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Investigation of wind energy resource and wind turbine characteristics in Urumqi, China

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ABSTRACT

The ten-year monthly mean data for wind speeds at 10, 50,100, 150 and 300 m heights over a typical year were statistically analyzed in this study to determine the potential for wind power generation in Urumqi, China, using the two-parameter Weibull distribution function. The shape factor k and scale factor c were estimated by the maximum likelihood method. Eight small to medium-sized commercially available wind turbines were selected for this region, and their mean energy outputs and capacity factors were analyzed. Results showed that the highest monthly mean wind speeds at the different heights occurred in November, and the lowest occurred in June. The long-term monthly mean wind speeds were found to be higher from September to May than in other months in a typical year. The Urumqi site indicated poor wind characteristics. The mean energy outputs for the selected wind turbines ranged from 2,062 to 79,968 kWh/yr. Their capacity factors ranged from 5.2% to 15.9%. © 2016 Trade Science Inc. - INDIA

KEYWORDS

Wind energy resource;
Weibull distribution;
Wind power density;
Capacity factor;
Urumqi.

INTRODUCTION

Wind is an abundant and inexhaustible nature resource that can provide significant quantities of energy to support demands. However some sites exhibit strong short-term and seasonal variations in their energy outputs. The use of wind power generation has expanded rapidly in the past 20 years, and it is now a mature, reliable and efficient technology for electricity production. The application of wind power generation is based on an assessment of the wind energy as a basis for wind farm project development; however, wind energy resource assessment is a difficult process that demands well-situated anemometer towers, appropriately chosen measurement techniques and modeling procedures, quality equipment, trained staff and thorough data analysis techniques[1-3].

Wind power potential has been assessed and studied in many countries[4]. For example, Ahmed Shata and Hanitsch[5] conducted a technical and economic assessment of electricity generation using wind turbines at a promising site in Hurghada, Egypt, for which they used WAsP software to calculate the wind speed frequency from data recorded over 23 years. Ucar and Balo[6] analyzed the monthly and yearly wind speed distribution and wind power density for the period 2000–2006 at six locations in Turkey, and carried out a technical assessment of electricity generation for four wind turbines with 600, 1000, 1500 and 2000 kW capacities. Fyrippis et al.[7] investigated the wind power potential at Koronos village in the northeast of the Greek island of Naxos, using observed wind data from a measurement mast. They showed that the selected site falls into Class 7 of the international system of wind classification. The mean annual recorded wind speed was 7.4 m/s, corresponding to an estimated annual mean power density of 420 W/m^2. They found that the Weibull distribution model fitted the data better than Rayleigh distribution model. Ohunakin et al.[8] analyzed the wind energy potential at seven locations in the northwestern geopolitical zone of Nigeria based on the wind data from 1971 to 2007 using two-parameter Weibull distributions, and carried out a technical electricity generation assessment of four commercial wind turbines. Dahmouni et al.[9] estimated the wind energy potential and optimal electricity generation for a site in Borj-Cedria. The mean wind speed, wind probability distribution function and wind power density were reported for each season at three altitudes. Wu et al.[10] assessed the wind energy potential for a site in Inner Mongolia, China. They analyzed the two-parameter Weibull, Logistic and Lognormal wind-speed distribution models using data measured at the site for the three- year period 2009-2011. The results showed that the area is suitable a wind farm. Dong et al.[11] assessed the wind energy resource at four locations in Huitengxile, Inner Mongolia, based on wind speed data collected four times a day for the past 63 years, which was first collected for mutation tests using the sliding *T*-test and the sliding *F*-test. In addition, some new criteria, such as matching index, turbine cost index and an integrated matching index were proposed as criteria for choosing the most suitable wind turbine for the Huitengxile wind farm in accordance with the local environment and economic cost. Tizpar et al.[12] analyzed the wind power potential of the Mil-E Nader region,Iran, based on 10 min measured short-term wind data. This analysis showed that 80m-high wind turbines had the highest production.

To date, few assessments have been conducted on wind energy at different heights in Urumqi. This paper describes a comprehensive analysis of wind energy resources at different heights based on average monthly wind speed data over 10 years, adopting the two-parameter Weibull distribution. The suitability of a selection of wind turbines for this region was also studied, providing a theoretical foundation for local wind energy resources.

