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Power Supply to Local Communities Through Wind Energy Integration: An Opportunity Through China-Pakistan Economic Corridor (CPEC)

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ABSTRACT Global warming and depletion of fossil fuels have urged the world to control their impacts and find clean and green energy sources. Due to this paradigm shift, renewable energy resources (RESs) have received tremendous attention around the globe and amongst other RESs, wind energy has been proving itself a promising renewable resource. However, still, the proper selection of wind turbines (WTs) and their installation is considered a major challenge. Presently, due to the economic boom of Pakistan as a regional power under the China Pakistan Economic Corridor (CPEC) and increasing energy demand, it needs to meet the energy shortage. This paper aims to conduct a pre-feasibility ainvestigation of wind farm exploitation at Gwadar and Quetta, major cities of Baluchistan province in Pakistan by harnessing the wind energy potential and electricity generation cost through different WT models. The wind speed (WS) data is recorded by a professional wind mast at different measurement heights during F.Y 2016 and analyzed using Five approaches, Modified Maximum Likelihood Method (MMLM), Graphical Method (GM), Empirical Method of Lysen (EML), Empirical Method of Jestus (EMJ) and Energy Pattern Factor Method (EPF) at the proposed site and EPF shows the best performance than other approaches. Different WTs models are also evaluated and out of them, the GW121 WT gives the lowest cost in dollars and lowest payback period at each site so it can be recommended as one of the most feasible WT for electricity generation for powering local communities at the proposed sites.

INDEX TERMS Wind energy integration, planning, wind speed data, Weibull distribution, CPEC, electricity cost.

I. INTRODUCTION

With the rapid depletion of fossil fuels and accelerated environmental pollution, wind generation has received enormous attention. The selection of wind turbines (WTs) and their installation is still deemed to be a key challenge. At Present, China Pakistan Economic Corridor (CPEC) has provided a strong economic thrust to Pakistan, so it extremely needs to cope with the snowballing energy crisis, by exploiting immense wind energy potentials available in Pakistan. Therefore, it's imminent to move towards clean, green, inexpensive, sustainable, and renewable sources of energy including wind energy is the seventh goal of Sustainable Development Goals [1]. The International Energy Agency (IEA), the Renewable Energy Policy Network 21 century (REN 21), and United Nations Environmental Program (UNEP)

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resolved that without the expansion of renewable energy, the goals set for climate change could not be accomplished. Clean and sustainable global energy evolution from fossil fuel-based energy is the significant inclination of the worldwide energy transformation.

Energy security is crucial in industrial productions while energy consumption is regarded as an important factor of economic growth. In Pakistan, industries are dying due to the dearth of energy, which becomes the major cause of the least productions and results in meager economic growth. Energy security, in the long term, is the availability of electricity at reasonable rates without any interruptions, which encompasses prompt investments for the supply of electrical power in line with the environmental needs and economic developments. In the short term, systems should have the ability to respond timely to bridge the energy gap between supply and demand. So, both the energy resources and energy production are considered to meet energy security for the system. Because of the fast exhaustion of fossil fuels at the domestic level and their high import costs and environmental damages, Pakistan is steering towards clean, sustainable, and renewable sources of energy including hydel, solar, wind and bioenergy generation in all the major cities and towns of its domain. According to the NREL, PMD, AEDB, and Global Wind Atlas, Pakistan has a gargantuan potential for wind energy which can be exploited to achieve energy security. The environmentally friendly, economical, and cost-effective generation of wind energy appeals to Public and Private sectors to invest in wind energy, to overcome the energy shortage which has deeply affected Pakistan's economy and living standards of people. This massive availability of wind potential is the reason that Pakistan should increase wind power generation.

To achieve this, the wind resources assessment is important to estimate the suitable sites, wind power generation, cost estimation, and wind farm designs. There are five different levels in which wind potential can be divided, meteorological, geographical, technological, implementation, and economic. Therefore, an in-depth study is needed. The statistical representation of wind speed with Weibull distribution is recommended by many authors, owing to its simplicity, flexibility, and capability to fit a wide range of wind data. For this purpose, the Weibull distribution function is opted to evaluate wind resources; furthermore, five Weibull methods are used to ensure greater accuracy for each selected site and to set up commercial wind farms. In this study, ten different wind turbine models are taken into consideration to evaluate wind resources and, to estimate capacity factor and the power generated by them at suitable sites because of the reason that the power output of a turbine depends on wind speeds at the selected locations. The lifespan of the turbine depends on the atmospheric conditions of the site. The distributed wind power system is another solution to the distant windy areas because being in proximity to the load center and reduces the load on the national gird.

This paper executes various Weibull distribution techniques 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) to evaluate wind power generation, capacity factor, and GWh/year at the proposed sites and test different types of WTs model to check which one works out better and gives the least payback period.''

II. WIND POTENTIAL IN PAKISTAN

Among alternative and renewable resources, wind power has been recognized as a significant potential source of renewable energy in Pakistan. The country has a total estimated gross wind power potential installable capacity of 346,000 MW [2]. In [3], authors have forecasted the realization of about 40–70% of Pakistan wind power potential by the year 2030. There are different departments and organizations in Pakistan which are gathering wind data using different tools, such as Weather Satellites, Geospatial methods, Wind Mast, and Sonar technology.

A. WIND ENERGY DATA SOURCES

Pakistan has vast wind energy potential which is being deliberated and calculated in the form of wind data including mean, direction, variance, and standard deviation for wind speeds (m/sec), temperatures, humidity, and atmospheric pressure at different heights using wind masts and SODAR technologies. MESOMAP system and historical weather data from satellites record, PMD, and airports are also used to get geospatial data of wind potential in Pakistan.

In this study, the authors have used wind data from the following sources:

B. PAKISTAN METEOROLOGICAL DEPARTMENT (PMD)

The Pakistan Meteorological Department is a public sector organization in Pakistan, PMD records wind power potential across major regions all over the country. There have been 42 different locations in Northern parts (Including the Federally Administered Tribal Areas), 44 different places in the coastal belt of Sindh and Baluchistan respectively in the country, where wind data get collected. Wind data is saved at ten minutes' interval including wind speed (m/sec) and wind direction in degree at the10 m and 30 m heights [4], [5].

C. ALTERNATIVE ENERGY DEVELOPMENT BOARD (AEDB)

Like PMD, the Alternative Energy Development Board (AEDB) is also a public-sector organization of Pakistan, which was formed to implement policies, programs, and projects through the private sector in renewable energies [6], AEDB has requested a minimum of 25 wind masts owing to large windy areas and interests of IPPs in the wind sector. In the province of Sindh (Gharo, Bhambore, Jhimpir, Lakha, and Kuttikun) eighteen wind IPPs (each of 50 MW capacity) out of which twelve have submitted feasibility reports [7]–[9].

TABLE 1. Pakistan wind electric potential [22]. Good to Excellent Wind Recourse at 50 m (Utility Scale).

Wind Resource Utility Scale	Wind Class	Wind Power (W/m^2)	Wind Speed (m/sec)	Land Area (km^2)	Percent Windy Land	Total Capacity Installed (MW)
Good	4	400 – 500	6.9 – 7.4	18,106	2.1	90,530
Excellent	5	500 – 600	7.4 – 7.8	5,218	0.6	26,090
Excellent	6	600 – 800	7.8 – 8.6	2,495	0.3	12,480
Excellent	7	> 800	> 8.6	543	0.1	2,720
Total				26,362	3.1	131,820

Assumptions
Installed capacity per km^2 = 5 MW, Total land area of Pakistan = 877,525 km^2, The only land area included in calculations, NREL's SARI-Energy Activities

D. NATIONAL RENEWABLE ENERGY LABORATORY (USAID)

This report [10] analyses the data of Wind Masts installed in Gharo-Keti Bandar Wind Corridor, Sindh province. The current tariff of wind energy in Pakistan is discussed in [11]. In 2007, under USAID, the National Renewable Energy Laboratory (NREL) through the South Asia Regional Initiative for Energy Cooperation and Development (SARI-Energy) had taken steps to measure wind potential in Pakistan and Afghanistan, which concluded a mesoscale map of Pakistan [12]. NREL has developed the Geospatial Toolkit (GST) for USAID which has the high-resolution (1 km) annual wind power maps developed using a numerical modeling technique [13]. Resource Map and Tool kit to check different parameters for renewable energy sources in Pakistan are further deliberated in [14].

