



# A techno-economic analysis for power generation through wind energy: A case study of Pakistan



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## ABSTRACT

Pakistan needs to overcome the cost of power generation and the ever-increasing demand for energy with environment-friendly renewable energy resources. Several research efforts have been made with the support of Pakistan Meteorological Department in the last two decades for wind resource assessment (WRA) across the country. However, the practical installation of wind farms is quite a fraction of the total forecast wind energy potential. In this feasibility, WRA of Umerkot and Sujawal districts located in Sindh provinces of Pakistan has been analyzed by analyzing mean wind speeds, estimated Weibull parameters, power and energy densities calculation for various heights of selected wind turbines. Further, this paper analyzes the overall energy potential for these locations with implementation cost and pay-back period for investment. These locations are selected by the World Bank initiative of wind profiling campaigns to record wind speed data during 2016 and 2018 with 10 min resolution. It is observed that Umerkot and Sujawal sites are suitable for energy production. The highest values of power and energy densities for Sujawal are 414.18 W/m<sup>2</sup> and 3628.22 kWh/m<sup>2</sup>/Yr and for Umerkot these values are 303.86 W/m<sup>2</sup> and 2661.81 kWh/m<sup>2</sup>/Yr. The results indicate that using Nordex N90/2500 wind turbines are highly beneficial for Umerkot and Sujawal. The associated costs of energy are 0.074 \$/kWh and 0.056 \$/kWh respectively and the payback period is estimated to be around 7 years with 20 years life time of the project. This work suggests the possibility of wind farm installation and commissioning based on power density calculation and cost of land acquisition. This work emphasizes the investment for wind farms at Sujawal and Umerkot for the sustainable growth of the country. This helps out policymakers for long term planning, development of wind energy projects and attracting investment for the country.

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## 1. Introduction

Global sustainable development is heavily dependent on annual energy production (AEP) which is expected to reach three times its current value by 2050 (Kalogirou, 2004) particularly for the rapid economic growth of countries like China and India (Kaygusuz, 2012; Black et al., 2015). The per capita energy consumption is influenced by the demographic conditions of any region and escalates by time. The gap in annual energy yield consumes millions of barrels of oil equivalent (BOE) and hence contributing to the greenhouse effect and global warming. This situation is severe in developing and third world countries for

their rapid increase in population and scarcity of fossil fuel resources with time. The affected countries mostly lie in Africa and Asia that cannot afford the increasing budget of importing fossil fuels. This results in a worldwide paradigm shift to green energy harnessing from renewable resources (Mohammadi et al., 2016). For economical growth and reduced dependency over fossil fuel, Pakistan which is situated in South Asia is also paying high attention to environment-friendly distributed renewable energy (DRE) generation and its integration with the national grid. Alternate Energy Development Board (AEDB) of Pakistan has an upfront task to encourage local and foreign investment for DRE generation. The building of micro-hydro dams, solar and wind power plants in KPK, Punjab, and Sindh provinces respectively are the result of this focus. The DRE generation depends on the geographical location of a particular site and its feasibility for solar, wind, micro-hydro, biomass power plants, or hybrid generation. World Bank (WB) has collected wind speed/direction and solar irradiation data of specific sites that are selected based on

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## Nomenclature

GM	Graphical Method.
RMSE	Root Mean Square Error
R	Correlation Coefficient
MAPE	Mean Absolute Percentage Error
RRMSE	Relative Root Mean Square Error
k	shape parameter of Weibull distribution
c	scale parameter of Weibull distribution (m/s)
EPF	Energy Pattern Factor
EM	empirical method
MLE	maximum likelihood estimate
PD	power density
v	wind speed (m/s)
T	number of observations
F(v)	cumulative distribution function
f(v)	Weibull, probability density function
$\rho$	density of surrounding air (kg/m <sup>3</sup> )
$\Gamma$	gamma function
r	inflation rate
n	No of years

satellite images and resource mapping. Pakistan Meteorological Department(PMD)also provides this data through Climate Data Processing Center (CDPC). However, in this feasibility, WB data is used for WRA of the two selected sites from among twelve sites.

Global wind energy installed capacity is 597GW (Jacobson et al., 2017; Söderholm et al., 2011). At the moment, total wind power capacity installed in Pakistan is 287MW, while 306MW wind power projects are in the development and planning phase (Baloch et al., 2016). However, Pakistan has a wind power potential of around 174 GW (Shami et al., 2016) whereas the AEP of two provinces Sindh and Balochistan amounts to 7.653 GWh, and 5.456 GWh respectively (Baloch et al., 2017). Wind energy inherits an intermittent nature and wind turbine (WT) output power is proportional to the cube of wind speed. Wind speed variations cause large fluctuations in the output power of WT. However adopting suitable WT technologies can compensate these variations of wind speeds and provide tight voltage, frequency, and power regulation before it is fed to utility grid using step-up transformers and power electronics-based AC-DC and DC-AC converters. For economic dispatch and deployment of such wind energy-based projects require precise WRA by taking into account stochastic wind speed patterns. It is reported in the literature that a good wind regime with probably 6 – 8 m/s wind speeds helps achieve economic objectives of wind farm realizations and installations (Murthy and Rahi, 2017).

## 2. Related work

Pakistan is bordered by the Arabian Sea to the south, Iran, and Afghanistan to the west, India to the east and China to the north. Pakistan is situated in southern Asia at 30.3753°N, 69.3451°E with a population density 287 per sq. km and overall population of 207 million (2017, PBS (Hassan, 2019)). The four provinces of Pakistan are Punjab, Khyber-Pakhtunkhwa (KPK), Sindh, and Balochistan. Punjab has 56% of the country's total population facing energy crisis while KPK, now includes the federally administered tribal area (FATA), has 12% residents of Pakistan. The KPK has diverse demographic conditions and terrain. The diverse

climatic condition of KPK makes it feasible for hybrid solar–wind–hydro power systems and small-scale wind turbines. KPK having demography with low population density uses an off-grid power system such as a micro-hydro and Photovoltaic (PV) system for lighting and water pumping. These projects are supported by the Pakistan Poverty Alleviation Fund (PPAF) and German development bank, KfW. Sindh spanned over an area of 140,914 sq. km with its capital in Karachi that is a metropolitan city and commercial hub of Pakistan. Balochistan occupies 44% of the country's land spread over 347,190 sq. km approximately. Topographically, Balochistan has a large plateau with rough terrain separated by basins of sufficient heights and ruggedness. Balochistan has four different types of terrains that spanned over upper and lower plateaus, deserts, and plain land. Balochistan has a low population density facing water shortage in most areas. Notably, Balochistan has two wind corridors feasible for wind farms. These are at least 50% more power efficient compared to Gharo in Sindh province but their potential needs to be explored. Mainly, wind power projects are developed in Sindh province at Jhampir and Gharo. A 49.5 MW wind power project is developed in Jhampir by Fauji Fertilizer Energy Company Limited with the cooperation of Nordex and Descon Engineering Limited. Three Gorges is also planning for two 50 MW projects in Jhampir, Sindh (Siddique and Wazir, 2016; Baloch et al., 2019, 2016). Sindh province has a total wind power installed capacity of about 935 MW (Ahmed et al., 2019).

Pakistan can import electricity from Central Asian states having surplus energy. Central Asian countries like Turkmenistan and Uzbekistan are enriched with fossil fuels and hence produce electricity at a very low cost. That energy can be utilized in Pakistan and common neighbor Afghanistan to meet the energy crisis. Along with electricity, these Central-Asian states are looking for market access to their fossil fuels which can also be met by energy export by producing less-expensive energy generation through fossil fuels. On the other hand, consuming fossil fuels has an adverse impact on the environment so to exploit the wind energy potential of these countries has paramount importance. The hybrid energy generation will reduce the requirement of fossil fuel without affecting energy exports.

In Arian et al. (2019b), the techno-economic feasibility of wind energy production is determined for eighteen sites located in Turkmenistan. The paper depicts that the range of power and energy densities in Turkmenistan lies between 35.88 – 222.12 W/m<sup>2</sup> and 314.27 – 1948.79 kWh/m<sup>2</sup> respectively and based on Goldwind GW 140/3.0, a large scale wind turbine, the AEP is 11.9 GWh/yr. The Levelized Cost of Energy (LCOE) reaches 0.0435 – 0.0893 USD/kWh which is quite above comparing the current energy price in Turkmenistan of 0.005 USD/kWh. But it helps Turkmenistan in energy export through 500 kV transmission lines to Pakistan through Afghanistan. A TAP (Turkmenistan–Afghanistan–Pakistan) transmission line project is already in the construction phase along with the Turkmenistan–Afghanistan–Pakistan–India (TAPI) gas pipeline project for gas to electricity generation.

A similar study has been conducted for Uzbekistan (Arian et al., 2019a) for the first time to investigate the potential of wind energy for seventeen sites. The results show that the average annual wind speed, power density, and energy production are in the range between 0.61 and 3.98 m/s, 1.74 – 88.55 W/m<sup>2</sup>, and 15.27 – 775.72 kWh/m<sup>2</sup>, respectively at a height of 10 m above the ground. It is observed that Nukus, Kungrad, Ak Bajtal, and Buhara are the best sites for wind energy development in Uzbekistan.

Iran is another neighbor of Pakistan enriched with fossil fuel that can also exploit wind energy. In Amir et al. (2019), another techno-economic feasibility of Lotak and Shandol of the Sistan-Balochestan province of Iran is presented. According to this study,

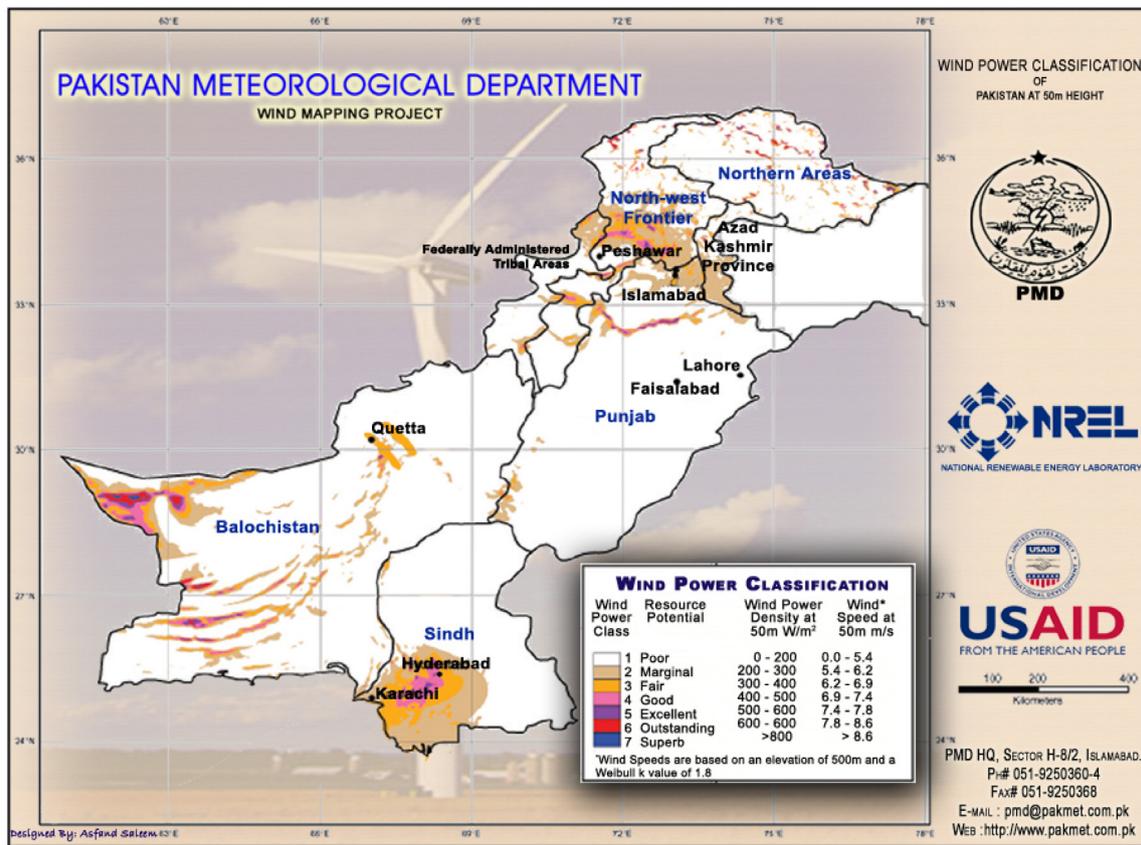


Fig. 1. Wind resource potential of Pakistan.

maximum seasonal wind speed occurs in summer for Lotak and Shandol which are 10.37 m/s and 9.34 m/s respectively. The highest energy densities of Lotak and Shandol are 797.37 and 834.90 kWh/m<sup>2</sup>. Dongfang DF100 wind turbine achieves the highest AEP of 13,249 and 12,498 GWh/yr respectively for the two cities and the LCOE is 0.0830 and 0.0786 USD/kWh. In 2016, Baloch et al. performed a wind speed analysis of Zarrineh, Iran (Mohammadi and Mostafaeipour, 2013). The measured mean wind power and yearly mean wind speed are 161.44 W/m<sup>2</sup> and 4.07 m/s respectively. Due to below-average wind regime that site is suitable for installation of small wind turbines.

Wind power potential is also estimated in Chandel et al. (2014) for twelve sites in Western Himalaya, India indicating good wind resources for roof-top micro-wind turbines, battery charging, water pumping and wind power generation.

In Ali and Jang (2020) techno-economic optimum design of a small hybrid renewable energy system (HRES) consisting of wind-solar primary sources of energy with battery and pumped hydro storage (PHS) for secondary power was carried out for Deokjeokdo Island, Korea. LCOE and net present cost (NPC) of the system was estimated by varying the values of input variables such as discount rate, project lifetime and daily load. A hybrid PV-wind-diesel-battery bank system was proposed in Al-Shamma'a and Addoweesh (2014) to evaluate the techno-economic prospective of the hybrid energy system to meet the load demand of a remote village in the northern part of Saudi Arabia. The situation of renewable energy projects in Pakistan is improving since the last decade.

