Int. J. of Thermal & Environmental Engineering
Volume 19, No. 2 (2022) 77-85

Assessment of Wind Speed and Power Density Using Weibull and Rayleigh Distributions at Turbat, Balochistan, Pakistan

Asif Jalal [a] *, Ussama Ali [a]

[a] *Mechanical Engineering Department, University of Engineering and Technology Lahore, Pakistan*

Abstract

The meager economic situation, indefinite energy crisis, industrial modernization, and hazardous contamination impulse the empiricist to transcend the attention on renewable energy resources in Pakistan. One of the most rapidly growing renewable energy sources is wind energy. The main goal of this research work is to examine the wind characteristics and wind potential at the site of Turbat, Balochistan, Pakistan. For this purpose, the measured hourly time series data was collected from the Pakistan Meteorological Department (CPDC, Karachi) for 21 months (Jan 2012 – Sep 2013). After evaluating the monthly average wind speed (> 4 m/s), the average value of most probable wind speed (3.83 m/s), the average value of wind speed carrying maximum energy (7.732 m/s), and the standard deviation of the data (1.699 – 3.306), the results are used to statistically evaluate the data by Weibull and Rayleigh distributions for the selected site. The monthly average value of wind power and energy densities of the selected site is 140.145 W/m^2 and 101.775 kWh/m^2, respectively. A comparison was made between the mean power potential of the site and the power potential assessed using the Weibull and Rayleigh distributions. It was revealed that the Weibull distribution depicted the data more accurately. This statement is further enriched by the assessment of the performance of both distributions with the RMSE, χ^2, and R^2 tests.

Keywords: *Wind energy; Weibull distribution; Rayleigh distribution; Wind energy density; Turbat, Pakistan*

1. Introduction

Pakistan falls under the category of a country where the shortfall of electricity is increasing progressively because of the increase in industrial growth and depleted hydropower and fossil fuel resources. Firstly, the economy of the country does not allow it to bear the heavy expenses of the import of fossil fuels, and secondly, the usage of fossil fuels generates serious environmental effects such as air pollution, acid rain, and global warming. Hence, it becomes necessary to discover resources that are not only renewable but also eco-friendly to meet the electricity demand of the country. Pakistan is an emerging country with a population of 177 million people, but the yearly average per capita energy consumption is about 450 kWh, while the world's energy utilization per capita is about 2730 kWh [1]. Almost 37% population of inaccessible and rural areas is yet to be attached to the national grid [1].

The wind is the fastest growing, clean, abundant, and reliable source as it does not affect the environment. Wind energy added more consideration and importance worldwide after the oil crisis in 1973 and 1979 [2]. Currently centered on the international statistics of wind energy, the total wind energy capacity of the world at the end of June 2022 was 874,182 MW with an added capacity of 28,872 MW in six months only, having an annual growth rate of 13% [3]. The wind energy capacity of the world at the end of 2021 and June 2022 was 874,182 MW and 845,310 MW, respectively [3]. Fig. 1 shows the overall installed capacity of wind energy around the world from the year 2012 to 2022 [3].

China is at the top of the list having a total install capacity of 359,770 MW with the addition of 13,100 MW in the year 2022 only in six months [3]. The USA came second in the list with an overall installed capacity of wind of 139,145 MW at the end of June 2022. Germany, India, and Spain are at the number 3rd, 4th, and 5th spots, respectively, having total installed capacity of 64,642 MW, 40,900 MW, and 29,512 MW, respectively by the end of month June 2022 as per installed capacity [3].

* Corresponding author. Tel.: +92-331-4471512
E-mail: asifjalal42@gmail.com

DOI: 10.5383/ijtee.19.02.004

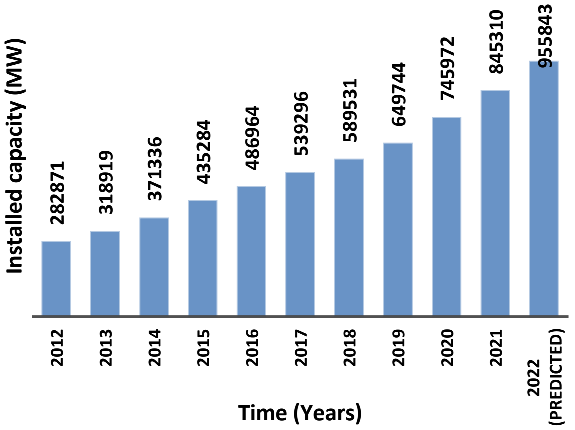

Fig. 1. World-wise wind energy installed capacity from 2012 to 2022

The European countries have diverse trends, where the United Kingdom installed 2.6 GW and 2.2 GW in the year 2021 only. Both are leading in Europe for the said year [3]. In Asia, China is at the top of installed wind capacity, which has installed 55.8 GW in the year 2021 only with an annual growth rate of 19.4% beating its record. After China, India has the second largest wind power installed capacity which is more than 40 GW by the end of the year 2021 [3]. In Pakistan, work is in progress on different projects regarding wind energy, and the currently installed capacity of wind is 1336 MW by 2021, with the addition of 98 MW only in the subsequent year [3].

Pakistan has a potential of around 346,000 MW for wind energy [4]. Currently, the total installed power generation capacity (containing hydel and thermal sources) of Pakistan is around 25000 MW, which fluctuates in the summer and winter seasons due to many factors. The shortfall of electricity can easily be encountered by the installation of more wind power projects due to its huge potential.

