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Site-specific technical and economic analysis of wind power potential and energy generation using Weibull parameters

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Abstract

Purpose – The purpose of this paper is to find out a new potential site for energy generation to maximize the energy generation via installing utility wind turbines.

Design/methodology/approach – In this paper, Weibull two-parameter methodologies are used to determine the effectiveness of the wind speed at three different heights including 80, 60 and 30 m. Standard deviation and wind power density (WPD) are also calculated for the site. After analyzing the wind resource, the wind turbine selection is materialized to maximize the energy production, considering the best configuration of the wind turbines that is suitable for the site. In the end, economic aspect is also calculated.

Findings – The mean Weibull dimensionless parameter k is found to be 2.91, 2.845 and 2.617, respectively. The mean Weibull scale parameter c is found to be 6.736, 6.524 and 6.087 at the heights of 80, 60 and 30 m, respectively. The mean standard deviation is found to be 2.297, 2.249 and 2.157 at the heights of 80, 60 and 30 m at the heights of 80, 60 and 30 m, respectively. Wind power densities are calculated to be 265, 204 and 157.9 W/m^2 at the heights of 80, 60 and 30 m, respectively (highest in the month of July when the mean wind speed is 7.707 m/s and WPD is 519 W/m^2). Finally, site-specific economic analysis of wind turbines is carried out, which shows $0.0230 per kWh at the height of 80 m.

Originality/value – The results show that the site is beneficial for the installation of small and large wind turbines.

Keywords Energy production, Economic analysis, Capacity factor, Weibull parameters k and c, Wind analysis, Wind power density

Paper type Research paper

1. Introduction

Pakistan is an energy deficit country whose energy needs are solely fulfilled by oil and gas (Figure 1). The oil imports rose 3.8 percent per year after 1991 up to 2014. Similarly, the demand rose again in the year 2015 by 4.4 percent. The average price of oil in 2001 was $23 barrel, and within the same year, the price of oil increased rapidly to reach a value of $50.05 barrel. This was an almost 115 percent rise in the price in a short span of time. Energy availability of any country has a direct relation with its socio-economic growth. According to the national economic review, the country witnessed a decrease of 4.5 percent in the GDP in the last few years due to energy shortages. It resulted in closing of factories, thus paralyzing the industrial production and exacerbating unemployment.

The other important reason behind the energy crisis is the worst financial position of the country. In simple words, the liquidity ratio of the country is very low. The current demand for electricity is 19,000 MW, whereas the supply is 10,500 MW. The supply and demand gap is 8,500 MW. This gap can be overcome by the renewable energy resources, including solar energy and wind energy. According to National Renewable Energy Laboratories (NREL), Pakistan has a total of 61,650 m^2 land appropriate for the installation of wind turbines. It accounts for 8 percent of the total land, i.e. 770,875 m^2. The coastal belt of Sindh and Baluchistan has been termed as the wind corridor of the country (Shami *et al.*, 2016).

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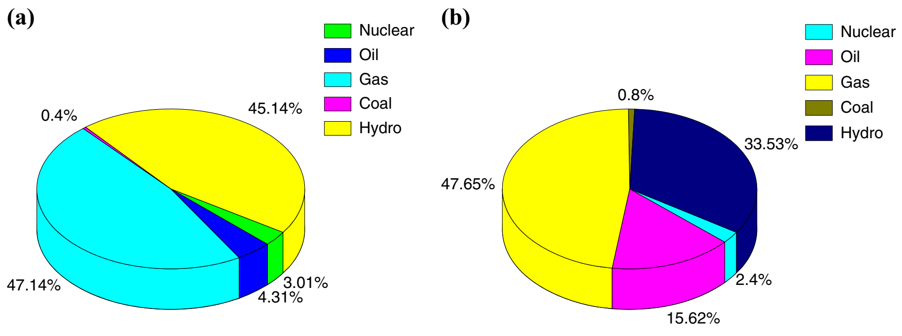

Notes: (a) 1978; (b) 2010

Figure 1. Comparative statement of usage of energy resources in Pakistan

2. Literature review

Kaldellis described the past perspectives of fossil fuels and discussed the importance of wind energy to overcome the need of electricity (Kaldellis and Zafirakis, 2011). Mostafaeipour *et al.* (2011) conducted a feasibility study of the wind energy potential of Shahrbabak city of Kaman province of Iran. The authors used a two-parameter Weibull distribution function for wind analysis. Mostafaeipour (2010) in his another feasibility study of Yazd province of Iran used the extrapolation method for the wind analysis at the height of 10 m. Keyhani *et al.* (2010) investigated the influence of wind climate on the energy production of Tehran, the capital city of Iran, and analyzed metrological wind records at the altitude of 10 m. Kwon (2010) investigated the wind uncertainty of the Kwangyang bay and calculated it to be 11 percent.

Mohammadi and Mostafaeipour (2013) estimated the wind power potential of Zarinah and used standard deviation and wind power density (WPD) methods to find the accurate WPD of the site. Mostafaeipour *et al.* (2013) investigated the wind potential of Binalood of Iran and concluded that the site has a potential for installation of wind turbines at the heights of 10, 30 and 40 m. Mirhosseini *et al.* (2011) conducted a feasibility study of five towns of Saman province of Iran. The study was based on the collection of wind data at the heights of 10, 30 and 40 m. Baseer *et al.* (2017) analyzed the wind resources of seven locations in Jubail, Saudi Arabia. The authors estimated Weibull parameters by using the maximum likelihood, least-squares regression method and WAsP algorithm.

