WIND RESOURCE ASSESSMENT FOR AN INDUSTRIAL CITY IN SAUDI ARABIA

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ABSTRACT

This study presents the wind resources assessment of Jubail Industrial City, Saudi Arabia. The hourly mean wind speed measurements at 10, 50, and 90 m above ground level (AGL) for five years (2008 to 2012) are used for this study. The wind resources assessment includes annual, seasonal and diurnal wind speed statistics, wind roses, Weibull distribution parameters, local values of wind shear exponent (WSE) and energy output from a 2 MW rated wind turbine. At 10, 50, and 90 m AGL the mean wind speeds were found to be 3.34, 4.79 and 5.35 m/s respectively. The monthly wind speed variation showed that the wind speed was highest in month of June and lowest in October over the entire period of data collection. The annual mean wind speed showed a decreasing trend from 2008 to 2010 but again increased in 2011 and 2012. The most prevalent wind direction at all three heights was from north-west. Wind was found to be available around 76% of time above 3.5 m/s at 50 and 90 m AGL. The local wind shear exponent calculated using wind speed values at three heights was found to vary seasonally from 0.146 to 0.283. Wind shear exponent correlation is presented for wind speed extrapolation to required hub heights. The mean power density at 10, 50 and 90 m was 50.92, 116.03, and 168.46 W/m^2. The annual energy production from a commercially available wind turbine was estimated to be 3,847 MWh/year with a plant capacity factor of 22%.

NOMENCLATURE

V_1	[m/s]	Wind speed at height of anemometer 1
V_2	[m/s]	Wind speed at height of anemometer 2
Z_1	[m]	Height of anemometer 1
Z_2	[m]	Height of anemometer 2
$P_{(v)}$	[-]	Frequency of occurrence of wind speed, v
c	[m/s]	Weibull scale factor
k	[-]	Weibull shape parameter

Special characters

α	[-]	Wind shear coefficient

INTRODUCTION

The term Green Energy is being used for those sources of energy which do not produce any of the harmful greenhouse gases. Further, the cleanest sources of energy are those which utilise the natural flows of the earth. These sources are known as renewable sources of energy and they will never die out unlike fixed reserves of fossil and nuclear fuels. Some of the common sources of renewable energies are wind, solar photovoltaic, solar thermal, hydro, wave, geothermal, biomass and landfill gases. Wind energy is the fastest-growing source of energy and is getting worldwide attention due to the technological advances in harnessing wind power and its competitive cost of production compared with traditional means [1].

It is very important to conduct a wind resource assessment of any site to determine the economic feasibility of the installation of wind power plants. The energy output is highly dependent on wind speed and its characteristics at the site of a particular geographical location [2]. Precise measurements of wind speed and accurate predictions at a given site minimise the risk of huge investments [6]. The two-parameter Weibull distribution is often used to characterise wind regimes because it has been found to provide a good representation of wind data [3, 4, 5].

The wind measurements are usually made at a height different from the hub height of the wind machine. The wind speed can be extrapolated to the hub height by using the well-known 1/7th wind power law. In fact, the wind speed, at a given site, increases with height by a power factor known as wind shear factor or coefficient. This coefficient is highly dependent on the site where the measurements are made.

Some of the wind resource assessment studies reported worldwide were reviewed in this study. The hourly mean wind speed from 2003 to 2005 was analysed at 10, 30 and 60 m height and the data was statistically analysed to determine the potential of wind power generation in the Kingdom of Bahrain [7]. The wind speed characteristics were analysed using the wind speed data collected from six meteorological stations in Turkey during the period from 2000 to 2006 [8]. The wind characteristics were statistically analysed using the Weibull and Rayleigh distribution functions for a remote location in Greece [9]. The wind energy potential was estimated by comparing applications of five kinds of mixture probability functions [10]. The assessment for offshore power potential was performed by optimised use of the multi-population genetic algorithm (MPGA), which aims at getting a minimum cost of energy (COE) with a maximum power generation [11].

SITE, EQUIPMENT AND DATA DESCRIPTION

In September 1933, geologists explored oil for the first time in Jubail, Saudi Arabia. In 1983, the largest engineering and construction project ever was started at Jubail industrial city. Presently, Jubail industrial city is host to more than 160 industrial enterprises and home to almost 70 000 full-time residents.

Jubail infrastructure has the capability to operate continuously without failure of power in any of the existing facilities while meeting community requirements within high modern living standards where all the necessities of life and tourism and recreational facilities are available.

