Analysis of Wind Power Potential Characteristics and Feasibility in Kuwait for Possible Electricity Production

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Abstract- This technical paper presents an assessment of wind energy potential for six locations in Kuwait using measured meteorological data. These locations are; Abdaly, Mitribah, Jal Aliyah, Abraque Al-Habari, Kuwait international airport (KIA) and Julaia port. the results show that at 10 m height, Jal Aliyah has the maximum average wind speed of 3.96 m/s. In addition to that, to evaluate the performance of wind power systems in these sites, analysis of electricity production of large scale wind turbines (1 MW and above) is conducted. It is found that the energy generation of the proposed power systems varies from 1092 to 3580 MWh per life time , In the meanwhile, the availability factor is in the range of 47%-89%. In the meanwhile the capacity factor is in the range of (11%-20%). Based on that the cost of energy generated by these systems is found to be in the range of (0.21-0.67) USD/kWh.

Keywords Weibull Distribution, wind power, Wind energy density.

1. Introduction

Kuwait heavily relies on fossil fuels to meet its energy requirements. Fossil fuels such as heavy oil, crude oil, gas oil, and gas are providing 100% of Kuwait's electrical energy demand. The demand of electricity has increased rapidly by almost three quarter from 6.2 GW in 1999 to 10.9 GW in 2010. During that, the electrical energy generation increased rapidly by almost 81% (from 31.6 TWh to 57.1 TWh) [1]. Although Kuwait is a leading crude oil producer, the decision makers in the country are interested in taking an active part in utilizing wind energy whereas, the total dependence on crude oil for electricity generation and desalination is a waste of natural resources.

Due to the continuous improvements in turbine efficiency and higher fuel prices, wind power could become economically competitive with conventional power production for the State of Kuwait. According to the Global Wind Energy Council [1], the global installed wind power capacity reached 237.7 GW at the end of year 2011, which is about ten times more than what has been installed in 2001. In addition, GWEC predicts that the global market of wind turbines will grow to about 493.3 GW at the end of year 2016. Following that wind power could supply 11.5 to 12.7% of global electricity consumption by 2020.

2. Assessment Criteria of the Wind Power

In this paper, assessment of wind power potential for six locations in the state of Kuwait is performed. The meteorological data at these locations are taken from the meteorological department at Kuwait airport. The locations and elevations of the meteorological weather stations of sites are given in Table 1. The meteorological data were used to evaluate and analyze wind energy characteristics and to determine the location with highest wind energy potential.

Table 1. Locations of the six sites

Station Name	Elevation (m)	Latitude	Longitude
Abdaly	23.78	30° 03\` 57\`\`	47° 41\` 27\`\`
Mitribah	118.06	29° 49\` 29\`\`	47° 21\` 35\`\`
Jal Aliyah	119.10	29° 36\` 35\`\`	47° 34\` 36\`\`
Abraque Al-Habari	235.63	29° 17\` 50\`\`	46° 59\` 54\`\`
(KIA)	46.20	29° 13\` 19\`\`	47° 57\` 58\`\`
Julaia Port	7.51	28° 51\` 53\`\`	48° 17\` 23\`\`

In this research technical values that assess wind power potential are used namely wind energy density, wind speed, capacity factor and investment rate of return. Wind energy density (WED) is one of the critical parameters influences the potential of wind generated electricity. According to [2], WED defined as the energy in the region per unit rotor area and time and it is a function of the velocity and distribution of wind in the region. The classification of WED varies between fair and excellent, based on the mean wind speed as shown in Table 2, which is based on the mean wind speed at 30 meters of height from ground level [2].

Table 2. Classification of wind energy density.

Wind Speed (m/s) at 30 m	Wind Energy Density (W/m2)	Resource Potential
4.4-5.6	100-200	Fair
5.6-6.4	200-300	Moderate
6.4-7.5	300-500	Good
>7.5	>500	Excellent

Other important parameters are, most frequent wind speed and the wind speed carrying maximum energy. These parameters can help to properly select suitable wind turbines for a given site. In the meanwhile the capacity factor can be defined as the ratio of the rated production to the actual production of the wind turbine. Finally the rate of return is defined as the ratio of the investment amount to the annual saving. In this research wind turbine characteristics are estimated and examined for several utility-scale large wind turbines (1 MW and above) available from several manufacturers worldwide.

