ORIGINAL ARTICLE

Modeling predictive assessment of wind energy potential as a power generation sources at some selected locations in Pakistan

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Abstract

The present paper aims to investigate the wind power potential at seven selected locations, namely, Gujranwala, Islamabad Capital Territory, Jhimpir, Kati Bandar, Khanewal, Multan and Sialkot in Pakistan. Wind speeds were collected over a period of 2005–2016 and measured at 10 m height. In this study, ten distribution functions were applied to analyze the wind speed characteristics of these selected locations and estimate the wind power density. The results showed that Kati Bandar has the highest annual wind speed of 4.04 m/s in comparison to other locations, while the lowest value of 1.33 m/s was obtained in Islamabad Capital Territory. During the investigation period, it is observed that the maximum power density of 258.75 W/m^2 is occurred in July at Kati Bandar, while the lowest minimum wind power density of 1.68 W/m^2 occurred in September at Islamabad at 10 m height. The analysis result of the wind power and energy density as functions of tower height shows that higher tower height will produce higher wind power and energy density. Therefore, it is concluded that the wind power density values in the locations (Gujranwala, Islamabad Capital Territory, Khanewal, Multan, and Sialkot) are substantial and can be utilized using small-scale wind turbines for generating electricity. Consequently, the performances of four small-scale wind turbines were evaluated. Based on the results, the Pitch wind/30 kW Grid wind turbine had the highest annual capacity factor of 56.366%, whereas, WS-12/8 kW wind turbine had a minimum at 15.416%. The Minimum and the Maximum annual electricity cost in the studied locations are 0.005 $/kW h and 0.032 $/kW h using Pitch wind/30 kW Grid and WS-12/8 kW, respectively.

Keywords Wind characteristics · Wind energy potential · Statistical analysis · Wind power density · Probability distribution function · Pakistan locations

Introduction

Renewable energy sources have gained the attention of researchers, policy makers and also the consumers due to the increased demand for energy and also to reduce the environmental hazards caused by the fossil fuels (Benedek et al. 2018; Adams et al. 2018; Kimet al. 2018; Andreas et al. 2018; Dai et al. 2018).

Today, wind energy is widely used to produce electricity in many countries. It is becoming the fastest growing renewable energy in the world. Thanks to the decisive improvement of technology over the past 30 years, the production of electricity by wind energy have reached a high level of technological maturity and industrial reliability (Nze-Esiaga and Okogbue 2014).

Before investing in a wind energy harvesting system at a certain location, the available wind energy (potential) and the feasibility of utilizing a wind energy conversion system need to be assessed in order to use the full potential of the available kinetic energy that wind can provide. The first parameters that need to be considered are the speed and characteristics of the wind at concerned location (Wagner and Mathur 2012).

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Effective use of wind energy necessitates detailed information of the wind characteristics and the distribution of wind speeds of the region. Many factors, such as the wind speed, the wind power, the generator type, and a feasibility study, have to be taken into account to install wind energy transformation system in a site. Many studies of the wind characteristics and wind power potential have been conducted in many countries worldwide by researchers (Ullah et al. 2010; Shami et al. 2016; Al Zohbi et al. 2015; Soulouknga et al. 2018; Ozay and Celiktas 2016; Katinas et al. 2017). For an instant, Ullah et al. (2010) investigated the wind power potential at Kati Bandar in Pakistan based on the Weibull distribution function. They concluded that this site is classified to be good with the average power density of 414 W/m² at 50 m height. Shami et al. (2016) analyzed the wind speed characteristics in various part in Pakistan (Sindh Province, KPK Province, Balochistan Province, Jiwani area). The result showed that the wind farm projects could be beneficial for generating electricity in Pakistan.

Pakistan is among one of those countries that suffer from the acute energy crisis and at the same time is recognized as one of the fastest growing markets for the assessment of wind power potential in Asia (Shoaib et al. 2017). It is estimated that daily electricity demand is over 20,000 MW whereas a daily shortfall of 4500–5500 MW (Shoaib et al. 2017). The large gap between demand and supply of electricity, increasing the cost of imported fossil fuels and worsening air pollution demand an urgent search for energy sources such as wind energy. Wind energy is thus a potentially attractive source of renewable energy whose availability needs to be investigated.

Therefore, the aim of this study was to determine the wind energy potentials at seven selected cities namely Gujranwala (GRW), Islamabad Capital Territory (ICT), Jhimpir (JHI), Kati Bandar (KAT), Khanewal (KHA), Multan (MUX), Sialkot (SKT) in Pakistan. To have an improved understanding of potential uses of wind energy, ten probability distribution functions are employed to determined wind power potential in the studied regions. The wind speed data were measured at 10 m height. The wind speed characteristics were analyzed using Hourly wind speeds data, which collected over a period of 2005–2016. Moreover, wind power densities as a function of hub height were used in order to classify the wind energy resource in the selected cities in Pakistan. Moreover, a technical and economic assessment has been made for the generation of electricity using a different type of wind turbines at seven locations distributions over Pakistan.

Wind data measurement

Pakistan has significant wind energy resources that could be exploited for power generation. The exploitation of wind energy sources can help Pakistan achieve many of its environmental and energy policy targets including reducing energy import dependency. Pakistan has very big wind energy potential, especially in three Provence namely, Khyber Pakhtunkhwa (KPK) old name is North West Frontier Pakistan (NWFP), Sindh and Balochistan. Fourth Punjab province has very limited wind energy potential. Gujranwala, Khanewal, Multan, Sialkot these selected city locations are from Punjab Provence. The Provence of Punjab has very limited wind energy potential and hence is not considered for wind energy (Shami et al. 2016). Jhimpir, Kati Bandar these locations are from Sindh Provence. Pakistan has the potential of producing 15,000 MW of wind energy, of which only the Sindh corridor can produce 4000 MW (Mirza et al. 2010).

For the assessment of wind energy potential, the wind characteristics at the desired locations should be fully understood. Anemometers are installed at a 10 m height at the areas, namely Gujranwala, Islamabad Capital Territory, Jhimpir, Kati Bandar, Khanewal, Multan, and Sialkot. In this study, the measurement data are adopted for the statistical analysis with the purpose of the investigation of wind characteristics and the assessment of wind energy potential over different terrain conditions. Wind speeds were measured continuously during the period from January 2005 to January 2016. The details and geographic information of the selected region are shown in Fig. 1 and Table 1.

Gujranwala (GRW)

GRW is a city in Punjab, which is located to the north of the provincial capital of Lahore. GRW is located at 32.1877°N, 74.1945°E and is 226 m above sea level.

Islamabad Capital Territory (ICT)

Islamabad Capital Territory is the capital city of Pakistan. ICT is placed inside the Pothohar Plateau in the northeastern part of the country, between Rawalpindi District and the Margalla Hills National Park. ICT is located at latitude 33.7214813°N and longitude 73.0432892°E, it is 604 m above sea level.