Pakistan Meteorological Department (PMD), together with the collaboration of the National Renewable Energy Laboratory (NREL) and the U.S. Agency for International Development (USAID), has developed a mesoscale map of Pakistan as shown in Fig. 2. This map shows that there is an immense wind potential available in areas of southern Sind, north Balochistan, central KPK, Gilgit-Baltistan, and different areas of Punjab and Azad Kashmir.

PMD also conducted a survey (Phase-I) along the coastal belt of Sind province, having a total area of 9300 sq. km, and pointed out that this area has an exploitable electric potential of about 11,000 MW [5]. The wind corridor of Gharo-Keti Bandar, spreading 60 km along the coast of Sind alone, holds a wind potential of 60,000 MW [6].

Alongside PMD, many researchers also calculated the power potential of the wind at various sites in Pakistan and other countries. In Pakistan, wind power potential has been calculated at the site of Hawksbay Karachi, Gharo, Kati-Bandar, Jiwani, Quetta, Babaurband, and Jhimpir (mostly along the coastal belt of Pakistan). In [1], the potential is calculated at Hawksbay Karachi, Sindh, Pakistan. Two years (2009 – 2010) of data were taken, and power densities were calculated using Weibull and Rayleigh distributions. In [2], the wind power potential was calculated at Gharo, Sindh, Pakistan, and estimated the wind power as 260 W/m^2 and energy density as 2300 kWh/m^2 [2]. In [4], the wind power potential of three provinces of the country was analyzed, Jiwani (a site of Balochistan) was taken as a case study, and its specific power density was assessed. A practical scheme was proposed for the integration of wind power into the national grid. Kharo et al. [7] assessed the wind power density of Babaurband, Sindh, Pakistan, at four different altitudes and then assessed the wind power likely to be produced over commercial wind turbines. At 80m height, the yearly mean wind speed and power density were found to be 6.712 m/s and 310 W/m^2 respectively.

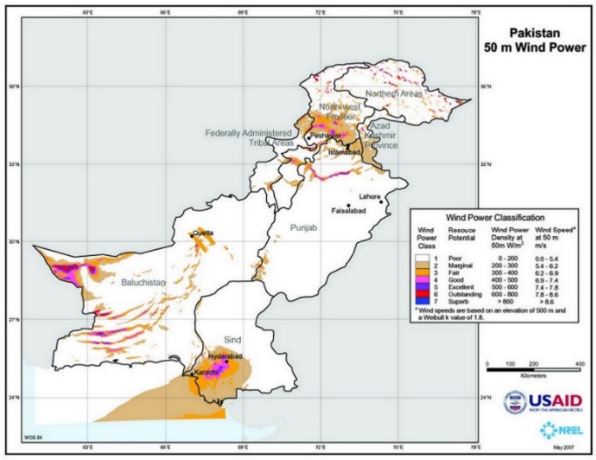

Fig. 2. Wind map of Pakistan showing wind potential of all provinces [5]

Calculation of wind power potential outside Pakistan includes the work of Pishgar-Komleh et al. [8], as they calculated the potential of wind using Weibull and Rayleigh distribution at Firouzkooh region of Iran. They analyzed ten years of data (2001-2010) based on a 3-h period. The average value of wind power was found to be 203 and 248 Wm^{-2} year^{-1} based on mean and root mean cube speed approaches, respectively. Akpinar et al. [9] evaluated the wind energy potential at Keban-Elazig, Turkey. Five years of data (1998 – 2002) was taken and analyzed through the Weibull and Rayleigh distribution functions. The average power density was found to be 15.603 W/m^2, therefore it was concluded that the selected site is not suitable for grid connection solicitations. Fyrippis et al. [10] examined the potential of Koronos village, a location on Naxos Island, Greece. Wind characteristics were assessed with the help of the Weibull and Rayleigh distribution function and annual mean wind speed and power density found to be 7.4 m/s and 420 W/m^2, respectively. Safari and Gasore [11] statistically investigated the potential of the wind using Weibull and Rayleigh distributions in Rwanda at five different stations. Ayodele et al. [12] examined the wind parameters in the coastline region of South Africa at ten different sites. Various researchers have also calculated the wind characteristics and wind potential at different locations such as the determination of wind energy potential in Bishkek, Kyrgyzstan presented in [13], statistical analysis of wind power density using Weibull and Rayleigh models in Malaysia [14], wind characteristics and calculation of energy potential in Akure, Southwest Nigeria presented in [15], and wind parameters assessment in Osmaniye, Turkey [16].

The purpose of this article is to mark the power potential of the wind and energy density at the site of Turbat, Balochistan, Pakistan. Data collected through Pakistan Meteorological Department is analyzed, and results are statistically equated using Weibull and Rayleigh distribution functions. Both distributions are evaluated with the help of performance tests to determine which distribution function describes the actual data precisely.

2. Methodology

2.1. Site description and data collection

Turbat is a city situated in southern Balochistan, which is the largest province of Pakistan based on the area. Turbat is positioned on the left bank of the Kech river. It is a populated city of the province. The climate of Turbat is relatively cool and windy. Turbat metrology station is located at 25^0 59' N latitude and 63^0 04' E longitude at a height of 155m (508 feet) above sea level. The site has a high population and many limitations (like hilly areas) in supplying energy. Therefore, searching for other alternatives renewable energy sources like wind or solar is essential.

