Wind potential estimation and proposed energy production in Southern Punjab using Weibull probability density function and surface measured data

Muhammad Sumair1, Tauseef Aized1, Syed Asad Raza Gardezi2, Syed Ubaid Ur Rehman1 and Syed Muhammad Sohail Rehman1

Abstract
Current work focusses on the wind potential assessment in South Punjab. Eleven locations from South Punjab have been analyzed using two-parameter Weibull model (with Energy Pattern Factor Method to estimate Weibull parameters) and five years (2014–2018) hourly wind data measured at 50 m height and collected from Pakistan Meteorological Department. Techno-economic analysis of energy production using six different turbine models was carried out with the purpose of presenting a clear picture about the importance of turbine selection at particular location. The analysis showed that Rahim Yar Khan carries the highest wind speed, highest wind power density, and wind energy density with values 4.40 ms⁻¹, 77.2 W/m² and 677.76 kWh/m²/year, respectively. On the other extreme, Bahawalnagar observes the least wind speed i.e. 3.60 ms⁻¹ while Layyah observes the minimum wind power density and wind energy density as 38.96 W/m² and 352.24 kWh/m²/year, respectively. According to National Renewable Energy Laboratory standards, wind potential ranging from 0 to 200 W/m² is considered poor. Economic assessment was carried out to find feasibility of the location for energy harvesting. Finally, Polar diagrams drawn to show the optimum wind blowing directions shows that optimum wind direction in the region is southwest.
Keywords
Weibull probability density function, wind potential assessment, energy produced from wind turbines, capacity factor, South Punjab

Introduction
Wind energy, being a significantly economical and renewable form of energy, is seeking attention throughout the world these days (Rehman et al., 2018; Shoaib et al., 2017a, 2017b). Currently, the 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 which was 106 MW in 2014 (Khahro et al., 2014a). 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., 2014c). Before the exploitation of wind energy, accurate estimation of wind potential is important (Bilir et al., 2015b). So far, numerous sites throughout the world have been investigated. Oyedepo et al. (2012) investigated the wind potential at three locations (Enugu, Owerri, and Onitsha) in Nigeria using wind speed data measured at a hub height of 10 m. Analysis showed that Enugu has maximum wind speed while Owerri has least. Furthermore, the energy generation by using typical turbines was also determined.

Wind potential estimation of Rwanda was made using hourly wind data over a period of 20 years (1974–1993) at a hub height of 10 (Safari and Gasore, 2010) using Weibull and Rayleigh distributions. Furthermore, wind characteristics were also investigated on higher heights to evaluate the wind shear effects. Weisser (2003) used two-parameter Weibull probability density model to investigate the wind characteristics and to evaluate wind power density (WPD) and wind energy density (WED) at Grenada, West Indies. Hourly wind data were utilized and diurnal variations were observed.

Uludağ (a region in Turkey) was investigated using wind data collected over a span of seven years (2000–2006) (Ucar and Balo, 2009). Shape and scale parameters were estimated and it was found that mean wind speed at investigated location is 7.06 m/s. Moreover, economic feasibility of certain wind power projects was also carried out. Wind characteristics in Kayathar, Tamil Nadu, India were investigated using wind speed data measured by SODAR technique (Chaurasiya et al., 2017) along with a comparative analysis of nine different Weibull parameters estimation methods. Furthermore, the study compared the accuracy of data collected using sonic detection and ranging (SODAR) technique and cup anemometer method.

Wind potential at Kumta and Sirsi (India) was investigated (Ramachandra et al., 1997) by using two years wind data and two-parameter Weibull distribution with power density method (PDM) used to estimate Weibull parameters. Seasonal variation was investigated
and the analysis showed that the period from May to August is a good period to obtain wind energy.

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., 2014c), Baburband, Sindh (Shoaib et al., 2017a), Jiwan, Balochistan (Shami et al., 2016), and other potential sites have been investigated so far.

However, province of Punjab has not been investigated as no literature is available for that. The aim of current work is to investigate the true wind potential using surface measured data in South Punjab and the determination of suitability of various turbine models. The output from this study is useful to determine the effectiveness of certain wind project planned to be launched in future.

**Materials and methods**

**Wind data modeling**

There are a number of distributions available to model various phenomenon in nature such as three-parameter Weibull distribution, two-parameter Weibull distribution, Rayleigh Distribution, two-parameter lognormal distribution, and two-parameter gamma distribution (Baseer et al., 2017; Bassyouni et al., 2015b) but two-parameter Weibull model has been most widely used throughout the literature to estimate the wind potential. Two-parameter Weibull model is given as follows (Aized et al., 2019; Hulio et al., 2019; Shoaib et al., 2019)

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

\[
F(V) = 1 - e^{-\left( \frac{V}{C} \right)^K}
\]

where 

- \( f(V) \) = probability density function
- \( F(V) \) = cumulative density function
- \( K \) = dimensionless shape parameter
- \( C \) = scale parameter (ms\(^{-1}\))

**Weibull parameters estimation methods**

There are a number of methods available to estimate Weibull distribution parameters graphical method (GM) (Bilir et al., 2015b), maximum likelihood method (MLM) (Shoaib et al., 2017a), empirical method (EM) (Bilir et al., 2015b; Ouammi et al., 2010), method of moments (MOMs) (Shoaib et al., 2017a), etc. In this study, Energy Pattern Factor Method (EPFM) is used.

