



A Techno-Economic Investigation of Wind Power Potential in Coastal Belt of Sindh: Preventing Energy Crisis in Pakistan

Kalsoom Bhagat¹ · Shengyong Ye² · Chaohua Dai¹ · Jingru Lian¹ · M. Zubair Bhayo³

Received: 21 November 2020 / Revised: 27 April 2021 / Accepted: 7 June 2021 / Published online: 15 June 2021
© The Korean Institute of Electrical Engineers 2021

Abstract

Pakistan has been facing an energy crisis for many years. Techno-economic analysis of wind power generation is carried out to meet energy demand. Wind data from 2016 to 2018 has been selected for a coastal site of Sindh, Pakistan. For this purpose, four distribution functions, namely Weibull, Gamma, Rayleigh, and Lognormal are used. These distribution functions are compared using the coefficient of determination (R^2) and root mean square error tests. Wind potential on a daily, monthly, yearly and seasonal basis is evaluated. In this regard, various turbine models are selected to estimate their power generation capacity. The assessment results for a hub height of 100 m shows the average wind speed for three years is 7.9 m/s with direction dominated between the West and Southwest. The most probable wind speed is 9.5 m/s having a maximum energy density of 455 kWh/m² in May. The maximum mean wind speed of 8.55 m/s is in the spring. The Weibull distribution function ($k=2.92$ & $C=8.86$ m/s) performs the best. The maximum capacity factor for Fuhrlander LLC WTU 3.0–120 is 55.49% and for Siemens SWT-3.15–142 is 55.22%. Likewise, the estimated lowest LCOE (\$/kWh) for Fuhrlander LLC WTU 3.0–120 and Siemens SWT-3.15–142 is \$0.04016 and \$0.04035 respectively. Thus, this site contains suitable technical and economic characteristics of the wind power plant.

Keywords Annual energy generation · Capacity factor · Cost of energy generation · Cumulative and probability distribution functions · Wind power and energy densities

List of symbols

A	Area
AP_{Avg}	Annual Energy Generation
C	Celsius
E	Energy

Erf	Error Function
Exp	Exponential Function
$g(v)$	Gamma Probability Distribution Function
$G(v)$	Gamma Cumulative Distribution Function
H_H	Hub Height
Ln	Natural Logarithm
N	The Number Of Bins
N	The Total Number Of Observations
P	Power
P_D	Performance Derating
P_{out}	Power Output
P_R	Rated Power
PV_{Net}	Net Present Value
R	Specific Gas Constant
R^2	Coefficient Of Determination
R_D	Rotor Diameter
R_{Rate}	Rate Of Return On Investment
S_{PP}	System Payback Period
\$	United States Dollar
\$/kWh	Cost Of Per Kilowatt Hours Generation In Usd
T	Air Temperature
T	Time

✉ Kalsoom Bhagat
kalsoombhagat@gmail.com

Shengyong Ye
yeshengyong410@126.com

Chaohua Dai
daichaohua@swjtu.edu.cn

Jingru Lian
lianjingru@foxmail.com

M. Zubair Bhayo
muhammadzubairbhayo@gmail.com

¹ School of Electrical Engineering, Southwest Jiaotong University, Chengdu 610031, China

² State Grid Sichuan Economic Research Institute, Chengdu 610041, China

³ University of Electronic, Science and Technology, Chengdu 611731, China

TC_{ins}	The Total Cost Of Installation Of A Wind Turbine
$T_{Spec.}$	Turbine Specifications
v	Wind Speed
v_{100}	Wind Speed At 100 Meters
v_{80}	Wind Speed At 80 Meters
v_c	Cut-In Wind Speed
v_f	Cut-Out Wind Speed
v_i	Ith Wind Speed
v_r	Rated Wind Speed
W_a	Availability Of Wind In Percentage
WT	Wind Turbine
x_i	Ith Predicted Frequency
y_i	The Ith Observed Frequency
z_i	The Average Wind Speed
Γ	Gamma
P	Air Density
Σ	Standard Deviation
σ^2	Variance
\bar{v}	Average Wind Speed
P_r	Air Pressure
Δt	Period

Abbreviations

AEP	Annual Energy Production
ARE	Alternative Renewable Energy
AEDB	Alternative Energy Development Board
CDF	Cumulative Distribution Function
CF	Capacity Factor
GoP	Government Of Pakistan
IPPs	Independent Power Producers
KESC	Karachi Electric Supply Company
NTDC	National Transmission And Dispatch Company
PAEC	Pakistan Atomic Energy Commission
PDF	Probability Distribution Function
PMD	Pakistan Meteorological Department
PPIB	Private Power And Infrastructure Board
RE	Renewable Energy
RMSE	Root Mean Square Error
USD	United States Dollar
WAPDA	Water And Power Development Authority
WPD	Wind Power Density
WSD	Wind Speed Distribution

Units

GW	Gigawatt
GWh/year	Gigawatt Hours Per Year
J/kg	Joule Per Kilogram
kg/m^3	Kilogram Per Cubic Meter
kW	Kilowatt
kWh/m^2	Kilowatt Hours Per Square Meters
M	Meter
m/s	Meter Per Second

N/m^2	Newtons Per Square Meters
C°	Celsius
Pa	Pascal
W/m^2	Watt Per Square Meters

Parameters

a	Gamma shape parameter
B	Gamma scale parameter
C	Weibull scale parameter
K	Weibull shape parameter
M	Log mean
Σ	Log standard deviation
a	Rayleigh scale parameter

1 Introduction

Electrical energy is one of the primary inputs for the socio-economic development of any country. This means Energy consumption reflects the development of a country [1]. Electrical energy is very vital for the industrial growth of a country having a large population [2]. The increase of energy requirement and its low supply slows the industrial development of any country [3].

Especially where the limited and costly non-renewable energy resources are major share in its energy mix. Like fossil fuels, which contribute to air pollution and cause global warming. Besides this the renewable energy like wind energy which has been increasingly used for energy generation because of eco-friendly attention and the rising cost of fossil fuels [4, 5]. This utilization of wind power production is advantageous for the environment. The global wind energy production has added 50 GW of size each year since 2014. As compared to 2017, wind energy generation has been increased by 9.6% and has reached 591 GW in 2018 [5]. Moreover, the International Energy Association of World Energy Outlook forecasts that wind power will remain the outstanding share of electric power in 2040 [6]. But for that energy corporations are facing the huge cost of this technology. There is another problem faced by them the delivery uncertainties owing to the rising rivals within the electric power market. Hence there is a significant need for attention to risk management. As a result, energy generation structures require them to allow the production of electricity based on mutual agreements [7].

Due to the energy crisis in Pakistan, people have to face severe difficulty like load shedding for prolonging times [8]. Pakistan has got plenty wind power potential in renewable energy sources [9]. It has enough wind energy density to meet its electrical power demand, which can be used through proper planning. Furthermore, it can also solve energy security [10]. As many countries set a Renewable Energy (RE) electricity generated targets based on the global energy

landscape [11]. The GoP plans to use 30% more renewable energy in total power generation by the year 2030, especially in the wind, small hydro, solar and biomass [12]. In Pakistan, there exists four power producers, i.e., Water And Power Development Authority (WAPDA), the Pakistan Atomic Energy Commission (PAEC), Karachi Electric Supply Company (KESC) and Independent Power Producers (IPPs). WAPDA and PAEC are state-controlled institutions, whereas IPPs are private sectors. The IPPs sell the energy to the National Grid. The efficiency of the power sector of Pakistan can be enhanced by improving its structural design [13]. The structural diagram of the power sector of Pakistan is presented in Fig. 1.

The process of wind resource evaluation includes collecting the wind data and processing it into MATLAB program. The data is collected through wind mast which has sensors installed for the measurements of wind speed, direction, air pressure, humidity, and air temperature. This data is recorded either for a minimum of ten minutes or hourly based mean for at least a year. Processing of data involves the following steps: At first, the data provide wind speed distribution (WSD). The distribution functions are applied to the measured WSD. Then, the wind power density (WPD) is calculated which varies from one site to another site, and it widely depends on wind speeds. The highest wind velocity yields more wind power density and vice versa [14]. In the next step, the wind turbine power curve helps in the estimation of its wind energy generation [15]. Moreover, the wind speed shear model is considered for the annual energy production (AEP). Therefore Authors [16] estimated the monthly mean air density (ρ) and temperature (T) for Germany and concludes that air density is significant for the assessment of wind resources of a site. The increase in

hub height of a turbine gives more electricity generation. As, the more hub height means more rotor diameter, which means more power output. But an increase in hub height (H_H) also increases the overall cost of energy generation. Thus, it is essential to select the most optimal hub height in wind resource estimation [17].