Dahmouni *et al.* (2011) investigated wind variation at the heights of 10, 20 and 30 m for energy production, considering 1.5 MW wind turbine for Borj-Cedria of Tunisia. Li and Li (2005) assessed the wind energy potential for Waterloo, Canada. Lashin and Shata (2012) analyzed the wind resources for energy generation at Port Said of Egypt. Himri *et al.* (2012) conducted the feasibility study based on eight years record of the wind speed at Tindouf of Algeria. Đurišić and Mikulović (2012) conducted the study of wind energy potential for the South Banat region of Serbia and developed a mathematical model based on the least-squares method and concluded that the site is suitable for setting up the wind farm. Rehman *et al.* (2012) studied the wind power potential of seven sites in Saudi Arabia and used Weibull parameters to study the wind speed characteristics at three heights.

Ouarda *et al.* (2015) evaluated the wind speed with reference to probability density function and used suitable PDF to minimize the wind power estimation error. Al-Abbadi (2005) assessed the wind power potential of Yanbu, Saudi Arabia. The wind data analyzed on annual, seasonal and diurnal basis suggested that the site has a potential for installation of small wind turbines. Bassyouni *et al.* (2015) analyzed the wind characteristics based on 11-year wind data record of Jeddah city of Saudi Arabia. The characteristics include the daily, monthly and annual wind speed, wind probability density distribution, and shape *k* and scale *c* parameters at 10 m height.

This paper provides a detailed analysis of wind speeds at the heights of 80, 60 and 30 m. The two-parameter Weibull distribution function is used for the wind data analysis. The WPD is also analyzed and the energy production is estimated at the heights of 80, 60 and 30 m. To achieve the maximum output, three different wind turbines are compared at each height and predicted the energy output according to the wind data available at each height. The wind data are collected for a period of one year, i.e. from January 2009 to December 2009. The capacity factor is also calculated for each considered height. The economic analysis is carried out to choose the best wind turbine for the site, based on the configuration and extraction of maximum energy from the wind with minimum cost/kWh.

3. Site-specific features

Karachi is a major economic activity-generating city of Pakistan. Karachi also falls on the coastline of Arabian Sea that is 1,060 km long and connects two provinces, namely, Baluchistan and Sindh. The topographic features of Karachi coastal area are given in Table I.

4. Methodology

4.1 Weibull probability distribution

Wind speed is a random variable. Probability density function and cumulative functions are used to calculate the speed of wind variation over a period of time. The wind energy potential of a site depends on the speed and time duration of wind. The Weibull distribution function of two parameters (*k* and *c*, commonly known as shape and scale parameters) is the most appropriate distribution function for the wind data analysis. The Weibull $f(v)$ probability distribution function is written as (Akpinar and Akpinar, 2005):

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

Site-specific features of coastal area of Karachi

Station parameters	Unit	Features
Latitude	deg N	24° 52′ 02.025″
Longitude	deg E	66° 51′41.983″
Wind frequency	m/s	78.5/28.5 m
Mean wind speed at 30 m	m/s	5.199
Mean wind speed at 50 m	m/s	5.64
Mean wind speed at 60 m	m/s	5.79
Mean wind speed at 80 m	m/s	6.0
Wind direction	m/s	0-360°
Average temperature	°C	24°
Surface roughness	Sa	0.0024
Surface roughness class	Sa	0.50
Pressure	mbar	900-1,100
Terrain	–	Flat land
Obstacles	–	Nil
Relative humidity	%	0-100
Air density	kg/m^3	1.188

Table I. Site-specific features of south coastal area of Karachi where V refers to the wind speed, k refers to a shapeless parameter, and C refers to a scale parameter having a similar dimension of V.

The cumulative distribution function $f(v)$ is given below:

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

Mean wind speed is a commonly used measure to determine the potential of wind energy production and can be termed as V_{mean} potential. It can be used as follows:

$$V_{\text{mean}} = \frac{1}{N}\sum_{i=1}^{N} V_i \tag{3}$$

The wind speed variance can be used as follows:

$$\sigma^2 = \frac{1}{N-1}\sum_{i=1}^{N} \left(V_i - V_{\text{avg}}\right)^2 \tag{4}$$

The standard deviation can be calculated as follows:

$$\sigma^2 = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N} \left(V_i - V_{\text{avg}}\right)^2} \tag{5}$$

The average wind speed and variance are calculated by using the Weibull parameters as follows (Keyhani *et al.*, 2010):

$$V_{\text{avg}} = c\Gamma\left(1 + \frac{1}{k}\right) \tag{6}$$

$$\sigma^2 = C^2\left[\Gamma\left(1 + \frac{2}{K}\right) - \Gamma^2\left(1 + \frac{2}{K}\right)\right] \tag{7}$$

where Γ is the gamma function and it can be calculated by the following formula:

$$\Gamma_{(x)} = \int_0^{\infty} e^{-\mu} u^{x-1} \mathrm{d}u \tag{8}$$

4.2 WPD and energy generation

The wind power can be calculated as follows:

$$P = \frac{1}{2} p A_T v^3 \tag{9}$$

where P (W) refers to the wind power, V refers to the wind speed, p refers to the air density, and A_T refers to the swept area of the wind turbine blades.

According to the Betz theorem, 59 percent (16/27) or less of the kinetic energy can be converted into mechanical energy. Betz limit is denoted by C_p and can be expressed as follows:

$$P = \frac{1}{2} p C_p A_T v^3 \tag{10}$$

The WPD can be expressed by the following equation:

$$\text{WPD} = \frac{P}{A_T} = \frac{1}{2}\rho C_p v^3 \tag{11}$$

The WPD can be calculated with the Weibull distribution function as follows:

$$\text{WPD} = \frac{P}{A_T} = \frac{1}{2}\rho C_{p^3}\Gamma\left(1+\frac{3}{k}\right) \tag{12}$$

The extraction of wind energy is calculated by the following equation:

$$E = T\int_0^\infty P(V)f(V)dV \tag{13}$$

where E refers to the energy achieved, T refers to the time period, and $P(V)$ refers to the wind turbine power curve. Substituting the values of Equation (1) into Equation (13), we can get the following equation:

$$E = T\int \left(\frac{k}{C}\right)\left(\frac{V}{C}\right)^{K-1}\exp\left(-\frac{V}{C}\right)^k P(V)dV \tag{14}$$

The above equation represents the Weibull distribution function that is useful in estimating the wind energy.

