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Article

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Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Sumair, Muhammad; Aized, Tauseef; Gardezi, Syed Asad Raza; Ubaid ur Rehman, Syed; Rehman, Syed Muhammad Sohail (2020) : A newly proposed method for Weibull parameters estimation and assessment of wind potential in Southern Punjab, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, pp. 1250-1261, <https://doi.org/10.1016/j.egyr.2020.05.004>

This Version is available at:

<https://hdl.handle.net/10419/244117>

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Research paper

A newly proposed method for Weibull parameters estimation and assessment of wind potential in Southern Punjab

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ARTICLE INFO

Article history:

Received 11 March 2020

Received in revised form 8 April 2020

Accepted 5 May 2020

Available online xxxx

Keywords:

Wind potential assessment in South Punjab

Energy pattern factor method

Method of moment

Modified method of moment

Energy production from wind turbines

Capacity factor

ABSTRACT

Accuracy of wind potential estimation using two-parameter Weibull distribution relies on the accuracy with which Weibull distribution models the wind data. Therefore, there is always a thirst for developing better methods for the estimation of Weibull parameters. Current work focusses on the investigation of a newly proposed method called Modified Method of Moment (MMOM) and comparing it with two other methods i.e. Energy Pattern Factor Method (EPFM) and Method of Moment (MOM) to assess wind potential in South Punjab. Five years (2014–2018) hourly wind data measured at 50 m height and collected from Pakistan Meteorological Department (PMD) was utilized. Performance of EPFM, MOM and MMOM was evaluated using coefficient of determination, root mean square error and power error. Monthly, seasonal and annual variations in wind speed, wind power density (WPD) and wind energy density (WED) were analyzed and annual energy production using six turbine models was also estimated. The analysis showed that MMOM is the best method followed by MOM and EPFM respectively. Furthermore, the highest wind potential is observed in summer while lowest in winter in whole region. Polar diagrams showed that the optimum wind direction in the area is southwest.

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1. Introduction

Owing to economic and environmental concerns, wind energy is seeking attention throughout the world these days (Shoaib et al., 2017; Milanese et al., 2017, 2019). Global wind installed capacity reaches about 597 GW in 2019 (World Wind Energy Association, 2019) with China as the leading one having a share of 37.01% in global installed capacity followed by USA (16.14%), Germany (9.93%), India (5.46 %) and Spain (3.85%) (ETEnergyWorld, 2019). According to International Renewable Energy Agency (IRENA) report, 2019 (IRENA, 2019), India has total installed capacity of 35 GW whereas Pakistan has only 1186 MW. As Pakistan is an energy deficient country, having a huge reliance on fossil fuels for both the primary energy (with 87% and 80% share as of 2014 and 2019 respectively) and electrical energy generation (with 61% and 64% share as of 2014 and 2019 respectively) (Baloch et al., 2016; Sarim, 2019), therefore, to achieve the sustainable development, there is a need to harness wind energy (Khahro et al., 2014b). Before the exploitation of wind energy, accurate estimation of wind potential is important (Bilir et al., 2015).

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Two-parameter Weibull distribution has been used for wind potential estimation throughout the literature and the accuracy with which Weibull distribution models the wind data depends upon the method used to estimate Weibull parameters. There are a number of methods available for the estimation of Weibull parameters (Chang, 2011; Andrade et al., 2014; Saleh et al., 2012; Dorvlo, 2002) e.g. Graphical Method (GM), Empirical Method (EM), Energy Pattern Factor Method (EPFM), Power Density Method (PDM), Method of Moment (MOM), Maximum Likelihood Method (MLM), Modified Maximum Likelihood Method (MMLM), Least Square Method (LSM) and Alternative Maximum Likelihood Method (AMLM).

Chaurasiya et al. (2018) compared nine numerical methods for the estimation of Weibull parameters and concluded that MLM and MMLM have a good performance while GM, popularly used method in past, has poor performance. Akpinar and Akpinar (2005) conducted a comparative analysis of three methods known as EPFM, GM and MLM and concluded that EPFM is better in estimating the wind power potential than the other two methods. From literature, it is evident that a number of methods for Weibull parameters estimation are available and some of those methods have been modified in order to enhance the accuracy of Weibull distribution. However, there has always been a thirst regarding the development of new methods.

Chaurasiya et al. (2017) investigated wind characteristics in Kayathar, Tamil Nadu, India using wind speed data collected by SODAR technique. Comparative analysis of nine different Weibull parameters estimation methods was made. Furthermore, the wind shear effect was also investigated by conducting the analysis on three different heights i.e. 80 m, 100 m and 120 m. Finally, the study compared the accuracy of data collected using SODAR technique and cup anemometer method.

Wind potential at three cities (Chennai, Erode and Coimbatore) in the South Indian state of Tamil Nadu, India was investigated (Rehman et al., 2020) using thirty eight years wind data. Weibull distribution with three methods i.e. MLM, LSM and WASP algorithm was used. It was found that Chennai is the most ample site for wind energy utilization followed by Coimbatore and Erode respectively with wind power densities (WPDs) of 129 W m^{-2} , 97 W m^{-2} and 76 W m^{-2} .

Techno-economic feasibility analysis of wind power harvesting at Hawke's Bay was performed (Hulio et al., 2019a) using Weibull distribution at three heights of 30 m, 60 m and 80 m respectively. Five Weibull parameters estimation methods i.e. EM, MLM, MMLM, EPFM and GM were compared using correlation coefficient and root mean square error and it was found that all methods except GM give good fit. Further it was found that the site has WPD of 184 W m^{-2} , 231.5 W m^{-2} and 307.5 W m^{-2} at 30, 60 and 80 m respectively. Moreover, economic assessment showed that unit cost of energy is \$0.0556.

Wind power potential at Jhimpir (Sindh, Pakistan) was investigated (Shoaib et al., 2019) using 10 min average wind data collected over a period of three years. Weibull probability density function was used with MLM, MMLM and EPFM to estimate Weibull parameters. Coefficient of determination, root mean square error and chi-square tests were applied to find the goodness of fit. Results showed that MLM and MMLM are better than EPFM. Monthly, seasonal and annual power potential was estimated and it was found that investigated site has 1691, 2851, 4572, and 916 kWh in winter, spring, summer and autumn respectively.

A site, Nooriabad Pakistan was investigated (Hulio et al., 2017) using wind data collected over 1 year period. Weibull and Rayleigh functions were used and compared to estimate wind potential two heights of 30 m and 50 m respectively. Five methods i.e. EM, MLM, MMLM, EPFM and GM used for Weibull parameters estimation were compared using correlation coefficient and root mean square error. It was found that Weibull distribution gave good fit to data than Rayleigh distribution. Moreover, it was found that all methods gave good fit except GM. Mean WPDs were found to be 169 W m^{-2} and 416.7 W m^{-2} at 30 and 50 m heights respectively. Economic analysis of energy generation showed that energy with \$ 0.02189/kWh can be produced at Nooriabad at a hub height of 50 m.

Hong Kong, an island in China was investigated to assess the wind potential and to determine the suitability of certain wind turbine models, presented in Lu et al. (2002). A potential site in Brazil i.e. Paraiba was investigated and presented in Lima and Filho (2012). Similarly, Firouzkooh county of Iran (Pishgar-Komleh et al., 2015), Arizona (Acker et al., 2007), Tehran, Iran (Keyhani et al., 2010) and many others have been studied. In Pakistan, Gharo, Sindh (Khahro et al., 2014b), Baburband, Sindh (Shoaib et al., 2017), Jiwani, Balochistan (Shami et al., 2016) and other potential sites have been investigated so far. As no single method can always be accurate for the estimation of Weibull parameters, therefore, there is always a thirst for developing better methods for the estimation of Weibull parameters.