Authors of [18] have used distribution functions like Rayleigh Cumulative Distribution Function (Rayleigh-CDF) and Rayleigh Probability Distribution Function (Rayleigh-PDF) to estimate wind potential for the Hamirpur in Himachal Pradesh, India. They have also calculated Rayleigh scale parameter (c), the standard deviation (σ), monthly and annual mean wind speeds. Similarly, Authors of [19] selected Rayleigh Probability Distribution Function (Rayleigh-PDF) to estimate the average wind speed and AEP for Cleveland, the Ohio area. In which it is discussed that wind power is stochastic because the wind parameters are unpredictable and are time-varying from place to place. Authors [20] selected Weibull Probability Density Function (PDF) to measure wind speed distribution, including modeling of wind power. In [21], the work focuses on the Eastern part of Niger Delta using Weibull PDF. The Authors concluded that wind energy generation is economically feasible in Umudike (Umuahia), Nigeria. So, wind energy can be utilized there. The wind resource assessment for the coastal region (Tripoli, Beirut and Sidon) of Lebanon was analyzed using various distribution functions. Further, the authors use the Power-law method for the estimation of wind power density at higher altitudes [22]. Authors [23] have investigated the wind energy of Kati Bandar, Jhimpir, Multan, Gujranwala, Khanewal, Sialkot and Islamabad Capital Territory in Pakistan. They have selected different distribution functions for wind speed data which is recorded a height of 10m

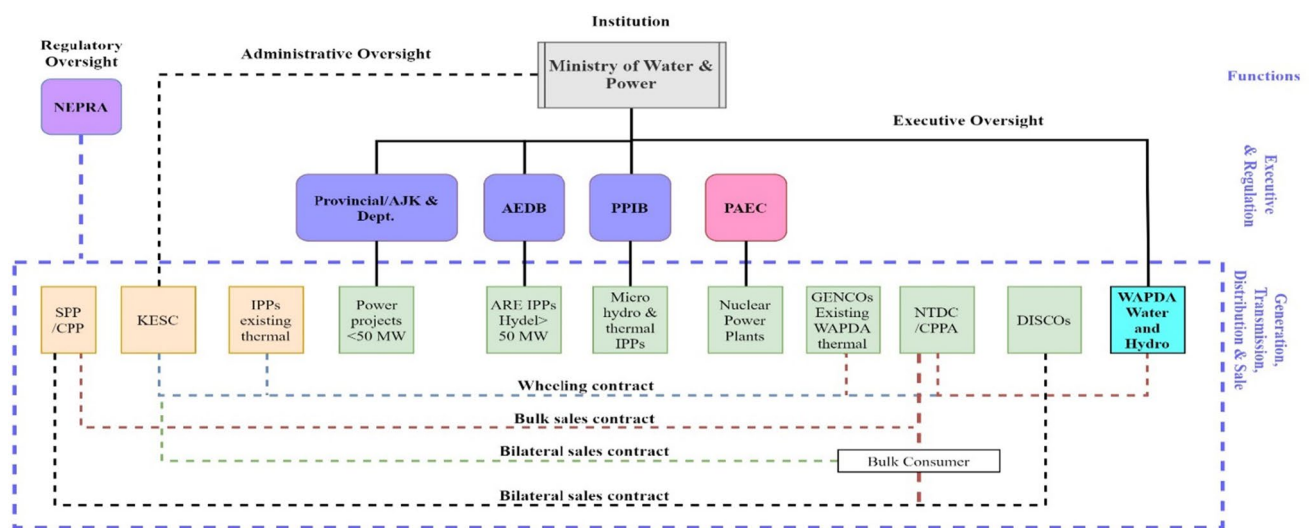


Fig. 1 Shows the power sector in Pakistan [13]

and it is concluded that increasing the hub height of tower yields more energy density. Because higher altitudes have more prospects of higher wind speeds. While, the Authors of [24] have used wind data of three years to estimate wind potential Gwadar, Lasbela and Ormara sites in the Southern province of Pakistan. Further, the extrapolation of wind data is carried out at the height of 60m and 80m. Which helps in the prediction of wind speed at a higher altitude by using the selected sample of wind speed of lower altitudes. Moreover, the Weibull CDF and PDF are applied to the data, and the numerical performance test is also done using two statistical tests, namely; Coefficient of Determination (R^2) and Root Mean Square Error (RMSE) tests. In [25], the authors have selected Hawksbay location near Karachi (Sindh province of Pakistan), and calculated WPD, C.F and AEP at three heights. In addition to this, the feasibility study is carried out for a wind turbine, and it is suggested that the site has the lowest cost of energy generation. It implies that the site can be used for the installation of a wind farm. Authors [26] have evaluated the wind energy in the Northern region of Pakistan and computed the seasonal wind parameters, including wind power density. The Pakistan Meteorological Department (PMD) has indicated that the coastal belt of Baluchistan and Sindh Provinces of Pakistan has massive potential for the wind projects. Therefore, in this work, wind resource estimation is carried out to the coastal site of Sindh province, Pakistan. The proposed site with the Sea breeze represented by yellow lines is shown in Fig. 2.

The data from 2016 to 2018 is used for the wind resource estimation for the selected site to obtain wind characteristics [27]. Along with this, the technical analysis involves the estimation of wind power density (W/m^2), energy density (kWh/m^2), the power output of a turbine (kW), annual energy generation ($kWh/year$), and a capacity factor of a turbine (%). On the other hand, the economic analysis yields the cost of energy generation ($\$/kWh$) of turbines selected in this study. In Fig. 3, the general research flow chart is illustrated.

So, the site characteristics are evaluated by fitting the probability and cumulative distribution functions over the measured data. Next, the above distribution functions are validated with the help of some statistical tests. These statistical tests give the best distribution function to obtain the technical parameters like wind power and wind energy densities of the site. The hourly average wind speeds, wind power and energy densities with the technical specification of each turbine will help in the estimation of annual energy generation. In the economic analysis, the cost of energy generation for each turbine model can be calculated through the estimated annual energy generation. Also, the data quality test can help in the validation of errors in measured data. The collected data successfully passed the data quality assurance test, except the data recorded in March 2018 because of some missing values. Which were replaced by average values of March 2016 and 2017. The result of the

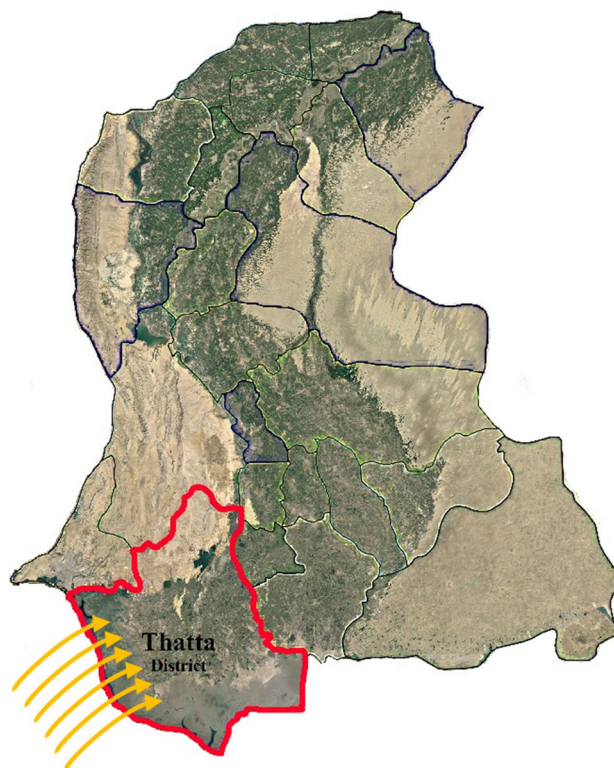


Fig. 2 Shows the coastal site in the Sindh province of Pakistan

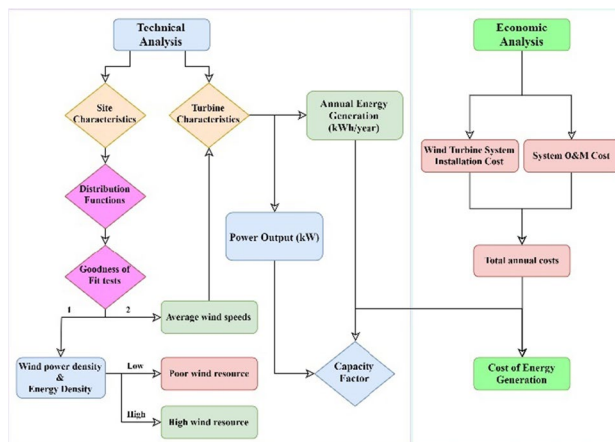


Fig. 3 Shows a general research flow chart

data quality assurance test of different sensors used to measure wind characteristics is shown in Fig. 4.