4.3 Capacity factor

Capacity factor can be calculated as follows:

$$cf = \frac{A_{\text{Power}}\text{ by wind turbine}}{R_{\text{Power}}\text{ of wind turbine}} \tag{15}$$

5. Economic analysis of wind turbine

Let I denote the initial investment and C_{om} denote the operation and maintenance cost, which is known to be n percent of the primary investment. T is termed as the lifetime of the wind turbine. The discounted costs of operation and maintenance for the lifetime t of wind turbine for the initial year can be calculated as:

$$PC_{om_{1-t}} = I\left[\frac{(1+i_r)^t-1}{i_r(1+i_r)}\right] \tag{16}$$

The net present worth can be calculated as follows:

$$\text{PW}_{1-t} = I\left[I+n\left\{\frac{(1-i_r)^t-1}{i_r(1+i_r)^t}\right\}\right] \tag{17}$$

So, cost is calculated as:

$$\text{NPW} = \frac{\text{PW}_{1-t}}{t} = \frac{1}{t}\left[I+n\left\{\frac{(1-i_r)^t-1}{i_r(1+i_r)^t}\right\}\right] \tag{18}$$

The total cost of the wind energy is calculated by the following equation:

$$T_c = \frac{\text{PW}}{E} \tag{19}$$

where E refers to the energy generated by the wind turbines annually. The annual energy is computed with the help of the following equation:

$$E = T_{Ah} \times R_P \times C_F \tag{20}$$

$$E = \frac{1}{T_{Ah}}\left(\frac{1}{R_p C_F}\right)\left[I + n\left\{\frac{(1-i_r)^t - 1}{i_r(1+i_r)^t}\right\}\right] \tag{21}$$

where E refers to energy, T_{Ah} refers to total time in year (hours), R_P refers to the rated power of the wind turbine and C_F refers to the capacity factor of the wind turbine.

6. Results and discussion

6.1 Wind speed variation at different heights

The wind data are considered for a period of one year that starts from January 2009 to December 2009 (Figure 2). Wind speed data are recorded at the heights of 30, 60, and 80 m. Wind speed at south coastal land mass is recorded by using a data logger manufactured by Wilmers. The Loggers is connected with wind vanes and anemometers placed at 80, 60 and 30 m heights. The mean wind speed for a year is 5.199, 5.64, 5.79 and 6 m/s at the heights of 30, 50, 60 and 80 m, respectively. The mean wind speed is more than 5.5 m/s at the height of 80 m. The monthly observed wind speed is higher at three heights during June and August 2009. The month July has the maximum wind speed value than other months. The seasonal analysis of the site showed that the summer season, from June to August, has higher frequency of wind speed at the three considered heights. The average wind speed at the height of 80 m is 6.0 m/s. For the year 2009, the average wind speed from April to September is found to be 6.89, 6.67 and 6.18 m/s at

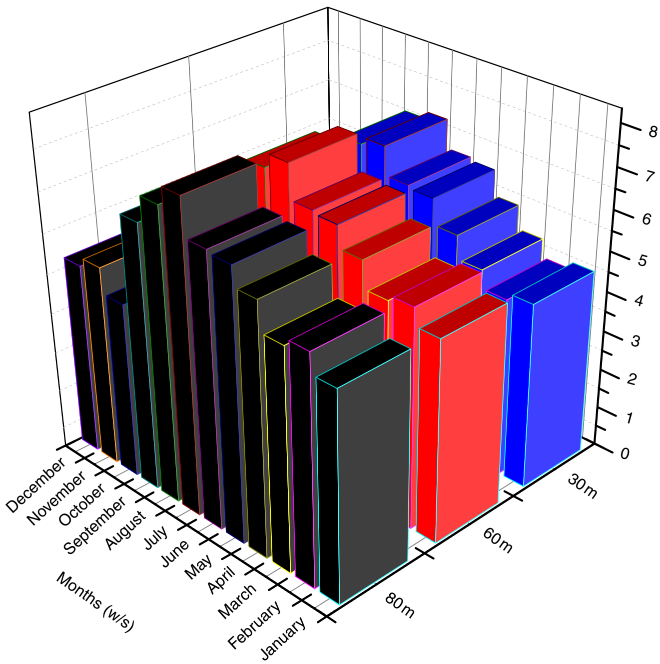

Figure 2.
Average wind speeds at three heights

the heights of 80, 60 and 30 m, respectively. In fact, seasons have a pivotal impact on wind speed. There are four seasons in Pakistan, including winter that starts from December and lasts up to February. Spring starts from March and ends in May, summer is from June to August and autumn is from September to November. The average seasonal wind speed during the months from December to February, March to May and June to August and September to November is 5.213, 6.154, 7.261 and 5.337 m/s at the height of 80 m, respectively. The maximum wind speed 7.261 m/s falls in the summer season of 2009 at the height of 80 m.

The mean wind speed at the height of 60 m is 5.79 m/s for the year 2009. The seasonal analysis of average wind speeds shows the following results: 5.015 m/s (December to February) 5.956 m/s (March to May) 7.056 m/s (June to August) and 5.13 m/s (September to November), which showed the influence of season on wind at the height of 60 m. The maximum wind 7.056 m/s falls in the summer season of 2009. Similarly, the average wind speed at the height of 30 m is found to be 5.199 m/s for a period of year 2009. The seasonal average wind speed from December to February, March to May, June to August and September to November is found to be 4.339, 5.265, 6.59 and 4.601 m/s at the height of 30 m, respectively. The maximum wind speed 6.59 m/s falls in the summer season 2009 at the height of 30 m.

