DUJASE Vol. 6 (2) 99-108, 2021 (July) *https://doi.org/10.3329/dujase.v6i2.59225*

Wind speed Weibull distribution and wind energy potential of Chandpur, Bangladesh

Himangshu Ranjan Ghosh

[1] *Institute of Energy, University of Dhaka, Dhaka-1000, Bangladesh*

E-mail: hrghosh@du.ac.bd

Received on 14 June 2021, Accepted for publication on 16 October 2021

ABSTRACT

Weibull distribution goes particularly well with wind speed data and is necessary to assess wind energy harnessing potential at a site. For the best estimation of the statistical distribution parameters at Chandpur (23.21116° N; 90.64237° E), located at the southern part of Bangladesh, six models: graphical method, method of moments, power density method, Justus method, Lysen method and maximum likelihood method have been analyzed for 18.8 m, 40.2 m and 59.9 m above ground level (AGL) using measured wind speed data for 2014-2017. Out of the six models, Justus method has showed the best result for estimation of Weibull parameters at all heights AGL with average RMSE of 0.0082 and R^2 of 0.9650. Further more to evaluate the wind energy potential at modern wind turbine hub height of 100 m, firstly the wind shear exponent at the site (the average value is 0.37 considering the 10 m elevation of the site above sea level) is estimated from the wind data of 3 heights; secondly average wind speed (4.88 m/s), wind power density (108.8 Wm^{-2}), Weibull distribution parameters (shape factor 2.29 and scale factor 5.33 m/s) and wind turbine power curve related wind speeds (cut in 2.28 m/s, rated 9.33 m/s and cut out 21.03 m/s)have been extrapolated at the hub height. The average wind speed and wind power density values show that the class of the site is 1 in the worldwide accepted wind power classification, based on long term practical wind farm installation experiences; the low cut in speed (<3 m/s) shows that suitable wind turbines for the site are commercially unavailable for the site and turbines with 3 m/s cut in speed have average annual capacity factor of 16.62 %, less than the commercially viable capacity factor >25 %. The wind power class (< class 3) and capacity factor (<25 %) strictly reveals that Chandpur is not suitable for wind energy exploration in near future until a high technical improvement of wind turbines and reduction of relevant costs.

Keywords: Weibull distribution, Wind energy, Wind power density, Most probable wind speed, Wind speed with maximum energy, Wind power class, Capacity factor.

1. Introduction

For social development and economic growth, one needs energy. Percentage of wind energy has been growing rapidly due the limitations of fossil fuels, especially the environment pollution and fuel cost.

Wind speed varies over space and time. Therefore, the knowledge of wind characteristics are essential for wind energy engineers to do micro siting and for wind turbine manufacturers to design their wind turbines for optimal performance [1]. Belu and Koracin [2] have estimated the wind potential in western Nevada and heir results have shown that the maximum seasonal wind speeds occur during the spring, a minimum during the late morning and a maximum during the late afternoon. Gokcek and Genc [3] have investigated the wind energy generation potential and cost in Central Anatolian-Turkey using time-series approach and the economic evaluation of various wind energy conversion systems (WECSs). Mostafaeipour [4] has statistically analyzed the wind speed of some major cities in Yazd province of Iran utilizing wind data of almost 13 years from 11 stations. He extrapolated wind data at different heights using Power law and for optimal selection of wind turbines he designed the wind turbine parameters based on wind data characteristics. The study found that most of the stations in Yazd have an annual average wind speed lower than 4.5 m/s which is considered as too low for a wind turbines installation. Diaf and Noton [5] have investigated the wind energy potential and economic analysis in 13 locations in Algeria. They examined technical and economic evaluations of electricity generation from different commercial wind turbines and the wind resource appears to be suitable for power production in the southern region of Algeria.

The frequency of wind speeds represents the percentage of occurance for each speed interval, whereas the statistical distribution of the wind speeds presents the wind speed data as a continuous function, important for more accurate wind potential analysis. There are different distribution functions[6, 7], as Weibull, Rayleigh, Johnson, Pearson, and Chi square distribution. Among these methods, the two parameter Weibull distribution function, a special case of gamma distribution [5], is versatile, qualified and accurate for determination of wind characteristics. When fitting the wind data in Weibull distribution, various methods have been studied to calculate the unknown parameters of the distribution [4]. Aynur and Figen [8] have worked with wind data insome locations of the coastal regions of Turkey. The mean annual value of Weibull shape parameter k is between1.54 and1.86 while the annual value of scale parameter c is between 2.52 m/s and 8.34 m/s.

To analyze the wind energy potential at a site one needs to find out the efficient method that gives the best fitting for wind speed data for the site, as wind speed has a cubic relation with wind power and estimated power may have a significant error even a small variation in wind speed distribution characteristics. In this study, six different methods for estimation of Weibull distribution parameters have been evaluated by two statistical error tools. Along with selection of a best method of Weibull parameters estimation, the wind shear exponent and at a desired hub height of 100 m, the Weibull parameters, wind power density, most probable wind speed, wind speed with maximum energy, three operating wind speeds of a wind turbine have been estimated and evaluated to find out the wind energy harnessing potential at Chandpur (23.21116^0 N, 90.64237^0 E), which is located in the southern part of Bangladesh.

2. Materials and Methods

Wind speed probability distribution

In probability theory and statistics, the Weibull distribution is a continuous probability distribution [9]. It probability density function (PDF) has three parameters: shape parameter, location parameter and scale parameter. But in wind energy applications the two parameter Weibull PDF is mostly used and expressed by [10,11]:

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

Where,

$v > 0$ is the wind speed in m/s

$k > 0$ is a dimensionless factor and known as shape parameter

$c > 0$ in m/s and known as scale parameter

k and c indicate how peak the wind speed distribution and how 'windy' a location under consideration respectively [12]. For most of the cases value of k and c vary from 1.5 to 3 and from 3 to 8 m/s respectively [13]. Most of the wind turbine manufacturers produce their turbines considering the value of $k = 2$ as default of the Rayleigh distribution and hence turbines fail to give optimal performance in the real world.

