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Wind resource and energy potential assessment of the Sujawal site, Sindh Pakistan

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Abstract

Purpose – The objective of this paper to assess the wind energy potential of the Sujawal site for minimizing the dependence on fossil fuels.

Design/methodology/approach – The site-specific wind shear coefficient and the turbulence model were investigated. The two-parameter, *k* and *c*, Weibull distribution function was used to analyze the wind speed of the Sujawal site. The standard deviation of the site was also assessed for a period of a year. Also, the coefficient of variation was carried out to determine the difference at each height. The wind power and energy densities were assessed for a period of a year. The economic assessment of energy/kWh was investigated for selection of appropriate wind turbine.

Findings – The mean wind shear of the Sujawal site was found to be 0.274. The mean wind speed was found to be 7.458, 6.911, 6.438 and 5.347 at 80, 60, 40 and 20 m, respectively, above the ground level (AGL). The mean values of *k* parameter were observed to be 2.302, 2.767, 3.026 and 3.105 at 20, 40, 60 and 80 m, respectively, for a period of a year. The Weibull *c* m/s parameter values were found to be 8.415, 7.797, 7.265 and 6.084 m/s at 80, 60, 40 and 20 m, respectively. The mean values of standard deviation were found to be 0.765, 0.737, 0.681 and 0.650 at 20, 40, 60, and 80 m, respectively. The mean wind power density (W/m^2) was found to be 287.33, 357.16, 405.16 and 659.58 for 20, 40, 60 and 80 m, respectively. The economic assessment showed that wind turbine 7 had the minimum cost/kWh US$ 0.0298.

Originality/value – The Sujawal site is suitable for installing the utility wind turbines for energy generation at the lowest cost; hence, a sustainable solution.

Keywords Weibull distribution function, Wind speed, Wind power density, Energy density, Economic analysis

Paper type Research paper

Nomenclatures

List of abbreviations

AGL	Above the ground level
NREL	National Renewable Energy Laboratory
GDP	Gross domestic productGross domestic product
TI	Turbulence intensity
HDIP	Hydro Development Institute of Pakistan
CDF	Cumulative distribution function
CF	Capacity factor
MTOE	Million Tons of oil Equivalent
GDP	Gross domestic productGross domestic product
AEDB	Alternate Energy Development Board
PMD	Pakistan Meteorological Department
WT	Wind turbine
WPD	Wind power density
Pdf	Probability distribution function
ED	Energy density

List of symbols

kWh	Kilowatt per hour
GWh	Gigawatts per hour
W/m^2	Watt per meter
kWh/m^2	Kilowatt hour per meter
R	Coefficient of correlation
A_P	Actual power
R_P	Rated power
k	Weibull shapeless parameter
c(m/s)	Weibull scale parameter (m/s)
V	Wind speed

Conflict of interest: The author declares that there is no conflict of interest.

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σ	Standard deviation	T_{ah}	Total annual hours
P_w	Present worth	W_p	Wind power
N_{pw}	Net present worth	O_m	Operation and maintenance
I_r	Interest rate	T_c	Total cost

1. Background

Renewable energy is now one of the most promising sources of energy. The role of renewable energy is showing the rising trend. Most of the countries are trying to get this cheaper source of energy. The renewable energy, particularly the wind energy is showing the growth with the every year passing. Figure 1 is showing the increasing trend of wind energy potential. There are some of the important benefits of the renewable source of energy including easy to install, economically feasible, minimizing the environmental effect and lowering the energy security risk. Also, the United Nations presented the Millennium Development Goals (MGDs) that focus on the sustainable development of people and planet. The same can be moved toward the Sustainable Development Goals (SGDs) with the same objective of upgrading the life of peoples around the globe.

Currently, the increasing yearly rise of worldwide installed size of wind power touched to 487 GWh at the end of year 2016 (Council, 2016). Like earlier years, China controlled the wind energy market with new installation of 2.333 GW in 2016. With new installed additions of 0.820, 0.544, 0.361 and 0.202 GW place the USA at second, Germany at third, India at fourth and Brazil at fifth, respectively. Furthermore, France, Turkey, The Netherlands, the United Kingdom and Canada took sixth to tenth place with new installed wind power capacity additions of 1.561, 1.387, 0.887, 0.736 and 0.702 GW, respectively (Council, 2016). Pakistan is an energy-deficit nation which is solely using the conventional source of energy to fulfill the basic requirement and needs. However, the conventional source of energy is costly for a developing country like Pakistan. Huge spending on oil creates an issue of balance of payments. According to the Hydro Development Institute of Pakistan (HDIP), "the oil imports statistics showed a rising trend at 3.8% since last 20 years. The oil consumption increased from 28.6 to 67 MTOE (Million Tons of Oil Equivalents) from 1990 to 2014. The overall consumption of oil and gas is accounted for 72%. Approximately 65% of energy generation is being achieved by using the oil. Natural gas has started to deplete due to increased

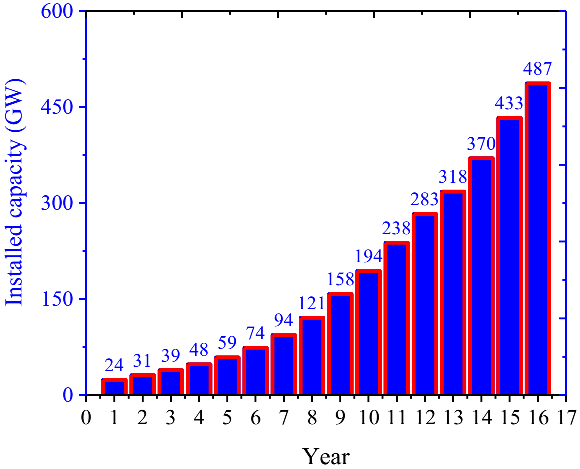


Figure 1. Global installed capacity of wind energy (Council, 2016)

dependence on it. Similarly, the energy load shedding is the major source of loss of gross domestic product (GDP), 2% during the last 10 years. The National Renewable Energy Laboratory (NREL) and the Pakistan Meteorological Department (PMD) of Pakistan assessed the wind energy resource and accounted that 9.06 % of land of total land is ideal for the realization of wind energy power plants. Table 1 is showing the wind site classification standards set by NREL, in which sites have been divided into seven classes. Figure 2(a) and (b) are showing the wind resource assessment at 80 m and the surface roughness factor of Pakistan, respectively.