DESCRIPTION OF THE LOCATION

Urumqi(42°45’32”–44°08’00”N,86°37’33” – 88°58’24”E) is the capital of the Xinjiang Uygur Autonomous Region, China. It is located in the hinterland of Eurasia in an alluvial fan-shaped basin on the northern slope of the Tianshan Mountains, which opens into the Junggar Basin to the north. It is the largest city between the capital of Gansu (Lanzhou) — the westernmost city on the Yellow River — and the countries of Uzbekistan, Kyrgyzstan, and Kazakhstan. Urumqi, far from the ocean, is in a semi-arid continental climate belt of the middle temperate zone, where the air is dry. Its features include continual drastic weather changes, significant temperature differences between day and night, and scant and irregular rainfall. The spring is short and windy, summers are hot, and winters are long and cold. A map showing the geographical position of Urumqi is shown in Figure 1[13,14].

Figure 1 : Location of urumqi, china [13]

MATHEMATICAL ANALYSIS

Wind speed probability distribution

The probability distribution of the wind speed is fundamental to wind energy potential assessment. In the specialized literature, several probability distributions have been proposed[10,11], including Lognormal distribution, Weibull distribution, Rayleigh distribution and Gamma distribution. Howeverÿthe two-parameter Weibull distribution is the most commonly used because of its flexibility to adjust the parameters to suit a given period of time—usually one month or one year[15]. Variation in the wind velocity, *V*, is characterized by two parameter functions: the probability density function, and the cumulative distribution.

The two-parameter Weibull probability density function (PDF) is given by the following equation[8]:

$$f(V)=\frac{k}{c}\left(\frac{V}{c}\right)^{k-1}e^{-\left(\frac{V}{c}\right)^{k}}\ ;\ (V\geq 0, k>0, c>1) \quad (1)$$

where *k* is a dimensionless shape parameter showing how spiked the wind distribution is, and *c* is a dimensionless scale parameter showing how 'windy' the wind location under consideration is.

The two-parameter Weibull cumulative distribution function (CDF) is the integral of the probability density function, which is given by the following equation[8]:

$$F(V)=1-e^{-\left(\frac{V}{c}\right)^{k}} \quad (2)$$

The parameters *k* and *c* may be determined by various methods, such as the Weibull probability plotting paper method, standard deviation method, moment method, maximum likelihood method, or energy pattern factor method. Of all these, the standard deviation method is commonly used because of its simplicity. The maximum likelihood method requires extensive numerical iterations, but it is the most accurate of these methods. For that reason, it was adopted in this study.

The shape factor *k* and the scale factor *c* are estimated from the following two equations[16]:

$$k=\left[\frac{\sum_{i=1}^{n}V_i^k\ln(V_i)}{\sum_{i=1}^{n}V_i^k}-\frac{\sum_{i=1}^{n}\ln(V_i)}{n}\right]^{-1} \quad (3)$$

$$c=\left(\frac{1}{n}\sum_{i=1}^{n}V_i^k\right)^{1/k} \quad (4)$$

Extrapolation of wind speed at different hub height

The available wind speed data was collected in Urumqi at different heights above ground level. Since wind speed increases with height, it is necessary to extrapolate the wind speed to the hub height of the turbine. According to the literature, the power law method is most commonly used to adjust the wind speed at one level to that at another level. This is given by[8]:

$$\frac{V_H}{V_{H_1}}=\left(\frac{H}{H_1}\right)^{\alpha} \quad (5)$$

where V_H and V_{H1} are the wind speeds at heights *H* and H_1; α is a power law coefficient representing the degree of roughness of the ground surface. The typical value for a wide-plain area, α=1/7, was used in this study.