3. Weibull Distribution of Wind Speed for Kuwait

Wind speed at any given location vary widely throughout the year and can be expressed by a statistical distribution model. According to [3], wind speed frequency distribution can be well represented by Weibull distribution function which is characterized by the probability density function and represented by

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

where f(V) is the distribution of wind speed V, the Weibull parameters k and c are the dimensionless Weibull shape and scale factors respectively. The values of Weibull parameters are evaluated at anemometer height of 10 m using the following relations [4]

$$k = \left(\frac{\sigma}{V_m}\right)^{-1.086} \quad (1 \le k \le 10) \quad (2)$$

$$c = \frac{V_m}{\Gamma(1+1/k)} \quad (3)$$

where, σ is the standard deviation, V_m is the average wind speed and Γ is the gamma function represented by the following integral

$$\int_0^\infty t^{x-1} e^{-t} dt \quad (4)$$

The average wind speed and standard deviation in equation 2 are determined using the following relations:

$$V_m = \frac{1}{N}\left[\sum_{i=1}^{N} V_i\right] \quad (5)$$

and

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(V_i - V_m)^2} \quad (6)$$

where N is the number of wind speed records measured at the site.

Weibull shape and scale factors, average wind speed and standard deviation at different heights are obtained using the power exponent function expressed by:

$$V(z) = V_r\left(\frac{z}{z_r}\right)^{\alpha} \quad (7)$$

where z is the height above ground level, V_r is the wind speed at the reference height z_r of 10 m above ground level, V(z) is the wind speed at height z, and α is an exponent which depends on the roughness of the terrain. In this study, the value of α is taken as 1/7 which is applicable for low surface roughness and well-exposed sites [5]

In this research, wind energy characteristics for Weibull distribution are estimated for six sites by using equations 8-13 as given below. The derivation of these equations can be found in [6]. The average wind speed and standard deviation of wind speed are obtained using the following relations

$$V_m = c\Gamma\left(\frac{k+1}{k}\right) \quad (8)$$

and

$$\sigma = c\sqrt{\left[\Gamma\left(\frac{k+2}{k}\right) - \Gamma^2\left(\frac{k+1}{k}\right)\right]} \quad (9)$$

The most frequent wind speed is determined using:

$$V_{F\,max} = c\left(\frac{k-1}{k}\right)^{1/k} \quad (10)$$

and wind speed carrying maximum energy V_{Emax} is obtained by:

$$V_{E\,max} = c\left(\frac{k+2}{k}\right)^{1/k} \quad (11)$$

The wind energy density E_D is defined as the energy available in the regime for a unit rotor area and time. It is determined by using the following equation:

$$E_D = \frac{3\rho c^3}{2k}\Gamma\left(\frac{3}{k}\right) \quad (12)$$

Multiplying equation 12 by time factor, the total energy available in the wind is determined by:

$$E_I = \frac{3\rho c^3 T}{2k}\Gamma\left(\frac{3}{k}\right) \quad (13)$$

The density ρ in equations 12 and 13 is estimated at different heights using the following relation [7],

$$\rho(z) = \frac{353.05}{T} e^{-0.034(z/T)} \quad (14)$$

4. Determination of Wind Turbines Characteristics

Based on the assessment of wind energy characteristics conducted for the six locations, the best location with highest wind energy potential is found. The characteristics of various utility-scale wind turbines at the predicted location are determined using equations 15 to 21 as given below [2,6].

The energy generated by an ideal wind turbine is obtained by:

$$E_{Tw} = T\int_{V_I}^{V_n} P_I\,(V)f(V)dV \tag{15}$$

PI(V) in equation (15), is the power available in the wind which is given by:

$$P_I\,(V) = \frac{1}{2}\rho V^3 \tag{16}$$

and f(V) is the Weibull distribution function defined by equation (1). In addition, the actual energy output from a wind turbine is estimated by:

$$E_{TA} = T\int_{V_I}^{V_n} P_A\,(V)f(V)dV \tag{17}$$

where PA(V) is the wind turbine power curve function and is obtained from RETScreen software for several commercial wind turbines having different operational characteristics. The power curve for a wind turbine indicates the net electrical energy output from a wind turbine as a function of the wind speed at hub height.

