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RESEARCH ARTICLE

A Parametric Approach to Compare the Wind Potential of Sanghar and Gwadar Wind Sites

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ABSTRACT Wind is one of the world's most rapidly expanding and environmentally friendly renewable energy sources (RES). The aim of this study is to analyze the wind potential availability in Sanghar and Gwadar cities through the wind characteristics' analysis. To analyze the wind potential at the both sites, one-year average wind speed data (including annual, monthly, day-night, and seasonal variations) for 2020 were used. A Weibull distribution parametric approach with five different technique was applied. Along with an analysis of the wind potential, an economic assessment was also out to estimate the installation cost, turbine-cost, capacity factor of ten different wind turbines with different rated power were used at the selected sites. The results show that at the Sanghar site, the maximum power of 1612.82 kW was generated by Vestas V126/3300 whereas the minimum power 383.44 kW was generated by Nordex n60/1300. At the Gwadar site, Vestas V126/3300 generated the maximum power of 745.10 kW and least power of 157.98 kW was generated by Nordex n60/1300. With respect to an economic assessment, Vestas V126/3300 and Suzlon S66/1250 had the highest and lowest installation cost of turbines respectively at both sites. At the Sanghar site, the lowest value i.e., 0.0422 kWh/$, 0.0893 kWh/$ and the highest values 0.081 kWh/$, 0.2028 kWh/$ were shown by Goldwind GW121/2500 and Nordex n80/2500 at the Gwadar and Sanghar sites respectively.

INDEX TERMS Wind, renewable energy, economic analysis, weibull distribution.

I. INTRODUCTION

Excessive use of fossil fuels, including natural gas, oil, coal, and gasoline, has resulted in severely hazardous air in recent years. The world's climate has been badly impacted as a result of these factors; massive amounts of greenhouse gases have been released as a result of inappropriate use of fossil fuels to generate electrical energy. Carbon dioxide (CO_2) is one of these toxic gases responsible for affecting the ozone layer and become a major cause of increasing global warming. Nevertheless, as energy use rises and fossil fuels deplete, it's crucial to shift to alternative energy generation that is affordable, clean, and sustainable in order to reduce reliance on all of these sources [1], [2]. Solar, Wind, Biomass, and Geothermal power are counted as the most active economical and viable renewable energy resources (RES). Amongst these RES, the wind is regarded as the most efficient, affordable, clean, and green, and universally used by almost all the developed and developing countries. Hence, due to rapid development and innovation, the wind energy has got extensive popularity in the recent years [3], [4]. Making wind energy more accessible, harnessing all available wind power can meet 35% of the world's electricity consumption [5]. The total capacity of all wind generators worldwide has already reached 837 gigawatts by 2022, according to a research published by the World Wind Energy Association (WWEA), underscoring the significance and demand for this source of energy in the future [6]. The Global Wind Energy Council (GWEC), which monitors cross - border investment in the

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wind energy industry, is trying hard to make wind power a major source of electricity generation. China, according to the GWEC assessment, is rapidly implementing energy policies and transitioning to new energy sources. China installed approximately 30 GW in 2021, making it in the first position with a total installed wind capacity of 310 GW which is the thirty nine percent of its total of capacity. The United States and Germany, which have total installed capacity of 134 GW and 56 GW, respectively and ranks second and third in the wind installation capacity [7]. Pakistan possesses negligible oil and gas reserves so most of its furnace-based power plants run on the exported oil and nuclear power plants require very high cost for the production of energy. As a result, harnessing renewable energy sources to generate electrical power and address the country's growing energy shortage is imperative. Pakistan is one of the privileged countries which possess almost all types of renewable energy resources in massive amount. The Pakistan Meteorological Department (PMD) gathers information to identify the optimal locations for wind and other renewable energy sources at different locations across the country. A 1100 km long and significant wind corridor exists along the shores of Sindh and Baluchistan provinces [8].

Before a wind project is established, its feasibility, investment cost, operational and management (O&M) cost, and energy potential should all be thoroughly examined to make sure the minimum investment risk and highest efficiency. To evaluate and examine the characteristics of wind data, several researchers have found statistical descriptors and probability distributions. When it comes to analysing wind data, the Weibull and Rayleigh distributions provide the best choice [9], [10], [11]. Amongst these probability and statistical descriptors, Weibull has emerged a standard because of its simplicity and flexibility, and, as per the international standards two-parameter Weibull is an appropriate method to analyze wind characteristics. These parameters—Weibull shape and scale parameters—are easily computed using multiple methods [12], [13].The statistical interpretation of wind speed is evaluated though different probability density functions for actual wind speed data [14].

Many authors have also focused on the wind potential of different area using the said technique [15], [16], [17], [18], [19], [20], [21], [22]. The Weibull statistical distribution is used to process and examine wind data from the Alacat region near Izmir.The simulation was performed continuously for five years at three different altitudes of 70, 50, and 30 m, in ten minute intervals, and the mean wind speed (WS) was found to be 8.11 m/s for the entire data set [23]. A similar study was conducted on four different Iranian sites—Mirjaveh, Zabol, Zahedan, and Zahak—in which the Weibull distribution was used to evaluate different wind data sets. Wind power and energy density parameters were utilized in this study to determine the cost of wind fields at the selected sites. Mirjaveh is suitable for off-grid generating and can be used for water pumping and battery charging [24]. Authors have carried out probabilistic and deterministic wind speed forecasting based on non-parametric approaches and wind characteristics in [25] and [26].

Along with the technical and statistical analysis of wind energy resources, it's also equally very pertinent to carry out economic analysis of the sites to avert an investment failure. Such economic studies are being carried out in cities such as Zahedan in Iran, Kutahya in Turkey, selected areas in Jordan, Johannesburg in South Africa, some onshore locations in China, the Kiribati Islands, and many more to explore how to reduce the risk of wind projects underperforming [27], [28], [29], [30], [31], [32], [33].

Multiple studies have been carried out in the past in various regions of Pakistan, in which different researchers assessed multiple aspects of wind data collected over temporal scales [34]. A similar study was conducted in Karachi explore its wind energy potential [35]. In Keti Bander, more investigations were carried out in [36], Gharo and Jhimpir [37], Jamshoro [38], and Babur [39]. These analyses show the significance of carefully examining wind speed data in order to accurately estimate wind power potential. In this paper two different locations present in Sanghar, and Gwadar districts of Sindh and Baluchistan province are selected, and a detailed wind potential and economics cost analyses of both locations are carried using five different techniques of Weibull parametric approach and simulated data of the ten different wind turbine models o possessing different specifications.

II. SITES DESCRIPTION AND DATA COLLECTION

In order to install a wind turbine at a location, many factors are needed to be considered. Capacity factor, site location, weather conditions, land area, terrain, future growth possibilities, unobstructed objects (buildings, trees, etc.), topography, closeness to main grid, and grid connectivity are to be considered for a site selection. Wind characteristics, particularly wind speed distribution (WSD), higher wind frequencies (HWF), and the Weibull shape parameter (k), which contribute to the analysis of the location under consideration, are the most important among these factors. The Weibull scale parameter (c) encompasses determining the wind energy potential of a specific site as well as wind rose diagrams that indicate the wind direction. Locations of Sanghar and Gwadar wind sites are vividly depicted in Fig 1. Details of both sites are given in Table 1.

