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Weibull Distribution Modelling Using the LLSM Approach: Application to Wind Speed Variation

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Abstract:

The most significant constraint of the wind force is the wind speed. Wind speed varies with the day and the season of the year and even some extent from year to year. Wind energy has inherent variances and hence it has been expressed by distribution functions. For this rationale, understanding wind ratings via Weibull distribution is very important. In this paper, We model the wind speed in Ikeja area of Lagos, Nigeria (Ikeja being the capital of Lagos, and Lagos being the most populous city of Nigeria, the second fastest-growing city in Africa and the seventh in the world) using among other methods, the Linear Least Square Method (LLSM) to estimate the Weibull distribution parameters, namely, shape parameter (k) and scale parameter (c). The Weibull distribution is an important distribution especially for reliability and maintainability analysis. The suitable values for both shape parameter and scale parameters of Weibull distribution are important for selecting locations of installing wind turbine generators. The scale parameter of Weibull distribution is also important to determine whether a wind farm is good or not.

Key words: Cumulative Density Function, Cut-in Speed, Linear Least Square Method, Probability Density Function, Weibull Distribution, Wind Speed.

Introduction

Navigation and agriculture have been using wind energy for centuries, but it is only during recent times that wind energy has been getting a lot of awareness due to the concentration on inexhaustible energies. The successful fitting of statistical distributions like the Weibull Distribution to wind speed data in wind energy means having a thorough understanding of the wind features at any particular location. Not only is understanding wind ratings important, but at the same time how to interpret the Weibull distributions for wind velocity is also crucial. Precise data about wind velocity is significant to determine best sites for wind turbines. Wind speeds also have to be calculated by those who are apprehensive about the dispersion of airborne pollutants.

Apart from this the energy requirement of the world is always increasing by 4-5% every year while fossil fuel reserves which address this want are decreasing much quicker than the need. Additionally, with the increasing, depressing consequences of fossil fuels on the environment, primarily developed countries and others have started utilizing renewable energy sources. These days, the most growing and most commonly utilized energy source is wind energy. Thus, when using energy from the wind, the most crucial parameter, that is wind velocity, has to be calculated, and this is where Weibull distributions play a part.

Today, most electrical energy is generated by burning huge fossil fuels and special weather conditions such as acid rain and snow, climate change, urban smog, regional haze, several tornados, etc., have happened around the whole world. It is now clear that the installation of a number of wind turbine generators can effectively reduce environmental pollution, fossil fuel consumption, and the costs of overall electricity generation. Although wind is only an intermittent source of energy, it represents a reliable energy resource from a long-term energy policy viewpoint. Among various renewable energy resources, wind power energy is one of the most popular and promising energy resources in the whole world today (Paritosh Bhattacharya, 2010).

At a specific wind farm, the available electricity generated by a wind power generation system depends on mean wind speed (MWS), standard deviation of wind speed, and the location of installation. Since year-to-year variation on annual MWS is hard to predict, wind speed variations during a year can be well characterized in terms of a probability distribution function (Paritosh Bhattacharya, 2010). This paper in addition addresses the relations among MWS, its standard deviation, and the two important parameters of the Weibull distribution.

Related Work

In Literature several distributions were applied to calculate the wind speed distribution. Justus et al. [1976] applied the Weibull and Lognormal distribution to Wind speed data from more than a hundred stations of the USA and concluded that Weibull Distribution rendered the best fit. Odo, Offiah and Ugwuoke (2012) applied the Weibull distribution for predicting wind potential in Enugu, Nigeria and concluded that the model can be used with acceptable statistical accuracy for prediction of wind potentials for the Enugu location. On the whole Weibull gave a good fit based on the shape and scale parameters. In recent years the Weibull distribution has been one of the most widely used and recommended tool to determine the potential of Wind Energy. Moreover it is used as a benchmark to estimate the wind energy commercially.

Materials and Methods

Wind Speed Data

Measured wind speed data are commonly available in time series format, in which each data point represents either an instantaneous sample wind speed or an average wind speed over some time period. An example of such data (giving yearly over a 13 year period is given) in Table 1 obtained from the Nigerian Meteorological Agency.

The Weibull Distribution of the Wind Speed

The Weibull distribution (named after the Swedish physicist Weibull, who applied it when studying material in tension and fatigue in the 1930s) provides a close approximation to the probability laws of many natural phenomena. It has been used to represent wind speed distribution for application in wind load studies for some time. In recent years most attention has been focused on this method for wind energy application not only due to its greater flexibility and simplicity but also because it can give a good fit to experimental data (Indhumathy, Seshaiah and Sukkiramathi, 2014).

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 (Odo, Offiah and Ugwuoke, 2012).