E. THE WORLD BANK (Incorporation WITH AEDB)

The World Bank incorporation with AEDB has installed 12 wind masts in important parts of four provinces of Pakistan that are recording wind characteristics since 2015 and 2016 at different heights of 85 m, 80 m, 60 m, 40 m, and 20 m along with a mesoscale map of the wind power density of Pakistan at the heights of 100 m. In reference [15], the authors give a diagnostic study for wind power potential in the FATA region in comparison to NREL projections. Whereas in [16], authors have analyzed the wind climatology at advanced turbine hub heights based on data measured on existing tall towers in Kansas, Indiana, and Minnesota. The mesoscale map of wind power density and wind speed at the height of 200 m, 100 m, and 50 m are available at the official website of Global Wind Atlas. The location and details of 12 wind masts funded by The World Bank to assess wind energy potential in Pakistan are given [17], [18] and an investigation on wind power potential of Sindh based on 03 years data is discussed in [19].

F. WIND ENERGY POTENTIAL OF BALUCHISTAN PROVINCES

According to the NREL report of June 2007 named Wind Resource Assessment and Mapping for Afghanistan and Pakistan, by Dennis Elliott, Pakistan has a total land area of about 877525 km^2 in which installed capacity is 5 MW per km^2. Out of the entire land area, only 26362 km^2 land area is considered with percent windy area which equals 3.0% and the total capacity installed of 131800 MW [20]. As most of the land lies in class 4 or higher with a percent windy area of about 3.5%, which confirms that wind power production in these areas is cost-effective [21]. It can be observed from Table 1 that out of 26362 km^2 land area,18106 km^2 lies in acceptable utility-scale wind class 4 percent windy region equals 2.1% with a wind power density between 400-500 W/m2, wind speed ranging 6.9-7.4 m/sec and total installed capacity is 90530 MW. Another 5218 km^2 land area lies inadequate utility-scale with wind class of 5 percent windy region which equals to 0.6% with wind power between 500-600 W/m^2, wind speed ranging 7.4–7.8 m/sec and total installed capacity is 26090 MW. Additional 2495 km^2 land area lies in outstanding utility-scale with wind class of 6 percent windy area equals to 0.3% with wind power between 600-800 W/m^2, wind speed ranging 7.8–8.6 m/sec and the total capacity installed is 12480 MW. The remaining 543 km^2 land area lies in the highest utility-scale with a wind class of 7 percent windy area equals 0.1% with wind power greater than 800 W/m^2, wind speed greater than 8.6 m/sec and the total capacity installed is 2720 MW [22].

Southwestern part of Pakistan, Baluchistan also has extensive potential for wind power. The southwestern region that borders Iran and Afghanistan has huge potential near Nokkundi and Hills and ridges in the Chagai area to the Makran area. Wind corridors and ridges are also in abundance near Quetta hills and Gendari [23]. It can be observed that Baluchistan has a total installed capacity of 146,145MW with 8.41% of the windy area out of 347,190 km^2 total areas, where wind power class is ranging from 3 to 7 as moderate to excellent [24]. These wind energy potential needs to be harnessed efficiently and rapidly to provide locals electricity by the implementation of small distributed generation (DG) stations of wind energy. International standards of wind power generation classification are shown in Table 2.

III. WIND DATA ASSESSMENT

Wind speed is continuously fluctuating over the period. Many parameters are affecting the power generation from wind speed including air density, atmospheric temperature, turbine clause, and its hub height. To effectively harness wind energy and boost the efficacy of wind energy markets, wind resources assessment especially determining the wind

TABLE 2. International standards of wind power generation classification.

Various Heights		@ 10 m Height		@ 30 m Height		@ 50 m Height	
#	Resource Class	m/s	W/m²	m/s	W/m²	m/s	W/m²
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

characteristics requires utmost significance. The frequency distribution of wind speed may give different wind power densities for the same wind speed, so the knowledge of wind power density needs to be much reliable. The wind power density in terms of W/m^2 for a location can be calculated based upon the probability distribution function of wind speed [25].

A. WIND CHARACTERISTICS

In wind power assessment, it is necessary to identify the different wind characteristics for a site. The wind is a variable entity that continuously changes its direction, magnitude, and density for time [26]. For effective assessment and utilization of wind energy, characteristics like average wind speed, variance, standard deviation, air density, wind power density, energy density, wind shear profile of site using power law, and wind turbulence intensity are essential for consideration. These characteristics are required for the statistical data analysis in the Weibull distribution function. The performance of wind turbines depends on wind distribution including frequency of higher wind speed and wind rose of a site [5], [27]–[29]. Moreover, these characteristics are essential to effectively utilize wind energy potential to meet commercial as well as domestic demands and mitigate energy crises [30], [31].

1) AVERAGE WIND SPEED (v_{avg})

Wind data gathered by Mast or Sonar is a set of wind speed over time, so the average wind speed or mean is given by:

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

2) VARIANCE $\left(\sigma^2\right)$

Wind speed data can be used to calculate variance by using:

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

3) STANDARD DEVIATION (σ)

The standard deviation can be computed as from Eq. (2):

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

where v_i is ith value of wind speed.

4) AIR DENSITY (ρ)

The air density for the proposed site can be obtained by using Eq. (4) [32], [33].

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

where P 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 ($C+273^0$).

5) WIND POWER DENSITY (WPD)

The wind power density is a primary indicator to determine the potential of wind resources and to represent the amount of wind energy for variable wind speed values in a location. WPD is computed based on the measured wind speed data and can be mathematically given by the following equation:

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

where ρ is the 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)

The energy output regarding Weibull distribution at the proposed site is determined by using Eq. (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 as measured with Weibull distribution at the proposed site in (kWh/m^2). $P(V)$, T, V, K and C are wind turbine's power curve, time, wind velocity, shape and scale parameters respectively [34].

7) SHEAR PROFILE

The exponent of wind shear and shear of the site are calculated from Eq. (7) and Eq. (8) respectively [36-38]. Alpha ($\propto$) is crucial to estimate wind velocities at higher altitudes by processing the wind velocities measured at lower or previous altitudes.

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

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

8) POWER LAW

The power law is used to predict wind speed at hub height by using Eq. (9) [37]:

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

9) WIND TURBULENCE INTENSITY

The Wind Turbulence Intensity is described as the ten-minute standard deviation of the velocity divided by the ten-minute mean of the wind speed, and it is given by Eq. (10) [38]:

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

where σ is a ten-min standard deviation of wind velocity, and V is the ten-min average velocity of the proposed site.

10) WIND POWER CLASSES

International wind power classes are suggested by Elliot and Schwartz to evaluate the installation of a wind turbine, as shown in Table 10 [39]–[42]. The wind classes are divided into seven sections, the section 1-2 is considered for rural applications only, where class 4 and above classes are recognized for high commercial applications [43]–[46]. These classes are defined at the height of 10m, 30m, and 50m with different parameters like wind speed (m/sec) and wind power density (W/m^2) [47]. Above 5.5 m/sec, the power generation is economical which ranges from class 4 and above, whereas Classes 1 and 2 are for the applications of small wind turbines [48].

B. WEIBULL DISTRIBUTION

Based on the wind speed data collection, the Weibull distribution can be represented as a probability density function $f(v)$ and a cumulative distribution function $F(v)$, determined by the following equations [49]–[52]:

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

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

Using Weibull parameters mean (v_{avg}) of wind speed is measured as follows:

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

Also, variance (σ) is figured by:

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

where Γ is gamma function of (y) given by:

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

C. DIFFERENT WEIBULL METHODS

In different literatures, several methods are proposed for the calculation of the shape (k) and scale (c) parameters of the Weibull distribution function. This paper focuses on five approaches; modified maximum likelihood method (MMLM), graphical method (GM), empirical method of Lysen (EML), empirical method of Jestus (EMJ), and energy pattern factor method (EPF) which are mostly used to calculate the value of k and c parameters, are selected for the evaluation of the wind power potential in cities of Gwadar and Quetta of Pakistan.