The novelty of this work lies in the fact that it is dual objective in nature. Firstly, it introduces a new method, Modified Method of Moment (MMOM), which is a modification of previously used

method called Method of Moment (MOM). To the best of authors' knowledge, this modified method has not been used throughout the literature to estimate the Weibull parameters. To verify whether this new method has a better accuracy than original MOM, it must be compared with MOM. Moreover, MMOM should also be compared with Energy Pattern Factor Method (EPFM) because EPFM has also been found significantly accurate in many studies and moreover, it is much easy to use EPFM which requires no numerical iteration, therefore, EPFM can be an attractive selection for anyone to estimate Weibull parameters. So overall, work compares MMOM with MOM and EPFM in order to evaluate whether it is better fit than the other two methods or not. Secondly, wind potential estimation in South Punjab, which has not been accessed so far, needs to be accessed for future power projects expected to be launched in this area by Government of Pakistan (GOP).

2. Materials and methods

2.1. Wind Data Modeling

Although there are many continuous probability density functions available to model various phenomenon (Pobočková et al., 2017; Carta et al., 2009), two-parameter Weibull distribution has been the most widely used to estimate wind power potential throughout the literature (Bagiorgas et al., 2012; Kitaneh et al., 2012). Two-parameter Weibull model is given as follows (Khahro et al., 2014a; Aized et al., 2019; Costa Rocha et al., 2012).

$$f(V) = \frac{K}{C} \left(\frac{V}{C}\right)^{K-1} e^{-\left(\frac{V}{C}\right)^K} \quad (1)$$

$$F(V) = 1 - e^{-\left(\frac{V}{C}\right)^K} \quad (2)$$

where

$f(V)$ = Probability Density Function

$F(V)$ = Cumulative Density Function

K = Dimensionless Shape Parameter

C = Scale Parameter (m s^{-1})

2.2. Methods for estimating Weibull parameters

There are a number of methods available to estimate Weibull distribution parameters. This study focused on three methods i.e. Method of Moment (MOM), Energy Pattern Factor Method (EPFM) and a newly proposed method in this study called Modified Method of Moment (MMOM). As the name suggests, MMOM is a new method developed through the modification of previously used method MOM, therefore, it must be compared with MOM in order to evaluate whether MMOM gives better results than original MOM or not (This is a proven and validated technique as whenever Modified Maximum Likelihood Method is used, it is necessarily compared with Maximum Likelihood Method (Shoaib et al., 2019; Hulio et al., 2017; Khahro et al., 2014a; Hulio et al., 2019b)). Moreover, MMOM was compared with EPFM as EPFM is also significantly accurate method and it is much easy to apply this method as it requires no numerical iterative procedure for the estimation of Weibull parameters but only simple formulation is applied (Hulio et al., 2019a; Shoaib et al., 2019; Hulio et al., 2017; Khahro et al., 2014a). Therefore, present study compared MMOM with MOM and EPFM.

i. Method of Moment (MOM)

Mean wind speed can be calculated using integral definition, as given by Eq. (3)

$$\bar{V} = \int_0^{\infty} V f(V) dV \quad (3)$$

Putting Weibull probability density function in Eq. (3), we get Eq. (4)

$$\bar{V} = \int_0^{\infty} V \frac{K}{C} \left[\left(\frac{V}{C} \right)^{K-1} \times e^{-\left(\frac{V}{C}\right)^K} \right] dV \quad (4)$$

Incorporating the definition of gamma function $\Gamma(y) = \int_0^{\infty} e^{-t} t^{y-1}$, and simplifying the results, average wind speed assumes the following form:

$$\bar{V} = C \Gamma \left(1 + \frac{1}{K} \right) \rightarrow C = \frac{\bar{V}}{\Gamma \left(1 + \frac{1}{K} \right)} \quad (5)$$

From basic definition of standard deviation, we have following mathematical relationship

$$\sigma = \sqrt{\int_0^{\infty} (V - \bar{V})^2 f(V) dV} \quad (6)$$

Integrating Eq. (6)

$$\begin{aligned} \int_0^{\infty} V^2 f(V) dV &= \int_0^{\infty} V^2 \left(\frac{K}{C} \right) \left(\frac{V}{C} \right)^{K-1} dV \\ &= \int_0^{\infty} C^2 y^{\frac{2}{K}} e^{-y} dy = C^2 \Gamma \left(1 + \frac{2}{K} \right) \end{aligned} \quad (7)$$

Simplifying the results, we have following form of standard deviation

$$\sigma = C \left\{ \Gamma \left(1 + \frac{2}{K} \right) - \Gamma^2 \left(1 + \frac{1}{K} \right) \right\}^{0.5} \quad (8)$$

Simultaneous numerical iterative solution of Eqs. (5) and (8) estimates Weibull parameters.

ii. Modified Method of Moment (MMOM)

This is a new method proposed in this study called modified method of moment (MMOM). This method is based on the fact that “Weibull scale parameter is proportional to mean wind speed”.

Let us suppose that mean wind speed and Weibull scale are equal i.e. $C = \bar{V}$. If this assumption is true, following relationship must hold good as well:

$$C = (\bar{V}^K)^{\frac{1}{K}} \quad (9)$$

However, the results of various studies show that Weibull scale parameter is not exactly equal to mean wind speed, however, it is closely related to mean wind speed. Thus establishing a best fit between Weibull scale parameter (calculated from other methods in literature) and mean wind speed gives a similar form (but not same) of relationship as Eq. (9) the following relationship as given in Eq. (10)

$$C = (\bar{V}^K)^{1/K} \quad (10)$$

Taking natural logarithm of Eqs. (8) and (10), we have Eqs. (11) and (12) respectively.

$$\ln(\sigma^2 + \bar{V}^2) = 2 \ln C + \ln \Gamma \left(1 + \frac{2}{K} \right) \quad (11)$$

$$\ln C = \frac{1}{K} \ln (\bar{V}^K) \quad (12)$$

Eliminating C from Eqs. (11) and (12), we get following Eq. (13)

$$\ln \Gamma \left(1 + \frac{2}{K} \right) + 2 \left(\frac{1}{K} \right) \ln (\bar{V}^K) - \ln (\sigma^2 + \bar{V}^2) = 0 \quad (13)$$

Numerical solution of Eq. (13) yields K and C is then estimated using Eq. (10). This Eq. (13) is a new equation which has not previously been used in literature.

iii. Energy Pattern Factor Method (EPMF)

This method relies on the fact that “Average power of wind is higher than power of the average wind”. A parameter to quantify this difference is known as Wind Energy Pattern Factor (WEPF), given below:

$$WEPF = \frac{\text{Average power of the wind}}{\text{power of average wind}} = \frac{\frac{1}{N} \sum_{i=1}^N (\frac{1}{2} \rho V_i^3)}{\frac{1}{2} \rho \left(\frac{1}{N} \sum_{i=1}^N V_i \right)^3} = \frac{\bar{V}^3}{\bar{V}^3} \quad (14)$$

Once WEPF is estimated, Weibull parameters can be calculated using Eq. (15) (Akdağ and Dinler, 2009; Akdağ and Güler, 2015) and Eq. (5) respectively

$$K = 1 + \frac{3.69}{WEPF^2} \quad (15)$$

2.3. Measure of goodness of fit

How good is the Weibull distribution to model the actual wind data? This question is answered by using different statistical measures given below:

i. Coefficient of Determination (R^2)