**Energy Pattern Factor Method (EPFM)**. In EPFM, Weibull parameters can be estimated using Wind Energy Pattern Factor (WEPF) (Akdağ and Dinler, 2009; Akdağ and Güler, 2015)
\[
WEPF = \frac{(V3)_{avg}}{(V_{avg})^3}
\]

\[
K = 1 + \frac{3.69}{WEPF^2}
\]

\[
C = \frac{V_{avg}}{\Gamma(1+\frac{1}{K})}
\]

where \(\Gamma()\) is a mathematical function known as Gamma function; as per calculus it is given as (Jowder, 2009)

\[
\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}dt
\]

**Wind potential**

Wind potential is not only determined by wind speeds but also from WPD and 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 (Azad et al., 2014; Pishgar-Komleh et al., 2015)

\[
WPD_w = \frac{1}{2} \rho C^3 \Gamma \left( 1 + \frac{3}{K} \right)
\]

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

\[T = \text{required time period}\]

Two important speeds in the estimation of wind resource are most probable wind speed (\(V_{mp}\)) and the optimum wind speed (\(V_{opt}\)) also known as the speed carrying the maximum wind energy (\(V_{maxE}\)) (Bagiorgas et al., 2016; Bassyouni et al., 2015a). \(V_{mp}\) is the wind speed with highest frequency for a given wind speed distribution and \(V_{opt}\) is the speed which carries the maximum energy as wind energy (over a period of time) does not depend only on average wind speed but also its distribution characterized by \(K\) and \(C\) (Rehman et al., 2012). Once the Weibull parameters are calculated, these speeds can be calculated using following mathematical relationships (Keyhani et al., 2010; Khahro et al., 2014c)

\[
V_{mp} = C \left( \frac{K - 1}{K} \right)^{\frac{1}{K}}
\]

\[
V_{opt} = V_{maxE} = C \left( \frac{K + 2}{K} \right)^{\frac{1}{K}}
\]
Measure of goodness of fit

In order to measure goodness of fit of Weibull distribution to actual wind data, correlation coefficient can be used.

\[ R^2 = \frac{\sum_{i=1}^{n} (y_i - z)^2 - \sum_{i=1}^{n} (x_i - z)^2}{\sum_{i=1}^{n} (y_i - z)^2} \]  

(11)

where

- \( y_i \) = actual wind speed probability value
- \( x_i \) = wind speed probability calculated from Weibull distribution
- \( z \) = mean of actual data

Energy production through turbines

Along with WPD and WED, power or energy produced through a wind turbine in a particular time period is also significant (Khahro et al., 2014b). According to Betz criterion, maximum theoretical efficiency or power coefficient (CP) of a wind turbine is 59% (Khahro et al., 2014c). However, actual efficiency does not depend only upon wind characteristics of a particular location but also on turbine design characteristics i.e. rated speed, cut-in speed, cut-out speed, rotor area, and hub height. An important factor to quantify the ratio of actual power produced from a turbine to rated power is called capacity factor (CF). CF and power generated can be calculated using equations (12) and (13), respectively

\[
CF = \frac{\text{Actual Power from Wind Turbine (} P \text{)}}{\text{Rated Power from Wind Turbine (} P_R \text{)}}
\]  

(12)

\[
P_{WT} = \begin{cases} 
\sum_{j=1}^{N_B} \left\{ \left[ \exp \left( -\frac{(v_j - 1)}{c} \right)^k \right] - \left[ -\left( \frac{v_j}{c} \right)^k \right] \right\} P_{WT} \left( \frac{v_j + v_{cut}}{2} \right) & \text{for } (v_{cutin} \leq v \leq v_r) \\
\sum_{j=1}^{N_B} \left\{ \left[ \exp \left( -\frac{(v_j - 1)}{c} \right)^k \right] - \left[ -\left( \frac{v_j}{c} \right)^k \right] \right\} P_{WT}(v_r) & \text{for } (v_r \leq v \leq v_{cutout}) \\
0 & \text{for } v < v_{cutin} \text{ and } v > v_{cutout}
\end{cases}
\]  

(13)

Economic assessment

Unlike conventional power sources, wind energy utilization does not require fuel supply. However, investment in turbines and others are involved which must be taken into account to estimate the economic feasibility of wind power project. Total cost involves the initial investment cost (I) and operation and maintenance cost (C_{om}). Today, most commercially available turbines cost from $1.3 to 2.2 per watt (WindIndustry). Unit cost of electricity (C)
and payback period (PP) are two important parameters, which need to be evaluated. Unit cost is estimated using following relationship (Khahro et al., 2014a, 2014b)

\[
C = \frac{NPW}{E}
\]  

(14)

where

\[
NPW = \text{net present worth}
\]

\[
E = \text{energy produced per year} = 8760 \times P_R \times C_F
\]

\[
P_R = \text{turbine rated power}
\]

NPW is calculated using equation (15)

\[
NPW = I \left[ 1 + n \left\{ \frac{(1 + i)^t - 1}{i(1 + i)^t} \right\} \right]
\]  