The data consisting of 21 months is based upon the 3-hourly time series and measured using an anemometer at a height of 8.8 m over the ground level. Fig. 3 shows the location of Turbat and nearby regions of the selected site in Balochistan. Wind resources assessment is the prerequisite for the connection of the wind turbine at any selected site in which the calculation of wind energy and power density is also included.

Fig. 3. Location of Turbat, Balochistan, Pakistan

2.2 Extrapolation of wind speed at different heights

Wind speed changes with the change in height, so there is a need for an equation that could predict wind speed from one height to another. To adjust the data with the required wind turbine hub height, the power law method is used [17]:

$$\frac{V}{V_r} = \left[\frac{Z}{Z_r}\right]^{\alpha} \quad (1)$$

where V is the speed of the wind at a required height of Z, V_r denotes the speed of the wind at reference height Z_r, and α is the surface roughness factor that fluctuates from 0.128 to 0.160 for a homogenous surface [18]. The typical value of the surface roughness factor is 0.14, which is widely accepted for low-roughness surfaces [12].

2.3 Estimation of the wind parameters from data

To calculate the wind characteristics like mean wind speed (V_{avg}), and the variance (σ^2) of observing wind speed data, the below equation can be used [11]:

$$V_{avg} = \frac{1}{n}\sum_{i=1}^{n} V_i \quad (2)$$

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n} (V_i - V_m)^2 \quad (3)$$

where V represents the speed of the wind, n denotes the total observing wind speed of available data, and V_m shows the monthly value of mean wind speed.

The other two parameters which show importance are the most probable wind speed (V_{mp}) and wind speed carrying maximum energy ($V_{max.\ E}$). The former corresponds to the peak of the probability density function, whereas the latter is used to approximate the design of the wind turbine or rated wind speed [2]. Both terms are calculated as [17, 19]:

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

$$V_{max.E} = c\left[\frac{k+2}{k}\right]^{1/k} \quad (5)$$

where k is a dimensionless shape parameter and c is the Weibull scale parameter.

To design a wind turbine, it is suggested that both the terms calculated above should have a close relationship [20].

2.4 Statistical Distributions

The scattering available in the wind speed data is extremely critical for the analysis. Wind speed data has wide ranges of wind, and to determine the key parameters from the data, we use statistical distribution functions. Various statistical models are being used to describe and analyze the wind data, such as normal, lognormal, Weibull, and Rayleigh distribution functions [21, 22]. Among all these distribution functions, Weibull and Rayleigh distributions are used and accepted worldwide because both these distributions give better approximations to available wind data [13].

2.4.1 Weibull distributions

The two-parameter Weibull distribution function with two-parameters is most appropriate, widely accepted, and recommended by many researchers for analyzing wind speed data [23, 24, 25]. The disparity in wind speed is categorized by the probability density function (PDF) and cumulative density function (CDF) in the Weibull distribution [2]. The former

(PDF) describes the likelihood of wind at a specified velocity of wind, while the latter (CDF) gives the possibility of wind velocity equal to, lower than, or inside the specified range of the wind speed. PDF is assessed through the following expression [2]:

$$f(V) = \left(\frac{k}{C}\right)\left(\frac{V}{C}\right)^{k-1} \exp\left[-\left(\frac{V}{C}\right)^{k}\right] \quad (6)$$

where *V* represents the wind speed, *k* and *C* characterize the dimensionless shape and scale parameters, respectively. C has the same unit just like wind speed, and *f (V)* is the probability of perceiving wind speed.

Similarly, the cumulative distribution function (CDF) is described as [2]:

$$F(V) = 1 - \exp\left[-\left(\frac{V}{C}\right)^{k}\right] \quad (7)$$

where *F (V)* represents the cumulative distribution function of observing wind speed *(V)*.

Different methods are used to verify the Weibull shape and scale parameters. Here these parameters are being calculated with the help of mean wind speed and standard deviation calculated through Eq. 2 and Eq. 3. The relationships are [2]:

$$k = \left(\frac{\sigma}{V_{avg}}\right)^{-1.086} \quad (8)$$

$$c = \frac{V_{avg}}{\Gamma\left(1+\left(1/k\right)\right)} \quad (9)$$

where v_{avg} represents the average value of wind speed.

where *Γ ( )* is the Gamma function and is expressed as [26, 27]:

$$\Gamma() = \int_0^{\infty} t^{x-1}\, e^{-1}\, dt \quad (10)$$

One method to calculate the Weibull scale parameter is given in [28] as:

$$c = \frac{V_{avg}\, k^{2.6674}}{0.184 + 0.816\, k^{2.7385}} \quad (11)$$

2.4.2 Rayleigh distributions

Besides having many advantages, the shortcoming of Weibull distribution is that it cannot represent the probability of zero wind speeds [29]. Therefore, another distribution, such as Rayleigh, is used and analyzed. In this study, two specified distributions are used, and the results are compared to realize which distribution is better for predicting the data.