Coefficient of determination is used to measure the accuracy of the wind model relative to the actual wind data. It can be evaluated using Eq. (16)

$$R^2 = \frac{\sum_{i=1}^N (Y_i - Z)^2 - \sum_{i=1}^N (X_i - Z)^2}{\sum_{i=1}^N (Y_i - Z)^2} \quad (16)$$

Y_i is actual wind speed probability

X_i is predicted wind speed probability

And Z is the mean of actual data

ii. Root Mean Square Error (RMSE)

Another measure to check the accuracy of wind model relative to the actual distribution is root mean square error. RMSE is calculated using Eq. (17)

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (Y_i - X_i)^2 \right]^{0.5} \quad (17)$$

It quantifies the deviation of predicted probability values from actual probability values. Therefore, the smaller is RMSE, the more accurate is the given model.

iii. Power Error (P.E)

Power error quantifies the relative difference between actual wind power density and predicted wind power density

$$P.E = \left| \frac{WPD_W - WPD_{act}}{WPD_{act}} \right| \quad (18)$$

2.4. Wind potential

Wind potential is described by not only the mean wind speeds but also by wind power density (WPD) and wind energy density (WED) because average wind speeds can be identical for different locations irrespective of whether they possess same or different wind power or wind energy densities. WPD and WED can be estimated using following mathematical relationships (Pishgar-Komleh et al., 2015; Azad et al., 2014):

$$WPD_W = \int_0^{\infty} \frac{1}{2} \rho V^3 f(V) dV = \frac{1}{2} \rho C^3 \Gamma \left(1 + \frac{3}{K} \right) \quad (19)$$

$$WED = \frac{1}{2} \rho C^3 \Gamma \left(1 + \frac{3}{K} \right) T \tag{20}$$

$T =$ Required time period

Two important speeds in the estimation of wind resource are most probable wind speed (V_{mp}) and the optimum wind speed (V_{opt}). Once the Weibull parameters are calculated, these speeds can be calculated using following mathematical relationships (Khahro et al., 2014b; Keyhani et al., 2010):

$$V_{mp} = C \left(\frac{K - 1}{K} \right)^{1/K} \tag{21}$$

$$V_{opt} = V_{maxE} = C \left(\frac{K + 2}{K} \right)^{1/K} \tag{22}$$

2.5. Energy production through turbines

Amount of power or energy produced over a period of time is an important consideration (Khahro et al., 2014a). Wind power extracted using a wind turbine does not depend only on wind characteristics of a site but also on turbine characteristics such as rated speed, cut-in speed, cut-out speed, rotor area and hub height (Liu and Yocke, 1980). Moreover, a turbine is normally rated to its maximum power (P_R) it can produce but practically, it would be able to produce a fraction of rated power. This relative difference is described in terms of capacity factor (CF). CF and power generated can be calculated using Eqs. (23) and (24) respectively:

$$C_F = \frac{\text{Actual Power from Wind Turbine (P)}}{\text{Rated Power from Wind Turbine (P}_R)} \tag{23}$$

$$\overline{P}_{WT} = \left\{ \begin{array}{l} \sum_{j=1}^{N_B} \left\{ \exp \left[- \left(\frac{v_{j-1}}{c} \right)^k \right] - \exp \left[- \left(\frac{v_j}{c} \right)^k \right] \right\} P_{WT} \left(\frac{v_{j-1} + v_j}{2} \right) \quad \text{for } (v_{cutin} \leq v \leq v_r) \\ \sum_{j=1}^{N_B} \left\{ \exp \left[- \left(\frac{v_{j-1}}{c} \right)^k \right] - \exp \left[- \left(\frac{v_j}{c} \right)^k \right] \right\} P_{WT} (v_r) \quad \text{for } (v_r \leq v \leq v_{cutout}) \\ 0 \text{ for } v < v_{cutin} \text{ and } v > v_{cutout} \end{array} \right. \tag{24}$$

3. Methodology

Wind potential estimation and energy generation in South Punjab, an expectedly high potential area in Punjab, was investigated using two-parameter Weibull Distribution function. Five years hourly recorded wind data at 50 m height was collected at eleven stations in South Punjab. Three methods to estimate Weibull parameters namely EPFM, MOM and MMOM were used and their comparative analysis was carried out based on R^2 , RMSE and P.E. monthly, seasonal and annual variations in wind speed, WPD and WED were observed. V_{mp} and V_{opt} were calculated using the method found the most accurate of three methods. Polar diagrams were drawn to demonstrate optimum wind direction at each of the investigated location. Finally, actual power produced from six turbine models from different manufacturers along with energy generation per year was also determined.

4. Results and discussions

4.1. Measure of goodness of fit

Three methods i.e. EPFM, MOM and MMOM were compared based upon three statistical measures i.e. R^2 , RMSE and P.E. Table 1 lists the values of Weibull Shape (K) and Scale (C) parameters calculated from all three methods for all locations. These values have been listed upto 5 decimal points with a view to making an in-depth comparison. Comparative analysis between MOM and MMOM shows that MMOM is superior in performance to MOM against all statistical tests of performance checking i.e. R^2 , RMSE and P.E. Similarly, comparison between MMOM and EPFM shows that MMOM is better than EPFM when compared w.r.t P.E for all locations. However, MMOM has been found better than EPFM upto 63% and 55% against R^2 RMSE respectively. Comparison between MOM and EPFM shows that MOM is superior to EPFM w.r.t P.E. for all locations; superior to EPFM for 63% locations against R^2 and inferior to EPFM for about 72% locations.

4.2. Weibull distribution

Weibull distribution estimates the actual wind data with significant accuracy. Table 1 shows that Weibull distribution estimates the actual data accurately with a minimum accuracy of more than 90% and for many locations more than 95%. Thus Weibull distribution has been found to give an accurate fit for all locations. The Weibull diagrams for all locations showing a comparison between three methods and actual data have been shown in Fig. 1.

4.3. Monthly, seasonal and annual variation in wind speeds

Monthly and average wind speed values have been listed in Tables 3 and 4 respectively. Graphically, monthly, seasonal and yearly mean wind speeds have been shown in Figs. 2–4 respectively. Analysis shows that at each of the investigated location, maximum mean wind speed occurs during summer season (Layyah shows exceptional behavior where maximum wind speed occurs during spring season) while minimum wind speed is observed during winter season (D.G. Khan and Muzaffargarh show exceptional behaviors with minimum wind speed occurring in autumn season). Comparison among investigated sites shows that Rahim Yar Khan (RYK) has the highest wind speed with 3.58, 4.28, 5.76 and 3.89 m s⁻¹ winter, spring, summer and autumn respectively with annual mean value of 4.38 m s⁻¹.

4.4. Monthly, seasonal and annual variation wind power and energy density

Monthly and annual WPD values are listed in Tables 3 and 4. Furthermore, monthly, seasonal and annual variation in WPD have been graphically represented in Figs. 5–7 respectively. Analysis shows that at each of the investigated location, highest WPD has been observed in summer season while lowest has been observed in winter (D.G. Khan and Layyah show exceptional behavior where lowest WPD has been observed in autumn). Moreover, RYK has the highest mean WPD of 42.84 W m⁻², 63.79 W m⁻², 149.42 W m⁻² and 52.36 W m⁻² in winter, spring, summer and autumn respectively with yearly average value of 77.10 W m⁻². Similarly, monthly, seasonal and annual variation in WED has been shown in Figs. 8–10 respectively. Analysis shows that the trend of variation in wind energy density is exactly same as wind power density. Moreover, RYK possesses highest WED with 91.50, 140.96, 329.21 and 113.95 kWh m⁻² season⁻¹ in winter, spring, summer and autumn respectively with yearly value of 675.62 kWh m⁻² year⁻¹.

