Assessment of wind energy potential of Bauchi in North-East, Nigeria

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Abstract. Twenty year (1995-2014) monthly mean wind speed and monthly mean wind direction data of Bauchi location were obtained from the Nigeria Meteorological Agency (NIMET) Lagos for the purpose of this study. The data was measured at 3 m height. In order to evaluate wind characteristics, statistical models such as Weibull and Rayleigh distribution were employed in the assessment of wind energy potential. It was observed that Weibull distribution suited the wind speed data more than Rayleigh. Wind rose plot of the monthly wind direction was plotted to determine the best possible direction to mount wind turbine in Bauchi station. Wind characteristics obtained at 3 m height were extrapolated for higher altitudes.

Keywords: wind speed, wind direction, probability density, Weibull, Rayleigh

1. Introduction

Clean energy technologies produce positive impacts and they do not pollute the environment. They produce less global warming, non depletable and is abundant. A great deal of information abounds about the development and increased production of our global energy needs through renewable energy sources. Solar energy, wind energy, biogas, hydrothermal energy are all alternative energy and they are clean. Government is seriously committed to the adoption of the Renewable Energy Master Plan (REMP) with a target of increasing the present generation capacity. The exploration of wind energy resource is one of the solutions of this master plan. The preliminary effort of resource assessment of locations to find out their potential for power generation has been going on in Nigeria. The northern part of Nigeria has been observed as a region possessing great potential for wind energy utilization. The focus of this study is therefore to evaluate the wind energy potential of Bauchi station and also to obtain other wind characteristics at different hub heights.

The authors observed that North-East, Nigeria has good wind energy potential. The study is aimed at modeling probability density functions of Bauchi in North-East, Nigeria using Rayleigh distribution and Weibull distribution function. The wind direction was estimated using wind rose diagram. The wind speed characteristics and wind power potential were extrapolated for higher heights at 10 m, 50 m and 60 m.

2. Materials and methods

2.1: Probability density functions

Various probability distribution models have been used in the past to analyze wind. Recently, many studies have been done to evaluate wind energy potentials in different regions using diverse probability distribution functions. Some of these probability distribution functions include normal, lognormal, gamma, Beta, Cauchy, Inverse Gaussian, Weibull and Rayleigh etc.
However, the Weibull distribution has been found to be accurate and adequate in analyzing and interpreting measured wind speed and in predicting wind characteristics of stations ([1],[2],[3],[4],[5],[6],[7]). Another widely accepted distribution function which is extensively used in modeling of the wind speed is Rayleigh function ([8],[9]). It typically models the wind speed at some sites where the Weibull function could not accurately model. It is a special case of the Weibull distribution where the value of Rayleigh shape parameter, k is 2 and Rayleigh scale parameter is σ.

In this study, two distribution models were employed, namely the Weibull and Rayleigh distribution models. In order to compare the observed and predicted wind speed frequencies of all locations under study, probability density function for all the locations were plotted against wind speed using MATLAB software as displayed in Fig 1. The geographical information of the station is shown in Table 1.

Table 1: Geographical information of Bauchi site in North-Eastern Nigerian.

| Places | Locality     | Latitude   | Longitude  | Elevation (m) |
|--------|--------------|------------|------------|---------------|
| Bauchi | Bauchi State | 10°17’ N   | 09°49’ E   | 609.7         |

The Weibull PDF is given by:

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

where \(f(v,k,c)\) is the probability of observed wind speed, k is the dimensionless Weibull shape parameter and c is the Weibull scale parameter.

The Cumulative distribution function (CDF) of the Weibull distribution is given by.

$$F(v,k,c) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right]$$ \hspace{1cm} (2)
where $F(v, k, c)$ is the cdf of observed wind speed, $v$, $k$ is the dimensionless Weibull shape parameter and $c$ is the Weibull scale parameter.

The probability density function $q(v)$ of Rayleigh distribution is expressed as:

$$q(v, \sigma) = \frac{v}{\sigma^2} \exp\left[-\frac{v^2}{2\sigma^2}\right]$$ (3)

where $v$ is the observed wind speed $v$, $k = 2$, is the dimensionless Rayleigh shape parameter and $\sigma$ is the Rayleigh scale parameter.

and the Rayleigh cumulative distribution function is given by:

$$Q(v, \sigma) = 1 - \exp\left[-\frac{v^2}{2\sigma^2}\right]$$ (4)

where $Q(v, \sigma)$ is the cdf of the Rayleigh distribution.

The evaluation of the accuracy and performance of Weibull and Rayleigh distributions was done in Table 2.