1) MODIFIED MAXIMUM LIKELIHOOD METHOD (MMLM)

In this method, wind speed data must be in frequency distribution format like Weibull distribution format and the numbers of iterations are performed to find shape (k) and scale (c) parameters for Weibull distribution function, both parameters are given by following equations [16]:

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

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

2) EMPIRICAL METHOD OF LYSEN (EML)

In this method, the mean and standard deviation of wind speed is required to get parameters. Lysen recommended that the shape (k) and scale (c) parameters are determined by Eq. (18) and Eq. (19) respectively [53]:

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

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

3) EMPIRICAL METHOD OF JESTUS (EMJ)

Jestus introduced this empirical method in which, the shape (k) can be calculated by Eq. (18) and scale (c) parameter is estimated by Eq. (20) as [54], [55]:

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

4) GRAPHICAL METHOD (GM)

In this method, the cumulative distribution function of Weibull distribution is adopted, in which wind data is distributed into bins due to the least square regression. The graphical method equation can be obtained by taking double logarithms of Eq. (12) as [58-59]:

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

By Comparing Eq. (21) with $y = ax + b$, we get

$$y = ln\,[-ln\,(1 - F\,(v))]\,, \quad x = lnv, \quad a = k \text{ and } b = -k\ln c \tag{22}$$

Using measured wind speed data, y and x can be calculated. The standard least regression method is applied to obtain the slope (a) and the intercept (b), then the shape (k) and the scale (c) parameters can be found by,

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

5) ENERGY PATTERN FACTOR METHOD (EPF)

In this method average wind speed data is analyzed to calculate shape (k) and scale (c) parameters of Weibull distribution; first, the parameter for the aerodynamic design of turbine should be defined as [58]:

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

From Eq. (24) Energy pattern factor (E_{pf}) can be calculated, which is defined as it is a ratio of the average of the cubic value of wind speed data over the cubic value of average wind speed data. The shape parameter (k) obtained as [58]:

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

The scale parameter (c) can be calculated from the same Eq. (20).

D. PREDICTION PERFORMANCE OF WEIBULL DISTRIBUTION MODELS

The performance of probability distribution functions should be compared using various tests. These tests include the Coefficient of Correlation (R), Coefficient of Determination (R^2), Mean Absolute Error (MAE), Mean Squared Error (MSE), and Root Mean Squared Error (RMSE). Five Weibull distribution methods namely Modified Maximum Likelihood Method (MMLM), Empirical Method of Lysen (EML), Empirical Method of Jestus (EMJ), Graphical Method (GM), and Energy Pattern Factor Method (EPF) compared by using statistical analyses tests, and a best-suited scheme is selected for each site to get the best results. These five mathematical models are as follow:

1) THE COEFFICIENT OF CORRELATION (R)

This numerical model works as a correlation between the estimated and observed wind speed frequency data. The correlation coefficient is given by Eq. (26) [59], [60].;

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

2) THE COEFFICIENT OF DETERMINATION (R^2)

The coefficient of determination (R^2) test gives a better model that fits best to the reference data if the value of R^2 nearer to one. The coefficient of determination (R^2) is provided by Eq. (27) [61]:

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

3) MEAN ABSOLUTE ERROR (MAE)

The mean absolute error (MAE) is calculated from absolute values and mean of the measured data. This test is also important because it gives detail about the mean magnitude of the errors present in the data, without affecting the positive and negative errors. This test also has a disadvantage when integrating the tremendous amount of wind energy into a grid network. The mean absolute error (MAE) can be obtained by using Eq. (28):

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

4) MEAN SQUARED ERROR (MSE)

The Mean Squared Error (MSE) test is used to get the best Weibull distribution method, the minimum mean squared error is considered for the best fit of the technique over given data. It is yielded by Eq. (29):

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

5) ROOT MEAN SQUARED ERROR (RMSE)

The Root Mean Square Error (RMSE) is a statistical test achieved to get the absolute measure of the reference data. It calculates discrete data points and is useful in the estimation of error or uncertainty. Due to the square root variance of residuals, the lower the value, the better it fits. The performance of this numerical model is better when its values tend to zero. The RMSE can be computed from Eq. (30) as follows [62]:

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

where x_i is the ith predicted wind speed, y_i is the ith actual wind speed, $\bar{y}$ is mean of actual wind speed and N is the number of observations.

IV. PROPOSED SITES

Multiple factors are important to be considered before selecting a site. The most important factors include the characteristics, speed distributions and frequencies of wind. Weibull shape parameter (k) helps in understanding the wind-wave characteristics of the site being investigated, Weibull scale parameter (c) assists in determining the wind power potential of the particular site and the wind rose is used to determine the direction of the wind from its blowing. Moreover, further factors include the site location (which includes how windy the site is), weather conditions (absence of storms like cyclones recorded in that site), land area, terrain, future expansion possibility, unobstructed objects (Buildings, Trees), topography (homogeneous), nearness to load centers and interconnectedness to the Grid [63]. In this paper, two

TABLE 3. Data quality assurance test for selected sites.

S.no	Site	Observations Pass (%)	Missing values	Clipped values			Sensor Stuck
				V	Dir	Temp	
1	Gwadar	100	0	0	0	0	0
2	Quetta	100	0	0	0	0	0

(a) Gwader site (b) Quetta site

FIGURE 1. Shows pictures of masts installed at (a) Gwader and (b) Quetta site.

sites are considered of Baluchistan province, Gwadar and Quetta. One-year data is assessed to evaluate the wind potential in these two popular CPEC beneficiary regions of Baluchistan.

A. GWADAR SITE

The world bank funds Gwadar wind mast. This mast is in GIT, district Gwadar, Baluchistan, Pakistan. The height of the pole is 80 m, and the geographic location of the Gwadar site is 25°16'47.30"N and 62°20'46.95"E. The site is flat with no significant obstruction, with an elevation of 13 m.

B. QUETTA SITE

The World Bank funds Quetta site wind mast. This mast is in BUITEMS, district Quetta, Baluchistan, Pakistan. The height of the pole is 67 m and the geographic location of the site is 30°16'17.17'' N and 66° 56'12.37'' E. The site is flat with ridges and has an elevation of 1582 m.

Precise wind means calculation depends on the high quality of data. For this purpose, the data quality assurance test was performed for the proposed sites before processing the data. The proposed sites passed the data quality assurance test to be ready to evaluate data in the next step, the details are given in Table 3.

The wind turbines are sensitive to the roughness; thus, the study of ground roughness helps in the understanding of economics. For the given roughness types, it can be determined that the repairing or cleaning of the blades is cost-effective with a performance loss. If performance losses are characterized, the future operators can better predict the performance for customers, which will reduce economic risk in the investment of wind form [64]. So, the effects of wind flow over hills, obstacles like buildings, land cover and lakes in the disturbing wind can be understood in [65]. For vertical extrapolation of wind speed profile, topography and roughness are very important because of the cubic nature of wind speed which is directly related to the energy available [66]. The topographic conditions using elevation and ground roughness maps of each site are shown in Fig. 2. The elevation maps (20 km $\times$ 20 km) with wind mast indicated by the red circle in the center are shown in Fig. 2, the ruggedness index (RIX) at any site is the percentage of the ground surface with a slope above a given threshold (here 30%) within a certain distance (here 3.5 km) [67]. In Gwadar and Quetta, there is a 10 m elevation difference between lines altitude is given maps which ranges from 0-365 m and 1530-2760 m. Moreover, using a radius of 3500 m with a steepness threshold of 30% (17°) and frequency distributed directional weight at above each site, the RIX values are 0.4% and 0.7%, respectively.

Whereas the ground roughness maps (20 km $\times$ 20km) with wind mast indicated by a red circle in the center for each site are also shown in Fig. 2. The background roughness length corresponding to low buildings and open field with distributed rows of trees at Gwadar is 0.03 m and due to arid areas at Quetta is 0.03 m. The roughness length for

TABLE 4. Roughness classes and the associated roughness lengths [68].

