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Wind characteristic analysis based on Weibull distribution of Al-Salman site, Iraq

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Abstract

This paper aims to analyze the characteristic of wind speed data in Al-Salman site — Iraq using Weibull distribution. Maximum likelihood method (MLM) was used to find out two essential Weibull parameters. The best wind distribution was described by using probability density function and cumulative distribution function. Based on Weibull parameters, an analysis is carried out for various wind turbine hub heights. The characteristics of wind wave for this site are regular, uniform, and close to Rayleigh function. Furthermore, the shape factor and scale factor have fluctuated from 1.8 to 3.2 and from 5.93 m/s to 8.3 m/s for different period respectively. It was found that, at 50 m height, the mean wind speed is 5.93m/s, mean power density for this site is 219 W/m and that almost 50% of the wind speed was above 5 m/s within the total hours per annum. As consequence, this site has a potential wind power to erect small wind turbines for electricity production. Wind turbine model was proposed relying on capacity factor.

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Keywords: Weibull distribution; Maximum likelihood method; Wind turbine

1. Introduction

Throughout the world, policy support and investment in renewable energy have continued to concentrate principally on the electricity sector. As a result, renewables have been considered for a growth ranking portion of electric generation capacity added globally each year. Wind energy is the least costly type of renewable energy technology, yet it is a massive source and according to some literatures, the total potential for wind energy alone can achieve the electricity world demand by 20 times [1]. Wind energy in Iraq can be divided into three zones, 48% of Iraq has low annual wind speed, 35% has annual wind speed 3.1–4.9 m/s, 8% has relatively high annual wind speed and the residual has calm values [2]. Wind speed (WS) is one of the most crucial characteristics of wind power generation. The way for assessing the potential of wind energy in a selected site is to analyze and explain the

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data collected from the metrological station which is installed at the same of location to ensure the accuracy of the analysis. The data may also be categorized on daily, monthly or yearly bases [3]. Identifying the potential of wind energy is very significant to determine the efficiency of suggested WTs [4]. In wind resource assessment projects, adequate statistical analysis is remarkable to implement the assessment [5]. In this paper, the characteristics analysis of WS will be implemented to assess the wind potential of Al-Salman site based on Weibull distribution.

2. Data acquisition

The wind data are obtained from the metrological mast in Al-Salman site (Al-Muthana Province) in Iraq. The data consist of WS and wind direction (at actual hub height 50 m) for 29 months. Data have been recorded on a 10 min interval, which is considered to be the international standard period for wind measurement. The WS data have been recorded by data logger type (Stylists-101), the wind direction data have been recorded by wind direction vane type (NRG#40C).

3. Weibull probability distribution function & cumulative distribution function

Weibull probability distribution function (abbreviated pdf) is desirable to depict the fluctuation in WS during any time interval using two parameters and it is given by [6];

$$F(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right), k > 0, v > 0, c > 1 \tag{1}$$

where c represents the scale parameter (m/s) and k represents the shape parameter. A credible approximation of the Weibull distribution parameters could be obtained through a simple curve fitting procedure.

Cumulative distribution function is the integration of Weibull pdf. It is the cumulative of relative frequency of each speed interval. The corresponding cumulative probability function of the Weibull distribution is given by [7];

$$F(v) = \int_0^v f(v)\, dv = 1 - \exp - \left(\frac{v}{c}\right)^{k} \tag{2}$$

Shape parameter gives the description of wind behavior according to its value; the wind speed is very weak as the k value is small. On the other hand, the high value of (k) indicates that the site undergoes even number of high and low wind speed. Most sites have typically wind distribution at k = 2.

4. Estimating and fitting Weibull distribution

The maximum likelihood method (MLM) is used to fit a Weibull distribution to a measured WS distribution [8]. This process uses the following equation to calculate, in an iterative form, the Weibull k parameter:

$$k = \left[\frac{\sum_{i=1}^{N} v_i^k \ln(v_i)}{\sum_{i=1}^{N} v_i^k} - \frac{\sum_{i=1}^{N} \ln(v_i)}{N}\right]^{-1} \tag{3}$$

where v_i is the WS at time step i, and N is the number of time steps.