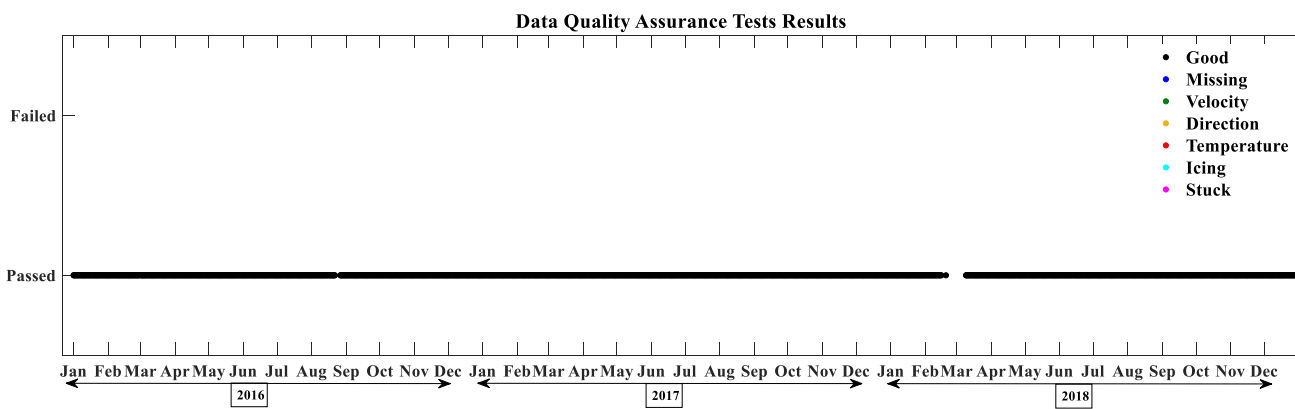


Fig. 4 Shows the results of the data quality assurance test

2 Wind Resource Estimation

2.1 Wind Speed Distribution Functions

The knowledge of WSD provides an understanding of wind resource estimation. It helps to analyze the performance of any Wind Turbine. Thus, estimation of the wind power potential and the economics of the system can be done [28]. The distribution function that is more accurate and fits nicely over the measured data gives better results in wind power density [29]. It is important to note that the PDF gives the probability of wind speed at measured data. While the CDF gives the probability of the wind speeds less than and higher than the measured data or is within the measured data. For this purpose, there are many wind speed distribution functions used among which Rayleigh, Weibull, Lognormal and Gamma distribution functions are worth notable.

2.1.1 Rayleigh Distribution

Rayleigh-PDF and Rayleigh-CDF are the most specific distribution functions with shape parameter (k) equal to 2. The Rayleigh PDF and CDF are given by Eq. (1) and (2), respectively [14, 30]:

$$f(v, a) = \frac{v}{a^2} \exp\left(\frac{-v^2}{2a^2}\right) \tag{1}$$

$$f(v, a) = 1 - \exp\left[-\frac{1}{2}\left(\frac{v}{a}\right)^2\right] \tag{2}$$

where v is wind speed, a is the Rayleigh scale parameter, and exp is the exponential function.

2.1.2 Weibull Distribution

The Weibull distribution function is widely used for potential wind estimation in many works. Eqs give the Weibull PDF and CDF. (3) and (4), respectively [31–34]:

$$f(v, k, c) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{3}$$

$$f(v, k, c) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{4}$$

where v, k and c are the wind speed, Weibull shape parameter and Weibull scale parameter, respectively. Eqs give the Weibull two parameters. (5) and (6), respectively [35–37]:

$$k = \left[\frac{\sum_{i=1}^n v_i^k \ln(v_i)}{\sum_{i=1}^n v_i^k} - \frac{\sum_{i=1}^n \ln(v_i)}{N} \right]^{-1} \tag{5}$$

$$c = \left[\frac{\sum_{i=1}^n v_i^k}{n} \right]^{\frac{1}{k}} \tag{6}$$

where v_i is the i th, wind speed in observed data.

The Average and variance of wind speed through the Weibull parameters can be obtained from Eqs. (7) and (8), respectively:

$$\bar{v} = c\Gamma\left(1 + \frac{1}{k}\right) \tag{7}$$

$$\sigma^2 = c^2 \left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{2}{k}\right) \right] \tag{8}$$

The wind power density (W/m^2) and energy density (kWh/m^2) can be calculated by using Eqs. (9) and (11), respectively [38, 39]:

$$\frac{P}{A} = \int_0^{\infty} \frac{1}{2} \rho v^2 f(v) dv = \frac{1}{2} \Gamma \rho c^3 \left(1 + \frac{3}{k}\right) \quad (9)$$

where (ρ) is the air density, which can be obtained by using Eq. (10):

$$\rho = \frac{P_r}{R \times T} \quad (10)$$

In Eq. (10), P_r is air pressure, T is the air temperature in kelvin ($C + 273^0$), and R is the specific gas constant (287 J/kg).

$$\frac{E}{A} = \left(\frac{P}{A}\right) n \Delta t = \frac{1}{2} \Gamma \rho c^3 \left(1 + \frac{3}{k}\right) n \Delta t \quad (11)$$

where n is the total number of observations of data for the period Δt .

2.1.3 Lognormal Distribution

The Lognormal PDF and CDF can be calculated by using Eqs. (12) and (13), respectively [40, 41]:

$$f(v, \mu, \sigma) = \frac{1}{v\sigma\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\frac{\ln(v) - \mu}{\sigma}\right)^2\right\} \quad (12)$$

$$f(v, \mu, \sigma) = \frac{1}{2} + \frac{1}{2} \operatorname{erf}\left[\frac{\ln(v) - \mu}{\sigma\sqrt{2}}\right] \quad (13)$$

where μ , σ , and erf are log means, log standard deviation parameter and the error function. The error function calculated using Eq. (14):

$$\operatorname{erf}(v) = \frac{2}{\sqrt{\pi}} \int_0^v \exp(-t^2) dt \quad (14)$$

2.1.4 Gamma Distribution

The Gamma PDF and CDF are obtained by using Eqs. (15) and (16), respectively [40, 41]:

$$g(v) = \frac{1}{b^a \Gamma(a)} v^{a-1} \exp\left(-\frac{v}{b}\right) \quad (15)$$

$$G(v) = \int \frac{v^{a-1}}{b^a \Gamma(a)} \exp\left(-\frac{v}{b}\right) dv \quad (16)$$

where a , b and $\Gamma(a)$ are the Gamma shape parameter, Gamma scale parameter, and gamma functions.

2.2 Goodness of Fit Tests

The performance of wind speed prediction techniques plays an important role and affects the efficiency of the wind energy system [42]. Which can be achieved by using different goodness of fit tests. For this purpose there are two tests, namely: root mean square error (RMSE) and coefficient of determination (R^2).

2.2.1 Root Mean Square Error

The RMSE is the rate of the real variation in the observed and predicted probabilities. It shows the best fit of a distribution function over the measured data when it is nearer to zero. The RMSE is calculated using Eq. (17) [43, 44]:

$$\operatorname{RMSE} = \sqrt{\frac{\sum_{i=1}^n (y_i - x_i)^2}{N - n}} \quad (17)$$

2.2.2 R^2 test

This test is used to measure the correlation in the predicted and observed cumulative probabilities of a distribution function. It shows the best fit when R^2 is nearer to 1, and it is calculated using Eq. (18) [43, 45]:

$$R^2 = \frac{\sum_{i=1}^n (y_i - z_i)^2 - \sum_{i=1}^n (y_i - x_i)^2}{\sum_{i=1}^n (y_i - z_i)^2} \quad (18)$$

2.3 Capacity Factor and Annual Energy Production

The capacity factor (C.F) of an energy conversion system is defined as the ratio of the average power produced, and maximum power production (rated power) of the generating system, as in Eq. (19). The average power can be calculated from Eq. (20). However, the CF of the WT depends on its specification. These specifications are given in Table 1. Mathematically, in terms of the specification of wind turbine that are: rated wind speed, cut-in wind speed and cut-out wind speed, the capacity factor for the actual wind speed at the proposed site are calculated using Eq. (21) [46, 47]:

$$\text{C.F} = \frac{\text{average power output}}{\text{peak power output}} \times 100 \quad (19)$$

Table 1 Specifications of wind turbines

T_{Spec}	P_R (kW)	H_H (m)	v_c (m/s)	v_r (m/s)	v_f (m/s)	R_D (m)
WT ₁	3000	90/100/120/120/140/160	3	12	25	120
WT ₂	3150	109/129/165	4	11	22.5	142
WT ₃	3000	99/114/134	3	11.5	20	131
WT ₄	3000	136/139	3	11.5	22	122
WT ₅	3000	90/100/140	3	12	25	120.6
WT ₆	3000	90/98.3/140	3	11.5	22	120
WT ₇	3000	67/87/92/122/135/149	2.5	12.8	34	115.7
WT ₈	3000	93.5/143	3	15	25	101

$$\text{average power} = \int_{v_{in}}^{v_{out}} p(v) * f(v)dv \tag{20}$$

$$C.F = \frac{\exp\left[-\left(\frac{v_c}{c}\right)^k\right] - \exp\left[-\left(\frac{v_r}{c}\right)^k\right]}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - \exp\left[-\left(\frac{v_f}{c}\right)^k\right] \tag{21}$$

The annual energy production of a wind turbine is the power output of a wind turbine multiplied by the number of hours in a year. The AEP can be calculated using Eq. (22) [43, 48]:

$$AEP = P_{out} \times 8760 \text{ kWh/year} \tag{22}$$

2.4 Wind Turbines Specification

The proper selection of wind turbines for wind resource estimation plays an important role. For the large-scale commercial purpose wind farms, their minimum hub height should be 80 m or above. In this paper, Authors select eight different wind turbine models, namely; Enercon E-115 EP3 3.000,

Fuhrlander LLC WTU 3.0-120, FWT 120/3000, Leitwind LTW101 3000, Nordex N131/3000 Delta, Senvion 3.0M122, Siemens SWT-3.15-142, and Vensys 120/3000. Specifications of above wind turbines are given in Table 1.