Roughness Class RC	Roughness Length, Z_0 [meter]	Energy Index [percent]	Landscape Type
0	0.0002	100	The watery surface.
0.5	0.0024	73	Entirely open terrain with a smooth surface, such as concrete runways in airports, mowed grass.
1	0.03	52	The open agricultural area without fences and hedgerows and very separate buildings. Only softly rounded hills
1.5	0.055	45	Agricultural lands with some houses and 8-meter-tall sheltering hedgerows within a distance of about 1,250 meters.
2	0.1	39	Agricultural lands with some houses and 8-meter-tall sheltering hedgerows within a distance of about 500 meters.
2.5	0.2	31	Agricultural lands with some houses, shrubs, and plants, or 8-meter-tall sheltering hedgerows within a distance of about 250 meters.
3	0.4	24	Small towns, villages, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain.
3.5	0.8	18	Urban centers with tall buildings.
4	1.6	13	Huge cities with tall buildings and skyscrapers.

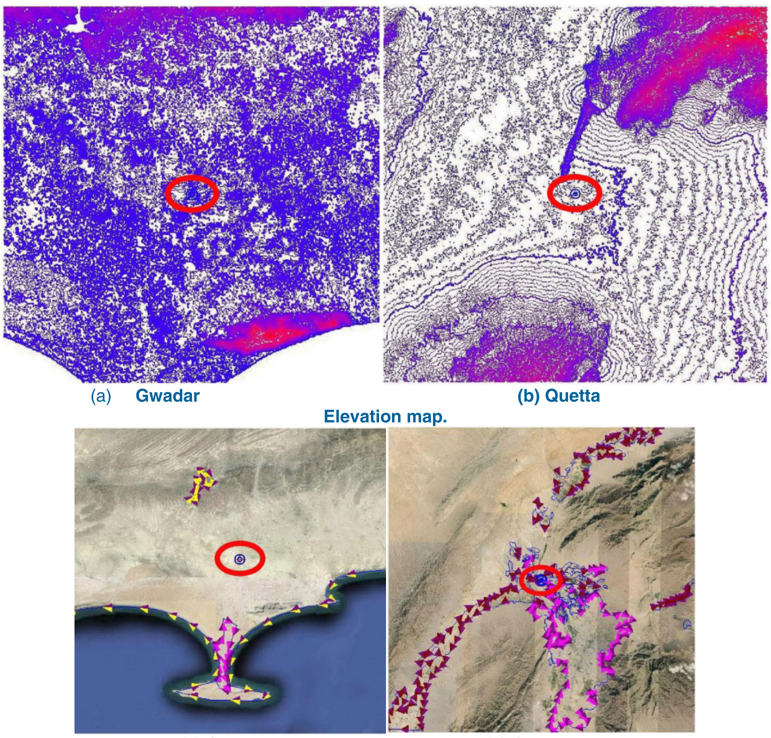

FIGURE 2. Show topographic conditions on elevation and ground roughness maps for each site [63].

specific areas at Gwadar, town (rose color), lake and sea (yellow color) are 0.5 m and 0 m. At Quetta, for lakes (yellow color), towns (rose color), distributed rows of trees and low buildings (purple color) are 0 m, 0.5 m, and 0.07 m. Hence the roughness class for Gwadar and Quetta sites is 1 and 2 respectively, using Table 4 [68].

V. RESULTS AND DISCUSSIONS

Average wind speed is helpful in the estimation of monthly wind velocities. One-year study data is not only used to estimate the average wind speed of each month and can be used for the calculation of seasonal average wind speeds, which is later used to estimate the most robust site during the

TABLE 5. The seasonal average wind speed ranking of each site.

Ranks	Winter		Spring		Summer		Autumn	
	Site	V_{avg}	Site	V_{avg}	Site	V_{avg}	Site	V_{avg}
1	Gwadar	4.63 m/sec	Gwadar	5.84 m/sec	Quetta	4.85 m/sec	Gwadar	5.22 m/sec
2	Quetta	4.30 m/sec	Quetta	4.70 m/sec	Gwadar	4.45 m/sec	Quetta	3.63 m/sec

TABLE 6. Diurnal ranking of sites at hub height in three provinces.

Rank	Time			
	Day	V_{avg}	Night	V_{avg}
1	Gwadar	5.66 m/sec	Gwadar	4.12 m/sec
2	Quetta	3.94 m/sec	Quetta	3.94 m/sec

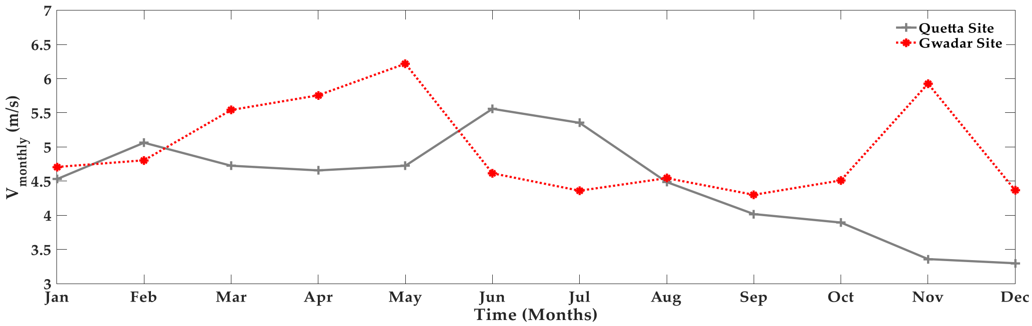

FIGURE 3. Monthly average wind speed Gwadar and Quetta sites.

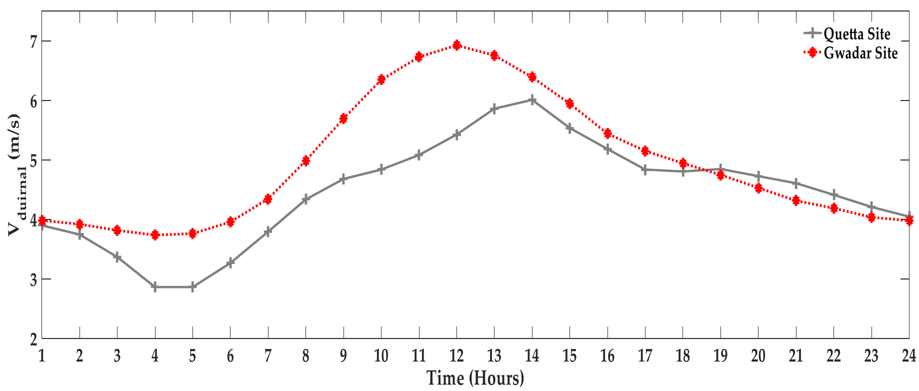

FIGURE 4. Hourly average wind speed in Baluchistan.

summer season when there is a peak load, and the national grid is overloaded. However, Table 5 shows the detailed ranking of each location. Whereas Fig 3, monthly average wind speed values are shown for each site. In Baluchistan province, the maximum monthly average wind speed recorded in a year, moreover, in May at Gwadar site is 6.219 m/sec and in June at Quetta is 5.558 m/sec. Whereas the minimum monthly average wind speed recorded, in December at Quetta is 3.298 m/sec and in September at Gwadar is 4.31 m/sec.

The diurnal wind speeds are the hourly average values of yearly wind speed data, which are used to estimate the average wind speed in each hour, and helps in the determination of average wind speed in both daytime and night-time. Fig 4 shows the hourly average wind speed of a site in Baluchistan. In Baluchistan province, during the day-time average wind speed at Gwadar and Quetta is 5.66 m/sec and 3.94 m/sec, whereas during night-time is 4.12 m/sec and 3.94 m/sec. Moreover, a detailed ranking for each site during daytime and night-time is given in Table 6.