In the Rayleigh distribution function, we assumed that the value of shape parameter (*k*) has a value of 2, which is fixed [19, 30], so both the functions are described as [2]:

$$f(V) = \frac{\pi}{2}\left(\frac{V}{V_{avg}^2}\right) \exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{V}{V_{avg}}\right)^2\right] \quad (12)$$

$$F(V) = 1 - \exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{V}{V_{avg}}\right)^2\right] \quad (13)$$

Here the shape parameter is taken to be 2, while the scale parameter can be calculated by Eq. 9 or Eq. 11.

2.5 Evaluation of Weibull and Rayleigh distributions

To assess the accuracy of both the distributions like Weibull and Rayleigh, the mean root square error (RMSE) test, the Chi-square (χ^2) test, and the correlation coefficient or coefficient of determination (R^2) can be used [12].

These parameters can be premeditated as follow [12]:

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2\right]^{1/2} \quad (14)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(y_i - x_i)^2}{N-n} \quad (15)$$

$$R^2 = \frac{\sum_{i=1}^{N}(y_i - z_i)^2 - \sum_{i=1}^{N}(x_i - y_i)^2}{\sum_{i=1}^{N}(y_i - z_i)^2} \quad (16)$$

where, y_i represents the i^{th} actual data, x_i shows the i^{th} predicted data calculated by making use of Weibull or Rayleigh distribution, *N* is the number of observations, and *n* is the number of constants [12].

The lesser the value of the RMSE and Chi-square, the better the curve fits the observed wind data. Ideally, the values of these two tests should be equal to zero. The value of R^2 should be highest, i.e., equal to 1, which describes the better fit of the data.

2.6 Calculation of the Wind power density

The wind power density is an estimator which displays the ability of the site regarding wind resources. The power available in the wind, which runs at speed *V* through a swept area *A,* increases as the cube of its velocity and is given by [31]:

$$P(V) = \frac{1}{2}\rho A V^3 \quad (17)$$

$$P_D = \frac{P(V)}{A} = \frac{1}{2}\rho V^3 \quad (18)$$

where *P (V)* denotes the wind power (*W*) and *P (V) / A* denotes the wind density having area *A* (Wm^{-2}), and ρ is the air density (kg/m^3) at this site. Here ρ can be calculated as [32]:

$$\rho = \frac{P}{RT} \quad (19)$$

where *P* and *T* are average air pressure (Pa) and temperature (*K*), and *R* is the gas constant (287 $JKg^{-1}K^{-1}$) for air.

Wind power density can be calculated utilizing Weibull distribution with the help of the given formula [2]:

$$P_{D,W} = \frac{1}{2}\rho C^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (20)$$

Wind power density in the case of Rayleigh distribution can be calculated as [30]:

$$P_{D,R} = \frac{3}{\pi}\rho V_m^3 \tag{21}$$

The error during the calculations of the above densities can be evaluated as [2]:

$$\text{Error}\ (\%) = \frac{P_{D(W,R)} - P_{D_M}}{P_{D_M}} \tag{22}$$

where P_{D_M} represents the power density of the wind calculated through perceived data and has been taken here as a reference, while $P_{D\ (W,\ R)}$ is power density (Wm^{-2}) determined through Weibull or Rayleigh function.

2.7 Wind energy density calculation

After estimating the wind power density using (Eqs. 18, 20, and 21), the wind energy density correspondingly can be calculated by multiplying these values with the desired time duration. The equation for energy density calculation is given as [11]:

$$\frac{E}{A} = \frac{1}{2}\rho C^3 \Gamma\left(1 + \frac{3}{k}\right)T \tag{22}$$

where T is the time duration in (h) for the year, and E is the energy density.

3. Results and Discussion

In this paper, wind speed data is analyzed to determine the potential of the site. Wind characteristics such as mean speed, availability of wind, wind duration, and standard deviations are determined to calculate the wind power potential and energy density at the selected site.

3.1 Analysis of average wind speeds

Table 1 and Fig. 4 display the monthly mean wind speeds (V_{avg}) and standard deviations (σ) at the site of Turbat for the years 2012 and 2013. The average value of wind speed is more than 4 m/s in each month. The average wind speed remains high from the start of the year to the mid of the year, i.e., January to June, and then it starts to decrease. The range of mean wind speeds is between 4.065 ms^{-1} to 6.422 ms^{-1}. The maximum monthly mean wind speeds are 6.422 ms^{-1} and 5.610 ms^{-1} for February 2012 and March 2012, respectively. Similarly, minimum speeds are 4.065 ms^{-1} and 4.180 ms^{-1} for October 2012 and September 2013, respectively. The value of the standard deviation ranges from 1.699 to 3.306 for January 2012 and February 2012, respectively.

Table 1. Monthly values of average wind speeds and standard deviations

Month	Parameter	2012 (m/s)	2013 (m/s)
January	V_{avg}	4.686	4.341
	σ	1.699	2.670
February	V_{avg}	6.422	4.235
	σ	3.306	2.146
March	V_{avg}	5.610	4.780
	σ	2.993	2.409
April	V_{avg}	5.186	4.283
	σ	2.599	2.229
May	V_{avg}	5.235	4.694
	σ	2.344	2.584
June	V_{avg}	5.567	5.300
	σ	2.823	2.954
July	V_{avg}	5.469	4.603
	σ	2.453	3.152
August	V_{avg}	4.255	4.647
	σ	1.683	2.774
September	V_{avg}	4.761	4.180
	σ	2.212	2.635
October	V_{avg}	4.065	-
	σ	1.955	-
November	V_{avg}	4.504	-
	σ	2.627	-
December	V_{avg}	4.578	-
	σ	2.686	-
Yearly	V_{avg}	5.028	4.563
	σ	2.448	2.683

From Fig. 4 the average value of wind speed in June, July, and August are higher, which are among the warmer months. The energy demand in these months also increases due to the hot weather in Pakistan. In contrast, the smallest values of mean wind speed are seen in October, November, and December, which are among the coldest months.