3 Results and Discussions

3.1 Air Density vs Temperature

The air pressure and temperature data are collected at the physical location of mentioned site. The air pressure sensor recorded data is used to obtain the air density of the site by using Eq. (10). Then the calculated air density and recorded temperature values are used to calculate monthly average values, as shown in Fig. 5. From Fig. 5, it is evident that both have an inverse relation. Moreover, the air density is an essential variable in the calculation of wind power density, which is required for energy density. The temperature value is in °C, and air density is given in kg/m³. The highest monthly average value of temperature and the lowest monthly average value of air density in May 2018 are 31 °C and 1.1559 kg/m³, respectively. The highest monthly mean value of air density (ρ) and the lowest monthly mean value of temperature in Jan 2016 are 1.2092 kg/m³ and 17.59°C,

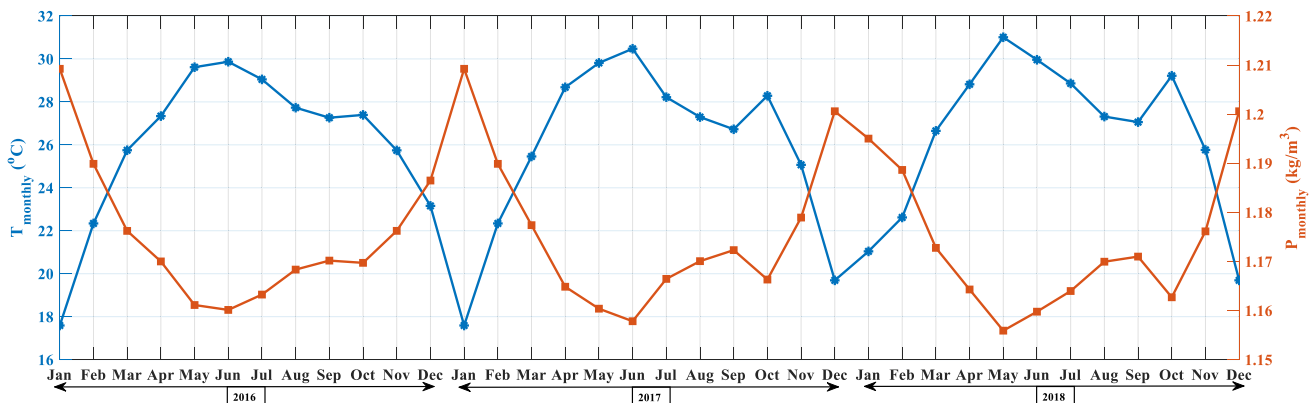


Fig. 5 Shows air density vs temperature graph

respectively. The yearly average values of air density for 2016, 2017 and 2018 are 1.1750 kg/m³, 1.1762 kg/m³ and 1.1734 kg/m³, respectively. The yearly average values of temperature for 2016, 2017 and 2018 are 26.07 °C, 25.80°C and 26.50°C, respectively. The three years' average values of air density and temperature are 1.1749 kg/m³ and 26.12°C, respectively.

3.2 Diurnal, Monthly, Seasonal, and Yearly Average Wind Speeds

The wind speed data can be used to predict the availability of the wind potential hourly, monthly, yearly and on a seasonal basis as wind power depends on the cubic value of wind speed. The diurnal winds velocity behavior helps in the understanding of the availability of the wind velocity potential through the hours of a day. From the analysis, it is observed that for the hub height of 100 m and 80 m, the maximum wind speed remained 8.43 m/s and 7.85 m/s from 8 pm and 3 pm, respectively. Also, the minimum wind speeds remained 7.23 m/s and 6.94 m/s during 10 am, and 6

am, respectively. Whereas for the three years, daily average values of wind speeds are 7.92 m/s and 7.45 m/s, respectively. So, Fig. 6 shows the diurnal wind velocity for the hub heights of 100 m and 80 m. The diurnal wind speed pattern suggests that the site has the highest wind speeds throughout the 24 hours.

The monthly average wind speed helps to find the availability of the wind potential in any month of a year. Through this, months during which the highest and the lowest wind speed is recorded will provide an estimation of the generation of higher and lower wind energy in those months. For the proposed site at the height of 100 m, the highest value of wind velocity for the years 2016 and 2017 is 10.54 m/s and 9.74 m/s in May respectively. For 2018, the highest wind speed observed is 9.52 m/s in Jun. The lowest values of wind speed for the years 2017 and 2018 are 6.43 m/s and 5.65 m/s in Oct, and for 2016, it is 6.02 m/s in Dec. However, for 80 m height, the highest values of wind speed for the years 2016 and 2017 are 10.08 m/s and 9.38 m/s in May. For 2018, the highest wind speed observed is 9.14 m/s in Jun. The lowest values of wind speed for the years 2016, 2017, and 2018 are

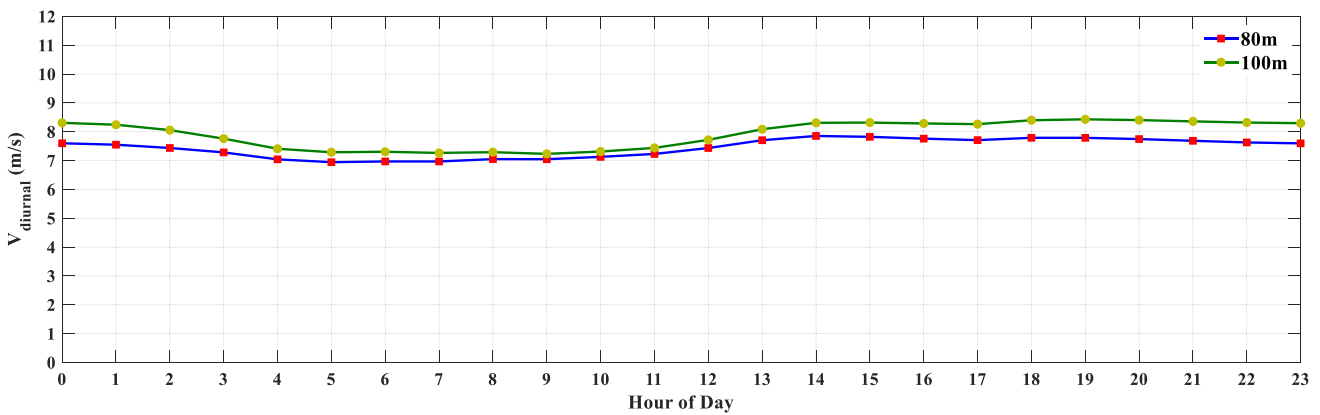


Fig. 6 Shows the diurnal wind velocity for the hub heights of 100 m and 80 m

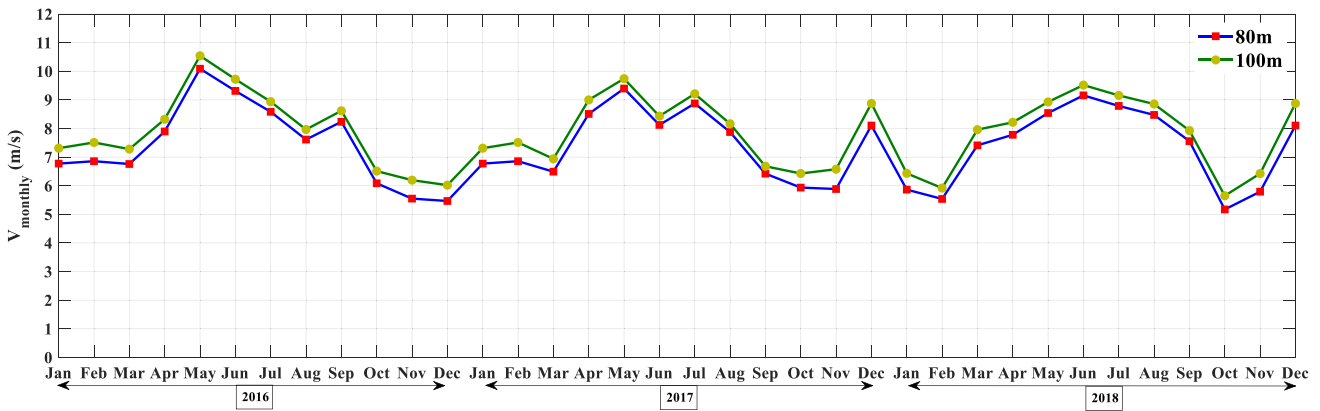


Fig. 7 Shows the monthly wind speed for the hub heights of 100 m and 80 m

5.5 m/s, 5.96 m/s and 5.22 m/s in Dec, Nov and Oct, respectively. The monthly average values of wind speed for the two hub heights are shown in Figure 7. The monthly wind speed pattern suggests that the site has prospects of higher wind speeds for the three years measured data.

The seasonal average wind speed also helps in the prediction of the availability of more wind power in a season. In Fig. 8, the seasonal and diurnal (Day & Night) average wind speeds are given. Also, the highest and lowest wind speeds in a season for different hub heights are indicated. So, in the summer season, when the demand for electrical energy is high in Pakistan, this site has wind speeds of 8.59 m/s and 8.22 m/s at hub heights of 100 m and 80 m. The lowest values are during the autumn season.