The wind rose diagram of the site shows from which direction the wind is blowing and what percentage of wind speeds lie in each direction. Fig 5 shows the wind rose diagrams of the proposed sites. It can be observed that at the Quetta site, the wind is blowing from all directions indicates that the site is not reliable because most of the times wind turbine would rotate to capture the wind. Moreover, for the percentage of

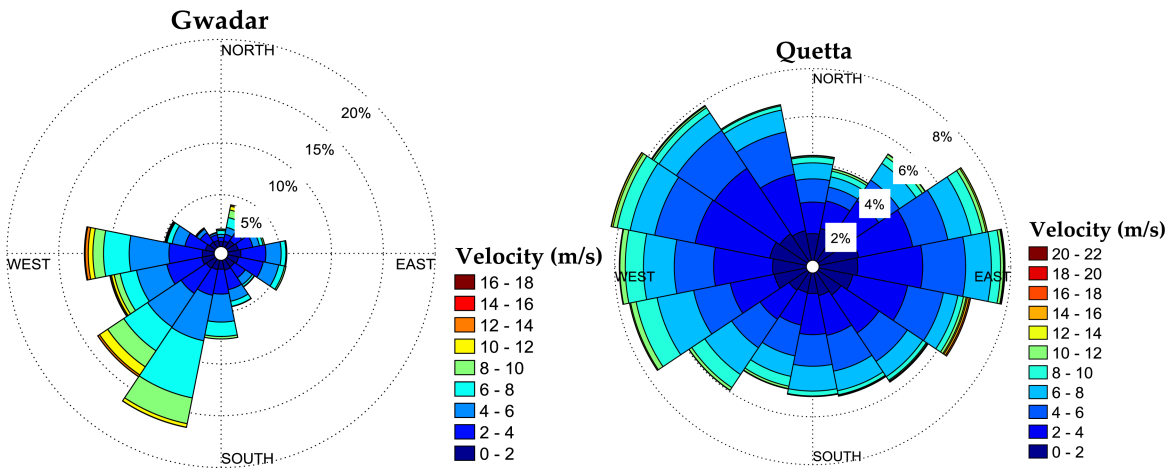

FIGURE 5. Wind rose diagram of each site.

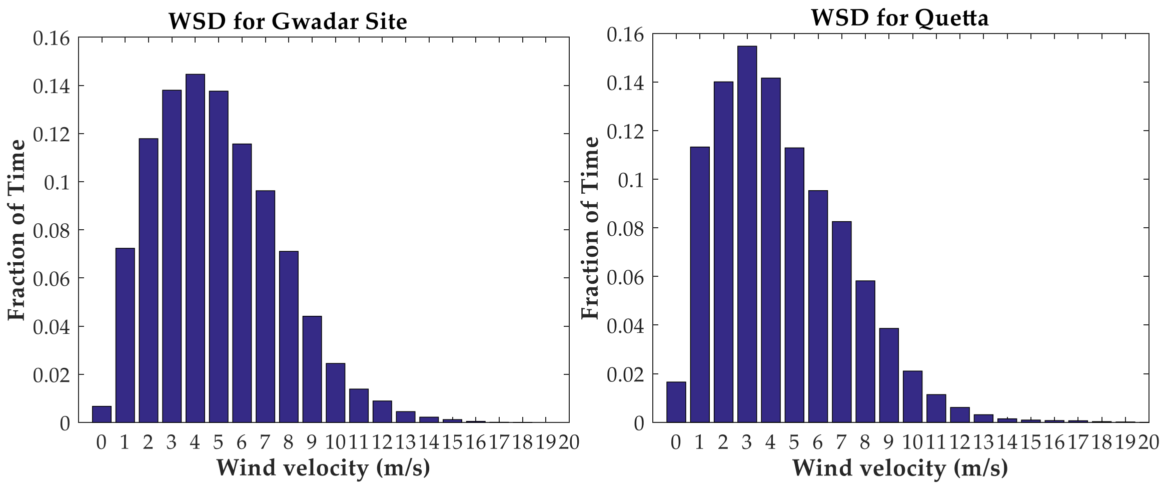

FIGURE 6. Wind speed distribution of each site.

wind speed magnitude to the wind speed direction, the reader is referred to the online form of this article.

Wind speed distribution is used to determine what percentage of wind speed is available at the site. It is the frequency distribution of wind speed, in which wind speeds are sorted into bins. The knowledge of the wind characteristics at location leads to the effective use of wind energy. Since the distribution of wind speed is one of the most critical aspects in wind resource assessment, the wind farms operating performance depends on the robustness of the wind speed distribution used for the selected site by investigating detailed knowledge of the wind characteristics [69], [72]. The wind speed distribution skewed to higher wind velocities suggests higher wind power density and energy at the site. In Fig. 6 wind speed distribution for each location is shown. In Baluchistan, distribution at both Gwadar and Quetta is slightly tilted to lower wind speeds. About 0.2 fraction of time wind speed remains 1 m/s and 2 m/s for the Gwadar site. While 0.28 fraction of time wind speed remains 1 m/s and 2 m/s for the Quetta site.

Air density is inversely proportional to the temperature and is directly proportional to the wind power density. Air density was calculated for 10 min average data for a complete year using Eq. (4). The monthly average temperature versus air density for each site is shown in Fig 7, while Table 6 shows seasonal and yearly average values at each proposed site.

The 10 min average wind speed at the height of 80 m, 60 m, 40 m, and 20 m are used to extrapolate at 100 m. The shear exponent of the power-law model for the atmospheric boundary layer was calculated using eq. (9). and the power-law model is computed using Eq. (10). Fig 8 shows the power law and the shear profile of each site, results suggested that at the height of 100 m at Gwadar and Quetta are 4.9 m/sec and 4.4 m/sec respectively. Both Gwadar and Quetta sites show small change in wind speed ranges from 4 m/sec to 4.9 m/sec at Gwadar and 3.4 m/sec to 4.4 m/sec at Quetta between 20 m to 100 m height.

Wind power density (WPD) at each site is calculated using Eq. (6). Whereas, Fig 9 shows monthly WPD for each location at the height of 100 m, 80 m, 60 m, and 40 m.

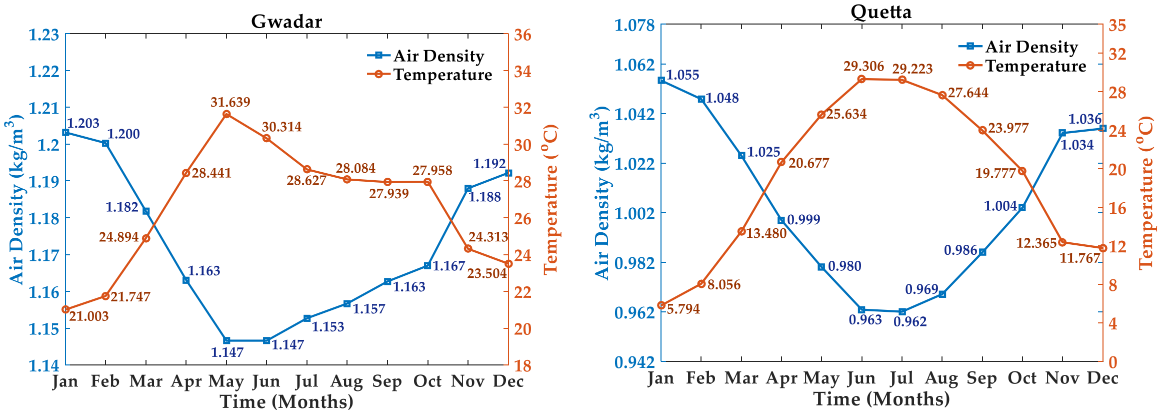

FIGURE 7. Air density and temperature of each site.