A meaningful parameter for evaluating wind turbine performance is turbine efficiency η. The efficiency of a wind turbine is defined as the ratio of the actual energy output from a wind turbine to the energy generated by ideal wind turbine. Therefore it is calculated by:

$$\eta = \frac{E_{TA}}{E_{Tw}} \tag{18}$$

In addition, the capacity factor c_f is also an important index in measuring the productivity of a wind [6]. According to [2], the capacity factor is defined as the ratio of the actual wind energy output E_{TA} in a time period to the energy produced if the wind turbine had run at its rated power over that period that is, rated wind energy E_{TR}. Thus

$$c_f = \frac{E_{TA}}{E_{TR}} \tag{19}$$

The rated wind energy E_{TR} in equation 19 is calculated by:

$$E_{TR} = T\,P_R \tag{20}$$

It can be seen from equation 20 that wind turbine produces so called the rated wind energy when it operates with full capacity for a duration T.

Another important parameter that need to be determined is the availability factor A_F, which is obtained using the following relation

$$A_F = \int_{V_I}^{V_o} f(v)\,dv \tag{21}$$

The availability factor A_F of a turbine is defined as the fraction of time when the turbine is available to produce power. According to [8], the availability for modern wind turbines typically in the range of 95% to 99%. Furthermore, equation 21 shows that wind turbines produce useful power only for wind speeds between the cut-in and cut-out wind speeds. The turbines operate at a level lower than its availability depending on wind conditions.

The integrals given in equations 15, 17 and 21 are performed using trapezoidal rule i.e.

$$\int_a^b f(x)dx = \frac{1}{2}\Delta x_n\left[f_a + f_b + 2\sum_{i=1}^{n-1} f(x_i)\right] \tag{22}$$

5. Results and Discussions

5.1 Analysis of Wind Energy Characteristics

The results of wind energy characteristics at heights 10 m and 40 m for different locations are given in Tables 3 and 4 respectively. The results show that for most of the locations at 10 m height are characterized by poor resource wind potential. The average wind speed lies in the range of 0.93-3.96 m/s. The maximum wind speed is evaluated at Jal Aliyah station. At 40 m height, the average wind speeds increased by about 22%. In addition, the average wind speed at Jal Aliyah can be characterized by fair resource potential since its average wind speed lies in the range of 4.4-5.6 m/s, when interpolated at 30 m and compared with Table 1.

Furthermore, columns 6 and7 of Tables 3 and 4 present two important wind characteristics of interest for wind project designer namely, most frequent wind speed and wind speed carry maximum energy. Their calculated values indicate that the most frequent wind speed is always less than the average wind speed, and wind speed carrying maximum energy is always higher. Besides that there are values that increase with the height above the ground surface. Table 3 shows that Jal Aliyah has maximum most frequent wind speed and wind speed carrying maximum energy at 10 m of 3.0 m/s and 6.5 m/s respectively.

Table 3. Wind Energy Characteristics for Various Locations at a 10 m Height

Location	V (m/s)	σ (m/s)	c (m/s)	k	$V_{F\,max}$ (m/s)	$V_{E\,max}$ (m/s)	E_D (W/m2)	E_I (kWh/m)	ρ (kg/m3)
Abdaly	1.26	1.19	1.28	1.05	0.07	3.52	6.20	54.48	1.181
Mitribah	3.43	2.12	3.84	1.66	2.21	6.17	56.08	492.60	1.180
Jal Aliyah	3.96	2.18	4.46	1.89	2.99	6.54	74.32	652.84	1.182
Abraque Al-Habari	3.14	1.98	3.50	1.62	1.94	5.74	44.41	390.12	1.184
KIA	2.12	1.47	2.33	1.46	1.06	4.22	15.82	138.99	1.179
Julaia Port	2.56	1.79	2.82	1.45	1.26	5.12	28.25	248.15	1.183

Table 4. Wind Energy Characteristics for Various Locations at a 40 m Height

Location	V (m/s)	σ (m/s)	c (m/s)	k	$V_{F\ max}$ (m/s)	$V_{E\ max}$ (m/s)	E_D (W/m2)	E_I (kWh/m2)	ρ (kg/m3)
Abdaly	1.53	1.46	1.56	1.05	0.09	4.30	11.20	98.34	1.177
Mitribah	4.18	2.58	4.68	1.66	2.69	7.52	101.22	889.14	1.176
Jal Aliyah	4.82	2.66	5.44	1.89	3.64	7.97	134.15	1178.40	1.178
Abraque Al-Habari	3.82	2.41	4.27	1.62	2.36	7.00	80.17	704.17	1.180
KIA	2.58	1.80	2.85	1.46	1.29	5.14	28.56	250.88	1.175
Julaia Port	3.12	2.18	3.44	1.45	1.54	6.24	50.99	447.91	1.179

