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Wind Energy Potential Assessment for Nooriabad Sindh Pakistan

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Abstract: Wind speeds recorded at regular intervals of time for a particular wind site correspond to intermittent source of energy. Reliable estimate of wind potential for the site requires fitting of the recorded data to a continuous distribution function. Weibull function with two parameters is widely used mathematical function for fitting wind speed data for the estimation of wind energy. In the present study, analysis on the data registered in steps of 1 minute interval for the years of 2003 and 2004 for Nooriabad, Sindh were carried out. Recorded data set contains wind speeds and wind directions at 30 m and 100 m mast heights, respectively. Weibull function is applied to the measured monthly and yearly data sets and Weibull shape scale parameters are computed with the help of six numerical methods. Accuracy of these numerical methods and their suitability are assessed by employing two test statistics, namely, R^2 and *RMSE*. The R^2 test statistics estimated for all methods gives a value of 0.99 and *RMSE* gave a lowest value (0.07) for the Method of Least Squares Error (MLE), suggesting MLE to be the most suitable method for obtaining Weibull parameters. Monthly and yearly probability density function (*pdf*), cumulative distribution function (*cdf*) and power densities are determined using Weibull distribution. Comparison between Weibull power density values and estimated power densities of raw data show close agreement. As an example, power density of raw data for the month of June is 1935.16 W/m^{2}and is in close agreement with Weibull power density for the same month, which is 1972.92 W/m^2.

Keywords: Weibull, shape and scale parameters, Nooriabad, power density.

Introduction

A rapid industrialization trend has brought with it an ever increasing demand for energy to ensure worldwide sustainable economic growth. In past, most of this energy requirement came from non-renewable sources, such as fossil fuels and coal. Production of energy from such sources is not only expensive due to its increasing shortage. Its ill-effects are harmful to the environment and eco-system of earth. This made scientists and policy makers to look for alternate renewable energy resources which are both environment friendly and economically feasible. The harmful effects associated with the burning of fossil fuel for the generation of electricity results in increased concentration of carbon monoxide, hydrocarbons, airborne particulate, ionizing radiation and trace elements (Kainkwa, 2000). Over the past ten years, the global renewable power capacity has increased from 1057,962 MW in 2008 to 2179,099 MW in 2017, an increase of more than 50% (IRENA, 2018).Wind is produced by differential heating of earth surface and atmosphere, which is present in vast amount over the entire global surface. In recent years energy associated with wind has emerged as a renewable, eco-friendly, cost-effective and fastest growing source of energy (Jamdade and Jamdade, 2012). It is economically viable and technically sound for the production of energy. This led to an increase in the usage of wind speed and to extract energy stored in wind for the production of electrical energy for useful purpose.

Mapping wind potential locally helps in predicting prevailing wind patterns at sites under investigation. Contrary to wind speeds recorded in discrete times, the actual wind speed profile shows continuous variability and has a diffuse data distribution. This requires fitting of recorded data distribution to a continuous function which is used to estimate wind potential. Commonly adopted procedure for estimating wind potential of a site consists of fitting recorded data to a two parameter Weibull function (Rehman et al., 1994; Rehman et al., 2012; Bagiorgas et al., 2012; Bagiorgas et al., 2011; Sopian et al., 1995; Seguro and Lambert, 2000; Odo et al., 2012). Sulaiman et. al. (2002) reported that such calculations and reliability of the fitted distribution to the given speed distributions are tested using known statistical techniques (*RMSE*, R^2 and χ^2-tests statistics). Garcia et al. (1998) used Weibull two parameter functions and a lognormal model on the recorded wind data.

Available wind data are modelled using different distribution functions, such as Weibull, Inverse Weibull, Gamma, Rayleigh and their performance is compared (Parajuli, 2016; Sarkar et al., 2017; Sohoni et al., 2016). These studies are conducted based on separating wind speeds into three wind speed classes, low, mid and high wind speed ranges. Studies indicate that smaller wind speeds are best described by Weibull function, whereas mid speed range cannot be described by the Weibull function. On the other hand, high wind speeds correspond to extreme value distribution. In all these scenarios, wind potential for the investigated site are determined using fitted functions. In a similar study (Dokur and Kurban, 2015), maximum likelihood method was used for the estimation of Weibull parameters, which is then used for determination of wind potential.