Once the shape parameter k has been defined, the next equation provides the value of the scale parameter c:

$$c = \left(\frac{\sum_{i=1}^{N} v_i^k}{N}\right)^{\frac{1}{k}} \tag{4}$$

Eqs. (3) and (4) gives the Weibull parameters at actual height (50) m, since these parameters should be determined at the hub height of WT, so it can be extrapolated according to Eqs. (5)–(7) [9];

$$c_2 = c_1 \left(\frac{z_2}{z_1}\right)^{n} \tag{5}$$

$$k_2 = k_1 \frac{1 - 0.088 \ln\left(\frac{z_1}{10}\right)}{1 - 0.088 \ln\left(\frac{z_2}{10}\right)} \tag{6}$$

$$n = \frac{0.37 - 0.088 \ln c_1}{1 - 0.088 \ln \frac{z_2}{10}} \tag{7}$$

The capacity of wind resources can be determined by wind power density *PDw* in a specified place. There are several approaches to estimate the PDw [10,11], monthly or annual PDw per unit area of a site based on a Weibull probability density function can be expressed as follows, [12]:

$$PDw = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{8}$$

where ρ is the air density ($\rho = 1.225$ kg/m^3) at standard atmosphere at sea level, Γ is the gamma function.

Based Weibull parameters, average WS can be expressed as [13];

$$\overline{v} = c\Gamma\left(1 + \frac{1}{k}\right) \tag{9}$$

$\overline{v}$ is the average WS.

Substituting the scale factor in above equation by the formula presented in Eq. (8), yields, [14]:

$$\overline{PDw} = \overline{v^3}\rho\Gamma(1 + 3/k)/2[\Gamma(1 + 1/k)]^3 \tag{10}$$

Wind turbines (WTs) have distinct hub heights, so the power law t can be used as follows to determine the WS at a hub height of the WTs;

$$v_2 = v_1\left(\frac{z_2}{z_1}\right)^{\alpha} \tag{11}$$

where v_2 is the WS at height z_2 (in meters), and v_1 is the known WS at a reference height z_1.

The exponent (α), one that varies depending on the stabilization of an atmosphere. It is commonly used to be constant (0.14) because the variations between both levels (z1, z2), is not usually great that can cause significant deviations in estimations. The standard deviation of the WS records in the data set can be calculated using the following formula

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(v_i - \overline{v})^2}{N - 1}} \tag{12}$$

Wind turbine performance placed in a site can be evaluated based on the amount of mean power output ($P_{\mathrm{e,avg}}$) and capacity factor C_{F}. The capacity factor C_{F} is the ratio of the mean power output to the rated electrical power (P_{rated}) of the selected wind turbine model. Based on Weibull distribution parameters, the mean power output ($P_{\mathrm{e,avg}}$) and capacity factor C_{F} of wind the turbine is determined using the Eqs. (13) and (14);

$$P_{e,avg} = P_{rated}\frac{e^{-\left(\frac{v_{in}}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_{in}}{c}\right)^k} - e^{-\left(\frac{v_{out}}{c}\right)^k} \tag{13}$$

$$C_F = P_{e,avg}/P_{rated} \tag{14}$$

5. Site description

Al-Salman site in Al-Muthana Province is located at the south-west of Iraq with an elevation of 215 m. The coordinates of the site are (44 34.382 longitudes, 30 34.248 latitudes).