The wind energy power plants are more common nowadays. For installing the wind power plants, the real values of wind speed of a site are significant. There are a number of wind resource assessment studies carried out at the different parts of the world and have also been published in the world-renowned journals. The oil producing countries have no exception. The Middle East countries including Saudi Arabia, Iran, Egypt, Bahrain, etc. are time to time assessing the renewable energy resources, particularly wind power potential of different parts of respective countries. The wind resource assessment of Jubail city, Saudi Arabia, using the 24 hours data wind measurements at three different heights was investigated, in which the authors used the Weibull distribution function (Baseer *et al.*, 2015). Similarly, there is another research work carried out for the mentioned region of Jubail, in which the authors took wind measurements of seven locations of Jubail and investigated the two parameters shape (*k*) and scale (*c*) of the Weibull distribution function by means of maximum likelihood, least square regression and WASP algorithms (Baseer *et al.*, 2017a). For selection of the best possible site to install wind farm, the authors used the multiple-criteria decision-making approach (MCDA) and the geographic information system (GIS)

Table 1.
Wind energy generation classification by the National Renewable Energy Laboratory (Hulio and Jiang, 2019)

Wind class	Resource	Height 30 m (AGL) Wind speed (m/s)	Height 30 m (AGL) Wind power density (W/m^2)	Height 50 m (AGL) Wind speed (m/s)	Height 50 m (AGL) Wind power density (W/m^2)
1	Poor	00–5.1	00–160	00–5.4	00–200
2	Marginal	5.1–5.9	16–240	5.4–6.2	200–300
3	Moderate	5.9–6.5	240–320	6.2–6.9	300–400
4	Good	6.5–7.0	320–400	6.9–7.4	400–500
5	Excellent	7.0–7.4	400–480	7.4–7.8	500–600
6	Excellent	7.4–8.2	480–640	7.8–8.6	600–800
7	Excellent	8.2–11.0	640–1,600	>8.6	>800

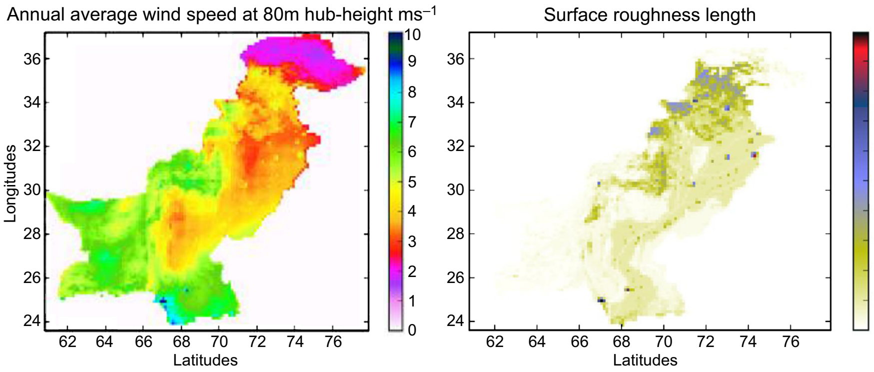


Figure 2.
Geographic wind resource assessments at 80-m height (Dee *et al.*, 2011) and the surface roughness length factor of Pakistan (Danielson and Gesch, 2011)

(Baseer *et al.*, 2017b). The wind characteristics assessment of Jeddah, Saudi Arabia, was investigated, in which the authors used the two-parameter Weibull distribution function (Bassyouni *et al.*, 2015). Similarly, the wind assessment studies for an industrial city Yanbu (Rehman, 2004), as well as for seven stations of Eastern province of Saudi Arabia in Rehman *et al.* (2012) and also used the Light Detection and Ranging (LIDAR)-based wind measurements in Rehman *et al.* (2018) and some more studies considering the wind measurement were carried out in Al-Abbadi (2005) and Rafique *et al.* (2018) with the objective of predicting the accurate energy generation.

Similarly, the wind power potential assessment of Borj Cedria in Tunisia was assessed in Dahmouni *et al.* (2011) at 10-, 20- and 30-m heights. The authors assessed the wind energy density based on the seasonal wind speeds. Also, the wind power potential of five cities including Tangier, Tetuan, Al- Hoceima, Nador and Larach of northern Morocco was investigated in Bidaoui *et al.* (2019). The wind characteristics of Port Said in Egypt were used to investigate the energy arena of site (Lashin and Shata, 2012). The authors used the energy flux method. The measured wind speed data were used for Tindouf in Himri *et al.* (2012), in which the authors considered the eight-year data and the Timimoun region of Algeria.

The wind energy potential of the Shaharbak city in the Kaman province of Iran was investigated in Mostafaeipour *et al.* (2011). In another work, Mostafaeipour (2010) assessed the wind energy potential at 10, 20 and 40 m of Yazd province, Iran. Also in another resource assessment of the capital of Iran, Tehran is investigated with the objective of installing a power plant. The study of energy potential was based on the 11 years wind speed records carried by Keyhani *et al.* (2010). The wind energy potential of the Zarinah city of Iran was studied in Mohammadi and Mostafaeipour (2013). The Binalud wind resource study was investigated at 10, 30 and 40 m by Mostafaeipour *et al.* (2013), and the Semnan Province wind resource assessment study was conducted by Mirhosseini *et al.* (2011).

The wind characteristics of South Banat constituency of Serbia were investigated by Đurišić and Mikulović (2012), in which the authors considered the wind speed data at 10-, 40-, 50- and 60-m measurement heights and analyzed the measured wind speed, direction and energy density of the site. Furthermore, there are a number of wind resource assessment studies available in the literature carried out at diverse parts of world including for Korea refer Lee *et al.* (2013), for China refer Wu *et al.* (2013), for Malaysia refer Irwanto *et al.* (2014), for India refer Chandel *et al.* (2014), for Egypt refer Ahmed (2012), for Pakistan refer Hulio *et al.* (2017); Hulio *et al.* (2019); Azad *et al.* (2015) and for Columbia refer Ochoa *et al.* (2019).

The present research study answers 4W's (what, why, when and how). Here, the first "W" what signifies the wind characteristics assessment of a site. The second "Why" signifies to select an alternate option of energy to minimize the dependence on costly fossil fuels. The third "When" is generally focused on the time period during the site wind measurement has been taken. In this study, the fourth "How" identifies the methods used to assess the wind site data corresponding to wind power production. The Sujawal site wind resource assessed to determine the wind energy potential of site at the lower cost/kWh.

In this paper, an analysis of wind characteristics is carried out to assess the wind energy potential of the Sujawal site. The measured wind speeds at 20, 40, 60 and 80 m were analyzed to assess the wind power prospective of the mentioned site. The Sujawal site was never studied before like this assessment. The wind frequency distribution including seasonal wind frequency and percentage of wind frequency has been investigated to determine the accurate wind power potential of the site. In this paper, the applications of Weibull probability density function for the estimation of wind energy resource assessment of Sujawal has been carried out. The annual wind power density, wind energy and capacity factors are calculated at the four different measured heights. Also, the economic assessment of the site has been assessed to check the viability of energy yield from suggested wind turbines at the lowest cost (US$/kWh).