A. SINDH PROVINCE

Sindh province is one of the richest provinces in Pakistan with respect to natural resources. Its capital city -Karachi is the major economic hub and metropolitan city of Pakistan. Sindh province not only possesses natural reserves including gas, minerals, and coal etc. in its different districts but also many wind corridors in its coastal and central areas i.e., Gharo, Thatta and Karachi and Hyderabad, Norriabad and

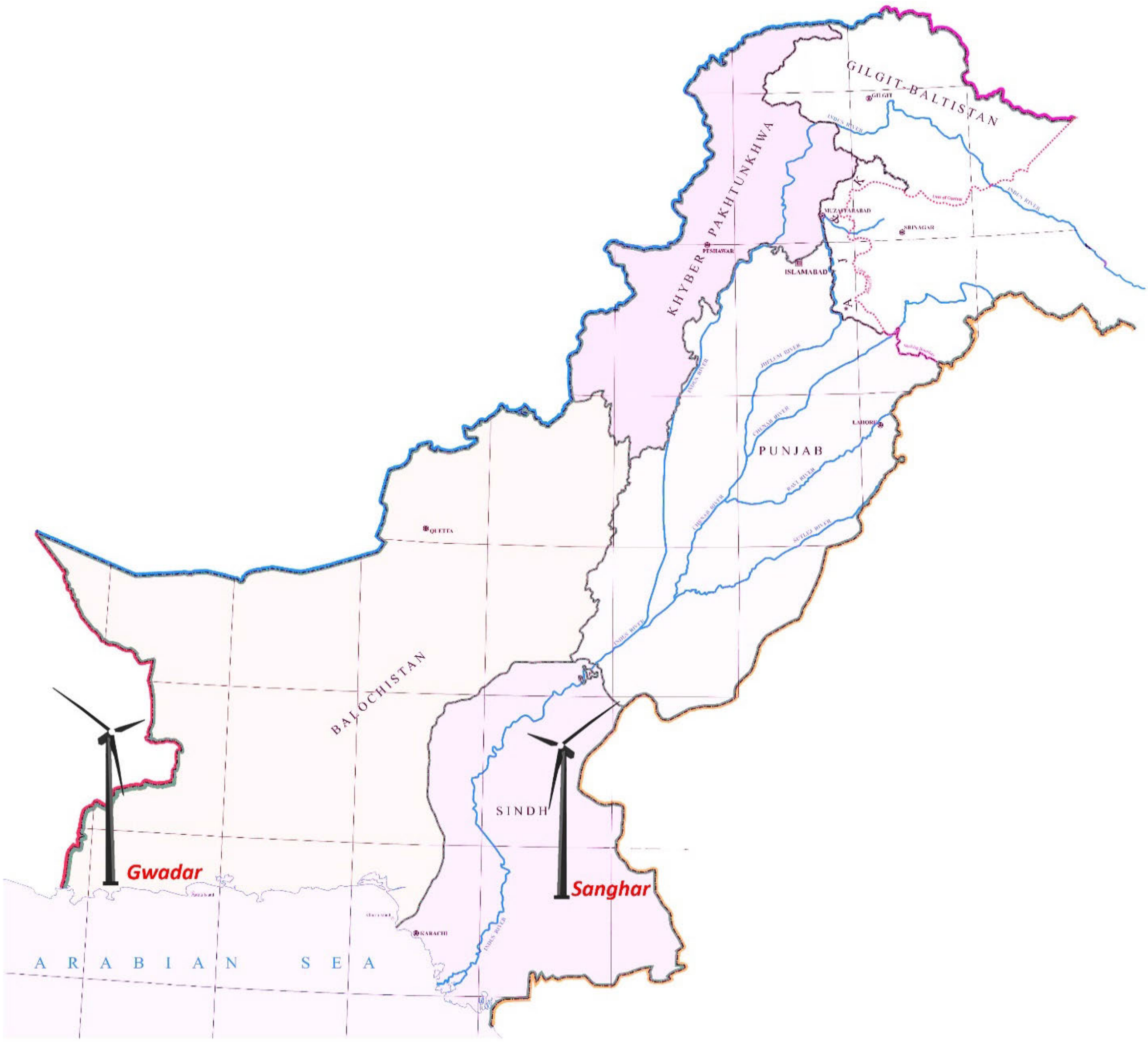


FIGURE 1. Locations of sanghar and gwadar wind masts on the pakistan in the world map.

TABLE 1. Wind sites installed at Sanghar and Gwadar location [40].

Province	Mast Name	District	Coordinates	Terrain	Elevation	Height
Sindh	Kandiari Site	Sanghar	25°48'57.26"N 69° 2'15.12"E	Flat, wide open with no obstruction	29 m	80 m
Baluchistan	GIT	Gwadar	25°16'47.30"N 62°20'46.95"	Flat with no obstruction or roughness	15 m	80 m

Jamshoro respectively. Sindh province is also included in China Pakistan Economic Corridor (CPEC), so the funds and investors attraction can be drawn towards this gargantuan wind potential available in Sindh.

Different studies have been conducted to examine the wind potential available in Karachi, Hyderabad, and Jamshoro districts, but no study has yet been conducted to investigate the wind potential available in Sanghar district.

1) SANGHAR CITY

Sanghar is a prominent city in Pakistan's Sindh province, located at longitude 68.9464 E and latitude 26.0488 N, with an elevation of 29 meters. The area is situated in one of Pakistan's major geographic locations. The distance between Sanghar and Karachi is 268 kilometers. It has road links with Hyderabad, Nawabshah, and Mirpur Khas cities. The elevation map and Ground Roughness Map of Sanghar city are shown in Fig 2 (a), (b).

2) KANDIARI WIND MAST FOR WIND RESOURCE ASSESSMENT

This wind mast is installed at Kandiari in district Sanghar, Sindh, Pakistan. The height of mast is 80m and geographic location of site is 25°48'57.26" N and 69° 2'15.12" E. The site is flat, wide open with no obstruction, at elevation of 20m. The elevation map and Ground Roughness Map of Sanghar are shown in Fig 2 (a), (b). The wind mast installed at Sanghar site is shown in Fig 4 (a).

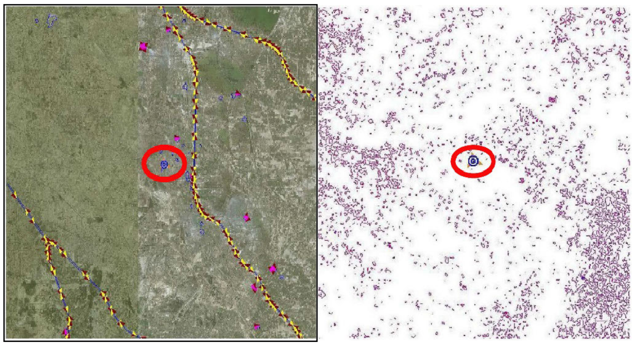

(a) Elevation Map (b) Ground Roughness Map

FIGURE 2. Sanghar city map overview: (a) Elevation map; (b) Ground roughness map.

B. BALUCHISTAN PROVINCE

Baluchistan province is the largest province of Pakistan with respect to area. This province is also enriched with natural resources including coal, minerals, natural gas, and wind potential etc. Its capital city -Quetta has got much attention due to the initialization of CPEC and its economy has boomed in the recent years.

1) GWADAR CITY

Gwadar is a district in Baluchistan located along the sea in the south of the Makran, at longitude 62.3225 E and latitude 25.126389 N, with an elevation of 15 m.The coastline of Gwadar District is about 600 Kilometers long.Gwadar is bordered to the east by the Lasbela district, to the south by the Arabian Sea, and to the west by Iran. Gwadar has got gargantuan attraction after being explored as the one of the deepest ports in the world and China Pakistan Economic Corridor (CPEC). Recently, developments being carried out at Gwadar on a massive level gives a boost to the economy of Pakistan. In order to meet the growing energy needs of Gwadar due to economic prosperity, Government of Pakistan has taken many initiatives to generate electricity in Gwadar. Because to be on the coastal belt, it attracts the wind on a good scale level. The elevation map and Ground Roughness Map of Gwadar city are shown in Fig 3 (a), (b).

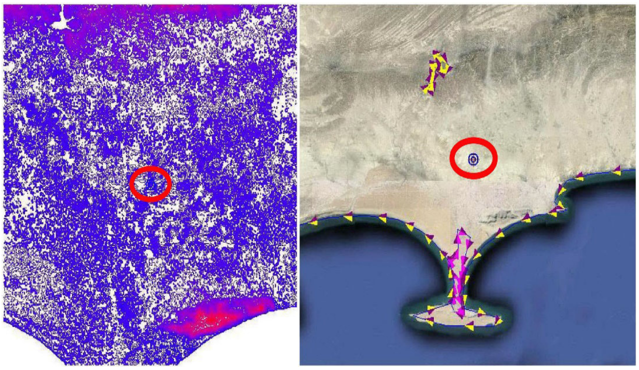

(a) Elevation Map (b) Ground Roughness Map

FIGURE 3. Gwadar city map overview: (a) Elevation map; (b) Ground roughness map.

2) GWADAR WIND MAST FOR WIND RESOURCE ASSESSMENT

Gwadar wind mast is funded by the world bank. This mast is installed in Gwadar, Balochistan, Pakistan. The wind mast is 80 m tall, and the Gwadar site is positioned at 25°16'47.30"N and 62°20'46.95"E. At a height of 13 metres, the location is flat and void of considerable obstacles. The wind mast installed at Gwadar site is shown in Fig 4 (b).