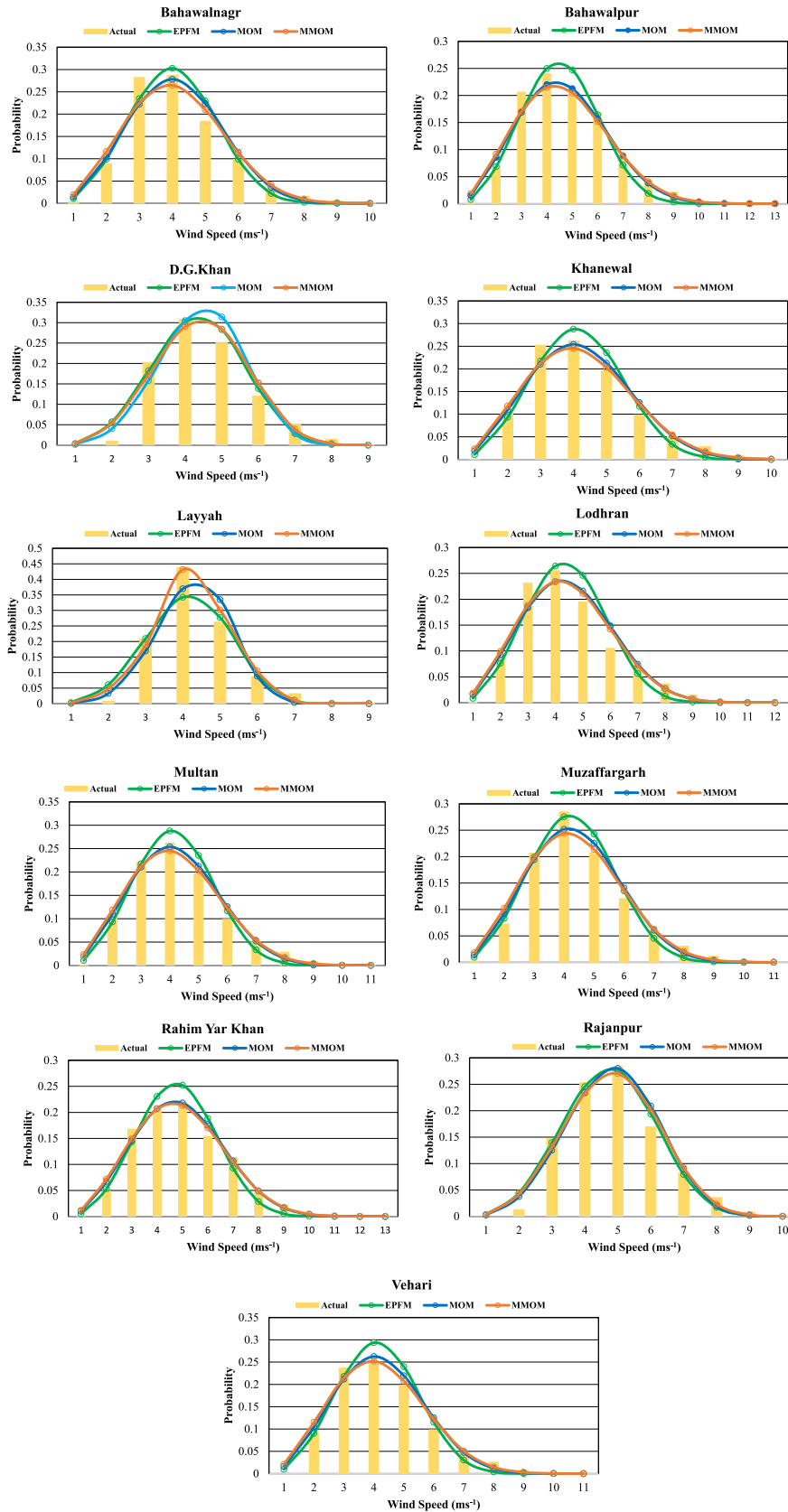


Fig. 1. Comparison of actual probability distribution with Weibull distribution.

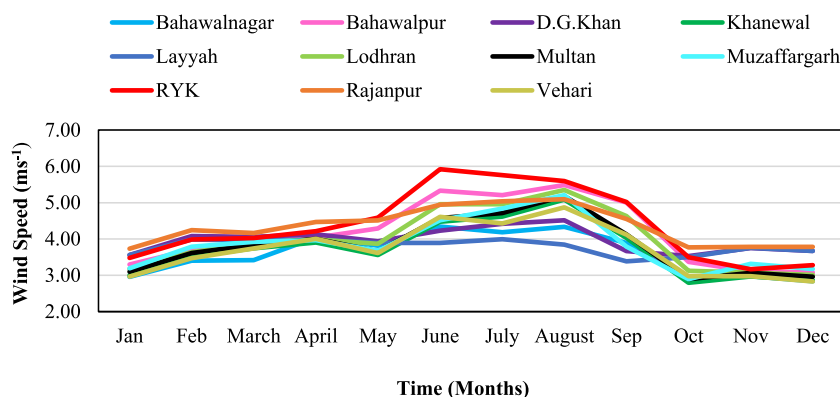


Fig. 2. Monthly variation in wind speed at 11 locations in South Punjab.

Table 1
Comparison of three methods for estimating Weibull parameters.

Location	EPFM					MOM					MMOM				
	K	C (m s ⁻¹)	R ²	RMSE	P.E	K	C (m s ⁻¹)	R ²	RMSE	P.E	K	C (m s ⁻¹)	R ²	RMSE	P.E
Bahawalnagar	3.06936	3.95905	0.97861	0.00240	0.12607	2.86558	4.06203	0.97444	0.01813	0.02741	2.68751	4.04015	0.97743	0.00461	0.01106
Bahawalpur	3.02400	4.53800	0.95594	0.00182	0.19589	2.61076	4.65206	0.96656	0.00989	0.06782	2.51076	4.66064	0.96918	0.00492	0.03972
D.G. Khan	3.51600	4.28400	0.95229	0.00123	0.06823	3.86208	4.37971	0.93128	0.01019	0.02664	3.49482	4.36980	0.94251	0.01012	0.00945
Multan	3.01265	4.09420	0.95185	0.00305	0.15143	2.65256	4.17722	0.95924	0.00248	0.04059	2.53260	4.15631	0.96395	0.00244	0.02825
Muzaffargarh	3.01911	4.24947	0.95374	0.00235	0.12947	2.76818	4.33428	0.95399	0.00618	0.03832	2.63155	4.31320	0.95871	0.00282	0.02565
Rahim Yar Khan	3.14164	4.79035	0.95776	0.00113	0.15305	2.74358	4.92905	0.97114	0.00515	0.01962	2.67566	4.90755	0.97437	0.01855	0.01915
Khanewal	3.01265	4.09420	0.95183	0.00305	0.15143	2.65528	4.17712	0.95904	0.02110	0.04123	2.53636	4.15747	0.96366	0.00239	0.02835
Layyah	3.68866	4.05509	0.95928	0.00680	0.06045	4.39488	4.15238	0.94233	0.00844	0.02304	3.90353	4.14870	0.94932	0.00109	0.00632
Lodhran	3.02109	4.37696	0.96510	0.01229	0.15153	2.64118	4.46988	0.97228	0.00232	0.05590	2.58763	4.41882	0.97694	0.00174	0.03453
Rajanpur	3.41524	4.71628	0.95836	0.00785	0.07952	3.52568	4.83132	0.94458	0.00489	0.01949	3.38730	4.82333	0.95018	0.00101	0.01295
Vehari	3.07559	4.08576	0.95864	0.02101	0.13533	2.75235	4.16182	0.96332	0.00366	0.03852	2.60283	4.14033	0.96793	0.00290	0.02334

4.5. Most probable and optimum wind speed

The analysis of Tables 2 and 4 shows that Rajanpur has the highest value of V_{mp} as 4.34 m s^{-1} and Bahawalnagar carries the lowest as 3.49 m s^{-1} . The highest V_{opt} is observed for RYK as 6.07 m s^{-1} and the minimum is for Layyah i.e. 4.59 m s^{-1} (lower than that of Bahawalnagar i.e. 4.89 m s^{-1}) (see Table 5).