To assess the feasibility of wind power generation at Jubail industrial city, the historical wind data for five years was obtained from the Environment and Control Department (Royal commission for Jubail). This governmental organisation is responsible for the maintenance, calibration and collection of meteorological data at Jubail industrial city. The present analysis is done from the data collected from Weather Station 1 (Fig. 1). Wind speed at this site is collected at three different heights, 10, 50 and 90 m. The latitude/longitude and UTM coordinates of the weather station are given in Table. 1. The specifications of the wind speed sensors installed on the wind tower are given in Table 2.

Table 1
Latitude/Longitude and UTM Coordinates of weather data collection site.

Degrees, Minutes, Seconds	UTM
27° 2'15.76"N	2,991,457.88
49°32'2.56"E	354,594.12

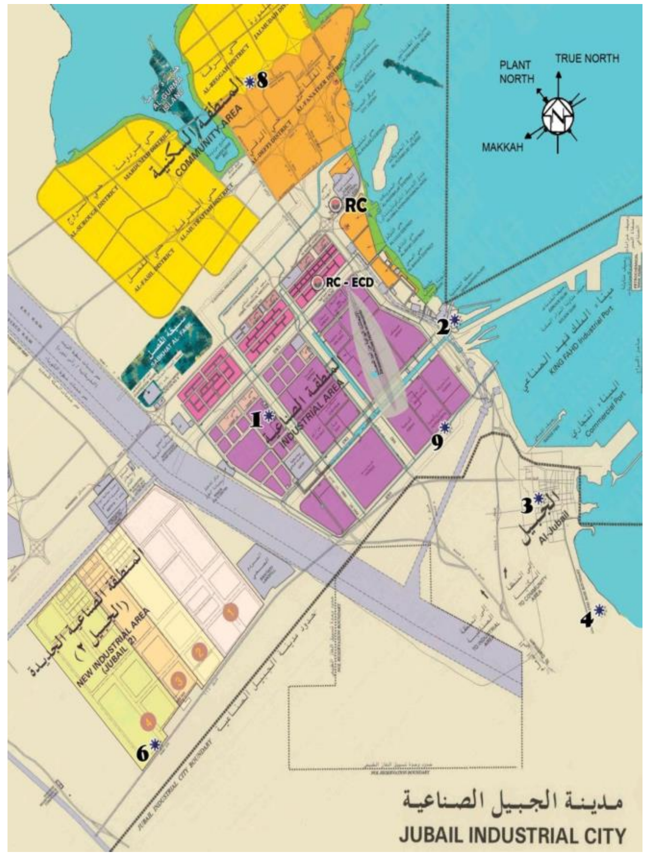

Figure 1 Weather stations at Jubail industrial city

Table 2
Specifications of the wind speed sensor at data collection site.

PERFORMANCE CHARACTERISTICS	
Maximum Operating Range:	0 - 125 mph (0 - 60 m/s)
Starting Speed:	0.5 mph (0.22 m/s)
Calibrated Range:	0 - 100 mph (0 - 50 m/s)
Accuracy:	±1% or 0.15 mph (0.07 m/s)
Resolution	<0.1 mph or m/s
Temperature Range:	-50°C to +65°C (-58°F to +149°F)
Distance Constant:	less than 5 ft (1.5m) of flow (meets EPA specifications)
ELECTRICAL CHARACTERISTICS	
Power Requirements:	12 VDC at 10 mA, 12 VDC at 350 mA for internal heater
Output Signal:	11 volt (pulse frequency equivalent to speed)
Output Impedance:	100 Ω maximum
PHYSICAL CHARACTERISTICS	
Weight:	1.5 lbs (.68 kg)
Finish:	Clear anodised aluminium; Lexan cup assembly.
CABLE & MOUNTING	
PN 1953 Mounting:	Cable Assembly; specify length in feet or metres PN 191 Crossarm Assembly

ANNUAL, SEASONAL AND DIURNAL BEHAVIOUR OF MEAN WIND SPEED

Annual and monthly average wind speed statistics from 2008 to 2012 for entire Jubail industrial city (Weather Stations 1, 2, 3, 4, 6, 8 and 9 as in Fig. 1) at 10 m height are presented in Table 4.