Wind power density

The wind power density (WPD) is commonly considered to be the best indicator of the wind resource at a site. The power of the wind that flows at speed *V* through a swept area *A* can be estimated by using the following equation[9]:

$$P(V)=\frac{1}{2}\rho AV^3 \quad (6)$$

In addition to the wind speed and air density, the WPD of a site also takes into account the Weibull probability density function, and is given by[17]:

$$p(V)=\int_0^{\infty}\frac{P(V)}{A}f(V)dV=\frac{1}{2}\int_0^{\infty}\rho V^3 f(V)dV=$$

$$\frac{1}{2}\rho c^3\Gamma\left(1+\frac{3}{k}\right)=\frac{1}{2}\rho \bar{V}^3\frac{\Gamma\left(1+\frac{3}{k}\right)}{\left[\Gamma\left(1+\frac{1}{k}\right)\right]^3} \quad (7)$$

where *p*(*V*) is the wind power density (WPD) (W/m^2), *P*(*V*) is the wind power (W), ρ is the air density at the site (kg/m^3), *A* is the swept area of the rotor blades (m^2), and Γ is the gamma function of *x*, given in the standard formula by[8]:

$$\Gamma(x)=\int_0^{\infty}e^{-u}u^{x-1}du \quad (8)$$

The air density at the site is of great importance in the estimation of WPD, and it depends essentially on the air pressure and the ambient temperature. At standard sea level (temperature 288K, air pressure 1.01325 kPa) the air density is 1.225kg/m^3. Most studies have assumed this to be a constant value when calculating the WPD of a location; however, this can result in an underestimation or overestimation of the wind power potential of a local wind regime. Accordingly, in the present study, the air density was calculated from the air pressure and temperature measured at the location, using the following equation[9,18]:

$$\rho = 3.4837\frac{P}{T} \tag{9}$$

where T is the ambient temperature (K) and P is the air pressure (kPa).

Capacity factor

The WPD and the capacity factor (C_f) are usually adopted as yardsticks to evaluate the energy potential, where C_f is the average power output over a period stated as a percentage of the rated electrical power [1]:

$$C_f = \frac{P_{ave}}{P_{rated}} \times 100\% \tag{10}$$

where P_{ave} is the average power output of the wind turbine (kW), and P_{rated} is the rated electrical power of the wind turbine (kW).

The average power output of the wind turbine is calculated as follows:

$$P_{ave} = \int_0^{\infty} P_e(V) f(V) dV \tag{11}$$

where $P_e(V)$ is the power output of the wind turbine (kW), which is calculated as follows[19]:

$$P_e(V) = \begin{cases} 0; 0 \le V < V_{cut-in} \\ \frac{1}{2}\rho A C_p(\lambda,\beta) V^3 \eta_t \eta_g; V_{cut-in} \le V < V_{rated} \\ \frac{1}{2}\rho A C_p(\lambda,\beta) V_{rated}{}^3 \eta_t \eta_g; V_{rated} \le V < V_{cut-out} \\ 0; V \ge V_{cut-out} \end{cases} \tag{12}$$

where C_p is the power coefficient, λ is the rotor tip speed ratio, β is the blade pitch angle (°), η_t is the mechanical transmission efficiency (%), η_g is the generator efficiency (%), V_{cut-in} is the cut-in wind speed (m/s), $V_{cut-out}$ is the cut-out wind speed (m/s), V is the wind speed at the height of the wind turbine hub (m/s), V_{rated} is the nominal wind speed (m/s).

Putting Eqs.(11) and (12) into Eq. (10), the capacity factor C_f of a wind turbine is given by:

$$C_f = \frac{P_{ave}}{P_{rated}} \times 100\%$$

$$= \frac{\int_{V_{cut-in}}^{V_{cut-out}} P_{wt}(V) f(V) dV}{\frac{1}{2}\rho_a A C_p(\lambda,\beta) V_{rated}{}^3 \eta_t \eta_g}$$

$$= \frac{\int_{V_{cut-in}}^{V_{rated}} P_{wt}(V) f(V) dV + \int_{V_{cut-in}}^{V_{rated}} P_{wt}(V) f(V) dV}{\frac{1}{2}\rho_a A C_p(\lambda,\beta) V_{rated}{}^3 \eta_t \eta_g}$$

$$= \frac{\int_{V_{cut-in}}^{V_{rated}} V^3 f(V) dV}{V_{rated}{}^3} + \int_{V_{rated}}^{V_{cut-out}} f(V) dV \tag{13}$$

The power output of a typical wind turbine is written as[1]:

$$P_e(V) = P_{rated} \times \begin{cases} 0; 0 \le V < V_{cut-in} \\ \frac{V^k - V_{cut-in}^k}{V_{rated}^k - V_{cut-in}^k}; V_{cut-in} \le V < V_{rated} \\ 1; V_{rated} \le V \le V_{cut-out} \\ 0; V > V_{cut-out} \end{cases} \tag{14}$$