(15)

where

\[
I = \text{total initial investment} = 1.3 \text{(cost of turbine)}
\]

Additional 30% take into account the initial cost associated with civil work, grid connections etc.

\[
i = \text{interest rate, assumed 10%}
\]

\[
n = \text{percent of } I \text{ which equals to } C_{om}, \text{ assumed 15%}
\]

\[
t = \text{turbine life time in years, assumed 20 years}
\]

**Payback period (PP).** The PP is the length of time (usually measured in years) required to recover the cost of an investment

\[
PP \text{ (year)} = \frac{\text{Total Investment Cost}}{\text{Annual Cash In Flow}}
\]  

(16)

Many regions are left untouched because of their moderate or low wind potential. With recent developments in the field of wind turbine technology and wind harvesting machines, number of wind turbine designs are available which can operate under medium to low wind conditions. Therefore, it is necessary to make careful assessment using preestablished methods like EPFM. Thus, this study focused on Southern Punjab which has never been assessed so far using two-parameter Weibull Distribution Function and EPFM. Wind data were obtained from Pakistan Meteorological Department (PMD) and no missing data points occurred during the data recording. Statistical analysis was performed to determine WPD and WED. Techno-economic analysis of actual power produced from six turbine models from different manufacturers along with energy generation per year was conducted. Finally, polar diagrams were drawn to demonstrate optimum wind direction at each of the investigated location.

**Results and discussion**

**Wind speeds**

Yearly average wind speeds have been shown in Table 1 along with shape parameter, scale parameter, and average WPD values. The analysis of Table 1 and Figure 1 shows that Rahim Yar Khan (RYK) has maximum wind speed averaged over five years period i.e. 4.40 m/s (with
Table 1. Annual average wind speeds, shape (K), scale (C) parameters, and wind power densities (WPD) 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 |
| Bahawalnagar      | 3.68 | 3.20 | 4.05 | 46.37 | 3.51 | 2.81 | 3.90 | 40.04 | 3.38 | 3.18 | 3.72 | 34.00 | 3.50 | 2.98 | 3.87 | 40.1 |
| Bahawalpur        | 4.35 | 3.20 | 4.77 | 80.29 | 4.12 | 2.99 | 4.53 | 62.89 | 3.94 | 2.97 | 4.16 | 50.10 | 3.96 | 2.89 | 4.38 | 61.00 |
| D.G Khan          | 3.8  | 3.50 | 4.13 | 43.86 | 3.82 | 3.36 | 4.17 | 43.72 | 3.81 | 3.56 | 4.11 | 41.00 | 3.96 | 3.54 | 4.27 | 47.70 |
| Muzaffargarh      | 3.78 | 3.00 | 4.17 | 52.73 | 3.75 | 2.90 | 4.16 | 46.97 | 3.62 | 2.97 | 3.99 | 41.10 | 3.81 | 3.03 | 4.21 | 51.80 |
| Multan            | 3.72 | 3.02 | 4.1  | 51.67 | 3.62 | 2.87 | 4.02 | 43.12 | 3.43 | 2.93 | 3.8  | 36.57 | 3.60 | 2.98 | 3.98 | 45.77 |
| Rahim Yar Khan    | 4.54 | 3.10 | 4.96 | 88.50 | 4.45 | 3.19 | 4.86 | 73.50 | 4.20 | 3.21 | 4.58 | 65.50 | 4.15 | 2.93 | 4.58 | 66.80 |
| Khanewal          | 3.72 | 3.02 | 4.10 | 51.67 | 3.62 | 2.87 | 4.02 | 43.12 | 3.43 | 2.93 | 3.80 | 36.57 | 3.60 | 2.98 | 3.98 | 45.77 |
| Layyah            | 3.66 | 3.72 | 3.92 | 35.74 | 3.60 | 3.54 | 3.90 | 35.80 | 3.67 | 3.67 | 3.93 | 35.99 | 3.77 | 3.71 | 4.03 | 38.31 |
| Lodhran           | 4.08 | 3.12 | 4.49 | 67.27 | 3.92 | 2.94 | 4.33 | 54.68 | 3.69 | 2.92 | 4.09 | 45.94 | 3.81 | 2.93 | 4.22 | 54.43 |
| Rajanpur          | 4.38 | 3.52 | 4.74 | 69.46 | 4.33 | 3.28 | 4.73 | 64.91 | 4.10 | 3.38 | 4.48 | 56.08 | 4.23 | 3.38 | 4.60 | 60.34 |
| Vehari            | 3.75 | 3.12 | 4.12 | 51.14 | 3.60 | 2.89 | 3.99 | 42.21 | 3.45 | 3.03 | 3.80 | 36.42 | 3.57 | 2.97 | 3.93 | 43.50 |

$V_{avg}$, $K$, $C$, and WPD are annual average wind speeds, shape (K), scale (C) parameters, and wind power densities, respectively.
the highest value observed in 2018 as 4.56 ms$^{-1}$ and minimum value in 2016 was 4.20 ms$^{-1}$). On the other hand, Bahawalnagar carries the minimum wind speed as 3.60 ms$^{-1}$ (with the highest value of 3.90 ms$^{-1}$ in 2018 and the lowest value of 3.38 ms$^{-1}$ in 2016).