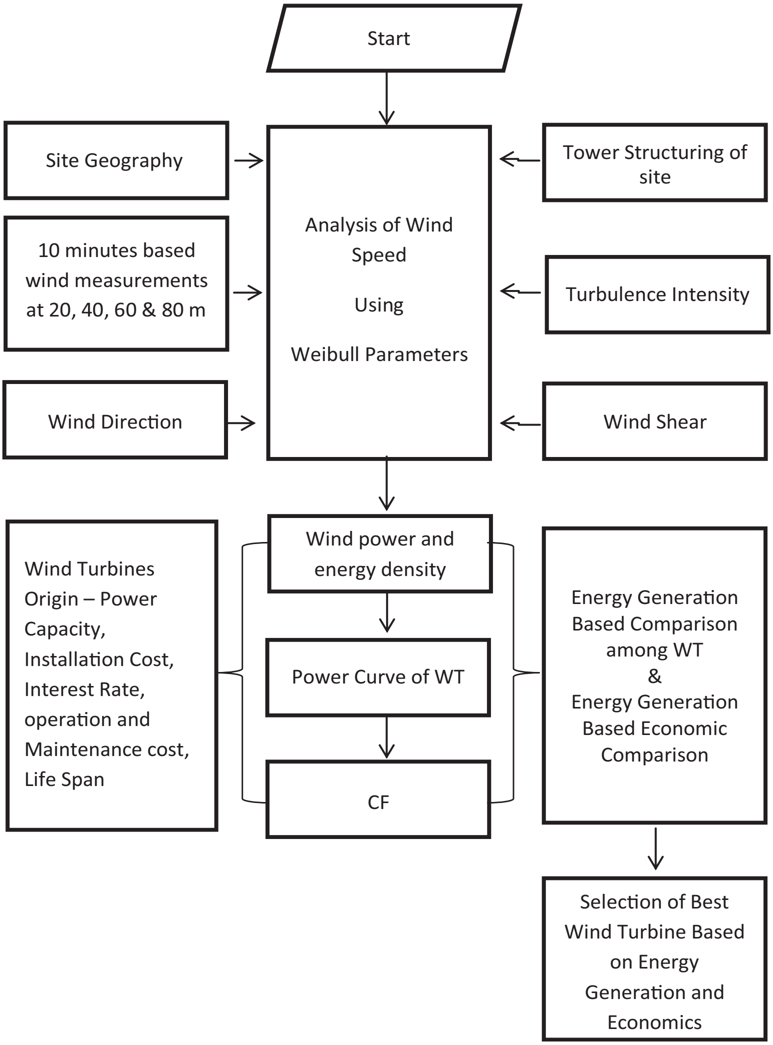


Figure 3.
Methodology mapping of assessment of wind characteristics and power potential of the Sujawal wind site

Table 2.
Technical parameters of the installed atmospheric sensors

Parameters	Wind speed sensor	Temperature sensor
Sensors	Cup type (M# 40)	6–ICT radiation plate (M # 110)
Operative assortment	1 – 90 m/s	−40 ~ 52.5℃
Correctness	±0.8%	±1.1℃
Temperature assortment	−55 ~ 60℃	−40 ~ 52.5℃
Distance constant	3.0 m	–
Display assortment	0 – 120 Hz	0 ~ 2.5V DC
Weightiness	0.2 kg	0.5 kg

2. Methods and site description

2.1 Site-specific geographical description

The studied site is a small town of Thatta district of Sindh known as Sujawal, Pakistan. The wind mast is situated in the peripheries of the Sujawal town. The geographic view of site and installed triangular guyed lattice tower structure and sensors. The measured wind speeds were taken at 20, 40, 60 and 80 m above the ground level (AGL). Figure 3 is showing the flow chart of methodology mapping of wind site. The flow chart provides better and easy understanding of the methods used in this paper. The meteorology mast is equipped with this data acquisition system. Table 2 is showing the specifications of the atmospheric sensors. The topographical location of location is 24°35'48"N and 67°26'39"E. The site can easily host or not the future wind farm projects based on the assessment of local wind characteristics. The Government of Pakistan took keen interest in the development of wind energy and established the Alternate Energy Development Board (AEDB). Also some prescribed standards have been set by the international wind energy forum under which the site assessment has been carried out. The standards set by NREL are providing the essential insights of wind energy generation and classification that is given in Table 1.

2.2 Assessment of wind data

Wind is referred as development of air in atmosphere. It is a highly changing atmospheric parameter that changes with respect to time. It is generally accepted that the wind speed variation is better calculated using probability density function.

2.3 Assessment of wind shear

The wind shear can be expressed as follows (Hulio *et al.*, 2017):

$$\alpha = \frac{\ln(V_2) - \ln(V_1)}{\ln(Z_2) - \ln(Z_1)} \tag{1}$$

where V_1 and V_2 is represent the wind speeds at two heights and Z_1 and Z_2 are denoting the two heights.

2.4 The log law

While considering the atmosphere of a site, the turbulent mix and molecular mixing can be taken in a similar way. It is known as k theory. For example, the mixing is ruled by the mechanical mixing which comprises the shear forces that can be derived as a relationship of wind speed (Carvalho *et al.*, 2014).

$$u = \frac{U_*}{k}\ln\left(\frac{Z - D}{Z_0}\right) \tag{2}$$

where U refers to friction, k is the von Karman constant, Z_0 is the roughness length and D is the displacement height.

The wind speed at a height Z can be computed as provided by the wind speed at a height Z_R is known. So it can be expressed as follows (Carvalho *et al.*, 2014):

$$\frac{U}{U_R} = \left(\frac{\ln\left(\frac{Z}{Z_0}\right)}{\ln\left(\frac{Z_R}{Z_0}\right)}\right) \tag{3}$$

where U_R refers to wind speed at the reference height Z_R.

2.5 The power law

Generally, the power law refers to increase in wind speed with the height owing to easier evaluation. It can be expressed as follows (Lange and Højstrup, 2001):

$$\frac{U}{U_R} = \left(\frac{Z - D}{Z_R}\right)^{\alpha} \tag{4}$$

where α is the power law exponent.

The power law exponent can be in between 0.1 and 0.32 that depending upon the land escape of site. The exponent can be calculated from the roughness length (Onea and Rusu, 2016).

$$\alpha = \frac{\ln\left(\ln\frac{\frac{Z}{Z_0}}{\frac{Z_R}{Z_0}}\right)}{\ln\left(\frac{Z}{Z_R}\right)} \approx \frac{1}{\ln\sqrt{\frac{Z.Z_R}{Z_0}}} \tag{5}$$

2.6 Turbulence intensity

Turbulence intensity (TI) generally considered as pointer of turbulence but not as absolute value. It is expressed by the following equation (Hulio and Jiang, 2020):

$$TI = \frac{\sigma}{V} \tag{6}$$

here σ refers to the standard deviation and V refers to the wind speed.

2.7 The Weibull probability distribution function

The Weibull distribution function is used to assess the effectiveness of wind potential. The probability density *f(V) and* cumulative distribution functions given in Eqns (5) and (6) as follows (Hulio *et al.*, 2017; Akpinar and Akpinar, 2005):

$$f(V) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^{k}\right] \tag{7}$$

$$F(V) = 1 - \exp\left[-\left(\frac{V}{c}\right)^{k}\right] \tag{8}$$

Rayleigh distribution is a diverse practice of the Weibull distribution function. In such instance, the value of k parameter is considered as 2. The probability and cumulative distribution functions are given as follows (Yaniktepe *et al.*, 2013; Gökçek *et al.*, 2007):

$$f(V) = \frac{\pi}{2}\left(\frac{V}{V_{\text{avg}}}\right)\exp - \left[\left(\frac{\pi}{4}\right)\left(\frac{V}{V_{\text{avg}}}\right)^{2}\right] \tag{9}$$

$$F(V) = 1 - \exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{V}{V_{\text{avg}}}\right)^{2}\right] \tag{10}$$

The average wind speed V_{avg}, variance and standard deviation are mathematically expressed as in Eqns (9)–(11), respectively (Akpinar and Akpinar, 2005):

$$V_{\text{avg}} = \frac{1}{N} \sum_{i=1}^{N} V_i \tag{11}$$

$$\sigma^2 = \frac{1}{N-1} \sum_{i=1}^{N} (V_i - V_{\text{avg}})^2 \tag{12}$$

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (V_i - V_{\text{avg}})^2} \tag{13}$$

