.4 Statistical Analysis of Wind Speed Distributions

The three fundamental popular correlation tests were performed in this study in order to assess statistically the relationship between the measured and predicted wind speed data using Weibull and Rayleigh probability density functions. The correlations used in this analysis includes the square of the correlation coefficient (R^2), the Chi-square (χ^2) and the root mean square error analysis (RMSE) that were used for the evaluation of performances of the Weibull and Rayleigh distributions density functions $[23]$. These parameters can be calculated as follows:

$$R^2=\frac{\sum_{i=1}^{N}(y_i-z_i)^2-\sum_{i=1}^{N}(x_i-y_i)^2}{\sum_{i=1}^{N}(y_i-z_i)^2} \qquad (17)$$

$$\chi^2=\frac{\sum_{i=1}^{n}(y_i-x_i)^2}{N-n} \qquad (18)$$

$$RMSE=\left[\frac{1}{N}\sum_{i=1}^{N}(y_i-x_i)^2\right]^{\frac{1}{2}} \qquad (19)$$

Where y_i is the ith measured data, Z_i is the mean value, χ_i is the ith predicted data with Weibull and Rayleigh distribution, N is the number of observations and n is the number of constant $[21]$.

Therefore the, the best distribution function can be selected according to the highest value of R^2 and the lowest values of χ^2 and $RMSE$. However, the errors can be calculated using the power densities obtained from the distributions in comparison to values of the probability distribution densities derived from measured values which can be found using the following equations [22]:

$$Error(\%) = \frac{P_{W,R} - P_{m,R}}{P_{m,R}} \qquad (20)$$

Where $P_{W,R}$ is the mean power density calculated from either the Weibull or Rayleigh function used in the calculation of the error and $P_{m,R}$ is the wind power density for the probability distribution derived from measured values which serves as the reference means power density $P_{m,R}$ can be calculated from the following equation [24]:

$$P_{m,R} = \sum_{j=1}^{n} \left[\frac{1}{2} \rho v_m^3 f(v_j) \right] \qquad (21)$$

Similarly, the annual average error value in calculating the power density using the Weibull function can be given by.

$$Error(\%) = \frac{1}{12} \sum_{i=1}^{12} \left[\frac{P_{W,R} - P_{m,R}}{P_{m,R}} \right] \qquad (22)$$

III. DATA ACQUISITION

The thirty-thirty minute interval wind speed data used in this analysis was monitored from weather stations installed by the centre for basic space sciences (CBSS), University of Nigeria Nsukka under the programme Micro-Wave propagation Project (MPP), where Weather stations were installed in well positioned location in an open spaces free of obstacles at Jos location (latitude 9.92^{0}N, Longitude 8.9^{0}E and Altitude 1295m), Nigeria, for the period of three years (2008-2010) for Weather monitoring purpose with the view to encourage collaborative research activities among our Research institutions and universities across the country. The wind speed measurement was by used of cup-anemometer mounted at a height of 10m above the ground along with other sensors were connected to a data logger model type ***Weather link 5.2.1***. The thirty minute interval values of wind speed were then calculated and stored sequentially in a permanent memory of the logger. The data was downloaded periodically at end of every month through the use of RS-232 serial cable to computer connection. The data was then tabulated in to daily and monthly mean wind speed frequency tables and analysed using Mat-lab self developed programme and Microsoft excel software.

IV. RESULTS AND DISCUSSION

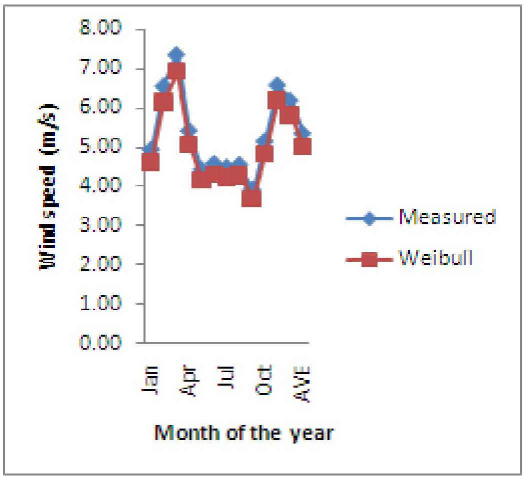

Figure1. Comparison of Monthly mean wind speeds data obtained from measurement and that obtained from Weibull Approximations

Table 1: Evaluated Monthly Properties of Jos, Nigeria.