Although there are quite a few studies in the open literature that have discussed the wind power potential of selected areas in Sindh, Pakistan (Ullah et al., 2010; Mirza et al., 2010; Shoaib et al., 2017), however, translation of this research into practical application needs to consider the wind power estimation, production

capacity, infrastructure for wind-power to utility grid integration, economic and technical aspects have never been presented together. The main thrust behind the current research is to estimate wind power density for two locations selected by WB namely, Umerkot and Sujawal situated in the Sindh area of Pakistan. The article has proposed three different wind turbine technologies of DeWind D4, DeWind D6, and Nordex N90 with their different rated powers and power-wind speed characteristics. These turbines can be installed at 40 m, 60 m, and 80 m heights. The main contribution of this study is that it was the first time that such a study was conducted to estimate Weibull parameters. The paper will serve as a benchmark for developing countries with similar renewable resources for electric power generation.

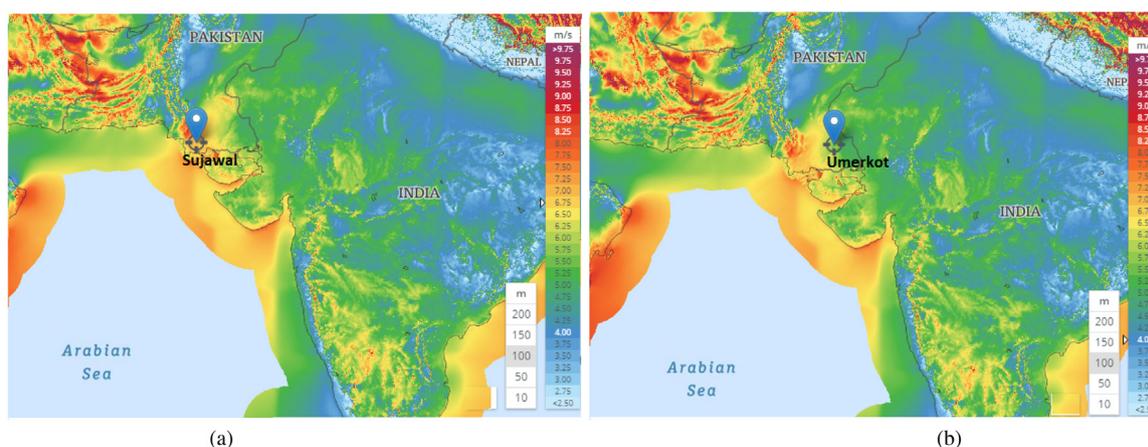
The key contributions of this paper are therefore summarized below.

- Weibull parameter estimation of selected sites of Pakistan
- Wind power density and energy density estimates for selected sites
- Wind turbine recommendation for selected sites
- Estimates of levelized cost of energy
- Payback period calculation for selected wind turbines

The paper organization is as follows. Section 3 provides detail of selected sites with wind energy potential. Section 4 provides a detailed research methodology adopted in this work. Section 5 outlines the detail of economic assessment for the integration of wind turbine technology with grid evaluating the cost of energy and payback period for wind turbine installations at selected sites. Discussion on results is provided in Section 6 and we conclude in Section 7.

**Table 1**  
Geographical location and duration of site data.

Site	Longitude	Latitude	Province	Total recorded data	Data period
Umerkot	69° 34' 13.22" E	25° 5' 1.75" N	Sindh	65219	8/2016–10/2017
Sujawal	68° 11' 18.50" E	24° 31' 25.15" N	Sindh	85743	3/2016–10/2017



**Fig. 2.** Map of (a) Sujawal (b) Umerkot. This map is printed using the Global Wind Atlas online application website (v.3.0) owned by the Technical University of Denmark. Please visit <https://globalwindatlas.info>.

### 3. Wind speed data

World Bank and Alternate Energy Development board (AEDB) of Pakistan are implementing Renewable Energy Mapping Project based on analysis of satellite data (2000 – 2010) and existing ground data which indicates good wind regime in the country as shown in Fig. 1 (Siddique and Wazir, 2016).

The World Bank in collaboration with AEDB have identified twelve sites where wind masts are installed in different areas in the province of Khyber Pakhtunkhwa, Punjab, Balochistan and Sindh. Among these, eleven are elevated at the height of 80m and one at the height of 67m located in Quetta city, capital of Balochistan province. According to National Renewable Energy Laboratory (NREL), USA wind resource mapping for Pakistan, wind speeds can be classified according to Fig. 1. Using this classification, it is easy to assess the wind regime of different parts of Pakistan by considering one year period for data analysis for all the sites. In this study, based on the time series wind speed data, only two sites in Sindh province are considered for analysis. The geographical details and periods during which wind speed data were recorded for selected sites are tabulated in Table 1. Location of these two sites are shown on the map in Fig. 2. Time series data of these sites with 10 min resolution has been converted to monthly and daily average wind speeds at heights of 20 m, 40 m, 60 m and 80 m.

### 4. Analysis methodology for wind potential assessment

International focus on wind energy growth expands the world wide trend of WRA of different locations. WB and Denmark Technical University (DTU) have jointly developed the online application software for global WRA namely Global Wind Atlas that helps policy makers and developers to select the particular site. Further, DTU proprietary software WAsP is available for both academic and commercial purpose that helps in analyzing wind data and estimating energy output. But in literature statistical models are developed for describing wind frequency distribution that represent wind potential. Some of these models include the Weibull, Rayleigh, Gamma, Beta, Log-Normal and Logistic functions. These methods help to estimate the total yield of a

wind energy conversion system (WECS). The actual wind data distribution are matched with statistical models to find a best fit. Difficulty arises in choosing the best model that fits the wind speed distribution accurately. The wind speed frequency distribution reflects the seasonal variation throughout the year as data taken spans more than a year. The suitability of selected method depends on data sample size, data location, format of sample data, distribution of sample data and statistical judgment criterion. The Weibull probability density function (PDF) characterized these variation and most commonly used to find a fit with actual wind distribution (Chang, 2011; Carta et al., 2008; Ulgen and Hepbasli, 2002) with two parameters namely shape parameter  $k$  and scale parameter  $c$ . The parameters of Weibull distribution are estimated using methods such as Maximum Likelihood Method (MLM), Modified Maximum Likelihood Method (MMLM), Method of Moments (MOM), Graphical Method (GM), Empirical Method (EM), Power Density Method (PDM) etc. In Akdağ and Dinler (2009), the PDM method has been preferred for easy formulation instead of binning and solving linear least square problem or an iterative procedure. In Teimouri et al. (2013) an L-moment estimator is proposed for the Weibull distribution and performed its comparison with other methods. In Chang (2011), Tian Pau Chang has compared the performance of six numerical methods for estimating Weibull parameters. The goodness of fit test is performed to test the accuracy of the parameter estimated for the Weibull PDF and actual wind speed distribution. Chang used Kolmogorov–Smirnov test, parameter error, root mean square error, and wind energy error method to check the goodness of fit. On the basis of this test, the author mentioned that graphical method is the worst one, followed by the empirical and energy pattern factor (EPF) methods. It can be inferred that any method is applicable if actual distribution matches with Weibull pdf otherwise MLM performs the best.

The Weibull parameters help in estimating the power density and output power. Apart from that, mean wind speed (daily, monthly and yearly) and its standard deviation, skewness and kurtosis helps in determining the electricity generated by wind turbine generator system.

In this feasibility, four parameter estimation techniques of Weibull distribution are compared to find a best fit with the

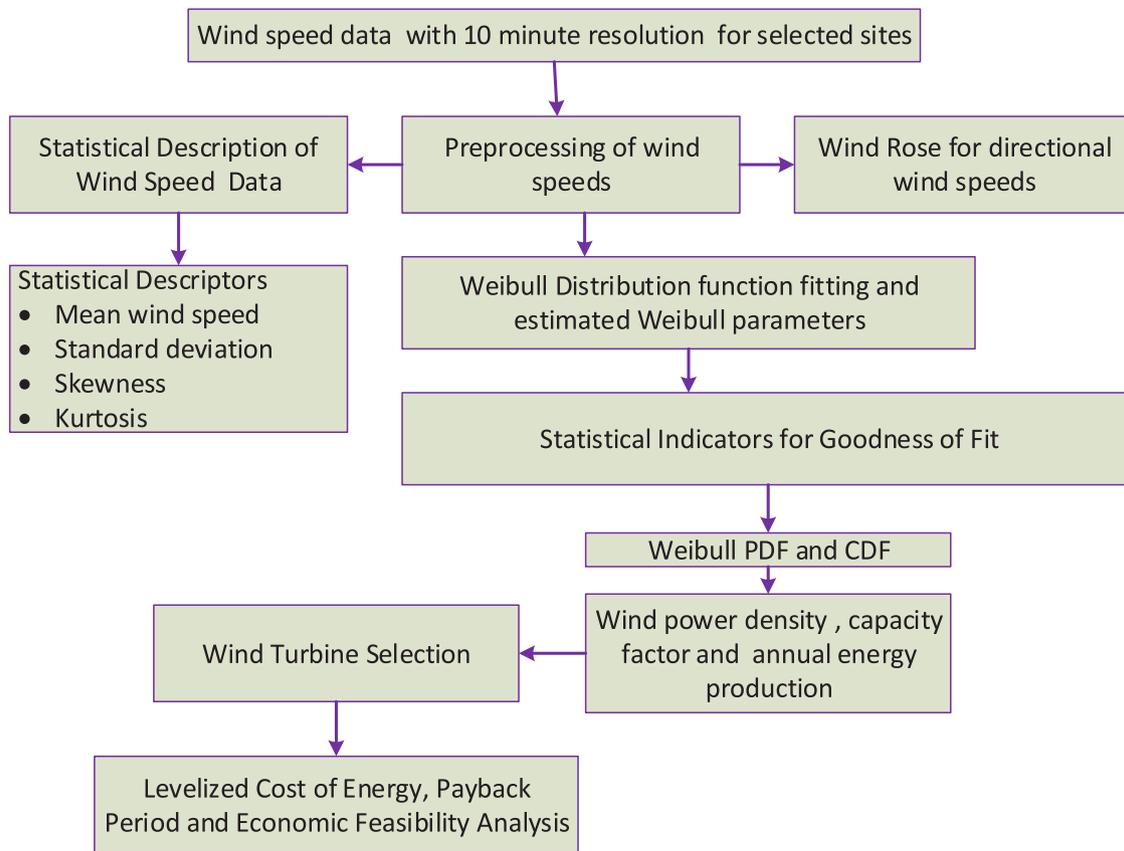


Fig. 3. Flow chart of research methodology.

actual data of two sites namely Sujawal and Umerkot. The results from the Weibull PDF function are used for the estimation of annual energy generated by wind turbines. The annual energy estimate is then used for calculation of feasible energy cost per kilowatt hour(kWh) for selected wind turbine. The overall research methodology adopted is depicted in a flowchart as shown in Fig. 3.

#### 4.1. Wind speed characteristics

The two statistical estimators (Third and Fourth moment) help to investigate the distribution pattern of wind time series named as skewness and kurtosis. Their expressions are mentioned in Wang et al. (2018);

$$skewness = \frac{1}{T-1} \sum_{i=1}^T \frac{(v_i - \bar{v})^3}{\sigma^3} \quad (1)$$

$$kurtosis = \frac{1}{T-1} \sum_{i=1}^T \frac{(v_i - \bar{v})^4}{\sigma^4} - 3 \quad (2)$$

where  $v_i$  is wind speed (m/s) at  $i$ th observation,  $\bar{v}$  is the mean wind speed,  $\sigma$  is the standard deviation of wind speed, skewness describes the symmetry of wind data and subsequently kurtosis depicts the increased degree of wind data. Further, zero skewness indicates that the distribution pattern of the wind time series is highly symmetric and increasing the absolute skewness reflects increasing skewness of wind time series. When kurtosis is zero, the wind series is in line with the standard normal distribution and positive value of kurtosis indicates its deviation from the normal distribution. The listed values for wind speed characteristics are shown in Table 2.

#### 4.2. Weibull parameter estimation

The Weibull PDF,  $f(v)$  to find the actual wind data fit is shown in (3).

$$f(v) = \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} \exp\left(-\frac{v}{c}\right)^k \quad (3)$$

Here  $c$  is the scale parameter and  $k$  is the shape factor. Several numerical methods (Carrillo et al., 2014; Werapun et al., 2015; Kaplan, 2017) can be used to estimate these two Weibull parameters using wind speed data. In this study graphical method (GM), empirical method (EM), energy pattern factor (EPF) method and maximum likelihood estimate (MLE) are used for analysis.

##### 4.2.1. Graphical method (GM)

The cumulative distribution function(CDF),  $F(v)$  is given by (4).

$$F(v) = 1 - \exp\left(-\frac{v}{c}\right)^k \quad (4)$$

Taking natural logarithms twice using graphical method (5) that is linear with the Weibull pdf parameters to be fit. The Weibull pdf parameters are therefore calculated from a plot of  $\ln(v)$  versus  $\ln[-\ln\{1 - F(v_i)\}]$ . In this plot shape parameter  $k$  equals the slope, and the scale parameter  $c$  is obtained from the intercept with  $y$ -axis.

$$\ln[-\ln\{1 - F(v_i)\}] = -k \ln c + k \ln v_i \quad (5)$$

##### 4.2.2. Empirical method (EM)

This method is firstly proposed by Justus et al. (1978) and hence called Justus Empirical method. Later, several empirical approaches are proposed in literature. For the empirical method

**Table 2**  
Wind characteristics for selected sites.

Site	Height	Mean speed (m/s)	std. (m/s)	Skewness	Kurtosis
Umerkot	20 m	4.70	2.46	0.58	2.85
	40 m	5.40	2.59	0.43	2.85
	60 m	5.99	2.80	0.32	2.88
	80 m	6.38	3.01	0.22	2.66
Sujawal	20 m	5.81	2.67	0.43	2.70
	40 m	6.65	2.84	0.35	2.82
	60 m	7.18	2.97	0.23	2.79
	80 m	7.56	3.21	0.13	2.57

$k$  and  $c$  are calculated by (6) and (7) respectively. The gamma function is defined by (8).

