applied system innovation

MDPI

Article

Estimating Weibull Parameters Using Mabchour's Method (MMab) for Wind Power at RAWA City, Iraq

Amani I. Altmimi [1], Safaa J. Al-Swaiedi [2] and Oday Ibraheem Abdullah [3,4,5,*]

[1] College of Energy and Environmental Sciences, Al-Karkh University of Science, Baghdad 10003, Iraq; dr.amani_altmimi@kus.edu.iq
[2] Directorate of Education in Al-Karkh Third, Iraqi Ministry of Education, Baghdad 10003, Iraq; Safaa.jasim1992@gmail.com
[3] Department of Energy Engineering, College of Engineering, University of Baghdad, Baghdad 10071, Iraq
[4] Department of Mechanics, Al-Farabi Kazakh National University, Almaty 050040, Kazakhstan
[5] System Technologies and Engineering Design Methodology, Hamburg University of Technology, 21073 Hamburg, Germany
* Correspondence: oday.abdullah@tuhh.de

Abstract: Wind power is one of the most important sources of renewable energy. In this research paper, we developed an approach to select the optimum site among four different locations in Iraq (Talafar, Nasiriyah, Baghdad and RAWA) according to wind power density. Based on the optimization process, it was found that the RAWA city is the optimal site. We adopted Mabchour's Method (MMab) to estimate the Weibull distribution parameters (c, k) for RAWA city at two heights (10 m and 50 m) for the period (2017–2019). It was found that the Mabchour technique (MMab) produced accurate results with minimum consumed time and effort. This was because the values of k and c were close to each other. Additionally, the coefficient values of the results of the Weibull measurements were very close to the average wind speeds that we measured. The values of the correlation coefficients between the Weibull scale parameters and the form were calculated and were equal to R^2 = 0.9971. The minimum value of the coefficient of variation (COV) for turbulence intensity was found to be 26% in July 2018, when the wind speeds reached their maximum. The highest error of wind power density between measured data (P_M) and Weibull distribution (P_W) was found to be 4.48%, at a height of 50 m.

Keywords: wind energy; wind power density; Weibull distribution; Mabchour's Method (MMab)

check for updates

Citation: Altmimi, A.I.; Al-Swaiedi, S.J.; Abdullah, O.I. Estimating Weibull Parameters Using Mabchour's Method (MMab) for Wind Power at RAWA City, Iraq. *Appl. Syst. Innov.* **2022**, *5*, 14. https://doi.org/10.3390/asi5010014

Academic Editor: Emmanuel Karapidakis

Received: 1 December 2021
Accepted: 18 January 2022
Published: 22 January 2022

1. Introduction

The fast growth of energy technology and the increasing use of fossil energy has led to a dramatic increase in the pollution of the environment. Recently, there has been a strong trend towards using green energy, where the most common forms of renewable energy generation are solar photovoltaic (PV), wind and hydro. In addition, there are many other types of renewable energy such as tidal and biomass, etc. These forms of renewable energy use energy resources that are renewed sustainably and at a faster rate [1]. Wind is one of the most available and fast-growing energy sources in the world [2]. The Weibull distribution is a continuous distribution and is commonly used in failure models which have three parameters. This method is important in the field of reliability and life testing and it also used for drawing and interpreting the behavior and distribution of wind [3]. There are several methods for calculating Weibull parameters [4]. Many studies have demonstrated that finding the optimal statistical distribution can represent change in wind gusts. Using this method, two parameters of the Weibull distribution (shape and scale) are calculated, from which the wind speed frequency curve for the site can be drawn [5]. In most studies concerning wind energy, the mentioned methods have been used to compare between different periods of time in many different ways [6].

The main objectives of this research paper are to find the most optimal site among different promising locations in Iraq, and in the next step apply the Mabshour method (MMab method) to calculate the error in estimations of wind power density by using the Weibull distribution function (P_W), compared with the measured data (P_M). The results present sequential wind speed data for 10 min, measured at different heights of 10 m and 50 m in the city of RAWA (optimal site), located in western Iraq.

2. Methodology

2.1. Mean of Wind Speed

The mean of wind speed is one of the important parameters used to estimate the potential of wind energy for any given location [7]. The mean of wind speed for a given location can be determined as the following:

$$v = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{1}$$

where v is mean wind speed, n is the number of wind data, and v_i is measured wind speed.

