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Assessment of Wind Characteristics and Electricity Generation Potential for Yanbu, Saudi Arabia

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Abstract

The analysis of recently collected wind speed data is presented for Yanbu (24°05′N 38°00′E), located at the west coast of Saudi Arabia. With an average wind speed of 5.3 m/s at a height of 40 m, the average wind speed varies from a minimum value of 4.44 m/s in October to a maximum value of 6.14 m/s in June. Wind characteristics and electricity generation potential have been assessed using a web tool, 'Wind Energy Assessment (WEA) Tool'. Weibull parameters, namely, Shape factor, k and Scale factor, c have been calculated using both Graphical method and Standard Deviation method for 12 months, May'11 – April'12. Along with the assessment of the wind energy density, the energy generation potential by Polaris P-21 wind turbine with rated power of 100 kW have been assessed using Weibull based approach and Rayleigh based approach. Total annual energy output of 154 MWh, 308 MWh, 170 MWh by this wind turbine have been estimated using Graphical method, Standard Deviation method and Rayleigh based approach, respectively. The cost of electricity have been calculated as US$ 0.097/kWh, US$ 0.048/kWh and US$ 0.088/kWh for capacity factors of 17.5%, 35.2% and 19.5% estimated using three different statistical models, respectively considering the turbine cost of US$ 160,000 and rate of return of 5%.

Introduction

Renewable energy have been drawing attention from the researchers, engineers, policy makers, governments and NGOs as the most promising solution for the current energy crisis. Wind energy, among other renewable energy resources, is considered to be cost competitive with fossil fuel based energy generation. Before establishing wind mills in a region, it is of utmost importance to analyze the wind energy potential for the certain site. Wind is stochastic in nature and it is very often helpful to make use of statistical models to assess the true wind energy potential.

Bhuiyan et al have assessed the wind energy potential in Kuakata island, Bangladesh for the months of March to September at 20m and 30m height using Wind Energy Assessment Tool (WEA). The paper also assessed the energy generation potential by a generic wind turbine having a capacity of 1kW [1]. The web based tool 'Wind Energy assessment tool' was developed at Islamic University of Technology which can be accesses at http://www.iutoic-dhaka.edu/wea/ . This tool assesses the wind energy potential for a specific site from its wind data using different statistical models. This calculates weibull parameters, energy estimation of wind regimes, energy generated by wind turbines etc.[2].

In Saudi Arabia, most of the renewable energy projects are pertaining solar energy because of the high solar insolation in the region. However, recently researchers have presented their finding on wind energy potential on different sites in Saudia Arabia. Al-Abbadi presented the analysis of wind data collected for five sites in Saudia Arabia, namely Dhulum, Arar, Yanbu, Gassim and Dhahran. He opined Dhulum and Arar to be suitable for remote wind energy application whereas Yanbu and Dhahran to be suitable for grid connected wind energy generation. He also showed calculation of annual energy produced by a Nordex N43 wind turbine in these five sites [3].

Rehman presented long term wind data analysis for Yanbu with the wind speed and wind directional hourly data collected from 1970 to 1983. Wind energy generation was calculated with 9 wind turbines with varying capacity ranging from 150 to 2500 kW. His analysis shows that at a height of 10 m above ground, the availability of wind speed above 3.5 m/s is for 59% of the time during the whole year. He also analyzed the capacity factor and concluded that smaller wind turbines have higher capacity factors as compared to the large ones and the capacity factor increases with the hub height [4].

Eltamaly et al have introduced a computer program in Matlab for choosing the best wind turbine suitable for a specific site considering the highest capacity factor and lowest cost of electricity. The program has been used for five locations in Saudi Arabia. The five locations are Dhahran, Douhlom, Yanbu, Riyadh and Qaisumah. The statistical parameter, weibull parameter values have been estimated using numerically and graphically and compared. The numerically and graphically estimated values were matching [5].

Theory and Methodology

Due to its stochastic nature, wind energy assessment requires statistical approach. Several statistical approaches are available in the literature. In this study, Rayleigh based approach and Weibull based approach (Graphical method and Standard Deviation) are considered.