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \tag{6}$$

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

$$\Gamma(X) = \int_0^\infty t^{X-1} e^{-t} dt \tag{8}$$

4.2.3. Energy pattern factor (EPF) method

This method is proposed in Akdağ and Dinler (2009), and is calculated by (9).

$$E_{pf} = \left(\frac{\bar{v}^3}{\bar{v}^3}\right) \tag{9}$$

$k$  parameter calculated by EPF method is given below and  $c$  parameter is given by (7).

$$k = 1 + \left(\frac{3.69}{(E_{pf})^2}\right) \tag{10}$$

4.2.4. Maximum likelihood estimate (MLE)

MLE methods is used when  $k$  and  $c$  parameter calculated for Weibull function from other methods does not fit with actual time series of wind data. MLE method used numerical iterations with likelihood function of the time series to calculate the best fit. The shape parameter  $k$  and the scale parameter  $c$  are estimated using (11) and (12) mentioned in Chaurasiya et al. (2018).

$$k = \left(\frac{\sum_{i=1}^T v_i^k \ln(v_i)}{\sum_{i=1}^T v_i^k} - \frac{\sum_{i=1}^T \ln(v_i)}{T}\right)^{-1} \tag{11}$$

$$c = \left(\frac{1}{T} \sum_{i=1}^T v_i^k\right)^{\frac{1}{k}} \tag{12}$$

where  $v_i$  is the wind speed in time step  $i$  and  $T$  is the number of non-zero instances in wind speed data.

4.3. Statistical indicators and goodness of fit

All the methods for calculating Weibull parameters are compared with statistical error indicators methods. To calculate the minimum error with actual data fit are performed by root mean square error (RMSE), mean absolute percentage error (MAPE), relative root mean square error (RRMSE) and coefficient of determination ( $R^2$ ) methods are mentioned in Arian et al. (2019b), Chaurasiya et al. (2018). The mean power density from Weibull pdf,  $P_{WB}$  and from actual measured data  $P_M$  are compared to determine the performance of the selected method. Here  $T$  is used for number of data samples.

4.3.1. Root mean square error (RMSE)

$$RMSE = \sqrt{\frac{1}{T} \sum_{i=1}^T (P_{i,WB} - P_M)^2} \tag{13}$$

RMSE provides short-term performance of these models. Smaller +ve values indicates the closeness of match between actual data  $P_M$  and estimated power density  $P_{WB}$ .

4.3.2. Mean absolute percentage error (MAPE)

$$MAPE = \frac{1}{T} \sum_{i=1}^T \left|\frac{P_{i,WB} - P_M}{P_M}\right| \tag{14}$$

4.3.3. Relative root mean square error (RRMSE)

$$RRMSE = \frac{\sqrt{\frac{1}{T} \sum_{i=1}^T (P_{i,WB} - P_M)^2}}{\frac{1}{T} \sum_{i=1}^T (P_M)} \tag{15}$$

Acceptable ranges of RRMSE for model’s accuracy are given below [68, 69]:

- Excellent for  $RRMSE \leq 10\%$ ;
- Good for  $10\% \leq RRMSE \leq 20\%$ ;
- Fair for  $20\% \leq RRMSE \leq 30\%$ ;
- Poor for  $RRMSE \geq 30\%$ .

4.3.4. Coefficient of determination ( $R^2$ )

$$R^2 = 1 - \frac{\sum_{i=1}^T (P_{i,M} - P_{i,WB})^2}{\sum_{i=1}^T (P_{i,M} - P_{avg,WB})^2} \tag{16}$$

$R^2$  can also measure the strength of the correlation between the simulated and control values. Higher  $R^2$  value indicates better model performance (Haghoosta, 2019; Arian et al., 2019b).

4.4. Power density estimation

Wind power density (power per unit area) in  $\frac{W}{m^2}$  for a selected site can be calculated using either time series wind speed data or using estimated parameters of Weibull distribution function (Tizpar et al., 2014).

4.4.1. Wind power density using measured data

$$\frac{P}{A} = \frac{1}{2n} \rho \sum_{i=1}^n v^3 = \frac{1}{2} \rho \bar{v}^3 \tag{17}$$

where  $P$  is power(kW) and  $A$  is the swept area of wind turbine blades.  $\rho$  is air density taken as  $1.225 \text{ kg/m}^3$  at standard temperature and pressure conditions.

**Table 3**  
Suitable Wind Turbines for Sites Under Consideration.

Turbine model	Rated power (kW)	$c_{in}$ (m/s)	$c_r$ (m/s)	$c_{out}$ (m/s)	Hub height(m)	Rotor diameter (m)	$C_i$ (USD)
Dewind D4	600	2.5	11.5	23	40	48	1158000
Dewind D6	1250	3	13	23	60	64.3	2178750
Dewind D8	2000	3	13	25	80	80	3486000
Nordex N90/2500	2500	3	13	25	80	90	4357500
Enercon E-40/600	600	2.5	12	28	46,50,58,65	40	1045800
Enercon E-53/800	800	3	12	34	50,60,73	52.9	1394400
Enercon E-58/1000	1000	2.5	12	28	70.5,89	58.6	1743000
Enercon E-66/15.70	1500	2.5	13	25	60,80,86,114	70	2614500
Enercon E-70/2300	2300	2.5	12	34	54,64,75,85,98	71	3486000

4.4.2. Wind power density estimate using Weibull parameters

In this case using Weibull parameters estimated through four methods (GM, EM, EPF and MLE), power density can be estimated;

$$\frac{P}{A} = \frac{1}{2} \rho \int_0^\infty v^3 f(v) dv = \frac{1}{2} \rho c^3 \Gamma(1 + \frac{3}{k}) \tag{18}$$

4.4.3. Annual energy production

Capacity factor (CF) is an important measure (Nematollahi et al., 2019) and can be calculated using wind turbine data as well as estimated Weibull parameters  $k$  and  $c$ . Another way to define capacity factor is take ratio between average electric power output to rated power. Most of the practical values for CF lie between 20% and 40% depending on site conditions and wind turbine technology installed.

$$CF = \frac{\exp[-(\frac{c_{in}}{c})^k] - \exp[-(\frac{c_r}{c})^k]}{(\frac{c_r}{c})^k - (\frac{c_{in}}{c})^k} - \exp[-(\frac{c_{out}}{c})^k] \tag{19}$$

The annual energy production in ( $\frac{Wh}{Yr}$ ) for each wind turbine can be calculated using its rated power,  $P_r$  and capacity factor.

$$E = CF . P_r . 8760 \tag{20}$$

5. Economic feasibility analysis

5.1. Selection of wind turbine technology

In this section economics of power generation from wind turbine technology will be assessed. After careful assessment of wind power potential of a site from recorded data analysis, suitable wind turbine technologies need to be considered in the next phase. Wind turbine generators (WTGs) come in a wide range of fixed and variable generators including double-fed induction generator (DFIG), permanent magnet synchronous (PMSG), squirrel cage induction generator (SCIG) and wound rotor induction generator (WRIG). WECS integrated with WTG and power electronics modules are greatly explored in Blaabjerg and Ma (2013), Orłowska-Kowalska et al. (2014) for possible choice of implementation and energy market trends. Technological and processing improvements, local capabilities involved in manufacturing and supply chain management of WTGs greatly affect turbine prices. The prices for wind turbines declined from 10% to 20% between 2017 and 2018 (IRENA, 2019) with growing competition in the expansion of energy market. International Renewable Energy Agency (IRENA) 2019 report mentioned that average WT global prices, which lie between USD 910 and USD 1050/kW in 2017, has reduced to USD 790 and USD 900/ kW other than China and India (IRENA, 2019). Total installed cost of wind power plant will continue to decrease due to this global market trend of WT cost declination.

For economic assessment of wind energy for selected sites based on their wind characteristics, variety of wind turbines are

available for selection based on their power rating, hub heights, market price and availability. The characteristics of most appropriate wind turbines are provided in Table 3. The generated power can be fed to utility grid. The characteristics comparison of various wind turbines from 600 kW to 2500 kW is provided in greater detail in Alam et al. (2011). The authors stated that annual energy yield increased by hub-height of WECS depending on manufacturer. The average increase in production is 7.91% and 3.02% by elevating hub from 50 to 60 m and 60 m to 70 m respectively. Nordex N90/2500 is a double-fed asynchronous generator for variable speed installations having a rated power of 2500 kW and 660 V generation voltage and 50 or 60 Hz frequency of operation. DeWind(USA) D4/48 and D6 models are also based on DFIG technology with 40 m and 60 m hub heights, 690 V and rated powers of 600 kW and 1250 kW respectively. ENERCON’s E-70 2 MW platform wind energy converter is well-suited for sites in coastal areas with high wind conditions. As per the law, the coastal areas comprise the coast of Thatta, Badin and Sujawal. The coastal belt of Pakistan stretches 1050 kilometers and falls only in Balochistan and Sindh. It is assumed that installation of wind turbines from these manufacturers for locations under consideration will result in the most cost effectiveness of energy per kilowatt. In this study wind turbines for 40 m, 60 m and 80 m are considered for economic analysis.

AEDB, Pakistan estimates cost of wind power project around USD 2.2 million per MW in Pakistan and suggests national electric power regulatory authority (NEPRA) to calculate upfront tariff in view of capital expenditure (CAPEX) of wind projects. The CAPEX relies on prices in international market and domestic factors such as logistic cost and infrastructure development. However NEPRA approved cost for wind power project was around 1.93 million USD/MW (USD 1930/kW) (NEPRA, 2017; Ahmad et al., 2018). With an International decline of WT cost even a reduced price can be conveniently used. NEPRA approved latest cost for nominal capacity WT is 1743 USD per KW that is used in this study as investment cost  $C_i$ . Pakistani Rupee (PKR) depreciation against USD from 60 PKR/USD in 2008 to 156 PKR/USD in Feb 09, 2020 is considered in all calculations.

5.2. Cost of electricity and payback period

There are numerous factors that affect harnessing energy from wind power in a region. Production cost of wind energy varies in different regions according to techno-economic and socio-political situation and the prevailing energy market trends. Analytical approach for cost of electricity (\$/kWh) relates to investment and capital cost, operation and maintenance cost (O&M). Capital cost is affected by interest rate and repayment of loan. The investment cost includes the wind energy conversion system, installation, land rent, grid connectivity, planning and licensing expenditures. The operation and maintenance costs include the repair, insurance, monitoring and management expenditures.

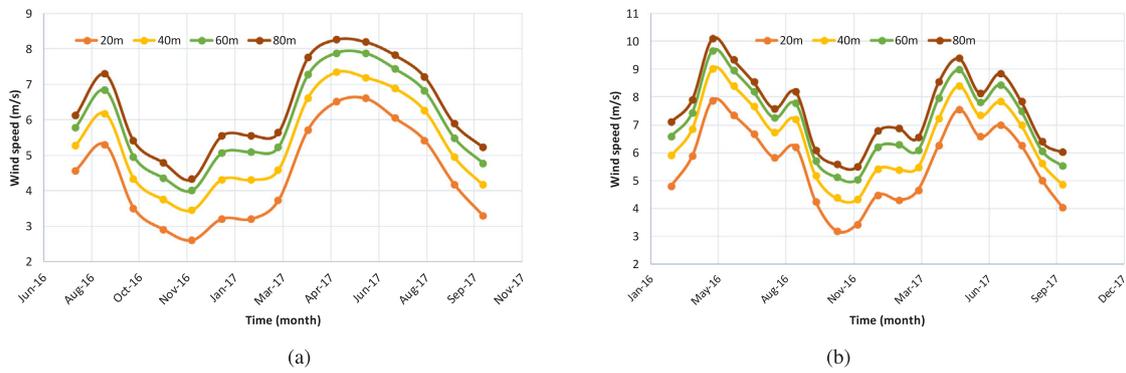


Fig. 4. Monthly average wind speed at various hub heights for (a) Umerkot and (b) Sujawal sites.

Present value cost (PVC) is evaluated based on the assumptions listed below:

1. ( $C_i$ ) includes cost of WTs, civil works, installation, land rent and cabling to the grid and is 1.74 million USD/MW.
2. Operations and maintenance (O&M) cost ( $C_{omr}$ ) was considered to be 25% of the annual cost of the turbine (machine price/lifetime) (Ziazi et al., 2017).
3. According to Trading Economics Pakistan's economic indicators, the rate of interest ( $i$ ) and inflation ( $r$ ) accelerate to 13.25% and 11.63% respectively by August 2019.
4. Life time of the project is ( $n$ ) years for WT.
5. Scrap value ( $S$ ) is 10% of the total investment cost.

With these assumption, the CoE per kWh can be calculated with the total yield  $E_{out}$  of WT during 20 years life time and PVC by using the following formula mentioned in Ziazi et al. (2017).

$$CoE = \frac{PVC}{E_{out}} \quad (21)$$

PVC can be obtained from (22) and the present value of benefits (PVB) can be obtained from (23) where UAB is the Uniform Annual Benefit, which is mainly obtained by selling of electricity,  $n$  is no of years and DR is the discount rate given by (24) (Ziazi et al., 2017).

$$PVC = C_{inv} + C_{omr} \left[ \frac{1+i}{r-i} \right] \left[ 1 - \left( \frac{1+i}{1+r} \right)^n \right] - S \left( \frac{1+i}{1+r} \right)^n \quad (22)$$

$$PVB = UAB \frac{(1+DR)^n - 1}{DR(1+DR)^n} \quad (23)$$

$$DR = \frac{1+r}{1+i} - 1 \quad (24)$$

UAB is estimated using the energy output from the wind turbine by considering the purchase tariff of the wind energy in Pakistan (0.09\$/kWh).

## 6. Results and discussion

### 6.1. Monthly mean wind speeds

The monthly mean wind speeds obtained from World Bank data set under Energy Sector Management Assistance Program (ESMAP) using MATLAB R2016a at heights of 20 m, 40 m, 60 m and 80 m for two locations is considered in this feasibility study. Data contains daily reports for wind speed, wind direction, air pressure, relative humidity, temperature and turbulence intensity. This data has been analyzed extensively and results are provided in Fig. 4.

Fig. 4(a) shows results for Umerkot site for the period starting from August 2016 to October 2017. Higher wind speeds occur from April to August with maximum wind speeds in May and

June. The highest wind speeds for four heights are 6.60, 7.33, 7.88, 8.26 m/s. The annual average wind speeds are 4.45, 5.13, 5.92 and 6.34 m/s. The wind speeds from September to March are relatively low with minimum values 2.59, 3.45, 4.00 and 4.32 m/s for four heights. With wind power classification given in Fig. 1, this site can be regarded as marginal to fair.