In this distribution, the cumulative distribution function, CDF, $F(v)$ represents the probability of the speed vm/s to be lower than a certain value v_0 m/s and given by the following equation.

$$F(v \le v_0) = 1 - e^{-\left(\frac{v_0}{c}\right)^k} \tag{2}$$

Mostly used six numerical methods for Weibull distribution parameter estimation are described below.

Graphical method (GM)

This method takes a double logarithmic transformation of CDF, expressed in Eq. (2)

$$\ln[1 - F(v \le v_0)] = \ln[e^{-\left(\frac{v_0}{c}\right)^k}]$$

Or,

$$\ln[-\ln\{1 - F(v \le v_0)\}] = kln(v_0) - \mathrm{kln(c)} \tag{3}$$

Equation (3) has a straight-line form of

$$y = mx + a \tag{4}$$

Where,

$y = \ln[-\ln\{1 - F(v \le v_0)\}]$

$m = k$

$x = \ln(v_0)$

$a = -kln(c)$

Thus the Weibull distribution parameter, k can be found from the slope of the straight line and other parameter, c can be found from the slope and y intercept as follows.

$$\frac{a}{m} = \frac{-kln(c)}{k}$$

Or,

$$c = e^{-(^a/_m)} \tag{5}$$

To find the values of m and $a$in the linear regression equation following statistical formulas can be used for n pairs of (x, y) values [14].

$$m = \frac{n\sum_1^n xy - \sum_1^n x \sum_1^n y}{n\sum_1^n x^2 - (\sum_1^n x)^2}$$

$$a = \frac{\sum_1^n y \sum_1^n x^2 - \sum_1^n x \sum_1^n xy}{n\sum_1^n x^2 - (\sum_1^n x)^2} \tag{6}$$

This method is also known as least square regression method as it uses the concept of least squares [14, 15].

Method of moments (MM)

From the raw data the mean, $\bar{v}$ and standard deviation, σ of the measured wind speed can be derived using the following two equations.

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{7}$$

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(v_i - \bar{v})^2} \tag{8}$$

Here, v_i is the wind speed measured at the time interval i and n is the number of data.

Utilizing the Weibull parameters the mean and standard deviation can be calculated as follows [16].

$$\bar{v} = c\Gamma\left(1 + \frac{1}{k}\right) \tag{9}$$

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

Where, Γ is the gamma function.This function is defined for a variable, $x > 0$ in improper integral form, known as Euler's integral of the second kind.

$$\Gamma(x) = \int_0^{\infty} x^{x-1} e^{-t} dt \tag{11}$$

Where, t is just a variable of integration. Any definite integral that has one or more infinite limits of integration, or an integrand that approaches infinity within its limits of integration is known as an improper integral.

The coefficient of variation (COV) demonstrates the mutability of wind speed [17, 18] and can be represented as:.

$$COV=\frac{\sigma}{\bar{v}}=\sqrt{\frac{\Gamma\left(1+\frac{2}{k}\right)}{\Gamma^2(1+\frac{1}{k})}-1} \tag{12}$$

Taking square of Eq. (12), one gets the following equation.

$$\left(\frac{\sigma}{\bar{v}}\right)^2=\frac{\Gamma\left(1+\frac{2}{k}\right)}{\Gamma^2(1+\frac{1}{k})}-1 \tag{13}$$

If the mean and standard deviation of the wind speed are known from Eqs. (7) and (8), then using Eqs. (13) and (9) one can find the value of shape parameter, k [19] and scale parameter, c.

Empirical method of Justus

One needs deep mathematical knowledge to find out the value of shape factor, k from Eq. (13). However, Justus [15] determined an acceptable approximation for k as Eq. (14).

$$k=\left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \tag{14}$$

Where, $1\leq k\leq 10$.

Justus [20] examined that k appears to be proportional to the square root of the mean wind speed.

$$k=d_1\sqrt{\bar{v}} \tag{15}$$

In this study, Eq. (14) has been used to find the value of k for empirical method of Justus the. For other Weibull distribution parameter, c, Eq. (9) has been solved.

Empirical method of Lysen

Lysen [21] estimated k using similar procedues of Justus given by Eq. (14). However He estimated the scale parameter, c follows.

$$c=\bar{v}\left(0.568+\frac{0.433}{k}\right) \tag{16}$$

Power density method (PDM)

It is based on an energy pattern factor [22], E_{pf}, a ratio of mean of cubic wind speed to cube of mean wind speed. Thus the PDM method is also known as energy pattern factor method.

$$E_{PF}=\frac{\overline{v^3}}{(\bar{v})^3} \tag{17}$$

Where,

$\overline{v^3}$ is the mean of the cube of the wind speeds

$(\bar{v})^3$ is the cube of mean the wind speeds

After calculating the E_{pf} byEq. (17), the Weibull parameters can be found from Eqs. (18) and (9).

$$k=1+\frac{3.69}{E_{pf}^2} \tag{18}$$

Maximum likelihood method (MLM)

In statistics, MLM is generally used by maximizing a likelihood function [23]. If x_1, x_2, x_3, …….., x_n be a random sample of size n drawn from a population with probability density function $f(x_i,\underline{\lambda})$, where $\underline{\lambda}=(k,c)$ is an unknown vector of parameters, then the likelihood function is [24]:

$$L=f(k,c)=\prod_{i=1}^{n}f(x_i,\underline{\lambda})$$

The maximum likelihood of $\underline{\lambda}=(k,c)$, which maximizes L when

$$\frac{\partial lnL}{\partial\underline{\lambda}}=0$$

Likelihood of Weibull probability density function for n random samples of wind is given as [25, 26].