3.3 Wind Power Density and Energy Density

Wind power density and energy density of a site are two other crucial characteristics. The wind power density of the proposed site is high. The monthly wind power densities of three years are given in Fig. 9. From the calculations, it is found that the wind power density at a hub height of 100

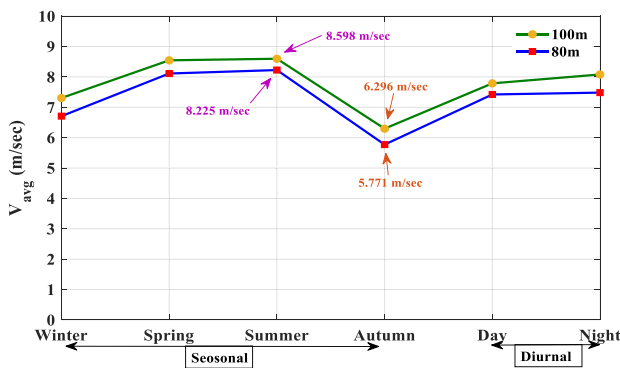


Fig. 8 Shows the seasonal, day and night time average wind speeds

m and the highest values 795.48 W/m² and 612.89 W/m² occurs in the month of May in 2016 and 2017. The highest value of 634.78 W/m² of 2018 in June. At the same time, the lowest values of WPD are 206.57 W/m² and 177.19 W/m² in Oct of 2016 and 2018. For the year 2017, the lowest value is 201.36 W/m² in Sept. The yearly average values for the year 2016, 2017 and 2018 are 417.76 W/m², 409.36 W/m² and 399.51 W/m², respectively. Moreover, the three years average WPD is 408.88 W/m². There is a prospect of more WPD in all months except Oct 2016 and 2018.

Similarly, wind energy density is also calculated. The monthly average wind energy densities are given in Fig. 10. From the results is found that the highest wind energy densities of 2016 and 2017 are 591.84 kWh/m² and 455.99 kWh/m², respectively. For the year 2018, it is 457.04 kWh/m² in Jun. Whereas the lowest monthly average energy densities for 2016 and 2018 are 153.68 kWh/m² and 131.83 kWh/m² in Oct. For 2017, the lowest energy density is 144.98 kWh/m² in Sept. The yearly average wind energy densities for 2016, 2017 and 2018 are 305.58 kWh/m², 299.2 kWh/m² and 292.54 kWh/m², respectively. The three years average energy density is 299.11 kWh/m².

3.4 Wind Rose Diagram

The wind rose diagram represents the percentage of wind speed according to its direction. Fig. 11 shows the wind rose diagrams of the proposed location. The wind dominates the west and south-west, As it is mostly in one direction. Hence the site is excellent with greater prospects of the wind energy. A wind turbine will rotate less and capture more wind energy.

3.5 Wind Speed Distribution Functions

Wind speed distribution (WSD) determines the percentage of wind speed recorded in the data set. The wind

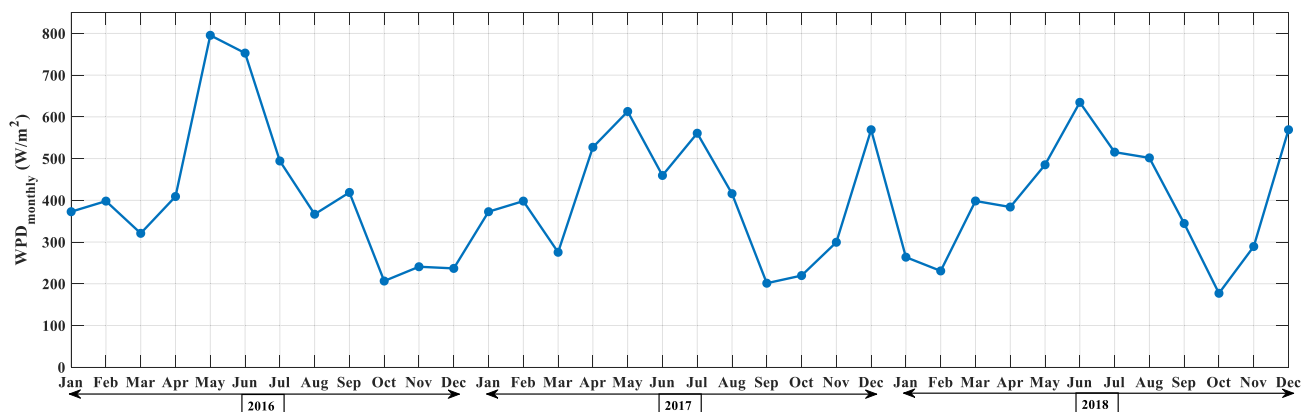


Fig. 9 The monthly average WPD (W/m²) for the hub height of 100 m

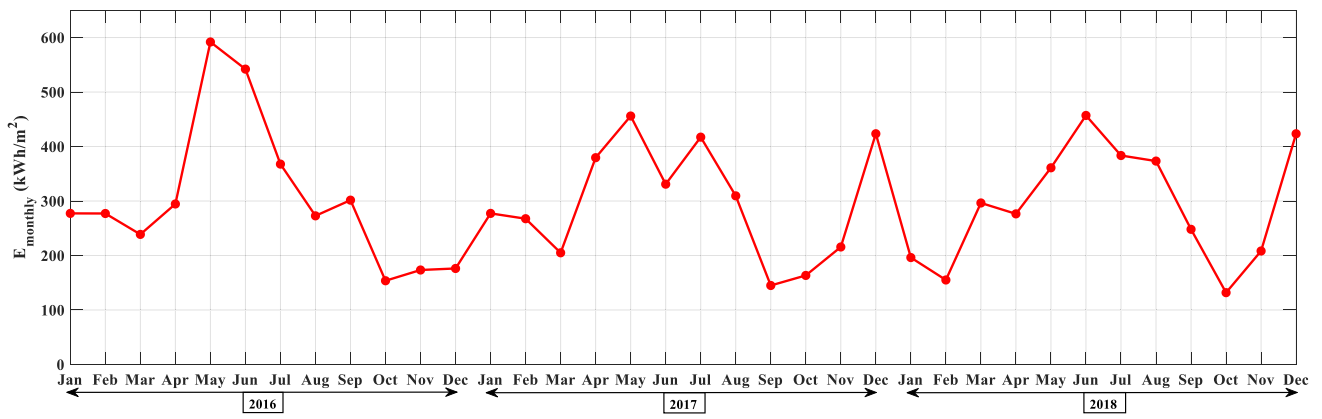


Fig. 10 The monthly average wind energy density (kWh/m²) for the hub height of 100 m