In statistical modelling of wind speed variation, the Weibull two-parameter (shape parameter k and scale parameter c) function have been widely used by many researchers. The function shows the probability of the wind speed being in a 1m/s interval centred on a particular speed (u), taking into account both seasonal and annual variations for the years covered by the statistics.

The Weibull distribution is characterized by two parameters; one is the shape parameter k (dimensionless) and the other is the scale parameter c (m/s) with its probability density function (*pdf*) defined as:

$$f(u) = \left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} exp\left[-\left(\frac{u}{c}\right)^{k}\right]; \quad u > 0, \; k, c > 0 \qquad \text{---(1)}$$

where $f(u)$ is the probability of observing wind speed u, k is the dimensionless Weibull shape parameter, c is the Weibull scale parameter, which have reference values in the units of wind speed.

The corresponding cumulative distribution function (*cdf*) of the Weibull distribution is given as:

$$F(u) = \int_0^{\infty} f(u)du = 1 - exp\left[-\left(\frac{u}{c}\right)^{k}\right] \qquad \text{---(2)}$$

where $F(u)$ is the cumulative probability function of observing wind speed u.

In Weibull distribution, the variations in wind speed are characterized by two functions which are the probability density function (*pdf*) and the cumulative distribution function (*cdf*). The *pdf* indicates the fraction of time (or probability) for which the wind is at a given speed u while the *cdf* of the speed u gives the fraction of the time (or probability) that the wind speed is equal or lower than u.

Estimation of Average and Standard Deviation of the Wind Speed

The average wind speed can be expressed as

$$\bar{u} = \int_0^{\infty} uf(u)du = \int_0^{\infty} u\left(\frac{k}{c}\right)\left[\left(\frac{u}{c}\right)^{k-1}\right] exp\left[-\left(\frac{u}{c}\right)^{k}\right] du \qquad \text{---(3)}$$

Let $\quad q = \left(\frac{u}{c}\right)^{k} \quad \Longrightarrow \quad q^{\frac{1}{k}} = \frac{u}{c} \quad$ and $\quad dq = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} du$

Equation (3) can be simplified as

$$\bar{u} = c\int_0^{\infty} q^{\frac{1}{k}} exp(-q)dq \qquad \text{---(4)}$$

By substituting a Gamma Function
$\Gamma(n) = \int_0^\infty e^{-q} q^{n-1} dq$ into Equation (4) and let $x = 1 + \frac{1}{k}$ then we have

$$\bar{u} = c\Gamma\left(1 + \frac{1}{k}\right) \qquad \text{---(5)}$$

The standard deviation of the wind speed u is given by

$$\sigma = \sqrt{\int_0^\infty (u - \bar{u})^2 f(u) du} \qquad \text{---(6)}$$

That is

$$\sigma = \sqrt{\int_0^\infty (u^2 - 2u\bar{u} + \bar{u}^2) f(u) du}$$

$$= \sqrt{\int_0^\infty u^2 f(u) du - 2\bar{u} \int_o^\infty u f(u) du + \int_o^\infty \bar{u}^2 f(u) du}$$

$$= \sqrt{\int_0^\infty u^2 f(u) du - 2\bar{u} \cdot \bar{u} + \bar{u}^2}$$

$$= \sqrt{\int_0^\infty u^2 f(u) du - 2\bar{u} \cdot \bar{u} + \bar{u}^2}$$

$$= \sqrt{\int_0^\infty u^2 f(u) du - \bar{u}^2} \qquad \text{---(7)}$$

But $\int_0^\infty u^2 f(u) du = \int_0^\infty u^2 \left(\frac{uk}{c}\right) \left[\left(\frac{u}{c}\right)^{k-1}\right] exp\left[-\left(\frac{u}{c}\right)^k\right] du$ ---(8)

Using appropriate substitution and transformation as with Equation (3), we have

$$\int_0^\infty u^2 f(u) du = c^2 \Gamma\left(1 + \frac{2}{k}\right) \qquad \text{---(9)}$$

Hence we get

$$\sigma = \sqrt{c^2 \Gamma\left(1 + \frac{2}{k}\right) - \left[c\Gamma\left(1 + \frac{1}{k}\right)\right]^2}$$

$$= \left[c^2 \Gamma\left(1 + \frac{2}{k}\right) - c^2 \Gamma^2\left(1 + \frac{1}{k}\right)\right]^{\frac{1}{2}}$$

$$= c\sqrt{\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)} \qquad \text{---(10)}$$

Computation of Weibull Parameters (k and c) of the Wind Speed

Several methods could be applied to calculate the wind speed distribution among which are Linear Least Square Mehtod (LLSM), Maximum Likelihood Method (MLM), Modified Maximum Likelihood Method (MMLM), Power Density Method (PDM), Mean Standard Deviation Method (MSDM) and Method of Moments (MOM).