	Jos					
Month	V_m	σ	k	c	V_{mp}	$V_{\max E}$
Jan	4.95	1.44	3.82	5.47	5.10	6.22
Feb	6.57	2.06	3.52	7.30	6.71	8.47
Mar	7.38	2.08	3.96	8.15	7.63	9.19
Apr	5.43	1.82	3.28	6.05	5.49	7.18
May	4.44	1.49	3.27	4.95	4.49	5.88
Jun	4.59	1.74	2.87	5.15	4.52	6.40
Jul	4.50	2.01	2.40	5.08	4.19	6.84
Aug	4.56	1.92	2.56	5.14	4.35	6.70
Sep	3.93	1.72	2.45	4.43	3.69	5.90
Oct	5.16	2.22	2.50	5.81	4.88	7.68
Nov	6.60	2.04	3.58	7.33	6.75	8.47
Dec	6.21	2.08	3.28	6.92	6.28	8.21
AVE	**5.36**	**1.89**	**3.11**	**5.99**	5.37	7.23

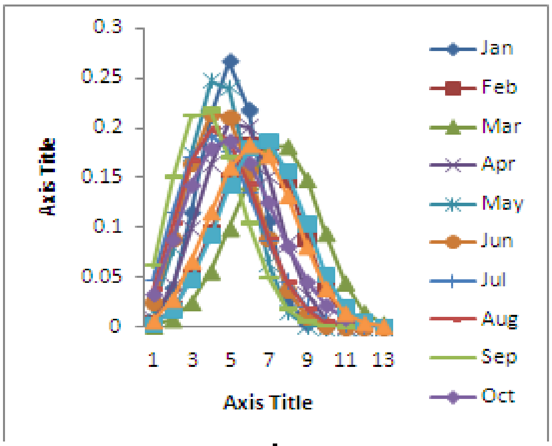

Figure 2: Jos Monthly Wind speed Probability Density Distribution for Whole year.

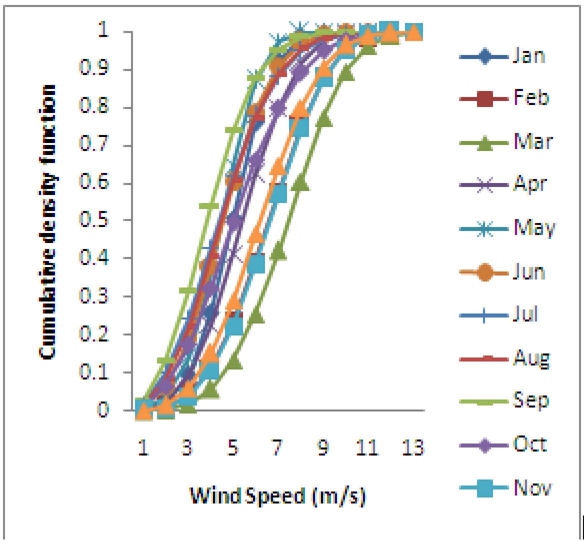

Figure 3: Jos Monthly Cumulative probability distributions of wind speed for Whole year.

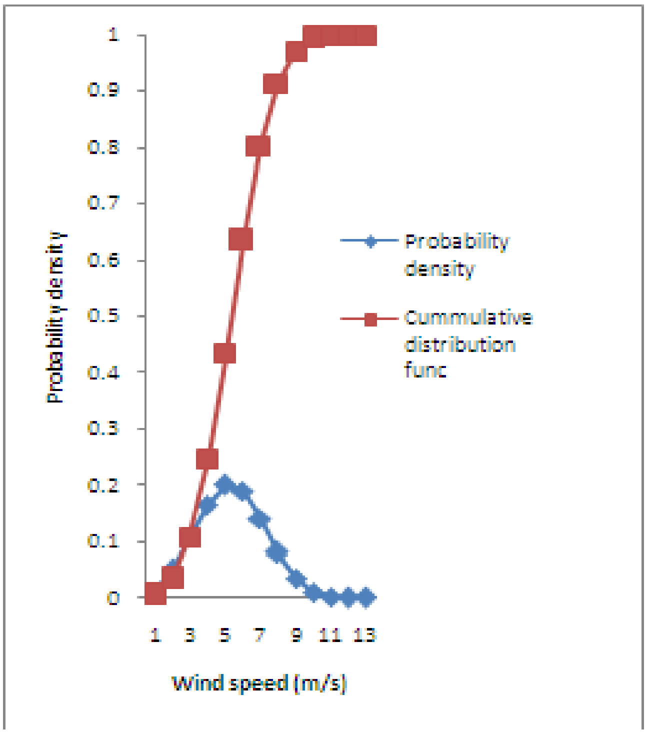

Figure 4: Annual wind speed probability density and cumulative probability distributions, derived from Weibull probability distribution model for Jos