The wind speed is also analyzed by the concept of the most probable point and maximum energy produced from the wind. The most probable wind speeds are 7.707 and 7.285 m/s in the months of July and August of the year 2009. The maximum energy extracted during July and August is 7.87 and 6.91 GWh at the height of 80 m, respectively, taking the parameters of the wind turbine into account. The most probable point at the height of 60 m is 7.452 and 7.104 m/s in July and August, respectively. The maximum energy that can be produced is 4.02 and 3.61 GWh in July and August, respectively. At the height of 30 m, the most probable point is 6.883 and 6.703 m/s in July and August, respectively. Similarly, the maximum energy produced is 0.88 and 0.82 GWh in July and August, respectively. The average wind speed during the months from April to September remains high but, more specifically, in July and August, it is comparatively much higher.

6.2 Weibull probability distribution function

In this paper, the two-parameter Weibull functions are used to determine the effectiveness of the wind. The k parameter is termed as the dimensionless parameter, whereas the c parameter is termed as the scale parameter. The higher value of the scale c parameter shows the higher tendency of average wind speeds. Similarly, the value of k factor is dimensionless; if it remains in between 1 and 2, the wind speed can be termed as the low-level wind. If the value of k factor shows the increasing tendency, the distribution can be considered as skewed to high level of winds.

The mean Weibull dimensionless parameter k at the heights of 80, 60, and 30 m is 2.91, 2.845 and 2.617, respectively (Figure 3(a)). At the height of 80 m, the value of the dimensionless parameter k is minimum, i.e., 1.868, in the month of November and maximum, i.e., 4.091, in September. Similarly, the dimensionless factor k at the height of 60 m is found to have a minimum value of 1.926 in the month of November and a maximum value of 3.891 in July. At the height of 30 m, the minimum value is 1.846 in October and maximum value is 3.761 in July. The k parameter results show the increasing tendency throughout the year 2009, except for November 2009 at the heights of 80 and 60 m and October at the height of 30 m. The results can be termed as skewed to high levels of winds at three heights, 80, 60 and 30 m.

The monthly mean Weibull scale parameter c at the heights of 80, 60 and 30 m is 6.736, 6.524 and 6.087, respectively (Figure 3(b)). According to the computed data, the Weibull scale parameter c is minimum in the month of October and maximum in July at the three heights. At 80 m height, the minimum value of 4.92 is found in the month of October and maximum

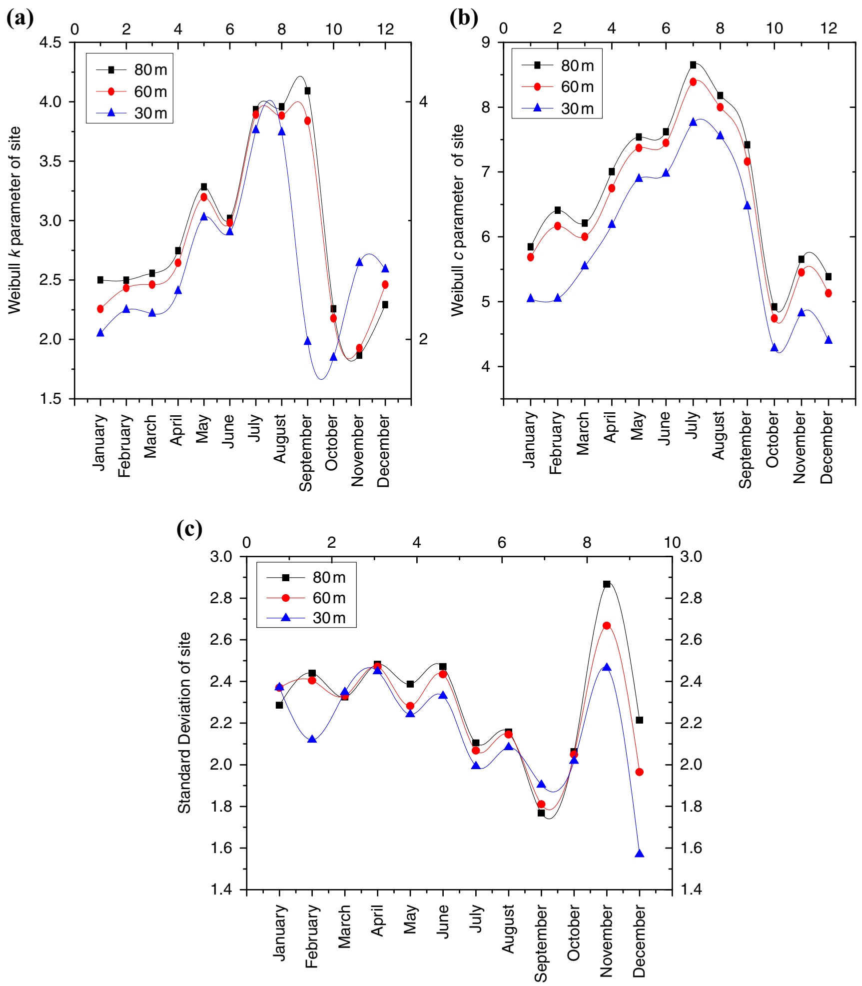

Figure 3.
Results of (a) monthly Weibull *k* parameter, (b) *c* parameter and (c) standard deviation at 80, 60 and 30 m heights

value of 8.65 in the month of July whereas at the height of 60 m, the minimum scale parameter is 4.74 and maximum is 8.39 in the months of October and July, respectively. At the height of 30 m, the scale parameter remains minimum in the month of October with a value of 4.278 and maximum with a value of 7.76 in the month of July. The maximum seasonal value is found to be 8.15, 7.95 and 7.43 during summer season (June to August) at the heights of 80, 60 and 30 m, respectively. The standard deviation is known as the moderate form of the average deviation. The average standard deviation is 2.297, 2.249 and 2.157 at the heights of 80, 60 and 30, respectively (Table II and Figure 3(c)).