The capacity factor of a typical wind turbine is given by:

$$C_f = \frac{P_{ave}}{P_{rated}} \times 100\% = \frac{e^{-(V_{cut-in}/c)^k} - e^{-(V_{rated}/c)^k}}{(V_{rated}/c)^k - (V_{cut-in}/c)^k}$$

$$- e^{-(V_{cut-out}/c)^k} \tag{15}$$

RESULTS AND DISCUSSION

Assessment of wind energy resource at different heights

The 10-year average monthly wind speed data at different heights in Urumqi was obtained from the National Aeronautics and Space Administrative (NASA) database[20]. This relates to measurements at 10, 50, 100, 150 and 300m above the ground, taken daily at 3-hourly intervals. The data is shown graphically in Figure 2, where it is seen that the monthly mean wind speeds increase with the increased height. It was also observed that the variation showed a similar tendency throughout this region. The maximum wind speed occurs in November, and the minimum in June. Figure 2 shows

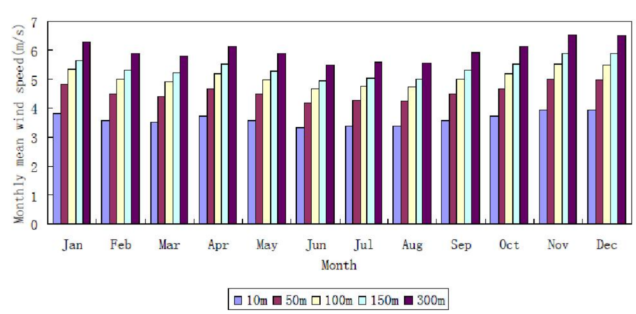

Figure 2 : Monthly mean wind speed at different heights in a typical year in Urumqi

that the long-term wind speeds are higher from September to May than at other times.

Figure 3 shows that both the annual WPD and the mean wind speed in Urumqi increase with increasing hub height. The annual WPD was calculated from Eq.(7) to be 52, 106, 145, 174 and 237 W/m^2 at heights of 10, 50, 100, 150 and 300m respectively, and the annual mean wind speeds were 3.61, 4.56, 5.06, 5.38 and 5.97m/s respectively.

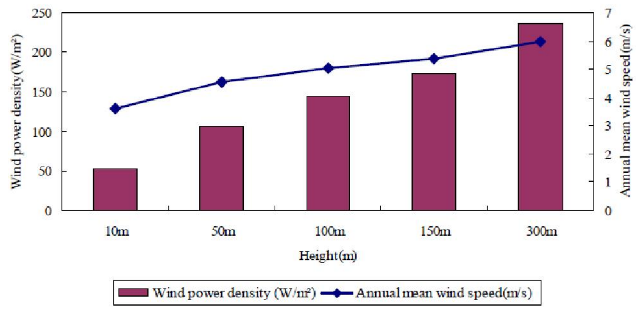

Figure 3 : Annual wind power density and mean wind speed at different heights in a typical year in Urumqi

Wind characteristics and associated values have been classified as follows[21]:

p(*V*)<100 W/m^2 — poor
p(*V*) ≈ 400 W/m^2 — good
p(*V*) >700 W/m^2 — excellent

By these criteria, the WPD at Urumqi is almost "poor". It was concluded that the site is not suitable for large-scale electric wind-power application; however, small-scale wind turbines or wind-hybrid power systems

might be a reasonable option for the site for supplying power for lighting, electric fans, chargers and so on.

The Weibull probability distributions of the wind speeds at the different heights (Figure 4) show that the highest wind speeds were 12, 15, 17, 18 and 20 m/s, and remained at 3.5 m/s or less for about 52.6%, 37.6%, 32.2%, 29.3% and 24.6% of the year, respectively. Thus it would be theoretically possible to exploit the wind energy on 47.4%, 62.4%, 67.8%, 70.7% and 75.4% of the year with a cut-in-speed of 3.5 m/s or more. It also suggests that the higher the wind turbine hub height is, the greater its power output would be; however, increasing the height of the wind turbine would also mean increasing the cost.

