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Weibull distribution-based model for prediction of wind potential in Enugu, Nigeria

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ABSTRACT

Modeling and prediction of wind characteristics are essential design inputs in the development of wind power systems for different locations. In this paper, the daily wind data for Enugu (6.3^0N; 7.3^0E; 450m), Nigeria, over a period of 13 years (1995 – 2007), is modeled in terms of the Weibull distribution function, in order to predict wind energy potential of the location. The daily, monthly, and annual wind speed probability density distributions at 10m meteorological height are modeled and the mean wind speed, skew, shape- and scale factors are determined with values of 2.5 ± 0.3m/s, -0.46, 2.21 and 4.31m/s respectively. The results suggest that while the wind speed is more concentrated at higher values above the mean, the distribution for Enugu departs significantly from the standard Raleigh distribution, with error of 10.5%. The coefficient of determination of the model is 0.74. Further statistics suggest that the model can be used, with acceptable accuracy, for prediction of wind energy output needed for preliminary design assessment of wind machines for the location.

Keywords: renewable energy - general, wind, Weibull distribution.

INTRODUCTION

Meteorology, the scientific study of the earth's atmosphere, includes the study of day-to-day or month-to-month variations and predictions of weather conditions. Meteorological study involves the systematic observations, recording and processing of various meteorological parameters of temperature, rainfall, wind, cloud cover, relative humidity and sunshine. Short term condition of the atmosphere is referred to as weather, while that over a considerably long time is called climate.

The influence of weather and climate over man's activities is unquestionable. Man's food, clothing, housing, works, mental and physical alertness are to a very great extent regulated by weather/climate. The direction of wind once controlled the pattern of trading routes (the trade winds), the safety of modern air transport, satellite technology and radio communication are closely tied to accurate meteorological reports from the ground stations [12]. Farmers and their crops are at the mercy of climate and weather despite the advances made in science and technology. Throughout history much of the progress in the discovery of the laws of Physics and Chemistry was stimulated by curiosity about atmospheric phenomena. Although, men are still unable to completely tame the forces of natural meteorological phenomena such as floods, droughts, typhoons, hurricanes, a sound knowledge of their trends (weather systems) often helps to avoid or at least reduce the seriousness of the weather associated calamities [16; 4]. Hence, knowledge of the weather of a particular place is not only important but often very essential.

Meteorological conditions also play significant role in the performance of renewable energy systems. In particular, renewable energy systems produce optimum output under certain desired meteorological conditions which are essentially location/site specific. Similarly, the force carried by the wind can also be harnessed for useful purposes such as grinding grain (in windmills) and generating electricity (in wind turbine generators). It is estimated that between 1.5 to 2.5% of the global solar radiation received on the surface of the earth is converted to wind [16; 15]. Hence, wind energy, which contributes very little pollution and few greenhouse gases to the environment, is a valuable alternative to non-renewable fossil fuels [14]. The extent to which wind can be exploited as a source of energy depends on the probability density of occurrence of different speeds at the site. To optimize the design of a wind energy conversion device, data on speed range over which the device must operate to maximize energy extraction is required, which requires the knowledge of the frequency distribution of the wind speed. Among the probability density functions that have been proposed for wind speed frequency distributions of most locations, the Weibull function has been the most acceptable distribution and forms the basis for commercial wind energy applications and software 913], such as the Wind Atlas Analysis and Application Program (WAsP) and the recently developed Nigerian Wind Information System (WIS) software.

The Weibull probability density function is a two-parameter function characterized by a dimensionless shape (*k*) parameter and scale (*c*) parameter (in unit of speed). These two parameters determine the wind speed for optimum performance of a wind conversion system as well as the speed range over which the device is likely to operate [9]. In principle, this opens up the need to estimate the model parameters, namely, *k* and *c*, from measured data of any location.

In previous papers [15; 10; 11], theoretical potentials of wind in Enugu and environs were examined based on annual mean wind speed. In this paper, the wind speed data over thirteen years for Enugu is modeled in terms of the Weibull distribution. The model will, no doubt, be of immense help to designers of wind machines for the studied location.