Jhimpir (JHI)

JHI is a village in Thatta District, Sindh, Pakistan. It is located 114 km away from Karachi. It is the site of Pakistan's first wind power project. Jhimpir Sindh is located at Latitude: 25.0243°N and Longitude: 68.0090°E. Pakistan has a potential of producing 150,00 MW of wind energy, of which only the Sindh corridor can produce 4000 MW (Mirza et al. 2010). The sites lie on a flat and hard rocky terrain with an elevation of approximately 40–50 m above sea level.
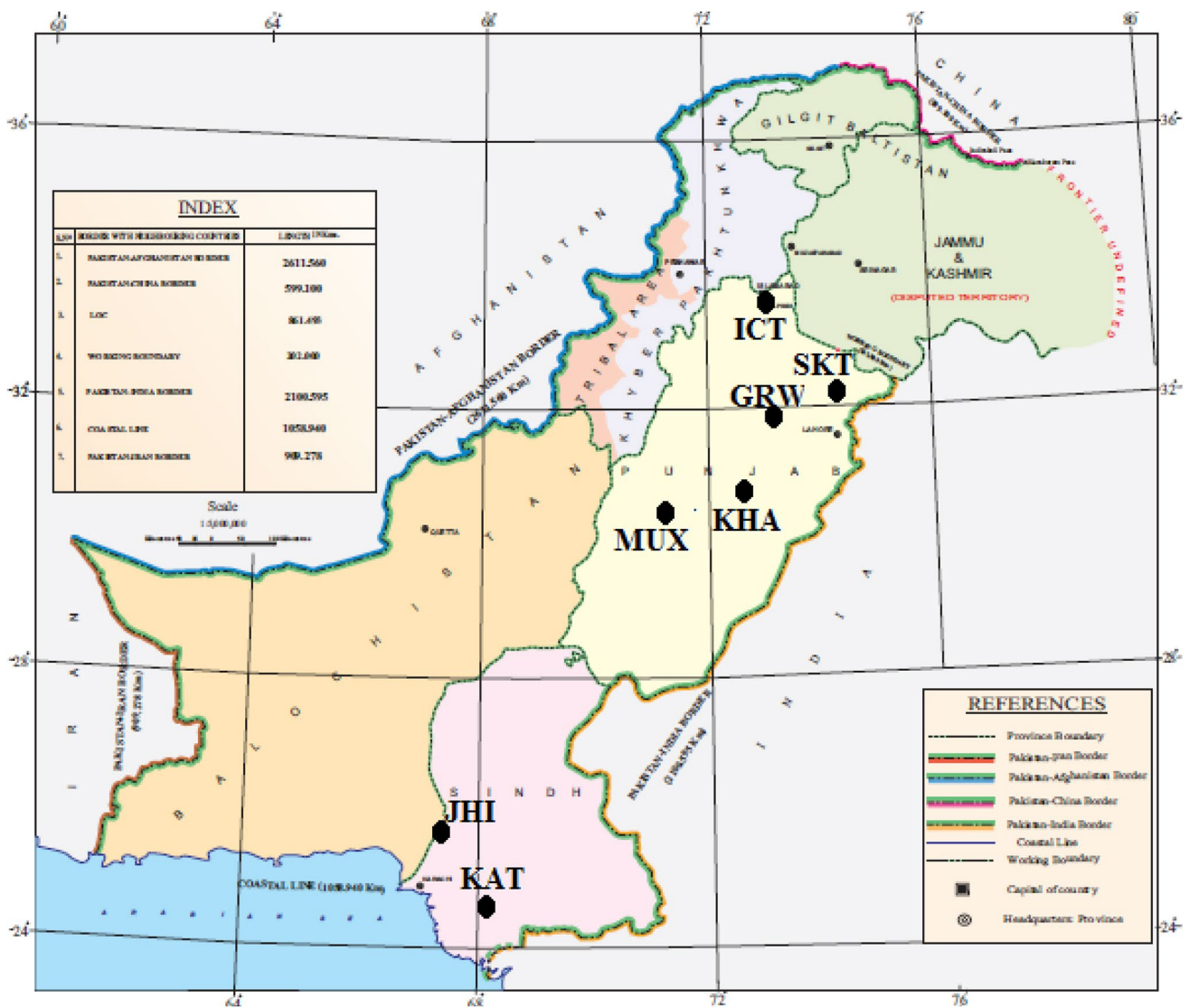
Fig. 1 The wind atlas for Pakistan and selected locations (Survey of Pakistan 2018)

Table 1 Summarization of selected locations adopted in this paper

Locations	Latitude	Longitude	Location characteristics
GRW	32.1877°N	74.1945°E	Urban
ICT	33.7214813°N	73.0432892°E	Capital city
JHI	25.0243°N	68.0090°E	Flat terrain
KAT	24.1429°N	67.4509°E	Castle area
KHA	30.286415°N	71.932030°E	Urban
MUX	30.181459°N	71.492157°E	Urban
SKT	32.4945°N	74.5229°E	Urban

Kati Bandar (KAT)

KAT is a port on the Arabian Sea, in the Thatta District, Sindh, Pakistan. It is located at 24.1429°N, 67.4509°E. Kati Bandar project has now been made part of the China Pakistan Economic Corridor (CPEC).

Khanewal (KHA)

Khanewal is a city and the capital of Khanewal District in the Punjab province of Pakistan. KHA is a small city in Punjab, central Pakistan, located about 35 miles east of Multan. Latitude and longitude coordinates of Khanewal are 30.286415°N, 71.932030°E. Its elevation is 32,000 m height above sea level.

Multan (MUX)

Multan is a Pakistani metropolis and the headquarters of Multan District inside the province of Punjab. Located at

the banks of the Chenab River, and is the main cultural and monetary center of southern Punjab. Multan is a small metropolis and the seat of the identical name district, positioned within the province of Punjab, Pakistan, approximately 40 miles northeast of the town of Muzaffargarh. Geographic coordinates of MUX are located at 30.181459°N, 71.492157°E. MUX elevation is 32,000 m height above sea level.

Sialkot (SKT)

Sialkot is a metropolis in Punjab, Pakistan. Sialkot is placed in north-east Punjab—considered one of Pakistan's normally especially industrialized areas. Along with the nearby towns of Gujranwala and Gujrat, Sialkot forms a part of the so-known as Golden Triangle of industrial cities with export-oriented economies. Geographic coordinates of SKT is located at 32.4945°N, 74.5229°E. SKT elevation is 256 m above sea level.

Probability distribution functions

Knowledge of wind speed data is required for renewable resource assessment. Several distribution functions are used in literature to present wind speed data of selected locations (Masseran 2015; Ouarda et al. 2015; Aries et al. 2018; Allouhi et al. 2017). In this paper, ten probability distribution functions are used to analyze distributions of wind speed at selected locations as shown in Table 2. In addition, the most methods used in literature to estimate the parameters of distribution functions are the graphical method, the method of moments, and the maximum likelihood method (Pobočíková et al. 2017). In this study, Maximum likelihood method is used to estimate the parameter values for each distribution function. In this study, Easy fit, and Matlab R2015a software were used in order to get the parameters of distribution functions.

Results and discussion

Monthly wind speed

Figure 2 illustrates the difference in wind speed over the 12 years of seven studied locations in Pakistan. It is observed that Kati Bandar and Jhimpir have the highest wind speeds compared to the other locations. The maximum wind speed of 8.61 m/s occurs in July 2006, while the minimum value of 3.21 m/s occurs in November 2012 at Kati Bandar. At Jhimpir, the maximum wind speed of 7.32 m/s occurs in June 2011, while the minimum value of 2.311 m/s occurs in November 2007. Additionally, it is noticed that the wind

speed values vary from 1 to 3.5 m/s for Gujranwala, Islamabad Capital Territory, Khanewal, Multan, and Sialkot. In addition, it is found that the lowest wind speed values were at Islamabad Capital Territory.

Annual wind speed

The annual mean wind speeds at selected seven locations in Pakistan are shown in Fig. 3. It is found that Kati Bandar has the highest annual wind speed as compared to other cites, as follow by Jhimpir locations. As shown in the figure, Gujranwala, Khanewal, Multan, and Sialkot have almost the same annual mean wind speed, which about 2 m/s. In addition, it is observed that the Islamabad Capital Territory has the lowest annual mean wind speed of 1.33 m/s.