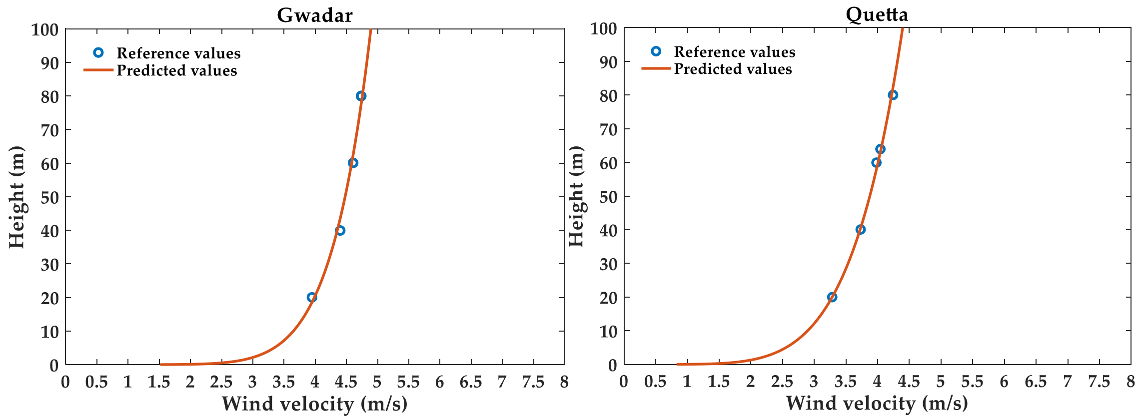

FIGURE 8. Shear profile and power-law of each site.

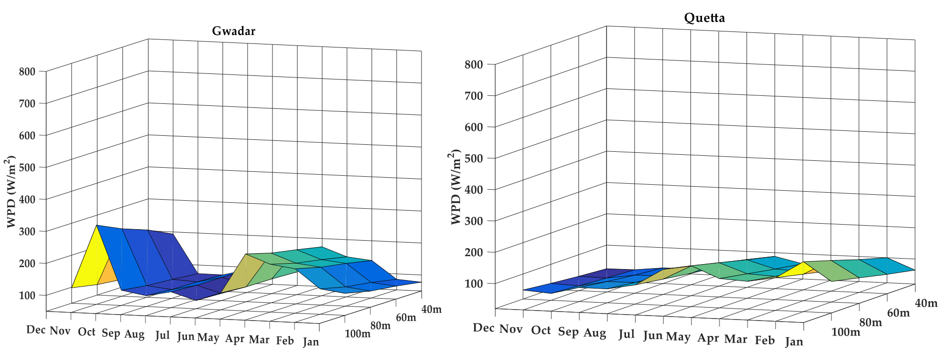

FIGURE 9. Wind power density on each site.

The maximum monthly WPD at hub height throughout the year, in February at Quetta is 179.56 W/m^2, and in November at Gwadar is 297.6 W/m^2, at Gwadar in July is 75.69 W/m^2, at Quetta in November is 180.96 W/m^2. The yearly average WPD at Gwadar and Quetta is 200.6 W/m^2 and 143.31 W/m^2, respectively. It implies that Gwadar and Quetta in Baluchistan province have very low WPD at 100m hub height.

Energy (kWh/m^2) at the suggested sites is calculated using Eq. (6). Fig 10 shows units generated at each location at different heights throughout one year. It can be seen that the maximum monthly energy generated at Quetta in February is 120.67 kWh/m^2, at Gwadar in November is 214.28 kWh/m^2. Whereas the minimum monthly energy generated through the year at Gwadar in September is 60.32 kWh/m^2 respectively, at Quetta in November is 30.19 kWh/m^2. The overall yearly energy (kWh/m^2) generated at Gwadar and Quetta is 1253.76 kWh/m^2, 896.41 kWh/m^2 respectively. It can be observed that Gwadar and Quetta sites generate low energy at the hub height of 100 m.

TABLE 7. Wind turbine characteristics used in this study.

Turbine Model	Rotor diameter (m)	Swept area (m^2)	Hub Heights (m)	Rated power (kW)	Cut-in wind speed (m/s)	Rated wind speed (m/s)	Cut-out wind speed (m/s)
Vestas V126/3300	126	12469	166, 149, 147, 137, 117, 87	3300	3	12	22.5
Goldwind GW121/2500	121	11595	120, 90	2500	3	9.3	22
Nordex n80/2500	80	5026	80, 70, 60	2500	3	15	25
Nordex n90/2300	90	6362	105, 100 80, 70	2300	3	13	25
Suzlon S97/2100	97	7386	120, 90	2100	3.5	11	20
Suzlon S88/2100	88	6082	100, 80	2100	4	14	25
Gamesa G97/200	97	7389.8	120, 104, 100, 90, 78	2000	3	19	25
G.E 1.6xle	82.5	5346	100, 80	1600	2	12	25
Nordex n60/1300	60	2828	69, 60, 46	1300	3	15	25
Suzlon S66/1250	66	3422	56, 74	1250	4	14	25

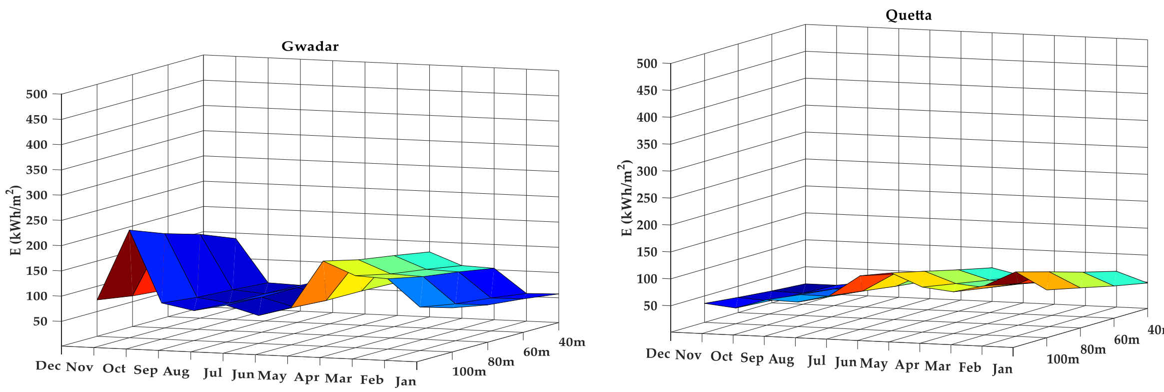

FIGURE 10. Shows energy generated by ten different wind turbines at each site.

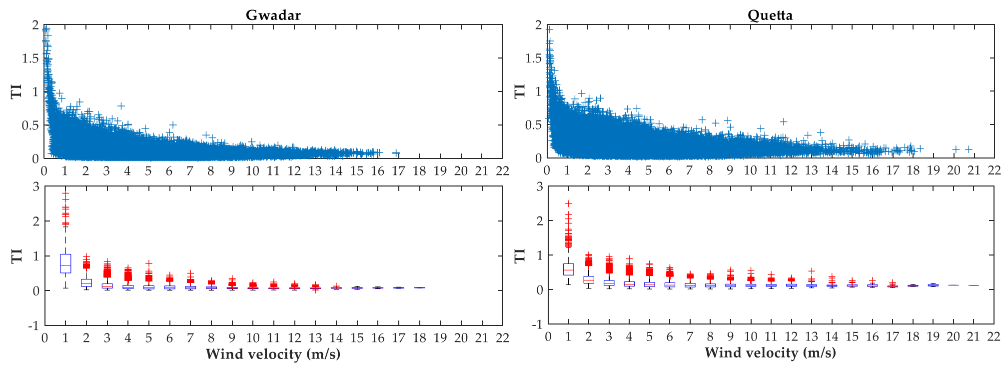

FIGURE 11. The turbulence intensity for each site.

The turbulence intensities calculated for each site using Eq. (10) and can be shown in Fig 11. The Gwadar and Quetta sites lie in roughness both in class 1 (See Table 4), respectively. The turbulence intensity was estimated minimum at the Gwadar site due to the boundary layer conditions as it happens to be on the sea level and provides the lowest friction to the ground level wind speeds. Similarly, Quetta also gives low wind turbulence because it lies in arid areas.