The annual shape and scale of Weibull parameters were determined by the maximum likelihood method (Figure 5), which shows the scale parameters increasing with greater height, since the increasing trend reflects

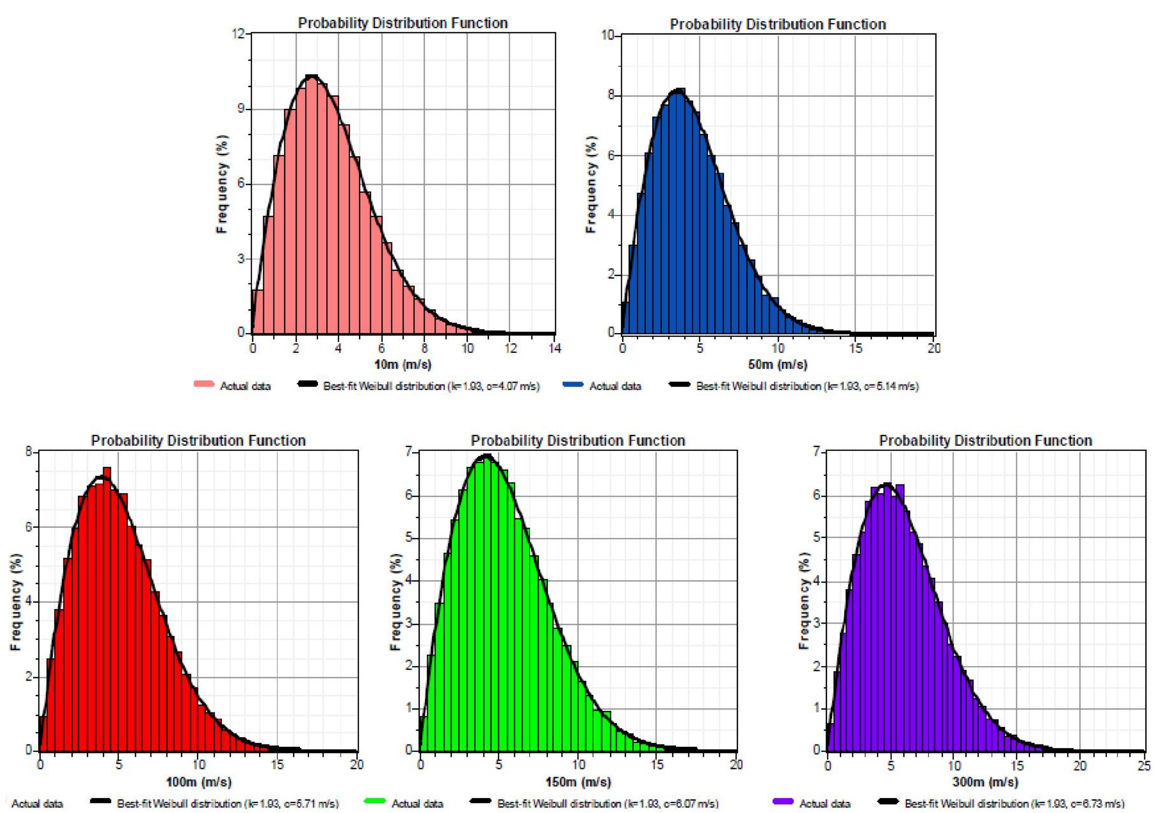

Figure 4 : Typical annual wind-speed probability distributions at different heights in Urumqi

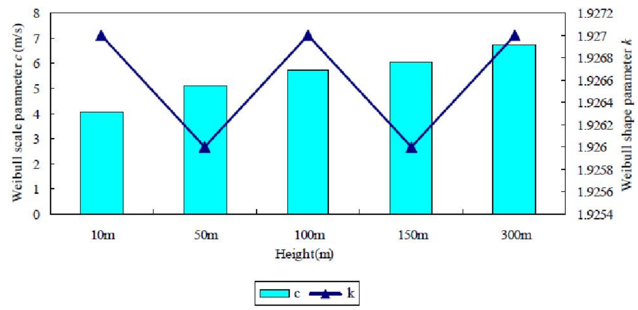

Figure 5 : Weibull parameters at different heights (maximum likelihood method)

the variation in annual mean wind speeds. The highest and lowest values of *c* (6.732m/s and 4.07 m/s) were at 300m and 10m heights respectively. The shape parameters (1.926 and 1.927) were found to be almost identical, suggesting that the shapes of the wind speed probability distributions are similar at the different heights.