6.3 Wind power calculation and annual energy density

The WPD at different heights, including 80, 60 and 30 m, is calculated. The mean WPD for the year 2009 is found to be 265, 204.9 and 158 W/m^2 at the heights of 80, 60 and 30 m, respectively. The maximum WPD for the month of July is found to be 519, 392 and 314 W/m^2 at the heights of 80, 60 and 30 m, respectively (Figure 4).

Table II. Monthly wind speed, standard deviation and Weibull k and c parameters at different heights for the year 2009

Parameter	January	February	March	April	May	June	July	August	September	October	November	December	Mean
Height 80 m													
W/S	5.18	5.68	5.512	6.235	6.716	6.791	7.707	7.285	6.606	4.388	5.017	4.779	6
σ	2.286	2.44	2.325	2.482	2.387	2.471	2.105	2.157	1.768	2.063	2.867	2.214	2.297
k	2.50	2.498	2.556	2.746	3.284	3.018	3.932	3.957	4.091	2.258	1.868	2.291	2.91
c	5.845	6.41	6.21	7.004	7.54	7.62	8.65	8.18	7.42	4.92	5.652	5.384	6.736
Height 60 m													
W/S	5.038	5.465	5.332	5.996	6.541	6.612	7.452	7.104	6.354	4.211	4.835	4.544	5.79
σ	2.37	2.405	2.331	2.471	2.282	2.434	2.068	2.145	1.81	2.049	2.668	1.965	2.249
k	2.255	2.432	2.46	2.645	3.196	2.98	3.891	3.884	3.84	2.177	1.926	2.461	2.845
c	5.685	6.166	6.0	6.75	7.37	7.45	8.39	8	7.16	4.74	5.45	5.13	6.524
Height 30 m													
W/S	4.645	4.472	4.198	5.485	6.114	6.184	6.883	6.703	5.736	3.794	4.274	3.9	5.199
σ	2.371	2.12	2.349	2.448	2.242	2.33	1.993	2.084	1.904	2.018	2.465	1.57	2.157
k	2.05	2.247	2.217	2.406	3.026	2.902	3.761	3.743	1.979	1.846	2.643	2.588	2.617
c	5.038	5.0462	5.545	6.185	6.894	6.973	7.76	7.55	6.468	4.278	4.819	4.397	6.087

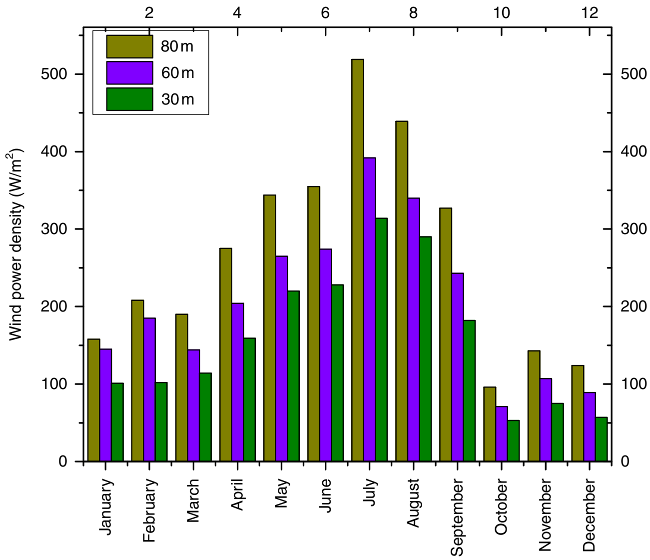

Figure 4.
Wind power density at 80, 60 and 30 m heights

The mean annual energies of three wind turbines are compared at the height of 80 m are found to be 747.2, 756 and 791.2 kWh/m^2 for wind turbines 1, 2 and 3, respectively. The mean annual energies of three wind turbines are compared at the height of 60 m and found to be 653.9, 637.9 and 641.5 kWh/m^2 for wind turbines 1, 2 and 3, respectively. Similarly, the calculated mean annual energies of three wind turbines compared at the height of 30 m are found to be 555.9, 526.8 and 504.1 kWh/m^2 for wind turbines 1, 2 and 3, respectively.

The mean annual energy is affected by seasonal wind variation. The mean annual energy is calculated on a seasonal basis to compare three wind turbines at the heights of 80, 60 and 30 m (Figure 5). In this paper, the season is divided into winter, spring,

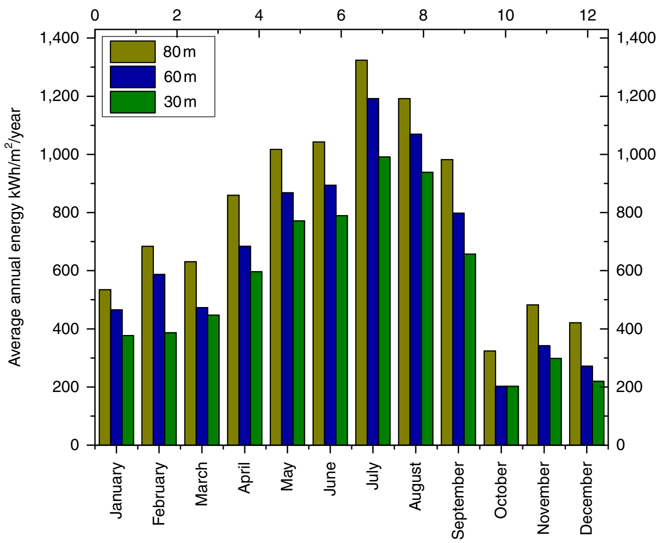

Figure 5.
Average annual energy at 80, 60 and 30 m heights

summer, and autumn. At the height of 80 m, the mean annual energy from December to February is 528.6, 525.6 and 546.6 kWh/m^2 for wind turbines 1, 2 and 3, respectively. The mean energy output from March to May is 791.6, 797.6 and 835 kWh/m^2 for wind turbines 1, 2 and 3, respectively. The mean annual energy from June to August is 1,098.6, 1,069.6 and 1,186.3 kWh/m^2 for wind turbines 1, 2 and 3, respectively. The mean annual energy from September to November is 569.6, 572.6 and 596 kWh/m^2 for wind turbines 1, 2 and 3, respectively.

