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Analysis of wind energy conversion system using Weibull distribution

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Abstract

In this study, the wind speed data has been statistically analyzed using Weibull distribution to find out wind energy conversion characteristics of Hatiya Island in Bangladesh. Two important parameters like Weibull shape factor “k” and Weibull scale factor “c” have been calculated by four methods. The probability density function $f(x)$, cumulative distribution function or Weibull function $F(x)$ have been used to describe the best wind distribution between observed and theoretically calculated data. There are six statistical tools used to analyze the goodness of curve fittings and precisely rank the methods. For a selected month the Weibull shape factor was found to be very close to the Raleigh function $k=2$ indicating the characteristics of wind wave are regular and uniform. For the other period ‘k’ varies between 1.99 to 3.31 and ‘c’ between 2.83 to 7.25 m/sec. The study found that more than 58% of the total hours in a year have wind speed above 6.0 m/s in Hatiya, therefore this site has enough available power to drive a small wind turbine for electricity generation. The proposed methodology can be used in any windy site to easily identify the potentiality of wind power.

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1. Introduction

In planning of offshore wind farm, analyzed the probability distributions for short term wind speeds. Short-term wind speeds play a central role in estimating various engineering parameters, such as power output, extreme wind load, and fatigue load [1, 2].

Nomenclature

v	Wind speed in m/sec.
k	Weibull shape factor.
c	Weibull scale factor in m/sec.
$F(x)$	Cumulative distribution function.
$f(x)$	Probability density function.
\bar{v}	Mean wind speed, m/sec.
σ	Standard deviation.
Γ	Gamma function.
\mathcal{E}_{vi}	Error.
W_{vi}	Observed frequency of wind speed.

In general, wind power prediction methods are categorized into two groups: physical and statistical. The first one implies physical considerations such as topography, terrains, local temperature and pressure to estimate the wind field more accurately and, subsequently, the energy potential [3]. The later one, on the other hand, use statistical models in order to establish the relationship between power and other variables as well as their historical and forecasted values [4, 5]. Weibull distribution provides better fit to probability distributions compared to Rayleigh model and analyzes the wind speed data by using statistical distributions [6, 7]. The Weibull distribution (named after the Swedish physicist W. Weibull, who applied it when studying material strength 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 distributions for application in wind loads studies for some time [8, 9]. For more than half a century the Weibull distribution has attracted the attention of statisticians working on theory and methods as well as various fields of statistics [10]. The research related to wind energy in Bangladesh originated as early as in 1979 in collaboration with Free University of Brussels (FUB), Belgium. In this work, only two islands (Hatiya and Sandwip) were selected due to its geographical location and by considering other factors such as potential of wind power, difficulties of fuel transportation by road etc. Hatiya is situated between 22°26' north latitude to 91°6' east longitude and Sandwip is situated in between 22°29' north latitude to 91°26' east longitude. These two islands are separated by Bangla-channel and the greatest Bay of Bengal Sea. So, the selected sites have more potential of wind energy to develop the country.

2. Outline of methodology

There are several methods by which Weibull shape factor “ k ” and scale factor “ c ” can be determined. In this work, there are four popular methods have been used to determine Weibull parameters, these are: a) Graphical method, b) Method of moments (MOM), c) Empirical method and d) Equivalent energy method. The Weibull distribution function, which is a three-parameter function, but for wind speed, it can be expressed mathematically in two parameter model as follows [11].

$$f(v) = \frac{dF(v)}{dv} = \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} \times e^{-\left(\frac{v}{c}\right)^k} \quad (1)$$