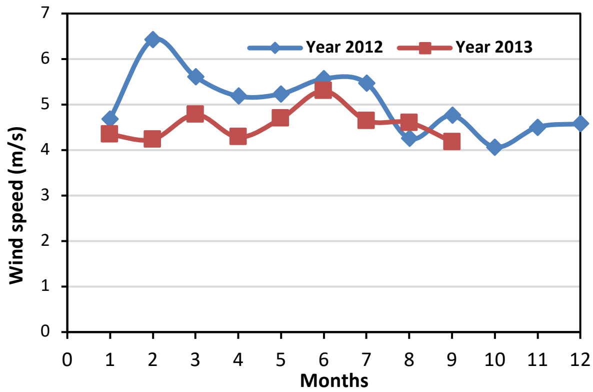

Fig. 4. Monthly average wind speed for the years 2012 & 2013

For better results, analysis was done every month, and the average value of all the months was calculated. Hence the overall average value of mean velocity is $V_{avg} = 4.83$ ms^{-1}, and the standard deviation is σ = 2.54.

Besides mean velocity and standard deviation, the other two important factors for the evaluation of wind power potential are most probable wind speed "V_{mp}" and wind speed carrying maximum energy "$V_{max.\ E}$". These parameters are also calculated here. In Table 2, the monthly values of both these velocities are shown. The maximum values of V_{mp} for the year 2012 are 5.244 ms^{-1} and 4.916 ms^{-1} for February and July, respectively. Similarly, for the year 2013, the max value of V_{mp} is 4.002 ms^{-1} and 3.974 ms^{-1} for June and March, respectively. The maximum values of $V_{max.\ E}$ for the year 2012 are 10.086 ms^{-1} and 9.009 ms^{-1} for February and March, respectively. Similarly, for the year 2013, the maximum values of $V_{max.\ E}$ are 8.928 ms^{-1} and 8.759 ms^{-1} for August and June, respectively. The average value of all the months for V_{mp} and $V_{max.\ E}$ are 3.83 ms^{-1} and 7.732 ms^{-1}, respectively.

Table 2. Estimated values of V_{mp} and $V_{max. E}$ every month

Month	2012 (m/s)		2013 (m/s)	
	V_{mp}	$V_{max. E}$	V_{mp}	$V_{max.E}$
January	4.588	6.214	2.876	7.702
February	5.244	10.086	3.505	6.588
March	4.434	9.009	3.974	7.412
April	4.332	8.015	3.464	6.772
May	4.711	7.612	3.592	7.694
June	4.603	8.666	4.002	8.759
July	4.916	7.959	3.218	8.061
August	4.051	5.842	2.481	8.928
September	4.194	7.055	2.659	7.561
October	3.499	6.138	-	-
November	3.220	7.682	-	-
December	3.245	7.842	-	-
Yearly	4.253	3.265	7.677	7.807

3.2 Analysis of wind speed distribution

Out of these two distributions, the Weibull distribution displays a better fit over measured wind speed data at the site because frequency values in the case of the Weibull distribution are closer to actual values than the Rayleigh distribution. Therefore, Weibull distribution is applied to assess the wind power potential at the selected site instead of using Rayleigh distribution.

The Weibull parameters k and c are calculated here by making use of Eq. 8 and Eq. 9, respectively. Table 3 shows the results of shape and scale parameters of Weibull distribution monthly for the years 2012 and 2013. The value of the shape parameter fluctuated from 1.508 in July 2013 to 3.010 in January 2012, while the scale parameter varied from 4.674 in September 2013 to 7.249 in February 2012. These parameters control the sketch of the curve formed by the Weibull and Rayleigh distributions.

Table 3. Weibull shape and scale parameter for years 2012 and 2013

Month	Parameter	2012	2013
January	k	3.010	1.695
	c	5.247	4.865
February	k	2.057	2.093
	c	7.249	4.782
March	K	1.978	2.105
	c	6.329	5.397
April	k	2.119	2.032
	c	5.856	4.834
May	k	2.393	1.912
	c	5.906	5.291
June	k	2.090	1.887
	c	6.285	5.972
July	k	2.388	1.508
	c	6.169	5.102
August	k	2.738	1.751
	c	4.782	5.218
September	k	2.300	1.650
	c	5.375	4.674
October	k	2.214	-
	c	4.590	-
November	k	1.796	-
	c	5.064	-
December	k	1.784	-
	c	5.145	-
Yearly	k	2.496	1.819
	c	5.666	5.137

The value of shape factor "c" shows the probability of wind speed flowing, so the greater value of c shows the higher value for the probability of wind speed. In contrast, the higher value of "k" shows the higher possibility of frequent and uniform wind blowing across the side.