Distribution parameters

The distribution parameters for seven locations in Pakistan were determined using hourly wind speed with the maximum likelihood method. The best distribution among the ten distribution functions for each location was evaluated with their Kolmogorov–Smirnov tests values.

The calculated parameters of each distribution functions are tabulated in Table 3 for each selected location along with their mean velocity and Variance. Additionally, Fig. 4 shows the fitted PDF and CDF model for the observed wind speed data for each location. In addition, Table 4 presents the goodness-of-fit statistics in term of Kolmogorov–Smirnov tests for each distribution function. Moreover, a distribution with a minimum value of Kolmogorov–Smirnov will be selected to be the best model for the wind speed distribution in the studied area.

Based on Kolmogorov–Smirnov tests, GEV has a minimum value, which is considered as the best distribution function to study the wind speed characteristics of Gujranwala, Kati Bandar, Khanewal, Multan, and Sialkot. In addition, L is considered the best distribution for analyzing the wind speed of Islamabad and Jhimpir. Moreover, it is noticed that the Rayleigh distribution function cannot be used to investigate the wind potential in the studied area as shown in Fig. 4.

Wind power density at 10 m height

The wind power density is an indicator that is frequently adopted to describe how energetic the winds are during a period of time (month, season, and year). The calculation of wind power density in W/m^2 using the PDF function is usually expressed as:

$$\frac{P}{A} = \int_0^\infty \frac{1}{2}\rho v^3 f(v)dv, \qquad (1)$$

Table 2 Expressions of statistical distributions used in this study

Distribution function	PDF	CDF
Weibull (W)	$PDF = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left(-\left(\frac{v}{c}\right)^k\right)$	$CDF = 1 - exp\left(-\left(\frac{v}{c}\right)^k\right)$
Gamma (G)	$PDF = \frac{v^{\beta-1}}{\alpha^\beta \Gamma(\beta)} exp\left(-\frac{v}{\beta}\right)$	$CDF = \frac{\gamma\left(\beta, \frac{v}{\alpha}\right)}{\Gamma(\beta)}$
Lognormal (LN)	$PDF = \frac{1}{v\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{ln(v)-\mu}{\sigma}\right)^2\right]$	$CDF = \frac{1}{2} + erf\left[\frac{ln(v)-\mu}{\sigma\sqrt{2}}\right]$
Logistic (L)	$PDF = \frac{exp\left(-\frac{v-\mu}{\sigma}\right)}{\sigma\left\{1+exp\left(-\frac{v-\mu}{\sigma}\right)\right\}^2}$	$CDF = \frac{1}{1+exp\left(-\frac{v-\mu}{\sigma}\right)}$
Log-logistic (LL)	$PDF = \left(\left(\frac{\beta}{\alpha}\left(\frac{v}{\alpha}\right)^{\beta-1}\right) \Big/ \left(1+\frac{v}{\alpha}\right)^\beta\right)^2$	$CDF = \frac{1}{\left(1+\frac{v}{\alpha}\right)^{-\beta}}$
Inverse Gaussian (IG)	$PDF = \left(\frac{\lambda}{2\pi v^2}\right)^{1/2} e^{\left[\frac{-\lambda(v-\mu)^2}{2\mu^2 v}\right]}$	$CDF = \Phi\left(\sqrt{\frac{\lambda}{v}}\left(\frac{v}{\mu}-1\right)\right) + exp\left(\frac{2\lambda}{\mu}\right)\Phi\left(-\sqrt{\frac{\lambda}{v}}\left(\frac{v}{\mu}+1\right)\right)$
Generalized extreme value (GEV)	$PDF = \frac{1}{\alpha}\left[1 - \frac{\zeta(v)-\mu}{\alpha}\right]^{\frac{1}{\zeta}-1} exp\left[-\left(1 - 1 - \frac{\zeta(v)-\mu}{\alpha}\right)^{\frac{1}{\zeta}}\right]$	$CDF = exp\left[-\left(1 - 1 - \frac{\zeta(v)-\mu}{\alpha}\right)^{\frac{1}{\zeta}}\right]$
Nakagami (Na)	$PDF = \frac{2m^m}{\Gamma(m)\Omega^m} v^{2m-1} e^{\left(-\frac{m}{\Omega}G^2\right)}$	$CDF = \frac{\gamma\left(m, \frac{m}{\Omega}v^2\right)}{\Gamma(m)}$
Normal (N)	$PDF = \frac{1}{\sqrt{2\pi\sigma^2}} exp\left(-\frac{v-\mu}{2\sigma^2}\right)$	$CDF = \frac{1}{2}\left[1 + erf\left(\frac{v-\mu}{\sigma\sqrt{2}}\right)\right]$
Rayleigh (R)	$PDF = \frac{2v}{c^2} e^{-\left(\frac{v}{c}\right)^2}$	$CDF = 1 - exp\left[-\left(\frac{v}{c}\right)^2\right]$

W			LL			Na			
k	Shape parameter			β	Shape parameter			m	Shape parameter
c (m/s)	Scale parameter			α	Scale parameter			Ω	Scale parameter
G									
β	Shape parameter		IG	λ	Shape parameter	N			
α	Scale parameter			μ	Mean parameter			σ	Standard deviation
LN								μ	Mean parameter
σ	Shape parameter		GEV	μ	Location parameter	R			
μ	Scale parameter			ζ	Scale parameter			c (m/s)	Scale parameter
L									
μ	Location Parameter			α	Shape parameter				
σ	Scale Parameter								

where P is wind power density in W/m^2, A is swept area in m^2, ρ is air density ($\rho = 1.225$ kg/m^3) and $f(v)$ is the probability density function (PDF).

Moreover, the mean wind power density can be calculated using Eq. (2)

$$\frac{\overline{P}}{A} = \frac{1}{2}\rho\overline{v}^3, \tag{2}$$

where $\overline{P}$ the mean wind power density in W/m^2 is, $\overline{v}$ is the mean wind speed in m/s.

Table 5 is tabulated the actual mean monthly wind power density using Eq. (2) of the studied regions. Table 6 describes the yearly wind power density based on the distribution parameters. It is observed that Kati Bandar has the highest mean monthly wind power density compared to other cities (locations). During the investigation period, it is observed that the maximum power density of 258.75 W/m^2 has occurred in July at Kati Bandar. While the lowest minimum wind power density of 1.68 W/m^2 occurred in September at Islamabad.
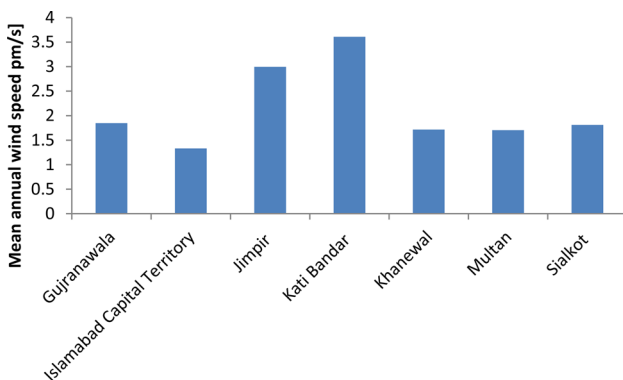
Mean wind speed and wind power density at various heights

