Wind Speed and Power Characteristics at Different Heights for a Wind Data Collection Tower in Saudi Arabia

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Wind speed and power characteristics at different heights for a wind data collection tower in Saudi Arabia

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Abstract: Generating energy with clean and renewable sources of energy has become imperative due to the present days' energy crisis and growing environmental consciousness. The objective of the present study is to assess the wind power, wind shear exponent, air turbulence intensity, energy yield, plant capacity factor and effect of hub height on energy yield and PCF for the site under consideration. To achieve the set objectives, wind speed measurements at different height made during the evaluation period were utilized. The site under consideration was found to be feasible for developing grid connected wind farms in the area with annual energy yield of 11.75GWh with plant capacity factor of 48.8% from one wind turbine of 2.75MW rated power with a hub height of 100m from Vestas.

Keywords: *Wind Energy, Saudi Arabia, Plant Capacity Factor, Wind Speed, Weibull Parameters, Wind Shear, Wind Turbulence*

1. Introduction

The adverse effect of climate change such as tsunami, floods, forest fires, have become common in the recent years due to alarmingly increasing pollution levels and increasing global population and thereof increasing power demands. Each megawatt of electricity generated using fossil fuel adds around half a ton of green house gases equivalent CO_2 in to the atmosphere. The accumulating effect of fast depletion of fossil fuels, alarmingly rising environmental pollution levels, and at the same time gradually emerging awareness of environmental degradation has given rise to the use of renewable sources of energy such as wind, solar, small and large hydro, geothermal, tidal, and bio-energy. Of these clean sources, the rapid development in wind energy conversion technology has made it an alternative to conventional energy systems in recent years. Wind energy is the fastest growing source of energy and is getting worldwide attention due to the technological advances for harnessing the wind power and its competitive cost of production compared to other traditional means. In order to conserve the conventional energy resources and to address the environmental problems, the wind power utilization is the answer to these problems. The worldwide wind power installed capacity is increasing rapidly due to new projects being commissioned in different parts of the world. United States of America (USA) is leading the world with regard to global wind power installed capacity. The other countries contributing towards wind power sectors are Germany, Spain, Denmark, India, China, United Kingdom, Egypt, and others.

Various wind speed and wind power characteristics studies have been reported in and around the Middle East region. Some of these studies include Marafia and Ashour [1] for offshore/onshore wind power project development in Qatar; El-Osta and Kalifa [2] for a proposed 6 MW wind farm in Zwara, Libya; Al-Nassar et. al. [3] showed that the annual mean wind speed in Kuwait lied in the range of 3.7 to 5.5 m/s with mean; Hrashyat [4] reported wind resource assessment of the south western region of Jordan; Elamouri and Amar [5] for Tunisia; Ucar and Balo [6] for Manisa, Turkey; Bagiorgas et. al [7] for Western Greece; Shahta and Hanitsch [8] studied the technical and economic assessment of wind power for Hurghada in Egypt; Toğrul and Kizi [9] for Bishkek, Kyrgyzstan; Jowder [10] reported wind resource assessment for Bahrain; and Himri et. al [11] provided review of renewable energy in general and the wind in particular for Algeria. Sahin and Bilgili [12] studied the wind characteristics of Belen-Hatay province of Turkey using hourly wind speed records between years 2004 and 2005.

The work on wind resource assessment in Saudi Arabia dates back to 1986, when Ansari et. al [13] used hourly wind speed data to develop a Wind Atlas for Saudi Arabia. In Saudi Arabia, work on wind speed data analysis such as Weibull parameter determination and distribution, wind speed prediction using different methods such as auto-regression and neural network, wind power generation cost determination, and so on has been reported in the literature. Rehman et. al. [14] presented the Weibull parameters for ten anemometer locations in Saudi Arabia and found that the wind speed was well represented by Weibull distribution function. Rehman and Halawani [15] presented the statistical characteristics of wind speed and diurnal variation. The autocorrelation coefficients were found to be matching with the actual diurnal variation of the hourly mean wind speed for most of the locations used in the study. Some of the other studies include Rehman et. al [16], Rehman and Aftab [17] and Rehman et. al [18].