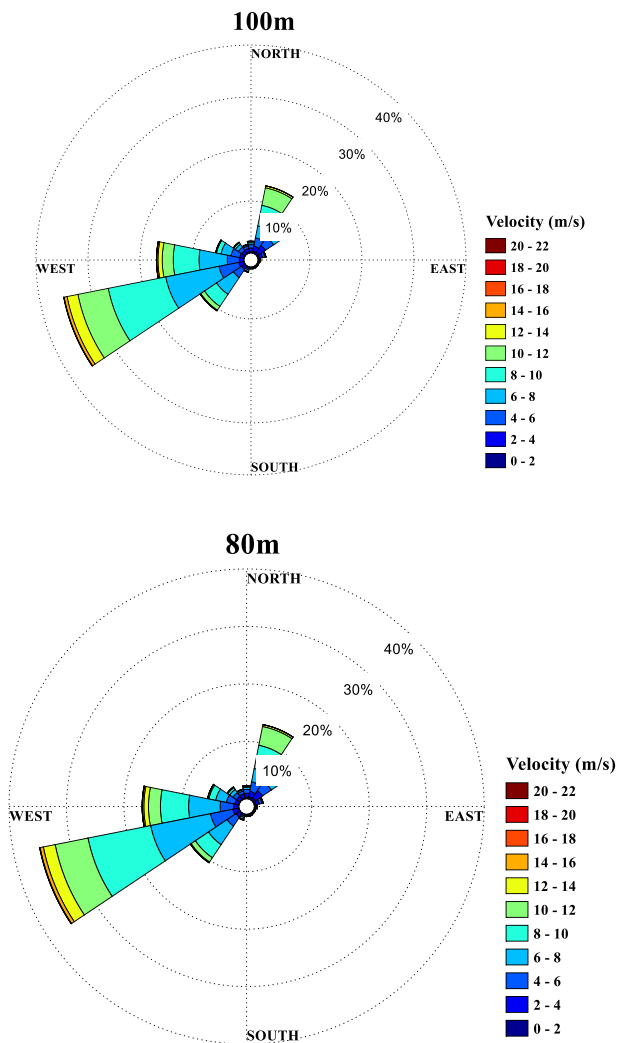


Fig. 11 Wind Rose diagrams for the hub heights of 100 m and 80 m

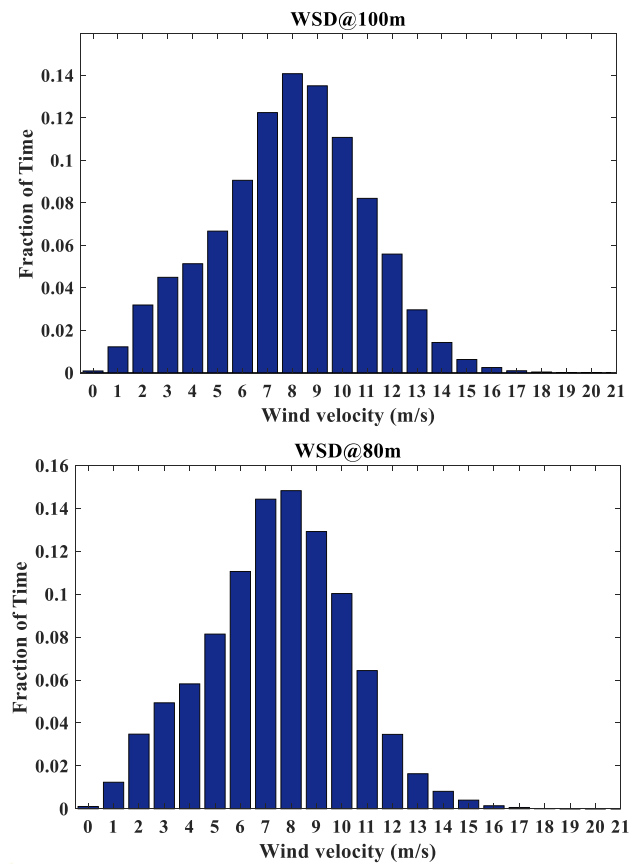


Fig. 12 Wind speed frequency diagram for the hub heights of 100 m and 80 m

speed, frequency shifted to higher wind velocities proposes higher WPD and wind energy density. Therefore, in Fig. 12, the WSD of the proposed site is shown, which has a higher WSD, and the proposed location has a greater possibility of higher WPD.

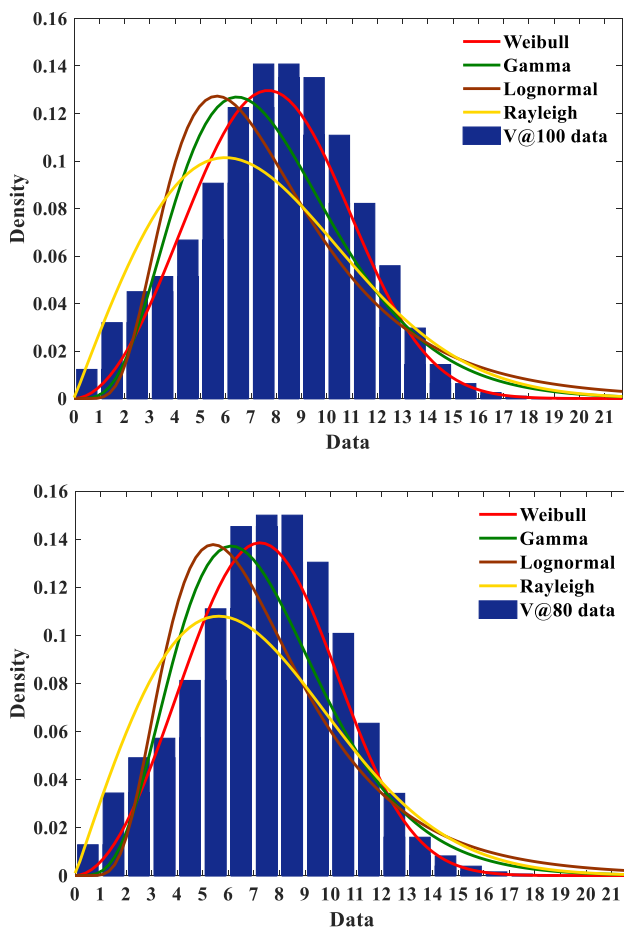


Fig. 13 Wind speed probability distribution functions for the hub heights of 100 m and 80 m

The probability and cumulative distribution functions of Rayleigh, Weibull, Gamma, and Lognormal distribution functions are provided in Figs. 13 and 14, respectively. The PDFs and CDFs are fitted over the measured data and provide the best proper distribution function. These curves help in the assessment and verification of the best distribution function to select for the wind resource estimation.

In this study, the Weibull PDF and CDF fitted best over the measured data, followed by Gamma, Rayleigh, and Lognormal distribution functions. The parameters of all distribution functions along with mean and variance are given in Table 2. In addition to this, the two performed goodness tests also revealed that the Weibull distribution function is best for the wind potential estimation. The details of RMSE and R^2 tests are provided in Table 3. Thus, the Weibull distribution is used to measure the wind characteristics for the power production of wind turbines.

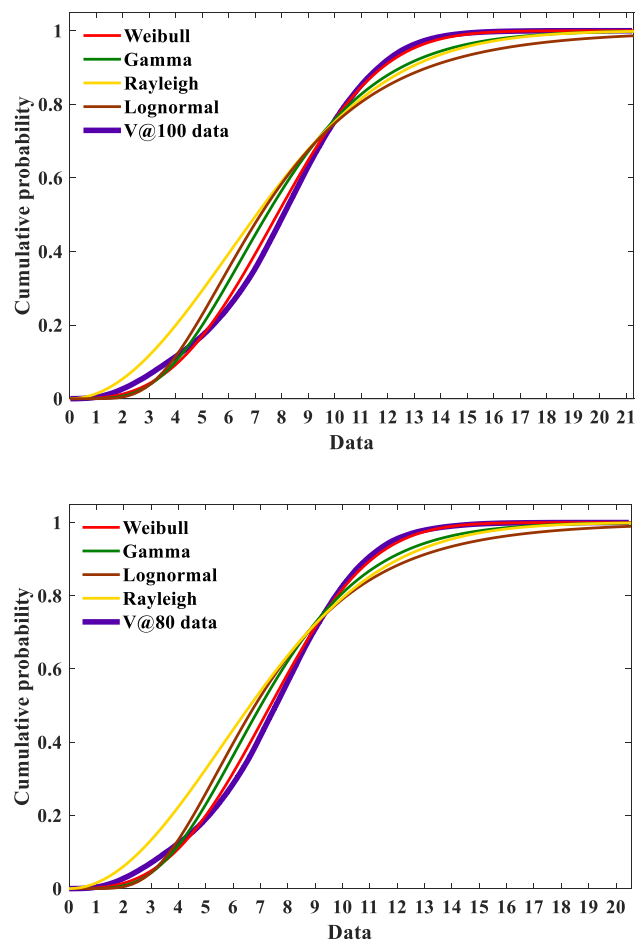


Fig. 14 Wind speed cumulative distribution functions for the hub heights of 100 m and 80 m

Table 2 Results of distribution functions

H_H (m)	DFs	Parameters		Mean	Variance
		A	B		
100	Weibull	8.8625	2.923	7.90527	8.64863
	Gamma	5.3688	1.4752	7.92017	11.684
	Rayleigh	5.9806	2	7.4956	15.351
	Lognormal	1.9734	0.49134	8.11821	17.9956
80	Weibull	8.3364	2.9372	7.43749	7.58916
	Gamma	5.5794	1.3353	7.45017	9.94819
	Rayleigh	5.6206	2	7.04439	13.5591
	Lognormal	1.9159	0.47801	7.61563	14.8887

3.6 Wind Turbine Energy Generation

In this work eight different wind turbines are considered with their CF (%) and AEP (GWh/year), system payback period (years), rate of return on investment (%), net present value (\$) and cost of energy generation (\$/kWh) calculated.

Table 3 The goodness of fit tests

H_H (m)	DFs	RMSE	R^2
100	Weibull	0.009616	0.958804
	Gamma	0.019599	0.828954
	Rayleigh	0.023782	0.755519
	Lognormal	0.026362	0.694169
80	Weibull	0.009339	0.965793
	Gamma	0.019455	0.852085
	Rayleigh	0.02485	0.766993
	Lognormal	0.026339	0.731335

The rating of the turbines to characterize technical as well as economic factors is given in Table 4. From the turbine models considered in this study, Fuhrlander LLC WTU 3.0-120, Siemens SWT-3.15-142, Nordex N131/3000 Delta, Senvion 3.0M122, FWT 120/3000, Vensys 120/3000, Enercon E-115 EP3 3.000 and Leitwind LTW101 3000 ranked highest to lowest from left to right. Fuhrlander LLC WTU 3.0-120, Siemens SWT-3.15-142, Nordex N131/3000 Delta, Senvion 3.0M122, FWT 120/3000, Vensys 120/3000, Enercon E-115 EP3 3.000, and Leitwind LTW101 3000, each has a capacity factor of 55.49%, 55.22%, 52.03%, 47.92%, 47.15%, 46.79%, 45.64% and 35.84%, respectively. Similarly, the cost of energy generation (1kWh) in USD (\$) by Fuhrlander LLC WTU 3.0-120, Siemens SWT-3.15-142, Nordex N131/3000 Delta, Senvion 3.0M122, FWT 120/3000, Vensys 120/3000, Enercon E-115 EP3 3.000, and Leitwind LTW101 3000 is \$0.04016, \$0.04035, \$0.04283, \$0.04650, \$0.04726, \$0.04763, \$0.04883, and \$0.06218, respectively. From the above analysis, it is clear that the highest capacity factor gives the lowest cost of energy generation and vice versa. Hence, all turbines considered in this study are feasible for the proposed site. Figure 15 shows the annual energy generation vs cost of units generated by each turbine with a hub height of 100 m.