In this paper we employed the Linear Least Square Method (LLSM) in computing the Weibull parameters. Linear least square method (LLSM) is used to calculate the parameter(s) in a formula when modelling an experiment of a phenomenon and it can give an estimation of the parameters (Paritosh Bhattacharya, 2010). Linear least square method is extensively used in engineering and mathematics problems that are often not thought of as an estimation problem (Salahaddin A. Ahmed, 2013).

With the help of this method the parameters are estimated with regression line equation by cumulative density function. From Equation (2), the cumulative distribution function of the Weibull distribution with two parameters was written as:

$$F(u) = 1 - exp\left[-\left(\frac{u}{c}\right)^k\right]$$

This function can be arranged as:

$$\frac{1}{1-F(u)} = exp\left[\left(\frac{u}{c}\right)^k\right] \qquad \text{---(11)}$$

If we take the *natural logarithm* of Equation (11)

$$\ln\left\{\frac{1}{1-F(u)}\right\} = \left[\left(\frac{u}{c}\right)^k\right] \qquad \text{---(12)}$$

And then retake the natural logarithm of Equation (12), we get the following equation:

$$\ln\left[\ln\left\{\frac{1}{1-F(u)}\right\}\right] = -k\ln c + k\ln u \qquad \text{---(13)}$$

Equation (13) can be written as a linear equation as:

$$Y = a + bX \qquad \text{---(14)}$$

where $$Y = \ln\left[\ln\left\{\frac{1}{1-F(u)}\right\}\right] \qquad \text{---(15)}$$

$$a = -k\ln c \qquad \text{---(16)}$$

$$b = k \qquad \text{---(17)}$$

and $$X = \ln u \qquad \text{---(18)}$$

By regression formula

$$b = \frac{n\sum_{i=1}^{n} X_i Y_i - \sum_{i=1}^{n} X_i \sum_{i=1}^{n} Y_i}{n\sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i\right)^2} = k \qquad \text{---(19)}$$

$$a = \frac{\sum_{i=1}^{n} X_i^2 \sum_{i=1}^{n} Y_i - \sum_{i=1}^{n} X_i \sum_{i=1}^{n} X_i Y_i}{n\sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i\right)^2} \qquad \text{---(20)}$$

and $$c = e^{-\frac{a}{k}} \qquad \text{---(21)}$$

The parameters k and c could equally be written in terms of the natural logarithm as

$$k = \frac{n\sum_{i=1}^{n} \ln u_i \, \mathrm{In}[-\mathrm{In}\{1-F(u_i)\}] - \sum_{i=1}^{n} \ln u_i \sum_{i=1}^{n} \mathrm{In}[-\mathrm{In}\{1-F(u_i)\}]}{n\sum_{i=1}^{n} \ln u_i^2 - \left(\sum_{i=1}^{n} \ln u_i\right)^2} \qquad \text{---(22)}$$

$$c = exp\left\{\frac{k\sum_{i=1}^{n} \ln u_i - \sum_{i=1}^{n} \mathrm{In}[-\mathrm{In}\{1-F(u_i)\}]}{nk}\right\} \qquad \text{---(23)}$$

There are various approaches to obtaining the empirical distribution function from that: one method is to obtain the vertical coordinate for each point. Let $u_1, u_2, u_3, \dots, u_n$ be a random sample of u, $F(u)$ is estimated and replaced by the *median rank* method as follows (Y. Lei, 2008):

$$F(u) = \frac{i - 0.3}{n + 0.4} \qquad \text{---(24)}$$

$$u_i,\ i = 1, 2, \dots, n \text{ and } u_1 < u_2 < \dots < u_n$$

where i is the rank of the data point and n is the number of data points.

Predicted Weibull Wind Speed ($\hat{u}$) Model

The predicted wind speed value $(\hat{u})$ can be obtained from Equation (24) as

$$\hat{u}_i = F(\hat{u}_i)\{\mathrm{n} + 0.4\} + 0.3 \qquad \text{---(25)}$$

Equation (15) gives $F(\hat{u}_i)$ as

$$F(\hat{u}_i) = 1 - \left[{}^{1}\!/_{\mathrm{e}^{\mathrm{e}^{\hat{Y}}}}\right] \qquad \text{---(26)}$$

where $\hat{Y}$ is the estimated Y value from Equation (14)

