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Analysis of wind energy prospect for power generation by three Weibull distribution methods

A. K. Azad*[1], M. G. Rasul[1], Rubayat Islam[2] and Imrul R. Shishir[2]

[1]School of Engineering and Technology, Central Queensland University, Rockhampton, QLD 4702,Australia
[2]Department of Mechanical Engineering, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh

Abstract

Wind energy is one of the fastest growing sectors in renewable energy. These energy resources are freely available throughout the world. It is one of the zero emission energy sources. The wind energy is used mainly for two purposes namely irrigation (water pumping) and electricity generation. The prospect of wind energy can be analyzed by different methods. Weibull distribution method is one of the widely acceptable methods for estimating wind energy. In this paper, the prospect of wind energy in Bangladesh is analyzed by Weibull distribution method. The data were collected from Meteorological Department of Bangladesh located in different areas of the country. Three different Weibull distribution methods were used to find out Weibull parameters which were verified using different widely acceptable statistical tools. Relative percentage error, chi-square error, analysis of variance etc. are the efficient statistical tools to rank the method which was used in this study. The study identified the most prospects windy site by applying efficient least square method with minimum error.

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Keywords: Wind energy; Renewable energy; Weibul distribution; Electricity generation.

1. Introduction

The energy demand is increasing day-by-day [1]. This increasing demand can be met by new and renewable energy sources which are considered as sustainable clean energy sources to lead clean operation and sustainable living [2, 3]. Wind energy is one of the fastest growing renewable energy by zero emission. The world total wind energy production capacity was 318,510 MW in 2013 [4]. Literatures reported that the capacity and growth of wind energy has increased every year but the growth rate per year has decreased and the highest growth rate (64.3%) was found in 1999 and lowest in 2013. So, the wind energy is a prospective sector throughout the world which is mainly used in two purposes namely,

* Corresponding author. Tel.: +61 469 235 722; fax: +61 7 4930 9382.
E-mail address: azad.cqu@gmail.com / a.k.azad@cqu.edu.au

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electricity generation and water pumping [5]. The use of wind energy depends on average wind speed and the variation of wind speed [6]. Several ways are available in the literature to find the most prospective windy sites. For example, two-parameter Weibull distribution has been commonly used in many fields including wind energy assessment, rain-fall, water level prediction etc. [7, 8]. Different research groups have developed different methods to use Weibull distribution for wind data analysis. Rocha et al. [9] studied wind energy generation in the northeast region of Brazil by seven numerical methods. Two key factors in Weibull distribution is used to justify the potential and characteristics of wind energy [10]. The behavior of wind speed is also important to analyze [11] because gusty wind [12, 13] or irregular wind [14, 15] is not suitable for installation of wind turbine for electricity generation [16]. Wind shear is also important parameter for wind data analysis [17]. After selection of prospective windy sites, a proper wind turbine design is needed based on the selected site data [18, 19]. In this study, three numerical methods have been used for determining the value of Weibull parameters [20-23]. These parameters are very important to identify the characteristics of wind and the potential of wind energy [24]. This statistical study involves identifying more prospective site as well as the easiest and efficient way to apply Weibull distribution for wind energy assessment at any site in the world.

2. Methodology

Weibull distribution is one of the widely used statistical methods in wind data analysis [25]. The Weibull shape factor (k) and scale factor (c) are the main variables to express Weibull probability density function and cumulative distribution function (Equation 1) [23, 26]. These two parameters can determine the optimum performance of the wind energy conversion system [27-29].

$$f(v) = \frac{dF(v)}{dv} = (\frac{k}{c})(\frac{v}{c})^{k-1} \times e^{-(\frac{v}{c})^k} \quad \text{and} \quad F(v) = 1 - e^{-(\frac{v}{c})^k} \tag{1}$$

Where, v is the wind speed in m/s, $k > 0$ is the dimensionless shape parameter, and $c > 0$ is the scale parameter in m/s. There are several methods such as power density method; least square method, maximum likelihood method etc. are available in the literature to determine these two factors. The methods are briefly discussed below.