6. Results and discussion

From the obtained raw data, the seasonal and daily WS profiles at the altitude of (50 m) are expressed and displayed in Fig. 1;

The left graph displays the average WS in each month of the year. The right graph presents the average WS variation during one day of the day It is clear that summer months have a high WS contrasted with other months. To determine the average daily profile of a set of raw data, the average value of all of the WS data that were recorded within the hour of 12:00 am to 1:00 am, then all those that were recorded within the hour of 1:00 am to 2:00 am, and so on for each of the 24 h of the day were represented as shown in Fig. 2;

Most of months have high WS within the hour of 6:00 am to 18:00 pm. Fig. 3, display the average daily profile of *PDw* which is drawn as the same procedure of the average daily profile of WS;

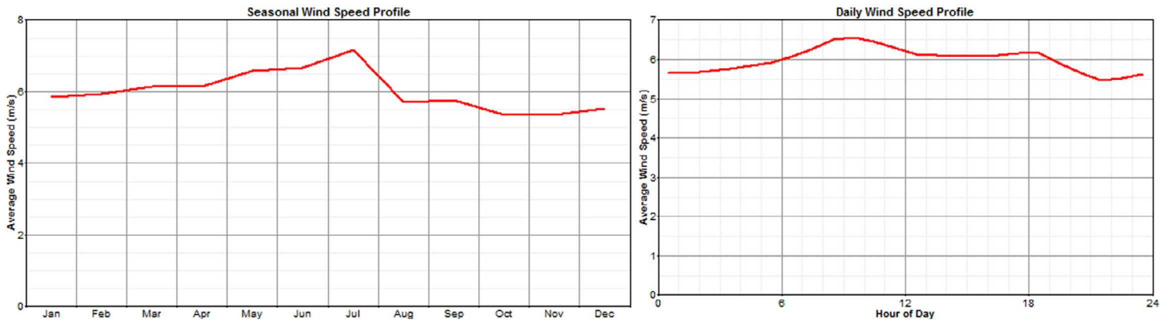

Fig. 1. Seasonal and daily WS profiles.

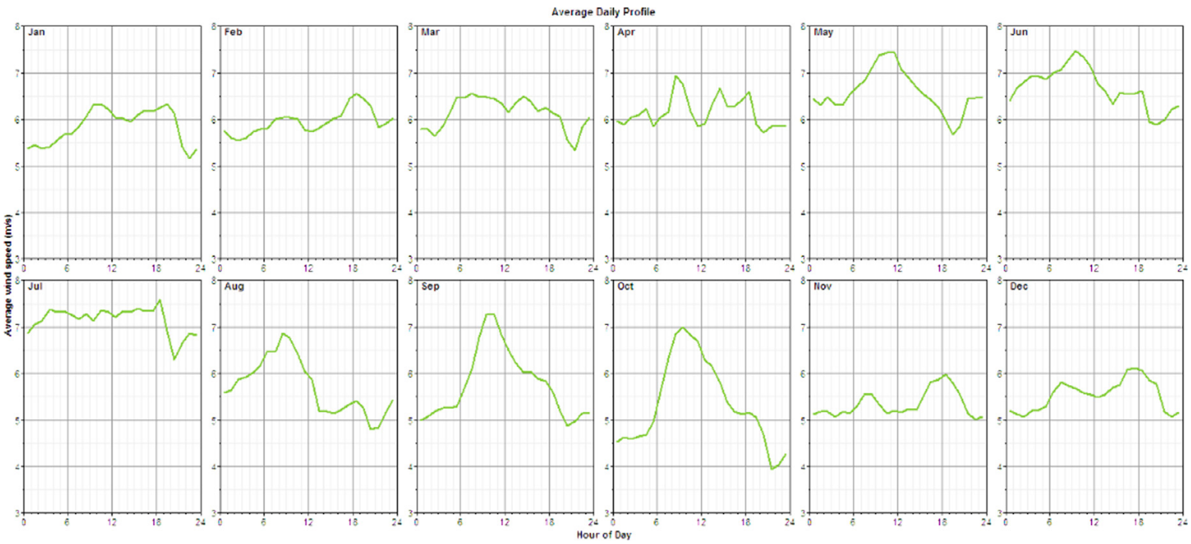

Fig. 2. Average daily profile of WS.