For any wind project, it is very important to estimate the wind speed at the wind turbine hub height. Therefore, the power law method is most commonly used to estimate the
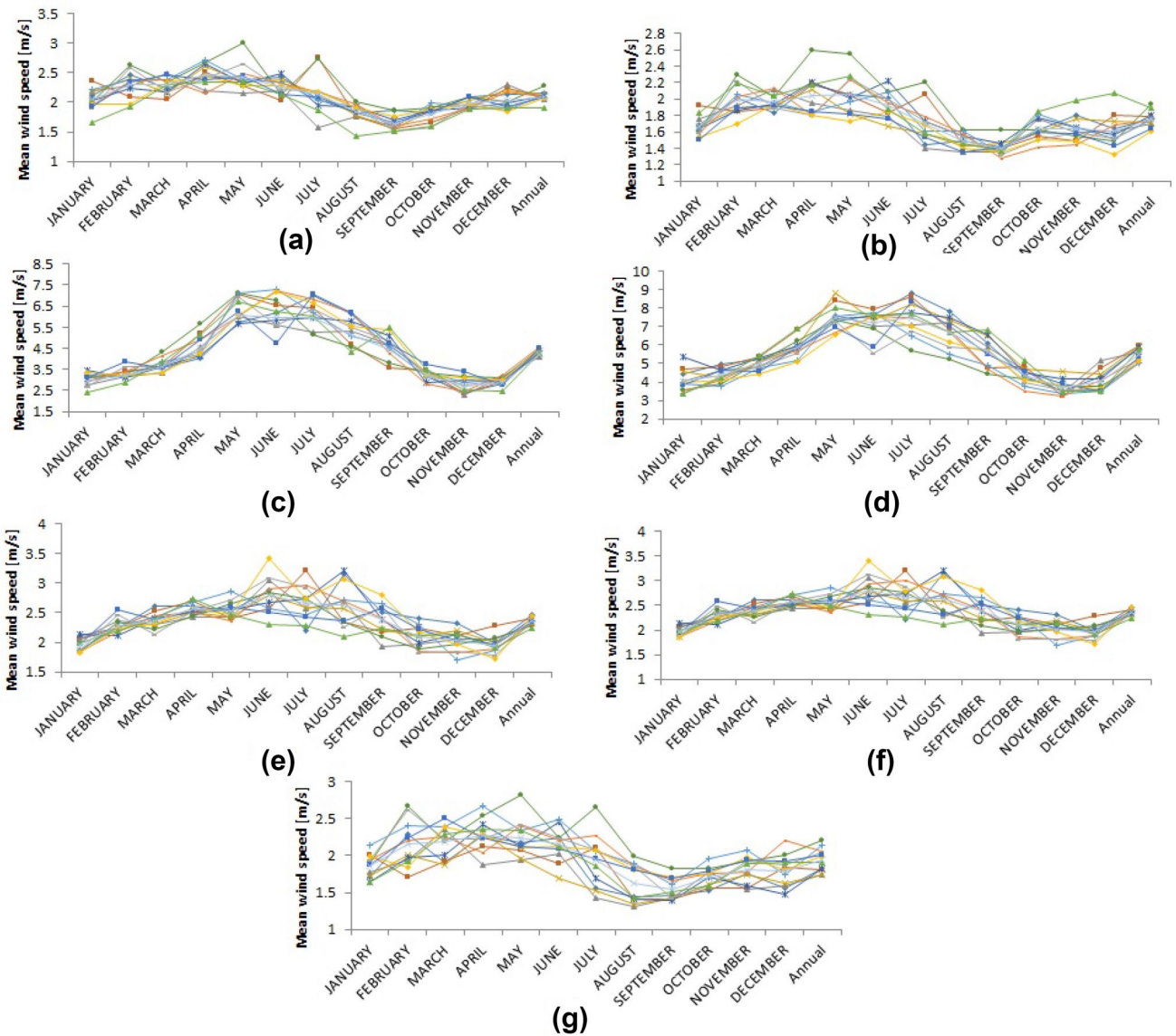
Fig. 2 Mean monthly wind speed at **a** Gujranwala, **b** Islamabad Capital Territory, **c** Jhimpir, **d** Kati Bandar, **e** Khanewal, **f** Multan, **g** Sialkot

Fig. 3 Annual mean wind speed at studied locations

wind speeds at various heights (Faghaniet al. 2018; Katinas et al. 2018). It is expressed as:

$$\frac{v}{v_{10}} = \left(\frac{z}{z_{10}} \right)^{\alpha},$$ (3)

where v is the wind speed at the wind turbine hub height z, v_{10} is the wind speed at original height z_{10}, and α is the surface roughness coefficient, which depends on the characteristics of the region (Mondal and Denich 2010). The value of α can be obtained from the following expressions (Bilir et al. 2015; Kassem et al. 2018):

$$\alpha = \frac{0.37 - 0.088 ln(v_{10})}{1 - 0.088 ln(z_{10}/10)}.$$ (4)

Table 3 Distribution parameters

Model	Parameter	Gujranwala	Islamabad Capital Territory	Jhimpir	Kati Bandar	Khanewal	Multan	Sialkot
W	Mean	2.065	1.722	4.155	5.397	2.314	2.322	1.901
	Variance	0.021	0.035	0.096	0.195	0.038	0.038	0.039
	c	2.128	1.802	4.290	5.589	2.398	2.406	1.986
	k	17.634	11.079	16.518	14.991	14.580	14.673	11.637
G	Mean	2.062	1.723	4.148	5.398	2.311	2.318	1.903
	Variance	0.046	0.045	0.194	0.311	0.071	0.072	0.054
	β	92.112	66.296	88.670	93.667	75.258	74.817	66.501
	α	0.022	0.026	0.047	0.058	0.031	0.031	0.029
IG	Mean	2.062	1.723	4.148	5.398	2.311	2.318	1.903
	Variance	0.054	0.050	0.223	0.354	0.082	0.083	0.062
	μ	2.062	1.723	4.148	5.398	2.311	2.318	1.903
	λ	163.328	101.570	319.697	443.847	150.260	149.821	110.927
GEV	Mean	2.061	1.725	4.144	5.397	2.310	2.317	1.905
	Variance	0.036	0.041	0.136	0.247	0.055	0.055	0.050
	ζ	-0.492	-0.404	-0.613	-0.539	-0.511	-0.520	-0.402
	α	0.206	0.214	0.402	0.539	0.255	0.255	0.236
	μ	2.014	1.665	4.075	5.285	2.254	2.261	1.838
LL	Mean	2.091	1.741	4.205	5.446	2.348	2.355	1.925
	Variance	0.026	0.036	0.126	0.200	0.047	0.048	0.041
	β	0.735	0.548	1.433	1.692	0.849	0.852	0.650
	α	0.042	0.060	0.046	0.045	0.051	0.051	0.058
L	Mean	2.088	1.734	4.197	5.434	2.342	2.349	1.919
	Variance	0.022	0.032	0.108	0.179	0.040	0.041	0.036
	μ	2.088	1.734	4.197	5.434	2.342	2.349	1.919
	σ	0.081	0.099	0.181	0.233	0.110	0.111	0.105
LN	Mean	2.063	1.725	4.151	5.401	2.313	2.320	1.904
	Variance	0.053	0.050	0.221	0.351	0.081	0.082	0.061
	σ	0.718	0.537	1.417	1.681	0.831	0.834	0.636
	μ	0.111	0.129	0.113	0.109	0.123	0.123	0.130
Na	Mean	2.061	1.722	4.146	5.395	2.310	2.316	1.902
	Variance	0.041	0.041	0.174	0.282	0.064	0.064	0.050
	m	25.937	18.105	24.756	25.914	21.077	20.955	18.358
	Ω	4.287	3.008	17.360	29.391	5.398	5.430	3.665
R	Mean	1.835	1.537	3.692	4.805	2.059	2.065	1.697
	Variance	0.920	0.645	3.725	6.307	1.158	1.165	0.787
	c	1.464	1.226	2.946	3.833	1.643	1.648	1.354
N	Mean	2.062	1.723	4.148	5.398	2.311	2.318	1.903
	Variance	0.036	0.038	0.156	0.256	0.057	0.058	0.045
	μ	2.062	1.723	4.148	5.398	2.311	2.318	1.903
	σ	0.386	0.195	0.395	0.506	0.239	0.240	0.213

The wind energy density for a period can be calculated as:

$$E = \overline{P}T, \tag{5}$$

where T is the period. For the annual wind, energy density estimation the value of 8640 h is used.