2.1 Power density method (PDM)

This method is one of the important methods to determine k and c. Firstly the energy pattern factor E_{pf} is computed which is defined as a ratio between mean of cubic wind speed to cube of mean wind speed [27, 30-32]. After calculating energy pattern factor, k and c can be determined by Equation 2.

$$k = 1 + \frac{3.69}{E_{pf}^2} \quad \text{and} \quad c = \frac{\bar{v}}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{2}$$

2.2 Least square method (LSM)

This method is commonly applied in engineering and mathematics problems that are often not thought of as an estimation problem. A linear relationship between the two variables can be assumed and after some exclusive calculation for minimizing the relationship, the expression takes the forms of equation 3.

$$k = \frac{n\sum_{i=1}^{n} \ln v \times \ln\left[-\ln\{1 - F(v)\}\right] - \sum_{i=1}^{n} \ln v \times \sum_{i=1}^{n} \ln\left[-\ln\{1 - F(v)\}\right]}{n\sum_{i=1}^{n} \ln v^2 - \left\{\sum_{i=1}^{n} \ln v\right\}^2} \quad \text{and} \quad c = \exp\left[\frac{k\sum_{i=1}^{n} \ln v - \sum_{i=1}^{n} \ln\left[-\ln\{1 - F(v)\}\right]}{nk}\right] \tag{3}$$

2.3 Modified maximum likelihood method (MMLM)

The MMLM can only be considered if the available data of wind speed are already in the shape of the Weibull distribution [33]. For solution of equations in MMLM requires some numerical iteration by Newton-Raphson method [7, 30]. The parameters can be estimated by the equations 4.

$$k = \left[\frac{\sum_{i=1}^{n} v_i^k \ln(v_i) f(v_i)}{\sum_{i=1}^{n} v_i^k f(v_i)} - \frac{\sum_{i=1}^{n} \ln(v_i) f(v_i)}{f(v \geq 0)} \right]^{-1} \quad \text{and} \quad c = \left[\frac{1}{f(v \geq 0)} \sum_{i=1}^{n} (v_i)^k f(v_i) \right]^{1/k} \tag{4}$$

Where, v_i is the wind speed central to bin i, n the number of bins. $f(v_i)$ represents the Weibull frequency for wind speed, and $f(v \geq 0)$ is the probability for wind speed equal to or exceeding zero.

2.4 Statistical tools

Statistical tools are used to find out the efficiency of the methods. It calculates the error percentage and the standard deviation from the practical measured values. These three tools namely, relative percentage error, chi-square error and analysis of variance are used to verify the accuracy of the results.

3. Results and discussions

In this study, ten minute time series wind speed data have been collected by DL9210 anemometer from three wind monitoring stations in Bangladesh. The data has been sorted out according to hourly, monthly and annually mean wind speed for the selected sites. Figure 1 shows the monthly variation of wind speed in Sandwip is higher than Sandwip and Khagrachari. The maximum wind speed (8.34 m/s) was found in April and minimum (2.28 m/s) in May of that site. In other sites, wind speed varies from 2 m/s to 4 m/s. So, Sandwip is more prospective with respect to Mongla and Khagrachari but more analysis is needed on wind steam characteristics. To get more information about the selected sites, anyone can analyse the wind duration curve. A typical wind duration curve is shown in Figure 2. Each point of this curve shows the number of hours in a year for which time either the corresponding velocity or higher velocity occurs. From this Figure, it can be easily visualize which site is the best and the most promising one, all wind duration curves for the selected sites are given in the same Figure. This curve shows good potential of wind energy in Sandwip as the wind speed is higher than other sites for longer period of time. Weibull distribution can give more realistic analysis to findout the characteristics of wind speed and the potential of it. Figure 3 to 5 presents the Weibull distribution analysis by three different methods.

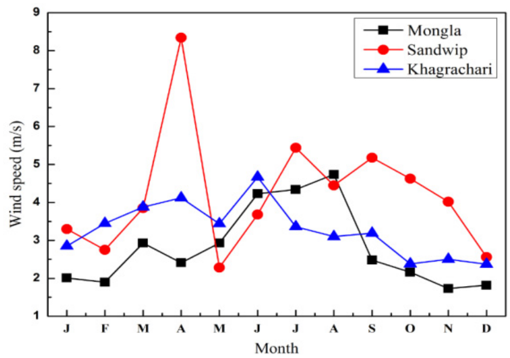

Figure 1: Monthly variation of wind speed in the selected sites.