MATERIALS AND METHODS

The Weibull wind speed probability density function

Wind power developers measure actual wind resources, in part, to determine the distribution of wind speeds because of its considerable influence on wind potential. The Weibull wind speed distribution is a mathematical idealization of the distribution of wind speed over time. The function shows the probability of the wind speed being in a 1m/s interval centred on a particular speed *(v)*, taking into account both seasonal and annual variations for the years covered by the statistics. The Weibull distribution function is given [17; 7] by:

$$p_{(v)} = \frac{k}{v}\left(\frac{v}{c}\right)^{k-1} \exp\left\{-\left(\frac{v}{c}\right)^{k}\right\}, \qquad (1)$$

where $p_{(v)}$ is the frequency of occurrence of wind speed *(v)*, *c* (in unit of m/s) is the scale factor which is closely related the wind speed for the location, and *k* is the dimensionless shape factor which describes the form and width of the distribution. The Weibull distribution is therefore determined by the two parameters *c* and *k*. The cumulative Weibull distribution $P_{(v)}$ which gives the probability of the wind speed exceeding the value *v* is expressed as:

$$P_{(v)} = \exp\left\{-\left(\frac{v}{c}\right)^{k}\right\} \qquad (2)$$

Equation (2) above suggests that both *k* and *c* could be obtained from a regression analysis of $P_{(v)} - v$ plot of the wind speed distribution data for a particular location.

However, meteorologists have characterized the distribution of wind speeds for many of the World’s wind regimes in terms of the speed distribution patterns. For example, in temperate climate (mid latitudes), a typical shape factor (*k)* of 2 offers a good approximation [6; 7]. For *k* = 2, equation (1) or (2) is called the Raleigh wind speed distribution. Hence, the Raleigh distribution is a special case of the Weibull function developed for estimation of wind potential in temperate climate locations. Wind characteristics are essentially location specific and the performance of wind power systems varies if actual wind conditions at the location differ from those standard speed distributions.

On the other hand, the shape *(k)* factor has been suggested [8; 7] to be obtainable using the mean wind speed data *(v)* and standard deviation *(σ)* for the location as:

$$k = \left(\frac{\sigma}{v}\right)^{-1.086}, \qquad (3)$$

while the scale factor has been given [13] as:

$$c = \frac{\mu}{\Gamma\left(1+\frac{1}{k}\right)}, \qquad (4)$$

where (Γ) is the gamma function defined mathematically in general x-variable [5] as:

$$\Gamma x = \int_0^\infty x^{n-1} e^{-x} dx \qquad (5)$$

Analysis of equation (2) suggests that the wind speed probability density for *v* is higher if the shape factor is high for that location. Hence, smaller values of *k* ($k < 1$) suggest that there is more concentration of energy in the wind below the average speed (*v)* for the site, while higher values of *k* ($k > 1$) could be interpreted that the wind speed in the site is dominated by values above the mean speed [9; 7]. This shows that knowledge of the exact value of *k* provides preliminary information on the wind speed regime for which wind turbines should be designed for any given location. On the other hand the value of *c* for any location provides preliminary information on the characteristic wind speed for the site for which a wind turbine should be designed. In this paper, we analytically, find the empirical values of *k* and *c* for the Enugu wind location.

RESULTS

In this work, we use 13 year (1995 – 2007) wind data for Enugu (6.3N, 7.3^{o}E, 450m), obtained from the Nigerian Meteorological Agency. The data were recorded on daily mean basis from which the monthly and annual mean data were calculated. We show the monthly mean wind speeds at 10m standard height for the location over the thirteen (13) year period in table 1. The histogram distribution of the speed data is shown in Figure 1. Apparently, the distribution, on average, is normal with annual mean wind speed of 2.5 ± 0.3m/s and a median value of 2.52m/s. However, the distribution skews to the left with a negative skew of -0.46. The negative skew suggests that the mass of the distribution is concentrated on the positive side of the mean, which means that there are relatively more values of wind speed higher than the annual mean in the distribution. The cumulative distribution of the wind speed data in 1m/s interval in the speed range $0 < v \leq 8$ is shown in figure 1. The data perfectly fits into the cumulative Weibull distribution statistics. Hence, the assumption of the Weibull distribution for the wind speed data of our study location is reasonable. The data therefore follow a standard 2-parameter Weibull distribution. To model the data in terms of the Weibull distribution, we plot $Ln(-LnP_{(v)})$ as a function of $Ln(v)$ in figure 2 and apply a one-dimensional regression analysis to the plot. The result gives the model equation as:

$$Ln(-LnP_{(v)}) = 2.21Ln(v) - 3.23, \qquad (6)$$

with $k \sim 2.21$, $c \approx 4.31$m/s and coefficient of determination $r^2 \sim 0.74$ for the model. Comparing our result with the standard Raleigh distribution, we find that it departs from the Raleigh distribution with a percentage error of 10.5%. Similarly, we compare the measured and estimated values of the wind probability density in terms of the model. A plot of the probability density, (measured and estimated), as a function of wind speed is shown in figure 3. It is apparent that while the measured value peaks at 2.7m/s, the estimated value peaks at 3.5m/s. The result is consistent with a percentage error of 30%.

Table 1: Monthly mean wind speed (m/s) for Enugu (1995 -2007)

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	2.4	3.0	2.8	3.3	3.0	3.0	2.7	2.7	2.7	2.5	2.0	2.0
1996	2.7	3.0	3.1	2.7	2.3	2.6	2.2	2.6	2.1	2.1	1.5	2.7
1997	3.2	2.6	2.3	2.1	1.9	2.0	2.5	3.2	2.3	2.1	2.5	2.6
1998	3.0	2.3	3.2	3.0	2.4	2.3	2.8	2.4	2.1	2.1	2.1	2.6
1999	2.7	1.7	3.1	2.6	2.2	2.4	2.6	2.7	2.3	1.9	2.2	3.2
2000	2.6	2.1	2.8	2.5	2.1	2.4	2.4	2.1	2.1	2.0	2.5	2.0
2001	2.1	2.6	2.9	2.8	2.8	2.5	2.6	2.5	2.4	2.2	2.5	1.8
2002	2.3	3.5	2.5	2.5	1.9	2.3	2.9	2.5	2.4	2.1	1.7	2.2
2003	3.2	2.6	2.8	3.1	2.6	2.3	2.8	2.5	2.5	2.1	1.7	2.4
2004	2.6	2.7	3.6	2.9	2.6	2.3	2.6	2.7	2.3	2.1	1.7	2.5
2005	2.5	3.0	2.9	3.3	2.5	2.4	2.7	2.7	2.5	2.0	1.9	2.8
2006	2.6	2.9	2.9	2.9	2.5	2.5	2.6	2.8	2.5	2.0	1.8	2.1
2007	3.2	2.8	3.0	3.0	2.5	2.5	2.4	2.5	2.3	1.8	1.8	2.7