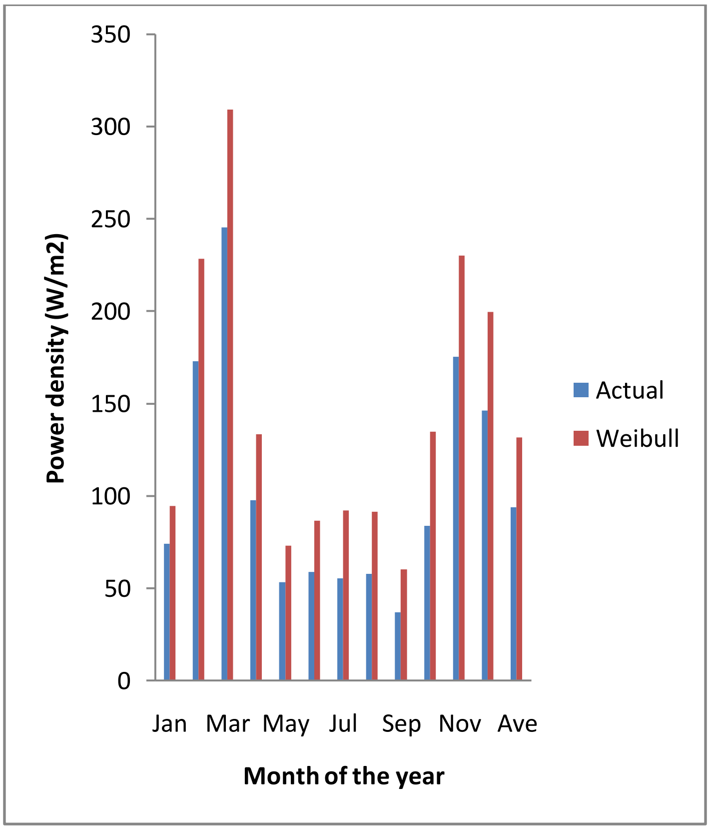

Figure 4: Monthly Power density for whole year's average data for Jos

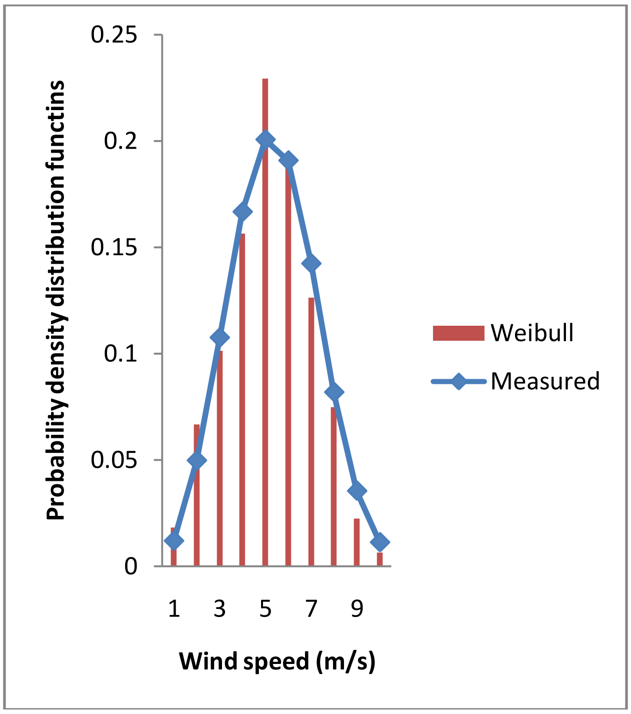

Figure5: Comparison of Probability density distributions obtained from Actual data and Weibull Probability density functions for the whole year.

Table 2: Statistical parameters of monthly wind speed distribution for the location

Month	R^2	χ^2	$RMSE$
Jan	0.93	0.105826	0.088
Feb	0.87	0.126826	0.0982
Mar	0.84	0.198682	0.126
Apr	0.94	0.129826	0.087
May	0.93	0.105826	0.088
Jun	0.94	0.110826	0.087
Jul	0.89	0.099826	0.094
Aug	0.85	0.120826	0.089
Sep	0.87	0.126826	0.098
Oct	0.96	0.086820	0.074
Nov	0.85	0.199826	0.097
Dec	0.88	0.127826	0.097
AVE	**0.897**	**0.111**	**0.0936**

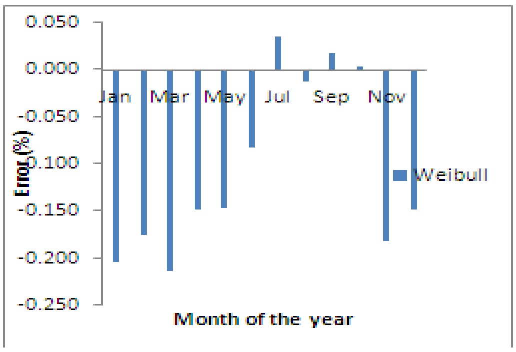

Figure 6: Monthly error values obtained in calculating the wind power density from Weibull models to wind power density obtained from the measured data.