In this communiqué two parameters Weibull distribution function is applied to the recorded wind speeds at Nooriabad. Six numerical methods are used to estimate the shape and scale parameters. Additionally, for detailed analysis of wind pattern in Nooriabad, monthly and yearly *pdf*, *cdf* and wind potential are also determined for two years (2003, 2004) and at two heights (30 m, 100 m). In order to be concise and to avoid repetition, yearly results of one-year (2004) are presented at 100 m height.

Materials and Methods

Determination of wind characteristics including wind energy potential requires empirical modelling of intermittent wind speed data at a site using probability distribution function. Furthermore, two parameters (shape and scale) Weibull function (1951) is mathematically fitted to the given set of data to assess variability in wind speed pattern. Range of values in the available data distribution is described by shape parameter and width is described by scale parameter. A wider and lower peaked distribution is characterized by a smaller shape parameter value. The advantage of using Weibull function lies in its flexibility towards wide ranging wind speeds. Weibull probability distribution function, $f(v)$, (Akpinar and Akpinar, 2004; Mathew et al., 2011) is expressed mathematically as,

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

where 'v' is the wind speed, 'k' and 'c' are shape and scale (in m/s) parameters, respectively. Cumulative function, $F(v)$, derived from Weibull function, is expressed as,

$$F(v)=1-e^{-(v/c)^k} \quad (2)$$

Weibull mean wind speed (V_m), the most probable wind speed (V_{mp}) and power density (P_D) are obtained using equations given below (Chang, 2011; Muhammad et al., 2017; AEDB, 2014),

$$V_m = cGamma\left(1+\frac{1}{k}\right) \quad (3)$$

$$V_{mp} = c\left(\frac{k-1}{k}\right)^{1/k} \quad (4)$$

$$P_D = \frac{\rho_a c}{2} Gamma\left(1+\frac{3}{k}\right) \quad (5)$$

Where *Gamma()* has the standard mathematical definition and is termed as Gamma function. The actual power density (P_A) is proportional to the third power of raw wind speeds with a proportionality constant of air density ρ_a (1.225 kg/m^3), viz.,

$$P_A = \frac{1}{2}\rho_a v^3 \quad (6)$$

Weibull Parameters Estimation

Weibull parameters (k and c) are estimated using recorded wind speed data using Maximum Likelihood Method (MLM), Method of Least Squares Error (MLE), Empirical Method (EM), Modified Maximum Likelihood Method (MMLM), Method of Moment (MoM) and Energy Pattern Factor Method (EPFM). These methods are based on iterative algorithm to give shape parameter value until self-consistency is achieved. A detailed description of these methods and their mathematical representations are given by Chang (2011) and Muhammad et al. (2017).

Assessment of Test Statistics

Suitability of Weibull functionis assessed using two test statistics or Goodness-of-Fit (GoF) that is, R^2 and *RMSE* tests. R^2 gives a measure of variance between two (or more) variables and is given by the expression,

$$R^2 = \frac{\sum_{i=1}^{n}(y_i - z_m)^2 - \sum_{i=1}^{n}(y_{ic} - y_i)^2}{\sum_{i=1}^{n}(y_i - z_m)^2} \quad (7)$$

where y_i and y_{ic} are recorded and estimated wind speeds and z_m is the mean of wind speeds. R^2 test give values ranging between 0 and 1, with higher values suggesting better fitting.

The average deviation in the fitted distribution is measured by Root Mean Square Error (RMSE). Consequently, such a measure of deviation can only be computed, provided data distribution is present. Mathematically, *RMSE* is expressed as

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2} \times 100 \quad (8)$$

where y_i and x_i are the recorded and predicted values of wind speed. In the present case *RMSE* is measured in percentage with a lower value indicating better fit.