4.6. Wind speed distribution

Cumulative frequency distribution has been shown in Fig. 11. Analysis shows that at the highest wind potential area i.e. RYK, wind blows at a speed greater than 3 m s^{-1} with more than 75% cumulative probability whereas for Bahawalnagar the wind blows at a speed greater than 3 m s^{-1} with approximately 62% cumulative frequency value. Wind speed of greater than 3 m s^{-1} is important as most of the wind turbines have cut-in speed equal to 3 m s^{-1} .

4.7. Polar diagrams

Polar diagrams are very important to show the optimum direction in which the wind blows at a certain location. The determination of this direction is important as the amount of energy extraction surely relies on the direction in which the turbine is installed. In Fig. 12, the polar diagrams have been shown for all 11 locations and results show that in South Punjab, the optimum direction for almost all locations is Southwest (SW).

4.8. Energy production from wind turbines

Energy production per year using six turbine models from different manufacturers has been investigated. These turbines

were selected for two reasons. Firstly, these are the most preferably used turbines in Pakistan, and secondly, these turbines are available at the same hub height (50 m) at which this potential estimation has been conducted. Turbine models used in this study are listed with their specifications in Table 6. It can be observed that all these models are available at 50 m height. Table 7 enlists power and annual energy production from various models and CF estimation at each of the investigated location in South Punjab.

It can be observed that at RYK, the highest energy output per year is 1743.85 MWh by Bonus 1300/62 and minimum is 777.59 MWh by Vestas V42. Same behavior can be analyzed for other locations also. From this observation, it can be easily concluded that wind energy production does not depend only on the wind potential of the site (as one might expect) but also on turbine characteristics.

5. Conclusion

Wind potential in a region of South Punjab has been investigated using two-parameter Weibull distribution with 5 years hourly average wind data. Three Weibull parameters estimation method i.e. EPFM, MOM and MMOM were used and compared based upon three statistical measures i.e. R^2 , RMSE and P.E. monthly, seasonal and annual variation in wind speed, wind power density and wind energy density were analyzed. The following conclusions have been drawn from the analysis:

- MMOM is better than MOM against all statistical tests of performance evaluation. Similarly, comparison between MMOM and EPFM shows that MMOM is better than EPFM when compared w.r.t P.E for all locations. However, it has been found better than EPFM upto 63% and 55% against R^2 and RMSE respectively. So overall it can be concluded that MMOM is also better than EPFM.

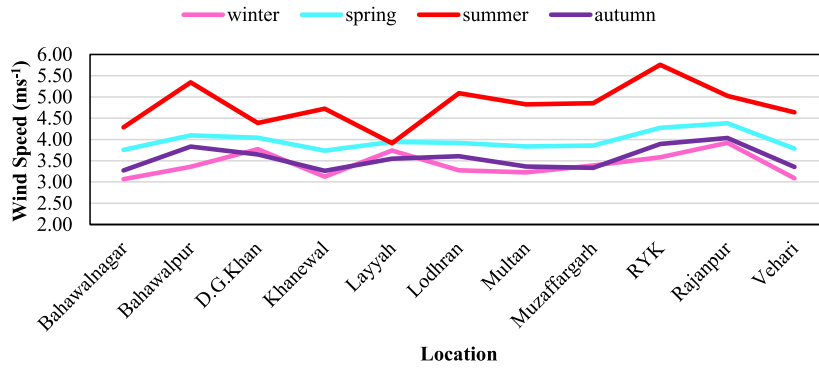


Fig. 3. Seasonal variation in wind speed at 11 locations in South Punjab.

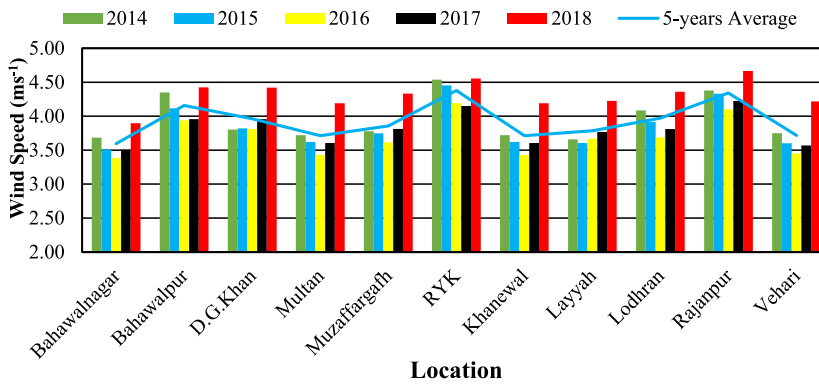


Fig. 4. Yearly average and 5-years average wind speeds ($m s^{-1}$).

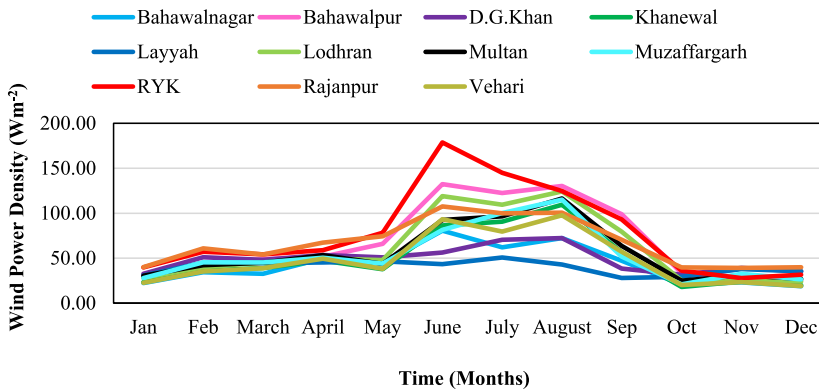


Fig. 5. Monthly variation in wind power density at 11 locations in South Punjab.

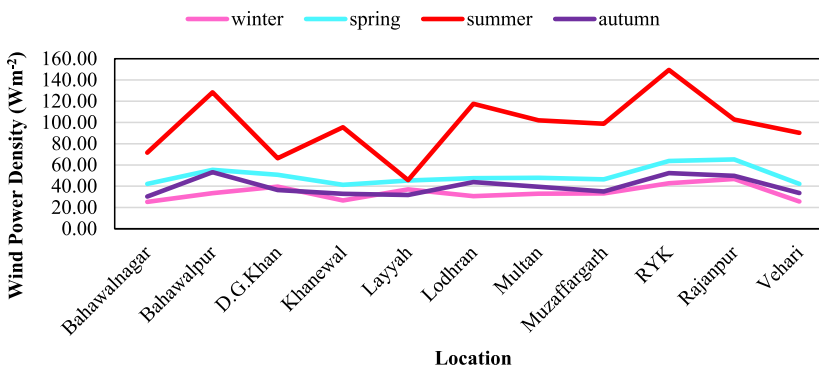


Fig. 6. Seasonal variation in wind power density at 11 locations in South Punjab.