The objective of the present study is to assess the wind power, wind shear exponent, air turbulence intensity, energy yield, plant capacity factor and effect of hub height on energy yield and PCF for the site under consideration.

2. Site, equipment and Data Description

The 40 meter tall tower was installed at Juaymah power plant, a site located in the eastern part of Saudi Arabia. The latitude, longitude and altitude of the measurements site were 26°47’ N, 49˚53’ E and near sea level, respectively. The data was collected for a period of 33 months stretching from July 01 2006 to April 01, 2009. The area is surrounded by government and private industries and power plants which are connected to the national electric grid. In order to assess the wind potential at the site, an instrumented 40 m tall wind tower, was installed. The meteorological data (wind speeds, wind direction, air temperature, relative humidity, surface station pressure, global solar radiation) were collected for a period of more than two years. The details of the equipment installed at the site are provided in Table 1.

Table 1. Details of the equipment installed at an isolated village.

Item Description	Technical Information
Wind speed sensor, NRG#40 Three cup anemometer	AC sine wave, Accuracy: 0.1 m/s, Range: 1-96 m/s Output: 0-125 HZ, Threshold: 0.78 m/s
Wind direction vane, NRG#200P Potentiometer	Accuracy: 1%, Range: 360^o Mechanical, Output: 0-Exc. Voltage, Threshold: 1 m/s, Dead band: Max - 8^o and Typical 4^o
Temperature sensor #110S Integrated circuit	Accuracy: ±1.1 ^{o}C, Range: -40 ^{o}C to 52.5 ^{o}C, Output: 0 – 2.5 volts DC, Operating temperature range: -40 ^{o}C to 52.5 ^{o}C
Barometric pressure sensor BP20	Accuracy: ±15 mb, Range: 150 – 1150 mb, Output: Linear voltage
Relative humidity sensor RH-5 Polymer resistor	Accuracy: ±5%, Range: 0 – 95 % Output: 0 – 5 volts, Operating temperature range: -40 ^{o}C to 54 ^{o}C
Pyranometer Li-Cor #LI-200SA Global solar radiation	Accuracy: 1%, Range: 0 – 3000 W/m^2 , Output: Voltage DC, Operating temperature range: -40 ^{o}C to 65 ^{o}C

3. Results and Discussion

This section provides detailed wind data analysis including calculation of site wind exponent and air turbulent intensity, wind energy yield and cost of energy. Over entire period of data collection the mean wind speeds at 10, 20, 30 and 40 meters AGL were 4.14, 4.84, 5.34 and 5.65 m/s respectively. The climatic parameters like average ambient temperature, relative humidity, barometric pressure, air density, wind shear exponent, roughness, and roughness class were 26.1°C, 17.3%, 1014 mbar, 1.181 kg/m3, 0.228, 0.239, 2.72, respectively.

3.1. Annual, seasonal and diurnal behavior of mean wind speed

The annual mean wind speeds build up a confidence on the amount of energy that could be generated and also provide future trends. In present case, the annual mean wind at 10, 20, 30 and 40 meters above ground level (AGL) were 4.1, 4.8, 5.3 and 5.6m/s, respectively, in the year 2007 and 4.2, 4.9, 5.4 and 5.8m/s, in the year 2008. This shows an increased of about 2% in wind speed in the year 2008 compared to that in 2007. The maximum wind speeds observed during these two years at 10, 20, 30 and 40 meters AGL were 15.9m/s, 17.8m/s, 18.4m/s and 19.5m/s, respectively. The prevailing wind direction was found to be NNW and NW during the data collection period.

Knowledge of monthly variation of wind speed provides confidence on the availability of energy in different months of the year. Monthly changes in wind speed at 10meters AGL, over entire data collection period, are shown in Fig. 2. Highest wind speed was observed in June while lowest in August at all the heights of wind speed measurements. At 40m AGL, the monthly mean wind speed always remained above 5.5m/s except during August to October, which means that a wind turbine with cut-in-speed of 3.5m/s can produce energy during all the months of the year at this site.