Results and Discussion

Nooriabad wind site is located in Thatta, Sindh with geographical coordinates 68.525° E and 25.894 ° N. Wind masts in Nooriabad are installed in an open terrain with no vegetation and on flat surfaces. Recorded wind data are obtained from Alternate Energy Development Board of Pakistan (AEDB, 2014). Data are recorded at two heights above ground, that is, 30 m and 100 m in 1-minute intervals and for a period of two years from 2003 to 2004 respectively. The data set contains a total of ca. 500000 wind speed data points per year. Recorded data set are pre-processed by calculating hourly averages, thereby reducing the size of data set from 500,000 to 7000 points per year (Table 1). Mean wind speed values for the year 2003 and 2004 at both heights lie between 5-7 m/s. The yearly histograms of binned wind speed data for 30 m and 100 m AGL for two years, are positively skewed (Figs. 1-4). Furthermore, longer tails on the higher wind speeds side are seen in the year 2004 compared to 2003. In both years, coefficient of variation (CV) statistics reveals that majority of high wind speed are clustered around distribution means (Table 1). In both years, yearly power densities are higher at 100 m height (325.75 W/m^2, 653.97 W/m^2) as compared to 30 m height (192.67 W/m^2, 291.79 W/m^2). Additionally, wind power density increases from 2003 to 2004, suggesting that higher wind speeds are recorded in the year 2004, compared to 2003.

Wind speeds for the data recorded in 2003 and 2004 and at heights 30 m and 100 m are used for mathematical modelling and determination of Weibull wind characteristics. Detailed analysis of the recorded data is performed both in monthly and yearly periods. Six numerical methods are used to calculate two parameters of Weibull distribution function and Weibull *pdfs* and *cdfs* are obtained for monthly and yearly periods. Yearly *pdf* and *cdf* traces at two heights and both years are overlapped on yearly histograms plots for respective heights and years (Figs. 1-4).

Table 1 Yearly description statistics for Nooriabad wind speeds for two heights.

Year and Height	# Data Points	Mean V(m/s)	Range (m/s)	σ (m/s)	K	S	P_A (W/m^2)	CV %	C.I. (95.0%)
2003, 30 m	6945 6945	5.74	21.79 21.795	2.58	0.65	0.65	192.67	45.03	0.06
2003, 100 m	7667	6.57	30.08	3.19	4.52	1.47	325.75	48.58	0.07
2004, 30 m	7565	5.93	27.87	3.40	4.63	1.58	291.79	57.29	0.08
2004, 100 m	7982	7.27	33.98	4.68	5.44	2.02	653.97	64.33	0.10

Table 2. Yearly Weibull wind characteristics from six methods.

Wind Characteristics	MLE	*MLM*	*MMLM*	MoM	EM	*EPFM*
Hours	7981	7981	7981	7981	7981	7981
k	2.14	1.71	1.73	1.62	1.61	1.48
c (m/s)	8.04	8.21	8.34	8.20	8.20	8.12
V_m (m/s)	7.05	7.25	7.36	7.27	7.27	7.27
V_{mp}(m/s)	5.99	4.89	5.06	4.53	4.51	3.78
P_D (W/m^2)	391.01	543.57	560.73	585.92	588.19	666.43
R^2	0.99	0.99	0.99	0.99	0.99	0.99
RMSE (%)	0.07	0.11	0.10	0.11	0.11	0.13

Table 3. Monthly and Yearly actual power densities (P_A) and Weibull power densities (P_D) for six methods and at 100 m mast height for the year 2004.

Period	Weibull Power Density, P_D (W/m^2)						Actual
	MLE	MLM	MMLM	MoM	EM	EPFM	P_A (W/m^2)
Jan	166.81	231.35	241.76	261.91	263.4	314.58	308.19
Feb	168.37	209.12	209.88	216.48	220.36	246.02	241.81
Mar	274.4	368.03	391.38	398.08	401.77	472.47	461.92
Apr	443.25	574.91	633.6	606.97	613.32	680.03	665.97
May	673.48	750.74	695.54	764.43	778.92	813.51	800.15
Jun	1209.7	1660.03	1665.14	1844.56	1849.17	1972.92	1935.16
Jul	984.05	1173.26	1176.72	1204.95	1225.21	1316.27	703.08
Aug	617.26	671.63	690.46	676.03	691.44	718.45	1294.14
Sep	258.04	337.85	362.15	360.65	363.94	414.56	405.45
Oct	160.72	238.45	218.73	284.9	285.4	332.46	332.11
Nov	123.33	187.88	161.99	229.08	229.59	291.58	295.05
Dec	182.65	234.76	225.06	258.44	260.37	308.88	301.82
Yearly	391.01	543.57	560.73	585.92	588.19	666.43	653.97