The wind data collected at any height can be extrapolated to other heights [6]. Wind speed increases logarithmically with height due to the boundary layer effect. If the wind data is measured at a height of Z and the roughness height is Z_0, then the wind speed at a height of Z_R can expressed as,

$$V(Z_R) = V(Z)\frac{\ln\left(Z_R/Z_0\right)}{\ln\left(Z/Z_0\right)} \qquad (1)$$

Average wind speed at a certain location may often lead to a wrong direction. For calculating the wind energy from the wind present, the speed should be weighed for its power content while calculating the average value[6]. When the velocity is presented in frequency distribution, the average and standard deviation for the wind speed can be written as,

$$V_m = \left(\frac{\sum_{i=1}^{n} f_i V_i^3}{\sum_{i=1}^{n} f_i}\right)^{\frac{1}{3}} \quad (2)$$

$$\sigma_V = \sqrt{\frac{\sum_{i=1}^{n} f_i (V_i - V_m)^2}{\sum_{i=1}^{n} f_i}} \quad (3)$$

Here, n = Number of wind data. V_m = Average velocity, V = mid value of the corresponding interval, f_i = Frequency.

The wind velocity can be expressed in terms of standard statistical functions. Researchers have concluded that Weibull and Rayleigh distribution can express the wind variation in a regime with acceptable accuracy [7,8,9].

The variations in wind velocity are characterized by the two functions in Weibull distribution namely, The probability density function, f(V) and The cumulative distribution function, F(V). These two functions can be expressed as:

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^k} \quad (4)$$

$$F(V) = \int_0^\infty f(V) dV = 1 - e^{-\left(\frac{V}{c}\right)^k} \quad (5)$$

Where, k is the shape factor and c is the scale factor.

The average velocity can be expressed as:

$$V_m = c\, \Gamma\, (1 + \frac{1}{k}) \quad (6)$$

The standard deviation of the wind velocity may be given as,

$$\sigma_V = c\left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)\right]^{1/2} \quad (7)$$

For estimating the wind variation using weibull distribution, one needs to estimate the value of shape factor, k and scale factor, c. The most common methods for estimating these weibull parameters are Graphical method and Standard deviation method.

In Graphical Method, the cumulative distribution function is transformed into a linear form, adopting logarithmic scale [6]. The cumulative distribution of wind speed can be written in transformed form as,

$$1 - F(V) = e^{-(V/c)^k} \quad (8)$$

Taking the logarithms twice, Equation (8) becomes,

$$\ln\{-ln[1 - F(V)]\} = k \ln(V_i) - k\, ln\, c \quad (9)$$

Plotting this relationship with ln (Vi) along the X axis and ln{-ln[1-F(V)]}along the Y axis, a straight line is obtained. From Equation. (9), k gives the slope of this line and –k ln c represents the intercept.

The weibull parameters, k and c can also be found using Standard Deviation Method. k and c are estimated from the mean and standard deviation of the wind data using the following equation.

$$\left(\frac{\sigma_V}{V_m}\right)^2 = \frac{\Gamma\left(1 + \frac{2}{k}\right)}{\Gamma^2\left(1 + \frac{1}{k}\right)} - 1 \quad (10)$$

Once σ_V V_m are calculated for a given data set, then k can be determined by solving Equation (10) numerically. When the value of k is determined, c can be calculated using the following equation.

$$c = \frac{V_m}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (11)$$

If the value of k and c are to be precisely calculated, adequate wind data collected over a short interval is required which is often not possible. On the other hand, it is easier to obtain mean wind speed over a period of time. In this regard, a simplified weibull model is derived where k=2 is approximated. This model is known as Rayleigh Distribution. Taking k =2,

$$V_m = c\, \Gamma\, (3/2) \quad (12)$$

$$c = \frac{2V_m}{\sqrt{\pi}} \quad (13)$$

Wind energy density and the energy available in the regime over a period can be considered as indices for assessing the energy potential. The wind energy density, E_D is a function of the velocity and distribution of wind. E_D is the energy available in the regime for a unit rotor area and time. V_{Fmax} is the most frequent wind velocity and V_{Emax} is the velocity contributing the maximum energy to the regime. In the probability density curve, V_{Fmax} represents the peak.