By using Weibull parameters, the mean and variance of wind speed can expressed as follows (Keyhani *et al.*, 2010):

$$V_{\text{avg}} = c\Gamma\left(1 + \frac{1}{k}\right) \tag{14}$$

$$\sigma^2 = c^2\left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)\right] \tag{15}$$

where Γ refers to gamma function and can be represented as follows:

$$\Gamma_x = \int_0^{\infty} e^{-u} u^{x-1} du \tag{16}$$

2.8 Assessment of the coefficient of variation

The coefficient of variation of wind speed is calculated by the following equation (Hulio and Jiang, 2020):

$$C_V = \frac{\sigma}{\bar{x}} \tag{17}$$

2.9 Wind power density

The wind power density W_P is mathematically described as follows (Wei *et al.*, 2018):

$$W_P = \frac{1}{2}\rho A_T V^3 \tag{18}$$

where V is the wind speed, ρ is the air density and A_T is the rotor area of the wind turbine. The Betz number is denoted by Cp and can be referred as (Hulio and Jiang, 2017):

$$W_P = \frac{1}{2}\rho C_p A_T V^3 \tag{19}$$

The wind power density (W_{pd}) is obtained from Eqn (15) is given as below:

$$W_{pd} = \frac{P}{A} = \frac{1}{2}\rho C_p V^3 \tag{20}$$

The W_{pd} with Weibull probability density function is expressed as follows (Ucar and Balo, 2009):

$$W_{pd} = \frac{P}{A_T} = \frac{1}{2}\rho V^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{21}$$

The energy is obtained by the wind turbine and is calculated by Eqn (20). While substituting Eqn (2) in Eqn (20) which can be read as follows:

$$E = T\int_0^\infty P(V)\,f(V)dV \tag{22}$$

$$E = T\int_0^\infty \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^k\right] P(V)d(V) \tag{23}$$

2.10 The capacity factor

The capacity factor is important measure of performance of wind turbine. The capacity factor can be expressed as follows:

$$C_f = \frac{\text{Actual Power}(Ap)}{\text{Rated Power}(Rp)} \tag{24}$$

3. Economic assessment of wind turbines

This section focuses on the assessment of cost of energy generated from wind resources using different types of wind turbines. The objective of cost assessment is to calculate the performance-based price of energy/kWh from each turbine. The economics of energy can be expressed as follows (Mostafaeipour, 2010):

$$P_{\text{com}} = I\left[\frac{(1 + i_r) - 1}{i(1 + i_r)}\right] \tag{25}$$

$$P_{W_{I-t}} = I\left[1 + n\left\{\frac{(1 - i_r)^t - 1}{i_r(1 + i_r)^t}\right\}\right] \tag{26}$$

$$N_{P_W} = \frac{P_{W_{I-t}}}{t} = \frac{1}{t}\left[1 + n\left\{\frac{(1 - i_r)^t - 1}{i_r(1 + i_r)^t}\right\}\right] \tag{27}$$

$$T_C = \frac{W_P}{E} \tag{28}$$

where E is energy production and the annual energy yield is computed from Eqn (29). In Eqn (29), T_{ah} is total hours in a year and R_P is RP rated power of turbine (Mostafaeipour, 2010):

$$E = T_{ah} \times R_p \times C_f \tag{29}$$

$$E = \frac{1}{T_{ah}}\left(\frac{1}{R_p C_f}\right)\left[1 + n\left\{\frac{(1 - i_r)^t - 1}{i_r(1 + i_r)^t}\right\}\right] \tag{30}$$

4. Results and discussion

In this paper, the wind characteristics and power potential assessment of the Sujawal site, Sindh Pakistan, has been studied. The site is located at wind corridor known as Gharo-Ketti

Bunder of Pakistan. The wind measurements were taken at 10-min-based interval at the heights of 20, 40, 60 and 80 m and analyzed for a period of a year. Furthermore, the results of wind resource and power assessment of Sujawal site are discussed below in the upcoming sections.

4.1 Wind shear coefficient of Sujawal site

Wind shear coefficient is one of most significant factor that can contribute toward the performance of the wind turbine. Also wind shear coefficient can be important for determining the effect of instantaneous wind loads on the wind turbine. Wind shear can be described as the variation in the speed and direction of wind. It is highly site dependent and changes with the time of the day, month and year. It also provides the essential and accurate information of the previous heights. The precision of wind shear coefficient is essential for near reality prediction of energy generation. The mean wind shear coefficient was found to be 0.274 for a period of a year. Generally, it is considered that if the wind shear coefficient is more than 0.2, then the wind turbine manufacturer must be consulted prior to wind farm installation. The wind shear may affect the energy generation and increase the load on wind turbine components, refer Wei *et al.* (2018). Similarly, the seasonal wind shear for four seasons including spring, summer, autumn and spring were observed to be 0.205, 0.260, 0.317 and 0.313, respectively, for a period of a year. It is observed from the assessed results that autumn and winter have much higher values compared to spring and summer seasons. The assessment showed that wind loads on the wind turbine are much higher during the winter and autumn seasons compared to other seasons. So the seasonal wind shear effect cannot be neglected while assessing the wind resource. Generally, the higher rate of wind shear coefficient can be a reason of higher wind turbine loads. The detailed monthly and seasonal wind shear coefficients for a period of a year are given in Tables 3 and 4, respectively.

4.2 Turbulence intensity

Figure 4 is representing the TI of the Sujawal wind site at 20, 40, 60 and 80 m AGL for a period of a year. The TI is known as the standard deviation of horizontal wind speed divided by the average wind speed. The wind data are showing the higher values of the TI found during the day time and falling down during the night time at the studied site. The similar trends are visible of TI at measured heights of 20, 40, 60 and 80 m. The mean values of TI are found to be 0.138, 0.1166, 0.100 and 0.093 at 20, 40, 60 and 80 m, respectively, for over a period of a year.

Months (March 2016 to Feb 2017)	Wind shear coefficient At 20 m (40–20)
March	0.216
April	0.207
May	0.193
June	0.190
July	0.199
August	0.393
September	0.213
October	0.286
November	0.454
December	0.338
January	0.274
February	0.327
Mean	*0.274*

Table 3. Wind shear coefficient of the Sujawal site

It is generally accepted that if wind speed fluctuates rapidly, the TI will be high. However, the site-specific assessment showed that the mean values of TI are decreasing with the increasing height. So it could be better to install wind turbine at higher heights. The major portion of prevailing TI values is observed in between 0.1 and 3 over a period of a year. The TI values are visible in Figure 4.

4.3 Monthly wind speed variation assessment

The wind speed of Sujawal is assessed for a period of a year at four different heights including 20, 40, 60 and 80 m AGL. The wind measurements were taken at 10-min-based interval for a period of a year. The time period of taken wind measurements starts from March 2016 to February 2017. The wind speed measurement project is being carried out by the World Bank under the program of the Energy Sector Management Assistance Program (ESMAP). The measured wind speed data are freely available on World Bank webpage. Other than the World Bank, the wind resource assessment was carried out by the PMD and NREL. In this work, the wind measurements are taken at four altitudes. Due to wind complexity, the wind characteristics are difficult to describe with single concept or value. It is generally accepted that wind speed varies site to site and time to time. Other than this, there is another variation that wind changes corresponding to height. The wind characteristics are unique from site to site but they are assessed by some common physical principles including lower height can see lower wind speed owing to friction with the objects and terrain features.