Yearly Weibull wind speed in the year 2004 for 100 m height is ca. 7 m/s, which is in good agreement with the corresponding yearly value calculated using raw wind speed data (Tables 1, 2). Estimated values of Weibull shape parameters using all six methods range from 1.48 to 2.14 with MLE giving a value of 2.14. A '*k'* value less than theoretical value of 2.6 is obtained from all six methods of estimation. Shape parameters suggest an asymmetry in *pdf*, i.e., majority of points fall to the right of distribution mean and therefore the distribution is positively skewed. This behaviour is also noted in the distribution of measured data which are also positively skewed. The extent of windiness or the breadth of wind speed distribution is expressed in terms of scale parameter values, which vary from 8.04 m/s to 8.34 m/s obtained using six methods of estimation and therefore such results are also consistent with the width of the raw data distribution. Estimated values of c and k from six methods show reliable fitting to the raw data (Figs. 1-4).

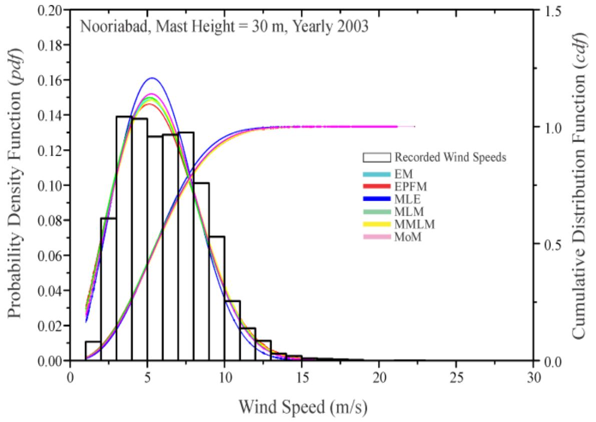

Fig. 1 Yearly histogram, *pdf* and *cdf* plots for 2003.

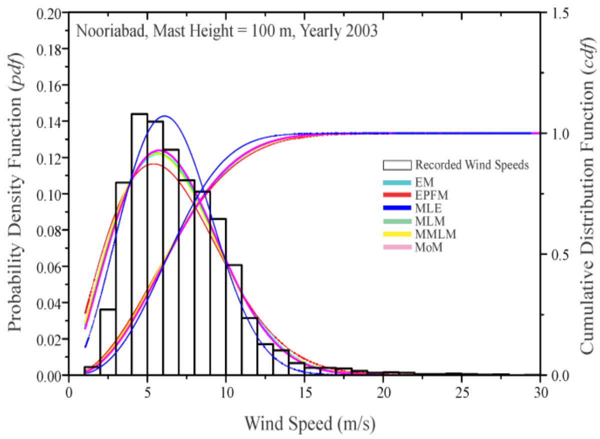

Fig. 2 Yearly histogram, *pdf* and *cdf* plots for 2003.

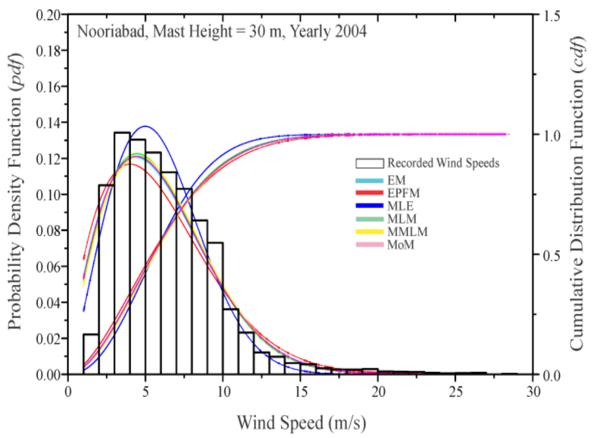

Fig. 3 Yearly histogram, *pdf* and *cdf* plots for 2004.