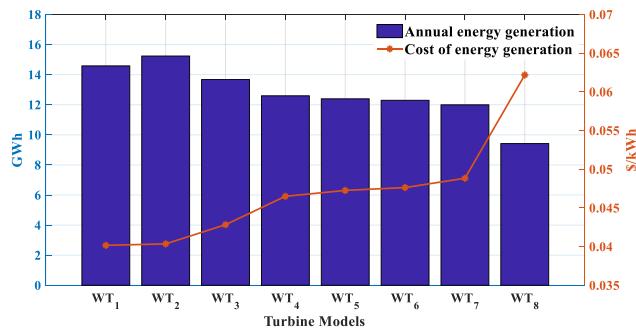


Fig. 15 Shows annual energy generation vs cost of unit generation by each turbine for the hub height of 100

4 Conclusion

Pakistan has a tremendous resource of wind energy in its Southern coastal belt stretching from the Sindh and Baluchistan provinces. In this paper, the techno-economic analysis is provided for the proposed site in a coastal region of Sindh province of Pakistan, and three-year wind data have been used for the wind resource estimation. For the technical purpose, four distribution functions are used, namely; the Weibull, Gamma, Rayleigh, and Lognormal. The statistical performance tests are performed to ensure the selection of the best distribution function. The estimation of wind potential is carried out on daily, monthly, yearly and seasonal basis. The economic analysis is done over eight turbines of different manufacturers. The results are summarized as below:

- The air pressure (ρ) and temperature (T) have an inverse relation. The three years’ average values are 1.1749 kg/m³ and 26.12 °C, respectively.
- From the diurnal analysis of wind data, it is observed that for the hub height of 100 m and 80 m, the mini-

Table 4 The rating of all turbines in terms of different technical and economic factors

Results	Wind Turbines							
	WT ₁	WT ₂	WT ₃	WT ₄	WT ₅	WT ₆	WT ₇	WT ₈
W_a (%)	95%	95%	95%	95%	95%	95%	95%	95%
TC_{ins} (\$)	\$4.5MM	\$4.7MM	\$4.5MM	\$4.5MM	\$4.5MM	\$4.5MM	\$4.5MM	\$4.5MM
P_D	10%	10%	10%	10%	10%	10%	10%	10%
\$/kWh	0.04016	0.04035	0.04283	0.04650	0.04726	0.04763	0.04883	0.06218
S_{pp} (years)	3	3	4	4	4	4	4	5
R_{Rate} (%)	37%	37%	35%	32	31%	31%	31%	24%
PV_{Net} (NPV)	\$58.85MM	\$61.48MM	\$54.9MM	\$50.21MM	\$49.34MM	\$48.92MM	\$47.60MM	\$36.41MM
AP_{Avg} (GWh)	14.582	15.238	13.673	12.593	12.392	12.295	11.993	9.418
C.F	55.49%	55.22%	52.03%	47.92%	47.15%	46.79%	45.64%	35.84%

mum wind speeds remained 7.23 m/s and 6.94 m/s during 10 am, and 6 am, respectively.

- At 100 m, the highest wind speeds for the three 2016 and 2017 are 10.54 m/s and 9.74 m/s in May, and for 2018 is 9.52 m/s in Jun. The three years mean wind speeds are 7.9 m/s and 7.4 m/s for heights of 100 m and 80 m, respectively.
- During the summer season and in the night time, there is an enormous potential for wind power density.
- The WSD is tilted to higher wind speeds, suggests greater WPD and ED.
- The WPD at 100 m, for 2016 and 2017 is highest (795.48 W/m² and 612.89 W/m²) in May, and for 2018 (634.78 W/m²) in Jun. The three year average is 408.88 W/m².
- Similarly, ED at 100 m, for 2016 and 2017, is highest (591.84 kWh/m² and 455.99kWh/m²) in May, respectively, for 2018 (457.04 kWh/m²) in Jun. The three year average is 299.11 kWh/m².
- Another factor like a wind rose diagram suggests that this site has a wind direction in between west and southwest direction. Hence the site is excellent in terms of wind rose characteristics.
- At 100 m and 80 m, the Weibull PDF and CDF fitted best over the measured data with shape (2.92 and 2.93) and scale (8.86 m/s and 8.33 m/s) parameters.
- From the turbine models, Fuhrlander LLC WTU 3.0–120 and Siemens SWT-3.15–142 have the highest CF, lowest cost of energy generation (\$0.04016 and \$0.04035), the shortest payback period and, highest annual energy generation.

From this study, it is observed that the site has prospects of higher wind power density and energy density. Weibull distribution function performed best as compared to other distribution functions. All turbines considered in this work give higher capacity factor and lower cost of energy generation and are feasible for the proposed site. As a result, eight turbine models used in this study show that this site has suitable technical and economic characteristics. It is evident that this site has a vast potential of wind energy generation, and commercial purposes wind farms can be installed there to meet Pakistan's energy demand.

Acknowledgements The paper is partly supported by State Grid Sichuan Economic Research Institute (SGSCJY00GH JS1900020). Data were obtained from the Pakistan Meteorological Department (PMD) under the Alternative Energy Development Board (AEDB) and the Energy Sector Management Assistance Program (ESMAP).

Declaration

Conflict of interest The authors declare no conflict of interest.

References

1. Keyhani A, Ghasemi-Varnamkhasti M, Khanali M, Abbaszadeh R (2010) An assessment of wind energy potential as a power generation source in the capital of Iran Tehran. *Energy* 35(1):188–201
2. Baloch MH, Chaudhary ST, Ishak D, Kaloi GS, Nadeem MH, Wattoo WA, Hamid HT (2019) Hybrid energy sources status of Pakistan: an optimal technical proposal to solve the power crises issues. *Energy Strat Rev* 24:132–153
3. Irfan M, Zhao ZY, Mukeshimana MC, Ahmad M (2019) Wind energy development in South Asia: Status, potential and policies. In: 2019 2nd international conference on computing, mathematics and engineering technologies (iCoMET). IEEE, pp 1–6
4. Mello MF, Santos EV, Falkembach MM, Pasqualli C, Siben M (2019) The importance of using alternative energy sources within a new global perspective. In: New global perspectives on industrial engineering and management. Springer, Cham, pp 21–29
5. Leung DY, Yang Y (2012) Wind energy development and its environmental impact: A review. *Renew Sustain Energy Rev* 16(1):1031–1039
6. Wang N, Li J, Hu W, Zhang B, Huang Q, Chen Z (2019) Optimal reactive power dispatch of a full-scale converter based wind farm considering loss minimization. *Renew Energy* 139:292–301
7. Wattoo WA, Kaloi GS, Yousif M, Baloch MH, Zardari BA, Arshad J, Tahir S (2020) An optimal asset allocation strategy for suppliers paying carbon tax in the competitive electricity market. *J Electr Eng Technol* 15(1):193–203
8. Baloch MH, Wang J, Kaloi GS, Memon AA, Larik AS, Sharma P (2019) Techno-economic analysis of power generation from a potential wind corridor of Pakistan: an overview. *Environ Prog Sustain Energy* 38(2):706–720
9. Hussain Baloch M, Ishak D, Tahir Chaudary S, Ali B, Asghar Memon A, Ahmed Jumani T (2019) Wind power integration: An experimental investigation for powering local communities. *Energies* 12(4):621
10. Jumani TA, Mustafa MW, Md Rasid M, Hussain Mirjat N, Hussain Baloch M, Salisu S (2019) Optimal power flow controller for grid-connected microgrids using a grasshopper optimization algorithm. *Electronics* 8(1):111
11. Gao X, Xia L, Lu L, Li Y (2019) Analysis of Hong Kong's wind energy: power potential, development constraints, and experiences from other countries for local wind energy promotion strategies. *Sustainability* 11(3):924
12. Kamran M, Fazal MR, Mudassar M (2020) Towards empowerment of the renewable energy sector in Pakistan for sustainable energy evolution: SWOT analysis. *Renew Energy* 146:543–558
13. Kamran M, Mudassar M, Abid I, Fazal MR, Ahmed SR, Abid MI, Anjum SH (2019) Reconsidering the power structure of Pakistan. *Int J Renew Energy Res* 9(1):480–492
14. Zhang B, Soltani M, Hu W, Hou P, Huang Q, Chen Z (2017) Optimized power dispatch in wind farms for power maximizing considering fatigue loads. *IEEE Trans Sustain Energy* 9(2):862–871
15. Paraschiv LS, Paraschiv S, Ion IV (2019) Investigation of wind power density distribution using Rayleigh probability density function. *Energy Procedia* 157:1546–1552
16. Jung C, Schindler D (2019) The role of air density in wind energy assessment—A case study from Germany. *Energy* 171:385–392
17. Lee JT, Kim HG, Kang YH, Kim JY (2019) Determining the optimized hub height of wind turbine using the wind resource map of South Korea. *Energies* 12(15):2949
18. Murthy KSR, Rahi OP (2019) Wind power density estimation using rayleigh probability distribution function. In: Applications of artificial intelligence techniques in engineering. Springer, Singapore, pp 265–275