Fig. 4(b) shows results for Sujawal site for the period starting from March 2016 to October 2017. Wind speeds are higher from March to August. The highest wind speeds for four heights are 7.87, 9.01, 9.65 and 10.08 m/s. The annual average wind speeds at four heights 5.57, 6.50, 7.12 and 7.56 m/s. The wind speeds from August to November are relatively low. The minimum values are 3.18, 4.32, 5.03 and 5.49 m/s for four heights. With wind power classification given in Fig. 1, this site can be regarded as fair to good with class designation between three and four.

### 6.2. Diurnal wind speeds

The diurnal wind speeds for two sites are shown in Fig. 5(a). As shown in Fig. 5(a), the wind speed for Umerkot varies between 3.26 to 5.87 m/s for all four heights of 20 m, 40 m and 80 m. Wind speeds start decreasing at 1 a.m. till noon and then start increasing till midnight. For Umerkot the minimum hourly wind speed is 3.72 m/s and maximum hourly wind speed is 6.944 m/s. A slightly different wind speed pattern can be observed for Sujawal site as shown in Fig. 5(b). From these patterns it is observed that Sujawal site has relatively higher hourly wind speeds.

### 6.3. Estimated Weibull PDF and CDF

The Weibull PDF is used to fit the actual wind speed data for selected sites. The estimated PDFs are provided in Figs. 6 and 7 for four heights of 20 m, 40 m, 60 m and 80 m using four different estimation methods. The Weibull PDFs reveal that the wind speeds of 5.5 and 7 m/s have the highest wind frequency at the height of 20 m with probability equal to 15% and 14% for two sites (Umerkot and Sujawal) respectively. At a height of 40 m, the wind speeds are 5.25 m/s and 6.5 m/s with corresponding maximum wind probabilities of 14% and 12% for two sites respectively. At a height of 60 m, the wind speeds are 5.10 m/s and 7 m/s with corresponding maximum wind probabilities of 14% and 12.5% for two sites. At a height of 80 m, the wind speeds are 4.25 m/s and 7 m/s with corresponding maximum wind probabilities of 13% and 11% for two sites respectively.

Cumulative distribution function (CDF) graphs are also shown in Fig. 8 for two sites at heights of 20 m, 40 m, 60 m and 80 m. Probabilities greater than cut-off wind speeds and lower than cut-in wind speeds can be obtained from CDF graphs and therefore, is a very useful statistical indicator for wind resource assessment.

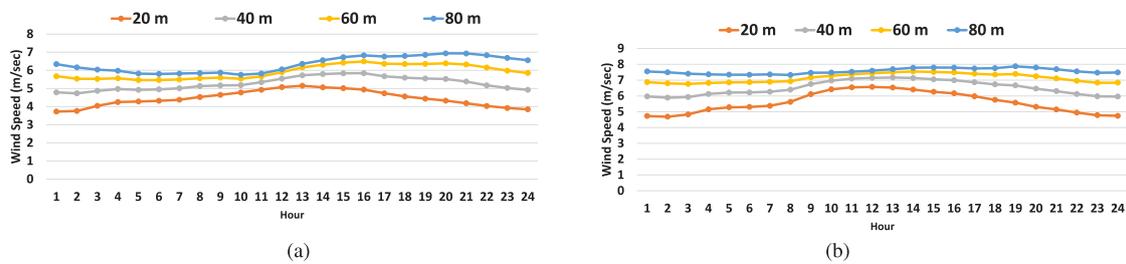


Fig. 5. Daily average wind speed at various hub heights for (a) Umerkot and (b) Sujawal sites.

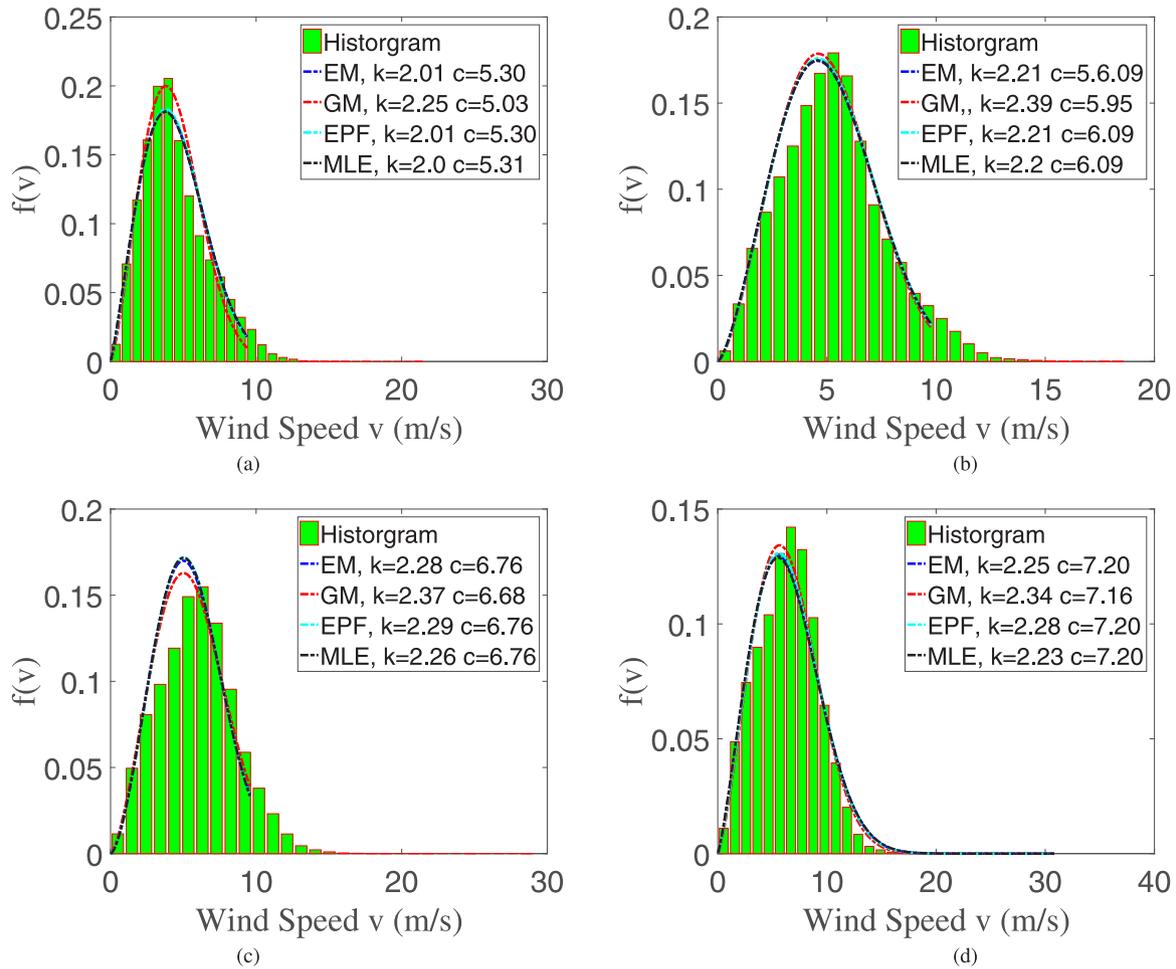


Fig. 6. Estimated PDF for Umerkot at (a) 20 m (b) 40 m (c) 60 m and (d) 80 m heights.

#### 6.4. Turbulence intensity and wind rose diagrams

##### 6.4.1. Turbulence intensity of selected sites

It can be observed from the topographical maps shown in Figs. 9 and 10 that the background roughness length is 0.054 m, corresponding to open field with distributed rows of trees and low buildings. Roughness length for specific areas in Sujawal is 0.03 m for inland humid zone and 0.0005 m for water bodies. Roughness length for specific areas in Umerkot is 0.5 m for towns, 0 m for lake and 0.03 m for desert. In the wind energy industry, turbulence is quantified with a metric called turbulence intensity – the standard deviation of the horizontal wind speed divided by the average wind speed over some time period, typically 10 min. If the wind fluctuates rapidly, then the turbulence intensity will be high. Conversely, steady winds have a lower turbulence intensity.

The Turbulence Intensities (TI) at 20 m, 40 m, 60 m and 80 m heights are analyzed using the available wind speed data for two selected sites. Figs. 11 and 12 show that as altitude above ground level increases, there is less wind turbulence. Therefore, relatively at 80 m or below heights, the wind velocities are more steady. For installation of wind turbines, International Electro technical Commission (IEC) has formed standards for TI up to 18%, for a wind speed of 15 m/s, and our selected sites have low TI.

##### 6.4.2. Wind rose diagrams of selected sites

The direction of wind at a particular site is important for installing wind farms. The wind frequency rose(%) for each site can be obtained from wind direction data and mean wind speed (m/sec). Wind vanes were installed at heights of 58.5 m and 78.5 m. Wind rose diagrams are obtained from Yilidrimar and Adiloglu (2018) and are reproduced here. Wind rose diagrams for two sites are shown in Figs. 13 and 14. The wind rose is drawn

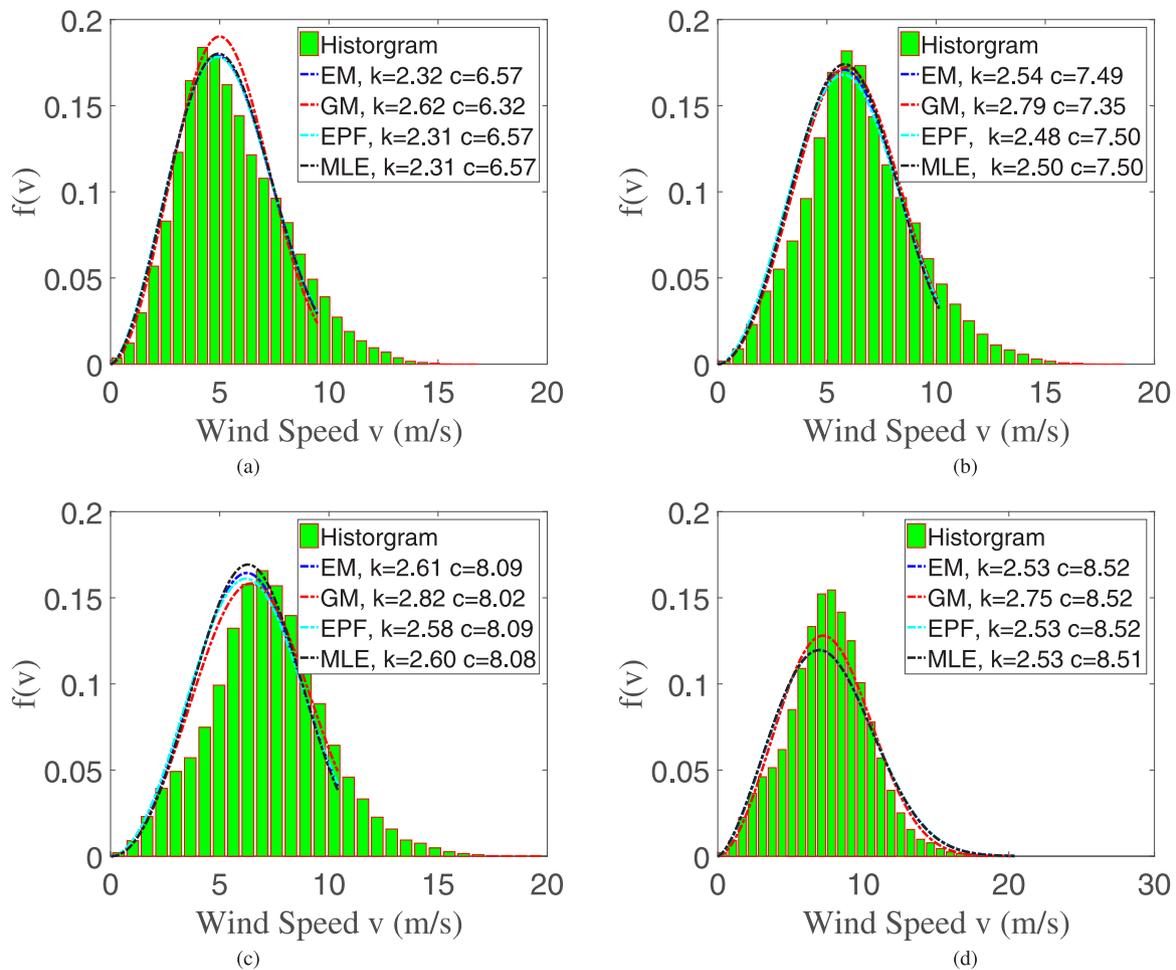


Fig. 7. Estimated PDF for Sujawal at (a) 20 m (b) 40 m (c) 60 m and (d) 80 m heights.