From Table 3, Weibull scale and shape factors vary between 0.99 to 4.46 m/s and 1.05 to 1.89 respectively. At 40 m, the scale factor increases to between 1.21 to 5.44 m/s. However, the shape factor has not showed any variation with height, because the change in the ratio of σ/Vm in equation 2 was insignificant with respect to the height. Since uniformity of wind at the site increases with shape factor [2], this indicates that the wind at the station of Jal Aliyah is the most uniform compared to other locations.

The two measure parameters for evaluating the energy potential at a site wind energy density and total wind energy are shown in columns 8 and 9 of tables 3 and 4. It is clear that their values increase with height and average wind speed. Table 3 shows that Jal Aliyah has maximum wind energy density of 74.3 W/m2 and total wind energy of 652.8 kWh/m2. Both values increased about 80% at height 40 m above the ground. At the same height, the calculated most frequent wind velocity is 3.6 m/s and wind velocity carrying maximum energy is 8.0 m/s.

Based on the results shown in tables 3 and 4, it can be concluded that Jal Aliyah has best wind energy potential compared with other locations. Therefore, for this site additional data are obtained and analyzed in more details, including the impact of heights on wind speed distribution and wind energy available. In addition, wind turbines with different operational characteristics are examined by estimating the electricity production costs based on their performance curves, installation, operating and maintenance costs.

A plot of wind speed distribution at height 10 m at Jal Aliyah station is shown in Fig. 1. In thisfigure, the data obtained by Weibull method using equations 1, 2 and 3 and meteorological method which was developed by [9]are compared together. The figure represents the frequency with which winds occur at various wind speed and illustrates the good representation of meteorological data by the Weibull distribution. It can be also seen from the figure that the wind speed distribution has a bell-shaped curve, with the peak of the curve represents the most frequent wind speed of 3.0 m/s and occurs at about 0.18 hours per year (i.e., 18% of the total hours per year).

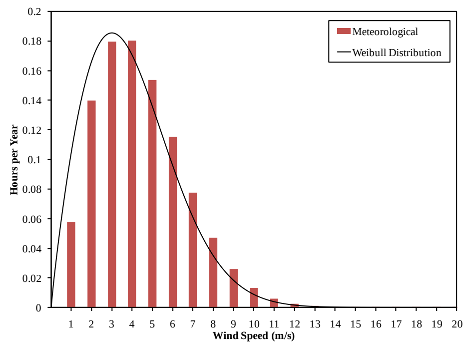

Fig. 1. Wind speed distribution at Jal Aliyah station using Weibull distribution and meteorological data.

Wind energy available at Jal Aliyah Station at 10 m height is expressed graphically in Fig. 2. The wind energy available at this location is obtained by the product of probability density function, the power available in the wind and duration time. The peak of the curve represents the maximum energy that the wind carries, and it is estimated to be 110 kWh/m^2 and evaluated at a wind speed of 6.5 m/s.

The impact of height on the Weibull distribution wind speed is displayed in Fig. 3. It can be noticed that as the height above ground surface increases, the curve shifts toward higher wind speeds on the right of the chart. This resulted in increase in average and most frequent wind speeds as well as wind speed carrying maximum energy. The figure also shows that between heights 40 m and 70 m, the influence of the height on the Weibull distribution wind speed become less. This is because the site is characterized as open desert area which means that the friction and turbulent is restricted in small distance above the ground.

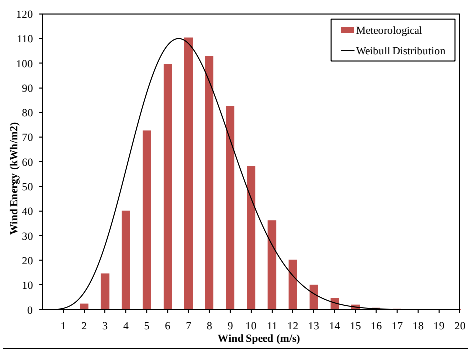

Fig. 2. Wind energy available at Jal Aliyah station using Weibull distribution and meteorological data.