2.2. Standard Deviation of Wind Speed

Standard deviation is defined as the square root of variance. Small values indicate that most wind speeds are close to the mean. That is, mean is an excellent convergence in the case of average wind speed, where it is appropriate for energy production. The large values indicate that wind speeds spread widely [7]. The standard deviation can be expressed by the following equation:

$$\sigma = \sqrt{Variance} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(v_i - v)^2}. \tag{2}$$

2.3. Coefficient of Variation (COV)

The *COV* is defined as the ratio between standard deviation and mean wind speed. It demonstrates the wind speed mutability, and it can be expressed as [8]:

$$COV(\%) = \frac{\sigma}{v} \times 100. \tag{3}$$

where the wind changes exponentially with the height. The law of the logarithmic equation, which is used to determine the speed of the wind at different heights, can be written as following [9]:

$$v_2(z_2) = v_1(z_1)\left(\frac{z_2}{z_1}\right)^{\alpha}. \tag{4}$$

where v_1 and v_2 are the wind speeds at z_1 and z_2, respectively. z_1 represents the known altitude with the wind speed v_1, which often occurs at the standard altitude, which is equal to 10 m. While α is the surface friction coefficient.

2.4. Weibull Distribution

Wind speed is not constant and is continuously changing. Hence, turbine design requires full data and knowledge concerning how often the wind blows strongly. This is considered an essential step to predict the energy production of wind turbines. In order to analyze the wind data, wind speed data are sorted into categories and then the relationship between the percentage of repetitions distribution and the wind speed is determined. The distribution appears as a curve and the peak of the curve represents the most common wind speed. Weibull distribution, which is the most common model in statistics and probability laws, can be used for many natural phenomena. The Weibull distribution includes more than one probability distribution function and a two-parameter function, which are the basis for wind energy applications and wind speed data analysis [4]. This function can be expressed by the following equation:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left(-\left(\frac{v}{c}\right)^{k}\right). \tag{5}$$

where: $f(v) \geq 0, v \geq 0; k > 0, c > 0$.
$f(v)$: Function probability of wind speed v.
k: The shape of the parameter, which indicates the fluctuation or stability of the wind speed v, which is a dimensionless parameter.
c: Scale parameter (m/s), which is associated with the mean wind speed.

There are different methods used to estimate the dimensionless scale and shape parameters of the Weibull distribution function, such as Energy Pattern Factor method, Probability Plot method, Modified Moment method, Maximum Likelihood method, Hazard Plot method and Mabchour's method (MMab). The proposed method by Mabchour (1999) was selected in the assessment of wind energy potential k and c as [10]:

$$k = 1 + (0.483 \times (v-2))^{0.51} \tag{6}$$

$$c = \frac{v}{\Gamma(1+1/k)} \tag{7}$$

2.5. Wind Power Density

It can be considered that wind power density is the criterion to assess wind energy at a specific site. Figure 1 presents the categories of the wind power density for the standard heights. For a specified site, the mean of available wind power density (P, w/m^2) is given as:

$$\langle P \rangle = \frac{1}{2}\rho\left\langle v^3\right\rangle \tag{8}$$

where ρ is the air density in kg/m^3. Where, the air density is other important factor affected the extracting energy from wind, where it can be found based on the following formula:

$$\rho = \frac{p}{RT} \tag{9}$$

where, p, R and T are the pressure of the air (locally), gas constant that equal to 287 J/kg-K for air, and temperate of the air (locally). In case there is no motion in the vertical axis, the equation of hydrostatic can be written as follows:

$$dp = -\rho\, gdz \tag{10}$$

g: acceleration of gravity. The following formula can be obtained when Combining Equations (9) and (10):

$$\frac{dp}{p} = -\frac{g}{R\,T}dz \tag{11}$$

The equation of the acceleration of gravity with height is:

$$g = g_o\left(1 - \frac{4z}{D}\right) \tag{12}$$

g_o: gravitational acceleration at ground level.
D: earth's diameter.

Where, it can be neglected the effect of height ($D > 4$z) and temperature has inverse relation with height. Then, it can be supposed the following,

$$\frac{dT}{dz} = c \tag{13}$$

So, the following formula can be obtained:

$$p = p_o \left(\frac{T}{T_o} \right)^{-g/cR} \quad (14)$$

where, p_o: the ground's air pressure; T_o: the ground's air temperature.