$$L(v_i,k,c)=\prod_{i=1}^{n}\left\{\left(\frac{\mathrm{k}}{\mathrm{c}}\right)\left(\frac{v_i}{\mathrm{c}}\right)^{\mathrm{k}-1}\mathrm{e}^{-\left(\frac{v_i}{c}\right)^{\mathrm{k}}}\right\} \tag{19}$$

On taking the logarithms of both sides of Eq. (19), one obtains the log-likelihood function:

$$\begin{aligned}\ln(L)=nln(k)-nkln(c)+(k-1)\sum_{i=1}^{n}\ln(v_i)\\-\sum_{i=1}^{n}\left(\frac{v_i}{c}\right)^k\end{aligned} \tag{20}$$

The maximum of the likelihood function can be estimated by differentiating Eq. (20) and equating to zero.

$$\frac{\partial lnL}{\partial c}=0=-n\left(\frac{k}{c}\right)+\left(\frac{k}{c}\right)\sum_{i=1}^{n}\left(\frac{v_i}{c}\right)^k \tag{21}$$

$$\begin{aligned}\frac{\partial lnL}{\partial k}=0=\left(\frac{n}{k}\right)+\sum_{i=1}^{n}\left(\frac{v_i}{c}\right)^k\\-\sum_{i=1}^{n}\left(\frac{v_i}{c}\right)^k ln\left(\frac{v_i}{c}\right)\end{aligned} \tag{22}$$

From Eqs. (21) and (22) one can get the equations of Weibull parameters k and c.

$$c=\left[\frac{1}{n}\sum_{i=1}^{n}(v_i)^k\right]^{\frac{1}{k}} \tag{23}$$

$$k = \left(\frac{\sum_{i=1}^{n} (v_i)^k \, ln(v_i)}{\sum_{i=1}^{n} (v_i)^k} - \frac{\sum_{i=1}^{n} ln(v_i)}{n} \right)^{-1} \tag{24}$$

Equation (24) is difficult to solve as it does not have a closed form of solution [27]. To solve this equation numerical iteration like Newton-Raphson method can be used to get approximate real roots (up to any degree of precision). When the value of k is obtained we can easily find the value of c from Eq. (23).

Wind speed and distribution parameters at desired height

In most cases the wind speed sensor are set at 10 m as per the recommendations of World Meteorological Organization (WMO). Current wind energy harvesting systems, e.g. wind turbines have hub heights at around 100 m, where measured data are not generally available.

The atmospheric boundary layer affects the wind and its distribution pattern varies with increase of height from the ground [28]. Thus, to predict wind speed Weibull distribution parameters at the desired hub height of a wind turbine, one needs to follow a consistent relationship.

Wind speed value at desired height

To predict the wind speed at the desired hub height of wind turbines researchers have developed different relationships [29, 30, 31]. Hellman [32] suggested the power law equation, Eq. (25), which is simple but yet useful in modelling the vertical wind profile [19].

$$\frac{v_2}{v_1} = \left(\frac{z_2}{z_1} \right)^{\alpha} \tag{25}$$

Where

v_1 is the measured wind speed at reference height $z_1$meter

v_2 is the predicted wind speed at desired height z_2 meter

α is the wind friction/Hellman exponent/power law exponent/wind shear exponent

The exponent, α is highly site specific as it changes with the wind speed at reference height [33], atmospheric stability [34] and the surface roughness [35]. Moreover, its value changes with time of the year from less than 1/7 during the day to more than 1/2 at night [36] and many measurements around the world shows the average value of α to be about 1/7[20]. In principle, this value is only appropriate for a smooth terrain, i.e. a typical rural terrainwith surface roughness ~ 1 cm and up to the first 200 m from the sea level during near-neutral (adiabatic) conditions [35, 36].

Wind speed distribution at desired height

If the Weibull shape parameter, k_1 and scale parameter, c_1 are known at any reference height z_1, then the values of Weibull shape parameter k_2 and scale parameter c_2 at other height z_2 can be estimated utilizing the following equations [19].

$$\frac{k_2}{k_1} = \frac{1 - 0.0881 ln\left(\frac{z_1}{10}\right)}{1 - 0.0881 ln\left(\frac{z_2}{10}\right)} \tag{26}$$

$$\frac{c_2}{c_1} = \left(\frac{z_2}{z_1} \right)^{n} \tag{27}$$

Where, z_1, z_2 are in meters and

$$n = \frac{0.37 - 0.0881 ln \, c_1}{1 - 0.0881 ln\left(\frac{z_1}{10}\right)} \tag{28}$$

Wind power assessment

Wind turbine utilizes the kinetic energy of wind and transforms it to other usable energy forms, depending on the end uses. If wind speed statistical distribution parameters are known then one can evaluate a site for wind energy applications in the following ways.

Wind power density (WPD)

One strong tool to evaluate a site for wind energy potential is WPD (Wm^{-2}), which istheamountofenergy available per unit time inaunitareaofwind turbines. There areseveral approaches to estimate the WPD [37, 38]. The average kinetic energy of n number of air streamsin a month or a year at speed v_i with frequency of occurrence f_i in different intervals, per unit time that is power, per unit area, available for the turbine is

$$WPD = \frac{1}{2n} \rho \sum_{i=1}^{n} v_i^3 f_i$$
$$= \frac{1}{2n} \rho \bar{v}^3 \tag{29}$$

Where,

$\rho$is theaverage airdensity for a specific period. Most of the researchers have considered a standard value of air density, which is $1.225 \, kgm^{-3}$ at standard testing conditions atmean sea level with a mean temperature of $15^0 \, C$ and pressure of 1atm [39].

If the wind speeds have a probability density function $f(v)$, more accurate WPD can be estimated from Eq. (30).

$$WPD = \frac{1}{2} \rho \int_0^{\infty} v^3 f(v) dv \tag{30}$$

From Weibull distribution parameters WPD can be estimated by Eq. (31) [40].

$$WPD = \frac{1}{2} \rho c^3 \Gamma(1 + \frac{3}{k}) \tag{31}$$

Most probable wind speed and Wind speed with maximum energy

In the wind distribution the two wind speeds differ from the wind speed with highest frequency and the highest wind speed respectively as in the raw data, because wind speed raw data forms a non-continuous distribution, whereas

Weibull probability density function forms a continuous wind speed distribution and a highest wind speed would carry a low amount of energy if it has a low frequency.