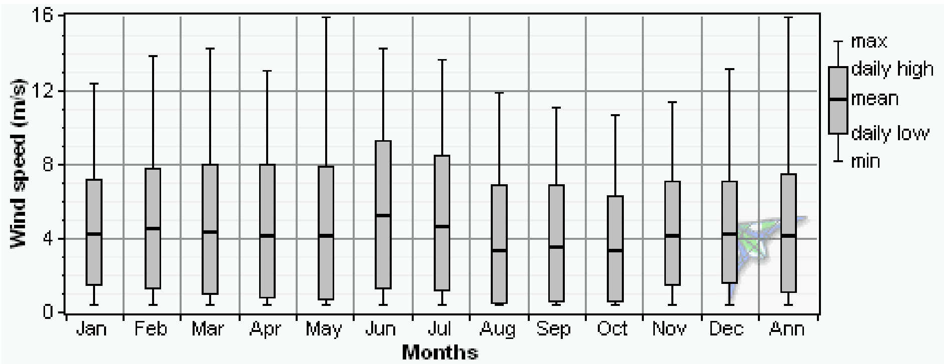

Fig. *1. Seasonal variation of mean wind speed at 10 meters AGL.*

Fig. 3 shows the variation of half hourly mean wind speed at different heights during entire data collection period. It is evident from this figure that as the height of wind measurements increases the wind speed range decreases. At 40m AGL, the half hourly mean wind speed varied from 4.7m/s to 7.0m/s (range=2.3m/s) while at 20m from 3.7m/s to 6.7m/s (range=3.0m/s). At 40m AGL, the wind speed was found above 5.2m/s for most of the time except between 8 P.M. and 12 mid night. This implies that power of the wind can be harnessed during entire day at the measurement site using a wind turbine with cut-in-speed of 3.5m/s and hub height greater than or equal to 40m.

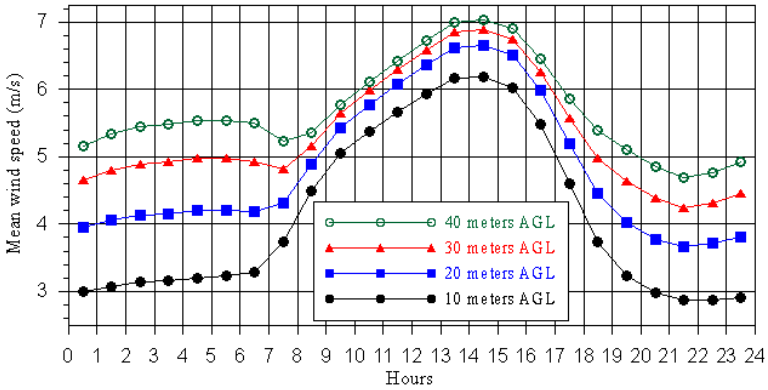

Fig. 2. Diurnal variation of hourly mean wind speed at Juaymah.

3.2. Wiebull parameters and wind frequency analysis

Wiebull distribution function is most widely used function for modeling the wind speed around the globe. The scale factor (c) of the Weibull distribution is related to the average wind speed at different heights and is calculated using the maximum likelihood method. Similarly, the Weibull (k) value is the dimensionless shape factor of the Weibull distribution. This factor reflects the breadth of the distribution. The variation of both scale and shape parameters with measurement heights is shown in Figs. 3 and 4 respectively. Since the wind speed increases with height, hence the scale parameter too follow the trend as can be seen from Fig. 3. The shape parameter also increases with height as shown in Fig. 4. This implies that as height increases, the shape of the distribution tends to be tight which implies less variation in the wind speed. The line of best fit show high values of coefficient of determination (~95%), as given in these figures. The scale parameter increases by about 0.058m/s for each meter increase in measurement height while the shape parameter increases by 0.0157 per meter.

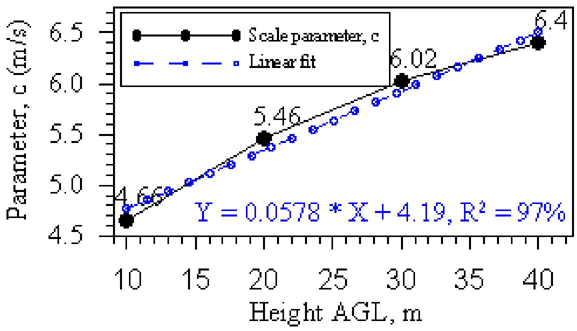

Fig. 3. Variation of scale parameter, c, with measurement height.