The mean wind speed was found to be 5.347, 6.438, 6.911 and 7.458 for 20, 40, 60 and 80 m, respectively. The mean wind speed values showing that the wind speed fall in the category of wind class 5 and on wards according to standards of NREL. The wind speed assessment results also indicated that the wind speed changes with the increasing height. At higher heights, the energy output can be higher. Table 5 is representing the measured monthly wind speed at 20, 40, 60 and 80 m heights. The measurement data showed that the wind speed is constantly changing, which negatively affects the wind turbine rotor moment that results in decrease of

Table 4.
Seasonal wind shear coefficient for a period of a year

Seasonal	At 20 m
Spring	0.205
Summer	0.260
Autumn	0.317
Winter	0.313

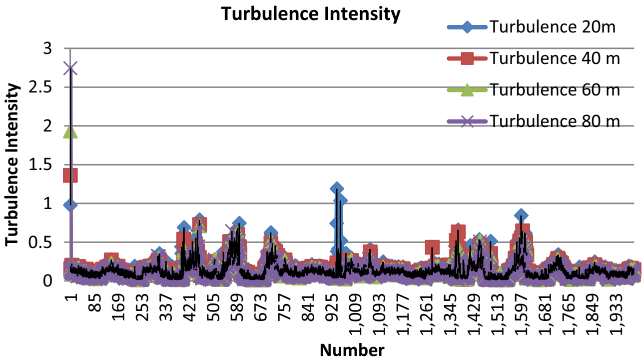
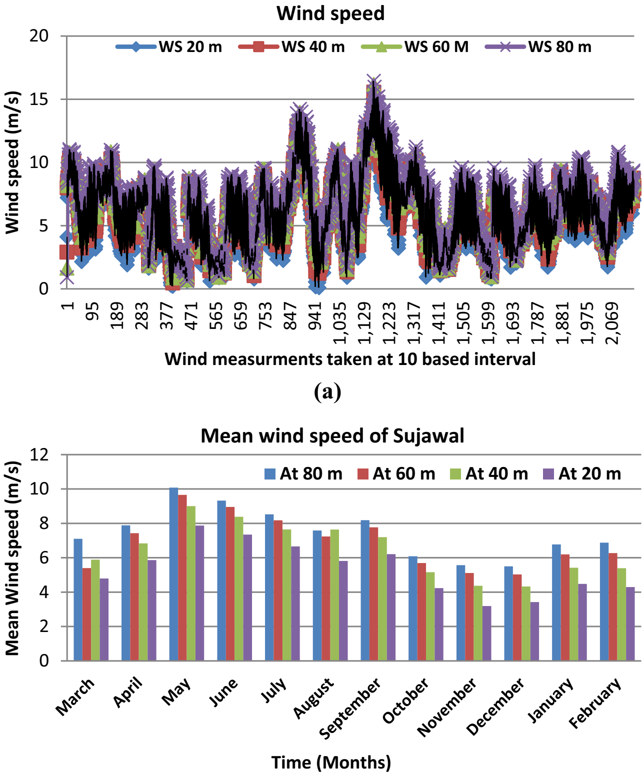


Figure 4.
Turbulence intensity of the Sujawal site at 20, 40, 60 and 80 m for a period of a year

energy generation. Figure 5 (a) is showing the wind speed of site taken at 10-min-based interval for a period of a year. The seasonal values for spring, summer, autumn and winter were found to be 6.175, 6.606, 4.543 and 4.067 at 20 m heights, respectively. The summer season was showing the higher tendency of wind speed available over a period of a year. Similarly, the

Table 5. Monthly mean wind speed of Sujawal at 80, 60, 40 and 20 m for a period of a year

Months (March 2016 to February 2017)	At 80 m	At 60 m	At 40 m	At 20 m
March	7.101	5.400	5.888	4.793
April	7.888	7.429	6.837	5.860
May	10.08	9.656	9.005	7.872
June	9.323	8.955	8.383	7.346
July	8.529	8.181	7.648	6.661
August	7.584	7.240	7.638	5.813
September	8.188	7.771	7.201	6.210
October	6.089	5.689	5.158	4.230
November	5.571	5.115	4.371	3.189
December	5.499	5.030	4.328	3.423
January	6.777	6.197	5.418	4.481
February	6.875	6.271	5.390	4.297
Mean	*7.458*	*6.911*	*6.438*	*5.347*



(a)

(b)

Figure 5. (a) 10 min based taken wind speed measurements and (b) monthly mean wind speed of the Sujawal site at 20, 40, 60 and 80 m

winter is less windy season compared to other season prevailing over site. At 40-m height, the seasonal wind speeds are observed to be 7.243, 7.889, 5.579 and 5.045 for spring, summer, autumn and winter, respectively. The wind speed analysis is showing the similar trends like a previous height of 40 m. At 60 m, the seasonal mean values were found to be 7.495, 8.125, 6.191 and 5.832 for spring, summer, autumn and winter, respectively. The maximum values of wind speed were found to be in summer season and minimum in winter season at the height of 60 m. At 80 m, the seasonal assessment of wind speed was found to be 8.356, 8.478, 6.616 and 6.383 for spring, summer, autumn and winter, respectively. The obtained results are indicating that the seasonal wind speed found to be higher during the summer season and lower in winter season. Further details of seasonal values for a period of a year are given in Table 6.

The two-parameter, *k* and *c* (m / s), Weibull distribution function is used to determine the prevailing wind conditions of the Sujawal site. The wind speed is better assessed with the help of Weibull distribution function. The two parameters *k* and *c* are generally known as Weibull shape and scale parameters. If the value of *k* is more than 2, the site is considered as the windy site. The detailed monthly values of *k* parameter for a period of a year are given in Table 7. The mean values of *k* parameters were observed to be 2.302, 2.767, 3.026 and 3.105 at 20, 40, 60 and 80 m respectively, for a period of a year. If we consider the *k* value 2, the studied site can be used for harnessing the wind energy. The mean values of shape *k* parameter showing higher values than 2 that site is suitable to generate energy from wind. The minimum values of *k* parameter was observed to be 1.27 and maximum 3.25 during the month of November and May at 20 m, respectively. Similarly, at 40 m, the minimum and maximum values of *k* parameter were observed to be 1.69 and 3.65 during November and May, respectively. At 60 m, the minimum and maximum values of *k* parameter were observed to be 1.77 and 4.85 during December and May, respectively. At 80 m, the minimum and maximum values of *k* parameter were observed to be 2.321 and 4.96 during the months of March and May, respectively, for a period of a year. The result of *k* Weibull parameter is showing that the

Table 6.
Seasonal wind speed at 80, 60, 40 and 20 m for a period of a year

Seasonal	At 80 m	At 60 m	At 40 m	At 20 m
Spring	8.356	7.495	7.243	6.175
Summer	8.478	8.125	7.889	6.606
Autumn	6.616	6.191	5.579	4.543
Winter	6.383	5.832	5.045	4.067

Table 7.
Weibull *k* parameter values at 80, 60, 40 and 20 m for a period of a year

Months (March 2016 to February 2017)	At 80 m	At 60 m	At 40 m	At 20 m
March	2.321	1.370	2.94	1.92
April	3.342	3.721	3.26	2.98
May	4.96	4.850	3.65	3.25
June	3.922	4.360	3.47	3.19
July	3.257	4.050	3.12	3.12
August	2.762	3.460	3.001	2.78
September	3.564	3.245	2.34	2.65
October	2.601	2.223	1.941	1.83
November	2.878	1.810	1.69	1.27
December	2.561	1.770	1.72	1.46
January	2.991	2.631	3.08	1.62
February	3.102	2.832	2.991	1.56
Mean	*3.105*	*3.026*	*2.767*	*2.302*

Sujawal site has strong prevailing conditions and tendency of higher wind speed which is significant for achieving the energy from wind.