Wind power and energy density

It has been observed from Table 1 and Figures 2 to 3 that RYK possesses both the maximum WPD and maximum WED as 77.2 W/m$^2$ and 677.76 kWh/m$^2$/year, respectively. On the other hand, the minimum values of both the WPD and WED have been observed for Layyah as 38.96 W/m$^2$ and 677.76 kWh/m$^2$/year, respectively. The important point to note here is that minimum wind speed has been observed for Bahawalnagar but it is not the location having minimum WPD and WED which shows that wind speed is not the true representative of wind potential but wind potential also depends upon the frequency distribution and probability of occurrence of certain wind speed.

Most probable and optimum wind speed

The analysis of Table 2 shows that RYK has the highest value of $V_{mp}$ as 4.25 ms$^{-1}$ and Bahawalnagar carries the lowest value as 3.44 ms$^{-1}$. The highest $V_{opt}$ is observed for RYK as 5.62 ms$^{-1}$ and the minimum is for Layyah i.e. 4.57 ms$^{-1}$ (lower than that of Bahawalnagar i.e. 4.71 ms$^{-1}$). This is the reason why Layyah has the lower WPD and WED than Bahawalnagar although Bahawalnagar has lower wind speed than Layyah.

Weibull distribution

Weibull distribution estimates the actual wind data with significant accuracy. Comparison of actual and Weibull Distribution has been shown in Figure 4 and correlation coefficient calculated is enlisted in Table 3. These parameters were found to fit the actual wind frequency distributions with acceptable correlation coefficient (>95%) for all locations. The Weibull diagrams for all 11 locations have been shown in Figure 5 which is consistent with K and C parameters listed in Table 1. The highest peak shown here is for Layyah (consistent with highest value of K i.e. 3.69). Similarly, the most widely spread curve on x-axis is for
Figure 2. Yearly average and five-years’ average wind power densities (W/m$^2$).

Figure 3. Yearly average and five-years’ average wind energy densities (kWh/m$^2$/year).

Table 2. Annual average values of most probable and optimum wind speeds for South Punjab.

| Locations    | 2014  | 2015  | 2016  | 2017  | 2018  |
|--------------|-------|-------|-------|-------|-------|
| Bahawalnagar | 3.55  | 4.8   | 3.31  | 4.75  | 3.28  | 4.36  | 3.32  | 4.66  | 3.76  |
| Bahawalpur   | 4.22  | 5.6   | 3.92  | 5.44  | 3.61  | 4.96  | 3.75  | 5.3   | 4.27  |
| D.G Khan     | 3.72  | 4.7   | 3.74  | 4.81  | 3.74  | 4.67  | 3.87  | 4.88  | 4.34  |
| Multan       | 3.57  | 4.9   | 3.45  | 4.85  | 3.28  | 4.56  | 3.43  | 4.79  | 4.06  |
| Muzaffargarh | 3.61  | 5     | 3.59  | 4.99  | 3.44  | 4.79  | 3.65  | 5.02  | 4.2   |
| Rahim Yar Khan | 4.39 | 5.8   | 4.3   | 5.7   | 4.07  | 5.34  | 3.95  | 5.5   | 4.42  |
| Khanewal     | 3.57  | 4.89  | 3.45  | 4.85  | 3.28  | 4.56  | 3.43  | 4.79  | 4.06  |
| Layyah       | 3.59  | 4.41  | 3.54  | 4.45  | 3.60  | 4.43  | 3.69  | 4.54  | 4.15  |
| Lodhran      | 3.94  | 5.28  | 3.73  | 5.21  | 3.52  | 4.92  | 3.62  | 5.09  | 4.21  |
| Rajanpur     | 4.29  | 5.41  | 4.22  | 5.49  | 3.99  | 5.20  | 4.12  | 5.31  | 4.58  |
| Vehari       | 3.61  | 4.87  | 3.45  | 4.85  | 3.31  | 4.53  | 3.37  | 4.74  | 4.12  |
**Figure 4.** Actual and Weibull distribution for South Punjab.

**Table 3.** Correlation coefficient between actual and Weibull distribution.

| Location         | $R^2$ |
|------------------|-------|
| Bahawalnagar     | 0.979 |
| Bahawalpur       | 0.956 |
| D.G. Khan        | 0.952 |
| Multan           | 0.952 |
| Muzaffargarh     | 0.954 |
| RYK              | 0.958 |
| Khanewal         | 0.952 |
| Layyah           | 0.959 |
| Lodhran          | 0.965 |
| Rajanpur         | 0.958 |
| Vehari           | 0.959 |
RYK (consistent with the highest value of scale parameter of $4.79\text{ ms}^{-1}$). Same is the case for other locations.