If the Weibull parameters are known, the values of the most probable wind speed, v_{mp} and wind speed with maximum energy, v_{max} can be determined by using the following expressions [16]:

$$v_{mp} = c\left(1 - \frac{1}{k}\right)^{1/k} \tag{32}$$

$$v_{max} = c\left(1 + \frac{2}{k}\right)^{1/k} \tag{33}$$

Operating speeds of wind turbine

A wind turbine is generally described by its power curve with three characteristic wind speeds, e.g., cut in, rated and cut out wind speeds. The rated wind speed should be close to the wind speed with maximum energy, $v_{max,}$ as turbines perform efficiently at this speed. Three important wind turbine operating speeds can be determined using Eq. (34) [41]

$$\begin{gathered} v_{max} \leq v_F \leq (2\ to\ 4)\ v_{max} \\ (1.5\ to\ 3) v_{mp} \leq v_R \leq v_F \\ 0.3\ v_{mp} \leq v_C \leq 0.8\ v_{mp} \end{gathered} \tag{34}$$

Where

v_F is the furling velocity (m/s) in which the system will shut off

v_R is the velocity (m/s) in which the turbine will be running at its full rating

v_C is the cut-in velocity (m/s) when the turbine starts to rotate

Annual capacity factor of wind turbines

One can predict the electrical power output of a wind turbine utilizing its power curve and relevant characteristic wind speeds, while the performance of a wind turbine can be estimated from the annual capacity factor, which is a unitless ratio of an actual electrical energy output over a given period to the maximum possible electrical energy output over that period. At an expected wind farm site researchers recommend a wind turbine when it has an annual capacity factor greater than 0.25, where the value greater than 0.40 indicates a strong potential of the turbine [29, 42].

A wind energy conversion system can operate at its maximum capacity factor when it is designed following the expected cut in, rated and cut out wind speeds at a site and hub height. In reality wind turbine installers use commercially available wind turbines as customization of the technologies is not always cost effective. Hence wind farm investors estimate the capacity factors (CFs) of available wind turbines using the Weibull distribution parameters at a hub height and wind turbine specified cut in, rated and cut out wind speeds as Eq. (35) [43].

$$CF = \frac{e^{-(v_C/c)^k} - e^{-(v_R/c)^k}}{(v_R/c)^k - (v_C/c)^k} - e^{-(v_F/c)^k} \tag{35}$$

Statistical error analysis

There are a good number of tools to find out the statistical errors. Two statistical tests, the coefficient of determination (R^2) and the root mean square error (RMSE) are generally used by many of the researchers to provide a measure of how well observed outcomes are replicated by a model and can be derived using the linear regression analysis methods [44] as in Eqs. (36) and (37).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i - x_i)^2}{\sum_{i=1}^{N}(y_i - \overline{y})^2} \tag{36}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2\right]^{\frac{1}{2}} \tag{37}$$

Where

y_i is the i^th^ actual data

$\overline{y}$ is the mean of the actual data

x_i is the i^th^ predicted data

N is the number of observations

Values of R^2 varies from 0 to 1 and its ideal value is equal to 1. The RMSE varies from 0 to infinity and its ideal value is 0. Hence to select a model to predict Weibull distribution parameters, highest value of R^2 and the lowest value of RMSE are generally considered.

3. Results and Discussions

Data collection and Validation

The Ministry of Power Energy and Mineral Resources, Bangladesh measured wind data at nine sites in Bangladesh for 2014-2017, through 'Technical Assistance project for wind resources mapping', implemented by the US Department of Energy's National Renewable Energy Laboratory (NREL) in cooperation with USAID Bangladesh [45]. At Chandpur, wind data and direction data were collected by NRG Class-1-three cup anemometer and NRG# 200P wind vanes of USA at heights 18.8 m, 40.2 m and 59.9 ma bove ground level (AGL), where the site was 10 meter elevated from the sea level. The collection intervals were 10 minutes and data recovery rate was 80.07%. The position of the station and meteorological tower are shown in the following Fig. 1.

Fig. 1. Meteorological tower and Position of measurement site in Bangladesh map

For data quality assessment, validation routines [46] have been applied. The measured data were compared to allowable upper and lower limiting values at a site. As the anemometers were first calibrated in the lab and there was no offset the range tests were done for 0 to 25 m/s. In general system check there were equal number of data fields as per the data parameters. There was no negative or unreadable values have been seen in the data. The highest values at 18.8 m, 40.2 m and 59.9 m AGL were 23.17 m/s, 22.53 m/s and 21.12 m/s respectively. To check the relational and trend tests among the data at the wind sensor heights diurnal and monthly averaged wind speeds have been compared in graphs (Figs. 2 and 3).

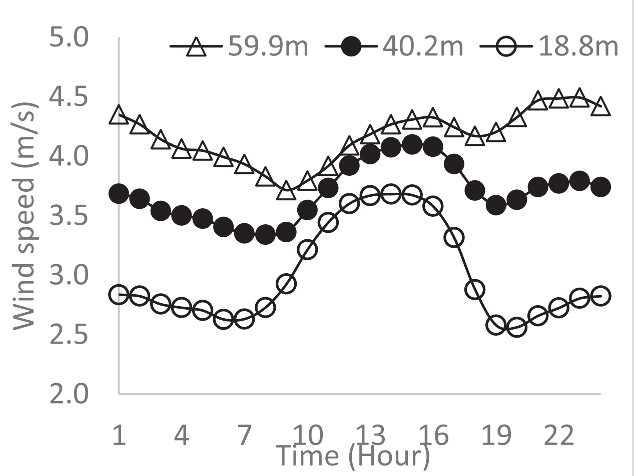

Fig. 2. Diurnal variation of wind speed

The results of the hourly mean wind speed, averaged over the entire duration of measurements, are shown in Fig. 2. From the figure, it can be seen that during the day wind speed normally starts increasing at 9 am and reaches the peak at around 4 pm then it starts to decrease and stabilizes at around 7 pm. It again reaches to the peak for 9 to 11 pm. This indicates that the site is windier more during the night compared to day.