Power available (P_V) in the wind stream of velocity V for a unit area of wind turbine rotor is

$$P_V = \frac{1}{2}\rho_a V^3 \quad (14)$$

Where ρ_a is the air density.

Probability density function f(V) is The fraction of time for which this velocity V prevails in the regime. The energy per unit time contributed by V is PV f(V). Thus the total energy, contributed by all possible velocities in the wind regime, available for unit rotor area and time may be expressed as [6],

$$E_D = \frac{\rho_a c^3}{2}\frac{3}{k}\Gamma\left(\frac{3}{k}\right) \quad (15)$$

After calculating E_D, The total available energy E_T can be calculated for time T,

$$E_T = E_D T = \frac{\rho_a c^3\, T}{2}\left(\frac{3}{k}\right)\Gamma\left(\frac{3}{k}\right) \quad (16)$$

The most frequent wind velocity, V_{Fmax} and the velocity contributing the maximum energy to the regime, V_{Emax} can be expressed as

$$V_{F_{max}} = c\left(\frac{k-1}{k}\right)^{1/k} \quad (17)$$

$$V_{E_{max}} = \frac{c\,(k+2)^{1/k}}{k^{1/k}} \quad (18)$$

Following Rayleigh Based approach, wind energy density and energy available for the unit area of the rotor can be expressed E_D and E_T may be expressed as,

$$E_D = \frac{3}{\pi}\rho_a V_m^{\ 3} \quad (19)$$

$$E_T = E_D\, T = \frac{3}{\pi}\, T \rho_a V_m^{\ 3} \quad (20)$$

Using the same approach, the most frequent wind speed and the velocity contributing maximum energy are defined as,

$$V_{F_{max}} = \frac{1}{\sqrt{2K}} = \sqrt{\frac{2}{\pi}}V_m \tag{21}$$

$$V_{E_{max}} = \sqrt{\frac{2}{K}} = 2\sqrt{\frac{2}{\pi}}V_m \tag{22}$$

Wind Turbines are used for generating energy from wind. The characteristic operational speeds of a wind turbine should match with the dominant wind spectra to ensure the maximum energy extraction from the wind. The important characteristic speeds of a wind turbine are its cut-in speed (V_I), rated speed (V_R) and the cut-out speed (V_O). The cut-in speed of a turbine is the minimum wind velocity at which the system begins to produce power. Rated speed is the speed at which the turbine generates its rated power.

If E_{IR} and E_{RO} be the energy developed by the system at its performance regions 1 (From V_I to V_R) and 2 (V_R to V_O) respectively, then E_{IR} can be computed by adding the energy corresponding to all possible wind velocities between V_I and V_R and E_{RO} can be computed by adding the energy corresponding to all possible wind velocities between V_R and V_O.

$$E_{IR} = T\int_{V_i}^{V_R} P_V\ f(V)dV \tag{23}$$

$$E_{RO} = TP_R\int_{V_{Ri}}^{V_O} f(V)dV \tag{24}$$

Then the total available energy over a period T is the summation of E_{IR} and E_{RO},

$$E_T = E_{IR} + E_{RO} \tag{25}$$

Capacity factor are often used as a benchmark for assessing the performance of wind turbines for generating energy. The capacity factor of a wind turbine, C_F is defined as the actual energy produced by the turbine to the energy it would have produced had it operated in its rated power throughout the time period.

$$C_F = \frac{E_T}{T\ P_R} \tag{26}$$

The cost of electricity generated by wind turbine can be expressed as,

$$c = \frac{C_I}{8760\ n}\left(\frac{1}{P_R C_F}\right)\left\{1 + m\left[\frac{(1+I)^n - 1}{I(1+I)^n}\right]\right\} \tag{27}$$

where C_I is the capital investment for the system, n is the expected life, P_R is the rated power, C_F is the capacity factor, m is the maintenance cost and I is the rate of return.