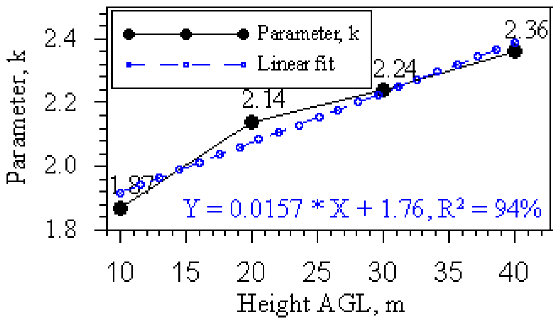

Fig. 4. Variation of shape parameter, k, with measurement height.

Wind speed frequency distribution in different wind speed bins is a very important parameter from energy yield estimation point of view. As the height of wind speed measurement increase, the percent frequency of occurrence of higher winds also increases, as shown in Figures 5(a) and 5(b) at 10 and 40meters AGL. The percent frequencies of 55%, 71%, 78% and 82% at 10, 20, 30 and 40 meters AGL, respectively, were found above 3.5 m/s. An increase of 10 meters in height (from 10 to 20 meters) of the wind speed measurements resulted in an increase of about 16% in the availability of wind speed above 3.5m/s while further increase of 10m in height results only 7% increase in frequency. This analysis confirms that a wind turbine with cut-in-speed of 3.5m/s or more could produce energy for 82% of time at the site of measurements. It is very evident from Figs. 5(a) and 5(b) that as the height increases, the Weibull function fit becomes increasingly better and the wind speed fluctuation also becomes less and less due to decrease in wind turbulence at higher altitudes.

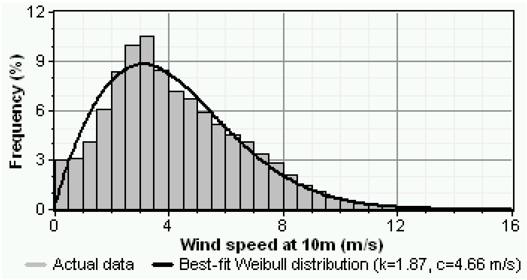

Fig. 5(a). Wiebull fit and frequency distribution of wind speed at 10 meters AGL.

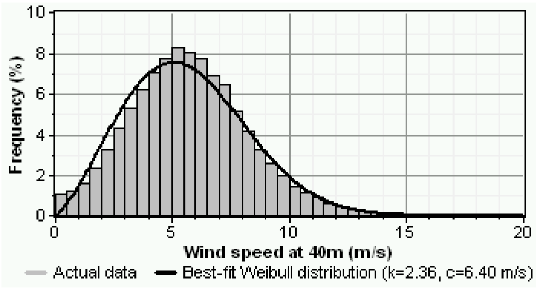

Fig. 5(b). Wiebull fit and frequency distribution of wind speed at 40 meters AGL.

3.3. *Air density and wind power density variation*

In this study, the measured values of air pressure and the temperature were used to calculate the local air density values at Juaymah measurement site. During diurnal cycle, the air density was found to vary between a minimum of 1.159 kg/m^3 during 13:00-14:00 hours and a maximum of 1.201 kg/m^3 during 04:00-05-00 hours. Higher values were noticed during nighttime and lower during day time due to corresponding lower and higher temperatures and air pressure. Around the year, highest mean air density of 1.236 kg/m^3 was obtained in the month of January which characterized by low temperature and relatively high air pressure. On the other hand, lowest air density of 1.136 kg/m3 was recorded in the month of July which is known for high temperature and relatively low air pressure. The mean wind power density values calculated using the local air density and the cube of wind speed during the data collection period at 10, 20, 30 and 40m AGL were 84.7, 119.1, 154.2 and 180.32 W/m^2, respectively. An increase of about 12% was noticed in wind power density in the year 2008 compared to that in 2007 at all measurement heights. The seasonal trends of wind power density values at different heights are depicted in Fig. 6 which indicative of highest values in June and lowest in October.