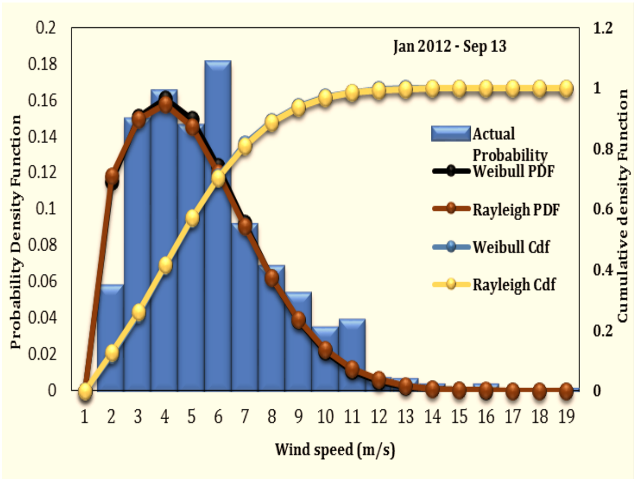

Fig. 5. Comparison of Actual, Weibull, and Rayleigh PDF, CDF for the year 2012 – 2013

Fig. 5 demonstrates the difference between the observed and predicted wind speed calculated with the help of the frequency distribution table for the site of Turbat. Weibull and Rayleigh distributions fit the perceived data well. The change lies within the value of the shape factor "k". In the Rayleigh distribution, k has a fixed value, i.e., 2. Consequently, in the Weibull distribution, the calculated value of k is also approaching 2, i.e., 2.059. Therefore, the results of both distributions are almost similar. Whereas the difference between these two distributions is very minor, but Weibull estimates the real data better than Rayleigh.

3.3 Performance estimation of Statistical models

To estimate the accuracy of the two distributions used here, an error analysis was conducted. The root mean square error (RMSE) test, the Chi-square (χ^2) test, and the coefficient of determination (R^2) test were used to check the precision of the distributions in this study, and the results are shown in the Table 4.

Table 4. Evaluation of statistical models

Index	Weibull	Rayleigh
R^2	0.946	0.942
RMSE	0.0040	0.0043
χ^2	2.019×10^{-6}	2.347×10^{-6}

For better estimation of the data, the values of RMSE and chi-square are close to zero, while the value of R^2 approaches unity. It can be seen from the Table 4 that Weibull distribution better fits the observed data than the Rayleigh because of the higher value of R^2 and lower values for both RMSE and χ^2.

3.4 Calculation of the power and energy density of the wind

The values of power density and energy density are presented in Table 5 and Table 6. The power density has a comparatively higher average value for the months of February to July than for the months from August to December. The power consumption of the country in these months (i.e., February – July) is also comparatively high than in the other months. The maximum value of average wind power density is for February 2012, i.e., 306.090 W/m^2, and the lowest value of average wind power density is for October 2012, i.e., 75.100 W/m^2. Likewise, the values of average wind energy density at the Turbat site are high from the months February to July and are lower than in August to December. The minimum value of energy density is 55.9 kWh/m^2, and the maximum value is 205.7 kWh/m^2 for October 2012 and February 2012, respectively.

The power density at the selected site is calculated from the actual wind speed data using Eq. 18 and compared with the power densities calculated with the help of Weibull and Rayleigh functions from Eq. 20 and Eq. 21, respectively. The comparison between the monthly variations of these power densities is demonstrated in Table 5.

Table 5. Monthly comparison of the power densities (W/m^2) estimated from actual data, Weibull, and Rayleigh functions

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2012												
Actual	89.804	306.090	217.871	152.694	143.480	196.318	165.020	71.593	111.739	75.100	125.795	134.627
Weibull	88.548	302.153	209.327	154.699	143.567	193.827	163.918	70.107	111.519	71.632	120.326	127.313
Rayleigh	120.703	310.725	207.154	163.699	168.317	202.402	191.865	90.352	126.649	78.795	107.213	112.542
2013												
Actual	120.211	86.817	128.245	94.460	131.545	182.391	160.701	138.836	109.709	-	-	-
Weibull	115.517	85.255	121.887	90.690	127.049	185.550	161.421	136.156	106.690	-	-	-
Rayleigh	95.990	89.129	128.122	92.196	121.336	174.685	114.398	117.739	85.657	-	-	-

The yearly value of Wind energy density for the year 2012 – 2013 is presented in Table 6, and the maximum value is for the year 2012, i.e., 1306.796 kWh/m^2.

Table 6. Yearly average values of wind power and energy density

Year	P_D (W/m^2)	E_D (kWh/m^2)
2012	149.178	1306.796
2013	128.102	830.099

The mean values of actual power density and energy density calculated by taking the mean of all months are 140.145 W/m^2 and 101.775 kWh/m^2, respectively.

In Table 7 wind classification is given at 10 m and 50 m height, and the site comes under class II of the wind classification at this height by keeping in view the results.