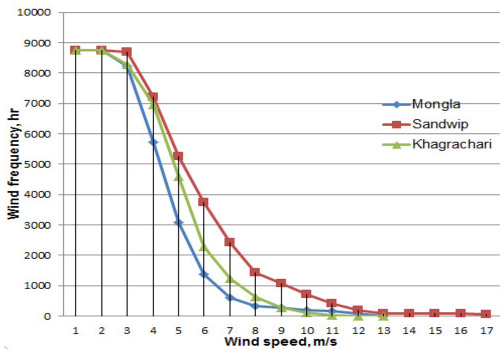

Figure 2: Wind duration curve for the whole year.

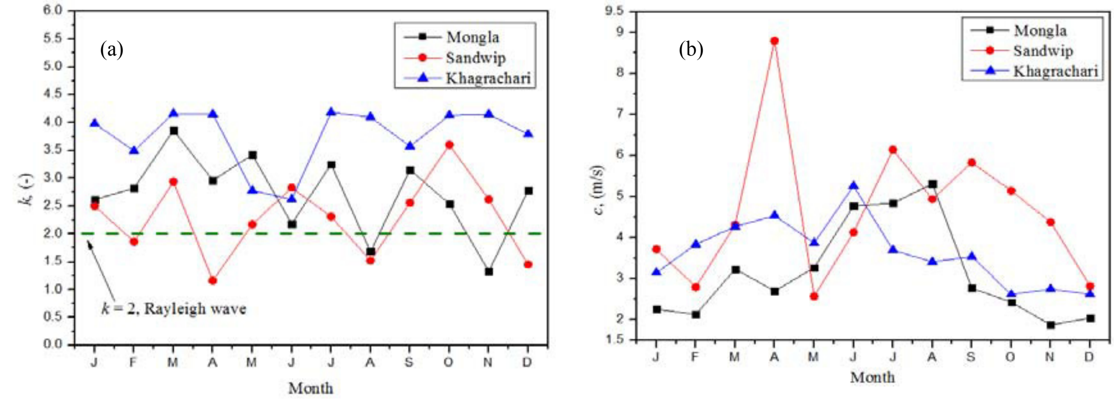

Figure 3: Monthly variation of Weibull (a) shape factor and (b) scale factor by power density method.

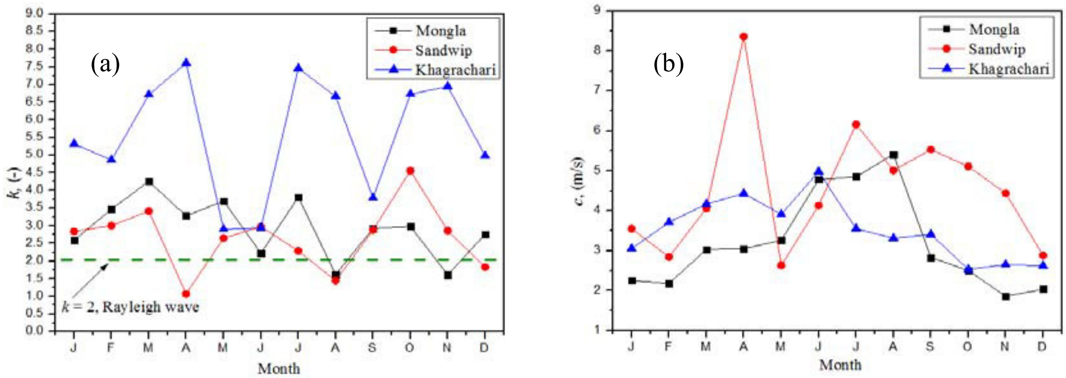

Figure 4: Monthly variation of Weibull (a) shape factor and (b) scale factor by least square method.