5. The wind rose plots at 10, 50 and 90 m heights are shown in Figs. 2, 3 and 4 respectively. The hourly values of wind direction and wind speed for an entire year are presented in these rose plots. It can be observed from these plots that the most prevailing wind direction at all three heights was from the north-west. The percentage of calm winds (wind speed less than 0.5 m/s) decreased with increasing height, i.e. 1.82, 0.61 and 0.56% at 10, 50 and 90 m height respectively.

The annual, seasonal and diurnal variations of hourly mean wind speed at 10, 50 and 90 m AGL over the entire period of data collection are shown in Figs. 5, 6 and 7 respectively.

It was observed that over a period of five years, the annual mean wind speed at 10, 50 and 90 m height was found to be 3.34, 4.79 and 5.35 m/s respectively. The standard deviation of annual mean wind speed at 10, 50 and 90 m AGL was found to be 0.14, 0.17 and 0.22 respectively.

The seasonal variation of wind speed shows that wind speed was the highest in the month of June and the lowest in the month of October. Moreover, the standard deviation for this seasonal mean wind speed was 0.33, 0.42 and 0.54 at 10, 50 and 90 m AGL respectively.

The diurnal variation shows that the wind speed was higher between 3:00 PM–4:00 PM. The values of wind speed at this time were found to be 5.26, 6.28 and 6.33 m/s at 10, 50 and 90 m AGL respectively. The wind speed was lower at midnight with values of 2.29, 4.19 and 4.77 m/s at 10, 50 and 90 m AGL respectively.

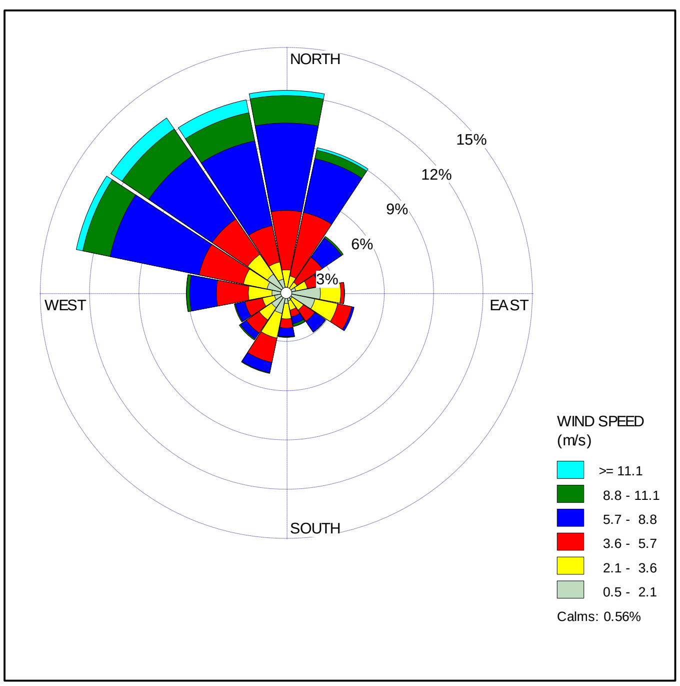

Figure 2 Wind rose plot at 90 m height.

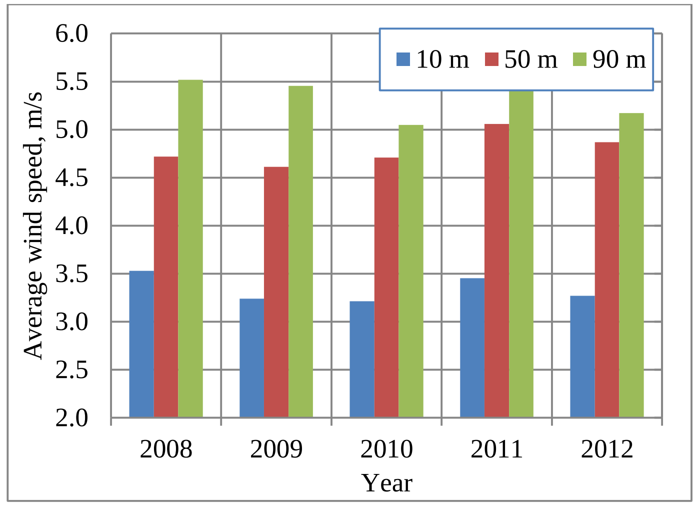

Figure 3 Annual variation of hourly mean wind speed at different heights.