Where, v is the wind speed in m/s, $k > 0$ is the dimensionless shape parameter, and $c > 0$ is the scale parameter with the same unit as wind speed. Weibull's cumulative distribution function can be expressed by [12]

$$F(v) = 1 - e^{-\left(\frac{v}{c}\right)^k} \tag{2}$$

Four methods used in this study are briefly defined below –

a) Graphical method (GM): The Weibull paper is constructed in such a way that the cumulative Weibull distribution becomes a straight line, with the shape factor k as its slope. Taking logarithm in both sides of the (Equation 1) can be rewritten as [13] -

$$-\ln\{1 - F(v)\} = k \ln(v) - k \ln(c) \tag{3}$$

b) Method of moments (MOM): The method of moments is one of the common techniques used in the field of parameter estimation. If \bar{v} represent the mean wind speed data then the value of k and c can be easily determined by the following equations [13] –

$$\bar{v} = c \Gamma\left(1 + \frac{1}{k}\right) \text{ and } k = \left(\frac{0.9874}{\frac{\sigma}{\bar{v}}}\right)^{1.0983}$$

c) Empirical method: In the empirical method, Weibull shape factor k and scale factor c can be estimated by the following equations [13-14]

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \text{ and } c = \frac{\bar{v}}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{5}$$

d) Equivalent energy method: The estimate of the parameter k may be obtained from an estimator of least squares. By this method, the parameters k and c are determined using the equations given below [14].

$$\sum_{i=1}^n \left[W_{vi} - e^{-\left[\frac{(v_i-1)\left\{\Gamma\left(1+\frac{3}{k}\right)\right\}^{1/3}}{(v_m^3)^{1/3}}\right]^k} + e^{-\left[\frac{(v_i)\left\{\Gamma\left(1+\frac{3}{k}\right)\right\}^{1/3}}{(v_m^3)^{1/3}}\right]^k} \right]^2 = \sum_{i=1}^n (\varepsilon_{vi})^2 \text{ and } c = \left(\frac{v_m^3}{\Gamma\left(1 + \frac{3}{k}\right)}\right)^{1/3} \tag{6}$$

3. Statistical analysis

The wind speed data is statistically analyzed to find out different wind characteristics of the selected sites. The ten years annual mean wind speed data is shown in Figure – 1. It is clear from the Figure that the wind speed at Hatiya Island is more than Sandwip. In Hatiya, from 1998 to 2004 annual mean wind speed was above 6.5 m/s, while at that

time Sandwip wind speed was just above 3.5 m/s. In order to get more clear idea of these two Islands, monthly and hourly variation of wind speed distribution is presented here, and Figure 2 shows the hourly mean wind speed measured at one of the selected wind site throughout the year in the Hatiya Island.

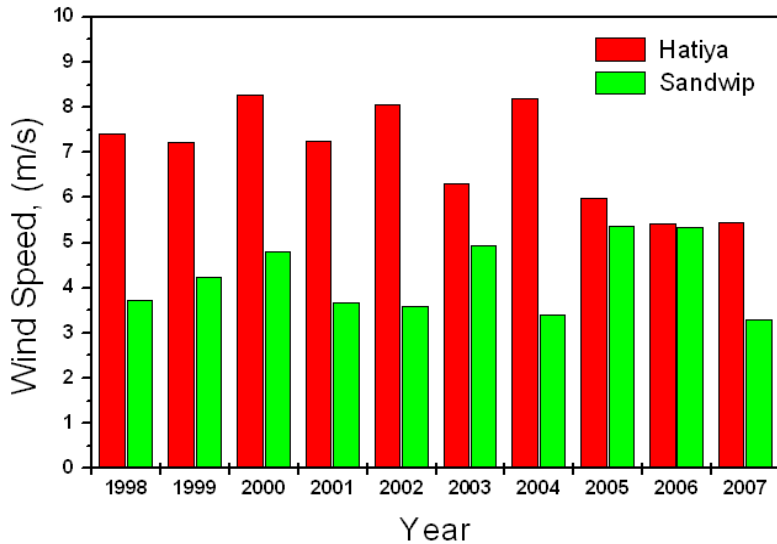


Fig. 1. Ten years annual mean wind speed between Hatiya and Sandwip.