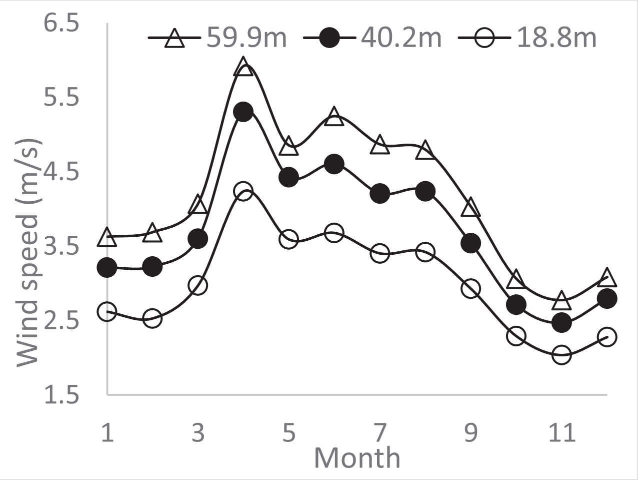

Fig. 3. Monthly variation of wind speed

The monthly averaged wind speeds are shown in Fig. 3. It is found that average wind speed is highest in the month of April. Here for the entire year, yearly averaged hourly values for 18.8 m, 40.2 m and 59.9 m AGL are 3.00 m/s, 3.69 m/s and 4.14 m/s respectively. Whereas for summer (March to September) and winter (October to February) the seasonal averaged hourly values for 18.8 m, 40.2 m, 59.9 m AGL are 3.46 m/s, 4.27 m/s, 4.83 m/s and 2.35 m/s, 2.88 m/s, 3.25 m/s respectively. From the results, it is observed that summer months are mostly windier at Chandpur.

Wind speed probability distribution

The 10-minute data sets were converted to hourly data and the hourly data were sorted in bins of 0.5 m/s for further analyses. From the binned data, the mean, variance and Weibull distribution parameters have been calculated according to the methods in Section 2.1 and considering bin interval of 0.5 m/s. The predicted Weibull distribution function (one at 59.9 m) in shown in Fig. 4 and the parameters are presented in Table 1 for all heights.

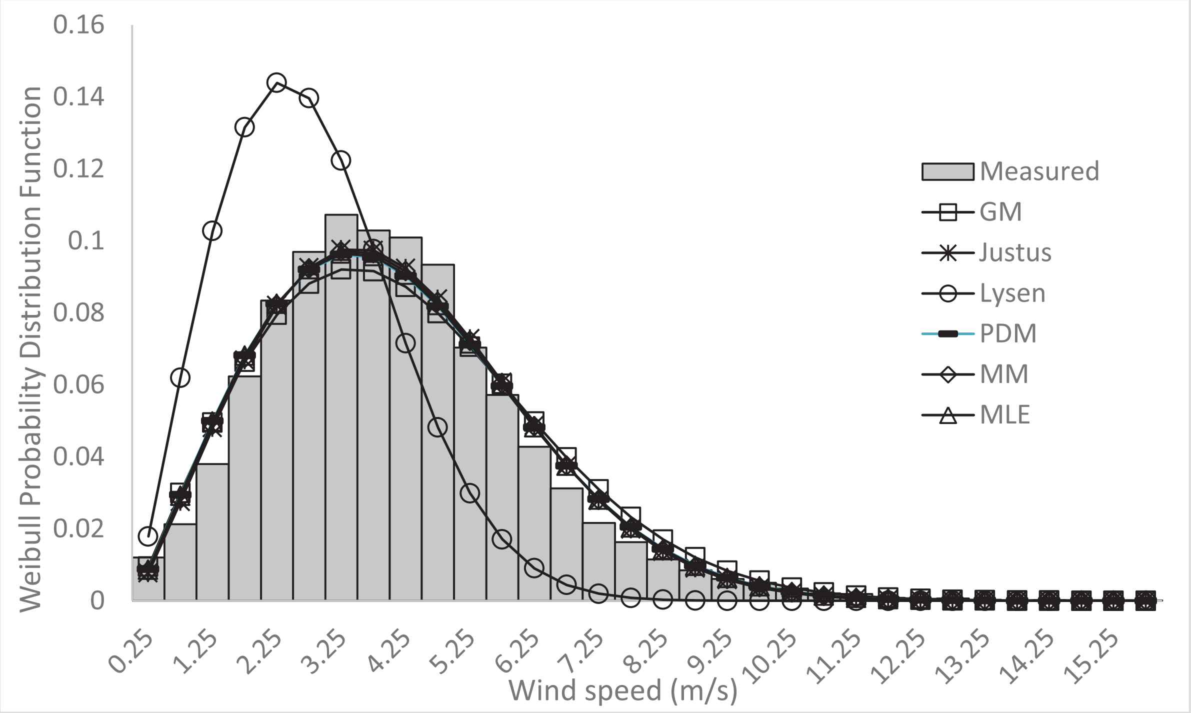

Fig. 4. Weibull distribution on measured probability distribution at 59.9 m AGL

Table 1: Weibull parameters in different methods

Sensor height AGL	Weibull parameters	GM	Justus	Lysen	PDM	MM	MLE
18.8 m	k	1.85	1.94	1.94	1.85	1.92	1.92
	c (m/s)	3.54	3.33	2.33	3.32	3.33	3.33
40.2 m	k	1.96	2.08	2.08	2.02	2.06	2.04
	c (m/s)	4.23	4.10	4.10	4.10	4.10	4.09
59.9 m	k	2.06	2.17	2.17	2.12	2.15	2.12
	c (m/s)	4.74	4.62	3.14	4.62	4.62	4.62

The errors in estimating the Weibull parameters in different methods are summarized in Table 2. From Fig. 4 and Table 1, it is seen that empirical method of Justus has the highest correlation with the raw data and least estimation error for all heights. The second one and third one choice of Weibull parameter estimation would be MM and MLE respectively.