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 three tests in this article, first is the coefficient of determination R^2 used to how well the regression model describes the data, second is root mean square error (RMSE) and third is the coefficient of efficiency (COE). These tests were computed based on the following equations:

$$R^2 = \frac{[\sum_{i=1}^{n}(u_i-\bar{u})(\hat{u}_i-\bar{u})]^2}{[\sum_{i=1}^{n}(u_i-\bar{u})^2][\sum_{i=1}^{n}(\hat{u}_i-\bar{u})^2]} \qquad \text{---(27)}$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(u_i - \hat{u}_i)^2\right]^{\frac{1}{2}} \qquad \text{---(28)}$$

$$COE = \frac{\sum_{i=1}^{n}(u_i-\hat{u}_i)^2}{\sum_{i=1}^{n}(u_i-\bar{u})^2} \qquad \text{---(29)}$$

where u_i is the actual or measured wind speed data, $\hat{u}_i$ is the predicted wind speed data with the Weibull distribution, $\bar{u}$ is the mean of the actual wind speed data and n is the number of observations.

Weibull Reliability Function

The reliability of a product/component constitutes an important aspect of product quality. Of particular interest is the quantification of product reliability, so that one can derive estimates of the product expected useful life. Knowing the probability of product/ component failures at different stages of its life can be very useful to make a decision about when to replace or overhaul the component.

The Weibull reliability function is defined as

$$R(u) = 1 - F(u) = exp\left[-\left(\frac{u}{c}\right)^{k}\right] \qquad \text{---(30)}$$

By manipulating Equation (30) for reliability, $R\%$ reliability is achieved after time t as

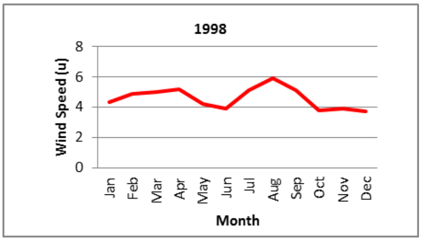
$$t = c[-\ln R]^{\frac{1}{k}} \qquad \text{---(31)}$$

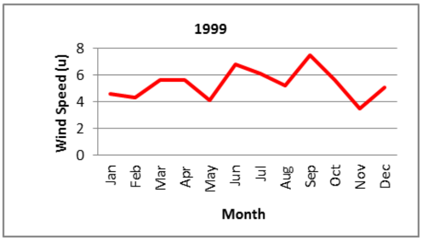
Results Output

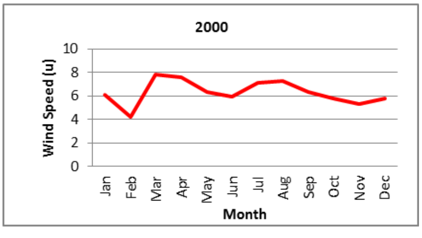
Table 1: Computation of Weibull Parameters (k and c) from the Measured Wind Speed (u)

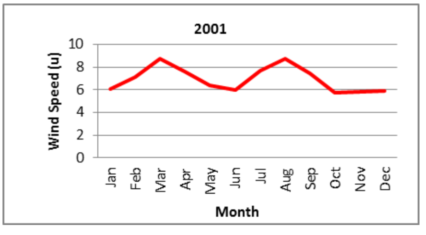
	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Jan	4.3	4.6	6.1	6.1	6	4	5	5.9	7.2	4.4	5.6	5.8	2.8
Feb	4.9	4.3	4.2	7.1	8	5	3	8.2	8.7	8.7	6.9	8	3
Mar	5	5.6	7.8	8.7	8.6	5	3	8.5	8.4	9	9.3	8.8	3
Apr	5.2	5.6	7.6	7.6	7.6	5	5	8.6	9	9.8	8.1	9.1	3
May	4.2	4.1	6.3	6.4	6.5	3	3	7.1	6.1	6.8	6.4	7.4	3
Jun	3.9	6.8	5.9	6	6.9	3	3	6.5	5.9	7.7	5.9	5.3	3
Jul	5.1	6.1	7.1	7.7	8	3	3	8.4	8.7	9.8	5.1	6.5	3
Aug	5.9	5.2	7.3	8.7	9.7	4	3	10.3	9.7	10.5	6.7	8.2	3
Sep	5.1	7.5	6.3	7.4	2.5	4	2	8.2	8	7.6	4.8	6.1	3.3
Oct	3.8	5.6	5.8	5.7	5.9	3	2	5.4	5.5	5.7	4.2	5.1	3
Nov	3.9	3.5	5.3	5.8	5.1	3.7	2	5.5	4.1	5.9	3.9	5.7	3.1
Dec	3.7	5.1	5.8	5.9	5.5	3.5	2	5.1	5	5	3.8	5	3.1
$\bar{u}$	**4.5833**	**5.3333**	**6.2917**	**6.9250**	**6.6917**	**3.8500**	**3.0000**	**7.3083**	**7.1917**	**7.5750**	**5.8917**	**6.7500**	**3.0250**
σ	**0.7056**	**1.1364**	**1.0308**	**1.0972**	**1.8985**	**0.8017**	**1.0445**	**1.6318**	**1.8168**	**2.0316**	**1.6930**	**1.4829**	**0.1138**
Range	**2.2**	**4**	**3.6**	**3**	**7.2**	**2**	**3**	**5.2**	**5.6**	**6.1**	**5.5**	**4.1**	**0.5**
k	**1.3369**	**1.3945**	**1.4629**	**1.6035**	**1.4383**	**1.2962**	**1.2777**	**1.6481**	**1.5661**	**1.6558**	**1.4800**	**1.5770**	**1.2609**
c	**8.6890**	**8.4551**	**8.3065**	**8.1283**	**8.1900**	**8.8784**	**8.9725**	**8.0213**	**8.0464**	**7.9324**	**8.1812**	**8.0983**	**9.1358**