The evaluations of the wind power and energy density are important information for the wind power project. During 2005–2016, the actual wind speeds for all locations are measured at 10 m above the ground level. By using Eq. (3), the mean wind speeds at various heights are determined for all selected locations and tabulated in Table 7. It is observed that at the height above the ground level increases, the mean wind speed increases.

The wind power and energy density were calculated using Eqs. (2) and (5), respectively and illustrated in Fig. 5. It is obtained that Kati Bandar and Islamabad
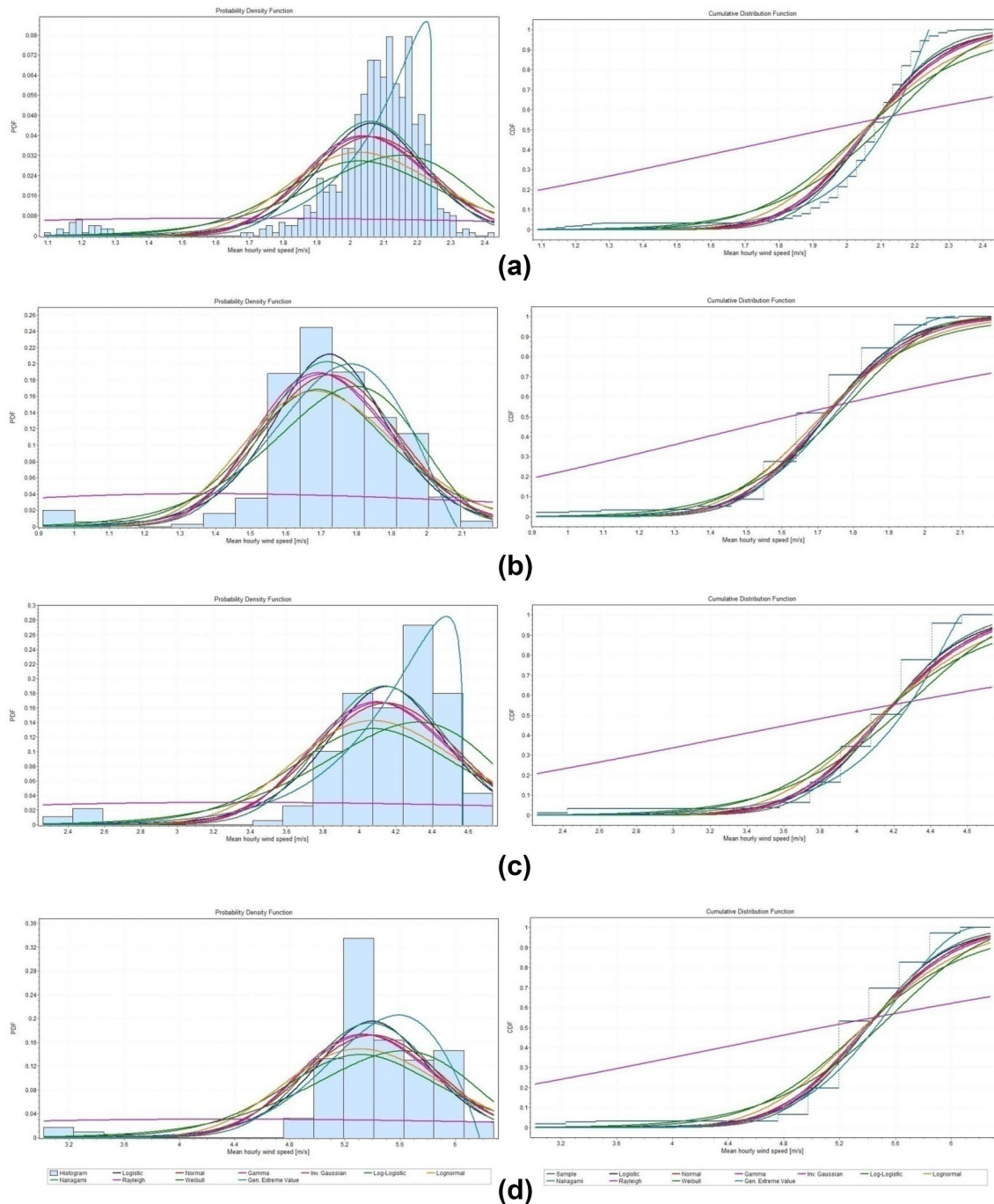
Fig. 4 Fitting PDF and CDF models to the wind speed data of **a** Gujranwala, **b** Islamabad, **c** Jhimpir, **d** Kati Bandar, **e** Khanewal, **f** Multan, and **g** Sialkot at 10 m height

Capital Territory have the highest and lowest annual mean wind power and energy density, respectively compared to other locations. Based on Fig. 5, the wind power density results indicate that the wind energy source in Gujranwala, Islamabad Capital Territory, Khanewal, Multan, and Sialkot is categorized as very poor.