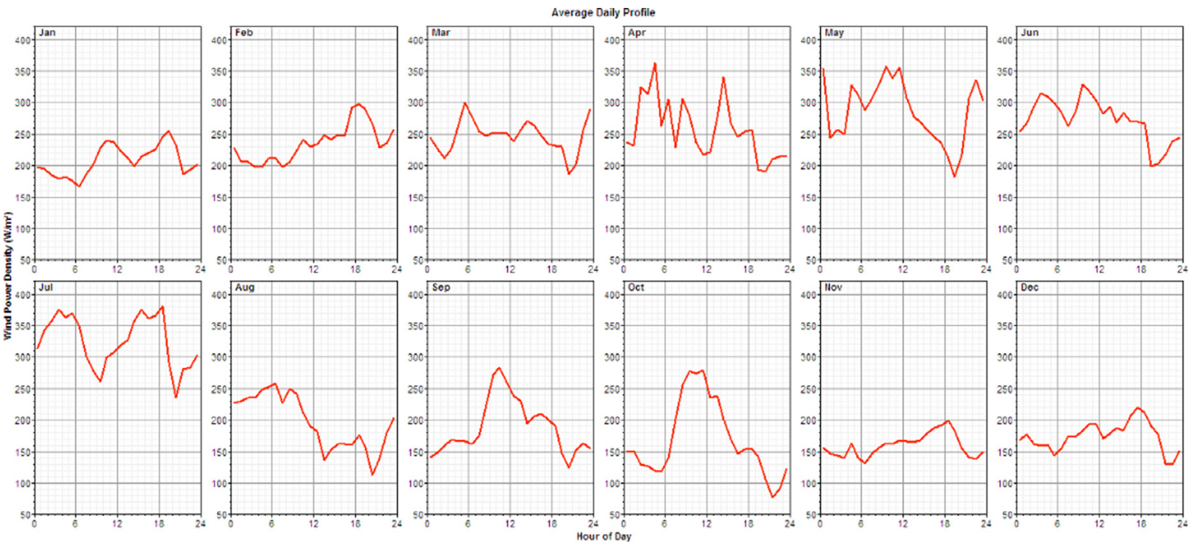

Fig. 3. Average daily profile of PDw.

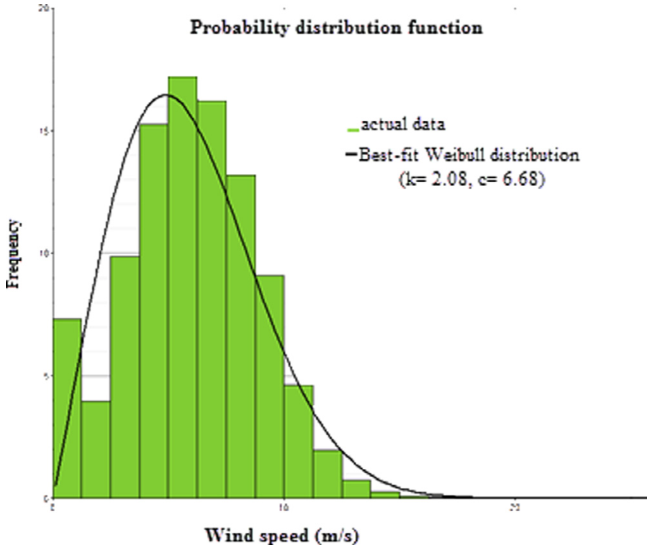

Fig. 4. Monthly average WS profile.