Considering the 10 m elevation of site and Eq. (25) the estimated wind shear exponent (WSE) is 0.37 for Chandpur. Utilizing the WSE the yearly averaged hourly wind speeds have been calculated for other heights (Table 3). From the table it is seen that the estimation of Weibull parameters using Eq. (31) is on an average 1.7% only based on the estimated WPD values.

Table 2: Errors in calculation of Weibull parameters in different method

Sensor AGL	Error	GM	Justus	Lysen	PDM	MM	MLE
18.8 m	R^2	0.9220	0.9456	0.7482	0.9325	0.9426	0.9427
	RMSE	0.0148	0.0118	0.0290	0.0133	0.0122	0.0122
40.2 m	R^2	0.9428	0.9625	0.6806	0.9543	0.9601	0.9572
	RMSE	0.0108	0.0083	0.0291	0.0093	0.0086	0.0090
59.9 m	R^2	0.9757	0.9867	0.6603	0.9829	0.9853	0.9836
	RMSE	0.0065	0.0045	0.0281	0.0052	0.0048	0.0051

Table 3: Estimated wind speeds and Weibull parameters and WPD at different heights

Sensor height AGL	Average wind and Weibull parameters	Raw data and Justus	Extrapolated values	WPD from Justus k, c (W/m^2)	WPD from extrapolated k, c (W/m^2)	Relative percentage error
18.8 m	v (m/s)	3.00				
	k	1.94		30.96		
	c (m/s)	3.33				
40.2 m	v (m/s)	3.69				
	k	2.08	2.09	53.75	54.26	0.94%
	c (m/s)	4.10	4.11			
59.9 m	v (m/s)	4.14				
	k	2.17	2.17	74.18	72.34	2.48%
	c (m/s)	4.62	4.58			
50 m	v (m/s)		3.89			
	k		2.13		63.22	
	c (m/s)		4.36			
100 m	v (m/s)		4.88			
	k		2.29		108.8	
	c (m/s)		5.33			

Characteristic wind speeds of the site and wind turbine power curve speeds

These wind speeds have been estimated from Eqs. (32) to (34) and summarized in Table 4. In calculation of wind turbine related speeds as in Eq. (34), the average values of ranges have been considered.

Table 4: Most probable wind speed, speed with maximum energy and Wind tubine related speeds

Velocities (m/s)	**18.8 m**	**40.2 m**	**59.9 m**	**50 m**	**100 m**
V_{mp}	2.29	3.00	3.47	3.24	4.15
V_{max}	4.79	5.66	6.24	5.94	7.01
V_C	1.26	1.65	1.91	1.78	2.28
V_R	5.16	6.74	7.81	7.28	9.33
V_F	14.37	16.98	18.73	17.83	21.03

Wind energy potential

As part of the US Department of Energy's Federal Wind Energy Program, the Battelle—Pacific Northwest Labs (PNL) developed a wind power classification scheme as in Table 5 [47]. The report indicates that the class 4 or greater are generally suitable for most the wind turbine applications; Class 3 are as may be suitable for future (in year 2000 and beyond) generation technology with tall towers; Class 2 areas are marginal and Class 1 areas are not suitable for wind energy development [48, 49].

The cut-in wind speed of a wind tubine is related to the amount of the initial torque of the turbine rotor shaft, which is required to overcome to produce an output. Table 4 shows that the required cut-in speeds for different heights is below 3.0 m/s, which is commercially absent in the market [50]. Moreover from Table 3 average wind speed and WPD values are found 3.89 m/sand 63.22 W/m^2 respectively. Even from Table 3 the wind speed and WPD values at 100 m height are less than the Class 1 criterion at 50 m height.

For annual capacity assessment 5 wind turbines with low cut in speeds and hub height of 100 m (more height is not considered here as the site is a cyclone prone area) have been considered. The wind turbine specifications and their corresponding capacity factors (from Eq. (35)) are shown in Table 6.

Table 5: Classes of wind power density (Battelle PNL)

Power class	Potential	Power density and wind speed at 10 m		Power density and wind speed at 30 m		Power density and wind speed at 50 m	
		Power (W/m^2)	Speed (m/s)	Power (W/m^2)	Speed (m/s)	Power (W/m^2)	Speed (m/s)
Class-1	Poor	≤100	≤4.4	≤160	≤5.1	≤200	≤5.6
Class-2	Marginal	≤150	≤5.1	≤240	≤6.0	≤300	≤6.0
Class-3	Moderate	≤200	≤5.6	≤320	≤6.5	≤400	≤7.0
Class-4	Good	≤250	≤6.0	≤400	≤7.0	≤500	≤7.5
Class-5	Very good	≤300	≤6.4	≤480	≤7.5	≤600	≤8.0
Class-6	Excellent	≤400	≤7.0	≤640	≤8.2	≤800	≤8.8
Class-7	Excellent	≤1000	≤9.4	≤1600	≤11.0	≤2000	≤11.9

Table 6: Wind turbine specifications and Annual capacity factors

Wind turbine	Rated power (MW)	Cut in wind speed (m/s)	Rated wind speed (m/s)	Cut out wind speed (m/s)	Rotor diameter (m)	Capacity factor (%)
V150-4.2 MW	4.2	3	12	24.5	150	12.4
S 130- 2.7 MW	2.7	3	12	20	130	12.4
S 120- 2.3 MW	2.33	3	11	20	120	15.2
S120-2.1 MW	2.1	3	9.5	26.1	120	21.3
GW165-4.0 MW	4	2.5	9.7	26	165	21.8

From Table 6, it is seen that there is no wind turbine which has capacity factor more than 25% or can be recommended for wind energy production at the site [28].

