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Statistical modelling of wind speed measurement with accuracy tests models

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Abstract

In harnessing wind energy, the development of modelling wind speed plays a vital role in helping to obtain the actual wind speed data for the benefit of power plant planning in the future. More importantly, the accuracy of the wind distribution model needs to be carried out. In this paper, six selected locations in Nigeria, Jos, Katsina, Kano, Kaduna, Bauchi, and Maiduguri, were considered for investigation. Real-time wind speed data were obtained from the Nigerian Meteorological Agency for these locations. The paper examines different statistical models in the literature. The Weibull distribution model was used to carry out the wind speed distribution modelling. Also, the accuracy of the predicted wind distribution was validated using three different methods, namely, root mean square error, mean absolute error, and chi-square test. For improved results of the test, the test was done at three different height positions of 10m, 30m, and 60m respectively. The results obtained showed three different outcomes from the different heights that were considered for a whole month for the six selected locations with little error margin.

Keywords: Data; Distribution; Modelling; Wind; Weibull

1. Introduction

The most common wind modelling techniques include Weibull, Rayleigh, Gamma, Lognormal, Exponential, Beta, Log-logistic, and Gaussian distribution functions. [1] [2]. The Weibull function is one of the most widely used and standard techniques for modelling the wind speed measurement due to its wide range of versatility, and flexibility, and it's useful for describing the wind variation at a site. [3]. The inability to accurately model the wind using an accurate statistical function will result in large errors in the predictability of wind potential at a given site. The prediction errors in the wind speed distribution will invariably give rise to the wrong classification of the site's wind power, which is a function of the wind power density.[4]. The Rayleigh function is extensively used in modeling the wind at a steady wind site for energy applications. The Rayleigh distribution is a special case of the Weibull distribution, which typically represents the wind characteristics at some sites. The Gamma function has found its applicability in the modelling of low wind speed sites, as well as in multi-level Poisson regression modelling.

2. Statistical Modelling of the Wind Speed Measurement

The application of a statistical model to wind speed measurement is for the determination of a suitable model to be used for the wind energy evaluation at a potential site. The probability wind distributions are used to describe the distribution of the wind speed, as well as the period a particular wind speed prevails at a site. [5]. The knowledge of the wind speed distribution at a site can be used to evaluate the performance, as well as to develop a site power curve model.

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The predominantly statistical modeling techniques available in the wind resource assessment are the Weibull, Rayleigh, Gamma, Logistic, Exponential, Lognormal distributions, etc.

2.1. Weibull Distribution Function

The Weibull distribution is the most widely used statistical distribution, which has found various applications in life data analysis, reliability engineering, partial discharge analysis and insulation aging, wind energy study; as well as in the modeling stochastic deterioration, etc. [6] [7]. In the wind energy study, the Weibull model is the standard statistical function used among several statistical distribution functions for modelling the wind speed at a given site. In the modelling of site wind speed using the Weibull distribution function, the wind speed variations are described by using its shape and scale parameters.

The Weibull cumulative distribution function (CDF) is defined by:

$$F_w(k, c) = 1 - \exp\left[-\left(\frac{v}{c}\right)\right]^k \tag{1}$$

where F_w is the Weibull CDF, k and c, are the shape parameter and scale parameter, respectively.

For Weibull 2-parameter distribution, the CDF is expressed as:

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

where f_w is the Weibull PDF.

2.2. Rayleigh Distribution Function

The Rayleigh function is widely used in statistical distribution functions, is defined by:

$$F_r(k, c) = 1 - \exp\left[-\frac{v}{c}\right]^2 \tag{3}$$

where F_r is the CDF of the Rayleigh distribution, and c is the Rayleigh scale parameter at k = 2.

If k = 2 put into Eqn. (3), the Rayleigh density function for a continuous wind distribution is defined by:

$$f_r(k, c) = \frac{2v}{c^2} \exp\left[-\left(\frac{v}{c}\right)\right]^2 \tag{4}$$

where f_r is the Rayleigh pdf.

2.3. Gamma Distribution Function

The gamma distribution function has found its applicability in the low wind speed data and for Poisson regression modeling errors in multi-level. The PDF is given by:

$$f_g(k, c) = \frac{v^{k-1}}{c^{k\tau(k)}} \exp\left[-\left(\frac{v}{c}\right)\right] \quad k, c > 0 \tag{5}$$

where f_g, k, c, are the probability density function, shape parameter, and scale parameter of a Gamma distribution, respectively.

The cumulative distribution function of a Gamma distribution is defined as:

$$F_g(k, c) = \frac{1}{c^{k\tau(k)}} \int_o^v t^{k-1} \exp\left(-\left(\frac{t}{c}\right)\right) dt \tag{6}$$

where F_g, $\tau(k)$ are the Gamma cumulative distribution and Gamma function of (k), respectively.