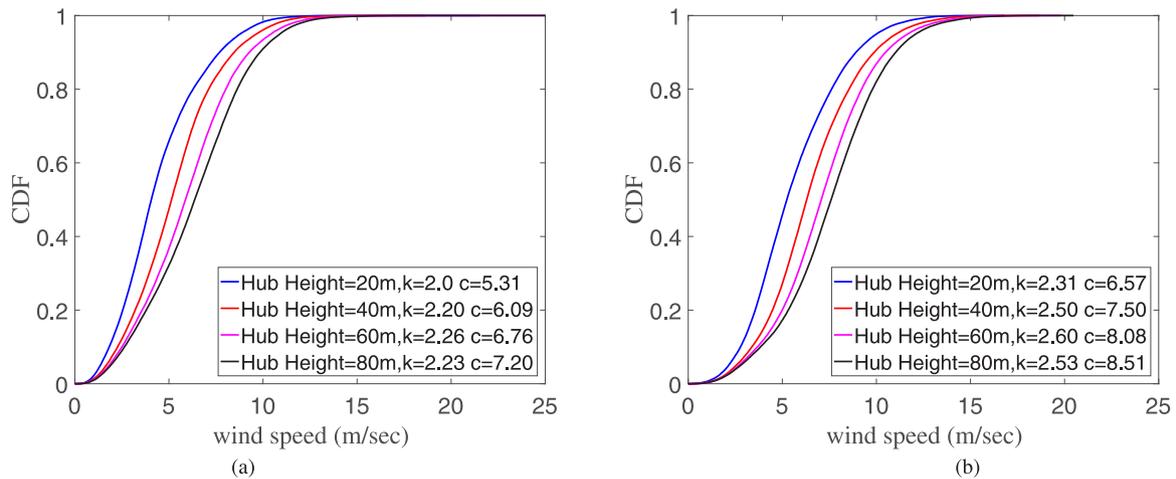
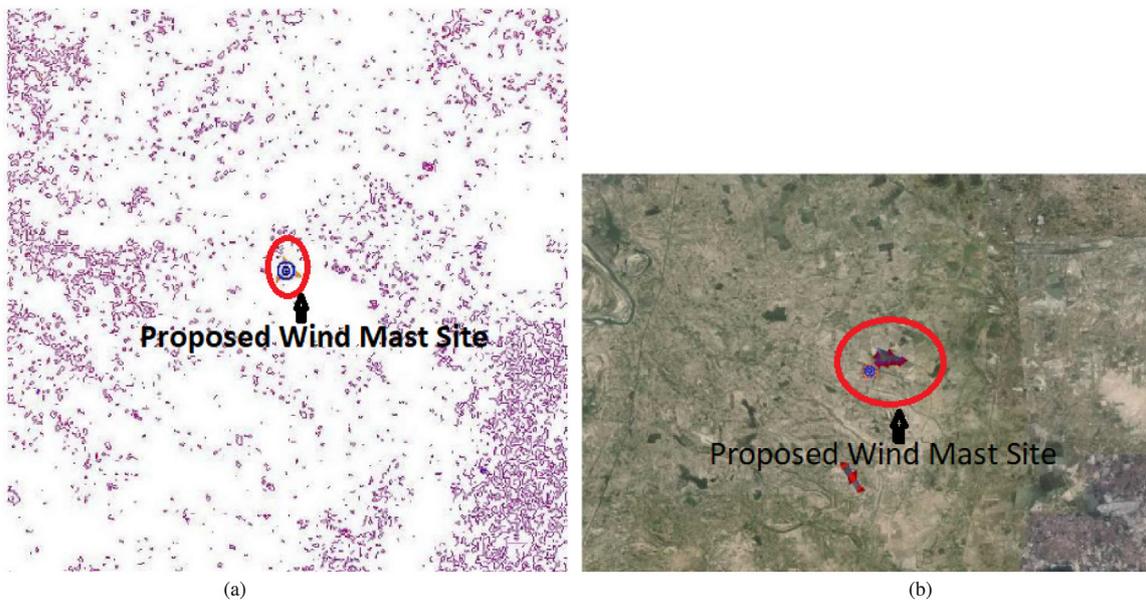


Fig. 8. CDF of (a) Umerkot and (b) Sujawal.

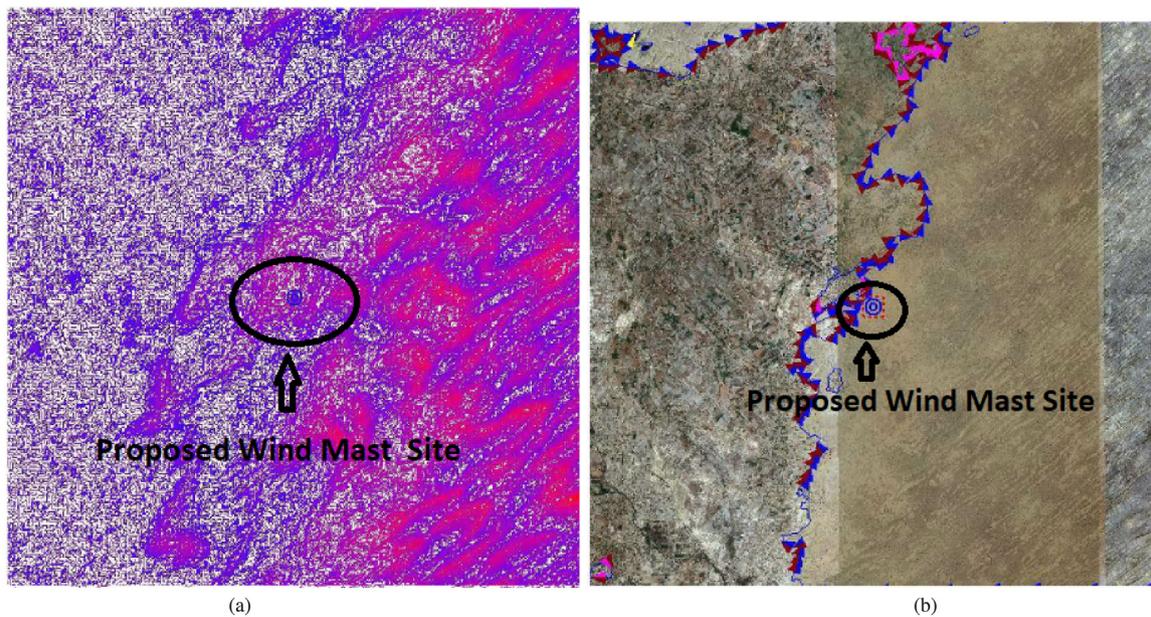
by using 10 min. average wind direction and wind speed data at 80 m height.

The wind speed rose diagram as shown in Fig. 13(a) clearly gives us an indication of how much wind blows in a particular direction with frequency of occurrence. The prevailing wind direction for Umerkot is SSW (S=south, W=West). At height of 80 m more than 6%, 7%, 7.5%, 3%, and 1% of wind is in the direction towards SW having wind speed ranges from 4 m/s to 6 m/s, 6 m/s to 8 m/s, 8 m/s to 10 m/s, 10 m/s to 12 m/s, and 12 m/s to

14 m/s, respectively. With these winds, the selected wind turbine such as Nordex N90/2500 can harness available wind power at this site since its cut-in wind speed is 3 m/s and rated wind speed is 13 m/s according Table 3 data. The capacity factor for this turbine is 25% according to Table 8. Two other less dominant wind directions are WSW and SSW with wind speeds between 6 m/s to 10 m/s. Energy rose as shown in Fig. 13(b) provides energy density (kWh/m<sup>2</sup>/Yr) which varies between 800–850 kWh/m<sup>2</sup>/Yr with probability of it occurrence above 4% respectively in SW



**Fig. 9.** Topographic maps for Sujawal site. (a) Elevation map  $20 \times 20$  km (with mast in center) with 10 m elevation difference between lines. Altitudes in map range from 5 m to 15 m. Site ruggedness index (RIX) value at mast is 0% using radius of 3500 m, steepness threshold of 30% (17 degree) and frequency distributed directional weight. (b) Ground roughness map  $20 \times 20$  km (with mast in center). Background roughness length is 0.054 m, corresponding to open field with distributed rows of trees and low buildings. Roughness length for specific areas is 0.03 mm for inland humid zone (purple color) and 0.0005 m for water bodies (red color). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 10.** Topographic maps for Umerkot site. (a) Elevation map  $20 \times 20$  km (with mast in center) with 10 m elevation difference between lines. Altitudes in map range from 0 m to 84 m. Site ruggedness index (RIX) value at mast is 0% using radius of 3500 m, steepness threshold of 30% (17 degree) and frequency distributed directional weight. (b) Ground roughness map  $20 \times 20$  km (with mast in center). Background roughness length is 0.07 m, corresponding to open field with distributed rows of trees and low buildings. Roughness length for specific areas is 0.5 mm for towns (rose color), 0 m for lake (yellow color) and 0.03 m for desert (blue color). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

direction, between 800–850 kWh/m<sup>2</sup>/Yr with probability of it occurrence above 16% and 14% in WSW and SSW directions respectively.

The wind speed rose diagram for Sujawal site as shown in Fig. 14(a) provides us a pictorial view of prevailing wind direction of WSW and W (S=south, W=West). At height of 80 m more than 4%, 5%, 4.5%, 2%, and 1% of wind is in the direction towards WSW having wind speed ranges from 2 m/s to 4 m/s, 4 m/s to 6 m/s, 6 m/s to 8 m/s, 8 m/s to 10 m/s, and 10 m/s to 12 m/s, respectively. With these winds, the selected wind turbines such as Enercon-E

series can harness available wind power at this site since their cut-in wind speeds are 2 m/s and rated wind speeds are 12 m/s according to Table 3 data. The capacity factors for these turbine vary between 23% and 31% according to Table 8 and therefore can capture most of the power in these wind regimes according to their power curves. Two other less dominant wind directions are W and SW with wind speeds between 6 m/s to 10 m/s. Energy rose as shown in Fig. 14(b) provides energy density (kWh/m<sup>2</sup>/Yr) which varies between 850–900 kWh/m<sup>2</sup>/Yr with probability of it occurrence above 24% respectively in WSW direction, between

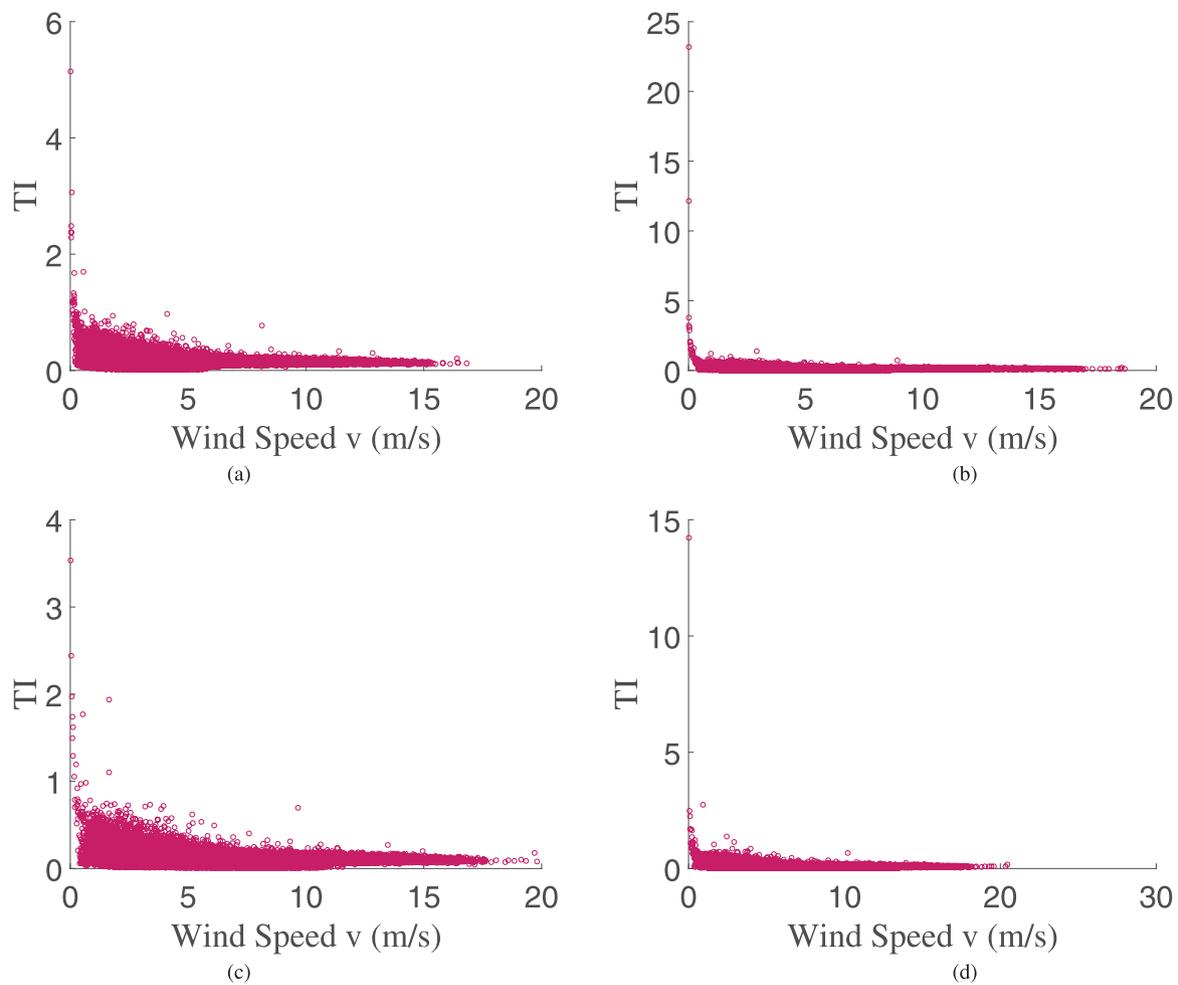


Fig. 11. Turbulence Intensity(TI) for Sujawal at (a) 20 m (b) 40 m (c) 60 m and (d) 80 m heights.

Table 4  
Estimated Weibull Parameters (k and c) for selected sites.

Site	Height	GM		EM		EPF		MLE	
		k	c	k	c	k	c	k	c
Umerkot	20 m	2.25	5.03	2.01	5.30	2.01	5.30	2.00	5.31
	40 m	2.39	5.95	2.21	6.09	2.21	6.09	2.2	6.09
	60 m	2.37	6.68	2.28	6.76	2.29	6.76	2.26	6.76
	80 m	2.34	7.16	2.25	7.20	2.28	7.20	2.23	7.20
Sujawal	20 m	2.62	6.32	2.32	6.57	2.31	6.57	2.31	6.57
	40 m	2.79	7.35	2.54	7.49	2.48	7.50	2.50	7.50
	60 m	2.82	8.02	2.61	8.09	2.58	8.09	2.60	8.08
	80 m	2.75	8.52	2.53	8.52	2.53	8.52	2.53	8.51

800–850 kWh/m<sup>2</sup>/Yr with probability of it occurrence above 8% and 4% in W and SW directions respectively.

6.5. Estimated k and c Weibull parameters

The Weibull parameters k and c are estimated using four methods described above in Section 4.2. The estimated values are shown in Table 4. The results from EM, EPF and MLE methods closely match with each other. However graphical method's result differ from rest of the three methods. GM has poor performance in estimating k and c Weibull parameters. It is obvious from Table 4 that at a height of 80 m, for a potential wind turbine installation, the representative k and c values are: 2.230, 7.20 and 2.52, 8.51 for Umerkot and Sujawal respectively with MLE estimate. k and c values can similarly be used from Table 4 for other heights of 20 m, 40 m and 60 m.