4. Conclusions

Wind speed data has wide ranges as it varies over space and time. Chandpur is windier in summer (March to September) seasons and in evening (9 to11 pm)of days. Empirical method of Justus has shown the best performance in estimation of Weibull statistical distribution parameters with RMSE 0.0082 and $R^2$of 0.9650. The wind shear exponent is 0.37 and at 100 m AGL the extrapolated average wind speed is 4.88 m/s, WPD is 108.8 W/m^2 and the designed cut in, rated and cut out wind speeds for wind turbines are 2.28 m/s, 9.33 m/s and 21.03 m/s respectively. The wind speed data and WPD reveal that the site is class 1 in the internationally accepted wind power classification (1 to 7) which was developed based on long period experiences on wind farm installations at different regions of the world. Moreover, to harness wind energy from low wind speeds (average wind speed <5 m/s) the rotor diameter and hub height needs to be increased, but as these add additional advanced engineering, space and project costs and thus wind turbines for this kind of site with low wind speed and cut in speed (<3 m/s) are not commercially available in the market. Available wind turbines with low cut in speed (=3 m/s) gives annual average capacity factor 16.62 % only, which is <25%, where it should be >25 % to become feasible for wind energy harnessing projects. From these findings-commercial unavailability of wind turbines with cut in speed less than 3 m/s, the site has wind power class 1 and annual average capacity factor <25% for available wind turbines with cut in speed equal to 3 m/s, the conclusion can be taken that Chandpur has a poor wind energy potential and unsatisfactory for wind energy development in the near future.

References

1. J. A. Carta, P. Ramirez and S. Velazquez, "A review of wind speed probability distributions used in wind energy analysis," *Renewable and Sustainable Energy Reviews,* vol. 13, pp. 933–955, 2009.
2. R. Belu and D. Koracin, "Wind characteristics and wind energy potential in western Nevada," *Renewable Energy ,* vol. 34, pp. 2246–2251, 2009.
3. M. Gokcek and M. S. Genc, "Evaluation of electricity generation and energy cost of wind energy conversion systems (WECSs) in Central Turkey," *Applied Energy,* vol. 86, pp. 2731–2739, 2009.
4. Ali Mostafaeipour, "Feasibility study of harnessing wind energy for turbine installation in province of Yazdin Iran," *Renewable and Sustainable Energy Reviews,* vol. 14, pp. 93–111, 2010.
5. S. Diaf and G. Notton, "Technical and economic analysis of large-scale wind energy conversion systems in Algeria," *Renewable and Sustainable Energy Reviews,* vol. 19, pp. 37–51, 2013.
6. A. Keyhani, M. Ghasemi-Varnamkhasti, M. Khanali and R. Abbaszadeh, "An assessment of wind energy potential as a power generation source in the capitalof Iran, Tehran," *Energy,* vol. 35, pp. 188-201, 2010.
7. I. Y. F. Lun and J. C. Lam, "A study of Weibull parameters using long-term wind observation," *Renewable Energy,* vol. 20, pp. 145–153, 2000.
8. A. Ucar and F. Balo, "Assessment of wind power potential for turbine installation in coastal areas of Turkey," *Renewable and Sustainable Energy Reviews,* vol. 14, pp. 1901–1912, 2010.
9. https://en.wikipedia.org/wiki/Weibull_distribution, accessed on 29 September 2021.
10. A. Parajuli, "A Statistical Analysis of Wind Speed and Power Density Based on Weibull and Rayleigh Models of Jumla, Nepal," *Energy and Power Engineering,* vol. 8, pp. 271-282, 2016.
11. N. Eskin, H. Artar and S.Tolun, "Wind energy potential of Gökçeada Island in Turkey," *Renewable and Sustainable Energy Reviews,* vol. 12, no. 3, pp. 839-851, 2008.
12. A. Mostafaeipour, A. Sedaghat, A. A. Dehghan-Niri and V. Kalantar, "Wind energy feasibility study for city of Shahrbabak in Iran," *Renewable and Sustainable Energy Reviews,* vol. 15, pp. 2545– 2556, 2011.
13. E. K. Akpinar and S. Akpinar, "Determination of the wind energy potential for Maden, Turkey," *Energy Conversion and Management,* vol. 45, pp. 2901–2914, 2004.
14. B. K. Saxena and K. V. S. Rao, "Estimation of wind power density at a wind farm site located in Western Rajasthan region of India," *Procedia Technology,* vol. 24, pp. 492 – 498, 2016.
15. C. G. Justus, W. R. Hargraves, A. Mikhail and D. Graber, "Methods for estimating wind speed frequency distributions," *J. Appl. Meteorol.* Vol. 17, pp. 350-353, 1977.
16. M. Jamil, S. Parsa and M. Majidi, "Wind power statistics and evaluation of wind energy density," *Renew Energ,* vol. 6, pp. 623–628, 1995.
17. K. Mohammadi and A. Mostafaeipour, "Using different methods for comprehensive study of wind turbine utilization," *Energy Conversion and Management,* vol. 65, pp. 463-470, 2013.