**Wind speed distribution**

Cumulative frequency distribution has been shown in Figure 6. Analysis shows that the highest wind potential area i.e. RYK has a wind speed greater than $3\text{ ms}^{-1}$ with cumulative probability distribution.
### Table 4. Various turbine models along with specifications.

| Turbine model | $P_R$ (kW) | $A_T$ ($m^2$) | $V_{cin}$ ($ms^{-1}$) | $V_R$ ($ms^{-1}$) | $V_{cout}$ ($ms^{-1}$) | Hub height (m) |
|---------------|------------|---------------|------------------------|------------------|------------------------|----------------|
| Bonus 1300/62 | 1300       | 3018          | 3                      | 14               | 24                     | 50,60,68,80    |
| Bonus 1MW/54  | 1000       | 2300          | 3                      | 15               | 25                     | 50             |
| 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    |

### Table 5. Energy production and capacity factor estimation of various turbine models.

| Location       | Turbine model | Bonus 1300/62 | Bonus 1MW/54 | Bonus 600/44 | Vestas V42 | GE600a | Enercon E-40/600 |
|----------------|---------------|---------------|---------------|---------------|-------------|--------|------------------|
| Bahawalnagar   | Pp (kW)       | 107.95        | 82.27         | 54.37         | 38.76       | 59.44  | 56.90            |
|                | Energy (MWh)  | 945.61        | 720.64        | 476.25        | 339.54      | 520.71 | 498.47           |
|                | C.F (%)       | 8.30          | 8.23          | 9.06          | 6.46        | 9.91   | 9.48             |
| Bahawalpur     | Pp (kW)       | 168.99        | 128.79        | 85.11         | 68.61       | 93.06  | 86.99            |
|                | Energy (MWh)  | 1480.38       | 1128.19       | 745.58        | 601.05      | 815.24 | 761.99           |
|                | C.F (%)       | 13.00         | 12.88         | 14.19         | 11.44       | 15.51  | 14.50            |
| D.G.Khan       | Pp (kW)       | 133.61        | 101.82        | 67.29         | 50.56       | 73.58  | 69.40            |
|                | Energy (MWh)  | 1170.39       | 891.94        | 589.46        | 442.89      | 644.53 | 607.93           |
|                | C.F (%)       | 10.28         | 10.18         | 11.21         | 8.43        | 12.26  | 11.57            |
| Multan         | Pp (kW)       | 121.52        | 92.61         | 61.20         | 45.51       | 66.92  | 63.56            |
|                | Energy (MWh)  | 1064.51       | 811.26        | 536.14        | 398.63      | 586.22 | 556.78           |
|                | C.F (%)       | 9.35          | 9.26          | 10.20         | 7.58        | 11.15  | 10.59            |
| Muzaffargarh   | Pp (kW)       | 136.99        | 104.40        | 69.00         | 53.04       | 75.44  | 71.17            |
|                | Energy (MWh)  | 1200.07       | 914.57        | 604.41        | 464.60      | 660.87 | 623.48           |
|                | C.F (%)       | 10.54         | 10.44         | 11.50         | 8.84        | 12.57  | 11.86            |
| RYK            | Pp (kW)       | 197.00        | 150.14        | 99.22         | 82.13       | 108.49 | 100.84           |
|                | Energy (MWh)  | 1725.76       | 1315.19       | 869.17        | 719.42      | 950.37 | 883.38           |
|                | C.F (%)       | 15.15         | 15.01         | 16.54         | 13.69       | 18.08  | 16.81            |
| Khanewal       | Pp (kW)       | 121.52        | 92.61         | 61.20         | 45.51       | 66.92  | 63.56            |
|                | Energy (MWh)  | 1064.51       | 811.26        | 536.14        | 398.63      | 586.22 | 556.78           |
|                | C.F (%)       | 9.35          | 9.26          | 10.20         | 7.58        | 11.15  | 10.59            |
| Layyah         | Pp (kW)       | 110.48        | 84.20         | 55.64         | 38.58       | 60.84  | 58.08            |
|                | Energy (MWh)  | 967.84        | 737.58        | 487.45        | 337.99      | 532.98 | 508.78           |
|                | C.F (%)       | 8.50          | 8.42          | 9.27          | 6.43        | 10.14  | 9.68             |
| Lodhran        | Pp (kW)       | 150.56        | 114.74        | 75.83         | 59.65       | 82.91  | 77.86            |
|                | Energy (MWh)  | 1318.87       | 1005.10       | 664.24        | 522.49      | 726.30 | 682.10           |
|                | C.F (%)       | 11.58         | 11.47         | 12.64         | 9.94        | 13.82  | 12.98            |
| Rajanpur       | Pp (kW)       | 182.72        | 139.25        | 92.03         | 75.04       | 100.53 | 93.65            |
|                | Energy (MWh)  | 1600.64       | 1219.84       | 806.15        | 657.37      | 880.62 | 820.39           |
|                | C.F (%)       | 14.06         | 13.93         | 15.34         | 12.51       | 16.75  | 15.61            |
| Vehari         | Pp (kW)       | 119.69        | 91.21         | 60.28         | 44.47       | 65.91  | 62.65            |
|                | Energy (MWh)  | 1048.44       | 799.01        | 528.04        | 389.57      | 577.37 | 548.85           |
|                | C.F (%)       | 9.21          | 9.12          | 10.05         | 7.41        | 10.99  | 10.44            |
**Figure 7.** Performance of various turbine models w.r.t. Power produced (a), annual energy production (b) and capacity factor (c).
frequency of more than 75%, whereas for Bahawalnagar, the wind blows at a speed greater than 3 m/s with approximately 62% cumulative frequency value. Wind speed of greater than 3 m/s is important as most of the wind turbines have cut-in speed equal to 3 m/s.