$$\bar{\bar{u}} = \sum_{j}^{m} \bar{u} = 5.7244m/s$$









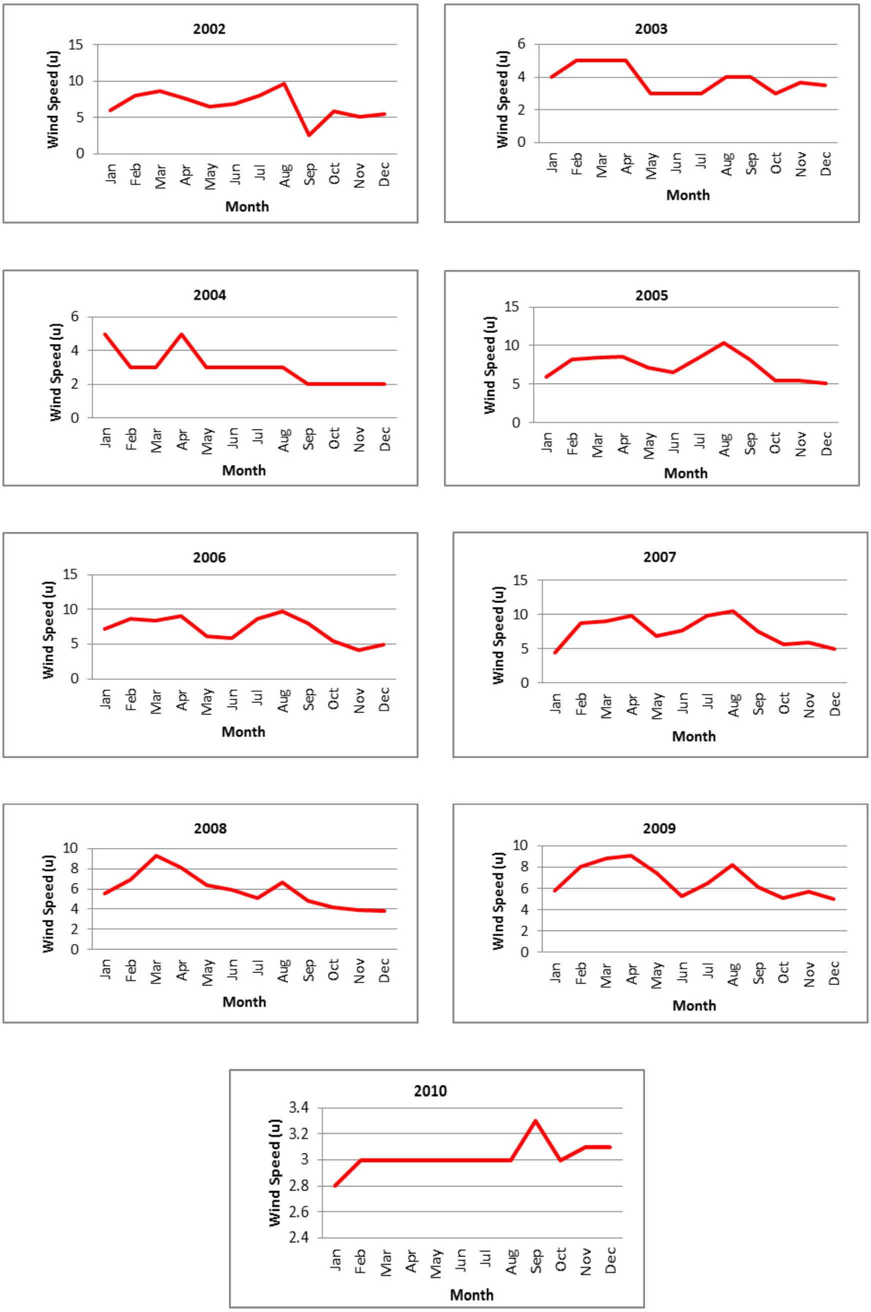


Figure 1: Monthly Measured Wind Speed Variation in Ikeja Between 1998 and 2010.