18. M.Rasul, A. Azad and S. Sharma, Clean Energy for Sustainable Development.Central Queensland University, Melbourne campus, Melbourne, Australia: Academic Press, 2017.
19. G. L. Johnson, Wind Energy Systems. Manhattan, KS, USA: Kansas State University, 2006.
20. C. G, Justus and A. Mikhail, "Height variation of wind speed and wind distribution statistics," *Geophys Res Lett,* vol. 3, pp. 261–264, 1976.
21. K. Mohammadi, O. Alavi, A. Mostafaeipour, N. Goudarzi and M. Jalilvand, "Assessing different parameters estimation methods of Weibull distribution to compute wind power density," *Energy Convers. Manag.,* vol. 108, pp. 322–335, 2016.
22. S. A. Akdağ and A. Dinler, "A new method to estimate Weibull parameters for wind energy applications," *Energy Convers Manage,* vol. 50, pp. 1761–1766, 2009.
23. R. J. Rossi, Mathematical Statistics: An Introduction to Likelihood Based Inference. New York: John Wiley & Sons, 2018.
24. F. Nwobi and C. A. Ugomma, "A Comparison of Methods for the Estimation of Weibull Distribution Parameters," *Metodološki zvezki,* vol. 11, no. 1, pp. 65-78, 2014.
25. J. H. Gove, "Moment and maximum likelihood estimators for Weibull distributions under length-and area-biased sampling," *Environ. Ecol. Stat. ,* vol. 10, pp. 455–467, 2003.
26. A. Kalam Azad, M. G. Rasul and T. Yusaf, "Statistical Diagnosis of the Best Weibull Methods for Wind Power Assessment for Agricultural Applications," *Energies,* vol. 7, pp. 3056-3085, 2014.
27. R. A. Fisher, "Frequency distribution of the values of the correlation coefficient in samples from an indefinitely large population," *Biometrika, London,* vol. 10, pp. 507–521, 1915.
28. S. Mathew, Wind energy: fundamentals, resource analysis and economics. Berlin, Heidelberg: Springer, 2006.
29. J. F. Manwell, J. G. Mcgowan and A. L. Rogers, Wind energy explained: theory, design and application. Amherst (USA): John Wiley & Sons, 2002.
30. S. Rehman and N. M. Al-Abbadi, “Wind shear coefficient, turbulence intensity and wind power potential assessment for Dhulom, Saudi Arabia,” *Renewable Energy*, vol. 33, no. 12, pp. 2653–2660, 2008.
31. E. Simiu and D. Yeo, Wind Effects on Structures. New York: Wiley, 1978.
32. G. Hellman, "Uber die Bewegung der Luft in den untersten Schichten der Atmosphere," *Meteorol Z,* vol. 34, pp. 273-285, 1916.
33. J. W. Reed, "Wind Power Climatology," *Weather wise,* vol. 27, pp. 237-242, 1974.
34. A. G. Davenport, "The Relationship of Wind Structure to Wind Loading," *Proc. of conf. on wind effects on structures*, London, England, 1963.
35. D. A. Spera, Wind Turbine Technology: Fundamental Concepts of Wind Turbine Engineering. New York: ASME Press, 2009.
36. J. Counihan, "Adiabatic atmospheric boundary layers: a review and analysis of data collected from the period 1880-1972," *Atmos Environ ,* vol. 9, pp. 871-905, 1975.
37. M. Al-buhairi, "Assessment and analysis of wind power density in Taiz-Republic of Yemen," *Assiut Univ Bull Environ Res ,* vol. 9, pp. 13-21, 2006.
38. S. H. Pishgar-Komleh, A. Keyhani and P. Sefeedpari, "Wind speed and power density analysis based on Weibull and Rayleigh distributions, A case study: Firouzkooh county of Iran," *Renew Sustain Energy Rev,* vol. 42, pp. 313-322, 2015.
39. C. Carrillo, J. Cidrás, E. Díaz-Dorado and A. F. Obando-Montaño, "An approach to determine the Weibull parameters for wind energy analysis: The case of Galicia (Spain)," *Energies,* vol. 7, pp. 2676-2700, 2014.
40. K. A. Nigim and P. Parker, "Heuristic and Probabilistic Wind power Availability Estimation Procedures: Improved Tools For Technology and Site Selection," *Renewable Energy,* vol. 32, pp. 638-648, 2007.
41. D. Kang, K. Ko and J. Huh, "Comparative Study of Different Methods for EstimatingWeibull Parameters: A Case Study on Jeju Island, South Korea," *Energies,* vol. 11, pp. 1-19, 2018.
42. M. S. Adaramola, M. Agelin-Chaab and S. S. Paul, “Assessment of wind power generation along the coast of Ghana,” *Energy Conversion and Management*, vol. 77, pp. 61–69, 2014.
43. E. KavakAkpinar and S. Akpinar, “An assessment on seasonal analysis of wind energy characteristics and wind turbine characteristics,” *Energy Conversion and Management,* vol. 46, pp. 1848–1867, 2005.
44. M. Jacobson, C. Draxl, T. Jimenez, B. O’Neill, T. Capozzola, J. A. Lee, F. Vandenberghe, and S. E. Haupt, "Assessing the Wind Energy Potential in Bangladesh: Enabling Wind Energy Development with Data Products," *United States of America: National Renewable Energy Laboratory (NREL),* 2018.
45. AWS Scientific, Wind resource assessment handbook: Fundamentals for conducting a successful monitoring program, Golden, USA: National Renewable Energy Laboratory, 1997.
46. W. F. S. Elliott, "Wind Energy Resource Atlas of the United States," Colorado:Solar Energy Research Institute, 1987.
47. D. Elliott and M. Schwartz, "Wind Energy Potential in the United States," *Proceedings of the Project Energy ’93: Real Energy Technologies—Environmentally Responsible—Ready for Today, Independance*, MO, USA, 1993.
48. X. Yu and H. Qu, "Wind power in China—Opportunity goes with challenge," *Renew. Sustain.Energy Rev. ,* vol. 14, pp. 2232–2237, 2010.
49. W. Zhou, H. Yang and Z. Fang, "Wind power potential and characteristic analysis of the Pearl River Delta region, China," *Renew. Energy,* vol. 31, pp. 739–753, 2006.
50. Oluseyi O. Ajayi, Olorunfemi Ojo and Ahmed Vesel, "On the need for the development of low wind speed turbine generator system," *IOP Conf. Series: Earth and Environmental Science*, 2019.