By using MLM, the best-fit Weibull distribution for the available data is presented in Fig. 4; the graph shows the frequency with which the variable falls within different bins;

It is clear that the WS falls within the range of 0 to 1 m/s about 7% of the time,1 to 2 m/s about 4% of the time, 2 to 3 m/s about 10% of the time, 3 to 4 m/s about 15% of the time, 4 to 5 m/s about 17% of the time and so on. The Weibull parameters (c, k) given in Eqs. (3) and (4) are 6.69 m/s and 2.08 at 50 m height sequentially. The average value of PDw is (219.4 W/m^2), which is described as a marginal class and classified as (class II). The monthly wind rose aids in explaining the variability in the wind direction every month as shown in Fig. 5.

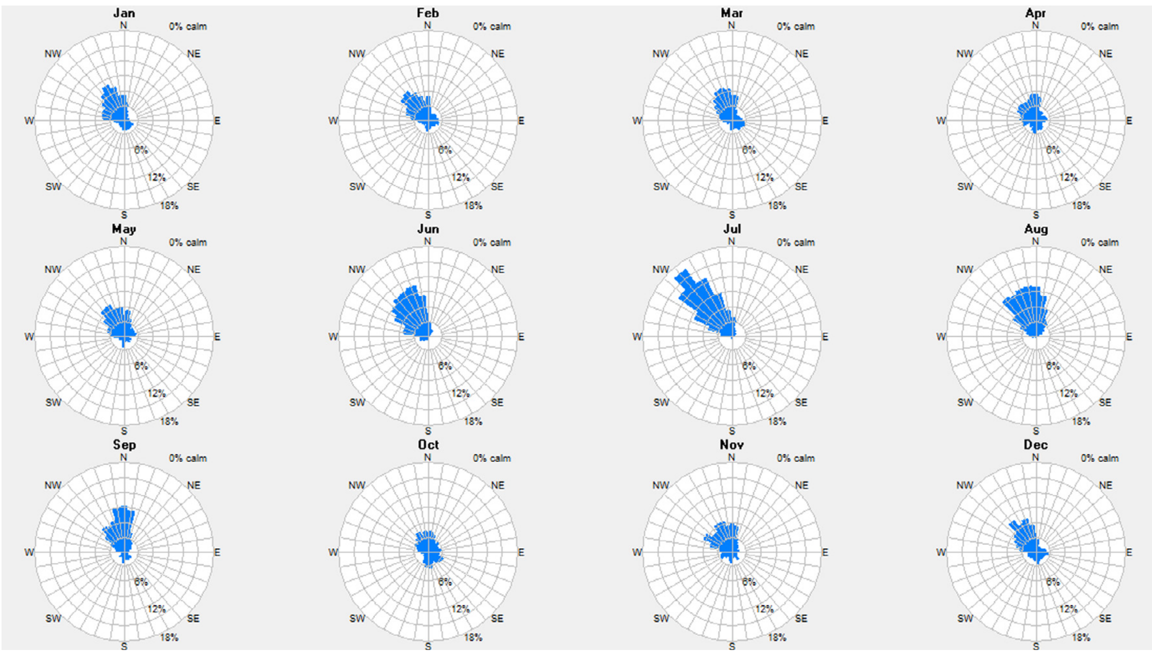

Fig. 5. Wind rose.

Simply, it could be inferred that the main prevailing wind direction at the study area is north-western, while the dominant wind direction in months March, April range between north-west to north. The cumulative distribution function in Fig. 6 depicts the probability that a variable is fewer than or similar to a distinct value and shows that approximately 90% of the recorded WS is below (10 m/s).