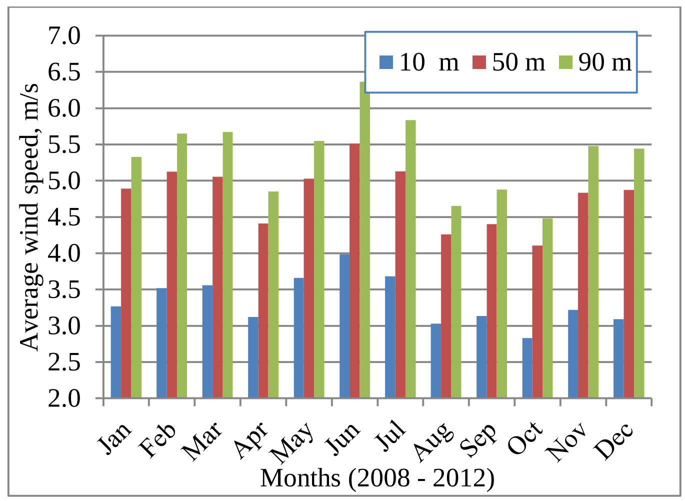

Figure 4 Seasonal variation of hourly mean wind speed at different heights.

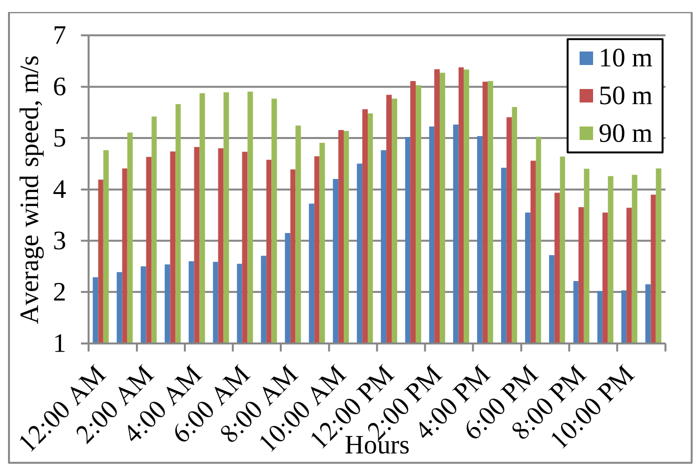

Figure 5 Diurnal variation of hourly mean wind speed at different heights.

The power law exponent is a number that characterises the wind shear, which is the change in wind speed with height above ground level. The shape of the wind shear profile typically depends on several factors, most notably the roughness of the surrounding terrain and the stability of the atmosphere.

The wind shear profile for the location under study is shown in Fig. 6.

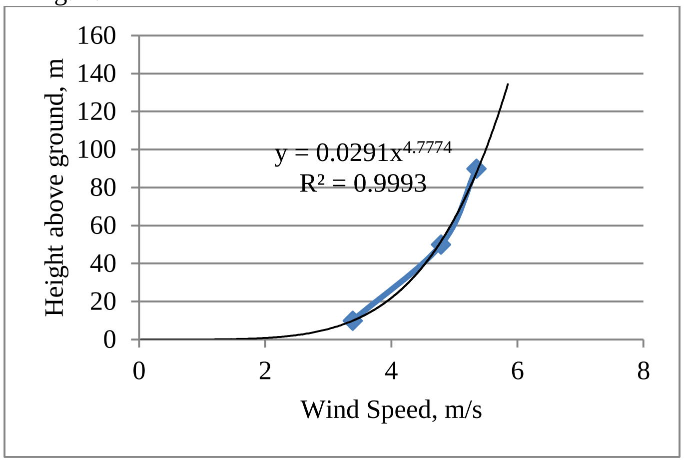

Figure 6 Variation of wind speed with height and fitting curve.

The wind shear coefficient, α, was calculated using the following power law equation:

$$\alpha = \frac{\ln(V_2)-\ln(V_1)}{\ln(Z_2)-\ln(Z_1)} \qquad (4)$$

Where V1 is the wind speed at height Z1, and V2 is the wind speed at height Z2.