The cumulative probability distributions of wind speeds at different heights in a typical year in Urumqi are shown in Figure 6. It is clear that these have similar tendencies, but some difference in the range of variation of wind speeds is evident.

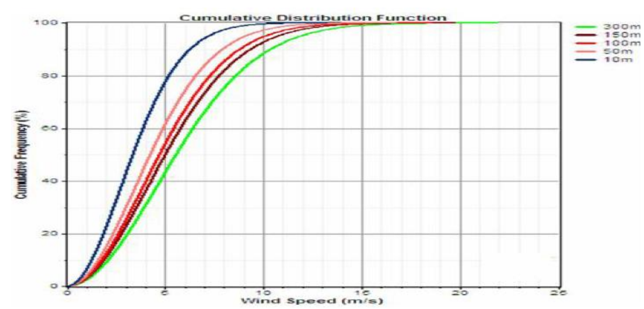

Figure 6 : Wind speed cumulative probability distributions at different heights in a typical year in Urumqi

Wind turbine characteristics

Eight small- to medium-sized commercially available wind turbines (Endurance G-3120, Southwest Skystream 3.7, Endurance E-3120, Fuhrländer 30, Fuhrländer 100, Entegrity eW-15 50 Hz, Endurance S-250 and Wind Matic WM 15s, with rated power ranging from 1.8 to 100 kW) were selected for assessment of their performance in Urumqi. Their characteristics and power curves are shown in Table 1 and Figure 7[22-27].

The mean energy outputs and capacity factors of the selected wind turbines in Urumqi are shown in Figure 8, which indicates that their mean energy outputs would range from 2,062 kWh/yr to 79,968 kWh/yr. The Fuhrländer 100 seems to have the highest mean energy output of 79,968 kWh/yr at a hub height of 35 m. The reasons for this may be due to its low cut-in wind speed (2.5m/s) and high rated output (100kW) compared to the others. The Southwest Skystream 3.7 has the lowest mean energy output of 2,062 kWh/yr for a 33.5 m hub height. Therefore, if an investment decision were to be primarily based on annual mean energy output, the Fuhrländer 100 (or turbines with similar design

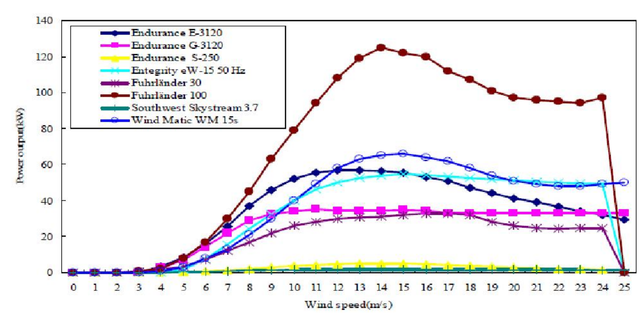

Figure 7 : Power curves for selected wind turbines

TABLE 1 : Characteristics of the selected wind turbines

Turbine model	Diameter (m)	Hub height (m)	Rated output (kW)	V_{cut-in} (m/s)	V_{rated} (m/s)	$V_{cut-out}$ (m/s)
Endurance G-3120	19.2	30.5	35	3.5	8	25
Southwest Skystream 3.7	3.7	33.5	1.8	3.5	9	25
Endurance E-3120	19.2	30.5	55	3.5	11	25
Fuhrländer 30	13	30	30	3	12	25
Fuhrländer 100	21	35	100	2.5	13	25
Entegrity eW-15 50 Hz	15	31	50	3.5	14.5	25
Endurance S-250	5.5	36.6	5	4	14	24
Wind Matic WM 15s	15.5	24.4	66	3.5	15	25