Table 2: Evaluation of accuracy and performance of Weibull and Rayleigh distributions of Bauchi site located in North-Eastern zone of Nigeria

| Station | Weibull distribution | Rayleigh distribution |
|---------|----------------------|-----------------------|
| Bauchi  | $R^2$ 0.7808   | RMSE 0.0412   | $R^2$ 0.7609 | RMSE 0.0430 |

2.2. Variation of wind speed with height above the Earth’s surface

Generally, wind speed increases with height and wind measurements are obtained at a standard altitude of 10 m above the earth surface. In this work, measurements were taken at an altitude of 3 m. For projects involving wind energy conversion systems, wind speed are estimated at various altitudes using commonly power law stated below.

$$v = v_0 \left(\frac{z}{z_a}\right)^\alpha$$ (5)

where $v$ is the wind speed at the required height $z$, $v_0$ is the wind speed at the anemometer height $z_a$ and $\alpha$ is the surface roughness coefficient. The value of the exponent $\alpha$ varies from less than 0.10 over the tops of steep hills to over 0.25 in sheltered locations ([10]). The typical value for flat coastal regions is 0.143, which is termed the one-seventh power law ([11]). Surface roughness coefficient can also be evaluated from the following expression:

$$\alpha = [0.37 - 0.088\ln(v_0)]/[1 - 0.088\ln(z_a/10)]$$ (6)

From equation (6), $\alpha$ for Bauchi is obtained as 0.23. Weibull probability density function could be used to obtain the extrapolated values of wind speed at different heights. Parameters of Weibull distribution functions $k_z$ and $c_z$ for altitudes $z$ above the anemometer level are obtained using the following relations:
\[ k_z = k_a \left[ 1 - 0.088 \ln(z_a/10) \right] / \left[ 1 - 0.088 \ln(z/10) \right] \]  
\[ c_z = c_a (z/z_a)^n \]

where \( k_a \) and \( c_a \) are respectively, the shape parameter and scale parameter at the anemometer height \( z_a \) and the exponent \( n \) is given by the relation:

\[ n = \left[ 0.37 - 0.088 \ln c_a \right] / \left[ 1 - 0.088 \ln z_a / 10 \right] \]

Table 3 shows parameters and fundamental data of the Weibull distribution.

| Height (m) | n  | k  | c  | \( \nu_{mp} \) | \( \nu_{rms} \) | \( \nu_{mean} \) | \( \nu_{max} \) | \( P_{mc} \) |
|-----------|----|----|----|--------------|-------------|-------------|-------------|----------|
| 3         | 0.23 | 2.22 | 4.08 | 3.12 | 4.34 | 3.61 | 5.45 | 25.04 |
| 10        | 2.45 | 5.38 | 4.35 | 5.58 | 4.77 | 6.85 | 53.11 |
| 50        | 2.86 | 7.79 | 6.70 | 7.85 | 6.94 | 9.38 | 147.91 |
| 60        | 2.91 | 8.13 | 7.03 | 8.17 | 7.25 | 9.73 | 166.79 |

2.3: Evaluation of mean wind power density

The wind power density is the available power of wind per unit area. Its unit of measurement is Watt per square metre (Wm\(^{-2}\)). The power of the wind that flows at speed \( \nu \) through a blade swept area \( A \), increases as the cube of its velocity is given by (Li & Li, 2005).

\[ P(\nu) = \frac{1}{2} \rho A \nu^3 \]  

where \( P(\nu) \) represents the wind power (Watt), \( \rho \) is the mean air density (kgm\(^{-3}\)), and \( \nu \) is the mean wind speed. The commonly used value is \( \bar{\rho} = 1.225 \) kg/m\(^3\) (at average atmospheric pressure at sea level and at 15°C, which depends on altitude, air pressure and temperature). Air density is assumed to be constant since its variation does not significantly affect wind resource calculation.

The power density distribution gives the distribution of wind energy at different wind speeds. It is obtained by multiplying the wind power density with the probability of each wind speed as follows:

\[ \frac{P(\nu)}{A} f(\nu, k, c) = \frac{1}{2} \bar{\rho} \nu^3 f(\nu, k, c) \]  

Weibull mean wind power density is obtained by integrating Eq. (11) for the period of study:

\[ \bar{P} = \frac{1}{2} \bar{\rho} \int_{0}^{\infty} \nu^3 f(\nu, k, c) d\nu = \frac{1}{2} \bar{\rho} c^3 \Gamma \left( 1 + \frac{3}{k} \right) \]
2.4: Wind direction
A wind rose gives a succinct but information-laden view of how wind directions are typically distributed at a particular location. Wind rose plot of Bauchi stations is displayed in fig. 2 and prevailing wind directions determined.

Results and discussions
3.1 Estimated values of Weibull and Rayleigh parameters
From fig.1 and table 2, it was realized that Weibull distribution fitted the wind speed data better than Rayleigh in Bauchi station. The dimensionless shape factor k also determines the shape and width of the distribution while the scale factor c in ms\(^{-1}\) is indicative of mean wind speed. Bauchi correspond to moderate wind site with k values lying between 2 and 3.

3.2 Evaluation of extrapolated wind characteristics
The results of the extrapolated wind characteristics are shown in table 3. Generally, good values of means of monthly wind and power density are obtained at the height of 60 m (\(v_{\text{emc}} = 8.17\text{m/s}, \ P_{\text{mc}} = 166.79\text{W/m}^2\)).

3.3 Conclusion
We have been able to determine the wind power density of Bauchi in North-East, Nigeria. Root mean square error (RMSE) and coefficient of determination (R\(^2\)) were employed in the determination of the accuracy and performance of Weibull and Rayleigh distributions. The results revealed that Weibull distribution gave better fit in Bauchi station. The overall wind direction and frequency were plotted and evaluated. Our analysis of wind rose showed that Bauchi confirmed north-easterly wind as its prevailing direction with an occurrence of 22.1%.

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