3. Accuracy Tests of the Statistical Models

To determine whether the predicted wind distributions obtained in the statistical models were accurate for describing the wind speed prevalence at the wind farm, accuracy tests need to be conducted on the models. There are several testing techniques available for the validation of the accuracy of the predicted wind distribution obtained from the statistical models. They include the Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Chi-Square Test, Correlation Coefficient (R), Coefficient of Determination (COD), mean square error (MSE), Standard Deviation of the Absolute Error (Std.) etc. The various tests for determining the accuracy of the statistical models are explained as follows:

3.1. Root Mean Square Error (RMSE)

The RMSE is used to compare the actual deviation's predicted and actual (measured) values. RMSE is also more advantageous than the mean absolute error in detecting extremely large errors because the mean absolute error is less sensitive to extreme values.

3.1.1. RMSE is therefore obtained as follows:

$$\mathrm{RMSE} = \left[\frac{\sum_{i=1}^{N}(y_i - x_i)^2}{N}\right]^{\frac{1}{2}} \tag{7}$$

N is the number of wind speed data points. x_i is the i^{th} actual wind pdf; y_i is the i^{th} predicted wind distribution.

3.2. Chi-Square Test

It is used for testing purposes between the predicted and actual wind distribution. It can be applied to discrete distributions while others are restricted to a continuous distribution. It is defined mathematically as:

$$x^2 = \frac{\sum_{i=0}^{n}(y_i - x_i)^2}{N - n} \tag{8}$$

where x_i, y_i , and N are defined in Eqn. (7) n is the number of constant wind speed data.

3.3. Mean Average Error (MAE)

This is the average of all absolute errors.

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|x_i - x| \tag{9}$$

where n is the number of errors and $|x_i - x|$ is the absolute error.

4. Wind Energy Forecast Error of the Selected Locations

Six selected locations in Nigeria, namely Jos, Katsina, Kaduna, Kano, Bauchi, and Maiduguri, were considered in the investigation. They were carefully chosen from the literature for the potential wind speed availability throughout the year for electricity generation using wind turbines. The Weibull distribution method was used in determining the wind distribution of the selected locations. The RMSE, MAE, and Chi-square are statistical methods used for the validation of the accuracy of the predicted wind distribution for the selected locations across the country. The validation process was carried out at 10m, 30m, and 60 m height, respectively. The month of July 2010 was chosen for all the locations for the statistical analysis.

5. Results

The results for the different methods of MAE, Chi, and RMSE for the heights 10m, 30m, and 60m, respectively were computed by the comparison of the results from the models with real measurement. The results obtained are presented in Tables 1 to 6.

Table 1 Weekly Forecast Error (m/s) for Jos in July 2010

WEEK				Jos					
		10 m			30 m			60 m	
	MAE	*RMSE*	*Chi*	*MAE*	*RMSE*	*Chi*	*MAE*	*RMSE*	*Chi*
1ST	0.34E-5	0.42E-5	7.42E-3	6.34E-5	7.16E-5	4.71E-3	0.23E-4	0.45E-5	1.36E-3
2ND	0.51E-5	0.64E-5	7.56E-3	6.78E-5	7.32E-5	4.78E-3	0.25E-4	0.37E-5	1.33E-3
3RD	0.31E-5	0.45E-5	7.54E-3	6.23E-5	7.27E-5	4.22E-3	0.26E-5	0.41E-5	1.42E-3
4TH	0.46E-5	0.56E-5	7.76E-3	6.46E-5	7.53E-4	4.67E-3	0.28E-5	0.43E-5	1.38E-3
5TH	0.41E-5	0.43E-5	7.38E-3	5.76E-5	6.38E-5	4.89E-3	0.21E-5	0.23E-5	1.17E-3

Table 2 Weekly Forecast Error (m/s) for Katsina in July 2010

				Katsina					
		10 m			30 m			60 m	
	MAE	*RMSE*	*Chi*	*MAE*	*RMSE*	*Chi*	*MAE*	*RMSE*	*Chi*
1ST	1.73E-5	2.43E-5	3.28E-3	0.49E-5	0.87E-5	2.16E-3	5.56E-5	7.76E-5	6.23E-3
2ND	2.46E-5	5.23E-5	4.34E-3	0.72E-5	1.43E-5	2.34E-3	6.45E-5	6.72E-5	6.45E-3
3RD	1.43E-5	2.17E-5	3.14E-3	0.35E-5	0.85E-5	2.67E-3	4.39E-5	5.65E-5	5.37E-3
4TH	1.36E-5	2.34E-5	3.45E-3	0.61E-5	1.23E-4	2.68E-3	5.58E-5	7.21E-5	6.53E-3
5TH	3.94E-5	6.58E-5	6.78E-3	0.66E-5	1.48E-5	2.34E-3	6.56E-5	1.08E-4	7.67E-3