Results and Discussion

In this study, wind data at 40 m height has been analysed using statistical models employing a web based tool. The study location is Yanbu (24°05′N 38°00′E), located at the west coast of Saudi Arabia. The wind speed is measured at a hub height of 10 m hourly which is then converted to the wind speeds at a height of 40 m using equation (1). The average wind speed varies from a maximum value of 6.14 m/s in June to a minimum value of 4.44 m/s in October. One year long hourly data (May'11-April'12) has been analysed in both monthly and yearly basis.

Analysing the data provides the following parameters essential for wind energy assessment: Mean velocity (V_m) (m/s), Shape parameter, k (dimensionless), Scale parameter, c (m/s), Most frequent wind velocity, V_{Fmax} (m/s), Velocity contributing maximum energy, V_{Emax} (m/s), Energy density, E_D (kW/m^2).

To assess the energy which may be obtained by a wind turbine, Polaris 100kW wind turbine with the following specifications has been considered. Rated power, P_R = 100kW, Cut in speed, V_i = 2.7 m/s, Rated speed, V_R = 11m/s, Cut out speed, V_O = 25 m/s, Ideal Velocity Power Proportionality, n= 2.8. The power curve for the turbine (Polaris 100kW) is shown in Fig. 1. Using the above specifications, Total energy output, E_T (MWh) and capacity factor, C_F has been obtained from the tool.

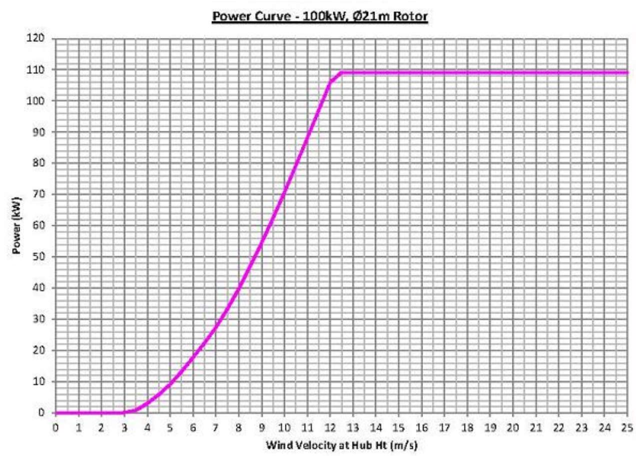

Figure 1. Power curve for Polaris 100kW wind turbine.

Rayleigh Based Approach						
Month	V_m (m/s)	V_{Fmax} (m/s)	V_{Emax} (m/s)	E_T (MWh)	C_F	E_D (kWh/m^2)
May'11	5.68	4.53	9.06	17.3	0.23	0.22
Jun'11	6.14	4.9	9.80	19.97	0.28	0.27
Jul'11	5.34	4.26	8.52	14.89	0.20	0.18
Aug'11	5.65	4.51	9.02	17.1	0.23	0.21
Sep'11	5.42	4.32	8.65	14.96	0.21	0.19
Oct'11	4.44	3.54	7.09	8.97	0.12	0.10
Nov'11	5.27	4.20	8.41	13.94	0.19	0.17
Dec'11	4.57	3.64	7.29	9.76	0.13	0.11
Jan'12	4.91	3.92	7.84	11.95	0.16	0.14
Feb'12	5.41	4.32	8.63	14.4	0.21	0.19
Mar'12	5.72	4.56	9.13	17.60	0.24	0.22
Apr'12	4.80	3.83	7.66	10.86	0.15	0.13

Table 1. Wind Speed analysis in Yanbu using Rayleigh Based approach

Monthly data analysis using Rayleigh based approach is presented in Table 1. Monthly data analysis using Weibull approach is presented in Table 2 and Table 3 for Graphical method and Standard deviation, respectively. From Table 2 and 3, annual average value of shape factor, k is 2.5 and 2.66 and the average value of scale factor, c (m/s) is 5.99 m/s and 7.89 m/s for graphical method and Standard deviation, respectively. The capacity factor, C_F, is highest in the month of June owing to the maximum average wind speed of 6.14 m/s for all three different models.