The mean seasonal annual energy at the height of 60 m is computed for the site. The mean energy calculated from December to February is 441.3, 435.6 and 432.6 kWh/m^2 for wind turbines 1, 2 and 3, respectively. From March to May, it is 675, 657.6 and 660.3 kWh/m^2 for wind turbines 1, 2 and 3, respectively. From June to August, it is 1,051, 1,014 and 1,034.6 kWh/m^2 for wind turbines 1, 2 and 3, respectively. The mean energy output for September to November is 447.3, 444 and 438.3 kWh/m^2 for wind turbines 1, 2 and 3, respectively.

At the height of 30 m, the mean energy attained from December to February is 327.3, 298.3 and 298.3 kWh/m^2 for wind turbines 1, 2 and 3, respectively. During the months from March to May, it is 604.6, 569.6 and 508.3 kWh/m^2 for wind turbines 1, 2 and 3, respectively. From June to August, it is 906, 882.6 and 859 kWh/m^2 for wind turbines 1, 2 and 3, respectively. Similarly, from September to November, it is 385.6, 356.3, and 350.6 kWh/m^2 for wind turbines 1, 2 and 3, respectively.

6.4 Selected wind turbines configuration and power curve

Wind energy is environment friendly. It is not a potential threat to environment as compared to the thermal and coal-fired power plants. The potential of wind can become the basis for the generation of energy. The power curve is the most important measure of the wind turbine which elaborates the power curve density of the site. The IEC 61400-12 also describes the power curve as an important measure of the wind turbine. Moreover, the selection of the wind turbine and its features are necessary for the maximum output. The features of the wind turbine include hub height, rotor diameter and swept area, cut in and out speed, rated power and gear ratio, etc. In this paper, the analysis of wind turbines is carried out to get the maximum energy output at different hub heights, including 80 m, 60 m and 30 m. In this regard, three different wind turbines are considered at each height. The features of wind turbines are given in Table III.

6.5 Energy generation

It is one of the most important steps to examine wind farm and calculate the energy produced by a wind turbine. A wind turbine can produce maximum energy if its technical composition, including cut in and cut out, hub height, swept area, rated power and ratio of the gearbox, is chosen according to wind characteristics. Currently, higher height wind turbines are available to extract maximum energy from the wind. The maximum power

	Hub height 80 m			Hub height 60 m			Hub height 30 m		
Features	WT 1	WT 2	WT 3	WT 1	WT 2	WT 3	WT 1	WT 2	WT 3
A_T	6,362	5,027	4,537	3,217	3,020	3,422	876	692.7	572
R_p (kW/h)	2,300	2,000	2,000	1,500	1,300	1,650	300	250	150
Blades	3	3	3	3	3	3	3	3	3
C_{in} (m/s)	3	4	4	5	3	4	3	3	3
C_{out} (m/s)	25	25	25	25	22.5	25	25	25	25
Gearbox	1:77.44	1:89	1:89	1:80	1:79	1:98	1:48	1:25	1:25

Table III. Salient features of three wind turbines compared at each height generated by the wind turbine at each hub height and their monthly mean capacity factor are listed in Tables IV-VI.

Wind turbine 1 has a maximum annual energy output of 57.04 GWh as compared to wind turbines 2 and 3, which have 45.6 and 43.01 GWh annual energy output at the height of 80 m, respectively, for the year 2009. Wind turbine 1 performs better than wind turbines 2 and 3 in terms of generation of maximum energy. The seasonal trend is visible in the annual energy output. The mean seasonal energy output from December to February, March to May, June to August, September to November is 3.36, 5.04, 6.99 and 3.62 GWh by the wind turbine 1, respectively. The maximum annual energy output is found to be 7.75 GWh in the month of July and the minimum energy output is found to be 2 GWh in the month of October for the year 2009.

Similarly, wind turbine 3 has a maximum annual energy output of 26.34 GWh as compared to wind turbines 1 and 2, which have 25.2 and 23.08 GWh annual energy output at the height of 60 m for the 2009, respectively. The mean seasonal energy output from December to February, March to May, June to August and September to November is 1.48, 2.25, 3.54 and 1.50 GWh by wind turbine 3, respectively. The maximum energy output is found to be 4.02 GWh in the month of July and minimum energy output is found to be 0.66 GWh in the month of October for the year 2009. The detailed results of the wind energy output of three wind turbines are described in Table V.

Wind turbine 1 has a maximum annual energy output of 5.87 GWh as compared to wind turbines 2 and 3, which have 4.124 and 4.29 GWh at the height of 30 m for the year 2009, respectively. The mean seasonal energy output from December to February, March to May, June to August, and September to November is 0.29, 0.52, 0.80 and 0.37 GWh by wind turbine 1, respectively. Similarly, the maximum minimum energy output is found to be 0.88 GWh and minimum energy output is found to be 0.18 in October for the year 2009. The detailed results are described in Table VI.

6.6 Capacity factor

Capacity factor is another measure to state the energy output from a wind turbine. It is also an important measure of performance of wind turbines. The calculated mean annual capacity factor at the height of 80 m is 23.6, 21.83 and 21.2 for wind turbines 1, 2 and 3, respectively. The calculated mean annual capacity factor at the height of 60 m is 16, 16.9 and 15.9 for wind turbines 1, 2 and 3, respectively. Similarly, the capacity factor at the height of 30 m is 18.6, 15.8 and 23.2 for wind turbines 1, 2 and 3, respectively. The capacity factor is found in the month of July and minimum in October at three heights of 80, 60 and 30 m. The details are given in Tables IV-VI. The maximum seasonal capacity factor is maximum found to be 34.3, 24.6 and 30 during summer season at the heights of 80, 60 and 30 m, respectively. The monthly calculated capacity factor of all wind turbines at different heights is shown in Tables IV-VI (Figures 6-8).