Similar statement can be considered for the *c* m/s parameter of Weibull distribution function. The *c* parameter have similar dimension like wind speed. However, if the values of scale *c* m/s parameter are showing higher tendency, then site is considered as a windy site. The mean values of scale (*c* m/s) parameter were found to be 6.084, 7.265, 7.797 and 8.415 at 20, 40, 60 and 80 m, respectively, for a period of a year. The mean values of scale parameter are showing higher wind speed corresponding to increasing height of measured site. The assessment showed that the higher heights are better for achieving the maximum energy. In this paper, the wind data are considered for a period of a year that starts from March 2016 to February 2017. The minimum value of *c* m/s parameter was observed to be 3.598 m/s and maximum is 8.882 m/s during the months of November and May at 20 m, respectively. This can be observed from the measured wind data that the wind flow is higher during the summer season, whereas lower in the winter season. At 40 m, the *c* m/s parameter was found to be higher (10.16 m/s) in May and lower (4.483 m/s) in December. At 60 m, the *c* m/s parameter was observed to be higher (10.89 m/s) in May and lower (5.676 m/s) in December. The similar trends can be observed from the upper height of 80 m. At 80 m, the maximum value was found to be 11.37 m/s in May, whereas the lower value of 6.205 m/s was found in December. The obtained measurement of *c* m/s parameter is showing that the wind speed is higher during the summer season and lower in the winter season of a year. Table 8 is representing the detailed calculated values of *c* (m/s) parameter for a period of a year.

4.4 Standard deviation of the site

Figure 6 is showing the standard deviation of the Sujawal site at 20, 40, 60 and 80 m that spread over a period of a year. In statistics, the standard deviation is the measure of amount of variation or dispersion of a set of values. The low value of the standard deviation is generally close to mean, whereas the higher value of the standard deviation indicates the spread over a wider range. The mean values of standard deviation are found to be 0.765, 0.737, 0.681 and 0.650 at 20, 40, 60 and 80 m, respectively, for a period of a year. At 80 m, the mean standard deviation value is close to the mean values and indicates that wind speed did not spread over a wide range. The standard deviation values are going to decrease with increase of the height, However, the further details concerning to seasonal values of standard deviation for a period of year are given in Table 9.

The coefficient of variation is known as statistical measure of dispersion of data points around the mean. It is very useful with statistical tool to compare variation of one data set to

Months (March 2016 to February 2017)	At 80 m	At 60 m	At 40 m	At 20 m
March	8.012	6.093	6.644	5.408
April	8.900	8.383	7.715	6.612
May	11.37	10.89	10.16	8.882
June	10.52	10.10	9.459	8.829
July	9.624	9.231	8.630	7.576
August	8.557	8.169	8.618	6.559
September	9.239	8.769	8.125	7.007
October	6.871	6.419	5.820	4.773
November	6.286	5.771	4.932	3.598
December	6.205	5.676	4.883	3.862
January	7.647	6.992	6.113	5.056
February	7.757	7.076	6.082	4.848
Mean	*8.415*	*7.797*	*7.265*	*6.084*

Table 8.
Weibull *c* (m/s) parameter values at 80, 60, 40 and 20 m for a period of a year

another set. The coefficients of variation of the different prescribed heights including 20, 40, 60 and 80 m were assessed. The mean coefficients of variation were found to be 0.089, 0.102, 0.120 and 0.154 at 20, 40, 60 and 80 m, respectively. The assessment showed that lower ratio of variation exit at 20 m compared to other measured heights. The details of monthly coefficient of variation are given in Table 10 for a period of a year.

4.5 The wind rose graph

The wind rose graph is another significant characteristic necessary for assessing the wind direction and appropriate installation of wind turbines. Most of the studies showing that wind direction putting enormous loads on the wind turbine that can lead to decreasing energy generation and rise to failure of wind turbine components. Figure 7(a)–(d) is showing the wind

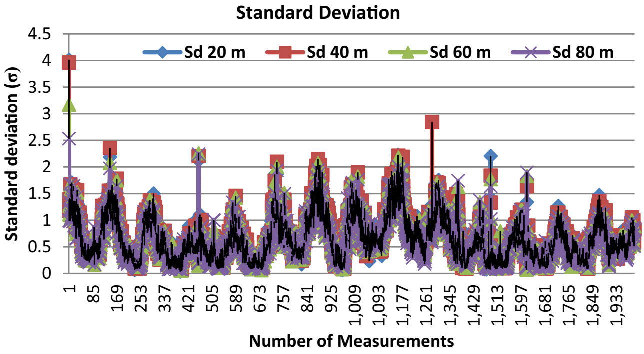


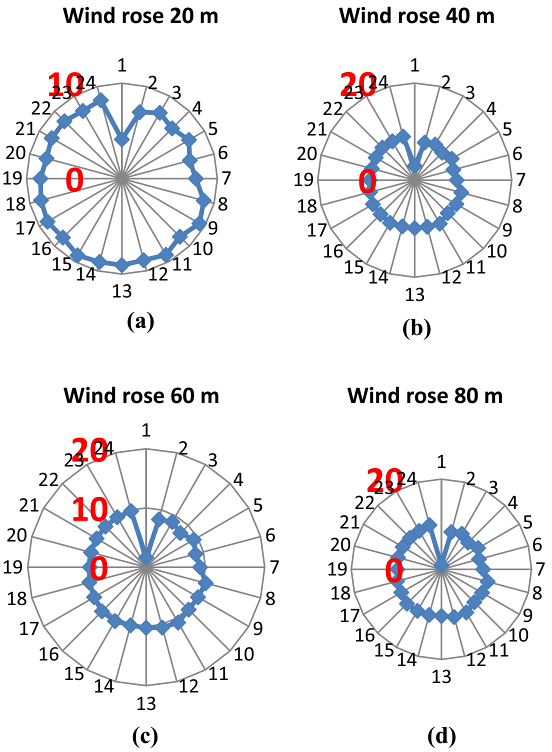
Figure 6.
Standard deviation of wind speed at 20, 40, 60 and 80 m for a period of a year

Table 9.
Seasonal standard deviation of the Sujawal site at 80, 60, 40 and 20 m for a period of year

Seasonal	At 80 m	At 60 m	At 40 m	At 20 m
Spring	0.762	0.801	0.860	0.896
Summer	0.834	0.875	0.967	0.978
Autumn	0.525	0.547	0.587	0.608
Winter	0.404	0.422	0.452	0.470

Table 10.
Monthly mean values of coefficient of variation (%) at 80, 60, 40 and 20 m for a period of a year

Months (March 2016 to February 2017)	At 80 m	At 60 m	At 40 m	At 20 m
March	0.091	0.126	0.125	0.159
April	0.082	0.091	0.107	0.130
May	0.064	0.070	0.081	0.097
June	0.069	0.076	0.087	0.104
July	0.076	0.083	0.096	0.114
August	0.085	0.094	0.097	0.131
September	0.079	0.087	0.102	0.123
October	0.106	0.119	0.142	0.180
November	0.117	0.133	0.168	0.239
December	0.118	0.135	0.170	0.223
January	0.095	0.109	0.136	0.170
February	0.094	0.108	0.137	0.178
Mean	*0.154*	*0.120*	*0.102*	*0.089*



(a) (b) (c) (d)

Figure 7. Thewind rose graph of the Sujawal site at 20, 40, 60 and 80 m

rose graph for 24 h a day at 20, 40, 60 and 80 m AGL. Most of the measurements were taken at 10-min-based interval, showing the wind blow from all sides including south, west, north and east at all measurement heights. There is similar trend of wind direction in all directions.