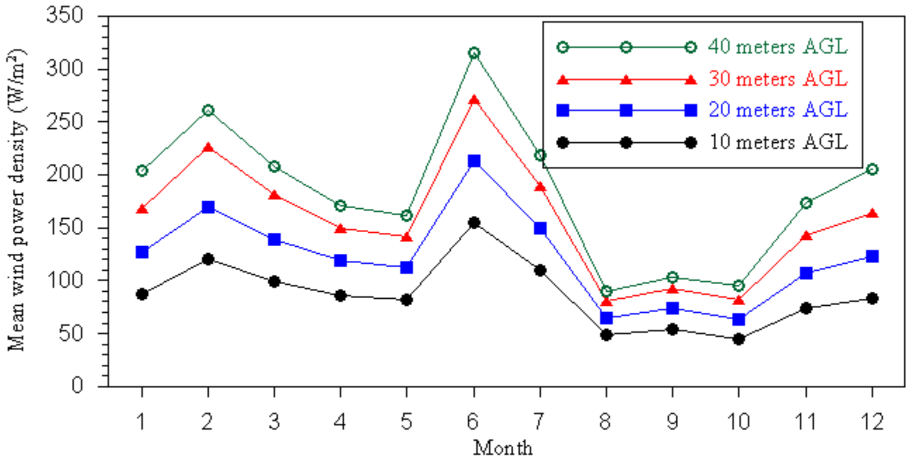

Fig. 6. Seasonal variation of wind power density at different measurement heights.

3.4. Wind shear exponent and turbulence analysis

The power law exponent is a number that characterizes the wind shear, which is the change in wind speed with height above ground. The wind shear exponent (WSE) obtained using all the data values was 0.273 while 0.269 and 0.279 for the data of years 2007 a nd 2008, respectively. Higher values of WSE (~0.285) were observed from October to January and relatively lower (~0.265) during rest of the months with lowest in September. The WSE values are very much dependent on the meteorological changes that take place during 24 hours of day as demonstrated in Fig. 7. It is clear from this figure that higher values of WSE (~0.4) were observed from 7 PM to 7AM and lower (~0.1) from 8:30 AM to 4:30 PM. For precise estimation of wind speed at higher altitudes, different values of WSE during day and nighttime could be used. The overall surface roughness was estimated as 1.124 m with highest of 1.386 m in October and lowest 0.995 m in June.

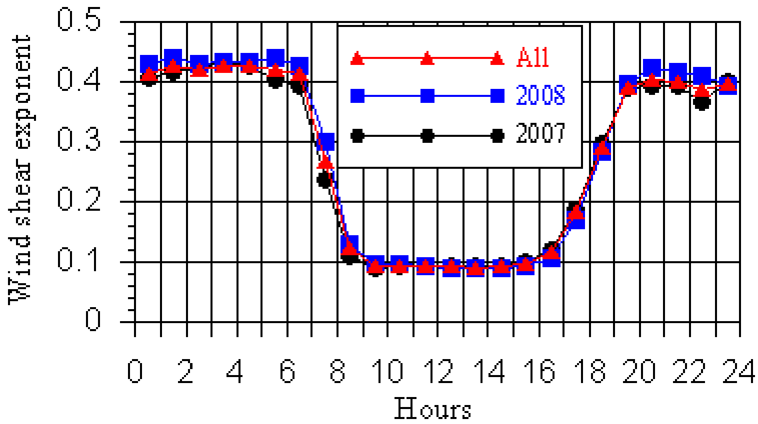

Fig. 7. Diurnal variation of wind shear exponent at Juaymah.

Wind turbulence intensity is critical parameter and dictates the durability or the operational life of the wind turbines. It is highly site dependent and should be well understood before any real time installation. According to International Electrotechnical Commission (IEC, IEC Standard 61400-1) there are standard category A and B values of the turbulence intensities. Any value between these two or below is said to be safe for the normal operation of the wind turbine. The characteristic turbulence intensity, which is another important parameter, is defined as the sum of mean turbulence intensity and the standard deviation of mean turbulence intensity in a wind speed bin. The overall mean turbulence intensity values over entire period of data collection were 0.172, 0.142, 0.127 and 0.122 at 10, 20, 30 and 40m AGL, respectively. The mean turbulence intensity decreases with increasing height AGL as the near ground turbulence effects minimize with height. The mean turbulence intensity along with IEC and characteristic turbulence values is given in Fig. 8. It is evident from this figure that the mean turbulence intensity at the site of measurements is much below even the category C of IEC limits and hence will be safe for normal operating life of the turbines.