7. Economic analysis of wind turbines

The economic analysis is essential while investing large amounts in the installation of large utility wind turbine plants. The first part of the analysis has been carried out which is based on the wind climate of the specific location. The second is about the selection of wind turbines, considering the mechanical configuration of the turbine suited to the location and produce maximum energy output. The maximum output is based on the wind climate of the region and selection of the turbine, considering the best mechanical features available in the market.

The estimated cost of a utility wind turbine, according to the thumb rule of US$1,000 kWh, is US$450,000. The installation cost is taken as 20 percent of the wind turbine cost, and operation and maintenance cost as 2 percent of the wind turbine cost per year. The estimated

PM	January	February	March	April	May	June	July	August	September	October	November	December	Mean
Wind turbine 1 (80 m)													
WPD	158	208	190	275	344	355	519	439	327	96	143	124	265
kWh/m^2	517	657	605	815	955	973	1,218	1,105	920	316	473	412	747.2
GWh	3.29	4.19	3.85	5.19	6.08	6.19	7.75	7.03	5.85	2.0	3.0	2.62	57.04
C_F	16	21	19	26	30	31	38	35	29	10	15	13	23.6
Wind turbine 2 (80 m)													
WPD	158	208	190	275	344	355	519	439	329	96	143	124	265
kWh/m^2	517	657	605	824	964	991	1,254	1,140	938	307	473	403	756
GWh	2.60	3.31	3.04	4.15	4.85	4.98	6.30	5.73	4.71	1.54	2.37	2.02	45.6
C_F	15	19	17	24	28	28	36	33	27	9	14	12	21.83
Wind turbine 3 (80 m)													
WPD	158	208	190	275	344	355	519	439	327	94	143	124	265
kWh/m^2	535	684	631	859	1,017	1,043	1,324	1,192	982	324	482	421	791.2
GWh	2.42	3.10	2.86	3.89	4.61	4.73	6.0	5.40	4.45	1.47	2.18	1.90	43.01
C_F	14	18	16	22	26	27	34	31	25	8	12	11	21.2

Table IV.
Wind power density, energy production and capacity factor at 80 m height for the year 2009

Table V.
Wind power density, energy production and capacity factor at 60 m height for the year 2009

PM	January	February	March	April	May	June	July	August	September	October	November	December	Mean
Wind turbine 1 (60 m)													
WPD	145	185	144	204	265	274	392	340	243	71	107	89	204.9
kWh/m^2	465	587	473	684	868	894	1,192	1,069	798	202	342	272	653.9
GWh	1.5	1.89	1.52	2.19	2.79	2.87	3.83	3.44	2.56	0.64	1.09	0.87	25.2
C_F	11	14	12	17	21	22	29	26	20	5	8	7	16
Wind turbine 2 (60 m)													
WPD	145	185	144	204	265	274	392	340	243	71	107	89	204.9
kWh/m^2	456	579	465	666	842	868	1,148	1,026	780	210	342	272	637.9
GWh	1.38	1.75	1.4	2.01	2.54	2.62	3.46	3.09	2.35	0.63	1.03	0.82	23.08
C_F	12	15	12	18	22	23	30	27	21	6	9	7	16.9
Wind turbine 3 (60 m)													
WPD	145	185	144	204	265	274	392	340	243	71	107	89	204.9
kWh/m^2	456	579	465	666	850	877	1,175	1,052	789	193	333	263	641.5
GWh	1.56	1.98	1.58	2.28	2.9	3	4.02	3.61	2.71	0.66	1.14	0.9	26.34
C_F	11	14	11	16	20	21	28	25	19	5	8	6	15.9

PM	January	February	March	April	May	June	July	August	September	October	November	December	Mean
Wind turbine 1 (30 m)													
WPD	101	102	114	159	220	228	314	290	182	53	75	57	157.9
kWh/m^2	377	386	447	596	771	789	991	938	657	202	298	219	555.9
GWh	0.33	0.34	0.39	0.52	0.67	0.71	0.88	0.82	0.57	0.18	0.26	0.2	5.87
C_F	13	13	15	20	26	26	33	31	22	7	10	7	18.6
Wind turbine 2 (30 m)													
WPD	101	102	115	159	221	228	315	291	182	53	75	57	158.2
kWh/m^2	351	351	412	561	736	763	973	912	631	175	263	193	526.8
GWh	0.232	0.232	0.27	0.37	0.48	0.5	0.64	0.6	0.41	0.12	0.17	0.1	4.124
C_F	11	11	12	17	22	23	29	27	19	5	8	6	15.8
Wind turbine 3 (30 m)													
WPD	101	102	71	159	221	228	315	291	182	53	75	57	154.6
kWh/m^2	351	351	245	552	728	745	938	894	622	167	263	193	504.1
GWh	0.2	0.2	0.14	0.31	0.42	0.43	0.53	0.51	0.35	0.95	0.15	0.1	4.29
C_F	15	15	11	24	32	32	41	39	27	7	11	8	23.2

Table VI. Wind power density, energy production, and capacity factor at 30 m height for the year 2009