6.6. Goodness of fit with statistical parameters for selected sites

The statistical indicators introduced in Table 5 offer a meaningful statistical insight regarding the distribution of wind power density. RMSE, RRMSE, MAPE and R<sup>2</sup> are used to compare the measured wind power and those obtained by Weibull function using four methods. It is clear that, best accuracy with RRMSE value of zero is obtained when EM, EPF and MLE are used to compute the Weibull parameters and lowest performance is achieved from GM method at all four heights. R<sup>2</sup> values are also close to 1 indicating a perfect match between measured and estimated parameters. It is obvious that there is lot of variability among these statistical parameters for various heights and hub heights. The reasons could be different terrain characteristics and wide variation of wind speeds. The obtained results can be used for sites with similar characteristics. EPF method gives lowest MAPE

**Table 5**  
Performance results of the 4 selected methods with statistical parameters for selected sites.

Site	Height	RMSE				MAPE				RRMSE				$R^2$			
		GM	EM	EPF	MLE	GM	EM	EPF	MLE	GM	EM	EPF	MLE	GM	EM	EPF	MLE
Umerkot	20 m	28.62	0.85	0.85	0.46	23.57	0.70	0.70	0.38	$5.56 \times 10^{-2}$	$4.90 \times 10^{-5}$	$4.90 \times 10^{-5}$	$1.50 \times 10^{-5}$	0.7586	0.9921	0.9932	0.9915
	40 m	21.18	0.58	0.58	0.06	12.62	0.35	0.35	0.03	$1.59 \times 10^{-2}$	$1.23 \times 10^{-5}$	$1.23 \times 10^{-5}$	$1.49 \times 10^{-7}$	0.6801	0.9822	0.9912	0.9971
	60 m	13.95	0.16	0.60	1.75	6.26	0.07	0.27	0.79	$3.92 \times 10^{-3}$	$5.59 \times 10^{-7}$	$7.49 \times 10^{-6}$	$6.24 \times 10^{-5}$	0.8903	0.9976	0.9961	0.9921
	80 m	10.36	2.31	0.59	4.34	3.83	0.85	0.22	1.60	$1.47 \times 10^{-3}$	$7.36 \times 10^{-5}$	$4.91 \times 10^{-6}$	$2.59 \times 10^{-4}$	0.7912	0.9932	0.9741	0.9912
Sujawal	20 m	36.96	0.62	0.05	0.05	18.26	0.30	0.02	0.02	$3.33 \times 10^{-2}$	$9.52 \times 10^{-6}$	$6.54 \times 10^{-8}$	$6.54 \times 10^{-8}$	0.7691	0.9987	0.9986	0.9877
	40 m	32.72	3.54	1.97	0.46	11.51	1.24	0.69	0.16	$1.33 \times 10^{-2}$	$1.56 \times 10^{-4}$	$4.83 \times 10^{-5}$	$2.66 \times 10^{-6}$	0.6898	0.9901	0.9987	0.9996
	60 m	22.34	0.50	2.92	0.01	6.43	0.14	0.84	0	$4.14 \times 10^{-3}$	$2.15 \times 10^{-6}$	$7.11 \times 10^{-5}$	$1.26 \times 10^{-9}$	0.7995	0.9966	0.9993	0.9995
	80 m	16.48	3.00	3.00	1.54	4.01	0.73	0.73	0.37	$1.61 \times 10^{-3}$	$5.34 \times 10^{-5}$	$5.34 \times 10^{-5}$	$1.42 \times 10^{-5}$	0.6940	0.9910	0.9999	0.9966

**Table 6**  
Measured and estimated power density ( $W/m^2$ ) and Annual Wind Energy Density ( $kWh/m^2/Yr$ ) from four selected methods.

Site	Height	Measured		Estimated							
		Power density	Annual energy density	GM	EM	EPF	MLE	Power density	Annual energy density	Power density	Annual energy density
Umerkot	20 m	121.43	1063.73	92.80	812.93	120.58	1056.28	120.58	1056.28	121.90	1067.84
	40 m	167.80	1469.93	146.61	1284.30	167.21	1464.76	167.21	1464.76	167.87	1470.54
	60 m	222.70	1950.85	208.75	1828.65	222.87	1952.34	222.09	1945.51	224.46	1966.27
	80 m	269.88	2364.15	259.51	2273.31	272.19	2384.38	269.28	2358.89	274.22	2402.17
Sujawal	20 m	202.44	1773.37	165.48	1449.60	201.82	1767.94	202.50	1773.90	202.50	1773.90
	40 m	284.24	2489.94	251.51	2203.23	280.69	2458.84	286.21	2507.20	284.70	2493.97
	60 m	347.36	3042.87	325.02	2847.18	347.87	3047.34	350.29	3068.54	347.37	3042.96
	80 m	411.17	3601.85	394.68	3457.40	414.18	3628.22	414.18	3628.22	412.72	3615.43

**Table 7**  
Wind power classification for sites.

Site	Wind power class	Class designator
Umerkot	Marginal to Fair	2-3
Sujawal	Fair to Good	3-4

values for 40 m and 60 m height compared to MLE. MLE has better performance as it achieves lowest values for MAPE for Sujawal site where 40 m, 60 m and 80 m turbine installations are more suitable.

### 6.7. Estimated power density and annual wind energy density

The wind power density are calculated using Eqs. (17) and (18). Measured and estimated values are listed in Table 6. Annual wind energy density is obtained by multiplying power density with 8760 h in a year. As seen from Table 6, the measured and estimated values closely match. It is evident that annual wind energy densities are higher at 80 m height than lower heights for all sites. It is clear from Table 6 that Sujawal has better wind power density compared to Umerkot. The value of power and energy density for Sujawal are 414.18 W/m<sup>2</sup> and 3628.22 kWh/m<sup>2</sup>/Yr, 414.18 W/m<sup>2</sup> and 3628.22 kWh/m<sup>2</sup>/Yr, 412.72 W/m<sup>2</sup> and 3615.43 kWh/m<sup>2</sup>/Yr using the EM, EPF and MLE estimates respectively. The corresponding measured values of power and energy density for Sujawal are 411.17 W/m<sup>2</sup> and 3601.85 kWh/m<sup>2</sup>/Yr. The measured and estimated power density and energy density values are closely matched.

If the values listed in Table 6 are compared with wind power classification given in Fig. 1, the wind power classes can be roughly inferred as shown in Table 7. Based on this classification, it can be concluded that Sujawal is good site for wind farm realization.

### 6.8. Turbine performance and analysis of cost of electricity

Many different types of wind turbines can be proposed for selected sites. The economic selection indicators are rate of return, CoE, payback periods, CF, power rating and available hub heights. All the calculations related to the suitable turbines are based on estimated  $k$  and  $c$  Weibull parameters given in Table 4. Using these parameters capacity factors are calculated according to (19). Annual energy yield is calculated using (20). The values are listed in Table 8. Looking at the values of cost of electricity with various types of wind turbine technologies from different manufacturers, it is evident that cost varies for two sites. If DeWind D6 is used then the costs are 0.034, 0.037 \$/kWh for Umerkot and Sujawal respectively. If DeWind D8 is used then costs are 0.087, 0.065 \$/kWh for Umerkot and Sujawal respectively. Therefore with this comparison it is obvious that DeWind D6 turbines are good if cost of energy is selection criterion.

Selecting Nordex N90/2500 wind turbines for Umerkot and Sujawal is even a better option compared to DeWind D8 as cost of energy is lower with corresponding values 0.056, 0.074 \$/kWh respectively with added advantage that more power can be harnessed from Nordex turbine. Using a wind turbine with higher rated power such as 2500 kW Nordex N90 is more economical for wind farm installation because reduced number of turbines would be required initially and less land area. However the higher investment costs could be a financial concern for a developing country like Pakistan unless some loan arrangements are made from banks.

Other options are to use Enercon series of wind turbines. Cost of energy (CoE) of turbine models such as Enercon E-40, E-53, E-58, E-66 and E-70 are also shown in Fig. 15. E-40 has lowest CoE

which is 0.036 and 0.040 \$/kWh whereas E-66 has highest value of CoE which is 0.043 and 0.049 \$/kWh for two respective sites for Enercon series of turbines.

It is evident from the listed values that Nordex N90/2500 provide the highest energy production associated with Umerkot and Sujawal sites over its life time of 20 years. There are many choices to select a suitable turbine for the two sites. A quick comparison of CoE can be visualized from Fig. 15 for various turbines.

### 6.9. Payback periods

Payback periods are also calculated for a selected set of turbines as mentioned in Table 8. Many other turbines were initially considered for economic analysis but some had very poor capacity factors so those were not included in payback periods analysis. The corresponding graphs for selected set of turbines are provided for comparison in Figs. 16 to 19 and payback periods are listed values in Table 9.

From these graphs one can see that turbines with payback period of 7 years or less are best choices. These are break-even points where PVC (cost) and PVB (benefit) curves intersect. E-58 has highest payback period and therefore not economically feasible. DeWind D8 has 7.5 years payback time. DeWind D6, Nordex N90/2500, E-53 and E-66 each has a payback period of 7 years. We would recommend Nordex N90/2500 as a potential candidate for wind turbine installation. Nordex N90/2500 will be economically more beneficial for its lifetime as mentioned earlier. Earlier published work such as done by Irfan Ullah in Ullah et al. (2010) and Shahnawaz Farhan Khahro in Khahro et al. (2014) mentioned that Nordex N90/2500 turbines have been successfully installed in Kati Bandar and Garo areas of province Sindh in Pakistan.

## 7. Conclusions

In this study, the wind energy resource assessment is investigated for two locations in Sindh province of Pakistan by estimating the shape and scale factors of Weibull distribution function using GM, EM, EPF and MLE methods. The parameters are used to estimate wind power density and annual energy yield. One year (2016–2017) wind speed data is analyzed to determine monthly mean wind speeds as well as daily averages for selected sites where wind masts had been installed by the World Bank. The data was observed on the daily basis with ten minute sampling interval in order to predict the behavior of wind more accurately. Different wind turbines models for electricity production in these locations are proposed for possibility of installing wind farms on these sites. Using the wind turbine technologies levelized cost of energy is estimated for Umerkot and Sujawal sites. The findings from this study can be summarized as follows:

Wind profiles of the sites closely fit to Weibull distribution function. From four Weibull distribution techniques, GM shows the worst performance, whereas, MLE, EM and EPF provide better and comparable performance. The listed values are validated using statistical error indicators. The scale parameters  $k$  and  $c$  for 80 m installations are average out to 2.5 and 8.52 for Sujawal site. Annual average wind speeds are 4.45, 5.13, 5.92 and 6.34 m/s for Umerkot and 5.57, 6.50, 7.12 and 7.56 m/s for Sujawal respectively. Skewness values for two sites were positive indicating that all distributions were skewed towards right side. Monthly and diurnal wind characteristics of the proposed sites indicate that these sites belong from marginal to good sites with class performance of two or higher wind potential. Using widely used Weibull distribution function and its estimated parameters,

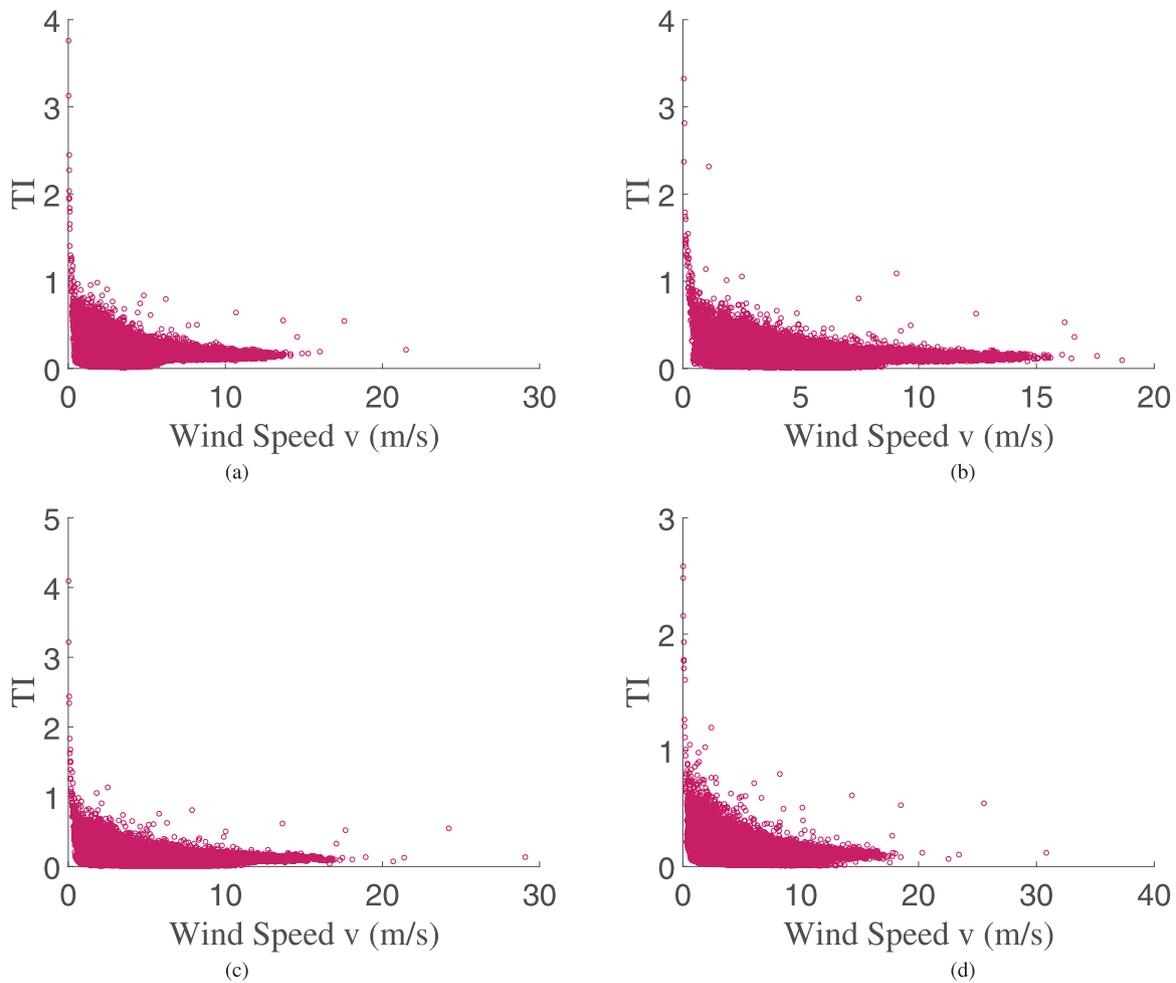


Fig. 12. Turbulence Intensity(TI) for Umerkot at (a) 20 m (b) 40 m (c) 60 m and (d) 80 m heights.