Moreover, the Weibull probability function curve of each numerical method, fitted to the wind speed data gives an analysis of the best contoured numerical method [75 & 78]. Fig 12 shows a comparison of five approaches to the wind speed data collected at each site in three provinces. They considered five ways in this study are fitted over reference data, and each curve shows Weibull probability density function, which helps in analysis and verification of each curve of five methods to the calculated data at each site. It helps in understanding which numerical technique fits best to the reference values of wind speed at each location. In this study modified maximum likelihood estimation method, the empirical method by Lysen and Justus all three give the superior fitting to reference values of average wind speed calculated at each site. Also, the energy pattern factor

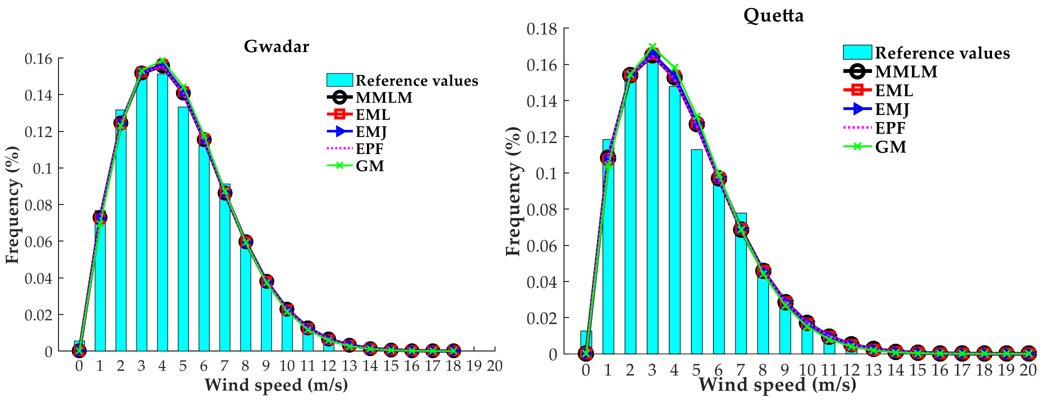

FIGURE 12. Weibull distribution methods used on the histogram of proposed sites.

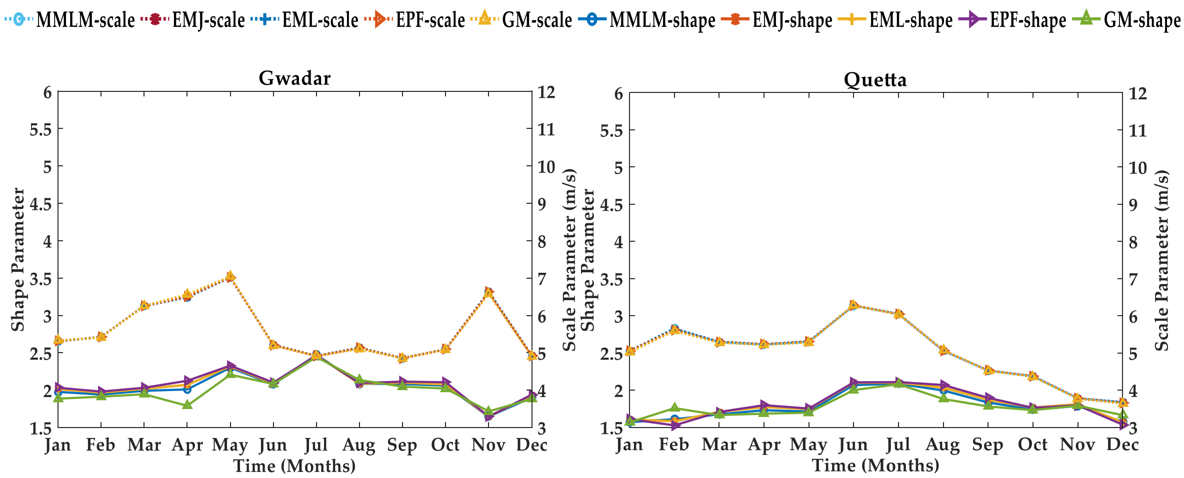

FIGURE 13. Shape (K) and Scale (C) Parameters of all Weibull parameter estimation methods.

method fits right over reference values, and the graphical method matches poorly at all locations.

The two Weibull parameters shape (k) and scale (C) are useful in the curve when the shape parameter (k) lies between 1 and 2 and this indicates that the distribution is towards lower values of wind speed, and if k is higher than distribution it is skewed towards higher values of wind speeds, which shows higher wind speed probability whereas the higher amount of scale parameter (C) indicates that the wind speed distribution is spread over a broader range thus higher probability of average wind speeds [79,83]. In Fig. 18 the monthly shape and scale parameters for each numerical method are shown and it is observed that the average shape parameter for which observed in Fig 7 and 13. So the shape and scale parameters of each method at Gwadar, Quetta, indicate that the distribution is tilted towards lower wind speeds and there is a lower probability of higher average wind speeds in these two sites. Moreover, the performance testing of numerical models (Table 8) shows that to Gwadar, Quetta, data, EPF, GM, GM, GM, GM, MMLM, EPF, EML, EPF, EPF, MMLM, and EPF showed best fitting respectively, followed by MMLM, EPF, EML, EPF, MMLM, EMJ, EML, EMJ, MMLM, MMLM, EMJ and MMLM. Therefore, in the overall ranking of five Weibull numerical methods, EPF shows robust performance as compared to the rest of the performance models, whereas MMLM stands second, EMJ and EML third and fourth, and GM ranked fifth, due to its poor-fitting performance for the seven sites. Thus, for each site mean wind speeds are calculated using the robust method available for that site as shown in Fig 13.

In this study, ten different wind turbine models are selected and capacity factor (%) and annual energy (GWh/year) generated at each site are estimated. The ratings of all turbine models to characterizes capacity factor are given in Table 9 and the details of wind turbine characteristics are presented in Table 7. The turbines in all sites, Goldwind GW121, Vestas V126, Gamesa G97, G.E 1.6xle, Suzlon S97, Nordex n90, Suzlon S88, Suzlon S66, Nordex n60 and Nordex n80 shows the highest to lowest capacity factor in the series. Whereas, Gwadar, Quetta, sites rank highest to lowest capacity factor (%) in series for all ten turbine models at four hub heights of 120 m, 100 m, 80 m and 60 m. Fig 14 shows the capacity factor calculated for ten turbines at four hub heights in each site. Similarly, annual energy generated in GWh/year by

TABLE 8. Performance models for each method used in this study.

Sites	Methods	MSE	RMSE	MAE	R	R^2
Gwadar	EPF	**0.00001158**	**0.00340329**	**0.00238099**	**0.998351741**	**0.9967062**
	MMLM	0.00001199	0.00346243	0.00242011	0.998279594	0.99656215
	EMJ	0.00001379	0.00371288	0.00260499	0.998084159	0.99617199
	EML	0.00001379	0.00371309	0.00259166	0.998071987	0.99614769
	GM	0.00002152	0.00463901	0.00326574	0.997205064	0.99441794
Quetta	EPF	**0.00002473**	**0.00497253**	**0.00295409**	**0.99648028**	**0.99297294**
	MMLM	0.00002731	0.00522554	0.00305945	0.99611911	0.99225327
	EMJ	0.00002926	0.00540951	0.00313312	0.99588419	0.99178532
	EML	0.00002932	0.00541471	0.00313891	0.99586472	0.99174654
	GM	0.00004381	0.00661871	0.00383117	0.99427336	0.98857952

TABLE 9. Rating of wind turbines in terms of cost $ per kWh estimated at each site.

100 m	Goldwind GW121	Vestas V126	Gamesa G97	Generic Energy	Suzlon S97	Nordex n90	Suzlon S88	Suzlon S66	Nordex n60	Nordex n80
Gwadar	0.0818	0.09382	0.0962	**0.1035**	0.10332	0.13144	0.13418	0.13918	0.17117	0.18137
Quetta	0.09523	0.1087	0.1133	0.1218	0.12259	0.15726	0.16077	0.16532	0.2042	0.21874

Cost of turbine = USD 1500/kW, Other Initial Cost = 30% of turbine's cost, Cost of maintenance & operations = 1.5% of turbine's cost, Life Span in years = 20

TABLE 10. Rating of wind turbines in terms of payback period in years at each site.