The wind energy generational potential of locations is classified according to average power density values given in Table 8. It is found that Kati Bandar region has a maximum wind power density value of 101.361 W/m^2 at 10 m and 228.854 W/m^2 at 30 m height. Hence, this location can be considered as of class power 2, which indicates
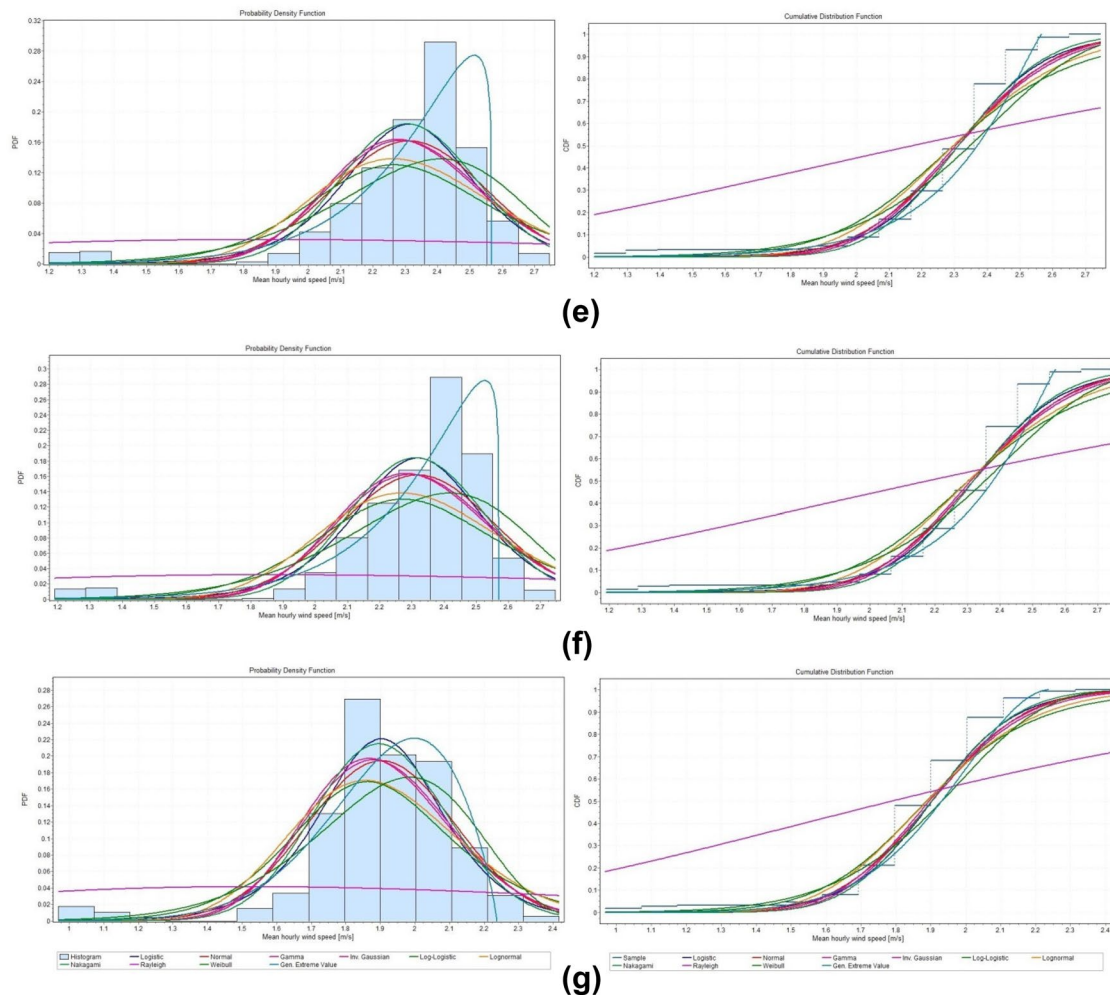
(e)

(f)

(g)

Fig. 4 (continued)

Table 4 Results of goodness-of-fit and the selected distribution (in bold) for each location

Locations	G	GEV	IG	LL	L	LN	Na	R	W	N
Gujranwala	0.1786	**0.0758**	0.1662	0.2221	0.1542	0.2096	0.1514	0.4107	0.2077	0.1786
Islamabad	0.1115	0.0880	0.0968	0.1473	**0.0866**	0.1447	0.0868	0.3914	0.1199	0.1115
Jhimpir	0.0709	0.0488	0.0532	0.0883	**0.0384**	0.0941	0.0524	0.3652	0.0716	0.0709
Kati Bandar	0.1896	**0.1328**	0.1771	0.2353	0.1604	0.2230	0.1591	0.4276	0.1852	0.1896
Khanewal	0.1473	**0.0791**	0.1336	0.1723	0.1334	0.1627	0.1342	0.3905	0.1635	0.1473
Multan	0.1429	**0.0737**	0.1292	0.1610	0.1337	0.1531	0.1344	0.3908	0.1718	0.1429
Sialkot	0.1226	**0.0753**	0.1076	0.1589	0.0919	0.1556	0.0941	0.3885	0.1188	0.1226

marginal wind energy potential. Furthermore, it is noticed that the locations have low wind power density, which ranges from 9.711 to 113.783 W/m^2 at 30 m height. Therefore, these locations can be classified to be poor. Consequently, commercial wind turbines with low capacities are suitable to be used in these locations.

The energy output of wind turbines

The mean parameters to estimate the wind energy of the turbine from wind speed characteristics and Power curve of the wind turbines, E_{wt} (Gökçek and Genç 2009). The total output power of the wind turbine can be expressed by Eq. (6):

Table 5 Actual wind power of the selected locations

Locations	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Gujranwala	5.22	7.54	7.38	9.14	8.69	7.02	6.02	3.77	2.73	3.58	4.75	5.18	5.69
Islamabad	2.80	4.84	4.67	5.22	5.26	4.37	2.96	2.00	1.68	2.67	2.66	2.57	3.32
Jimpir	15.68	20.60	28.66	55.29	137.99	129.83	127.79	82.75	53.48	20.13	12.29	14.87	45.99
Kati Bandar	40.37	50.97	77.12	126.49	258.85	228.38	258.75	180.88	109.49	50.62	30.42	39.94	101.36
Khanewal	4.57	7.35	8.18	10.30	10.03	13.47	11.43	11.10	8.32	5.60	5.07	4.59	8.00
Multan	4.60	7.48	8.33	10.49	10.13	13.57	11.54	11.16	8.27	5.67	5.06	4.61	8.07
Sialkot	3.92	6.10	6.48	7.22	6.84	6.09	4.45	2.64	2.26	3.02	3.61	3.55	4.47

Table 6 Annual wind power distribution calculated based on distribution parameters at 10 m height

Model	Gujranawala	Islamabad Capital Territory	Jhimpir	Kati Bandar	Khanewal	Multan	Sialkot
W	4.2	3.12	43.87	96.15	7.58	7.65	4.2
G	4.21	3.13	43.63	96.17	7.55	7.62	4.21
IG	4.21	3.13	43.63	96.17	7.55	7.62	4.21
GEV	4.22	3.14	43.52	96.13	7.54	7.6	4.22
LL	4.37	3.23	45.48	98.79	7.91	7.99	4.37
L	4.32	3.19	45.21	98.1	7.85	7.93	4.32
LN	4.22	3.14	43.73	96.35	7.57	7.64	4.22
Na	4.2	3.12	43.56	96.03	7.53	7.6	4.2
R	4.2	2.22	30.79	67.82	5.34	5.39	2.99
N	5.37	3.13	43.71	96.33	7.56	7.63	4.22

Table 7 Roughness surface values and annual mean wind speeds at various heights for all studied locations

Locations	Roughness surface	10 m	20 m	30 m	40 m	50 m	60 m	70 m	80 m	90 m	100 m
Gujranwala	0.307	2.04	2.53	2.86	3.13	3.35	3.54	3.71	3.87	4.01	4.14
Islamabad Capital Territory	0.325	1.66	2.08	2.37	2.61	2.80	2.97	3.13	3.27	3.39	3.51
Jhimpir	0.275	2.95	3.57	3.99	4.32	4.59	4.83	5.03	5.22	5.39	5.55
Kati Bandar	0.247	4.04	4.80	5.30	5.69	6.02	6.29	6.54	6.76	6.96	7.14
Khanewal	0.311	1.96	2.43	2.75	3.01	3.23	3.41	3.58	3.73	3.87	4.00
Multan	0.311	1.96	2.43	2.76	3.02	3.23	3.42	3.59	3.74	3.88	4.01
Sialkot	0.316	1.86	2.31	2.63	2.88	3.09	3.27	3.43	3.58	3.71	3.84

$$E_{wt} = \sum_{i=1}^{n} P_{wt(i)} \times t, \tag{6}$$

where t = time (number of hours in the investigation period).