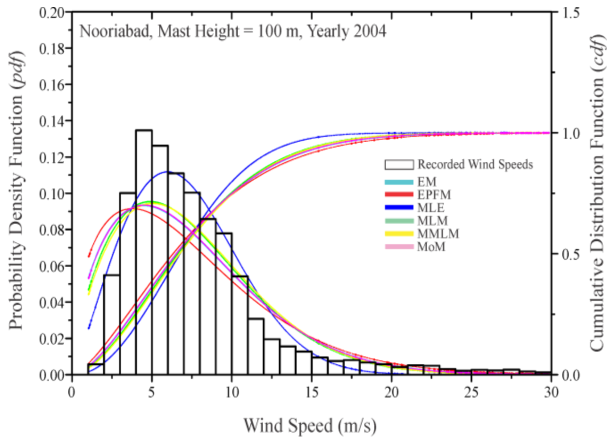

Fig. 4 Yearly histogram, *pdf* and *cdf* plots for 2004.

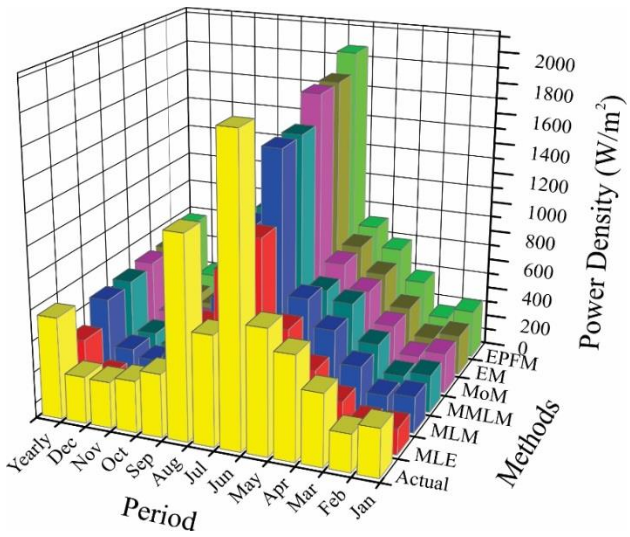

Fig. 5 Month wise and year wise actual and Weibull power densities.

Generally goodness-of-fit test statistics are conducted for all six methods of Weibull parameter estimation in monthly and annual periods and for the years 2003-2004 at 30 m and 100 m heights respectively (Table 3). Results of tests statistics show consistency of the fitted function towards recorded data distribution. R^2-test statistics values for the assessment of reliability of the fitted function to the collected data are close to 1, suggesting a good fit of Weibull function.

Table 3 lists monthly and yearly power density values determined using Weibull function for six different methods of estimation of Weibull parameters for 2004 at 100 m height. Monthly and yearly actual power densities for the same year and height (Table 3). A 3D bar graph of yearly and monthly actual and Weibull power densities have been plotted for six methods of Weibull parameters estimation methods for 2004 (Fig. 5). This figure shows a monthly increasing trend wherein power density values gradually increase up to a maximum value in June and then decreasing to lower values till December. Monsoon season in Pakistan is dominant during the period starting from May to September, which is evident from the graph. Estimated power density values of measured wind data and from

Weibull function show similar trends. Contrary to monthly and annual data fitted to Weibull distributions in which best fits are observed for MLE. The power density distributions estimated using measured wind speed data are best approximated by the fitted power density distribution, determined using EPFM for Weibull parameter estimation. An increasing trend is also observed for monthly and yearly Weibull power density values with an increasing order going from MLE to EPFM. During monsoon season, that is, from May to September the actual power densities (P_A) are 800.15, 1935.16, 703.08, 1294.14 and 405.45 W/m^2 at 100 m in 2004. Monthly Weibull power densities (P_D) during monsoon period and with Weibull parameters calculated using MLE are 673.48, 1209.7, 984.05, 617.26 and 258.04 W/m^2. Whereas with Weibull parameters estimated using EPFM, monthly Weibull power densities during monsoon period are 813.51, 1972.92, 1316.27, 718.45 and 414.56 W/m^2. Suggesting that a best fit data distribution is not necessarily a best estimator of power densities, that is, power density estimation depends on the moments of the distribution. Weibull function is convenient, but is limited by the fact that it can be used in the presence of data for its justification.

Conclusion

It is concluded that Weibull function can be applied to record discrete data distribution and for successfully mapping wind potential of the investigated site. The Weibull function is a unimodal function, which can conveniently be applied to unimodal wind speed data, as mostly wind speed patterns in Pakistan are unimodal, it can be applied to other regions of the country. The present work can further be extended to fit a wind turbine for extracting wind energy and generating electrical energy at Nooriabad wind site.

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