(**a**) Sanghar Wind mast (**b**)Gwadar Wind Mast

FIGURE 4. Locations of installed wind mast at: (a) Sanghar; (b) Gwadar.

III. METHODOLOGY

In this paper two sites are considered, one from the Sanghar district of Sindh province, and second from Gwadar district of in Baluchistan province, for the analysis of wind potential available there. In order to analyze the wind potential, one year data is analyzed. For the assessment of wind potential availability in the selected locations, Matlab software is used, and Weibull parametric estimation approaches are used to achieve the desired results. For ensuring accuracy in the simulation results, the data quality assurance tests are performed in the model for the analysis of wind potential available in the desired sites of Sanghar and Gwadar districts.

A. WIND DATA ASSESSMENT

The wind speed varies over a period of time, sometimes it blows at a maximum speed, sometimes with a minimum speed and sometimes with an average speed, so there is a continuous change in the speed of wind. As the wind speed does not blow at the constant speed so there are many factors which impact the generation of wind power which include air density, atmospheric temperature, and hub height of a wind turbine. There is an immediate need to evaluate wind resources available in the specified area employing wind characteristics in order to generate maximum capacity and impact the performance of wind potential in the energy markets. The frequency distribution of wind speed may result in different wind power densities for the same wind speed, so the knowledge of wind power density (WPD) needs to be taken into account for the analysis of wind potential. The WPD is expressed in terms of W/m^2 for the selected locations and is calculated based upon the probability distribution function of wind speed [41].

B. WIND CHARACTERISTICS

It is necessary to have the knowledge of different wind characteristics to do the wind power assessment of the selected sites. Wind continuously varies its magnitude, direction, and density due to its volatile nature [42]. In order to do the effective assessment and utilization of wind energy, wind characteristics needs to be considered precisely. How the wind turbines perform, it depends upon the wind rose of the site; speed and frequency of the wind [43], [44].

1) AVERAGE WIND SPEED

The data set of average wind speed collected by a wind mast or sonar can be measured using Equation (1).

$$v_{avg} = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{1}$$

2) VARIANCE (σ)

In order to calculate the variance from wind speed data, Equation (2) is used as,

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(v_i - v_{avg}\right)^2 \tag{2}$$

3) STANDARD DEVIATION (σ)

Standard deviation can be calculated using Equation (3) as,

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(v_i - v_{avg}\right)^2} \tag{3}$$

4) AIR DENSITY (ρ)

For the calculation of air density of the selected sites, the Equation (4) can be used as,

$$\rho = \frac{P_r}{R \times T} \tag{4}$$

where P_r is air pressure (Pa or N/m^2), R is the specific gas constant (287 J/kg), and T is air temperature at the site in kelvin ($C + 273^o$).

5) WIND POWER DENSITY(WPD)

Due to volatile nature of wind, wind speed varies, and the wind power density plays an important role in the determination at different speeds on the selected locations, and it's computed on the basis of wind speed data as given in Equation (5).

$$WPD = \frac{P}{A_T} = \frac{1}{2}\rho c_p v^3 \tag{5}$$

where ρ is air density,
c_p is Betz limit equal to (0.593),
A_T is swept area of turbine blades (m^2),
P is wind power (W) and v is wind velocity (m/s).

6) ENERGY (E)

At the selected wind sites, the Energy of the wind in terms of Weibull distribution can be calculated using Equation (6).

$$E = T\int\left(\frac{K}{C}\right)\left(\frac{V}{C}\right)^{k-1}\exp\left(-\frac{V}{C}\right)^{k} .P(V)dV \tag{6}$$

where E is energy output in terms of Weibull distribution at the proposed site in (kWh/m^2). $P(V)$, T, V, K and C are wind turbine's power curve, time period, wind velocity, shape and scale parameters respectively [45].

7) SHEAR PROFILE

Calculation of the wind shear of the selected sites can be done using Equations (7) and (8) respectively. In this process, Alpha ($\propto$) is very important to estimate wind velocities at higher altitude by processing the wind velocities measured at lower or previous altitudes [46], [47].

$$\alpha = \frac{\ln(V_2) - \ln(V_1)}{\ln(Z_2) - \ln(Z_1)} \tag{7}$$

$$\alpha = \frac{0.37 - 0.088\ln(h)}{1 - 0.088 \times \ln\left(\frac{2}{10}\right)} \tag{8}$$

8) POWER LAW

Wind speed at hub height can be calculated using Power law given in Equation (9) [48].

$$v_2 = v_1\left(\frac{z_2}{z_1}\right)^{\alpha} \tag{9}$$

9) WIND TURBULENCE INTENSITY

Equation (10) is used to calculate the Wind Turbulence Intensity [49] which is defined as the ten-minute standard deviation of the velocity divided by the ten-minute mean velocity of the wind.

$$TI = \frac{\sigma}{V} \tag{10}$$

C. WIND POWER CLASSES

Analysis for the installation of wind turbines is carried out on the basis of international wind power classes given in Table 2 [50]. The wind resource classes are divided into seven types and are analyzed at different heights i.e., 10 m, 30m, and 50 m and wind speeds (m/sec).These classes possess different wind speeds at the different heights which results indifferent wind power densities. Wind Class 1, Class 2, Class 3, Class 4, and Class 5-7 are regarded as poor, marginal, moderate, good, and excellent respectively. At the height of 10m, these all seven wind classes possess least power densities as compared to 30m and 50m heights. The wind speed range recorded in the excellent classes at 10m, 30m, and 50m heights is 6-11 m/s. These seven classes due to possessing different wind speed and power densities are classified into different categories, as the classes 1-2 are considered for rural applications where power demand is very low. The class 3 is considered for the areas where applications don't require hefty power. Class 4-7 are considered for commercial purposes [51], [52].

D. WEIBULL DISTRIBUTION

After the collection of wind speed data, Weibull distribution can be described as a probability density function $f(v)$, and cumulative distribution function $F(v)$ shown in Equation (11) and (12) respectively [45].

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left(-\frac{v}{c}\right)^{k} \tag{11}$$

$$F(v) = 1 - exp\left[1 - \left(\frac{v}{c}\right)^{k}\right] \tag{12}$$

Mean wind speed (v_{avg}) can be calculated using Weibull parameters as given in Equation (13).

$$v_{avg} = c\Gamma\left(1 + \frac{1}{k}\right) \tag{13}$$

Variance (σ) is calculated using Equation (14).

$$\sigma^2 = c^2\left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{2}{k}\right)\right] \tag{14}$$

Gamma Function $\Gamma_{(y)}$ can be calculated using Equation (15).

$$\Gamma_{(y)} = \int_0^t e^{-u}u^{y-1}du \tag{15}$$

1) DIFFERENT WEIBULL METHODS

The most important parameters of Weibull distribution function are shape (k) and scale (c) which are used for the evaluation of wind potential at the selected sites of Sanghar and Gwadar Districts. Many techniques for evaluating wind potential were analyzed during the review of the literature, but in this paper, five methods i.e., modified maximum likelihood method (MMLM), graphical method (GM), empirical method of Lysen (EML), empirical method of Jestus (EMJ), and energy pattern factor method (EPF) were selected to simulate wind models and access wind potential availability at the selected locations.