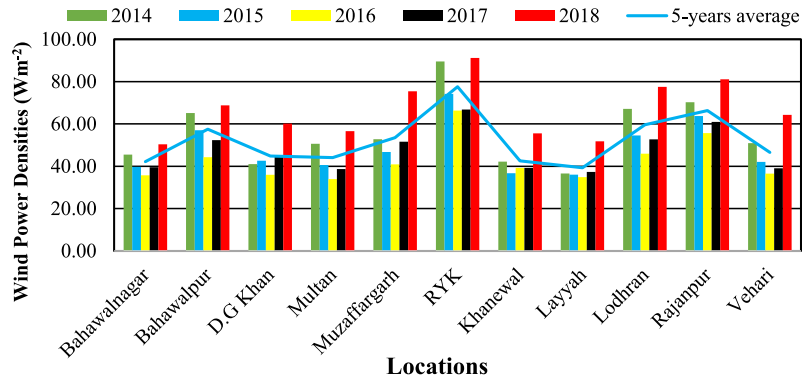


Fig. 7. Yearly average and 5-years average wind power densities ($W m^{-2}$).

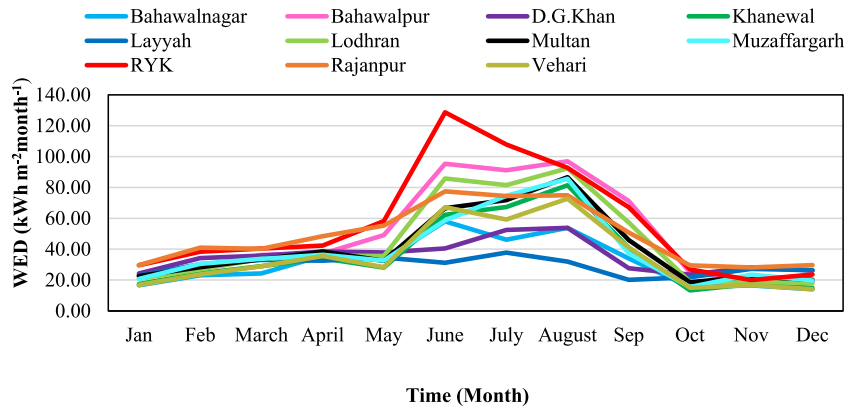


Fig. 8. Monthly variation in wind energy density at 11 locations in South Punjab.

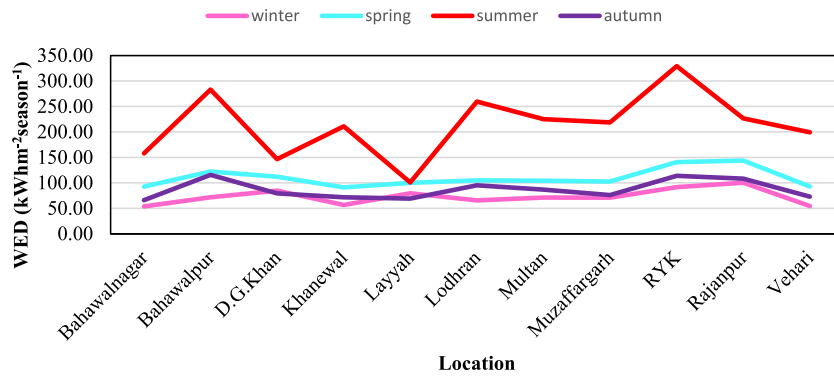


Fig. 9. Seasonal variation in wind energy density at 11 locations in South Punjab.

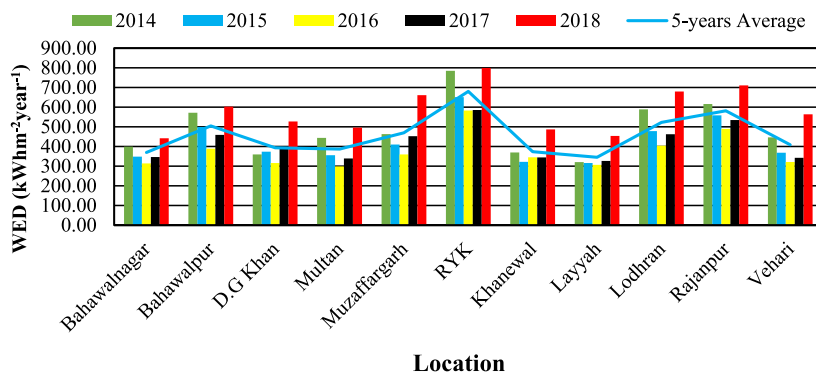


Fig. 10. Yearly average and 5-years average wind energy densities ($kWh m^{-2} year^{-1}$).

Table 2
Monthly average values of Weibull shape and scale ($m s^{-1}$) parameters.

		Jan	Feb	March	April	May	June	July	August	Sep	Oct	Nov	Dec
Bahawalnagar	K	2.90	2.85	3.40	3.47	3.28	2.54	2.95	2.92	3.32	3.18	2.94	3.07
	C	3.28	3.76	3.75	4.37	4.17	4.84	4.64	4.80	4.25	3.24	3.29	3.13
Bahawalpur	K	2.81	2.95	3.28	3.34	3.19	2.62	2.90	3.40	3.31	2.87	2.78	2.83
	C	3.67	4.10	4.33	4.40	4.71	5.45	5.77	5.96	5.45	3.74	3.47	3.42
D.G. Khan	K	3.62	3.53	3.60	3.46	3.03	3.70	3.30	3.51	3.46	3.65	3.59	3.71
	C	3.83	4.41	4.37	4.48	4.34	4.53	4.80	4.87	3.98	3.79	4.05	3.94
Khanewal	K	2.91	3.05	3.47	3.25	3.01	2.66	2.81	3.24	2.99	3.16	2.66	2.94
	C	3.33	3.88	4.04	4.27	3.93	4.99	5.13	5.56	4.44	3.07	3.31	3.17
Layyah	K	3.73	3.77	3.70	3.75	3.42	3.74	3.41	3.65	3.65	3.87	3.85	3.69
	C	3.77	4.27	4.26	4.27	4.25	4.15	4.31	4.10	3.61	3.71	4.01	3.94
Lodhran	K	2.86	3.04	3.37	3.31	3.08	2.60	2.81	3.31	3.28	3.07	2.69	2.83
	C	3.53	4.01	4.23	4.34	4.26	5.53	5.52	5.83	5.04	3.44	3.43	3.35
Multan	K	2.91	3.05	3.47	3.25	3.01	2.66	2.81	3.24	2.99	3.16	2.66	2.94
	C	3.33	3.88	4.04	4.27	3.93	4.99	5.13	5.56	4.44	3.07	3.31	3.17
Muzaffargarh	K	2.95	3.09	3.44	3.20	2.82	2.99	2.99	3.34	2.72	2.90	2.75	3.03
	C	3.53	4.18	4.25	4.36	4.09	4.99	5.33	5.67	4.22	3.20	3.70	3.47
RYK	K	2.61	2.76	3.05	3.28	3.31	3.13	3.43	3.78	3.56	3.10	2.93	2.75
	C	3.89	4.44	4.45	4.61	5.01	6.51	6.23	5.95	5.40	3.85	3.49	3.66
Rajanpur	K	3.42	3.27	3.48	3.54	3.20	3.01	3.30	3.53	3.51	3.52	3.65	3.53
	C	4.06	4.65	4.52	4.83	4.95	5.48	5.48	5.49	4.91	4.08	4.06	4.09
Vehari	K	2.91	2.98	3.47	3.39	3.14	2.71	2.77	3.18	3.20	3.29	2.85	3.02
	C	3.28	3.83	4.04	4.35	3.96	5.12	4.93	5.35	4.51	3.22	3.30	3.13

Table 3
Monthly average wind speed ($m s^{-1}$) and wind power densities ($W m^{-2}$).