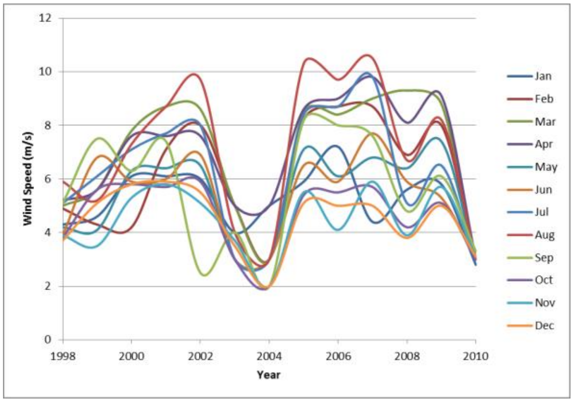


Figure 2: Yearly Measured Wind Speed Variation in Ikeja Between 1998 and 2010.

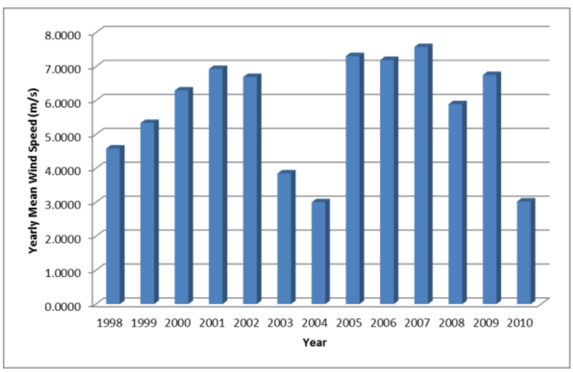


Figure 3: Yearly Mean Wind Speed Variation in Ikeja Between 1998 and 2010.

Table 2: Weibull Probability Distribution *f(u)* of the Measured Wind Speed

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Jan	0.0822	0.0846	0.0808	0.0883	0.0809	0.0808	0.0754	0.0922	0.0789	0.0973	0.0852	0.0890	0.0809
Feb	0.0797	0.0856	0.0888	0.0813	0.0661	0.0766	0.0821	0.0739	0.0657	0.0692	0.0766	0.0725	0.0807
Mar	0.0792	0.0798	0.0687	0.0674	0.0614	0.0766	0.0821	0.0710	0.0684	0.0661	0.0574	0.0653	0.0807
Apr	0.0782	0.0798	0.0702	0.0772	0.0692	0.0766	0.0754	0.0700	0.0630	0.0580	0.0672	0.0626	0.0807
May	0.0825	0.0861	0.0795	0.0864	0.0775	0.0829	0.0821	0.0838	0.0870	0.0869	0.0802	0.0776	0.0807
Jun	0.0834	0.0724	0.0820	0.0888	0.0746	0.0829	0.0821	0.0884	0.0883	0.0790	0.0835	0.0913	0.0807
Jul	0.0787	0.0769	0.0740	0.0763	0.0661	0.0829	0.0821	0.0720	0.0657	0.0580	0.0877	0.0846	0.0807
Aug	0.0744	0.0819	0.0725	0.0674	0.0528	0.0808	0.0821	0.0534	0.0566	0.0511	0.0781	0.0707	0.0807
Sep	0.0787	0.0675	0.0795	0.0789	0.0871	0.0808	0.0810	0.0739	0.0720	0.0800	0.0889	0.0872	0.0802
Oct	0.0836	0.0798	0.0826	0.0904	0.0815	0.0829	0.0810	0.0944	0.0904	0.0942	0.0905	0.0921	0.0807
Nov	0.0834	0.0869	0.0852	0.0899	0.0860	0.0817	0.0810	0.0940	0.0938	0.0932	0.0908	0.0895	0.0806
Dec	0.0839	0.0824	0.0826	0.0894	0.0839	0.0822	0.0810	0.0954	0.0925	0.0968	0.0908	0.0924	0.0806

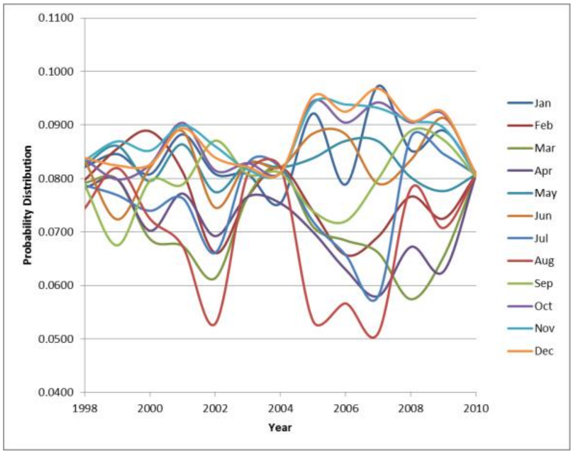


Figure 4: Yearly Wind Speed Probability Distribution in Ikeja between 1998 and 2010.