2) MODIFIED MAXIMUM LIKELIHOOD METHOD (MMLM)

This method needs wind speed data in the frequency distribution format and number of iterations are performed in order to determine shape (k) and scale (c) parameters of Weibull distribution function given in Equations (16) and (17) [53].

$$k = \left(\frac{\sum_{i=1}^{n} v_i^k ln\,(v_i) f\,(v_i)}{\sum_{i=1}^{n} v_i^k f\,(v_i)} - \frac{\sum_{i=1}^{n} ln\,(v_i) f\,(v_i)}{f\,(v \geq 0)}\right)^{-1} \tag{16}$$

$$c = \left(\frac{1}{f\,(v \geq 0)} \sum_{i=1}^{n} v_i^k f\,(v_i)\right)^{\frac{1}{k}} \tag{17}$$

3) EMPIRICAL METHOD OF LYSEN (EML)

In this method, Parameters, shape (k) and scale (c) are calculated using Equations (18) and (19) respectively [54].

$$k = \left(\frac{\sigma}{v_{avg}}\right)^{-1.086} \tag{18}$$

$$c = v_{avg}\left(0.568 + \frac{0.433}{k}\right)^{\frac{-1}{k}} \tag{19}$$

4) EMPIRICAL METHOD OF JESTUS (EMJ)

In this method, the shape parameter (k) and scale parameter (c) are calculated using Equations (18) and (20) respectively [55].

$$c = \frac{v_{avg}}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{20}$$

5) GRAPHICAL METHOD (GM)

This method uses the cumulative distribution functions of Weibull distribution in which wind data sets are sorted into bins because of the least square regression obtained. The graphical method equation can be obtained by taking double logarithms of Equation (12) [56].

$$ln\,[-ln\,(1 - F\,(v))] = klnv - k\ln c \tag{21}$$

By Comparing Equation (21) with $y = ax + b$, it yields Equation (22) as:

$$y = ln\,[-ln\,(1 - F\,(v))]\,, x = lnv, \tag{22}$$

$$a = k \text{ and } b = -k\ln c, k = a \text{ and } c = e^{-\frac{b}{k}} \tag{23}$$

TABLE 2. **Wind generation categorization as per global standards [5].**

Height		At 10m		At 30m		At 50m	
No:	Resource Class	m/s	W/m^2	m/s	W/m^2	m/s	W/m^2
1	Poor	0-4.4	0-100	0-5.1	0-160	0-5.4	0-200
2	Marginal	4.4-5.1	100-150	5.1-5.9	160-240	5.4-6.2	200-300
3	Moderate	5.1-5.6	150-200	5.9-6.5	240-320	6.2-6.9	300-400
4	Good	5.6-6.0	200-250	6.5-7.0	320-400	6.9-7.4	400-500
5	Excellent	6.0-6.4	250-300	7.0-7.4	400-480	7.4-7.8	500-600
6	Excellent	6.4-7.0	300-400	7.4-8.2	480-640	7.8-8.6	600-800
7	Excellent	>7.0	>400	8.2-11	640-1600	>8.6	>800

Parameters x and y are calculated using measured wind speed data in Equation (22).The slope (a), intercept (b), shape (k), and scale (c) parameters, on either hand, can be computed using the standard least regression technique as seen in Equation (23).

6) ENERGY PATTERN FACTOR METHOD (EPF)

This method takes wind speed data to calculate shape (k) and scale (c) parameters of Weibull distribution. In this method, the Energy pattern factor (E_{pf}) which is the ratio of average of cubic value of wind speed data over cubic value of average wind speed data can be calculated in Equation (24). The scale (c) and shape (k) parameters of the Weibull distribution are computed using wind speed data, as given in Equations (20) and (25) respectively [57].

$$E_{pf} = \frac{\frac{1}{n}\sum_{i=1}^{n} v_i^3}{\left(\frac{1}{n}\sum_{i=1}^{n} v_i\right)^3} = \frac{(v^3)_{avg}}{(v_{avg})^3} = \frac{\Gamma\left(1+\frac{3}{k}\right)}{\Gamma^3\left(1+\frac{1}{k}\right)} \tag{24}$$

$$k = 1 + \frac{3.69}{(Epf)^2} \tag{25}$$

E. PREDICTION PERFORMANCE OF WEIBULL DISTRIBUTION MODELS

In order to check the performance of all the Weibull distribution models used in this paper, five different statistical methods given below are selected to show that which method yields the best results amongst others. All the fives statistical models used in this paper are given as:

1) COEFFICIENT OF CORRELATION (R)

This numerical model corelates the estimated and observed wind frequency data. The Coefficient of Correlation (R) is expressed in Equation (26) [58].

$$R = \frac{N(\sum_{i=1}^{N} x_i y_i) - (\sum_{i=1}^{N} x_i)(\sum_{i=1}^{N} y_i)}{\sqrt{N(\sum_{i=1}^{N} x_i^2) - (\sum_{i=1}^{N} x_i)^2}\sqrt{N(\sum_{i=1}^{N} y_i^2) - (\sum_{i=1}^{N} y_i)^2}} \tag{26}$$

2) COEFFICIENT OF DETERMINATION (R^2)

If the value of R^2 is closer to one, the test yields a better model that fits the reference data the best. The coefficient of determination (R^2) is given in Equation (27) as [59].

$$R^2 = \frac{\sum_{i=1}^{N}(y_i-\bar{y})^2 - \sum_{i=1}^{N}(x_i-\bar{y})^2}{\sum_{i=1}^{N}(y_i-\bar{y})^2} \tag{27}$$

3) MEAN ABSOLUTE ERROR (MAE)

It gives the details about the mean magnitude of the errors present in the data without affecting the positive and negative errors. Mean absolute error (MAE) is obtained through Absolute values and mean of measured data as given in Equation (28).

$$MAE = \frac{1}{N}\sum_{i=1}^{N}(|x_i - y_i|) \tag{28}$$

4) MEAN SQUARED ERROR (MSE)

Equation (29) gives the Mean Squared Error (MSE) which is used to get best Weibull distribution method. The minimum Mean Squared Error is considered the best fit of method over given data.

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2 \tag{29}$$

5) ROOT MEAN SQUARED ERROR (RMSE)

The purpose of this statistical test is to determine the absolute measure of the statistical model's fit to the reference data. It's useful in calculating discrete data points for estimating error or uncertainty in the results. Owing to having the square root of the variance, the lower the value, the better the method.The performance of this numerical model is better when its values reach near to zero. The RMSE can be calculated from Equation (30) as follows [60].

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2\right]^{1/2} \tag{30}$$

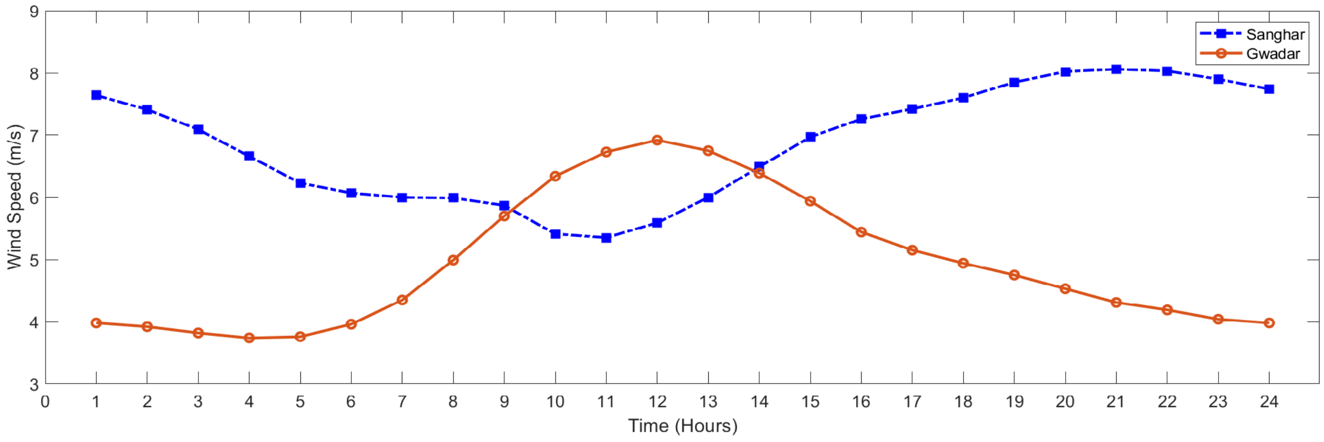


FIGURE 5. **Average wind speed of Sanghar and Gwadar wind sites.**

The values y_i, x_i, $\bar{y}$ and N represent *ith* actual wind speed, *ith* predicted wind speed, mean of actual wind speed and number of observations respectively in Equations (26-30).

IV. RESULTS AND DISCUSSION

In this study, one year wind data, from May 2020 to April 2021, was collected from the locations of Sanghar and Gwadar districts, located in Sindh and Baluchistan province of Pakistan respectively. Five different Weibull techniques were used to investigate the probability distribution of the wind speed data and in order to check the performance of all the Weibull distribution models used, five different statistical methods given are selected to show that which method yields the best results amongst others. Wind directions were analyzed to yield an optimum evaluation of the selected wind site. Finally, economic analysis was conducted to determine complete feasibility of the wind profile in the area. The following section is a discussion of the results obtained.