Energy production from wind turbines

Energy production estimation from six turbine models from different manufacturers has been investigated. The objective of using different turbine models, given in Table 4, is to give wind power project investors an idea of choosing better wind turbines for certain location. These turbine models were selected as they are commercially available at same hub height (50 m) as was the hub height used in this assessment. Table 5 enlists power and annual energy production from various models and CF estimation at each of the investigated location in South Punjab, also shown in Figure 7. It has been shown that for Bahawalnagar, the highest energy output per year is 945.61 MWh by Bonus 1300/62 and minimum is 339.54 MWh by Vestas V42. Although highest CF is not for Bonus 1300/62 but for GE600a. Apparently, it seems surprising because one might expect that the turbine producing maximum energy would be the one having maximum CF but this is not true. The reason is that CF does not depend only upon the energy produced by a turbine but also on the maximum energy a turbine can produce. Same trend can be observed for other locations also. It has been observed from Table 6 that CF is not as high as might apparently be attractive for wind energy applications; however, with the development in wind turbine technology, new turbines are being designed which may be able to harvest wind energy from low- to moderate wind speeds also (Goudarzi and Zhu, 2013; Kumar and Baredar, 2012). Therefore, with the development of new turbines CF can be increased.

Economic assessment

Economic analysis of energy production using six different turbine models has been carried out. Costs of turbines along with total initial investment cost (I) and operation and maintenance (C_{om}) have been listed in Table 6. Based on the energy production listed in Table 5 and costs listed in Table 6, cost per unit of electrical energy (C), and PP for all turbines at all locations have been calculated and listed in Table 7. It has been shown that GE600a turbine gives the lowest cost at RYK and Bonus 1300/62 has the highest cost at Bahawalnagar. This should be so as RYK has the highest wind speed and Bahawalnagar has the lowest. Similarly, PP for GE600a is lowest i.e. 4.72 years at RYK and is highest for Bonus 1300/62 i.e. 10.28 years at Bahawalnagar.

| Turbine model       | Turbine cost ($) | I ($)  | C_{om} ($) |
|---------------------|------------------|-------|------------|
| Bonus 1300/62       | 1,950,000        | 2,535,000 | 380,250    |
| Bonus 1MW/54        | 1,500,000        | 1,950,000 | 292,500    |
| Bonus 600/44        | 900,000          | 1,170,000 | 175,500    |
| Vestas V42          | 900,000          | 1,170,000 | 175,500    |
| GE600a              | 900,000          | 1,170,000 | 175,500    |
| Enercon E-40/600    | 900,000          | 1,170,000 | 175,500    |
Table 7. Cost/KWh and payback period (PP) of various turbine models at all selected locations.

| Turbine model | Bonus 1300/62 ($/kWh) | Bonus 1MW/54 ($) | Bonus 600/44 ($) | Vestas V42 | Enercon GE600a | PP (Years) | Bonus 1300/62 ($) | Bonus 1MW/54 ($) | Bonus 600/44 ($) | Vestas V42 | Enercon GE600a | Enercon E-40/600 |
|---------------|-----------------------|------------------|------------------|------------|----------------|-------------|------------------|------------------|------------------|------------|----------------|------------------|
| Bahawalnagar  | 0.52                  | 0.51             | 0.47             | 0.32       | 0.50           | 10.28       | 0.52             | 0.51             | 0.47             | 0.32       | 0.50           | 10.28           |
| Bahawalpur    | 0.48                  | 0.49             | 0.41             | 0.35       | 0.20           | 6.56        | 0.48             | 0.49             | 0.41             | 0.35       | 0.20           | 6.56            |
| D.G.Khan      | 0.09                  | 0.10             | 0.20             | 0.30       | 0.07           | 8.30        | 0.09             | 0.10             | 0.20             | 0.30       | 0.07           | 8.30            |
| Multan        | 0.18                  | 0.19             | 0.09             | 0.44       | 0.03           | 9.13        | 0.18             | 0.19             | 0.09             | 0.44       | 0.03           | 9.13            |
| Muzaffargarh  | 0.06                  | 0.07             | 0.02             | 0.25       | 0.09           | 8.10        | 0.06             | 0.07             | 0.02             | 0.25       | 0.09           | 8.10            |
| RYK           | 0.06                  | 0.07             | 0.09             | 0.10       | 0.01           | 5.63        | 0.06             | 0.07             | 0.09             | 0.10       | 0.01           | 5.63            |
| Khanewal      | 0.18                  | 0.19             | 0.09             | 0.44       | 0.04           | 9.13        | 0.18             | 0.19             | 0.09             | 0.44       | 0.04           | 9.13            |
| Layyah        | 0.29                  | 0.30             | 0.19             | 0.68       | 0.10           | 10.04       | 0.29             | 0.30             | 0.19             | 0.68       | 0.10           | 10.04           |
| Lodhran       | 0.03                  | 0.03             | 0.05             | 0.17       | 0.12           | 7.37        | 0.03             | 0.03             | 0.05             | 0.17       | 0.12           | 7.37            |
| Rajanpur      | 0.12                  | 0.13             | 0.06             | 0.21       | 0.01           | 6.07        | 0.12             | 0.13             | 0.06             | 0.21       | 0.01           | 6.07            |
| Vehari        | 0.20                  | 0.21             | 0.11             | 0.47       | 0.02           | 9.27        | 0.20             | 0.21             | 0.11             | 0.47       | 0.02           | 9.27            |
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 Figure 8, 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).