WEIBULL PARAMETERS AND WIND FREQUENCY ANALYSIS

The two-parameter Weibull distribution is often used to characterise wind regimes because it has been found to provide a good representation of wind data [3, 4, 5]. This distribution function shows the probability of the wind speed in a 1 m/s interval centred on a particular speed (v), taking into account both seasonal and annual variations for the years covered by the statistics. The Weibull distribution function is given by [12]:

$$P_{(v)} = \frac{k}{v}\left(\frac{v}{c}\right)^{k-1} \exp\left\{-\left(\frac{v}{c}\right)^{k}\right\}, \qquad (1)$$

where P(v) is the frequency of occurrence of wind speed, v. The scale factor, c in m/s, is closely related to the mean wind speed at the location and k is the dimensionless shape factor, which describes the form and width of the distribution. The Weibull distribution is therefore determined by the two parameters, c and k. The cumulative Weibull distribution, P(v), which gives the probability of the wind speed exceeding the value, v, is expressed as:

$$P_{(v)} = \exp\left\{-\left(\frac{v}{c}\right)^{k}\right\}, \qquad (2)$$

At all heights, the variations, c and k, are represented graphically in Figs. 7 and 8 respectively. The actual wind speed frequency distribution and Weibull fit at 90 m AGL is shown in Fig. 9. It is evident from this figure that actual wind speed data is very well represented by the two-parameter Weibull distribution.

The analysis of the Weibull percentage frequency distributions reveals that wind speed was found to be above 3.5 m/s for 49.28, 75.7 and 77.7% of time at 10, 50 and 90 m height respectively. This implies that at Jubail, a wind turbine with a hub height of 50 m and cut-in wind speed of 3.5 m/s can produce energy for approximately 75% of the time.

There is considerable increase in scale factor, c (m/s), as the height increases from 10 to 50 m but this increase is not significant when the height increases from 50 to 90 m AGL. There is no specific pattern observed in variation of shape factor, k, but the value is the highest at 50 m height followed by 90 m and then 10 m. This is indicative of the fact that the scattering of wind speed data is more at 90 m compared with at 50 m. This shows the wind speed is steady at 50 m compared with 90 m height.

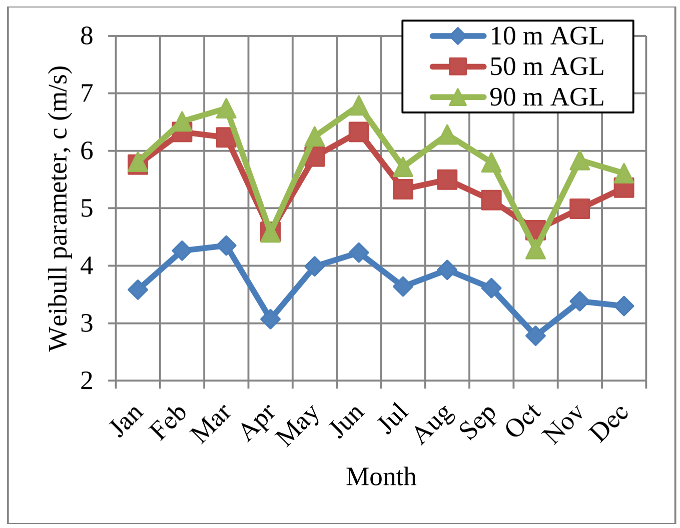

Figure 7 Seasonal variation of Weibull scale parameter, c, at Jubail.

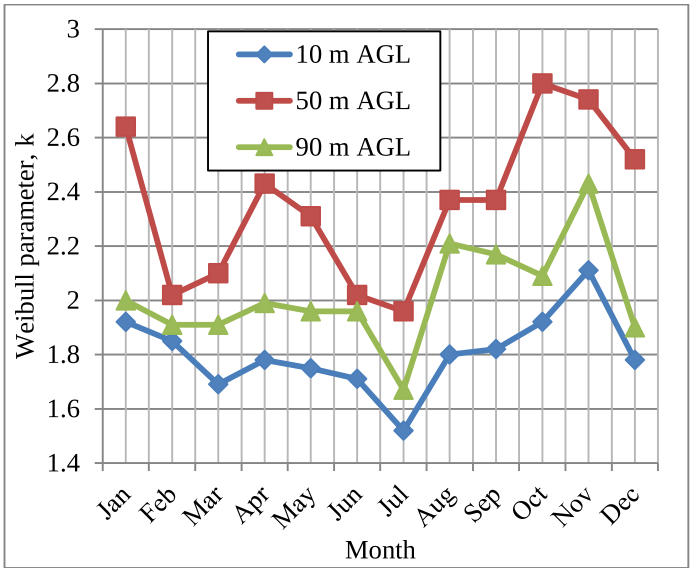

Figure 8 Seasonal variation of Weibull shape parameter, k, at Jubail.