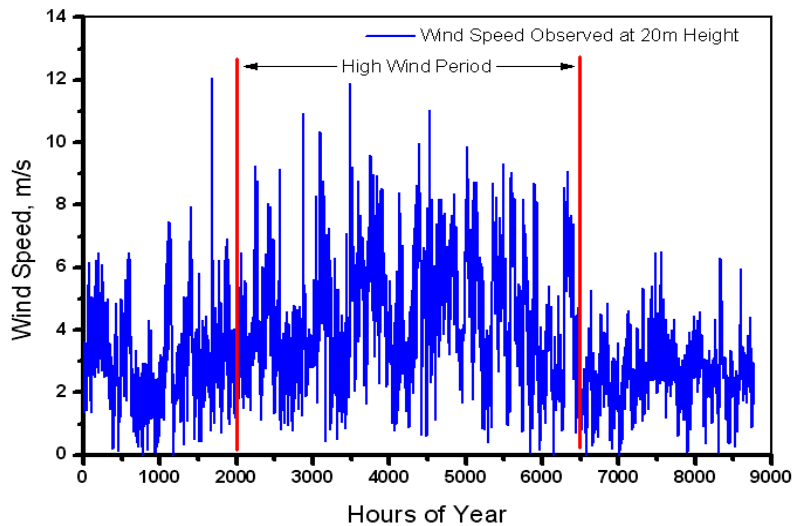


Fig. 2. Hourly mean wind speed variation at Hatiya throughout the year.

The data could be roughly classified into high wind period from April to September and low wind period from October to March, as marked by the vertical broken lines reflecting different monsoons. Using Table 1 represents the Weibull shape factor (k) and scale factor (c) which was determined and analyzed. It can be seen from Table 1 that in almost every month except September and November (by energy pattern factor method) the value of k is

greater than two i.e. Weibull functions follow very closer to the Raleigh function ($k=2$) for the selected sites. The Weibull shape factor is very important factor to know about the characteristics of the wind wave of a particular wind site. The value of k remains closer to 2, which means that the wind wave is regular and uniform in nature. It varies 1 to 4 according to the nature of wind wave. The Weibull scale factor (c) remains between 3.42 to 8.56 m/sec which indicates the potentiality of the wind power of that site. Greater the value of c means the more potential of wind sites.

Table 1. The value of Weibull parameters analyzed by different methods for Hatiya Island.

Month	Graphical method		MOM method		Empirical method		Equivalent energy method	
	k	c	k	c	k	c	k	c
January	2.50	4.51	2.24	4.96	2.85	3.98	2.92	3.42
February	3.00	5.02	2.51	5.61	3.38	4.99	3.31	4.96
March	3.10	4.98	2.38	5.06	3.09	4.98	3.04	4.92
April	2.55	6.58	2.22	7.04	3.01	6.65	3.05	6.56
May	2.40	6.61	2.14	7.36	2.51	6.62	2.64	6.48
June	2.70	6.79	2.29	6.59	2.89	6.75	3.01	6.66
July	2.83	7.58	2.41	7.99	3.32	7.48	3.12	7.42
August	2.18	7.99	2.11	8.56	3.32	7.67	2.58	7.52
September	2.10	7.12	2.09	7.85	2.45	6.46	1.95	6.46
October	2.70	4.23	2.36	6.12	2.72	4.59	2.71	3.83
November	2.93	4.53	2.39	5.11	2.13	4.30	1.99	4.24
December	2.15	3.59	2.04	4.09	2.05	3.42	2.02	3.44

Table 2. Statistical analysis/ goodness of curve fitting of Weibull distribution.