Table 7. Categories of wind power density at 10 m and 50 m height [33]

Wind Power class	Resource potential	10 m (33 ft)		50 m (164 ft)	
		Wind power density (W m^{-2})	Speed (m s^{-1})	Wind power density (W m^{-2})	Speed (m s^{-1})
1	Poor	0-100	0-4.4	0-200	0-5.4
2	Marginal	100-150	4.4-5.1	200-300	5.4-6.2
3	Moderate	150-200	5.1-5.6	300-400	6.2-6.9
4	Good	200-250	5.6-6.0	400-500	6.9-7.4
5	Excellent	250-300	6.0-6.4	500-600	7.4-7.8
6	Excellent	300-400	6.4-7.0	600-800	7.8-8.6
7	Excellent	>400	>7.0	>800	>8.6

The monthly values of the error estimated during each month for Weibull and Rayleigh functions in comparison to actual wind speed data is represented in Fig. 6 for the selected site. The power density calculated employing the Weibull function mostly underestimates for each year, while the values calculated using the Rayleigh function sometimes overestimate and sometimes underestimate the data. The value of average error estimation is high for November and low for June for common Weibull and Rayleigh distributions.

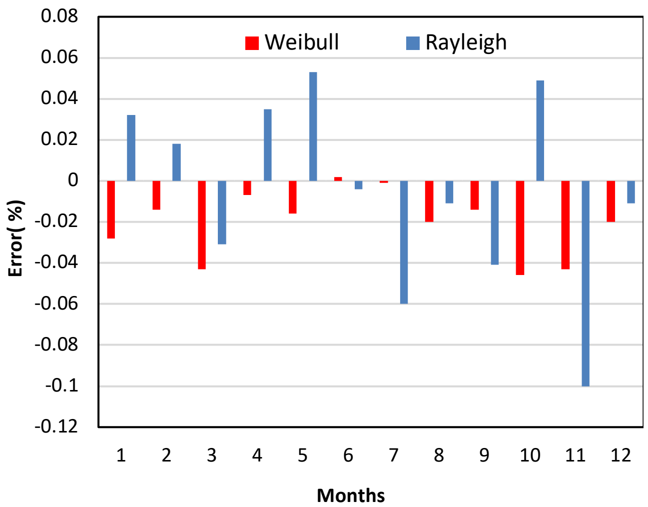

Fig. 6. Comparison of error estimated employing Weibull and Rayleigh functions against actual calculated wind data

The annual value of average error for the year 2012 – 2013 employing Weibull distribution is 2.2% and 2.8%, respectively, and for Rayleigh distribution it is 13.4% and 11.5%, for the years 2012 and 2013, respectively. The two years mean value of error for Weibull and Rayleigh functions is 2.12% and 3.71%, respectively. These statistics show that there is no significant difference between the power evaluated by monthly average values and estimated by using the Weibull distribution. The error between these two is only 2.2%.

4. Conclusions

Pakistan, currently facing a severe energy shortage, requires new sources of energy to lessen the misery. The country has immense wind potential but still has not yet been utilized completely. Thermal power plants have the main share in the power generation of the country. Millions of dollars are spent on the import of oil. Therefore, alternate resources like renewables can be exploited to decrease the burden on the economy. Wind energy is the most feasible option for the country due to its sustainability, low cost, and low environmental impact. In this study, 1 year and 9 months of wind speed data was taken, and a detailed evaluation of wind power potential was carried out with the help of Weibull and Rayleigh functions at the site of Turbat, Balochistan, Pakistan. The main conclusions of this work are:

- The monthly average value of wind speed is greater than 4 m/s, while the maximum and minimum values are 6.422 m/s for February 2012, and 4.065 m/s for October 2012.
- The most probable wind speed is 5.244 m/s for February 2012, and wind speed carrying maximum energy has the highest value of 10.086 m/s for February 2012.
- The Weibull shape parameter has the highest value of 3.010 for the month of January 2012 and has a range of 1.058 to 3.010, while the scale parameter has the highest value of 7.249 m/s for February 2012 and has a range of 4.674 m/s to 7.249 m/s.
- Wind power density has a maximum average value of 306.090 W/m^2 for the month of February 2012 and the lowest value of 75.100 W/m^2 for October 2012. Likewise, the maximum value of energy density is 205.7 kWh/m^{2,} and the minimum value is 55.9 Kwh/m^2 for October 2012 and February 2012, respectively.
- Weibull and Rayleigh models projected the wind data with a 94% probability. The result of the RMSE and Chi-square test for the Weibull model are 0.0040 and 2.019 × 10^{-6}, while for the Rayleigh model are 0.0043 and 2.347 × 10^{-6}, respectively (Table 4).
- Weibull distribution better predicts the data as compared to Rayleigh.
- At the height of 50 m, this site falls under class II of wind classification given in Table 7.
- Three to five years of monthly wind speed data will be best suited for more accurate results.

Acknowledgment

The author would like to express acknowledgment and sincere gratitude to Mr. Nadem Faisal, Deputy Director PMD (CPDC Karachi), Pakistan, for his help in this research work.

References

[1] Kharo SF, Soomro AM, Tabbasum K, Dong L, Liao X. Assessment of wind energy potential at Hawksbay Karachi Sindh, Pakistan. Telkomnika 2013; 11: 3479-90.

[2] Kharo SF, Tabbasum K, Soomro AM, Liao X, Alvi MB, Dong L, Manzoor MF. Techno-economic evaluation of wind energy potential and analysis of power generation from wind at Gharo, Sind Pakistan. Renewable and sustainable energy reviews 2014; 35: 460-74.

[3] World wind energy association. http://www.wwindea.org

[4] Shami SH, Ahmed J, Zafar R, Haris M, Bashir S. Evaluating wind energy potential in Pakistan's three provinces, wind proposal for integration into national power grid. Renewable and sustainable energy reviews 2016; 53: 408-21.