A. WIND SPEED ANALYSIS

Fig 5 gives the diurnal wind speeds of a complete one year i.e., May 2020 to April 2021, for 24 hours. It can be seen that Sanghar and Gwadar both have different wind speeds during the 24 hours. The wind speed was found maximum 8.06 m/s at 21:00 and 6.92 m/s at 12:00 at Sanghar and Gwadar sites respectively. The minimum speed was noted 5.35 m/s at 11:00 at Sanghar site and 3.74 m/s at 4:00 at Gwadar site. The wind speed pattern of Sanghar site shows that the wind speed reduces in the morning and noon hours but as the noon hours passes, it increases and gets stronger in the evening and mid night hours. The Gwadar has different wind pattern than the Sanghar. At Gwadar site, wind speed is low at the night and early morning hours but as the day breaks, the wind speed increases and get higher and attains the maximum speed at the noon. Wind speed at the Gwadar site gets slower and lower in the evening hours and night hours. From the volume aspect of wind speed, the Sanghar receives 164.65 m/s and Gwadar obtains 118.62 m/s during the one-day span.

Table 3 gives the seasonal average wind speed ranking at the selected sites. Sanghar site receives highest wind speed 8.05 m/s in the summer season and minimum wind speed 5.65 m/s in the autumn season. Wind Speed 7.10 m/s and 5.82 m/s was recorded at the Sangahr site in Spring and Winter season respectively.Gwadar site gets the maximum wind speed 5.84 m/s in Spring season and minimum wind speed 4.45 m/s in the summer season respectively. Whereas this site received wind speed 4.63 m/s in Winter season and 5.22 m/s in Autumn season.

Table 4 gives the day and night time average wind speeds at the selected sites of Sanghar and Gwadar sites. Sanghar site receives on average 6.61 m/s wind speed at the daytime and 7.45 m/s at the night time.

TABLE 3. **Average wind speed at the selected sites.**

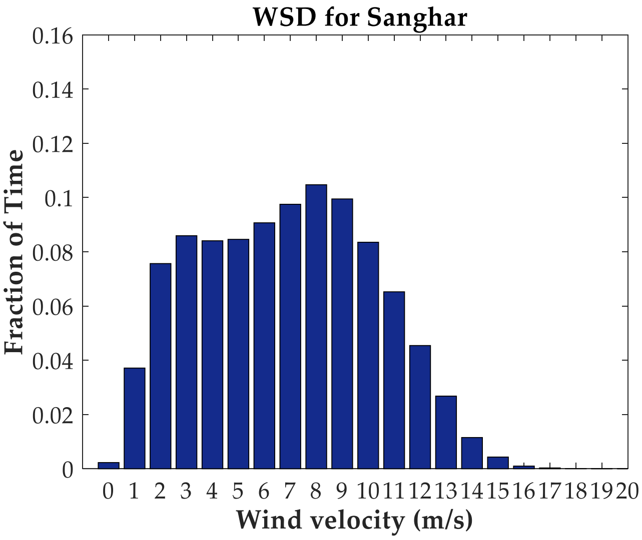
	Average wind speed (m/s)			
Site	Winter	Spring	Summer	Autumn
Sanghar	5.82	7.10	8.05	5.65
Gwadar	4.63	5.84	4.45	5.22

It can be analyzed that this site received the higher wind speed at the night time as compared to the day time. A Gwadar site receives the average wind speed of 5.66 m/s and 4.12 m/s at the day and night time respectively. It can also be observed that a Gwadar site gets higher wind speed at the day time as compared to night time. Data shows that Sanghar site receives more wind speed than the Gwadar site not only in terms of total volume but also with respect to day and night time.

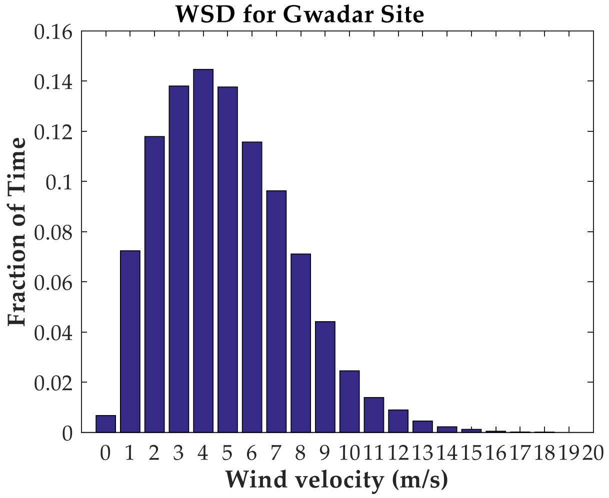
The wind speed distributions (WSDs) of the wind masts installed at the Sanghar and Gwadar are given in Figure 6 (a) and (b). Figure 6 (a) shows that the maximum wind speed of 8 m/s is generated at 0.1 fraction of time by the Wind Mast installed at the Sanghar site, whereas Figure 6 (b) shows the highest wind speed of 4 m/s at the 0.14 fraction of time recorded by the Wind Mast installed at Gwadar site.

TABLE 4. **Average wind speed of day and night time at the selected sites.**

	Average Speed (m/s)	
Site	Day Time	Night Time
Sanghar	6.31	7.45
Gwadar	5.66	4.12

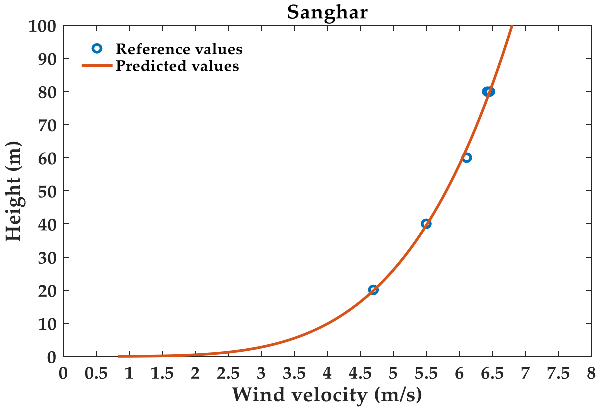


(a) Sanghar Wind mast

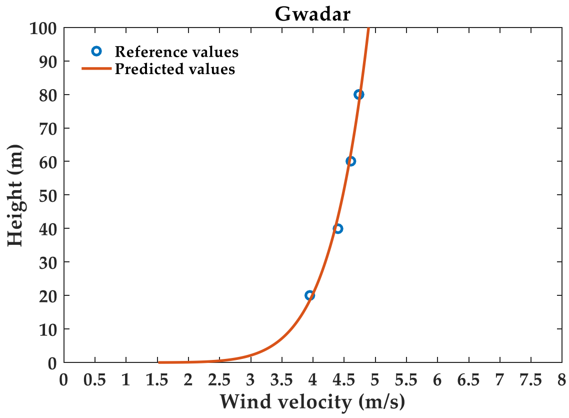


(b) Gwadar Wind Mast

FIGURE 6. **Shows wind speed distribution of the selected sites: (a) Sanghar site; (b) Gwadar site.**



(a) Sanghar Site



(b) Gwadar Site

FIGURE 7. **Shear profile and power law of the selected sites: (a) Sanghar site; (b) Gwadar site.**

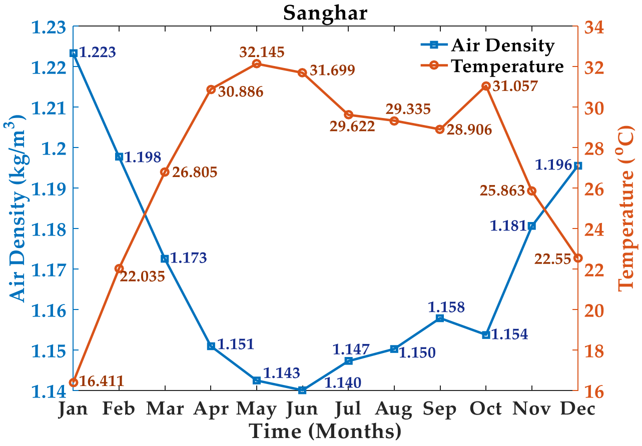
Shear profile and power law values of the Sanghar and Gwadar locations are given in Figure 7 (a) and (b) respectively in which wind velocity is calculated against the different height and the curve is drawn between predicted and reference values accordingly. Air density has inverse relation to temperature but direct relation to the wind power density.