100 m	Goldwind GW121	Vestas V126	Gamesa G97	Generic Energy	Suzlon S97	Nordex n90	Suzlon S88	Suzlon S66	Nordex n60	Nordex n80
Gwadar	11	12	13	14	14	17	18	18	22	23
Quetta	15	17	17	19	19	23	24	24	28	29

Nominal Electricity Escalation Rate (%/year) = 2%, Down payment Percentage (%) = 20%, Interest Rate (%/year) = 10%, Debt Term (years) = 5

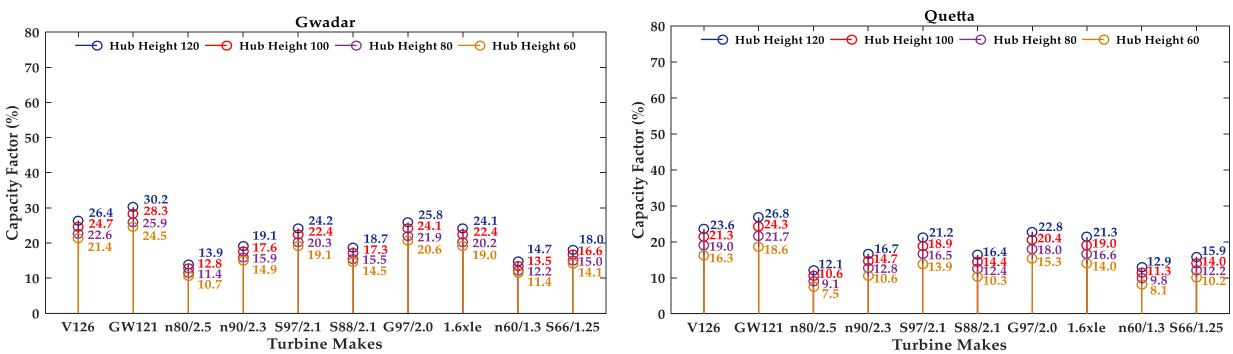

FIGURE 14. Shows capacity factor of ten different wind turbine makes at each sites.

each turbine at each site for different hub heights is shown in Fig 15.

Table 9 contains the cost of energy generated by different turbines at each site in US-Dollars. The cost assumed for each turbine is USD 1500/kW of rated power, initial costs like transportation cost and cost of installation are assumed to be 30% of the cost of turbine, and cost of operation and maintenance are assumed to be 1.5% of turbine's cost. The life span of the turbine is considered about 20 years. The Goldwind GW121 turbine gives the lowest cost in dollars at each site, it is followed by Vestas V126, Gamesa G97, Generic Energy, Suzlon S97, Nordex n90, Suzlon S88, Suzlon S66, Nordex n60, and the highest cost by Nordex n80.

Similarly, Table 10 contains the payback period of wind turbines considered at each site. Following considerations are taken: Nominal Electricity Escalation Rate (%/year) up to 2%, Down payment Percentage (%) equal to 20%, Interest Rate (%/year) of 10%, and Debt Term (years) for the period of 5 years. Results suggest that the lowest payback period would be for Goldwind GW121 turbine followed by Vestas V126, Gamesa G97, Generic Energy, Suzlon S97, Nordex n90, Suzlon S88, Suzlon S66, Nordex n60, and Nordex n80.

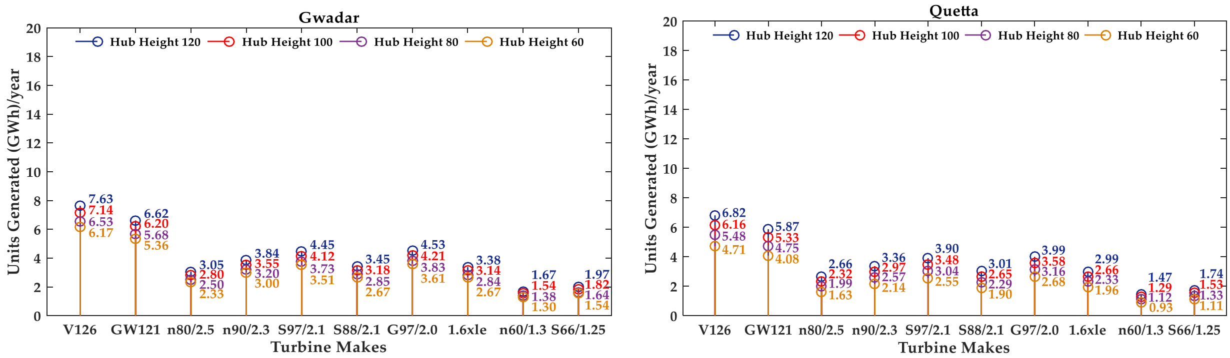

FIGURE 15. Shows GWh/year of ten different wind turbines makes at each site.

While the payback period of these turbines varies from site to site. Therefore, the proposed sites Gwadar and Quetta, have considerable payback periods for the first six and three turbine models (namely Goldwind GW121, Vestas V126, Gamesa G97, Generic Energy, Suzlon S97, Nordex n90) while longer payback period for the rest of the turbines. In the case of Gwadar and Quetta, both sites have marginal economic benefits with the first six turbines.

VI. CONCLUSION

To counter depleting fossil fuels and increasing environmental pollution impact, renewable energy resources (RESs) have been receiving tremendous attention around the globe. Amongst other RESs, wind energy has been proving itself a promising renewable resource. However, still, the selection of wind turbine (WT) and its installation is considered a major challenge. Presently, due to the economic boom of Pakistan as a regional power under the China Pakistan Economic Corridor (CPEC), it needs to meet energy shortage, by utilizing extensive wind energy capacities available in Pakistan. This paper aims to conduct a pre-feasibility investigation of wind farm exploitation at Gwadar and Quetta, major cities of Baluchistan province in Pakistan by harnessing the wind energy potential and electricity generation cost through different WT models. The wind speed (WS) data is recorded by a professional wind mast at different measurement heights during F.Y 2016.

The main conclusions are as follows:

- One-year wind data is used for wind resource estimation through five different Weibull distribution parameter estimation methods used EPF, MMLM, EMJ, and EML performs as best fitting over measured data, while GM gives a poor fit to the data at the proposed sites. The assessment of wind resources done on a monthly and daily basis. The results show that Gwadar and Quetta have tremendous wind potential. During the summer season, Quetta and Gwadar have the highest mean wind speed. In the day and night times, Gwadar has the highest mean wind speed.
- The wind rose graphs suggest that proposed sites have a tiny percentage of substantial direction change, except Quetta. The highest wind power density and energy generated were estimated at Gwadar and Quetta. Hence the proposed sites lie in wind power class 2 (marginal) and it is most suitable for small-scale wind turbines and most valuable for power generation to the off-grid community.
- Ten different wind turbine models are used to estimate energy output at each site, which shows that the highest capacity factor and GWh/year was obtained on Goldwind GW121. It also implies that there is commercial wind energy potential in the proposed sites. Moreover, the long-term period data can be used to estimate more accuracy in wind resource assessment. Economic evaluation for studied sites can be done to understand the feasibility of wind generation units' installation. The GOP can encourage IPPs and public power generation companies to exploit wind energy in Quetta and Gwadar.
- It can be seen that the maximum and minimum monthly energy generated (kWh/m2) at Quetta in February is 120.67, and at Gwadar in November is 214.28, whereas, in November is 30.19 and in September is 60.32 respectively. The overall yearly energy generated (kWh/m2) at Gwadar is 1253.76 and in Quetta is 896.41. Therefore, GW121 WT gives the lowest cost in dollars and the lowest payback period at each site.
- Results suggest that the lowest payback period would be for the GW121 WT. Moreover, it can be recommended as one of the most feasible WTs for electricity generation for powering local communities at the proposed sites.

It is concluded that effective institutions and their consistency in optimal policymaking for energy poverty, economic regulations, improved technology, research and development, proper studies on feasibility and cybersecurity will help GOP to achieve renewable energy transition which is beneficial for its local communities where are no electric grids to supply power. Thus, the energy shortage can be reduced, while industrial needs in the wake of CPEC can also be full filled, GDP can be increased, and the quality of life of the people of Pakistan can be improved.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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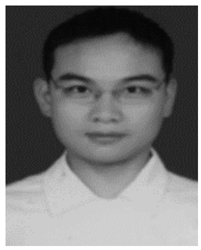

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