Validation of results

Historical data validation method has been used to compare the outcomes of this work. The validity of this particular model is determined with respect to method used and scope of research. This study uses two-parameter Weibull distribution model to estimate wind potential at multiple locations and this model has been found to be valid when compared with previous historical data (Bilir et al., 2015a; Carta et al., 2009; Chang, 2011; Chaurasiya et al., 2017; Indhumathy et al., 2014; Khahro et al., 2014b; Khan and Tariq, 2018; Mirhosseini et al., 2011; Rehman et al., 2012, 2020; Safari and Gasore, 2010).

Conclusion

A region in south Punjab consisting of 11 districts has been investigated and analyzed for wind potential assessment. Two-parameter Weibull distribution with five years daily average wind data have been employed to estimate the potential of wind. The following conclusions have been drawn from the analysis:

1. RYK is the highly windy area with maximum wind speed, WPD, and WED. 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.
2. According to National Renewable Energy Laboratory (NREL) standards, wind potential ranging from 0 to 200 W/m² is considered poor.
At same location, different turbine models produce different amounts of energy with different CF. Therefore, choice of turbine at particular location is also important.

Economic assessment shows that the locations having low wind potential have PP which is about half of total life time of project; therefore, will generate revenue in remaining life time. So it can be concluded that wind energy harvesting in area is economically feasible.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iD

Muhammad Sumair https://orcid.org/0000-0001-9026-1092

References

Acker TL, Williams SK, Duque EP, et al. (2007) Wind resource assessment in the state of Arizona: Inventory, capacity factor, and cost. Renewable Energy 32(9): 1453–1466.

Aized T, Sohail Rehman SM, Kamran S, et al. (2019) Design and analysis of wind pump for wind conditions in Pakistan. Advances in Mechanical Engineering 11(9): 1687814019880405.

Akdağ SA and Dinler A (2009) A new method to estimate Weibull parameters for wind energy applications. Energy Conversion and Management 50(7): 1761–1766.

Akdağ SA and Guler Ö (2015) A novel energy pattern factor method for wind speed distribution parameter estimation. Energy Conversion and Management 106: 1124–1133.

Azad AK, Rasul M, Alam M, et al. (2014) Analysis of wind energy conversion system using Weibull distribution. Procedia Engineering 90: 725–732.

Bagiorgas HS, Mihalakakou G, Rehman S, et al. (2016) Wind power potential assessment for three buoys data collection stations in the Ionian Sea using Weibull distribution function. International Journal of Green Energy 13(7): 703–714.

Baloch MH, Kaloi GS and Memon ZA (2016) Current scenario of the wind energy in Pakistan challenges and future perspectives: A case study. Energy Reports 2: 201–210.

Baseer MA, Meyer JP, Rehman S, et al. (2017) Wind power characteristics of seven data collection sites in Jubail, Saudi Arabia using Weibull parameters. 102: 35–49.

Bassoyuni M, Gubut SA, Javaid U, et al. (2015) Assessment and analysis of wind power resource using Weibull parameters. Energy Exploration & Exploitation 33(1): 105–122.

Bilir L, Imamir M, Devrim Y, et al. (2015) Seasonal and yearly wind speed distribution and wind power density analysis based on Weibull distribution function. International Journal of Hydrogen Energy 40(44): 15301–15310.

Carta JA, Ramirez P, Velazquez SJR, et al. (2009) A review of wind speed probability distributions used in wind energy analysis: Case studies in the Canary Islands. 13(5): 933–955.

Chang TP (2011) Performance comparison of six numerical methods in estimating Weibull parameters for wind energy application. Applied Energy 88(1): 272–282.

Chaurasiya PK, Ahmed S and Warudkar V (2017) Study of different parameters estimation methods of Weibull distribution to determine wind power density using ground based Doppler SODAR instrument. Alexandria Engineering Journal 57: 2299–2311.
ETEnergyWorld (2019) *World's Top 10 Countries in Wind Energy Capacity*. Available at: https://energy.economictimes.indiatimes.com/news/renewable/worlds-top-10-countries-in-wind-energy-capacity/68465090 (accessed 12 February 2020).

Goudarzi N and Zhu WD (2013) A review on the development of wind turbine generators across the world. *International Journal of Dynamics and Control* 1(2): 192–202.

Hulio ZH, Jiang W and Rehman S (2019) Techno-economic assessment of wind power potential of Hawke’s Bay using Weibull parameter: A review. *Energy Strategy Reviews* 26: 100375.

Indhumathy D, Seshaiyah C and Sukkiramathi K (2014) Estimation of Weibull parameters for wind speed calculation at Kanyakumari in India. *International Journal of Innovative Research in Science, Engineering and Technology* 3: 8340–8345.

IRENA (2019) Renewable capacity statistics 2019. International Renewable Energy Agency (IRENA), Abu Dhabi ISBN 978-92-9260-123-2.