Table 3: Cumulative Probability Distribution of the Measured Wind Speed

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Jan	0.0822	0.0846	0.0808	0.0883	0.0809	0.0808	0.0754	0.0922	0.0789	0.0973	0.0852	0.0890	0.0809
Feb	0.1618	0.1701	0.1696	0.1695	0.1470	0.1574	0.1575	0.1660	0.1446	0.1665	0.1619	0.1615	0.1617
Mar	0.2411	0.2500	0.2383	0.2369	0.2083	0.2339	0.2396	0.2370	0.2130	0.2326	0.2193	0.2268	0.2424
Apr	0.3193	0.3298	0.3086	0.3141	0.2776	0.3105	0.3149	0.3071	0.2760	0.2906	0.2865	0.2894	0.3232
May	0.4018	0.4159	0.3881	0.4005	0.3550	0.3934	0.3970	0.3908	0.3630	0.3775	0.3667	0.3671	0.4039
Jun	0.4852	0.4883	0.4700	0.4893	0.4296	0.4763	0.4791	0.4793	0.4513	0.4565	0.4502	0.4584	0.4847
Jul	0.5639	0.5652	0.5440	0.5657	0.4957	0.5591	0.5612	0.5512	0.5170	0.5145	0.5379	0.5430	0.5654
Aug	0.6383	0.6471	0.6165	0.6330	0.5485	0.6399	0.6433	0.6046	0.5736	0.5656	0.6160	0.6137	0.6461
Sep	0.7171	0.7146	0.6960	0.7119	0.6356	0.7207	0.7243	0.6785	0.6457	0.6456	0.7050	0.7010	0.7264
Oct	0.8007	0.7944	0.7786	0.8023	0.7171	0.8035	0.8053	0.7729	0.7361	0.7398	0.7954	0.7930	0.8071
Nov	0.8841	0.8814	0.8638	0.8922	0.8031	0.8852	0.8864	0.8670	0.8299	0.8330	0.8862	0.8825	0.8877
Dec	0.9679	0.9638	0.9463	0.9816	0.8870	0.9674	0.9674	0.9623	0.9224	0.9298	0.9770	0.9749	0.9683

Table 4: Predicted Wind Speed ($\hat{u}$) from the Weibull Parameters (*k* and *c*)

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Jan	4.3083	4.6167	6.1391	6.1031	6.1563	4.0121	4.9788	5.9136	7.3481	4.1935	5.6918	5.8314	2.7996
Feb	4.9107	4.3002	4.1242	7.1563	7.9843	4.9893	3.0104	8.3039	8.6948	8.8332	6.8079	8.0505	3.0001
Mar	5.0093	5.6379	7.7191	8.6345	8.4585	4.9893	3.0104	8.5734	8.4453	9.0848	8.9982	8.7343	3.0001
Apr	5.2045	5.6379	7.5467	7.6477	7.6487	4.9893	4.9788	8.6608	8.9342	9.7004	8.0709	8.9723	3.0001
May	4.2062	4.0873	6.3378	6.4280	6.6473	2.9947	3.0104	7.2269	6.2143	6.9866	6.5134	7.4917	3.0001
Jun	3.8976	6.7720	5.9373	5.9933	7.0244	2.9947	3.0104	6.5858	5.9969	7.9138	6.0057	5.2721	3.0001
Jul	5.1072	6.1239	7.0996	7.7429	7.9843	2.9947	3.0104	8.4848	8.6948	9.7004	5.1554	6.5854	3.0001
Aug	5.8674	5.2365	7.2812	8.6345	9.2370	4.0121	3.0104	9.9607	9.4533	10.1738	6.9998	8.2281	3.0001
Sep	5.1072	7.3791	6.3378	7.4542	2.3577	4.0121	1.9943	8.3039	8.0970	7.8153	4.8267	6.1592	3.2995
Oct	3.7940	5.6379	5.8352	5.6598	6.0557	2.9947	1.9943	5.3347	5.5535	5.7472	4.1586	5.0446	3.0001
Nov	3.8976	3.4428	5.3149	5.7716	5.2237	3.7099	1.9943	5.4516	3.9431	5.9796	3.8213	5.7208	3.1001
Dec	3.6902	5.1346	5.8352	5.8828	5.6453	3.5067	1.9943	4.9816	4.9860	4.9167	3.7088	4.9303	3.1001