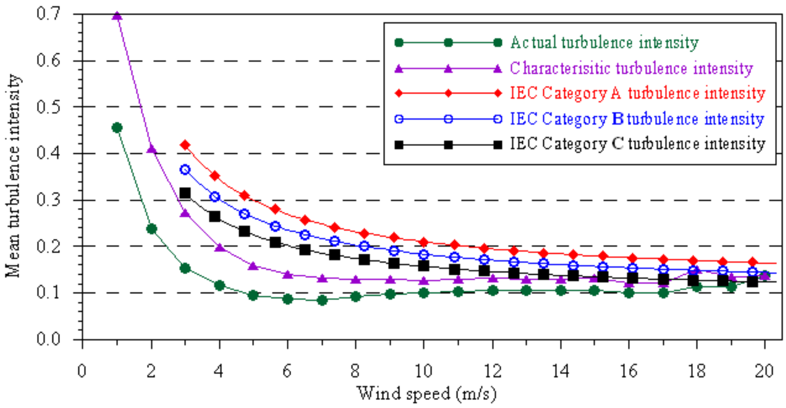

Fig. 8. Varitaion of mean turbulence intensity with wind speed.

3.5. Wind energy yield analysis

For energy yield estimation, a three bladed wind turbine of 2.75MW rated power with rotor diameter of 100m from Vestas was chosen. The net energy yield was calculated by considering the down time, array, soiling and other losses as 4, 5, 1 and 4%, respectively. For energy yield estimation, three hub heights of 60, 80 and 100 meters were considered. The

Annual average wind speed at 60, 80 and 100m AGL was found to be 6.3, 6.8 and 7.2m/s, respectively. The chosen wind turbine could produce average net power of 1,103; 1,239 and 1,341kW corresponding to wind speed at hub heights of 60, 80 and 100m; respectively. Furthermore, the annual net energy equivalent to 9,664; 10,851 and 11,747MWh could be produced with an average plant capacity factor (PCF) of 40.1, 45.0 and 48.8% corresponding to hub heights of 60, 80 and 100m, respectively, from the chosen wind turbine. On an average, the rated power could be produced for only 4% of the time during the year with a hub height of 100m. There will be certain times when the wind turbine will have zero output. It is evident that on annual basis, only 3.6% of the times there will be no power with a hub height of 100m and around 3.9% of the times for 60m hub height. Since wind is an intermittent source of energy, one has to bear with this type of situation.

4. Conclusions

The analysis of the measured data showed that the annual average wind speeds were 4.1, 4.8, 5.3 and 5.7 m/s at 10, 20, 30 and 40m AGL, respectively. The prevailing wind direction was found to be NNW and NW during measurement period. Highest wind speed was observed in June while minimum in August and October at all the heights of wind speed measurements. During entire data collection period, the average wind power density values at 10, 20, 30 and 40m AGL were 85.5, 119.1, 154.2 and 180.3W/m^2, respectively.

The wind shear exponent (WSE) obtained using all the data values was 0.273 while 0.269 and 0.279 for the data of 2007 and 2008, respectively. No definite seasonal trend could be noticed in the values of WSE. The overall mean turbulence intensity values over entire period of data collection were 0.172, 0.142, 0.127 and 0.122 at 10, 20, 30 and 40m AGL, respectively.

The monthly average minimum energy of 526, 600 and 661MWh was generated in August while a maximum of 1,034; 1,127 and 1,192MWh in June corresponding to hub heights of 60, 80 and 100m, respectively. The monthly mean plant capacity factor (PCF) varied between 25.7 and 52.2% for 60m hub height, 29.3 and 57.0% for 60m and between 32.3 and 60.2% for 100m hub height in the months of August and June, respectively.

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