Jowder FA (2009) Wind power analysis and site matching of wind turbine generators in Kingdom of Bahrain. *Applied Energy* 86(4): 538–545.

Keyhani A, Ghasemi-Varamakhasti M, Khanali M, et al. (2010) An assessment of wind energy potential as a power generation source in the capital of Iran. *Energy* 35(1): 188–201.

Khahro SF, Tabbassum K, Soomro AM, et al. (2014a) Techno-economical evaluation of wind energy potential and analysis of power generation from wind at Gharo, Sindh Pakistan. *Renewable and Sustainable Energy Reviews* 35: 460–474.

Khahro SF, Tabbassum K, Soomro AM, et al. (2014b) Evaluation of wind power production prospective and Weibull parameter estimation methods for Babaurband, Sindh Pakistan. *Energy Conversion and Management* 78: 956–967.

Khan KS and Tariq M (2018) Wind resource assessment using SODAR and meteorological mast—A case study of Pakistan. *Renewable and Sustainable Energy Reviews* 81: 2443–2449.

Kumar R and Baredar P (2012) Solidity study and its effects on the performance of a small scale horizontal axis wind turbine. *Impending Power Demand and Innovative Energy Paths* 290–297.

Lima LdA and Filho CRB (2012) Wind resource evaluation in S~ao~ Jo~ao~ do Cariri (SJC)—Paraiba, Brazil. *Renewable and Sustainable Energy Reviews* 16(1): 474–480.

Lu L, Yang H and Burnett J (2002) Investigation on wind power potential on Hong Kong islands—An analysis of wind power and wind turbine characteristics. *Renewable Energy* 27(1): 1–12.

Mirhosseini M, Sharifi F and Sedaghat A (2011) Assessing the wind energy potential locations in province of Semnan in Iran. *Renewable and Sustainable Energy Reviews* 15(1): 449–459.

Ouammi A, Dagdougui H, Sacile R, et al. (2010) Monthly and seasonal assessment of wind energy characteristics at four monitored locations in Liguria region (Italy). *Renewable and Sustainable Energy Reviews* 14(7): 1959–1968.

Oyedepo SO, Adaramola MS and Paul SS (2012) Analysis of wind speed data and wind energy potential in three selected locations in south-east Nigeria. *International Journal of Energy and Environmental Engineering* 3(1): 7.

Pishgar-Komeleh S, Keyhani A and Sefeedpari P (2015) Wind speed and power density analysis based on Weibull and Rayleigh distributions (a case study: Firouzkoooh county of Iran). *Renewable and Sustainable Energy Reviews* 42: 313–322.

Ramachandra T, Subramanian D and Joshi N (1997) Wind energy potential assessment in Uttara Kannada district of Karnataka. *Renewable Energy* 10(4): 585–611.

Rehman S, Mahbub Alam A, Meyer JP, et al. (2012) Wind speed characteristics and resource assessment using Weibull parameters. *International Journal of Green Energy* 9(8): 800–814.

Rehman S, Mohandes MA and Alhems LM (2018) Wind speed and power characteristics using LiDAR anemometer based measurements. *Sustainable Energy Technologies and Assessments* 27: 46–62.

Rehman S, Natarajan N, Vasudevan M, et al. (2020) Assessment of wind energy potential across varying topographical features of Tamil Nadu, India. *Energy Exploration and Exploitation* 38: 175–200.
Safari B and Gasore J (2010) A statistical investigation of wind characteristics and wind energy potential based on the Weibull and Rayleigh models in Rwanda. Renewable Energy 35(12): 2874–2880.

Sarim M (2019) Pakistan’s energy mix. Available at: https://tribune.com.pk/story/1879268/6-pakistan-energy-mix/ (accessed 15 January 2020).

Shami SH, Ahmad J, Zafar R, et al. (2016) Evaluating wind energy potential in Pakistan’s three provinces, with proposal for integration into national power grid. Renewable and Sustainable Energy Reviews 53: 408–421.

Shoaib M, Siddiqui I, Amir YM, et al. (2017a) Evaluation of wind power potential in Baburband (Pakistan) using Weibull distribution function. Renewable and Sustainable Energy Reviews 70: 1343–1351.

Shoaib M, Siddiqui I, Rehman S, et al. (2019) Assessment of wind energy potential using wind energy conversion system. Journal of Cleaner Production 216: 346–360.

Shoaib M, Siddiqui I, Rehman S, et al. (2017b) Speed distribution analysis based on maximum entropy principle and Weibull distribution function. Environmental Progress Sustainable Energy 36(5): 1480–1489.

Ucar A and Balo F (2009) Investigation of wind characteristics and assessment of wind-generation potentiality in Uludağ-Bursa, Turkey. Applied Energy 86(3): 333–339.

Weisser D (2003) A wind energy analysis of Grenada: an estimation using the ‘Weibull’ density function. Renewable Energy 28(11): 1803–1812.

WindIndustry. How much do wind turbines cost? Available at: http://www.windindustry.org/how_much_do_wind_turbines_cost (accessed 21 March 2020).

World Wind Energy Association (2019) Wind Power Capacity Worldwide Reaches 597 GW, 50.1 GW added in 2018. Available at: https://wwindea.org/information-2/information/ (accessed 15 February 2020).