Wind speed	Jan	Feb	March	April	May	June	July	August	Sep	Oct	Nov	Dec
Bahawalnagar	2.96	3.40	3.42	4.04	3.81	4.34	4.18	4.33	3.89	2.95	2.97	2.84
Bahawalpur	3.30	3.70	3.97	4.04	4.29	5.33	5.21	5.49	5.01	3.37	3.12	3.08
D.G. Khan	3.56	4.08	4.06	4.13	3.94	4.23	4.42	4.52	3.67	3.53	3.75	3.67
Khanewal	3.00	3.51	3.74	3.91	3.56	4.48	4.62	5.08	4.03	2.80	2.97	2.86
Layyah	3.56	3.98	3.96	3.98	3.89	3.89	3.99	3.85	3.38	3.50	3.76	3.67
Lodhran	3.17	3.63	3.90	3.99	3.87	4.96	4.96	5.35	4.63	3.13	3.07	3.01
Multan	3.10	3.61	3.84	4.01	3.66	4.58	4.72	5.18	4.13	2.90	3.07	2.96
Muzaffargarh	3.19	3.79	3.92	3.97	3.68	4.52	4.84	5.21	3.79	2.89	3.32	3.18
RYK	3.48	3.98	4.03	4.22	4.59	5.92	5.76	5.60	5.02	3.49	3.17	3.28
Rajanpur	3.73	4.25	4.16	4.47	4.51	4.95	5.04	5.10	4.55	3.77	3.78	3.78
Vehari	2.96	3.47	3.74	4.00	3.62	4.61	4.43	4.87	4.12	2.97	2.97	2.83
WPD	Jan	Feb	March	April	May	June	July	August	Sep	Oct	Nov	Dec
Bahawalnagar	22.32	34.37	32.59	49.59	44.15	80.61	62.07	72.30	47.21	20.72	23.02	18.85
Bahawalpur	31.65	43.12	48.69	51.48	65.97	132.34	122.42	130.30	98.80	33.50	27.13	25.52
D.G. Khan	32.59	50.94	48.12	53.38	50.88	56.22	70.50	72.32	38.39	31.64	39.15	35.28
Khanewal	23.37	36.17	39.00	47.35	37.69	86.48	90.54	109.41	56.72	17.93	24.15	20.03
Layyah	30.73	45.00	44.45	45.23	46.47	43.37	50.75	42.90	27.94	29.36	37.85	35.48
Lodhran	27.94	39.92	45.15	49.80	47.80	119.11	109.51	124.20	79.53	25.19	26.63	24.06
Multan	30.37	42.17	45.00	53.35	43.69	92.48	96.54	116.41	63.72	24.93	31.15	27.03
Muzaffargarh	27.84	45.40	45.29	50.42	43.85	81.39	100.22	115.09	51.75	20.84	32.63	26.47
RYK	39.71	57.11	54.22	58.85	78.29	178.69	144.89	124.67	93.18	36.12	27.77	31.69
Rajanpur	39.90	60.94	54.07	67.23	74.27	107.54	100.01	100.68	70.52	39.64	39.10	39.80
Vehari	22.63	35.20	38.90	49.47	38.13	93.45	79.59	97.76	57.17	20.24	23.29	18.93

Table 4
Annual average wind speeds ($m s^{-1}$), Shape (K), Scale, C ($m s^{-1}$) parameters and wind power density, WPD ($W m^{-2}$) for South Punjab.

Location	2014				2015				2016				2017				2018			
	V_{avg}	K	C	WPD	V_{avg}	K	C	WPD	V_{avg}	K	C	WPD	V_{avg}	K	C	WPD	V_{avg}	K	C	WPD
Bahawalnagar	3.68	2.72	4.14	45.55	3.51	2.82	3.98	39.75	3.38	2.98	3.87	35.71	3.50	2.74	3.95	39.51	3.90	3.07	4.36	50.36
Bahawalpur	4.35	3.15	4.77	65.20	4.12	2.99	4.53	57.02	3.94	2.97	4.16	44.28	3.96	2.89	4.38	52.33	4.42	3.12	4.85	68.78
D.G. Khan	3.80	3.46	4.13	41.03	3.82	2.77	4.06	42.64	3.81	2.81	3.85	36.01	3.96	2.57	4.06	44.46	4.42	3.66	4.72	60.16
Multan	3.72	2.44	4.20	50.65	3.62	2.87	4.02	40.59	3.43	2.93	3.80	33.96	3.60	2.98	3.98	38.73	4.19	3.26	4.57	56.64
Muzaffargarh	3.78	2.36	4.22	52.80	3.75	2.78	4.19	46.79	3.62	2.86	4.03	40.95	3.81	2.57	4.27	51.65	4.33	2.59	4.85	75.40
Rahim Yar Khan	4.54	2.48	5.09	89.55	4.45	3.10	4.97	74.23	4.19	2.74	4.70	66.32	4.15	2.59	4.66	66.82	4.55	2.47	5.12	91.18
Khanewal	3.72	3.02	4.10	42.21	3.62	3.94	4.02	36.73	3.43	4.11	4.12	39.26	3.60	4.11	4.12	39.26	4.19	4.15	4.63	55.59
Layyah	3.66	3.87	4.01	36.57	3.60	3.44	3.95	36.09	3.67	3.67	3.93	34.88	3.77	3.71	4.03	37.32	4.23	3.80	4.50	51.79
Lodhran	4.08	2.38	4.58	67.16	3.92	2.69	4.39	54.59	3.69	2.62	4.12	45.94	3.81	2.58	4.30	52.74	4.36	2.57	4.89	77.54
Rajanpur	4.38	3.00	4.86	70.29	4.33	3.72	4.81	63.75	4.10	3.53	4.58	55.67	4.23	3.30	4.69	60.96	4.67	3.39	5.17	81.12
Vehari	3.75	2.43	4.20	50.94	3.60	2.70	4.03	42.06	3.45	2.72	3.85	36.51	3.57	2.97	3.99	39.09	4.22	2.70	4.64	64.31

ii Comparison between MOM and EPFM shows that MOM is better than EPFM upto 100% and 63% w.r.t P.E. and R^2 respectively. However, EPFM has been found better than

MOM for about 72% locations w.r.t RMSE. Overall, MMOM can be declared as the best method followed by MOM and EPFM respectively.

Table 5

Yearly averaged most probable, V_{mp} (m s^{-1}) and optimum wind speed, V_{opt} (m s^{-1}).