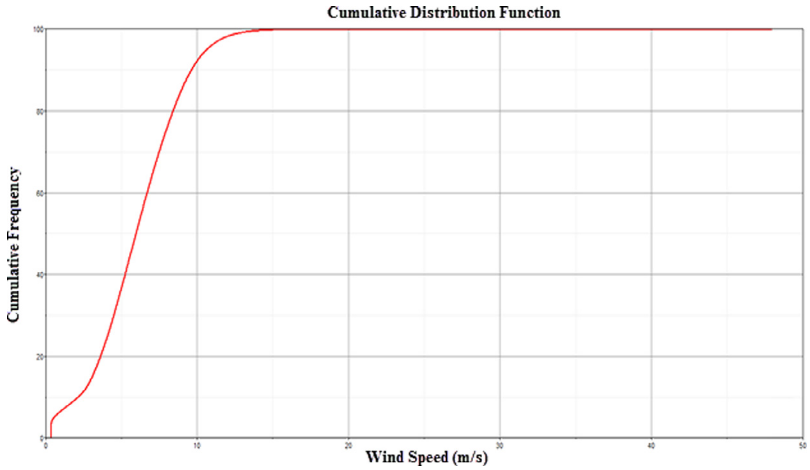

Fig. 6. The cumulative distribution function.

Annual statistics for WS obtained raw data is shown in a Table 1.

Table 1. Annual WS, SD, k and c.

Year	Records	Recovery rate %	Mean m/s	SD m/s	Weibull K	Weibull C
2014	5 760	100	5,441	2.516	2.154	6.064
2015	52 560	100	6.171	2.946	2.098	6.894
2016	52 560	100	5.908	2.842	2.080	6.600
2017	10 111	100	5.784	2.811	2.025	6.445
All data	121 135	100	5.989	2.877	2.081	6.690

The average value of standard deviation (SD) is (2.8) m/s, so that the ratio of the SD to the mean speed is found to be (0.47) and this reflects unsteadiness of the wind in the site. Annual statistics for PDw reflects raw data and is shown in a Table 2.

Table 2. Annual *PDw* and SD.

Year	Records	Recovery rate %	Mean W/m^2	SD W/m^2
2014	5 760	100	157.8	181.7
2015	52 560	100	239	339.5
2016	52 560	100	210.8	268.1
2017	10 111	100	197.7	228.4
All data	121 135	100	219.4	296

Table 3, resumes the monthly statistics for all recorded data that include the mean WS, standard deviation (SD), Weibull parameters (k, c).

Table 4, shows the monthly statistics for all recorded data. Mean *PDw*, (SD), k, and c are displayed.

According to the measured of WS and *PDw* at WT hub heights, it can be estimated that the suitable WT could be erected in this site depending on the annual energy output and capacity factor. Many of the horizontal axial wind turbines HAWT are tested, the power curve for each selected WT is illustrated in Table 5.

The hub height for each WT was determined according to Eq. (9), the results of the comparison between the selected WTs, the annual energy output, and capacity factor are shown in the table Table 5.

Table 3. Monthly statistics for all recorded data for a site (WS)

Year	Month	Mean WS (m/s)	SD (m/s)	Weibull K	Weibull c (m/s)
2014	Nov.	5.313	2.334	2.366	5.949
2014	Dec.	5.478	2.565	2.102	6.097
2015	Jan.	5.757	2.961	1.985	6.420
2015	Feb.	6.234	3.063	2.041	6.971
2015	Mar.	5.980	3.015	1.964	6.675
2015	Apr.	6.548	3.194	2.067	7.328
2015	May	6.495	2.962	2.219	7.269
2015	Jun.	7.252	2.739	2.781	8.067
2015	Jul.	7.767	2.609	3.277	8.594
2015	Aug.	6.625	2.810	2.402	7.378
2015	Sep.	5.532	2.754	1.970	6.164
2015	Oct.	5.139	2.735	1.845	5.727
2015	Nov.	5.148	2.567	1.987	5.746
2015	Dec.	5.567	2.680	2.065	6.213
2016	Jan.	5.861	2.841	2.078	6.557
2016	Feb.	5.898	3.135	1.844	6.572
2016	Mar.	6.524	3.038	2.158	7.286
2016	Apr.	5.759	2.974	1.918	6.429
2016	May	6.676	2.921	2.345	7.466
2016	Jun.	6.106	2.603	2.414	6.819
2016	Jul.	6.546	2.928	2.296	7.320
2016	Aug.	4.807	2.517	1.868	5.357
2016	Sep.	6.009	2.511	2.475	6.700
2016	Oct.	5.574	2.671	2.102	6.233
2016	Nov.	5.561	2.702	2.018	6.191
2016	Dec.	5.568	2.652	2.082	6.207
2017	Jan.	5.942	2.619	2.307	6.643
2017	Feb.	5.724	3.013	1.801	6.345
2017	Mar.	5.498	2.776	1.957	6.134
All data		5.989	2.875	2.083	6.689

Table 4. Monthly statistics for all recorded data for a site (*PDw*).