Monthly air density and temperature values for Sanghar and Gwadar are given in Figure 8 (a) and (b) respectively.

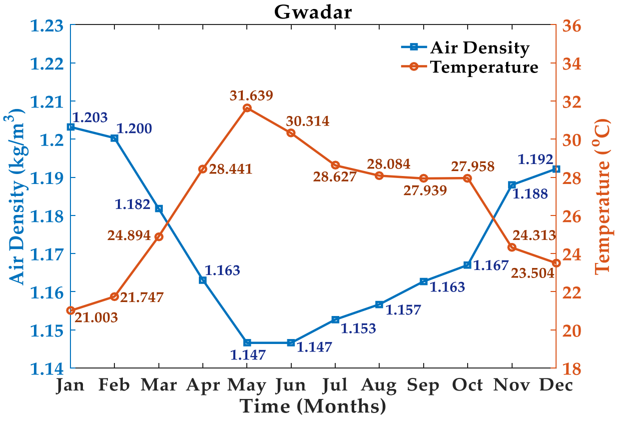
Monthly wind power density (WPD) calculated for the Sanghar and Gwadar sites at the height of 100m, 80m, 60m and 40m is shown in Figure 9 (a) and (b) respectively. Turbulence intensity calculated for the Sanghar, and Gwadar locations are given in Figure 10 (a) and (b), respectively. Results show least turbulence intensity as compared to Sanghar site because Gwadar site is very close to sea level and provides very low friction to ground level wind speeds [61].

B. WINDROSE DIAGRAMS

For determining of the maximum outputs from the wind sites; it's imperative to do its optimum configuration and wind directions play a pivotal role in obtaining such optimum results. The wind rose diagram of a place depicts the direction of the wind and the percentage of wind speeds in each direction. Wind directions can be analyzed using rose diagrams where 15°arc divides the whole diagram into 24 sectors and 0°, 90°,180°, 270° represents North, East, South and West directions respectively. Figure 11 (a) and (b) gives the wind rose diagrams of Sanghar and Gwadar sites districts for a complete year 2021. Using data, MATLAB is used to construct the wind rose diagrams to find the overall wind direction frequency of the selected sites. It can be noted from the wind rose diagram given in Figure 11 (a) that at the Sanghar sites wind blows mostly from the West direction and it receives maximum wind 30% from this direction.

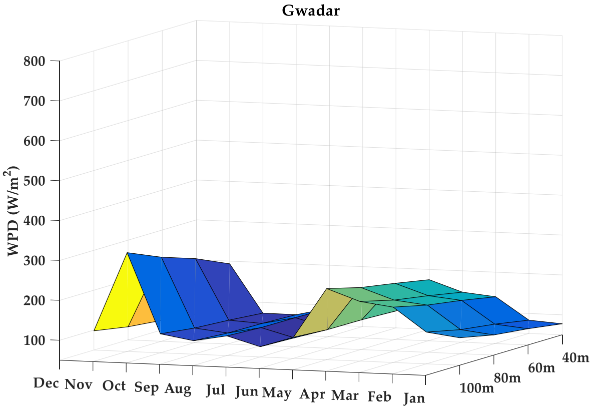


(a) Sanghar Site

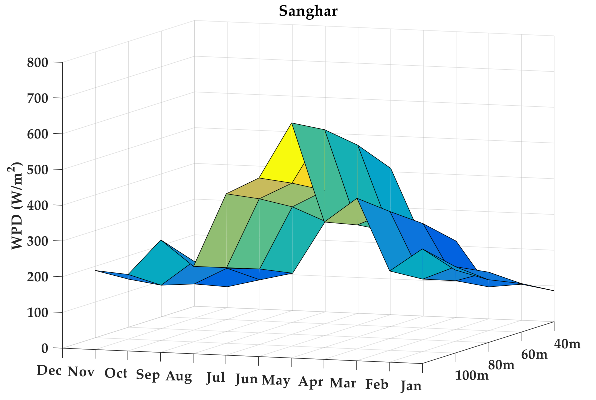


(b) Gwadar Site

FIGURE 8. **Air density and temperature of the selected sites: (a) Sanghar site; (b) Gwadar site.**



(a) Sanghar Site



(b) Gwadar Site

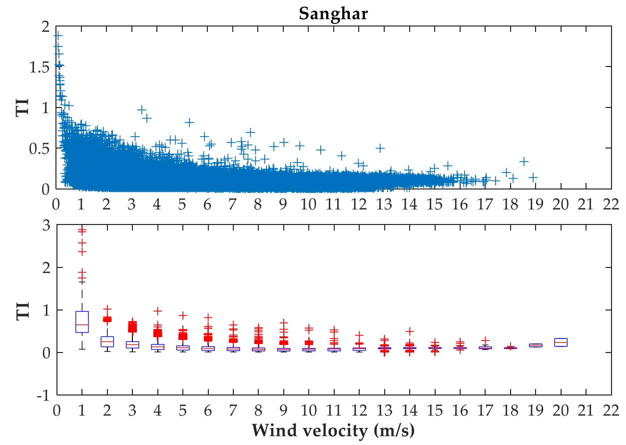
FIGURE 9. **Wind power density of the selected sites: (a) Sanghar site; (b) Gwadar site.**

Figure 11 (b) shows the wind rose diagram of Gwadar site and it can be seen that at this site wind is mostly influenced from between the West and South directions and attains 15% from the South-West direction. Wind rose diagrams further gives information that the maximum wind speed achieved by Sanghar, and Gwadarsites lies between 12 m/s to 4 m/s and 8 m/s to 11 m/s respectively.

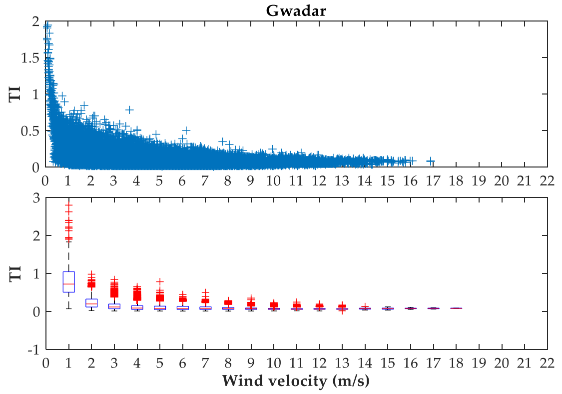
C. ENERGY GENERATION AT SITES

A wind power project's total energy generation and capacity factor are important. It's necessary to choose the proper turbine for a certain area in estimating the best energy output. The average wind speed for the various hub heights was calculated using the power law. The hub heights that were investigated varied from 46 to 166 m, with average wind speeds ranging from 2 to 8 m/s. For the entire data set, the 3 m/s. In order to find optimal wind power generated (kW), wind energy produced (MWh), capacity Factor, and Cost/kWh (¢) at Sanghar and Gwadar sites, 10 different wind turbine models with different companies i.e., Vestas, Goldwind, Nordex, Suzlon, Gamesa, and G.E, are selected. The power rating of the chosen wind turbines ranges from 1250 kW to 3300 kW. The Vestas V126/3300 and Suzlon S66/1250 possess maximum power rating of 3300 kW and 1250 kW respectively. The rotor diameters of the selected wind turbines also vary and lie in the range from 60 m to 126 m. The Nordex n60/1300 and Vestas V126/3300 possesses the lowest and highest diameters of 60 m and 126 m respectively. The selected Wind Turbines (WTs) possess the cut-in wind speed, cut-out wind speed, rated wind speed which lie between the range of 2 m/s and 4 m/s, 20 m/s and 25 m/s, and 9.3 m/s and 19 m/s respectively.