The following formula can be obtained for air density by combining Equations (14) and (9),

$$\rho = \rho_o \left(\frac{T}{T_o} \right)^{-(\frac{g}{cR}+1)} = \rho_o \left(1 + \frac{cz}{T_o} \right)^{-(\frac{g}{cR}+1)} \quad (15)$$

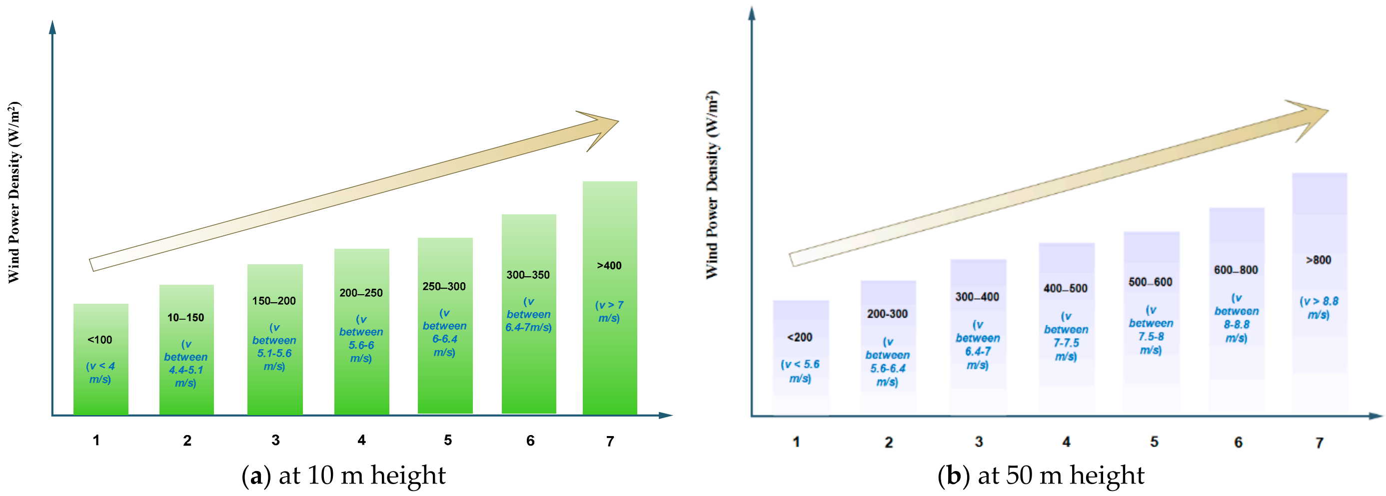

Figure 1. The categories of wind power density, adopted from Ref. [11].

There is another equation to calculate the air density used by Tizgui et al. [12], which is:

$$\rho = \rho_0 - 1.194 \times 10^{-4} \times H_m \quad (16)$$

where, H_m is the elevation of site (m) and ρ_0 is the air density at sea level. A small difference was found between the values of air density obtained by Equations (15) and (16).

It can be noticed that the available wind power density increases with the mean cube of wind speed [10]. There are two methods to calculate the mean cube of wind speeds. The first one is the direct equation. It is given by Equation (10) and the second one by using the distribution models, (Weibull distribution) as represented in Equation (18) [13].

$$\left\langle v^3 \right\rangle = \frac{1}{n} \sum_{i=1}^{n} v_i^3 \quad (17)$$

$$< v^3 >= c^3 \Gamma \left(1 + \frac{3}{k} \right) \quad (18)$$

where n is the numbers of data.

2.6. Error in Estimating Wind Power Density

Wind power density is calculated by measured data, where wind power density can be estimated using the function of Weibull distribution, expressed in the following equations [4,13]:

$$P_M = \frac{1}{2} \rho \frac{1}{N} \sum_{1=3}^{N} v_i^3 \quad (19)$$

$$P_W = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (20)$$

The error in the estimation of wind power density by function of the Weibull distribution compared with the measured data can be expressed as [13]:

$$Error\% = 100 \times \left(\frac{P_W - P_M}{P_M}\right) \quad (21)$$

Figure 2 shows the details of the developed approach used in this research paper to analyze the wind in different sites of Iraq, in order to find the optimal site and analyze the wind energy at this site.