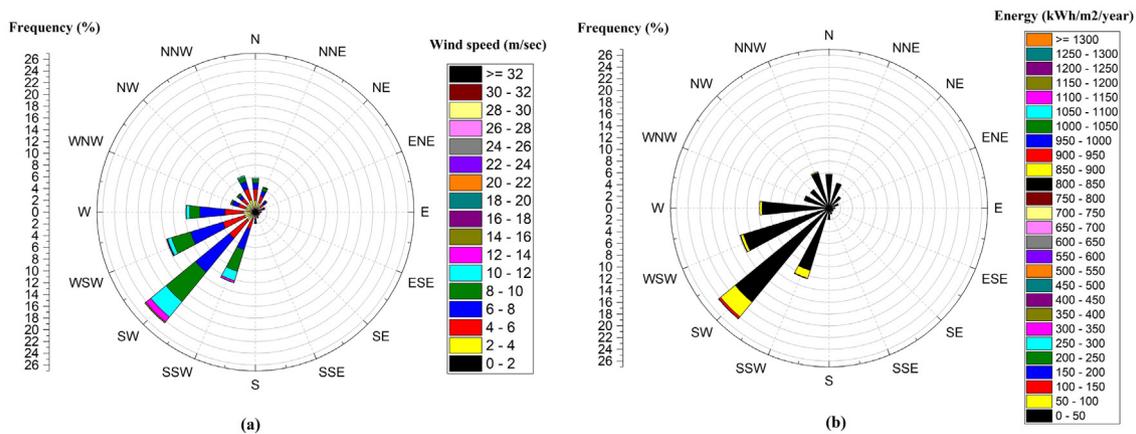


Fig. 13. Wind Rose of Umerkot (a) Wind Speed Rose with wind speed at 80 m and direction sensor at 78.5 m height (b) Wind Energy Rose with wind speed at 80 m and direction sensor at 78.5 m height.

capacity factor and wind power density for two sites were determined. Wind power density is highly significant as it helps determine the wind power potential of a site and installation of wind farms for utility scale energy production.

It is evident from the listed values that DeWind D6 and Nordex N90/2500 provide the best capacity factors among all turbine

technologies. The highest values supported are 34% from DeWind D6 and 30% from Nordex N90/2500 for Sujawal site. The highest energy production is also associated with Umerkot and Sujawal site if Nordex N90 turbines are installed.

In term of energy production and capacity factor, Sujawal is the most promising site for wind energy projects followed by

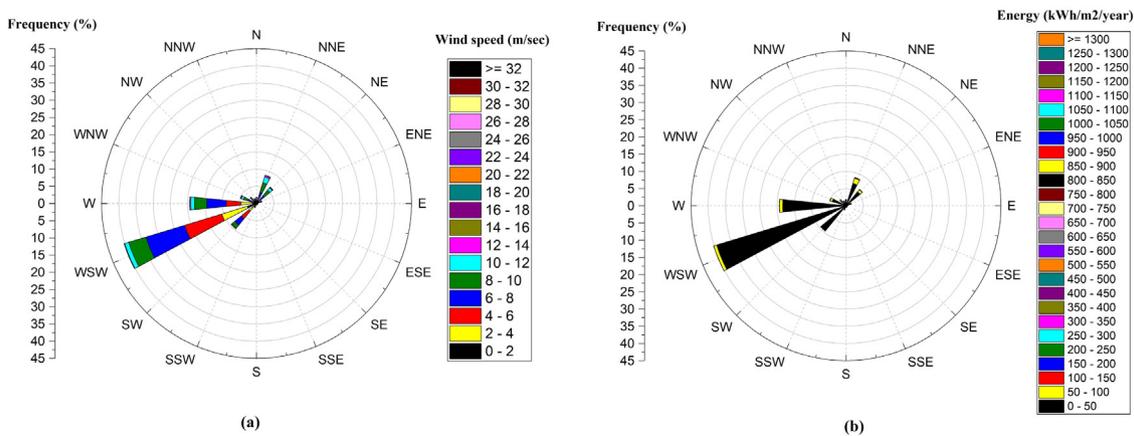


Fig. 14. Wind Rose of Sujawal (a) Wind Speed Rose with wind speed at 80 m and direction sensor at 78.5 m height (b) Wind Energy Rose with wind speed at 80 m and direction sensor at 78.5 m height.

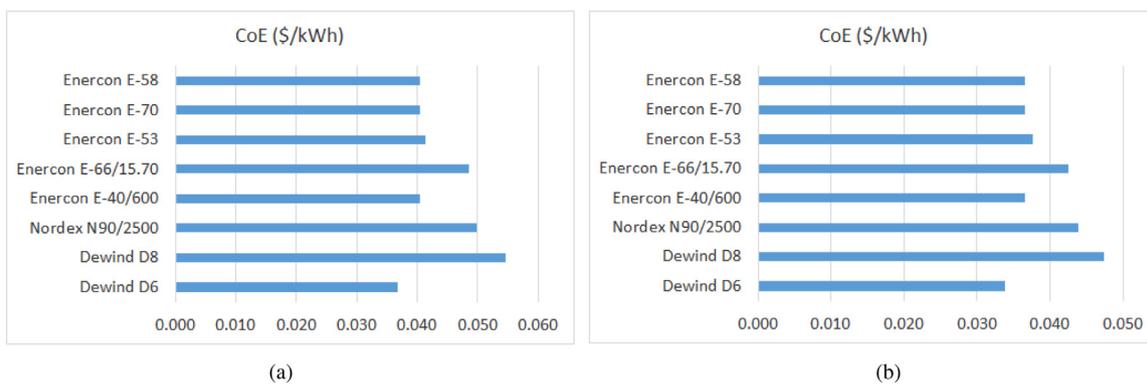


Fig. 15. Cost of Energy using different wind turbines at (a) Sujawal (b) Umerkot sites.

Table 8  
Cost of Energy(CoE).

Turbine	Rotor diameter	Site	k	c	$V_{avg}$ (m/s)	$E_{out}$ (kWh)	CF	CoE (\$/kWh)
DeWind D6	60 m	Umerkot	2.23	7.20	6.38	74716296	0.19	0.034
	60 m	Sujawal	2.53	8.51	7.56	68536377	0.34	0.037
DeWind D8	80 m	Umerkot	2.23	7.20	6.38	85129400	0.19	0.047
	80m	Sujawal	2.53	8.51	7.56	73968072	0.34	0.055
Nordex N90/2500	90 m	Umerkot	2.23	7.20	6.38	114908643	0.26	0.074
	90 m	Sujawal	2.53	8.51	7.56	101234148	0.30	0.056
Enercon E-40	43.7 m	Umerkot	2.23	7.20	6.38	33193902	0.31	0.036
	43.7 m	Sujawal	2.53	8.51	7.56	29992629	0.28	0.040
Enercon E-53	52.9 m	Umerkot	2.23	7.20	6.38	42957644	0.30	0.038
	52.9 m	Sujawal	2.53	8.51	7.56	38967284	0.27	0.041
Enercon E-58	58.6 m	Umerkot	2.23	7.20	6.38	55323170	0.31	0.036
	58.6 m	Sujawal	2.53	8.51	7.56	49987716	0.28	0.040
Enercon E-66	70 m	Umerkot	2.53	7.20	6.38	71126392	0.27	0.043
	70 m	Sujawal	2.53	8.51	7.56	62414528	0.23	0.049
Enercon E-70	71 m	Umerkot	2.23	7.20	6.38	110646343	0.31	0.036
	71 m	Sujawal	2.53	8.51	7.56	99975432	0.28	0.040

Umerkot. If DeWind D6 turbine is used then lowest costs are 0.034 and 0.037 \$/kWh for Umerkot and Sujawal respectively. Selecting Nordex N90/2500 wind turbines for Umerkot and Sujawal is even a better option compared to DeWind D6 as it results in higher energy production with low payback period. Using a wind turbine with higher rated power such as 2500 kW Nordex N90 is even more economical for wind farm installation. The leveled cost of energy are highly viable for the proposed sites.

The sites are however, very underprivileged, therefore production of electricity from these sites will uplift the economic situation of not only for its local inhabitants but will also improve the economic conditions of neighboring areas by creating more jobs for community, prosperity and better climate with low carbon emissions.

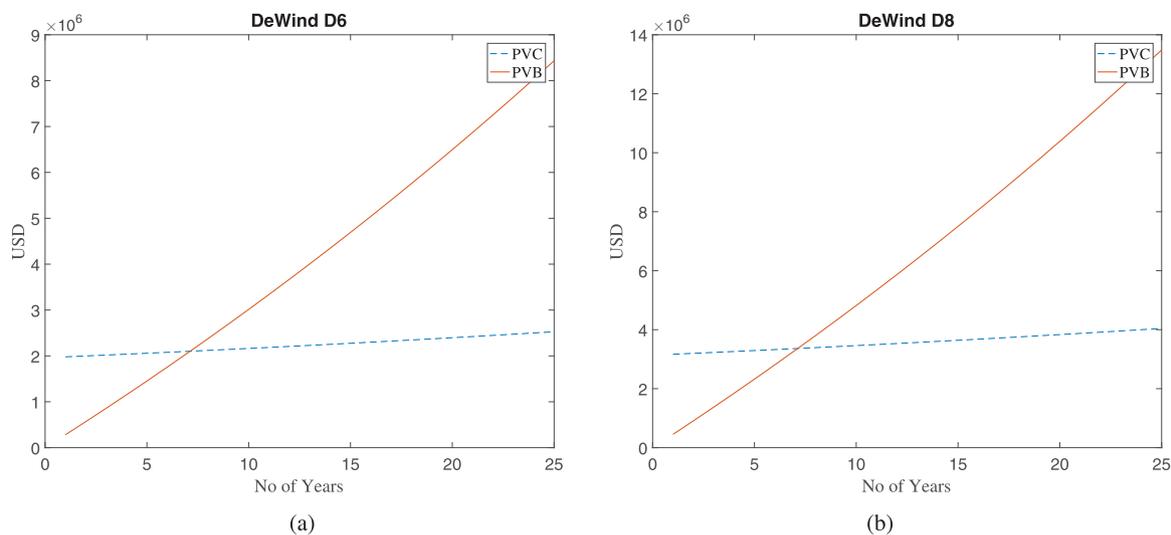


Fig. 16. Payback Period using (a) Dewind D6 (b) Dewind D8.

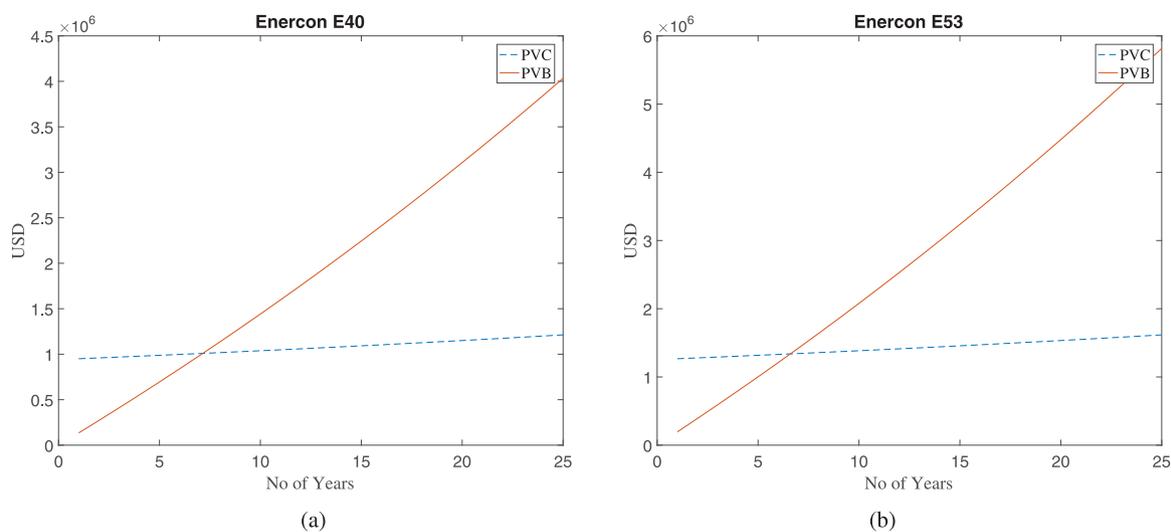


Fig. 17. Payback Period using (a) Enercon-40 (b) Enercon-53.

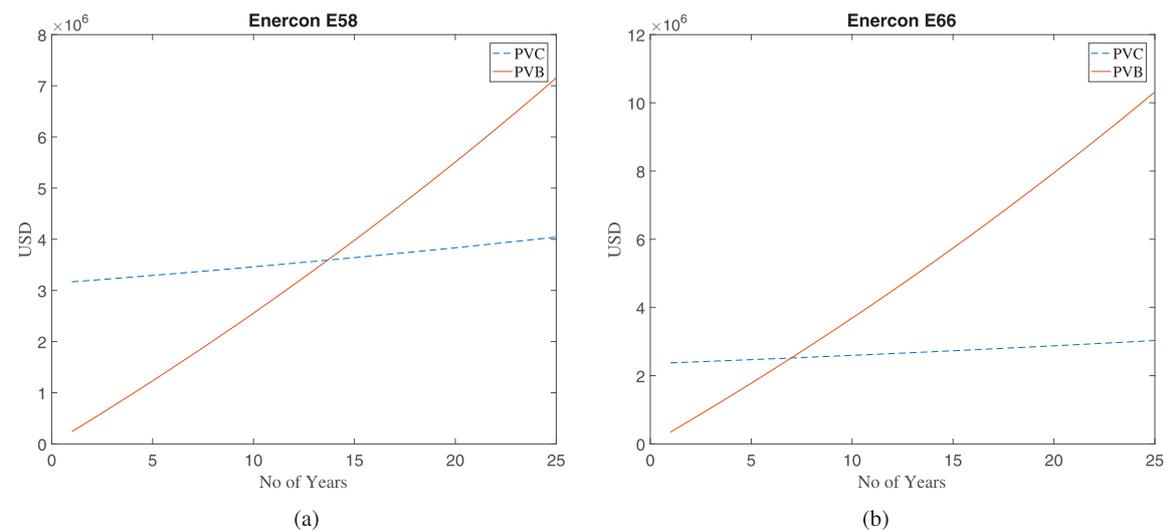


Fig. 18. Payback Period using (a) Enercon-58 (b) Enercon-66.