4.6 Wind power and energy densities and output assessment

The calculated values of wind power and energy densities and energy yield are given in the following Tables 11–13, respectively. The mean values of wind power density (W/m^2) were found to be 287.33, 357.16, 405.16 and 659.58 W/m^2 at 20, 40, 60 and 80 m, respectively, for a period of a year. The seasonal values of wind power density were found to be 409, 455, 178 and 107.3 W/m^{2}for spring, summer, autumn and winter, respectively, at 20 m. The seasonal values of wind power density were found to be 474, 572, 229.7 and 153 W/m^2 for spring, summer, autumn and winter, respectively, at 40 m. At 60 m, the seasonal values were found to be 534.6, 587, 280.6 and 218.3 W/m^2 for spring, summer, autumn and winter, respectively. At 80 m, the seasonal values were found to be 913, 890.6, 452 and 382.6 W/m^2 for spring, summer, autumn and winter, respectively. The wind power density analysis showed that the maximum wind power density can be found during the summer season, whereas the lowers during the winter season. The overall wind resource assessment shows that the maximum wind speed flow (windy period) can be observed from the months of May to August of a year. The summer season is ideal to harness the energy from wind at the Sujawal site. Table 11 contains the details of wind power density at each considered height.

The energy density is an important factor that can be assessed for the realization and selection of wind farm site. The mean energy density was found to be 768.4, 964.3, 1,171.5 and

Table 11.
Monthly mean values of wind power density W/m^2 at 20, 40, 60 and 80 m for a period of a year

	20 m (W/m^2)		40 m (W/m^2)		60 m (W/m^2)		80 m (W/m^2)	
Months	In	Out	In	Out	In	Out	In	Out
March	169	63	236	81	202	71	572	139
April	309	101	370	116	439	127	702	163
May	749	169	816	189	963	193	1465	212
June	609	152	682	170	769	175	1160	199
July	454	129	518	145	586	151	888	181
August	302	99	516	144	406	121	624	155
September	368	113	433	129	502	138	786	172
October	116	45	159	55	197	69	323	105
November	50	19	97	32	143	52	247	86
December	62	24	94	31	136	49	238	184
January	138	53	184	64	255	86	445	129
February	122	47	181	63	264	88	465	132

Table 12.
Monthly mean values of energy density (kWh/m^2) at 20, 40, 60 and 80 m

Months	20 m	40 m	60 m	80 m
March	561	622	640	1218
April	929	1113	1367	1455
May	1560	1692	2086	1972
June	1411	1534	1885	1823
July	1192	1324	1630	1630
August	912	1061	1297	1367
September	1043	1210	1490	1543
October	394	605	736	894
November	149	456	543	728
December	193	430	517	701
January	465	754	920	1122
February	412	771	947	1148
Mean	*768.4*	*964.3*	*1171.5*	*1300.1*

1,300.1 kWh/m^{2}at 20, 40, 60 and 80 m, respectively. The maximum value of energy density was found to be 1,560 during May and minimum value 149 kWh/m^2 during November at 20 m. Similarly, at 40 m, the higher value of energy density was found to be 1,692 and lower 430 kWh/m^2 in May and December, respectively. At 60 m, the higher and lower values of energy density were found to be 2,086 and 517 kWh/m^2 in May and December, respectively. At 80 m, the maximum value was found to be 1,972 kWh/m^2 in the month of May, whereas the minimum of 701 kWh/m^2 in the month of December.

The seasonal values for energy density were found to be 1,016.6, 1,171.6, 528.6 and 365.6 kWh/m^2 for spring, summer, autumn and winter at 20 m, respectively. At 40 m, the seasonal values of energy density were found to be 1,142.3, 1,306.3, 757 and 651.6 kWh/m^2 for spring, summer, autumn and winter, respectively. At 60 m, the seasonal values of energy density were found to be 1,364.3, 1,604, 923 and 794.6 kWh/m^2 for spring, summer, autumn and winter, respectively. At 80 m, the seasonal values of energy density were found to be 1,548.3, 1,606.6, 1,055 and 990.3 kWh/m^2 for spring, summer, autumn and winter, respectively. The overall energy density assessment showed that site has maximum energy density values during the period of summer, whereas lower values in winter season. Furthermore, the details of the energy density of the Sujawal site are given in Table 12.

For assessing the energy output being generated by the wind turbines having different power capacities and different parameters were compared. The wind turbine power size is

Table 13. Monthly values of energy yield of considered wind turbines for a period of a year

Months	WT 1 (Bonus MK- 600 kW)	WT 2 (NEG –MICON 600 kW-43)	WT 3 (Vestas-V 600 kW/44)	WT 4 (Vestas V 600 kW/42)	WT 5 (Nordex N50–800 kW)	WT 6 (Vestas V 1750 kW/66)	WT 7 (Nordex 2300 kW)	WT 8 (NEG – MICON 2750 kW/ 92)
March	839,725	814,720	759,751	983,128	1,222,052	2,189,284	7,751,597	8,099,940
April	1,346,226	1,349,380	1,279,581	1,408,795	2,185,924	4,678,470	9,090,002	9,673,310
May	2,252,596	2,265,939	2,145,965	2,295,365	3,321,916	7,137,665	11,822,571	13,111,414
June	2,026,004	2,049,529	1,959,359	2,064.614	3,012,100	6,447,891	11,097,610	12,120,774
July	1,719,438	1,731,279	1,666,122	1,760,994	2,599,012	5,578,175	10,093,806	10,838,769
August	1,319,568	1,323,920	1,252,923	1,748,849	2,082,652	4,438,548	8,643,867	9,090,580
September	1,506,174	1,514,869	1,452,858	1,566,678	2,375,256	5,098,332	9,591,904	10,256,039
October	599,804	572,850	519,830	667,963	1,187,628	2,519,176	5,855,523	5,943,841
November	253,250	216,410	173,277	388,633	895,024	1,859,392	4,795,952	4,836,655
December	319,895	280,060	239,922	376,488	843,388	1,769,421	4,684,418	4,661,836
January	706,436	674,690	626,462	777,266	1,480,232	3,148,970	7,193,928	7,458,938
Feburay	626,462	598,310	546,488	765,122	1,514,656	3,238,941	7,361,228	7,633,756
Total	*13,515,578*	*13,391,956*	*12,622,538*	*14,803,895*	*22,719,840*	*48,104,265*	*97,982,406*	*103,725,852*

given in Figure 8. The basic objective of energy output assessment is selection of the best wind turbine which is suitable to the Sujawal site. Also, the energy economics/kWh was calculated on the basis of energy output of considered wind turbines. According to assessments of results, the maximum energy was generated by wind turbine 8 having the output 103,725,852 kWh/year, whereas the lowest energy generated was 13,515,578 kWh/year by wind turbine 1. The detailed monthly energy output of considered wind turbines is given in Table 13 for a period of a year. Also, the technical specifications of wind turbines are given in Table 15.