The graph showing the wind speed and generated power of all turbines used at Sanghar and Gwadar sites are given in Figure 12 respectively, whereas the technical specifications of the wind turbines used at the site are given in Table 5. In order to get the optimal results from the wind turbines, design parameters i.e., rated power, cut out and cut in speed, rated speed, and hub height, of wind turbines were selected according to the wind characteristics of the desired sites. The results obtained in the Table 6 and VII show that, at the Sanghar site, Vestas V126/3300 generated the maximum power 1612.869 kW and energy 14128.731 MWh followed by Goldwind GW121/2500 with generated power and energy of 1369.459 kW and 11996.465 MWh respectively. The third wind turbine amongst the ten i.e., Gamesa G97/200 has generated power of 974.237 kW with an energy

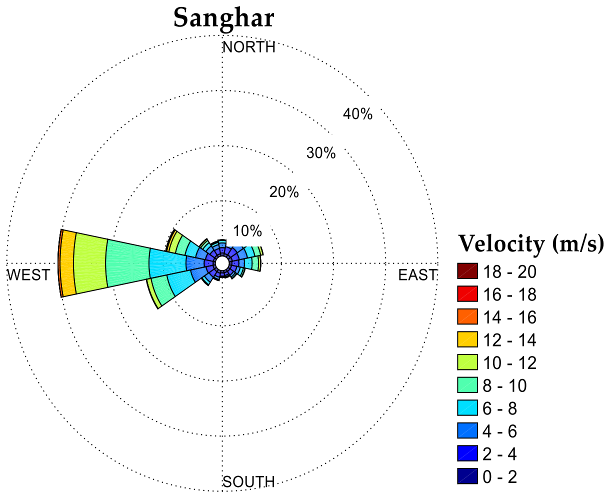


(a) Sanghar Wind mast

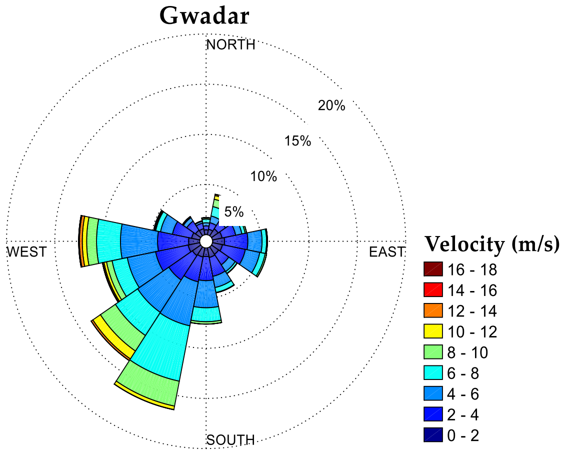


(b) Gwadar Wind Mast

FIGURE 10. **Turbulence intensity of the selected sites: (a) Sanghar site; (b) Gwadar site.**



(a) Sanghar Site



(b) Gwadar Site

FIGURE 11. **Wind rose diagram of the selected sites: (a) Sanghar site; (b) Gwadar site.**

of 534.314 MWh. The maximum capacity factor of 54.78% and lowest Cost/kWh of 4.2278(¢) were achieved by Goldwind GW121/2500 followed by other wind turbines at the Sanghar Site.

Table 7 shows that at the Gwadar site, the maximum power and energy are generated by Vestas V126/3300 which are 745.105 kW and 6527.119MWh respectively followed by Goldwind GW121/2500 with the generated power and energy of 647.858 KW and5675.235 MWh respectively. The Capacity Factor of 25.91% at the Gwadar site is received by Goldwind GW121/2500 followed by Vestas V126/3300 with value of 22.58%. The lowest Cost/kWh of 0.089¢ is obtained by Goldwind GW121/2500 followed by Vestas V126/3300 with 0.103¢. Performance testing of numerical methods carried out in this paper is given in Table 8. Both Sanghar and Gwadar sites are tested separately on the numerical methods, results show that Graphical method (GM) shows the best performance than other at the Sanghar site, whereas the Energy pattern method (EPF) shows the good performance among others numerical methods at the Gwadar site.

D. COST PROSPECT ANALYSIS AND TESITNG

The detailed results carried out at Sanghar, and Gwadar Sites are vividly expressed in Table 9 and 10 respectively. The rated power for both sites are fixed as per the requirement of Wind Turbines. The wind turbines i.e., Vestas V126/3300 and Suzlon S66/1250 chosen for the three selected sites have the maximum and minimum rated power of 3300 kW and 1250 kW respectively. Different wind turbines have generated the power according to their characteristics and efficiency. At the Sanghar site, the maximum power 1612.82 kW is generated by Vestas V126/3300 followed by Goldwind GW121/2500 with 1369.45 kW, whereas the minimum power 383.44 kW is generated by Nordex n60/1300, followed by by Suzlon S66/1250 with 447.35 kW.

The optimal capacity factor analyzed shows that Goldwind GW121/2500 showed the first ranking with respect to capacity factor of 0.5477followed by Vestas V126/3300 with 0.4887. The lowest capacity is shown by Nordex n80/2500 with 0.2858 followed by Nordex n60/1300 with 0.2949.

TABLE 5. Technical specifications of wind turbines (WTs).

Turbine Model	Power Rated (kW)	Turbine diameter (m)	Hub Heights (m)
Vestas V126/3300	3300	126	166, 149, 147, 137, 117, 87
Goldwind GW121/2500	2500	121	120, 90
Nordex n80/2500	2500	80	80, 70, 60
Nordex n90/2300	2300	90	105, 100 80, 70
Suzlon S97/2100	2100	97	120, 90
Suzlon S88/2100	2100	88	100, 80
Gamesa G97/200	2000	97	120, 104, 100, 90, 78
G.E 1.6xle	1600	82.5	100, 80
Nordex n60/1300	1300	60	69, 60, 46
Suzlon S66/1250	1250	66	56, 74

TABLE 6. Estimated power, annual energy output, capacity factor, and Cost/kWh (¢) of wind turbines (WTs) at 80m Sanghar site.

Turbine Model	Power Generated (kW)	Energy Produced (MWh)	Capacity Factor	Cost/kWh (¢)
Goldwind GW121/2500	1369.459	11996.465	54.78%	4.2278
Vestas V126/3300	1612.869	14128.731	48.87%	4.7385
Gamesa G97/200	974.237	8534.314	48.71%	4.7544
G.E 1.6xle	744.393	6520.880	46.52%	4.9779
Suzlon S97/2100	976.226	8551.740	46.49%	4.9819
Nordex n90/2300	872.157	7640.097	37.92%	6.1075
Suzlon S88/2100	784.577	6872.895	37.36%	6.1989
Suzlon S66/1250	447.351	3918.791	35.79%	6.4713
Nordex n60/1300	383.443	3358.965	29.50%	7.8518
Nordex n80/2500	714.572	6259.654	28.58%	8.1026

TABLE 7. Estimated power, annual energy output, capacity factor, and Cost/kWh (¢) of wind turbines (WTs) at 80m Gwadar site.

Turbine Model	Power Generated (kW)	Energy Produced (MWh)	Capacity Factor	Cost/kWh (¢)
Vestas V126/3300	745.105	6527.119	22.58%	0.103
Goldwind GW121/2500	647.858	5675.235	25.91%	0.089
Nordex n80/2500	285.424	2500.316	11.42%	0.203
Nordex n90/2300	365.173	3198.916	15.88%	0.146
Suzlon S97/2100	426.320	3734.560	20.30%	0.114
Suzlon S88/2100	325.775	2853.792	15.51%	0.149
Gamesa G97/200	437.566	3833.082	21.88%	0.106
G.E 1.6xle	323.960	2837.890	20.25%	0.114
Nordex n60/1300	157.986	1383.954	12.15%	0.191
Suzlon S66/1250	187.449	1642.056	15.00%	0.154

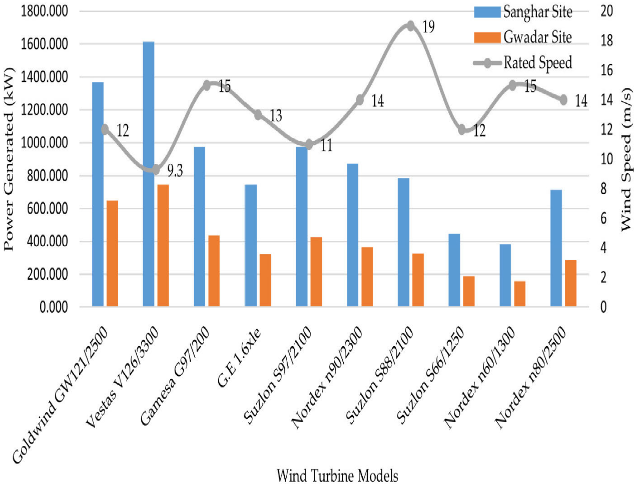


FIGURE 12. Comparison of wind speed and power generation of different wind turbines (WTs) simulated at the Sanghar and Gwadar sites.