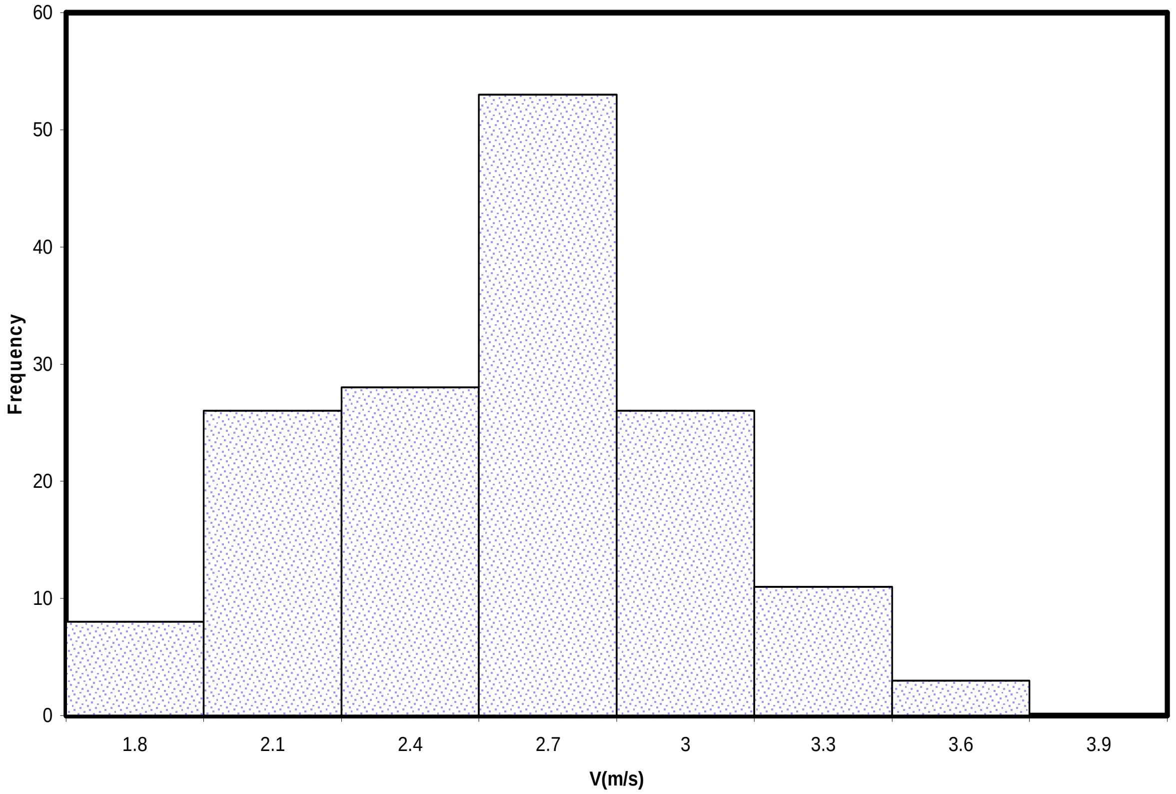

Figure 1: Histogram distribution of wind speed for Enugu (1995 - 2007)

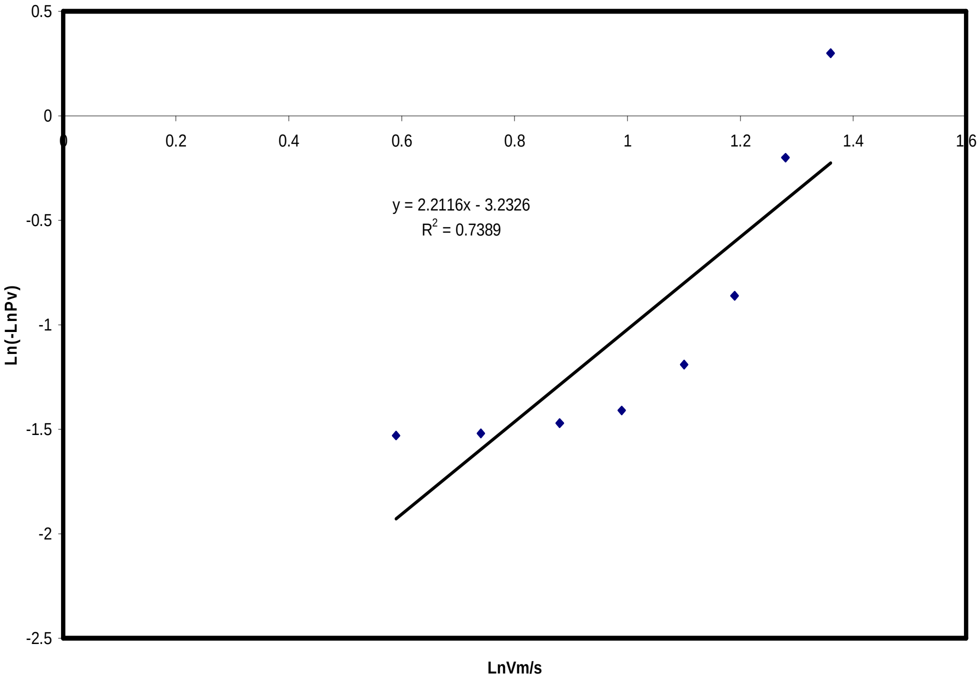

Figure 2: Ln(-LnPv) vs Ln(vm/s) plot for Enugu (1995 - 2007)