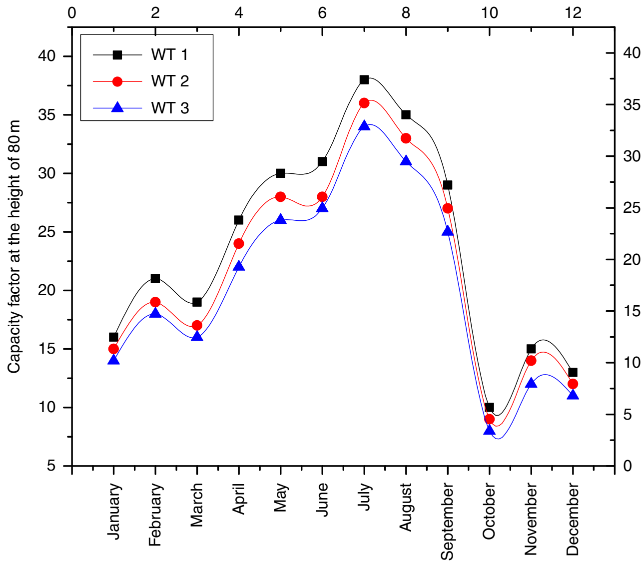

Figure 6.
Monthly wind turbine capacity factor at 80 m height

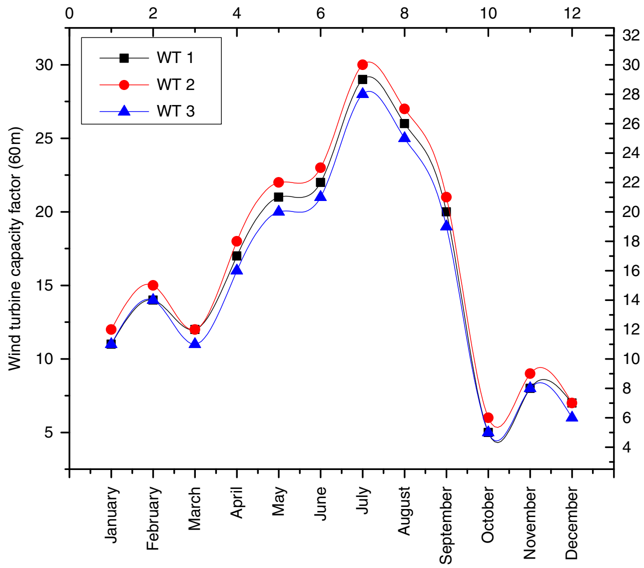

Figure 7.
Monthly wind turbine capacity factor at 60 m height

wind turbine life is 20 years with a real interest rate of 5 percent (Ullah and Chipperfield, 2010; Danish Wind Industry Association, 1999). The calculated results of the economic analysis of compared wind turbines at the heights of 80, 60 and 30 m are presented in Table VII.

According to their mechanical configuration, the wind turbines have been selected and analyzed, for three heights of 80, 60, and 30 m. According to the results, wind turbine 1 has the lowest energy value of US$(cents) 0.023 /kWh.

The assessment of wind energy potential at the south coastal land of Karachi shows that it is one of the potential sites for the installation of wind turbines at the considered heights.

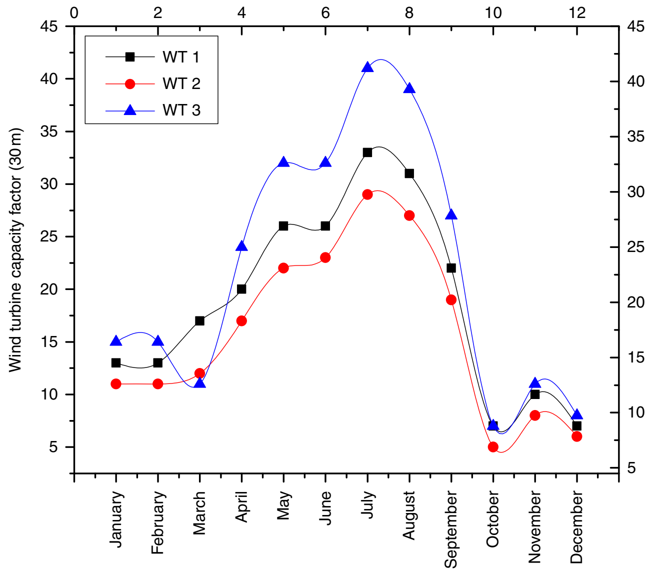

Figure 8. Monthly wind turbine capacity factor at 30 m height

Table VII. Economic analysis of wind turbines

Parameter	WT 1	WT 2	WT 3
80 m	0.023	0.025	0.0265
60 m	0.0392	0.03178	0.0413
30 m	0.0312	0.038	0.028

Another advantage of this site is fall in the major economic hub of Pakistan where already a grid network is available, unlike far away destination. The assessment showed that a strong wind is available during the summer especially from April to September. The summer is a peak load time when demand surges in an upward direction.

8. Conclusion

In this paper, the wind speed and energy generation of south coastal land of Karachi is studied by using measurements at the heights of 80, 60 and 30 m. The mean wind speed is found to be 6, 5.79 and 5.199 m/s at the heights of 80, 60 and 30 m, respectively. The mean k parameter is found to be 2.91, 2.845 and 2.617 at the heights of 80, 60 and 30 m, respectively. The mean c parameter is found to be 6.736, 6.524 and 6.087 at the heights of 80, 60 and 30 m, respectively. The mean standard deviation is found to be 2.297, 2.249 and 2.157 at the heights of 80, 60 and 30 m, respectively. The average WPD is found to be 265, 204.9 and 158 W/m[a] at the heights of 80, 60 and 30 m, respectively. Wind turbine 1 at the height of 80 m has the highest energy output of 57.04 GWh. Similarly, wind turbine 3 at the height of 60 m and wind turbine 1 at the height 30 m have a maximum energy output of 26.34 and 5.87 GWh, respectively. The energy economic assessment has been carried out which shows that wind turbine 1 at the height of 80 m has the lowest energy generation cost of US$(Cents) 0.023 kWh. The overall assessment showed that the site is beneficial for installing the utility wind turbines. The south coastal land of Karachi has another advantage, that is, it is centrally connected to the national grid and is also a major economic industrial hub of Pakistan.

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