4.7 Capacity factors assessment

The capacity factor is another important measure of performance of wind turbine. The capacity factor has been investigated for the wind energy potential assessment of the Sujawal site. The mean capacity factors for different wind turbines ranged in between 21.5% and 40.58% for a period of a year. The lowest value of capacity factor was found to be 21.25% for wind turbine 2, whereas the highest value was found to be 40.58 % for wind turbine 7. The

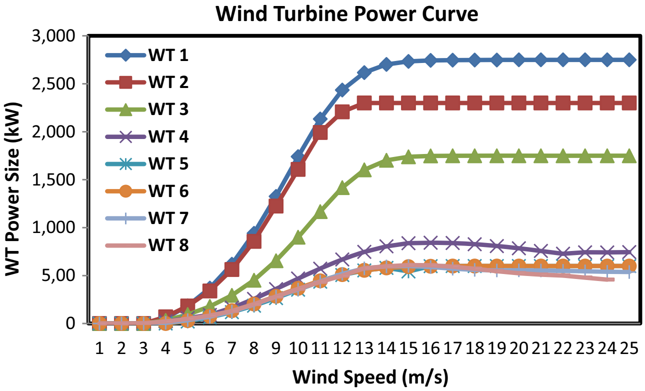


Figure 8.
Power curve of wind turbines

Table 14.
Monthly mean values of capacity factor of considered wind turbines

Months	WT 1 (Bonus MK-600 kW)	WT 2 (NEG –MICON 600 kW-43)	WT 3 (Vestas-V 600 kW/44)	WT 4 (Vestas V 600 kW/42)	WT 5 (Nordex N50–800 kW)	WT 6 (Vestas V 1750 kW/66)	WT 7 (Nordex 2300 kW)	WT 8 (NEG – MICON 2750 kW/92)
March	16	15	14	19	17	14	38	34
April	26	26	24	27	31	30	45	40
May	43	43	41	44	47	47	59	54
June	39	39	37	39	43	42	55	50
July	33	33	32	33	37	36	50	45
August	25	25	24	33	30	29	43	38
September	29	29	28	30	34	33	48	43
October	11	11	10	13	17	16	29	25
November	5	4	3	7	13	12	24	20
December	6	5	5	7	12	12	23	19
January	13	13	12	15	21	21	36	31
February	12	12	10	15	22	21	37	32
Mean	*21.5*	*21.25*	*20*	*23.5*	*27*	*26.08*	*40.58*	*35.91*

Table 15. Technical specification of wind turbines

Wind turbines	Cut-in speed (m/s)	Cut-out speed (m/s)	Rated power (kW)	Rated speed (m/s)	Rotor diameter (m)	Hub height
WT 1	3	25	600	11.5	44	35
WT 2	4	25	600	11.5	43	40
WT 3	4	20	600	11.5	44	35
WT 4	4	25	600	11.5	42	35
WT 5	3	25	800	11.5	50	46
WT 6	4	25	1,750	11.5	66	66
WT 7	3	25	2,300	15	90	100
WT 8	3	25	2,750	14	92	77

assessment showed that the maximum capacity factor is observed during the summer season and minimum during the winter season. As per the assessment of wind characteristic of site, the higher wind flows during the summer season. So the performance of wind turbine can achieve the peak during the windy season. Further details of capacity factors of considered wind turbine is given in Table 14.

5. Economic assessment of the Sujawal site

The economic assessment is essential for the realization of wind energy power projects. According to rule of thumb, the projected cost of wind turbine is US $ 1000/ kW. For the economic analysis of the considered wind turbines, the other significant parameters are installation cost taken as 20%, maintenance and operation taken as 2% and the real interest taken as 5%. However, the estimated life of wind turbine is 20 years. In this study, the results of economic assessment of considered wind turbines and their assessed cost (US$) per kWh is given in Table 16.

The economic assessment of wind turbines ranged from 0.0298–0.603US$ cost/kWh. The detailed assessed cost of all considered values is given in Table 16. The minimum estimated cost/kWh is US$ 0.0298 for wind turbine 7. Similarly, the wind turbine capacity factor is more than the other wind turbines. The results indicate that wind turbine 7 is ideal wind turbine for lower cost/kWh as well as maximum generation of energy.

6. Conclusion

The present research study may answer 4 W's. The first "What" corresponds to wind characteristics assessment of site that showed the suitable prevailing wind conditions of site. The second "Why" points out that site can generate energy as an alternate option. The third "When" is generally focused that summer time is an ideal time period during which energy can be achieved. The fourth "How" id entifies the methods which have been used to assess the wind site data corresponding to wind power production. The methods used in this study show potential of site corresponding to availability of wind and energy generation from wind at lowest cost/kWh. The Sujawal site wind resource assessed to determine the wind energy potential site at the lower cost/kWh.

The details of the Sujawal site assessment carried out in this paper are as follows: the wind resource assessment has been carried out at 20, 40, 60 and 80 m AGL of the Sujawal site for a period of a year. The two-parameter, *k* and *c*, Weibull distribution function is used to determine the intensity of the wind speed of the site. The standard deviation and TI is carried out at four different heights. The wind power density of site is investigated to make decision regarding the site suitability to generate energy and selection of most suitable wind turbine. The mean wind shear coefficient of the Sujawal site is found to be 0.274, that

Table 16.
Economic assessment (US$) of wind turbines

Wind turbine	US $ Cost/kWh
WT 1	0.0563
WT 2	0.0569
WT 3	0.0603
WT 4	0.0514
WT 5	0.0447
WT 6	0.0462
WT 7	0.0298
WT 8	0.0336

is, generally found to be higher than prescribed by manufacturer of wind turbine (i.e. 0.2). So the wind turbine can be manufactured according to wind parameter of a site. The mean values of TI are found to be 0.138, 0.1166, 0.100 and 0.093 at 20, 40, 60 and 80 m, respectively, for over a period of a year. The TI results are indicating that the wind turbine should be installed at higher heights owing to lower TI values, whereas higher at lower height. The mean wind speed is found to be 7.458, 6.911, 6.438 and 5347 at 80, 60, 40 and 20 m, respectively, AGL. The Weibull *c* m/s is found to be 8.415, 7.797, 7.265 and 6.084 m/s at 80, 60, 40 and 20 m, respectively. The mean values of standard deviation are found to be 0.765, 0.737, 0.681 and 0.650 at 20, 40, 60, and 80 m, respectively. The mean wind power density (W/m^2) is found to be 287.33, 357.16, 405.16 and 659.58 for 20, 40, 60 and 80 m, respectively. The maximum wind speed, shape and scale parameter and power density were found to be higher at the height of 80 m. So it can be concluded from the results of assessment that maximum energy at the lowest cost can be achieved at the higher heights compared to lower heights. The economic assessment is showing that wind turbine 7 has the minimum cost/kWh US$ 0.0298. The overall assessment showed that the site has strong presence of wind speed at each height that could be conducive for harnessing of wind power. According to NREL standards, the site can fall in wind class 5. The values of *k* and *c*, wind power density and energy output and economics showed the suitability of site. Also, if we can compare the mean wind speed values with standards of NREL, the site fall in the wind class "Excellent." It can be concluded from the overall assessment that the Sujawal site is suitable for installing the utility wind turbines.

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