The power curve of wind turbines can be approximated with a parabolic law as given by (Pallabazzer 2003):

$$P_{wt(i)} = \begin{cases} \Pr \frac{v_i^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} & v_{ci} \leq v_i \leq v_r \\ \frac{1}{2}\rho A C_p v_r^2 & v_r \leq v_i \leq v_{co} \\ 0 & v_i \leq v_{ci} \text{ and } v_i \geq v_{co} \end{cases}, \tag{7}$$

where v_i is the vector of possible wind speed at a given site, $P_{wt(i)}$ is the vector of corresponding wind turbine output power (W), P_r is the rated power of the turbine (W), v_{ci} is the cut-in wind speed (m/s), v_r is the rated wind speed (m/s) and v_{co} is the cut-off wind speed (m/s) of the wind turbine. C_p is the coefficient of performance of the turbine; it is a function of the tip speed ratio and the pitch angle. The coefficient of performance is considered to be constant for the entire range of wind speed (Nouni et al. 2007) and can be calculated as:
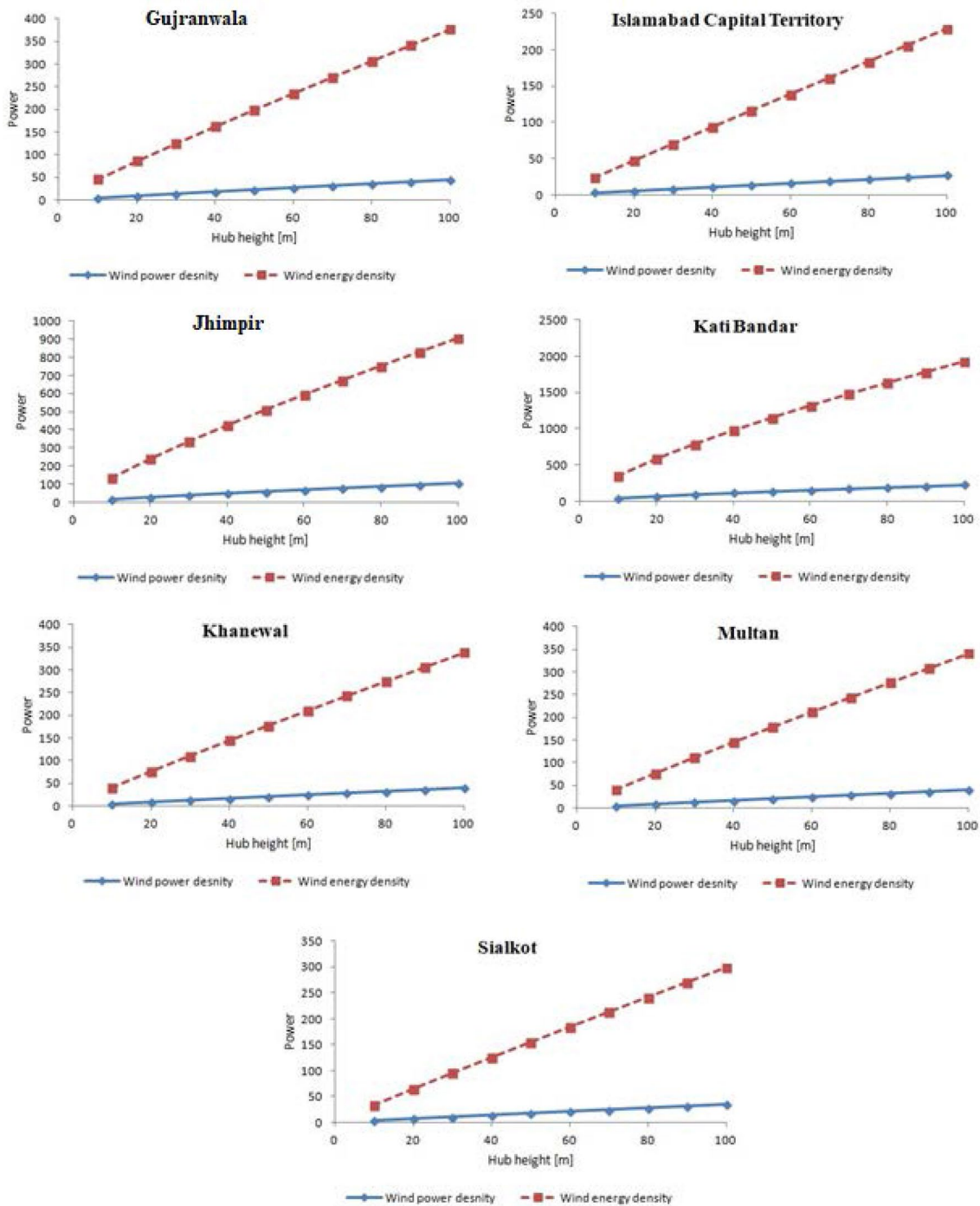
$$C_p = 2 \frac{Cp}{\rho A v_r^3}. \tag{8}$$

Fig. 5 Wind power density (W/m^2) and wind energy density (kW/m^2) for all locations at various heights

The capacity factor (CF) of a wind turbine is the fraction of the total energy generated by the wind turbine over a period to its potential output if it had operated at a rated capacity during the entire time. The capacity factor of a wind turbine based on the local wind regime of a given site can be estimated as:

$$CF = \frac{E_{wt}}{P_r \cdot t}. \tag{9}$$

Economic analysis of wind turbines

The main parameters that govern wind power costs (Gölçek et al. 2007; Gökçek and Genç 2009) are:

- Capital costs, including wind turbines, foundations, road construction, and grid connection.

Table 8 Wind energy generation potential of locations according to wind power classification

Power class	P @10 m (W/m^2)	P @30 m (W/m^2)	
Wind power classification			
1 (Poor)	≤ 100	≤ 160	
2 (Marginal)	≤ 150	≤ 240	
3 (Moderate)	≤ 200	≤ 320	
4 (Good)	≤ 250	≤ 400	
5 (Excellent)	≤ 300	≤ 480	
6 (Excellent)	≤ 400	≤ 640	
7 (Excellent)	≤ 1000	≤ 1600	
Locations	P @10 m (W/m^2)	P @10 m (W/m^2)	Classification
Wind energy generation potential of locations			
Gujranwala	5.589	15.647	1 (Poor)
Islamabad Capital Territory	3.323	9.711	1 (Poor)
Jhimpir	45.993	113.783	1 (Poor)
Kati Bandar	101.361	228.854	2 (Marginal)
Khanewal	7.996	22.285	1 (Poor)
Multan	8.065	22.564	1 (Poor)
Sialkot	4.47	12.647	1 (Poor)

- Cost of operation and maintenance system.
- Production of electricity depends on the location of the site and feature of a wind turbine.
- The economic design life of the wind turbine of the investment and discount rate.

These factors may vary from country to country and region to region (Gökçek and Genç 2009). Table 9 has been shown the cost of the wind turbine based on the rated power of the turbine (Gölçek et al. 2007; Gökçek and Genç 2009; Mathew 2006).

Numerous methods have been used to estimate the wind energy cost such as PVC methods (Adaramola et al. 2011). The present value of costs (PVC) is given in (Adaramola et al. 2011) as the following equation:

$$PVC = \left[I + C_{omr}\left(\frac{1+i}{r-i}\right) \times \left[1 - \left(\frac{1+i}{1+r}\right)^n \right] - S\left(\frac{1+i}{1+r}\right)^n \right],$$
(10)

where r is the discount rate, i is the inflation rate, n is the machine life as designed by the manufacturer, the C_{omr} is the cost of operation and maintenance, I is the investment summation of turbine price and other initial costs, including provisions for civil work, land, infrastructure, installation and grid integration and S is the scrap value of the turbine price and civil work has been shown in Table 10.