Table 5: Weibull Parameters, Model Performance Parameters and Reliability Test

	Weibull Parameters		**Model Performance Parameters**			**90% Reliability**
Year	***k***	***c*** (m/s)	**R^2**	**RMSE**	**COE**	
1998	1.3369	8.6890	0.999705310	0.011690	0.000299	1.614112
1999	1.3945	8.4551	0.998222281	0.047012	0.001867	1.683752
2000	1.4629	8.3065	0.998315821	0.044694	0.002051	1.783801
2001	1.6035	8.1283	0.998315821	0.043150	0.001687	1.997591

2002	1.4383	8.1900	0.991594889	0.177898	0.009578	1.713112
2003	1.2962	8.8784	0.999859173	0.009281	0.000146	1.564388
2004	1.2777	8.9725	0.999885667	0.011821	0.000140	1.541722
2005	1.6481	8.0213	0.993283120	0.128223	0.006736	2.047602
2006	1.5661	8.0464	0.995980028	0.111329	0.004096	1.912288
2007	1.6558	7.9324	0.992665231	0.167394	0.007406	2.037807
2008	1.4800	8.1812	0.992419823	0.142220	0.007698	1.788398
2009	1.5770	8.0983	0.997808336	0.066640	0.002203	1.943833
2010	1.2609	9.1358	0.999996731	0.000198	0.000003	1.533373
Mean	**1.4614**	**8.3873**	**0.996773**	**0.073965**	**0.003378**	**1.781675**

Discussion of Results

In this study, wind speed data for Ikeja, Nigeria, over a 13 year period from 1998 to 2010 were analysed. The analysis were done using Microsoft Excel® package. The Weibull distribution parameters in terms of *k* and *c*, mean wind speed, probability distribution, cumulative probability distribution and predicted wind speed were determined.

Figure 1 shows the monthly wind speed variation in Ikeja over the period of 13 years from 1998 to 2010, while the yearly mean wind speed values, standard deviations and ranges are presented in Table 1. It can be seen in Table 1 that the highest yearly mean wind speed of 7.5750 m/s occurs in the year 2007, while the minimum mean wind speed of 3.0000m/s occurs in the year 2004. The highest yearly wind speed standard deviation of 2.03160 also occurs in the year 2007, while the minimum mean wind speed of 0.1138 occurs in the year 2010.

Table 2 shows the Weibull probability distribution of the measured wind speed, Table 3 shows the Weibull cumulative probability distribution of the measured wind speed and Table 4 shows the predicted wind speed energy from the Weibull parameters for the 13 years period.

The model prediction performance parameters (R^2, RMSE and COE) for the yearly wind speed distributions range from 0.991594889 to 0.999996731, 0.000198 to 0.177898 and 0.000003 to 0.009578 respectively.

Estimated mean shape parameter (k) indicates $k > 1$ which implies that on the average wind energy fall rate increases yearly in Ikeja, Nigeria.

Mean value of 0.996773 for R^2 indicates that approximately 99.7% of the total variation in the wind speed energy in Ikeja area of Lagos, Nigeria is being explained by the Weibull distribution model.

The recorded low value of the wind speed mean RMSE indicates better fit of the Weibull distribution model to the measured wind speed data. This implies that the model accurately predicts the wind speed energy in Ikeja area of Lagos, Nigeria.

The Mean COE value of 0.003378 indicates that on the average wind speed energy is approximately 0.338% efficient in Ikeja area of Lagos, Nigeria.

The 90% reliability estimate indicates that wind speed energy in Ikeja area of Lagos, Nigeria will on the average be reliable for approximately 1.8years.

The results give the model equation as:

$$\mathrm{In}[-\ln\{1 - F(u)\}] = -3.11 + 1.46\ln u \qquad \text{---(32)}$$

Conclusion

We have modelled the 13 year wind speed data of Ikeja 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 the data is consistent with the Weibull function with an average shape factor of 1.46. The analyses suggest that the model can be used with acceptable statistical accuracy for prediction of wind potentials for the Ikeja location. For a planned wind plant in Ikeja, investment may not turn out useful. The analyses suggest that there is insufficient allocation of wind speed energy in the location and the reliability of such wind energy is on the average of approximately 20 months. If the need be to select a wind turbine for Ikeja, the most favourable cut-in speed should on the average be approximately 5.72 (m/s).

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

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