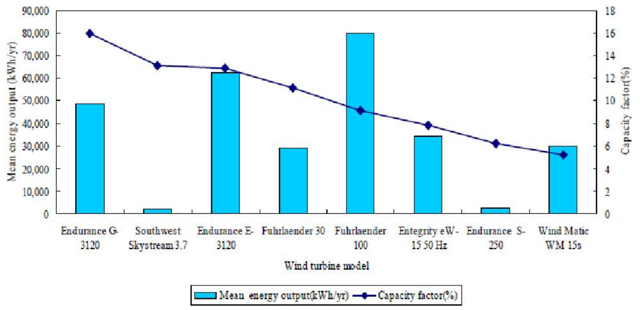

Figure 8 : Energy output and capacity factor for the selected wind turbines

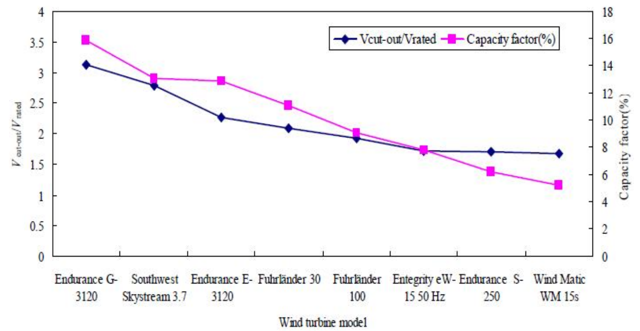

Figure 9 : Values of C_f and $V_{cut-out}/V_{rated}$ for the wind turbines selected for Urumqi

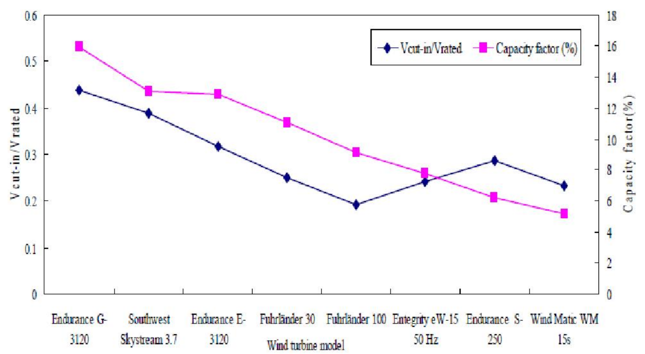

Figure 10 : Values of C_f and V_{cut-in}/V_{rated} for the wind turbines selected for Urumqi

characteristics) would be best suited for this site[23].

The capacity factors for these wind turbines at this location range from 5.2% to 15.9%. The Endurance G-3120 has the highest capacity factor (15.9% at 30.5 m hub height). The Wind Matic WM 15s has the lowest(5.2% at 24.4 m hub height).

Figure 9 shows the capacity factor, C_f and $V_{cut-out}/V_{rated}$ for the selected wind turbines, indicating that C_f increases as $V_{cut-out}/V_{rated}$ increases. Figure 10 shows that C_f also basically increases as V_{cut-in}/V_{rated} increases. In other words, a wind turbine possesses a higher capacity factor than other wind turbines if it has higher V_{cut-in}/V_{rated} and $V_{cut-out}/V_{rated}$ ratios[28].

CONCLUSIONS

In this study, the wind energy resource in Urumqi at 10, 50,100,150 and 300m above the ground, along with the wind turbine characteristics, were analyzed based on the 10-year monthly mean wind speed data, using a two-parameter Weibull distribution. It is concluded that:

- The highest monthly mean wind speeds at these different heights occur in November; the lowest occur in June.
- The long-term monthly mean wind speeds are higher from September to May than in other months.
- The Urumqi site possesses poor wind characteristics because of the low monthly and mean wind speed and wind power density over a whole year.
- The site is not suitable for large-scale electric wind generation, but small-scale wind turbines or wind-hybrid power systems might be a suitable option for the supply of power for lighting, electric fans, chargers and so on.
- The highest wind speeds reached were 12,15,17,18 and 20 m/s in the course of a year at heights of 10,50,100,150 and 300m, respectively.
- The wind speed remains at or below 3.5 m/s for about 52.6%, 37.6%, 32.2%, 29.3% and 24.6% of the year at heights of 10,50,100,150 and 300 m, respectively.
- The highest and lowest values of *c* (6.732m/s and 4.07 m/s) were observed at heights of 300m and 10m, respectively, and the values of the shape parameter (1.926 and 1.927) were found to be almost identical in Urumqi.
- The mean energy outputs for the wind turbines selected for Urumqi ranged from 2,062 to 79,968 kWh/yr.
- The capacity factors for the wind turbines selected for Urumqi ranged from 5.2% to 15.9%.

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