Similarly, the impact of height on wind energy available per unit rotor area is illustrated in Fig. 4. It is clear that the wind energy increases with the height. At higher wind speed (e.g. over 6.0 m/s), the impact of height is significant this is due to increase in wind speed with height which in turns increase Weibull distribution. In addition, it can be observed that the maximum energy that the wind carries shifts to right of the figure and towards higher wind speed as the height increases. This in turns shifts the wind speed that carries maximum energy to value approaching rated-wind speed of 11 to 18 m/s for most of the wind turbines available in the market.

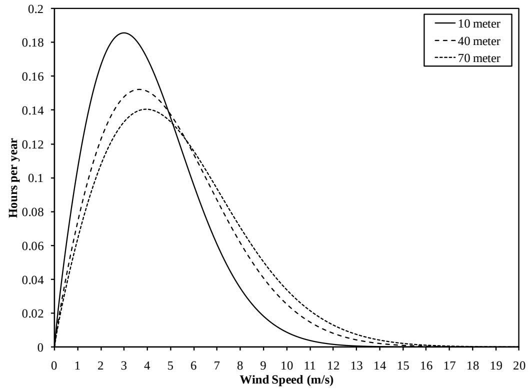

Fig. 3. Weibull wind speed distribution at different heights at Jal Aliyah.

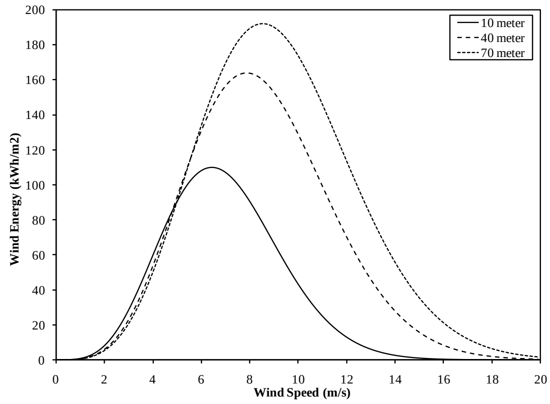

Fig. 4. Wind Energy Available at different heights at Jal Aliyah

5.2 Analysis of Wind Turbines Characteristics For Jal Aliyah Location

For Jal Aliya site, Table 5 shows the characteristics of different commercial wind turbines having different operational characteristics that is, cut-in cut-out and rated speed, rated power, rotor diameter and hub height. At this site, the Table shows that the annual energy generated for various rated capacity wind turbines is in the range of 1092 and 3580 MWh. The minimum energy is generated by M-O1 wind turbine model, and maximum energy is generated by M-C2 model, mainly contributed by its large rated capacity in addition to its hub height. The model has cut-in, rated and cut-out wind velocity of 4 m/s, 14 m/s and 25 m/s respectively and rotor diameter of 88 m.

Furthermore, Table shows that the efficiency of the wind turbines varis from 0.32-0.44. In fact, different wind turbines were examined and found that most of the wind turbines operate at their maximum efficiency when wind speed in range of 7 to 10 m/s. It is also noted that wind turbines may have same operational characteristics but could have different efficiencies at same wind speeds,

From Table 6, it is concluded that for a wind energy project designer to carefully look at and examine the power curves of the wind turbines to select the most efficient wind turbine available.

The calculated availability factor in Table 5 varies from a minimum 0.47 up to a maximum 0.89 which is lower than the typical values range of 0.95 to 0.99 for modern wind turbines [8]. This is expected since the measured average wind speed at this location is fair according to [10]classification. The table also shows that wind turbines with lower cut-in and rated speeds and higher hub heights increase the availability factor.

Table 5 also demonstrates that the capacity factor lies in the range of 0.11-0.20 which is well below range 0.25-0.40 of a reasonable efficient wind turbine [2]. The highest capacity factor is estimated for M-U1 wind turbine model. This resulted from lower rated wind speed of 11 m/s that the model is having compared to other wind turbines.

5.3 Financial Assessment of Wind Power Systems in Kuwait

According to [11] the average cost of a wind power systems is about 1 USD/Wp which means that a 1 MW wind power system may cost about 1 million dollars. In the meanwhile the value of the salvage value of this system is high (20-25%) due to the nature of system's components. On the other hand the average estimated life time of a wind power system is about 15 years. Based on this the cost of energy generated by wind power systems in Kuwait is around 0.21 USD/kWh. In general the accepted rate of return of wind power system is 7 years. This to say that to encourage wind power systems installation in Kuwait, the average feed in tariff price must be around 0.5 USD/kWh so as to return the whole investment within 7 years. This means that the government have to subsides the wind power generation by 250%. The results of this brief analysis shows that the wind power systems are not that feasible for Kuwait region as compared to other renewable energy sources such as photovoltaic power systems according to [12].