Location	2014		2015		2016		2017		2018	
	V_{mp}	V_{opt}	V_{mp}	V_{opt}	V_{mp}	V_{opt}	V_{mp}	V_{opt}	V_{mp}	V_{opt}
Bahawalnagar	3.50	5.07	3.41	4.81	3.38	4.60	3.35	4.83	3.83	5.14
Bahawalpur	4.23	5.58	3.95	5.38	3.62	4.95	3.78	5.25	4.29	5.68
D.G Khan	3.74	4.71	3.46	4.94	3.29	4.66	3.35	5.08	4.32	5.31
Multan	3.38	5.36	3.46	4.83	3.30	4.54	3.47	4.73	4.08	5.29
Muzaffargarh	3.34	5.47	3.57	5.10	3.46	4.85	3.52	5.34	4.02	6.05
Rahim Yar Khan	4.13	6.47	4.38	5.84	3.98	5.74	3.86	5.81	4.15	6.51
Khanewal	3.59	4.86	3.73	4.46	3.85	4.54	3.85	4.54	4.34	5.09
Layyah	3.71	4.47	3.58	4.52	3.61	4.43	3.70	4.52	4.15	5.03
Lodhran	3.65	5.92	3.70	5.39	3.43	5.12	3.56	5.38	4.04	6.12
Rajanpur	4.25	5.76	4.43	5.40	4.17	5.20	4.20	5.41	4.67	5.93
Vehari	3.38	5.38	3.39	4.94	3.25	4.71	3.48	4.75	3.91	5.69

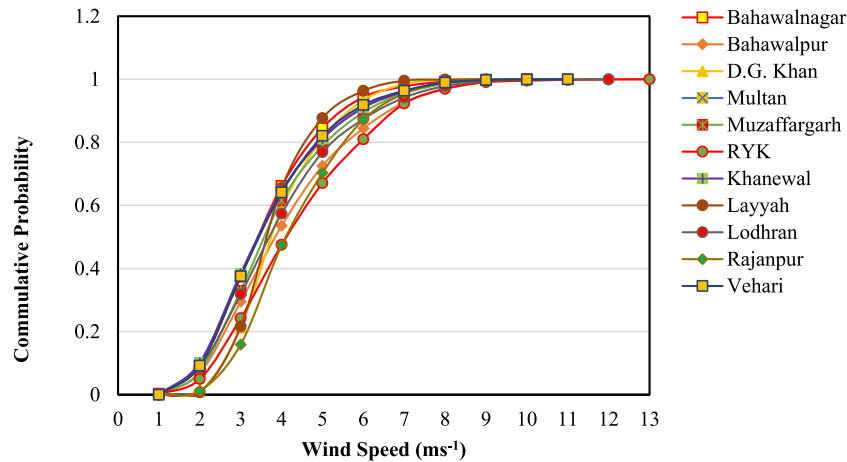


Fig. 11. Cumulative probability distribution for South Punjab.

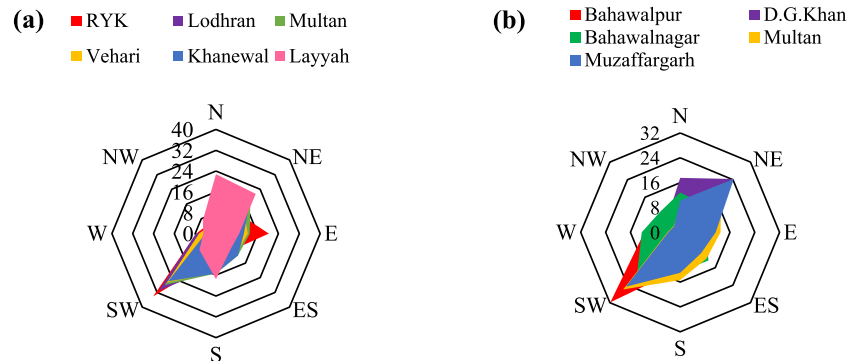


Fig. 12. Polar diagrams – showing the optimum wind direction – for South Punjab.

- iii Monthly and seasonal analysis shows that entire region has highest wind speed, WPD and WED in summer season followed by spring, autumn and winter respectively.
- iv RYK is the highly windy area with maximum wind speed, WPD and WED as 4.38 m s^{-1} , 77.10 W m^{-2} and 675.60 kWh m^{-2} year $^{-1}$ respectively.
- v On the other hand, Bahawalnagar is the poorest area as far as wind speed is concerned. But the minimum WPD and WED has been observed for Layyah rather than Bahawalnagar. The difference is associated with the difference in V_{opt} values.
- vi At same location, different turbine models produce different power and energy output per year with different

Table 6

Different turbine models with their specifications.

Turbine model	P_R (kW)	A_T (m^2)	V_{cin} ($m s^{-1}$)	V_R ($m s^{-1}$)	V_{cout} ($m s^{-1}$)	Hub height (m)
Bonus 1300/62	1300	3018	3	14	24	50, 60, 68, 80
Bonus 1 MW/54	1000	2300	3	15	25	50, 60
Bonus 600/44	600	1520	3	13	25	40, 45, 50, 60
Vestas V42	600	1385	4	17	25	35, 40, 50, 55
GE600a	600	1662	3	14	20	50
Enercon E-40/600	600	1520	2.5	12	28	46, 50, 58, 65

capacity factor. Therefore, choice of turbine at particular location is also important.

Table 7
Power production, P_p (kW), annual energy production (MWh) and capacity factors, C.F (%) for various locations in South Punjab.

Location	Turbine model	Bonus 1300/62	Bonus 1 MW/54	Bonus 600/44	Vestas V42	GE600a	Enercon E-40/600
Bahawalnagar	Pp	108.15	83.25	55.15	39.58	60.45	58.01
	Energy	947.34	729.27	483.11	346.72	529.54	508.17
	C.F	8.36	8.33	9.20	6.60	10.07	9.67
Bahawalpur	Pp	170.05	130.87	86.89	70.68	95.00	88.09
	Energy	1489.64	1146.42	750.18	610.15	815.24	761.99
	C.F	13.08	13.09	14.48	11.78	15.83	14.68
D.G. Khan	Pp	135.61	103.81	69.14	52.60	75.80	70.40
	Energy	1187.94	909.38	605.67	460.78	664.01	616.70
	C.F	10.43	10.38	11.52	8.77	12.63	11.73
Multan	Pp	123.45	94.15	63.30	47.55	68.90	65.50
	Energy	1081.42	824.75	554.51	416.54	603.56	573.78
	C.F	9.50	9.42	10.55	7.93	11.48	10.92
Muzaffargarh	Pp	139.06	106.47	71.07	55.11	77.51	73.24
	Energy	1218.17	932.68	622.57	482.76	678.99	641.58
	C.F	10.70	10.65	11.85	9.19	12.92	12.21
RYK	Pp	199.07	152.21	101.29	84.20	110.56	102.91
	Energy	1743.85	1333.36	887.30	737.59	968.51	901.49
	C.F	15.31	15.22	16.88	14.03	18.43	17.15
Khanewal	Pp	123.59	94.68	63.27	47.58	68.99	65.63
	Energy	1082.65	829.40	554.25	416.80	604.35	574.92
	C.F	9.51	9.47	10.55	7.93	11.50	10.94
Layyah	Pp	112.55	86.27	57.71	40.65	62.91	60.15
	Energy	985.94	755.73	505.54	356.09	551.09	526.91
	C.F	8.66	8.63	9.62	6.78	10.49	10.03
Lodhran	Pp	152.63	116.81	77.90	61.72	84.98	79.93
	Energy	1337.04	1023.26	682.40	540.67	744.42	700.19
	C.F	11.74	11.68	12.98	10.29	14.16	13.32
Rajapur	Pp	184.79	141.32	94.10	77.11	102.60	95.72
	Energy	1618.76	1237.96	824.32	675.48	898.78	838.51
	C.F	14.21	14.13	15.68	12.85	17.10	15.95
Vehari	Pp	121.76	93.28	62.35	46.54	67.98	64.72
	Energy	1066.62	817.13	546.19	407.69	595.50	566.95
	C.F	9.37	9.33	10.39	7.76	11.33	10.79

CRedit authorship contribution statement

Muhammad Sumair: Conceptualization, Methodology, Software, Writing - review & editing. **Tauseef Aized:** Supervision, Data curation, Writing - original draft. **Syed Asad Raza Gardezi:** Writing - review & editing. **Syed Ubaid ur Rehman:** Software, Validation, Writing - review & editing. **Syed Muhammad Sohail Rehman:** Visualization, Investigation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

Data generated at a central, large scale facility. Raw data were generated at the Pakistan Meteorological Department, large scale facility. Derived data supporting the findings of this study are available from the corresponding author upon reasonable request

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