The monthly mean wind speed values and standard deviations calculated from the whole year data and winds speed data obtained from Weibull probability model are presented in table 1. As indicated for the three years average (whole year), the mean wind speeds is about 5.36m/s. the wind speed for the period ranged between 3.93m/s in September to 7.38m/s in the month of March. The variation of wind speed is described very well by the Weibull two-parameter density function as can be seen on same figure. The Weibull probability distribution function is a statistical method which is widely accepted for evaluating local wind load probabilities and considered as a standard approach [21]. The Weibull parameters calculated analytically and whole years monthly mean and standard deviations along with most probable and maximum energy carrying wind speed are presented in table 1. It can be observed from the table that the scale parameter varies between 4.43m/s in September to 8.15m/s in March, while the shape k parameter ranges from 2.40 in the month of July to 3.96 in March. Hence, with regards to the Weibull shape parameters k for this location, wind speed is more uniform in March, while it is least uniform in July [17]. The most probable wind speed are very close to monthly mean wind speed on monthly basis where the annual average most probable wind speed of 5.37m/s was calculated as against 5.36m/s recorded monthly average.

The monthly Weibull probability density and cumulative distributions of the measured data for the whole year of the location is shown in figure 2 and figure 3 respectively. The curves can be seen to have a similar tendency of wind speeds for the two distributions. The peak of the density function frequencies of the location skewed towards the higher values of the mean wind speed, which also indicate the most frequent velocity [17]. From figure 2 the most frequents wind speed of the location were found to vary from about 3m/s in the month of September with peak frequency of approximately 21% to 8m/s expected in the month of March with approximate peak frequency of 18.2%. Furthermore, critical observation of the figure reveals that there is tendency of obtaining wind speed ≥ 9m/s in all the months while November, December and March have the likelihood of wind speeds exceeding 12m/s. The annual probably density and cumulative distributions are shown in figure 4.

The Weibull approximations of the actual probability density distribution of power densities for the whole years are shown in figure 4, where the variation of power density can be clearly observed from 37.03W/m^2 to 245.19W/m^2 and 60.41W/m^2 to 309.04W/m^2 for Actual measured data and that derived from the Weibull probability density model respectively, while comparison of the Weibull approximations with the actual probability distribution is given in figure 5, where it can be seen that Weibull probability distribution function perfectly fit the probability density obtained from the measured values. The correlation coefficient values are used as the measures of the fitness of the probability density distributions obtained from the Weibull distributions, where the monthly parameters for the statistical analysis correlation coefficient, R^2, Chi-square error and the root mean square error (RMSE), are given in table 2. As expected the best correlation are described by the higher value of correlation coefficient R^2, and lower value of Chi-square and RMSE. As can be observed from the table 2, the values of correlation coefficient are higher in the month of October (0.96) and lowest in March (0.84) and the values of Chi-square and RMSE are lowest in October and highest in March of 0.0868 to 0.1908 and 0.074 to 0.126 for Chi square and RMSE respectively, this invariably indicated that the best correction occurs in the month of October and least correlation in the month of October. Similarly, the errors obtained as a result of calculating the wind power densities from the use of Weibull distributions in comparison to those using the measured probability density distributions are presented in figure 6, as can be observed from the figure the highest error values occur in the month of March (21%) and lowest error of (0.4%) in the month October.

V. CONCLUSION

Wind energy resource potentials of Jos has been analysed statistically using Weibull probability distribution density, based on the analysis the following conclusions were arrived:

[1] The actual annual mean wind speed of 5.36 m/s at 10m height was measured for the three years average; this showed that Jos is viable location for wind energy development.

[2] Weibull probability density function can be used to predict wind speed for Jos location from the values of wind speed and power densities obtained from Weibull approximation that fitted the measured wind speed and probability distribution densities on monthly basis for the whole year.

[3] The monthly mean power density obtained from Weibull and actual measurements were found to vary from 60.41W/m^2 to 309.04W/m^2 and 37.03W/m^2 to 245.19W/m^2 respectively.

[4] The month of October recorded least percentage error of 0.4 %, while month of March recorded the highest percentage error of 21% for the whole year which agreed well with the values of correlation coefficient determined.

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