Table 3 Weekly Forecast Error (m/s) for Kaduna in July 2010

WEEK				Kaduna					
		10 m			30 m			60 m	
	MAE	*RMSE*	*Chi*	*MAE*	*RMSE*	*Chi*	*MAE*	*RMSE*	*Chi*
1ST	0.64E-5	2.37E-5	3.45E-3	0.52E-5	0.92E-5	3.13E-3	5.93E-5	6.73E-5	4.17E-3
2ND	1.34E-5	2.43E-5	4.34.E-3	0.81E-5	1.36E-5	2.85E-3	4.59E-5	8.17E-5	3.76E-3
3RD	2.46E-5	3.23E-5	3.10E-3	0.54E-5	1.99E-5	2.25E-3	4.35E-5	4.91E-5	2.33E-3
4TH	1.45E-5	4.56E-5	3.27E-3	0.63E-5	1.16E-4	4.57E-3	6.56E-5	6.68E-5	4.25E-3
5TH	1.36E-5	3.37E-5	6.27E-3	0.74E-5	1.23E-5	2.64E-3	8.27E-5	3.09E-4	6.54E-3

Table 4 Weekly Forecast Error (m/s) for Kano in July 2010

WEEK				Kano					
		10 m			30 m			60 m	
	MAE	*RMSE*	*Chi*	*MAE*	*RMSE*	*Chi*	*MAE*	*RMSE*	*Chi*
1ST	1.31E-5	1.56E-5	2.45E-3	0.25E-5	0.27E-5	3.45E-3	4.93E-5	7.73E-5	4.58E-3
2ND	0.36E-5	3.34E-5	4.34E-3	0.67E-5	1.63E-5	2.96E-3	6.59E-5	9.17E-5	5.31E-3

3RD	0.73E-5	2.15E-5	2.10E-3	0.41E-5	1.17E-5	2.86E-3	4.35E-5	5.91E-5	4.78E-3
4TH	1.56E-5	2.34E-5	1.27E-3	0.37E-5	1.43E-4	2.56E-3	5.56E-5	7.68E-5	6.81E-3
5TH	2.76E-5	3.54E-5	5.39E-3	0.62E-5	1.38E-5	2.75E-3	8.27E-5	1.09E-4	6.67E-3

Table 5 Weekly Forecast Error (m/s) for Bauchi in July 2010

WEEK				**Bauchi**					
		10 m			**30 m**			**60 m**	
	MAE	***RMSE***	***Chi***	***MAE***	***RMSE***	***Chi***	***MAE***	***RMSE***	***Chi***
1ST	1.56E-5	3.29E-5	2.49E-3	1.34E-5	2.67E-5	1.36E-3	4.24E-5	6.34E-5	5.24E-3
2ND	1.23E-5	4.38E-5	3.52E-3	1.67E-5	1.61E-5	2.56E-3	3.65E-5	7.11E-5	4.32E-3
3RD	1.84E-5	3.42E-5	3.47E-3	1.51E-5	0.82E-5	2.72E-3	5.67E-5	6.24E-5	6.35E-3
4TH	1.56E-5	3.28E-5	4.52E-3	1.48E-5	1.41E-4	3.15E-3	5.31E-5	5.34E-5	5.12E-3
5TH	2.75E-5	5.42E-5	5.41E-3	1.46E-5	1.72E-5	2.19E-3	6.33E-5	2.16E-4	4.67E-3

Table 6 Weekly Forecast Error (m/s) for Maiduguri in July 2010

WEEK				**Maiduguri**					
		10 m			30 m			60 m	
	MAE	*RMSE*	*Chi*	*MAE*	*RMSE*	*Chi*	*MAE*	*RMSE*	*Chi*
1ST	0.34E-5	2.23E-5	4.74E-3	0.47E-5	1.41E-5	2.11E-3	5.41E-5	5.76E-5	5.51E-3
2ND	1.13E-5	2.65E-5	3.21E-3	0.66E-5	1.65E-5	2.36E-3	4.11E-5	7.56E-5	6.17E-3
3RD	1.34E-5	2.45E-5	3.33E-3	0.41E-5	1.38E-5	2.59E-3	4.67E-5	6.76E-5	4.19E-3
4TH	1.45E-5	2.11E-5	2.44E-3	0.47E-5	2.21E-4	2.71E-3	4.36E-5	5.43E-5	6.32E-3
5TH	2.25E-5	3.18E-5	4.35E-3	0.56E-5	1.43E-5	2.23E-3	6.31E-5	3.19E-4	7.34E-3

6. Conclusion

The Weibull distribution model was used in this paper for the wind speed analysis. The other distribution models were equally mentioned, as well as their area of applicability. The RMSE, MAE, and Chi-square are statistical methods used for the validation of the accuracy of the predicted wind distribution for the selected locations. The results were determined for different height positions of 10m, 30m, and 60m, respectively. The results vary for the different methods at different heights that were considered. However, the results reveal an overall marginal error margin for the six selected locations.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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