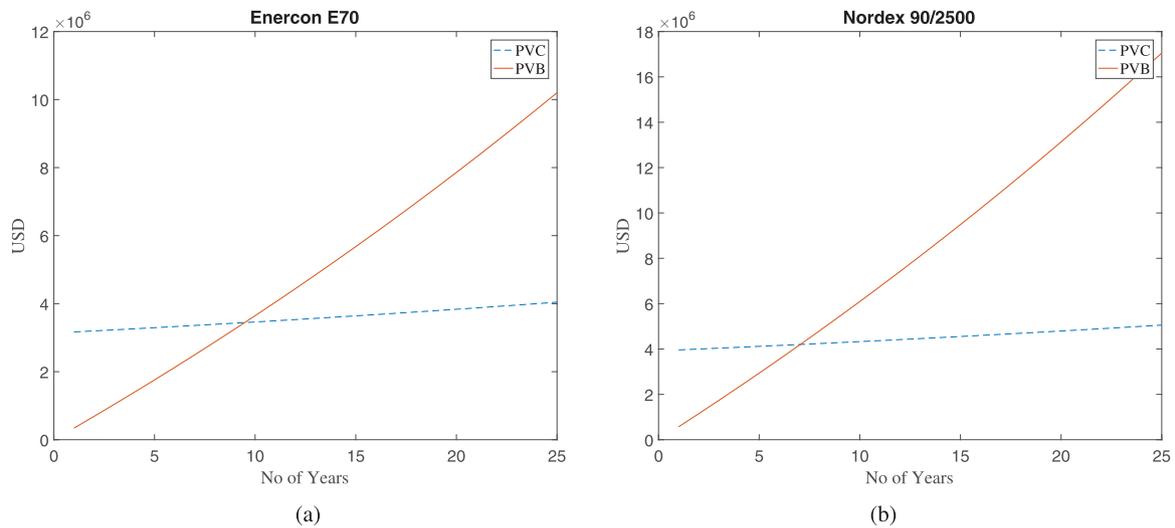


Fig. 19. Payback Period using (a) Enercon-70 (b) Nordex N90/2500.

Table 9

Payback periods of wind turbines.

Turbine	Payback period (years)
DeWind D6	7
DeWind D8	7.5
Nordex N90/2500	7
Enercon E-40	7.3
Enercon E-53	7
Enercon E-58	14.5
Enercon E-66	7
Enercon E-70	9.5

**CRedit authorship contribution statement**

**Muhammad Adnan:** Writing - original draft, Data curation, Visualization. **Jameel Ahmad:** Conceptualization, Methodology, Investigation, Writing - original draft. **Syed Farooq Ali:** Investigation, Data curation, Writing - original draft. **Muhammad Imran:** Supervision, Project administration, Funding acquisition, Formal analysis.

**Declaration of competing interest**

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

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**References**

Ahmad, J., Imran, M., Khalid, A., Iqbal, W., Ashraf, S.R., Adnan, M., Ali, S.F., Khokhar, K.S., 2018. Techno economic analysis of a wind-photovoltaic-biomass hybrid renewable energy system for rural electrification: A case study of Kallar Kahar. *Energy* 148, 208–234.

Ahmed, M., Ali, M.N., Memon, I.A., 2019. A review of wind energy potential in Sindh, Pakistan. *AIP Conf. Proc.* 2119 (1), 020017. <http://dx.doi.org/10.1063/1.5115376>.

Akdağ, S.A., Dinler, A., 2009. A new method to estimate Weibull parameters for wind energy applications. *Energy Convers. Manage.* 50 (7), 1761–1766.

Al-Shamma'a, A.A., Addoweesh, K.E., 2014. Techno-economic optimization of hybrid power system using genetic algorithm. *Int. J. Energy Res.* 38 (12), 1608–1623.

Alam, M.M., Rehman, S., Meyer, J.P., Al-Hadhrami, L.M., 2011. Review of 600–2500kW sized wind turbines and optimization of hub height for maximum wind energy yield realization. *Renew. Sustain. Energy Rev.* 15 (8), 3839–3849.

Ali, S., Jang, C.-M., 2020. Optimum design of hybrid renewable energy system for sustainable energy supply to a remote island. *Sustainability* 12 (3).

Amir, T., Arian, B., Hanifa, T., Maryam, V., Abdullah Oraj, H., 2019. Assessment of wind energy potential in the southeastern province of Iran. *Energy Sources, Part A: Recovery, Util., Environ. Eff.* 42, 329–343.

Arian, B., Amir, T., Chiemeka, O.O., Hamidreza, S., 2019a. Technical and economic analysis of wind energy potential in uzbekistan. *J. Cleaner Prod.* 223, 801–814.

Arian, B., Amir, T., Chiemeka, O.O., Nima, K., 2019b. Assessing the feasibility of wind energy as a power source in turkmenistan; a major opportunity for central Asia's energy market. *Energy* 183, 414–427.

Baloch, M.H., Abro, S.A., Sarwar Kaloi, G., Mirjat, N.H., Tahir, S., Nadeem, M.H., Gul, M., Memon, Z.A., Kumar, M., 2017. A research on electricity generation from wind corridors of Pakistan (two provinces): A technical proposal for remote zones. *Sustainability* 9 (9).

Baloch, M.H., Chauhdary, S.T., Ishak, D., Kaloi, G.S., Nadeem, M.H., Wattoo, W.A., Younas, T., Hamid, H.T., 2019. Hybrid energy sources status of Pakistan: An optimal technical proposal to solve the power crises issues. *Energy Strategy Rev.* 24, 132–153.

Baloch, M.H., Kaloi, G.S., Memon, Z.A., 2016. Current scenario of the wind energy in Pakistan challenges and future perspectives: A case study. *Energy Rep.* 2, 201–210.

Blaabjerg, F., Ma, K., 2013. Future on power electronics for wind turbine systems. *IEEE J. Emerg. Sel. Top. Power Electron.* 1 (3), 139–152. <http://dx.doi.org/10.1109/JESTPE.2013.2275978>.

Black, G., Black, M.A.T., Solan, D., Shropshire, D., 2015. Carbon free energy development and the role of small modular reactors: A review and decision framework for deployment in developing countries. *Renew. Sustain. Energy Rev.* 43, 83–94.

Carrillo, C., Cidrás, J., Dí az Dorado, E., Obando-Montaño, A.F., 2014. An approach to determine the Weibull parameters for wind energy analysis: The case of Galicia (Spain). *Energies* 7 (4), 2676–2700.

Carta, J.A., Ramírez, P., Velázquez, S., 2008. Influence of the level of fit of a density probability function to wind-speed data on the WECS mean power output estimation. *Energy Convers. Manage.* 49 (10), 2647–2655.

Chandel, S., Ramasamy, P., Murthy, K., 2014. Wind power potential assessment of 12 locations in western himalayan region of India. *Renew. Sustain. Energy Rev.* 39, 530–545.

Chang, T.P., 2011. Performance comparison of six numerical methods in estimating Weibull parameters for wind energy application. *Appl. Energy* 88 (1), 272–282.

Chaurasiya, P.K., Ahmed, S., Warudkar, V., 2018. Study of different parameters estimation methods of Weibull distribution to determine wind power density using ground based doppler sodar instrument. *Alex. Eng. J.* 57 (4), 2299–2311.

Haghiroost, T., 2019. Comparative study on typhoon's wind speed prediction by a neural networks model and a hydrodynamical model. *MethodsX* 6, 633–640.

- Hassan, Z., 2019. Monthly bulletin of statistics 2019. Pak. Bureau Stat. 67 (22), 1–314.
- IRENA, 2019. Renewable Power Generation Costs in 2018. International Renewable Energy Agency, Abu Dhabi.
- Jacobson, M.Z., Delucchi, M.A., Bauer, Z.A., Goodman, S.C., Chapman, W.E., Cameron, M.A., Bozonnat, C., Chobadi, L., Clonts, H.A., Enevoldsen, P., Erwin, J.R., Fobi, S.N., Goldstrom, O.K., Hennessy, E.M., Liu, J., Lo, J., Meyer, C.B., Morris, S.B., Moy, K.R., O'Neill, P.L., Petkov, I., Redfern, S., Schucker, R., Sontag, M.A., Wang, J., Weiner, E., Yachanin, A.S., 2017. 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world. *Joule* 1 (1), 108–121.
- Justus, C.G., Hargraves, W.R., Mikhail, A., Graber, D., 1978. Methods for estimating wind speed frequency distributions. *J. Appl. Meteorol.* 17 (3), 350–353.
- Kalogirou, S.A., 2004. Environmental benefits of domestic solar energy systems. *Energy Convers. Manage.* 45 (18), 3075–3092.
- kaplan, Y., 2017. Determination of the best Weibull methods for wind power assessment in the southern region of Turkey. *IET Renew. Power Gener.* 11 (1), 175–182.
- Kaygusuz, K., 2012. Energy for sustainable development: A case of developing countries. *Renew. Sustain. Energy Rev.* 16 (2), 1116–1126.
- Khahro, S.F., Tabbassum, K., Soomro, A.M., Liao, X., Alvi, M.B., Dong, L., Manzoor, M.F., 2014. Techno-economical evaluation of wind energy potential and analysis of power generation from wind at Gharo, Sindh Pakistan. *Renew. Sustain. Energy Rev.* 35, 460–474.
- Mirza, I.A., Khan, N.A., Memon, N., 2010. Development of benchmark wind speed for Gharo and Jhimpir, Pakistan. *Renew. Energy* 35 (3), 576–582.
- 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.
- Mohammadi, K., Mostafaeipour, A., 2013. Using different methods for comprehensive study of wind turbine utilization in Zarrineh, Iran. *Energy Convers. Manage.* 65, 463–470.
- Murthy, K., Rahi, O., 2017. A comprehensive review of wind resource assessment. *Renew. Sustain. Energy Rev.* 72, 1320–1342.
- Nematollahi, O., Alamdari, P., Jahangiri, M., Sedaghat, A., Alemrajabi, A.A., 2019. A techno-economical assessment of solar/wind resources and hydrogen production: A case study with GIS maps. *Energy* 175, 914–930.
- NEPRA, 2017. Determination of new tariff for wind power generation projects. National Electric Power Regulatory Authority Islamic Republic of Pakistan.
- Orłowska-Kowalska, T., Blaabjerg, F., Rodriguez, J., 2014. *Advanced and Intelligent Control in Power Electronics and Drives*. Springer, Cham, Springer International Publishing Switzerland 2014.
- Shami, S.H., Ahmad, J., Zafar, R., Haris, M., Bashir, S., 2016. Evaluating wind energy potential in Pakistan's three provinces, with proposal for integration into national power grid. *Renew. Sustain. Energy Rev.* 53, 408–421.
- Shoaib, M., Siddiqui, I., Amir, Y.M., Rehman, S.U., 2017. Evaluation of wind power potential in Baburband (Pakistan) using Weibull distribution function. *Renew. Sustain. Energy Rev.* 70, 1343–1351.
- Siddique, S., Wazir, R., 2016. A review of the wind power developments in Pakistan. *Renew. Sustain. Energy Rev.* 57, 351–361.
- Söderholm, P., Hildingsson, R., Johansson, B., Khan, J., Wilhelmsson, F., 2011. Governing the transition to low-carbon futures: A critical survey of energy scenarios for 2050. *Futures* 43 (10), 1105–1116, Special Issue: Energy Futures.
- Teimouri, M., Hoseini, S.M., Nadarajah, S., 2013. Comparison of estimation methods for the Weibull distribution. *Statistics* 47 (1), 93–109.
- Tizpar, A., Satkin, M., Roshan, M., Armoudli, Y., 2014. Wind resource assessment and wind power potential of mil-e nader region in sistan and Baluchestan province, Iran – part 1: Annual energy estimation. *Energy Convers. Manage.* 79, 273–280.
- Ulgen, K., Hepbasli, A., 2002. Determination of Weibull parameters for wind energy analysis of Izmir, Turkey. *Int. J. Energy Res.* 26 (6), 495–506.
- Ullah, I., uz Zaman Chaudhry, Q., Chipperfield, A.J., 2010. An evaluation of wind energy potential at Kati Bandar, Pakistan. *Renew. Sustain. Energy Rev.* 14 (2), 856–861.
- Wang, J., Huang, X., Li, Q., Ma, X., 2018. Comparison of seven methods for determining the optimal statistical distribution parameters: A case study of wind energy assessment in the large-scale wind farms of China. *Energy* 164, 432–448.
- Werapun, W., Tirawanichakul, Y., Waewsak, J., 2015. Comparative study of five methods to estimate Weibull parameters for wind speed on Phangan Island, Thailand. *Energy Procedia* 79, 976–981, 2015 International Conference on Alternative Energy in Developing Countries and Emerging Economies.
- Yilidrimar, O., Adiloglu, B., 2018. Wind resource mapping in Pakistan : Twelve month site resource report. In: *Energy Sector Management Assistance Program (ESMAP)*. World Bank Group, Washington, D.C, pp. 1–104.
- Ziazi, R., Mohammadi, K., Goudarzi, N., 2017. Techno-Economic assessment of utilizing wind energy for hydrogen production through electrolysis. In: *Proceedings of the ASME 2017 Power Conference Joint With ICOPE-17 collocated with the ASME 2017 11th International Conference on Energy Sustainability, the ASME 2017 15th International Conference on Fuel Cell Science, Engineering and Technology, and the ASME 2017 Nuclear Forum*. Charlotte, North Carolina, USA. June 26–30, 2017. V002T09A019.