The cost per kW h of electricity generated (UCE) can be determined by the following expression (Adaramola et al. 2011):

Table 9 Cost of wind turbines based on the rated power

Wind turbine size (kW)	Specific cost (US$/kW)	Average specific cost ($/kW)
10–20	2200–2900	2550
20–200	1500–2300	1900
200>	1000–1600	1300

Table 10 Parameters of PVC

Parameter	Value	Parameter	Value
r (%)	8	I (%)	68
i (%)	6	S (%)	10
n (year)	20	C_{mor} (%)	7

$$UCE = \frac{PVC}{t \times P_r \times C_f}.$$
(11)

Economic analysis of electricity generation potential

Table 11 shows the characteristic properties for the four selected wind turbines. Equations (7) and (8) show how the annual output energy calculations and how the calculations for the capacity of different wind turbines for the studied site were carried out.

Two types of turbine, namely, horizontal axis wind turbine (HWAT) and vertical axis wind turbine (VAWT) are used for the electrical power generation in the selected locations. Both have their applications depending on the wind speed and the location to be fixed upon. The efficiency of the horizontal axis with propeller blades is 60% and is most commonly used and vertical axis wind turbine above 70% (Saad 2014). In this paper, the performance of both types is studied. Table 12 presented the comparative performance of a horizontal axis wind turbine and a vertical axis wind turbine (Aeolos 2018).

Among various turbines, the vertical axis wind turbine with many general applications, have been more popular in compared to another type because: (a) they are good for a low-wind-speed environment, (b) they can be installed on restricted-space locations such as rooftops, buildings or on top of communication towers; and (c) there is no need for yaw mechanism since they operate independently from the wind direction.

Moreover, economic analysis factor wind turbine is very important for rural people (a) Capital costs, including wind turbines, foundations, road construction and grid connection, (b) cost of operation and maintenance system, (c) production of electricity, which depends on location of region and feature of wind turbine, and (d) economic design life of wind turbine of the investment and discount rate (Gölçek et al. 2007; Gökçek and Genç 2009).

Table 13 is summarized the values of total energy power, CF, and UCE of each wind turbine selected in this study. It is observed that the highest capacity factor is computed as 56.366% using pitch wind/30 kW Grid (HWAT) of 62 m hub height, while the lowest is calculated as 1.406% with WS-12/8 kW (VWAT) wind turbine model and hub height is 10 m and rated wind speed of 20 m/s.

Economically, the lowest value of electricity cost is found $0.005 kW h with the minimum specific cost of the wind turbine using Pitch wind/30 kW Grid model, the high capacity factor of 56.366%. Furthermore, the highest costs of unit energy per kW h using Eq. (11), are obtained using Stealth Gen D400/0.4 kW turbine. However, pitch wind/30 kW Grid of wind turbine can establish of a wind farm in the

Table 12 Comparison performance of horizontal axis wind turbine and vertical axis wind turbine

Performance	Horizontal axis	Vertical axis
Power generation efficiency	50–60%	Above 70%
Blade rotation space	Quit large	Quite small
Starting wind speed	High (2.5–5 m/s)	Low (1.5–3 m/s)
Noise	5–60 dB	0–10 dB
Maintenance	Completed	Convenient
Rotating speed	High	Low
Power curve	Depressed	Full
Failure	High	Low

selected locations can be considered economically viable with 20 years a turbine life.

Additionally, although the computed price of electricity is reasonable using WS-12/8 kW (VWAT) turbine model with $0.032 kW h, hub height is 30 m and rated wind speed of 20 m/s and capacity factor of 15.416%, as compared to another turbine model WRE.060/6 kW (VWAT). The majority of the people in the rural community most probably can afford it. Therefore, lowering the cost, it would be recommended for the rural local communities (selected locations) to adapt the turbine model WS-12/8 kW (VWAT).

Conclusions

In the contents of this study; wind speed and wind energy potential for the seven selected locations (Gujranwala, Islamabad Capital Territory, Jhimpir, Kati Bandar, Khanewal, Multan, and Sialkot) in Pakistan are investigated. The data were measured at a height of 10 m above ground level over a 12-year period (2005–2016). Ten probability distribution functions were used to analyze characteristic wind speed at selected regions. The main results and conclusions from this study are as follows:

- It is found that Kati Bandar and Jhimpir have higher wind speed in comparison to other locations. The mean monthly wind speed at Kati Bandar and Jhimpir were

Table 11 Characteristics of the selected wind energy turbines

Turbine type	Characteristics	Pr (kW)	Hub height	Rotor diameter (m)	Number of blades	Sweep area (m²)	v_{ci} (m/s)	v_r (m/s)	v_{c0} (m/s)
HWAT	Stealth Gen D400/0.4 kW	0.4	20, 30, 40	1.1	5	0.95	2	16	None
HWAT	Pitch wind/30 kW Grid	30	20, 62	14	2	154	2	15	None
VWAT	WS-12/8 kW	8	10, 20, 30	2	2	12	2	20	None
VWAT	WRE.060/6 kW	6	10, 20, 30	3.3	2	14.52	2	14	None

Table 13 Annual power production and economic calculated for selected wind turbines

Wind turbine model (characteristics)	Hub height (m)	Total energy power of wind turbine (kW)	CF (%)	UCE ($/kW)
Stealth Gen D400/0.4 kW	20	1.376	14.335	1.542
	30	2.326	24.225	0.912
	40	3.158	32.895	0.672
Pitch wind/30 kW Grid	20	117.687	16.345	0.018
	62	405.832	56.366	**0.005**
WS-12/8 kW	10	2.700	1.406	0.349
	20	17.514	9.122	0.054
	30	29.598	15.416	**0.032**
WRE.060/6 kW	10	4.176	2.900	0.508
	20	27.093	18.814	0.078
	30	45.785	31.795	0.046

between 8.61 m/s in July 2006—3.21 m/s in November 2012 and Jhimpir between 7.32 m/s in June 2011—2.311 m/s in November 2007.

- The annual mean wind speed of Gujranwala, Khanewal, Multan, and Sialkot have almost the same value, which about 2 m/s. In addition, it is observed that the Islamabad Capital Territory has the lowest annual mean wind speed of 1.33 m/s.
- Based on Kolmogorov–Smirnov tests, GEV has a minimum value, which is considered as the best distribution function to study the wind speed characteristics of Gujranwala, Kati Bandar, Khanewal, Multan, and Sialkot. Also, L is considered as the best distribution for analyzing the wind speed of Islamabad and Jhimpir. And Rayleigh distribution function cannot be used to investigate the wind potential in the studied area.
- Kati Bandar has the highest mean monthly wind power density compared to other locations. The highest mean power density with 258.75 W/m^2 at Kati Bandar and September has the lowest with 1.68 W/m^2 at Islamabad.
- The data suggest that the wind potential of Kati Bandar, second is Jhimpir and Islamabad have the highest and lowest annual mean wind power and energy density. Kati Bandar and Jhimpir is suitable for wind energy and could be acceptable for connecting to power grids, Compare to other locations (Gujranwala, Islamabad Capital Territory, Khanewal, and Multan).
- During the studied period, authors concluded that small-scale wind turbine use could be suitable for generating electricity for low mean wind speed locations.
- Among all analyzed wind turbine, the highest capacity factor was obtained using Pitch wind/30 kW Grid model for selected locations. While on the other hand, the lowest capacity factor was obtained using WS-12/8 kW wind turbine for selected locations.
- For all the studies selected locations conclude that lowest value of electricity cost during the studied period is obtained using pitch wind/30 kW grid (HWAT) of 62 m hub height and WS-12/8 kW (VWAT) wind turbine model and hub height is 10 m, in the future may use for wind farm and households.

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