6. Conclusion

In this study, assessment of wind energy characteristics have been performed for 6 locations in Kuwait using measured metrological data. Characteristics such as average wind speed, standard deviation, most frequent wind speed, wind speed carrying maximum energy, wind energy density and total energy available were analyzed. Based on this analysis, it has been found that Jal Aliyah has the most promising wind energy potential compared to other locations.

Table 5. Wind Turbines Characteristics for Jal Aliyah Location

Model	Ideal Turbine Energy (MWh)	Actual Turbine Energy (MWh)	Turbine Efficiency	Rated Wind Turbine Energy (MWh)	Available Factor	Capacity Factor
M-A1	5680	2520	0.44	17568	0.87	0.14
M-B1	7209	3114	0.43	17568	0.89	0.18
M-C1	6790	2509	0.37	15811	0.61	0.16
M-D1	7129	2615	0.37	15811	0.61	0.17
M-E1	7622	2765	0.36	15811	0.63	0.17
M-F1	8491	3020	0.36	15811	0.65	0.19
M-G1	6790	2698	0.40	17568	0.61	0.15
M-H1	7674	2814	0.37	17568	0.61	0.16
M-I1	8204	2977	0.36	17568	0.63	0.17
M-J1	9140	3256	0.36	17568	0.65	0.19
M-K1	7489	2647	0.35	17568	0.75	0.15
M-L1	7293	2757	0.38	17568	0.75	0.16
M-M1	7782	2914	0.37	17568	0.76	0.17
M-N1	8644	3182	0.37	17568	0.77	0.18
M-O1	2742	1092	0.40	8784	0.58	0.12
M-P1	2874	1139	0.40	8784	0.59	0.13
M-Q1	3117	1223	0.39	8784	0.61	0.14
M-R1	3336	1297	0.39	8784	0.62	0.15
M-S1	4050	1397	0.34	8784	0.75	0.16
M-T1	4325	1501	0.35	8784	0.75	0.17
M-U1	4608	1717	0.37	8784	0.75	0.20
M-V1	4050	1445	0.36	10980	0.75	0.13
M-W1	4608	1789	0.39	10980	0.75	0.16
M-X1	4608	1788	0.39	10980	0.75	0.16
M-Y1	4901	1887	0.39	10980	0.75	0.17
M-Z1	8096	2622	0.32	13176	0.63	0.20
M-A2	9325	3303	0.35	18446	0.63	0.18
M-B2	10274	3580	0.35	18446	0.65	0.19
M-C2	4622	1683	0.36	14494	0.61	0.12
M-D2	4852	1760	0.36	14494	0.61	0.12
M-E2	5187	1871	0.36	14494	0.63	0.13
M-F2	4622	1787	0.39	15372	0.61	0.12
M-G2	4852	1870	0.39	15372	0.61	0.12
M-H2	5187	1988	0.38	15372	0.63	0.13
M-I2	6790	2655	0.39	15811	0.47	0.17
M-J2	7129	2765	0.39	15811	0.48	0.17
M-K2	7622	2921	0.38	15811	0.49	0.18
M-L2	6790	2383	0.35	15811	0.47	0.15
M-M2	7129	2484	0.35	15811	0.48	0.16
M-N2	7622	2628	0.34	15811	0.49	0.17
M-O2	4622	1802	0.39	17568	0.61	0.10
M-P2	4852	1888	0.39	17568	0.61	0.11
M-Q2	5187	2010	0.39	17568	0.63	0.11
M-R2	6790	2514	0.37	17568	0.61	0.14
M-S2	7129	2625	0.37	17568	0.61	0.15
M-T2	7622	2781	0.36	17568	0.63	0.16
M-U2	8491	3049	0.36	17568	0.65	0.17

Consequently, wind turbine characteristics at this location have been investigated for several utility-scale commercial wind turbines available worldwide. It has been found that the operational characteristics such as cut-in cut-out and rated wind speeds as well as the performance curve of a wind turbine can result in change in the electrical energy production and other characteristics. The annual energy production is estimated between 1092 and 3580 MWh. In the meanwhile the cost of energy for these system is 0.21 USD/kWh.

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