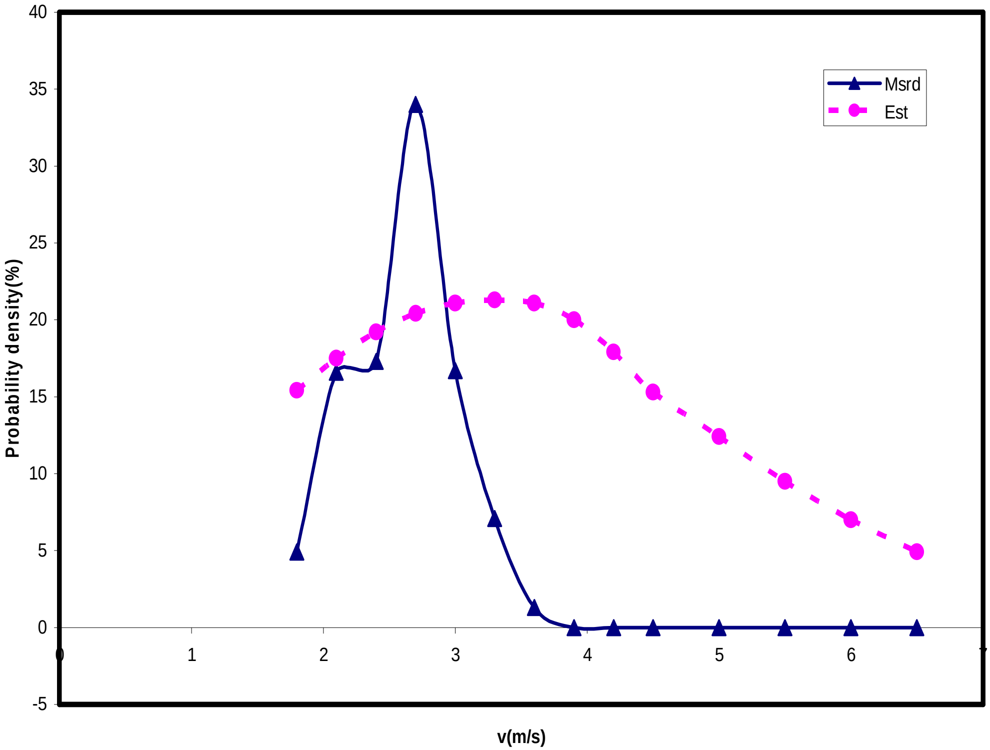

Figure 3: Comparison of estimated and measured wind probability density for Enugu (1995 - 2007)

DISCUSSION

Modeling and prediction of wind characteristics are major design inputs in the development of wind power systems for any location. However, the wind speed distribution for many of the world's wind regimes have been characterized and wind power systems are optimized based on these standard distributions. In fact, the Raleigh distribution (k = 2) is often employed by most wind power system developers. The result is that many wind power systems perform poorly in many different locations because the actual wind conditions at the locations differ largely from those standard distributions [9; 3].

We have shown in our results that at a height of 10m above the ground, the distribution of wind speed in Enugu over the studied period has annual mean of 2.5 ± 0.3m/s, with negative skew. The negative skew suggests that the wind speed at the study location is concentrated more on values above the annual mean. Hence, wind machines designed for 2.5m/s wind speed regimes at 10m hub height are expected to produce meaningful output for a greater part of the year since the speed is concentrated above 2.5m/s.

We have also shown in the results that the Weibull shape factor for the Enugu location is 2.21, while the scale factor is 4.31m/s. The actual value of k is greater than unity for the location. It shows that the wind speed at the site is more concentrated above the annual mean, which is consistent with the result of the negative skew shown above. Furthermore, the value of the shape factor presented in this paper suggests that the width of the distribution for Enugu is wider than the standard Raleigh distribution used to optimize most wind energy conversion systems by 0.21, representing a percentage error of 10.5%. The implication of this is that any wind power system optimized with the Raleigh distribution may not effectively catch the wind for 10.5% of the expected full load operation time in the Enugu location.

Another important outcome of our result is the very significant statistical coefficient of determination of the developed model which has been shown to be 0.74. Correlation between variables is significant if the magnitude of the coefficient $r^2 \geq 0.5$, otherwise it is not significant. A significant correlation between two variables suggests that the data are acceptably related by the model applied to them [1; 2]. Hence the model for the Enugu location based on the Weibull distribution can acceptably be used to predict wind potential for the location.

CONCLUSION

We have modeled the 13 year wind speed data of Enugu in terms of the Weibull probability density function and determined values for both the shape and scale parameters, in order to accurately predict wind energy potentials for the location. Our results suggest that while the data is consistent with the Weibull function, the distribution departs significantly from the Raleigh distribution, upon which many wind power systems have been based, with a shape factor of 2.21. The analyses suggest that the model can be used with acceptable statistical accuracy for prediction of wind potentials for the Enugu location.

We recommend that the analyses be extended to other locations in Nigeria where installation of wind energy conversion systems is being proposed.

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