[5] Pakistan Meteorological Department. www.pmd.gov.pk/wind/wind project files/page 558.html.

[6] Alternate Energy development Board. http://aedb.org/index.php/ae-technologies/wind-project/wind-re

[7] Kharo SF, Tabbasum K, Soomro AM, Dong L, Liao X. Evaluation of wind power prospective and weibull parameter estimation methods for Babaurband Sind, Pakistan. Energy conversion and management 2014; 78: 956-67.

[8] Pishgar-Komleh SH, Keyhani A, Safeedpari P. Wind speed and power density analysis based on weibull and rayleigh distribution (a case study: at Firouzkooh country of Iran). Renewable and sustainable energy reviews 2015; 42: 313-22.

[9] Akpinar EK, Akpinar S. A statistical analysis of wind speed data used in installation of wind energy conversion systems. Energy conversion and management 2005; 46: 515-32.

[10] Fyrippis L, Axaopoulos JP, Panayiotou G. Wind energy potential assessment in Naxos Island, Greece. Applied energy 2010; 87: 577-86.

[11] Safari B, Gasore J. A statistical investigation of wind characteristics and wind energy potential based on the weibull and rayleigh models in Rwanda. Renewable energy 2010; 35: 2874-80.

[12] Ayodele TR, Jimoh AA, Munda JL, Agee JT. A statistical analysis of wind distribution and wind power potential in the coastal region of South Africa. International journal of green energy 2013; 10: 814-34.

[13] Torgul IT, Kizi MI. Determination of wind energy potential and wind speed data in Bishkek, Kyrgyzstan. International journal of green energy 2008; 5: 157-73.

[14] Albani A, Ibrahim MZ. Statistical analysis of wind power density based on the Weibull and Rayleigh models of selected site in Malaysia. Pak.j.stat.oper.res 2013; 4: 393-406.

[15] Okeniyi JO, Moses IF, Okeniyi ET. Wind characteristics and energy potential assessment in Akure, south west Nigeria: econometrics and policy implication. International journal of ambient energy 2012; 1-19.

[16] Yaniktepe B, Koroglu T, Savron MM. Investigation of wind characteristics and wind energy potential in Osmaniye, Turkey. Renewable and sustainable energy reviews 2013; 21: 703-11.

[17] Akpinar EK, Akpinar S. Assessment of seasonal analysis of wind energy characteristics and wind turbine characteristics. Energy conversion and management 2005; 46: 1848-67.

[18] Kwon, SD. Uncertainty Analysis of Wind Energy Potential Assessment. Applied Energy 2010; 87: 856–65.

[19] Bagiorgas HS, Assimakopoulos MN, Theoharopoulos D, Matthopoulos D, Mihalakakou GK. Electricity generation using wind energy conversion system in the area of western Greece. Energy conversion manage 2007; 48: 1640-55.

[20] Mathew S, Pandey KP, Kumar AV, analysis of wind regimes for energy estimation. Renew energy 2002; 25: 381-99.

[21] Fagbenle RO, Katende J, Ajayi OO, Okeniyi JO. Assessment of wind energy potential of two sites in North-East, Nigeria. Renew energy 2011; 36: 1277-83.

[22] Ozerdem B, Turkeli M. An investigation of wind characteristics on the campus of Izmir institute of Technology, Turkey. Renewable energy 2003; 28: 1013-27.

[23] Ucar A, Balo F, Evaluation of wind energy potential and electricity generation at six locations in Turkey. Applied Energy 2009; 86: 1864-72.

[24] Justus CG, Hargraues WR, Mikhail A, Graber D. Methods for estimating wind speed frequency distribution. J Applied Meteorology 1978; 17: 350-3.

[25] Akdag SA, Bagiorgas HS, Mihalakakou G. Use of two components weibull mixtures in the analysis of wind speed in the eastern Mediterranean. Applied energy 2010; 87: 2566-73.

[26] Ouammi A, Dagdougui H, Scile R, Mimet A. Monthly and seasonal assessment of wind energy characteristics at four monitored locations in Liguria region (Italy). Renewable and sustainable energy reviews 2010; 14: 1959-68.

[27] Jowder FAL. Wind power analysis and site matching of wind turbine generators in kingdom of Bahrain. Applied energy 2009; 86: 538-45.

[28] Balouktsis A, Chassapi D, Karapantosis TD. A nomogram method for estimating the energy produced by wind energy turbine generators. Sol Energy 2002; 72: 251-9.

[29] Islama MR, Saidor R, Rahin NA. Assessment of wind energy potential at Kudat and Labuan, Malaysia using Weibull distribution function. Energy 2011; 36: 985-92.

[30] Celik AN. A statistical analysis of wind energy density based on the Weibull and Rayleigh models at the southern region of Turkey. Renewable energy 2009; 29: 593-604.

[31] Chang TJ, Wu YT, Hsu HY, Chu CR, Liao CM. Assessment of wind characteristics and wind turbine characteristics in Taiwan. Renewable energy 2003; 28: 851-71.

[32] Keyhani A, Ghasemi-Varnamkhasti M, Abbaszadeh R. An assessment of wind energy potential as a power generation source in the capitol of Iran, Tehran. Energy 2010; 35: 188-201.