Statistical methods	Weibull parameters		Statistical test efficiency					
	k	c	RPE (%)	RMSE	MPE (%)	MAPE (%)	Chi-SE χ^2	Effic. R^2
	(-)	(m/s)						
Graphical method	2.60	5.79	0.8860	0.1730	0.6520	1.7146	0.0460	0.9200
Method of moments (MOM)	2.27	6.36	-0.5450	0.1470	-0.5370	0.5750	0.0019	0.9990
Standard deviation method	2.81	5.66	1.7680	0.2610	2.3910	3.5380	0.2456	0.9520
Equivalent energy method	2.69	5.49	0.4810	0.1370	0.6560	1.5980	0.0245	0.9920

The goodness of curve fitting depends on the accuracy of the Weibull parameters. The more effective methods in determining the Weibull factors for the available data, six statistical test tools like relative percentage of error (RPE), root mean square error (RMSE), mean percentage of error (MPE), mean absolute percentage of error (MAPE), chi-square error (χ^2), and analysis of variance (R^2) were used to precisely rank the methods. Table 2, shows that the efficiency of the methods is relatively closer but MOM method shows more efficient and lower percentage of error. So, MOM is the best method than any other methods to determine the Weibull distribution. The value of ' c ' varies between 3.42 m/s to 8.56 m/s. Maximum value reaches at 8.56 m/s in August and minimum at 3.42 m/s in January. In high wind period from April to September, Hatiya have higher value of c than other periods. By using the value of k and c by MOM method a comprehensive study of observed and theoretical pdf and Weibull function is discussed below. Figures 3 to 5 compare the theoretical probability density functions with observed wind speed histogram in bin size of 1 m/s for April to September as representative of high wind month. Therein the corresponding cumulative probability distributions are also plotted.

These Figures, have shown the fitting of Weibull probability density function $f(v)$ and Weibull function for both observed data and calculated data. The curve fittings for every month has shown in the same Figure so that it can easily identify which months have more wind potential and closely fitted the curves between each other. In all of the figures for Hatiya have shown that the observed and calculated data are closely fitted with each other except only little variation in August. Closely fitting of the curves means there more potential of wind power and energy density is more in the wave of the wind there.

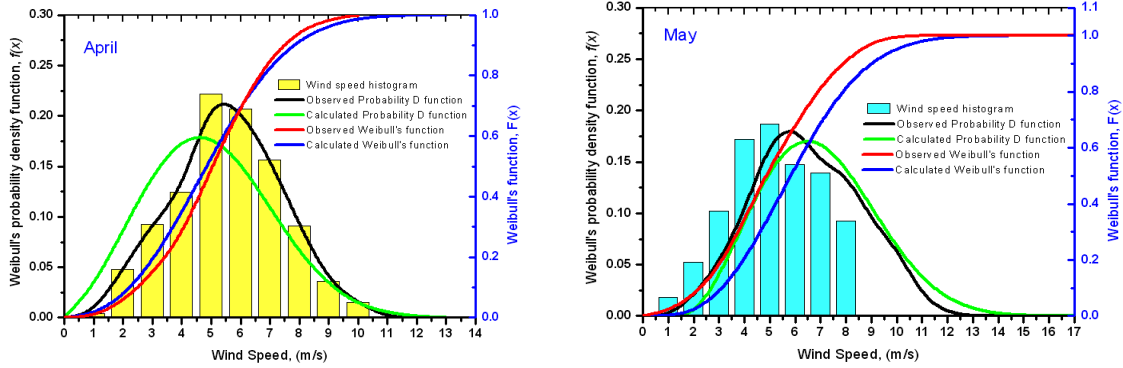


Fig. 3. Comparison between theoretical and observed probability density function, Weibull function and observed wind speed histogram for April and May.