Year	Month	Mean PDw (W/m^2)	SD (W/m^2)
2014	Nov.	141.2	146.3
2014	Dec.	162.6	190.4
2015	Jan.	201.3	263.7
2015	Feb.	253.8	325.9
2015	Mar.	230.1	314.4
2015	Apr.	294.0	424.7
2015	May	278.0	647.6
2015	Jun.	324.4	332.6
2015	Jul.	370.1	294.1
2015	Aug.	265.4	274.9
2015	Sep.	174.7	186.0
2015	Oct.	154.7	230.7
2015	Nov.	144.6	191.2
2015	Dec.	177.3	231.0
2016	Jan.	209.4	272.9
2016	Feb.	232.3	323.5
2016	Mar.	275.9	341.3
2016	Apr.	211.4	339.4
2016	May	282.6	348.5
2016	Jun.	210.5	234.4

(*continued on next page*)

Table 4 (*continued*).

Year	Month	Mean PDw (W/m^2)	SD (W/m^2)
2016	Jul.	266.8	277.5
2016	Aug.	120.9	141.0
2016	Sep.	195.7	194.3
2016	Oct.	176.8	213.7
2016	Nov.	173.8	183.1
2016	Dec.	172.8	193.2
2017	Jan.	199.0	227.6
2017	Feb.	204.6	234.7
2017	Mar.	176.6	213.2
All data		219.4	296.0

Table 5. Selected different HAWT, annual energy output, and capacity factors.

WT type	Installed capacity	Hub height (m)	WS (hub height)	V cut-in	V rated	V cut-off	C (z_2)	K (z_2)	CF	$P_{e,ave}$ kW	Energy kWh (no losses)
Gamesa G52	850	55	7.6	4	16	25	6.80	2.10	13%	107.0	937,294
Enercon E33	330	50	7.5	2.5	12.5	34	6.70	2.00	25%	82.9	726,047
Suzlon S60	1000	65	7.78	3	13	25	7.10	2.10	24%	241.5	2,115,434
Siemens SWT 1.3–62	1300	68	7.83	3	14	22	7.20	2.10	22%	279.7	2,450,383
Nordex N43	600	60	7.7	2.5	15	25	7.00	2.10	18%	109.6	960,176
Vestas V42	500	50	7.5	3	14.5	25	6.70	2.00	18%	90.2	790,459
Aeronautica 47–750	750	65	7.78	3.5	14.5	25	7.10	2.10	18%	138.6	1,214,252

According to the results grouped in this table, it can be concluded that Enercon E33 have the highest capacity factor among these wind turbines.

7. Conclusion

A wind characteristics analysis for Al-Salman site in Iraq is conducted using Weibull distribution. The seasonal and daily wind speed profiles were drawn and wind speed was found to be relatively 5.9 m/s. Maximum likelihood method (MLM) was used to determine Weibull parameters that described the characteristics of wind wave. Shape parameter for the selected site is close to Rayleigh wave which indicates that the wind behavior is regular and uniform. From the results, it can be concluded that Weibull probability density function and actual data have closely matching curves and more than 50% of the wind speed was above 5 m/s within the total hours per annum. Therefore, this site has adequate power to erect small wind turbines for electricity production. However, the shape factor and scale factor have fluctuated from 1.8 to 3.2 and from 5.93 m/s to 8.3 m/s for different period respectively.

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