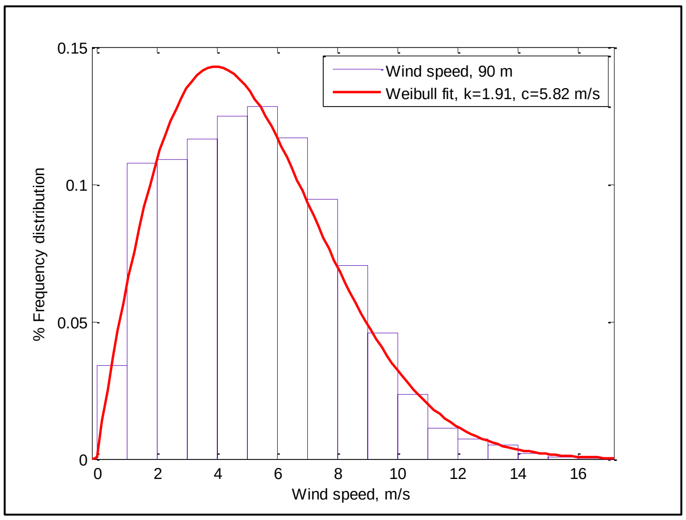

Figure 9 Actual wind speed frequency distribution and Weibull fit at 90 m AGL.

ENERGY YIELD

Energy production from single wind energy conversion system (WECS) was obtained from wind power curves of the wind machines and the frequency distribution of number of hours during which the wind remained in certain wind speed intervals [13]. This wind speed frequency at different hub heights was determined by vertical extrapolation using the site's power law exponent value of 0.217.

The technical information of the selected wind machines of size 2 MW is summarised below [14]:

Rated power: 2,000 kW (50/60 Hz)
Cut-in wind speed: 3 m/s
Rated wind speed: 11.5 m/s
Cut-out wind speed: 20 m/s

The energy yield and plant capacity factor (PCF) is summarized in Table 3 shown below:

Table 3
Wind speed distribution at machine hub height, power curve data and power output from selected wind machine.

Wind Speed (m/s)	Frequency at 80m	Power curve (kW)	Energy calculations (kWh)
0	143	0	0
1	804	0	0
2	1094	0	0
3	1189	23	27357.56
4	1245	140	174360.97
5	1247	314	391693.89
6	1072	549	588261.43
7	748	900	672891.52
8	562	1347	756668.84
9	327	1775	580164.29
10	142	1972	279902.29
11	76	1999	151857.47
12	59	2000	117944.64
13	32	2000	63965.52
14	15	2000	29994.24
15	5	2000	10003.92
16	1	2000	1997.28
17	0	2000	0.00
18	0	2000	0.00
Power output per year (kWh)			**3847063.85**
Plant capacity factor %			**22%**

CONCLUSION

The wind data analysis presented in this paper reaches the following main conclusions:

- At 10, 50 and 90 m AGL, the annual mean wind speeds over the period 2008-2012 were 3.34, 4.79 and 5.35 m/s respectively.
- There was not much variation in mean annual wind speed. The monthly variation shows the wind speed was the highest in June and the lowest in October over the entire period of data collection. The diurnal variation of wind speed shows the wind speed was high during daytime and low during night-time.
- Most prevailing wind direction at all three heights was from the north-west.

- The percentage of calm winds (wind speed less than 0.5 m/s) decreased with increasing height, i.e. 1.82, 0.61 and 0.56% at 10, 50 and 90 m height respectively.
- The Weibull parameter, c, was the highest in the month of March and the lowest in the month of October at all the three heights. The Weibull parameter, k, did not show any specific pattern but it indicated that the wind speed was scattered at 90 m AGL compared with at 50 m AGL.
- The wind speed was found to be above 3.5 m/s for 49.28, 75.7 and 77.7% of time at 10, 50 and 90 m height respectively. The air density was observed to be the lowest in the month of July and the highest in the month of January.
- The wind shear profile at the site fitted the power law curve with a value of R^2 = 99.9 and the profile equation was $y = 0.0291\ x^{4.7774}$.
- The diurnal wind shear variation showed low values in daytime, i.e. from 9:00 AM to 3:00 PM. The seasonal variation of wind shear exponent did not show any specific pattern.
- The annual energy production from a commercially available wind turbine of 2 MW rated power was estimated to be 3,847 MWh/year.

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