The highest and lowest installation cost of turbines i.e., 6435000 $ and 2437500 $ are possessed by Vestas V126/3300 and Suzlon S66/1250 respectively. Amongst the whole turbine, the lowest Cost of Turbine (kWh/$) of 0.0893 $ is achieved by Goldwind GW121/2500 leaving behind the other wind turbines.

At the Gwadar site, the wind turbines used for the power generation are mentioned with details in Table 10. The wind turbines with different rated power are utilized in order to analyze the different power generation capacity at the site. When the data were simulated, the Wind Turbine Vestas V126/3300 with the rated power of 3300 kW generated the maximum power of 745.10 kW followed by Goldwind GW121/2500 with the rated power and generated power of 2500 kW and 647.85 kW respectively. The wind turbine with the least generated power of 157.98 kW was Nordex n60/1300 having the rated power of 1300 kW. Suzlon S66/1250 was wind turbine with the minimum rated power of 1250 kW which has had a generated power of 187.44 kW which is a degree better than the Nordex n60/1300. The Wind turbine with the maximum Capacity Factor 0.2591 was found to be Goldwind GW121/2500 followed by the Vestas V126/3300 having the capacity factor value of 0.2257. The wind turbines having the least capacity factor was Nordex n80/2500 with a value of 0.1141 followed by Nordex n60/1300 with a capacity factor of 0.1215. The wind turbines installation cost and cost of turbine (1500$/kW) are the same which were at the Sanghar site because of the same rating power of the wind turbines. An important factor of wind turbines i.e., energy generation cost of turbine (kWh/$), Goldwind GW121/2500 is the best amongst all by achieving value of 0.0893 kWh/$, followed by

TABLE 8. Five numerical models to test the performance of different weibull techniques.

Wind Locations	Methods	M.S.E	R.M.S.E	M.A.E	R	R^2
Sanghar	**G.M**	**0.00000573**	**0.01070514**	**0.00763257**	**0.97049255**	**0.94185578**
	M.M.L.M	0.0001293	0.01137117	0.00757251	0.96885682	0.93868353
	E.M.L	0.00013166	0.01147433	0.00757319	0.96860396	0.93819363
	E.M.J	0.00013208	0.01149265	0.00757921	0.96853246	0.93805512
	EPF	0.00014224	0.01192628	0.00770554	0.96723086	0.93553554
Gwadar	**E.P.F**	**0.00001158**	**0.00340329**	**0.00238099**	**0.99835174**	**0.9967062**
	M.M.L.M	0.00001199	0.00346243	0.00242011	0.998279594	0.99656215
	E.M.J	0.00001379	0.00371288	0.00260499	0.998084159	0.99617199
	E.M.L	0.00001379	0.00371309	0.00259166	0.998071987	0.99614769
	G.M	0.00002152	0.00463901	0.00326574	0.997205064	0.99441794

TABLE 9. Cost assessment of wind turbine (WT) models tested at the Sanghar wind site.

Wind Turbine Model	Rated Power (kW)	Generated Power (kW)	Capacity Factor (C.F)	Cost of Turbine (1500 $ /kW)	Installation Cost of Turbine ($)	(kWh/$) Cost of Turbine
Vestas V126/3300	3300	1612.86	0.4887	4950000	6435000	0.0473
Goldwind GW121/2500	2500	1369.45	0.5477	3750000	4875000	0.0422
Nordex n80/2500	2500	714.57	0.2858	3750000	4875000	0.0810
Nordex n90/2300	2300	872.15	0.3791	3450000	4485000	0.0610
Suzlon S97/2100	2100	976.22	0.4648	3150000	4095000	0.0498
Suzlon S88/2100	2100	784.57	0.3736	3150000	4095000	0.0619
Gamesa G97/2000	2000	974.23	0.4871	3000000	3900000	0.0475
G.E 1.6xle	1600	744.39	0.4652	2400000	3120000	0.0497
Nordex n60/1300	1300	383.44	0.2949	1950000	2535000	0.0785
Suzlon S66/1250	1250	447.35	0.3578	1875000	2437500	0.0647

TABLE 10. Cost assessment of wind turbine (WT) models tested at the Gwadar wind site.

Wind Turbine Model	Rated Power (kW)	Generated Power (kW)	Capacity Factor (C.F)	Cost of Turbine (1500/kW)	Installation Cost of Turbine($)	(kWh/$) Cost of Turbine
Vestas V126/3300	3300	745.10	0.2257	4950000	6435000	0.1025
Goldwind GW121/2500	2500	647.85	0.2591	3750000	4875000	0.0893
Nordex n80/2500	2500	285.42	0.1141	3750000	4875000	0.2028
Nordex n90/2300	2300	365.17	0.1587	3450000	4485000	0.1458
Suzlon S97/2100	2100	426.31	0.2030	3150000	4095000	0.1140
Suzlon S88/2100	2100	325.77	0.1551	3150000	4095000	0.1492
Gamesa G97/2000	2000	437.56	0.2187	3000000	3900000	0.1058
G.E 1.6xle	1600	323.96	0.2024	2400000	3120000	0.1143
Nordex n60/1300	1300	157.98	0.1215	1950000	2535000	0.1905
Suzlon S66/1250	1250	187.44	0.1499	1875000	2437500	0.1544

Vestas V126/3300 with a value of 0.1025 kWh/$. The highest value in terms of kWh/$ is had by Nordex n80/2500 with a value of 0.2028 kWh/$ followed by Suzlon S66/1250 with 0.1544 kWh/$.

V. CONCLUSION

In this paper, the wind potential analysis and economic assessment of Sanghar and Gwadar locations is carried out to assess the power generation which are located in two different provinces of Pakistan i.e., Sindh and Baluchistan respectively. One-year complete real time wind data of the both locations along with its different behaviors including seasonal, temperature and day-night variations was analyzed to compute the different wind indicators required to find out the wind potential availability in the respective area.

Weibull distribution parametric approach with five different techniques is applied to analyze the wind potential availability at the desired sites. Along with an analysis of the wind potential, an economic assessment has also been carried out to estimate the installation cost, cost of turbine, capacity factor of ten different wind turbines with different rated power are used at the desired sites. The research in this paper concludes that the Sanghar site possesses the enough wind power potential to install wind turbines for the commercial purposes whereas the Gwadar site owns the wind potential which is suitable for the domestic usage. This paper concludes as:

- The wind speed is found maximum with a value 8.06 m/s at 21:00 and 6.92 m/s at 12:00 at the Sanghar and Gwadar sites respectively.
- The minimum speed was noted 5.35 m/s at 11:00 at Sanghar site and 3.74 m/s on 4:00 at Gwadar site.
- Sanghar site receives highest wind speed 8.05 m/s in the summer season and minimum wind speed 5.65 m/s in the autumn season.
- Wind Speed 7.10 m/s and 5.82 m/s was recorded at the Sangahr site in Spring and Winter season respectively.
- Gwadar site gets the maximum wind speed 5.84 m/s and minimum wind speed 4.45 m/s in the spring and summer season respectively.
- The power generation shows that,
- At the Sanghar site, the maximum power of 1612.82 kW is generated by Vestas V126/3300 whereas the minimum power 383.44kW is generated by Nordex n60/1300.
- At the Gwadar site, Vestas V126/3300 generated the maximum power of 745.10 kW and least power of 157.98 kW was generated by Nordex n60/1300.
- With respect to the economic assessment,
- Vestas V126/3300 and Suzlon S66/1250 possess the highest and lowest installation cost of turbines respectively at both Sanghar and Gwadar sites.
- The lowest value i.e., 0.0422 kWh/$ and highest value i.e., 0.081 kWh/$ are shown by Goldwind GW121/2500 and Nordex n80/2500 at the Gwadarsite.
- The lowest value i.e., 0.0893 kWh/$ and highest value i.e., 0.2028 kWh/$ are shown by Goldwind GW121/2500 and Nordex n80/2500 at Sanghar site.

VI. RECOMMENDATIONS

Pakistan has been struggling badly to cope with the increasing load demand because due to price hikes in fuel prices, it's been extremely difficult to meet the load demand, so following the recommendations are given:

- Pakistan needs to harness wind potential available and integrate massive wind turbine in its wind corridors especially in Sindh and Baluchistan provinces.
- The integration of wind turbines be made along with the PV panels in order to generate more reliable and sustainable power in the all the provinces.
- In order to complete the financial needs projects should be started along with assistance of IMF, world bank, and AEDB and also public-private partnerships projects be enhanced.

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