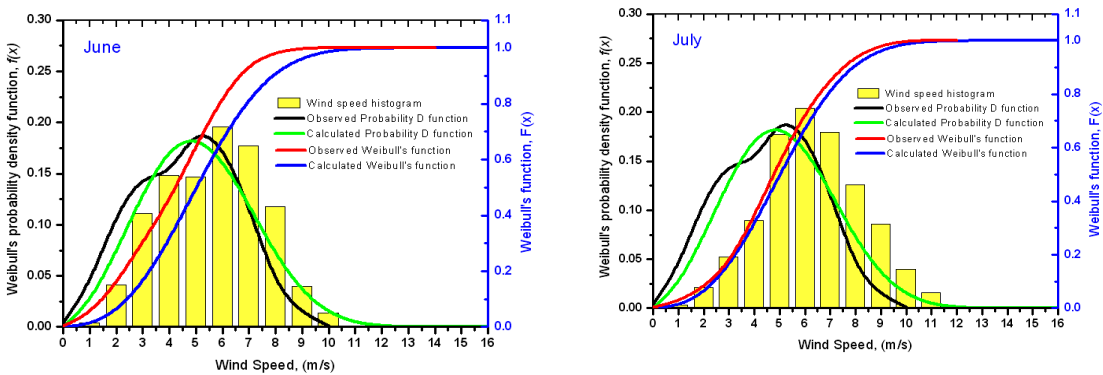


Fig. 4. Comparison between theoretical and observed probability density function, Weibull function and observed wind speed histogram for June and July.

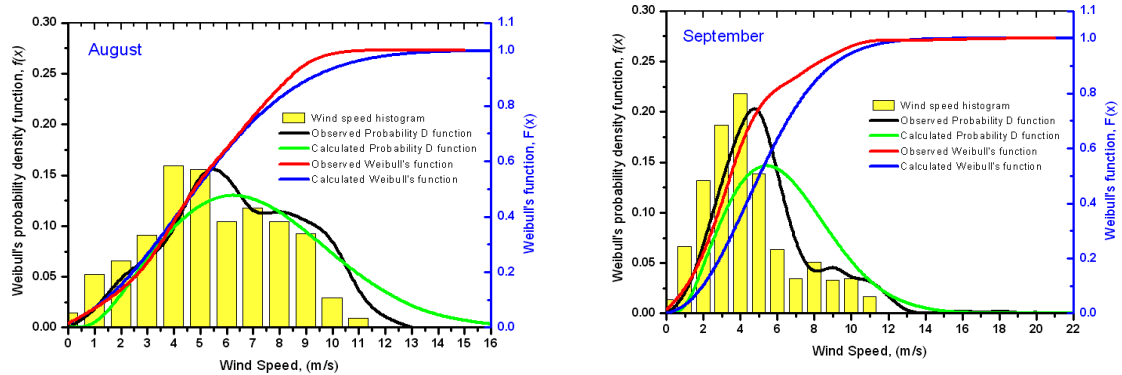


Fig. 5. Comparison between theoretical and observed probability density function, Weibull function and observed wind speed histogram for August and September.

On the basis of the Weibull distribution, several important quantities concerning wind characteristic in Hatiya Island are calculated for each month. As shown in Table 2, shape parameter lies between 1.99 and 3.31 and scale parameter is greater than the corresponding mean speed by about 2.5%. The speed carrying maximum energy is stronger than the mean speed and the most probable speed. Basically, different wind parameters reflect different wind regimes or energy potential determining these parameters accurately for particular time period is necessary for the applications of wind energy.

4. Conclusion

In the present study, the wind characteristics of Hatiya Island were investigated systematically. The monthly mean wind speed of Hatiya Island was found to be relatively higher velocity (2.62 to 14.01 ms^{-1}). But from April to September wind speed shows higher speed with minimum fluctuation which indicate high speed wind period. During the analysis of wind characteristics, it has been shown the closely matching of the curves for Weibull probability density function and Weibull function both observed and calculated data in the selected month. More than 58% of the total hours in a year have wind speed above 6.0 m/s in Hatiya. So, this site has enough available power to drive a small wind turbine for electricity generation. Two important parameters which described the characteristics of wind wave have been calculated by four methods. There were six statistical tools used to determine the goodness of curve fittings for the selected methods. The Weibull shape factor follows very closer to the Raleigh function $k=2$ for the selected site which means that the characteristics of wind wave is regular and uniform. However, for the other period the range of ' k ' is from 1.99 to 3.38 and that of ' c ' value is from 3.42 to 8.56 m/s.

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