Graphical Method							
Month	**k**	**c (m/s)**	**V_{Fmax} (m/s)**	**V_{Emax} (m/s)**	**E_T (MWh)**	**C_F**	**E_D (kWh/m^2)**
May'11	2.48	6.35	5.16	8.06	15.45	0.21	0.17
Jun'11	2.56	7.0	5.76	8.77	19.14	0.27	0.23
Jul'11	2.74	6.12	5.18	7.47	13.30	0.18	0.15
Aug'11	2.63	6.23	5.19	7.72	14.24	0.19	0.16
Sep'11	2.55	6.30	5.18	7.91	14.44	0.20	0.17
Oct'11	2.7	5.07	4.27	6.23	7.46	0.10	0.08
Nov'11	2.39	5.54	4.42	7.15	10.29	0.14	0.12
Dec'11	2.28	5.41	4.20	7.13	10.19	0.14	0.11
Jan'12	2.64	5.47	4.57	6.78	9.65	0.13	0.11
Feb'12	2.17	6.58	4.94	8.89	16.70	0.24	0.22
Mar'12	2.18	6.58	4.96	8.88	17.87	0.24	0.21
Apr'12	2.62	5.22	4.35	6.48	8.07	0.11	0.09

Table 2. Wind Speed analysis in Yanbu using Weibull Based approach: Graphical method

Standard Deviation							
Month	**k**	**c (m/s)**	**V_{Fmax} (m/s)**	**V_{Emax} (m/s)**	**E_T (MWh)**	**C_F**	**E_D (kWh/m^2)**
May'11	2.61	8.54	7.01	10.63	30.94	0.42	0.41
Jun'11	2.74	8.91	7.54	10.88	32.49	0.45	0.45
Jul'11	2.71	7.94	6.70	9.73	26.51	0.36	0.32
Aug'11	2.68	8.36	7.02	10.29	29.62	0.40	0.38
Sep'11	2.66	8.06	6.74	9.95	26.54	0.37	0.34
Oct'11	2.67	6.77	5.68	8.35	17.94	0.24	0.20
Nov'11	2.69	7.75	6.52	9.52	24.30	0.34	0.30
Dec'11	2.62	6.98	5.81	8.67	19.55	0.26	0.22
Jan'12	2.65	7.38	6.17	9.13	22.44	0.30	0.26
Feb'12	2.65	8.18	6.85	10.12	26.54	0.38	0.36
Mar'12	2.58	8.61	7.12	10.76	31.41	0.42	0.42
Apr'12	2.69	7.16	6.02	8.80	20.06	0.278	0.24

Table 3. Wind Speed analysis in Yanbu using Weibull Based approach: Standard Deviation

With a view to obtain the economic analysis of the energy generated, following estimation has been made. Price of Polaris P21-100kW wind turbine is $160000, initial installation cost for the wind turbine is $48000 (30% of the turbine cost), annual operation and maintenance cost is $5600 (3.5% of the turbine cost), Rate of return is i=5%, 10% and 15%, life time of turbine is 25 years.

Table 4 shows the annual energy generation by Polaris-P21 wind turbine as 170 MWh, 154 MWh and 308 MWh for Rayleigh based approach, Graphical method and Standard deviation method with the capacity factors of 19.45%, 17.54% and 35.18%, respectively. This table also shows the cost of electricity generated by Polaris-P21 wind turbine for different rate of return.

		Rayleigh Approach	**Graphical Method**	**Standard Deviation**
C_F		0.1945	0.1754	0.3518
E_T, MWh		170	154	308
COE ($/kWh)	**i = 5%**	0.09 $/kWh	0.1 $/kWh	0.05 $/kWh
	i = 10%	0.08 $/kWh	0.09 $/kWh	0.04 $/kWh
	i = 15%	0.07 $/kWh	0.08 $/kWh	0.04 $/kWh

Table 4.Cost of wind energy considering different rates of return.

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Conclusions

Recently collected one year wind speed data has been analysed using a web based tool Wind Energy Assessment Tool (WEA). The wind energy potential has been evaluated using Polaris-P21 100 kW wind turbine by three different statistical models. Total energy output, capacity factor and cost of electricity have been presented.

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