19. Gorla RSR, Pallikonda MK, Walunj G (2020) Use of rayleigh distribution method for assessment of wind energy output in Cleveland-Ohio. *Renew Energy Res Appl* 1(1):11–18
20. Güvenç U, Kaymaz E (2019) Economic dispatch integrated wind power using coyote optimization algorithm. In: 2019 7th International Istanbul smart grids and cities congress and fair (ICSG), IEEE, pp 179–183
21. Aririguzo JC, Ekwe EB (2019) Weibull distribution analysis of wind energy prospect for Umudike, Nigeria for power generation. *Robot Comput Integr Manuf* 55:160–163
22. Kassem Y, Gökçekuş H, Zeitoun M (2019) Modeling of techno-economic assessment on wind energy potential at three selected coastal regions in Lebanon. *Model Earth Syst Environ* 5(3):1037–1049
23. Khan MA, Çamur H, Kassem Y (2019) Modeling predictive assessment of wind energy potential as a power generation sources at some selected locations in Pakistan. *Model Earth Syst Environ* 5(2):555–569
24. Shoaib M, Siddiqui I, Rehman SU (2019) Determination of yearly wind energy potential and extraction of wind energy using wind Turbine for coastal Cities of Baluchistan, Pakistan. *Int J Econ Environ Geol* 10(3):56–63
25. Hulio ZH, Jiang W, Rehman S (2019) Techno-economic assessment of wind power potential of Hawke's Bay using Weibull parameter: a review. *Energy Strategy Rev* 26:100375
26. Saeed MK, Salam A, Rehman AU, Saeed MA (2019) Comparison of six different methods of Weibull distribution for wind power assessment: a case study for a site in the Northern region of Pakistan. *Sustain Energy Technol Assessm* 36:100541
27. [Data] "World Bank via ENERGYDATA.info, under a project funded by the Energy Sector Management Assistance Program (ESMAP).
28. Carta JA, Ramirez P, Velazquez S (2009) A review of wind speed probability distributions used in wind energy analysis: case studies in the Canary Islands. *Renew Sustain Energy Rev* 13(5):933–955
29. Ouarda TB, Charron C, Shin JY, Marpu PR, Al-Mandoos AH, Al-Tamimi MH, Al Hosary TN (2015) Probability distributions of wind speed in the UAE. *Energy Convers Manage* 93:414–434
30. Ali S, Lee SM, Jang CM (2018) Statistical analysis of wind characteristics using Weibull and Rayleigh distributions in Deokjeokdo Island-Incheon, South Korea. *Renew Energy* 123:652–663
31. Audu MO, Terwase AS, Isikwue BC (2019) Investigation of wind speed characteristics and its energy potential in Makurdi, north central Nigeria. *SN Appl Sci* 1(2):178
32. Mohammadi K, Alavi O, Mostafaeipour A, Goudarzi N, Jalilvand M (2016) Assessing different parameters estimation methods of Weibull distribution to compute wind power density. *Energy Convers Manage* 108:322–335
33. Mohsin M, Zhang J, Saidur R, Sun H, Sait SM (2019) Economic assessment and ranking of wind power potential using fuzzy-TOPSIS approach. *Environ Sci Pollut Res* 26(22):22494–22511
34. Mohammadi K, Mostafaeipour A, Sedaghat A, Shamshirband S, Petković D (2016) Application and economic viability of wind turbine installation in Lutak Iran. *Environ Earth Sci* 75(3):248
35. Masseran N, Razali AM, Ibrahim K (2012) An analysis of wind power density derived from several wind speed density functions: The regional assessment on wind power in Malaysia. *Renew Sustain Energy Rev* 16(8):6476–6487
36. Signe EBK, Kanmogne A, Emmanuel GD, Meva'a L (2019) Comparison of seven numerical methods for determining Weibull parameters of wind for sustainable energy in Douala, Cameroon. *Int J Energy Sector Manage*
37. Rocha PAC, de Sousa RC, de Andrade CF, da Silva MEV (2012) Comparison of seven numerical methods for determining Weibull parameters for wind energy generation in the northeast region of Brazil. *Appl Energy* 89(1):395–400
38. Mirhosseini M, Sharifi F, Sedaghat A (2011) Assessing the wind energy potential locations in province of Semnan in Iran. *Renew Sustain Energy Rev* 15(1):449–459
39. Mostafaeipour A (2010) Feasibility study of offshore wind turbine installation in Iran compared with the world. *Renew Sustain Energy Rev* 14(7):1722–1743
40. Samal RK, Tripathy M (2019) Estimating wind speed probability distribution based on measured data at Burla in Odisha, India. *Energy Sour Part A Recovery Utiliz Environ Effects* 41(8):918–930
41. Morgan EC, Lackner M, Vogel RM, Baise LG (2011) Probability distributions for offshore wind speeds. *Energy Convers Manage* 52(1):15–26
42. Hu R, Hu W, Gökmen N, Li P, Huang Q, Chen Z (2019) High resolution wind speed forecasting based on wavelet decomposed phase space reconstruction and self-organizing map. *Renewable Energy* 140:17–31
43. Chaurasiya PK, Kumar VK, Warudkar V, Ahmed S (2019) Evaluation of wind energy potential and estimation of wind turbine characteristics for two different sites. *Int J Ambient Energy*, pp 1–11
44. Kollu R, Rayapudi SR, Narasimham SVL, Pakkurthi KM (2012) Mixture probability distribution functions to model wind speed distributions. *Int J Energy Environ Eng* 3(1):27
45. Yu J, Fu Y, Yu Y, Wu S, Wu Y, You M, Li M (2019) Assessment of offshore wind characteristics and wind energy potential in Bohai Bay China. *Energies* 12(15):2879
46. Walia S, Sandhu KS (2019) Capacity factor of wind turbine system based on different power curves and Weibull distribution parameters. In: 2019 3rd international conference on computing methodologies and communication (ICCMC). IEEE, pp 1135–1138
47. Chang TP (2011) Estimation of wind energy potential using different probability density functions. *Appl Energy* 88(5):1848–1856
48. Li C, Liu Y, Li G, Li J, Zhu D, Jia W, Zhai X (2016) Evaluation of wind energy resource and wind turbine characteristics at two locations in China. *Technol Soc* 47:121–128

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Kalsoom Bhagat was born in Sindh Province, Pakistan. She received her B.E. degree in Electrical Engineering at Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh Province, Pakistan in 2010. She received her M.E. degree in Electrical Power Engineering at Mehran University of Engineering and Technology, Jamshoro, Sindh Province, Pakistan. She is doing Ph.D. in School of Electrical Engineering at Southwest Jiaotong University Chengdu, Sichuan, China since 2018. Currently she is Faculty Lecturer in Department of Electrical Engineering at MUET Shaheed Zulfiqar Ali Bhutto Campus Khairpur Mir's, Sindh Province, Pakistan. Her research interests include power electronics, power converters, power quality, hybrid renewable energy sources integration, energy storage devices, power system planning and operation optimization.



Shengyong Ye was born in China. He received the Ph.D. degree in 2010 in Electrical Engineering from Southwest Jiaotong University, Chengdu, Sichuan, China. He is now with State Grid Sichuan Economic Research Institute of State Grid Sichuan Power Company, Chengdu 610041, China. (Email: 1060584738@qq.com). His research interests include distribution system design and planning.



Jingru Lian was born in Shanxi Province, China, in 1989. She received her B.S. degree in Electrical Engineering and Automation from Kunming University of Science and Technology, Kunming, China, in 2012. She received her M.S. degree in Control Engineering from University of Electronic Science and Technology of China, Chengdu, China, in 2015. Her current research interest is new energy for rail transit.



Chaohua Dai received his Ph.D. degree in Electrical System Control and Information Technology from Southwest Jiaotong University in 2009, Chengdu, Sichuan, China. Currently, he is an Associate Professor and Doctoral Supervisor in the School of Electrical Engineering, Southwest Jiaotong University, and a candidate of Sichuan Academic Technology Leader. His research interests include new energies in traction power supply system, hydral & new energy vehicles, power system planning and operation optimization.

He has published nearly 100 refereed journal and conference papers, 3 books, and is the holder of more than 40 Chinese patents.



M. Zubair Bhayo was born in Sindh Province, Pakistan. He received his B.E. degree in Electrical Engineering at Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh Province, Pakistan in 2013. He received his M.E. degree in Electrical Power Engineering at Mehran University of Engineering and Technology, Jamshoro, Sindh Province, Pakistan. He is doing Ph.D. in School of Mechanical and Electrical Engineering at University of Electronic Science and Technology

Chengdu, China since 2019. His research interest is high voltage insulation, power system protection, optimal planning and operation of hybrid renewable energy sources, micro grid, and hybrid renewable energy sources integration.