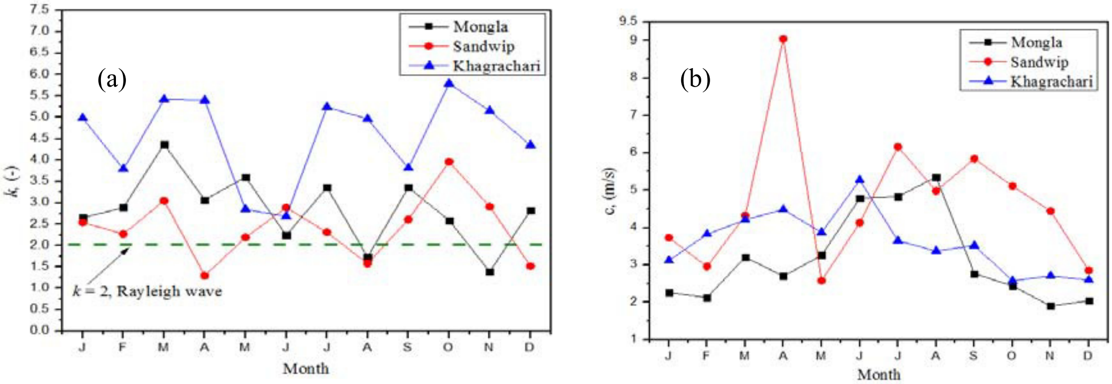

Figure 5: Monthly variation of Weibull (a) shape factor and (b) scale factor by modified maximum likelihood method.

Figures 3 to 5 illustrates the monthly variation of Weibull shape factor (Figure 3a, 4a and 5a) and scale factor (3b, 4b and 5b) for the selected sites. The analysis has been done by three different methods such as power density method, least square method and modified maximum likelihood method. The Figures 3a, 4a and 5a shows the monthly variation of Weibull shape factor in Sandwip is closer to Rayleigh wave (k=2). This indicates that the characteristics of wind are most likely uniform with respect to other sites. In the case of Mongla and Khargachari, the values of k largely differ from the Rayleigh wave. Figures 3b, 4b and 5b present the potential of wind energy where the scale factor curve for Sandwip is above all points except May with respect to other sites. This analysis found Sandwip is more potential site for wind energy application. The statistical error analysis has been conducted on the three used methods to find out the more efficient method. Summary of the results is presented in Table 1.

Table 1. Summary of the statistical analysis of wind speed by three Weibull distribution methods.

Weibull distribution method	Mongla		Sandwip		Khagrachari		Relative percentage of error, (%)	Chi-square error	Analysis of variance
	k(-)	*c(m/s)*	*k(-)*	*c(m/s)*	*k(-)*	*c(m/s)*			
Power density	2.71	3.14	2.29	4.63	3.76	3.63	1.9027	0.000005	0.9992
Least square	2.94	3.17	2.65	4.56	5.58	3.53	-1.0937	0.000001	0.9995
Modified max^{m} likelihood	2.84	3.14	2.43	4.68	4.54	3.60	5.9878	0.000245	0.9896

From the above analysis, it can be clearly seen that negative relative percentage error was found in least square method where chi-square error is also minimum in this method. The standard value of analysis of variance is unity. It also called efficiency of the method. For least square method this value is 0.9995, very closer to 1. So, least square method is more efficient with minimum error compared with power density method and modified likelihood method. So, the analytical values of Weibull factors by least square method are more relevant and comparable with other methods.

4. Conclusions

The potential of wind energy in three prospective windy sites have been studied in this analysis using widely used Weibull distribution technique. The Weibull parameters such as shape factor and scale factor have been calculated by three different methods such as power density method, least square method and modified likelihood method. Relative percentage of error and chi-square error has been analyzed for each method and also calculated the efficiency of these methods. The results found that Sandwip is the more prospective sites compared to Mongla and Khagrachari. The results have been verified by Weibull distribution technique where Weibull shape factor is relatively closer to Rayleigh wave and scale factor is higher than other sites. The statistical analysis also found the least square method is more efficient method with minimum error in the wind data analysis. The study presented the way to apply Weibull distribution for wind data analysis.

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