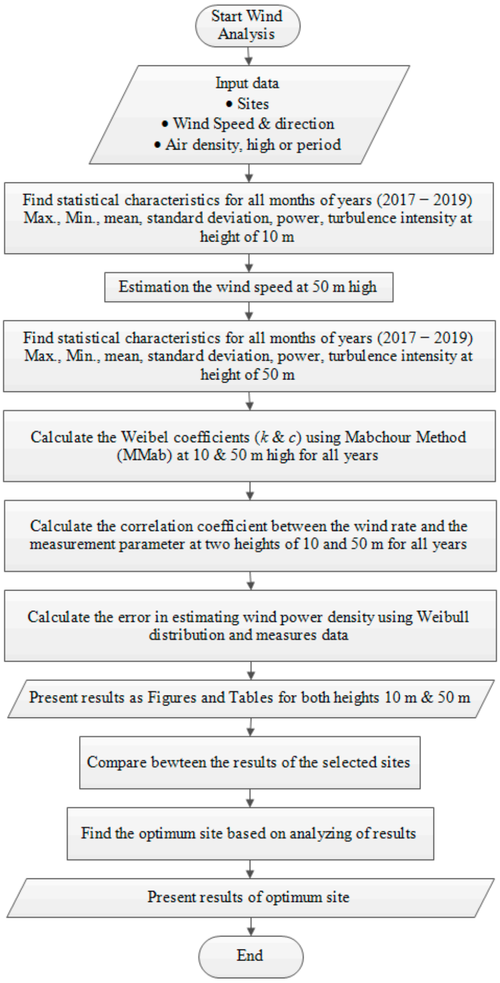

Figure 2. The flowchart of the developed approach to analyze the wind in Iraq.

2.7. Case Study (Selection the Optimal Site)

Statistical characteristics were used for four sites located in different directions in Iraq (North, South, East and West), specifically Tal Afar, Nasiriyah, Baghdad and RAWA, as shown in Table 1. According to the deep analysis of wind data and other variables affecting the wind speed for each site, it was found that the RAWA site has the highest wind speed in addition to the open areas, and less turbulence compared with other sites. The site of RAWA is located in the Anbar Governorate in western Iraq, and is located on the northern bank of the river, at the source of about 20 km from the much larger city of Anah. The location is displayed on the map of Iraq, as shown in Figure 3. Figure 4 illustrates the wind height diagram for RAWA city.

Table 1. Annual statistical characteristics of study area (2017, 2018, and 2019) at 10 m.

Site	Lat. (°)	Lon. (°)	Elev. (m)	T (°C)	RH (%)	v (m/s)
Talafar	36.35	42.35	348	20.44	42.05	3.15
Nasiriyah	30.84	46.06	6	27.24	44.31	3.91
Baghdad	33.44	44.31	35	25.29	36.1	3.41
RAWA	34.46	41.92	160	21.4	40.47	4.14

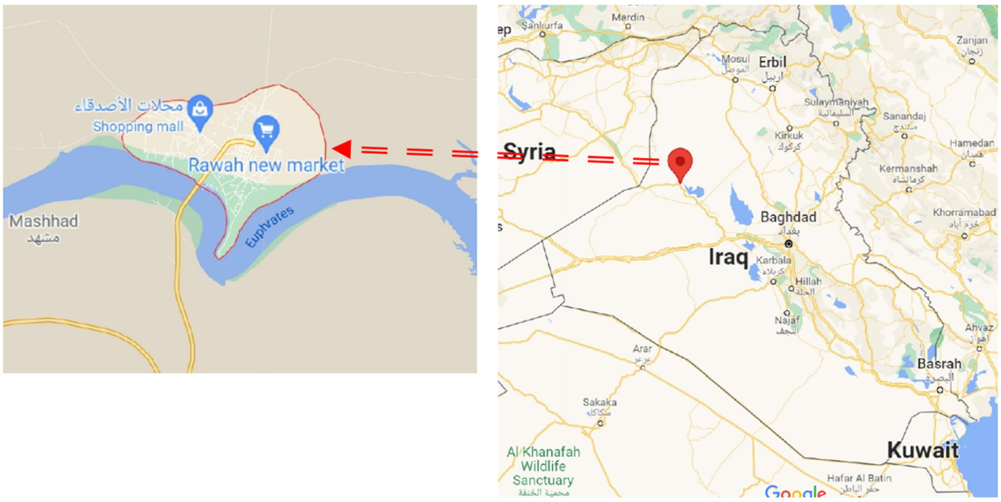

Figure 3. Location of study area (RAWA city).

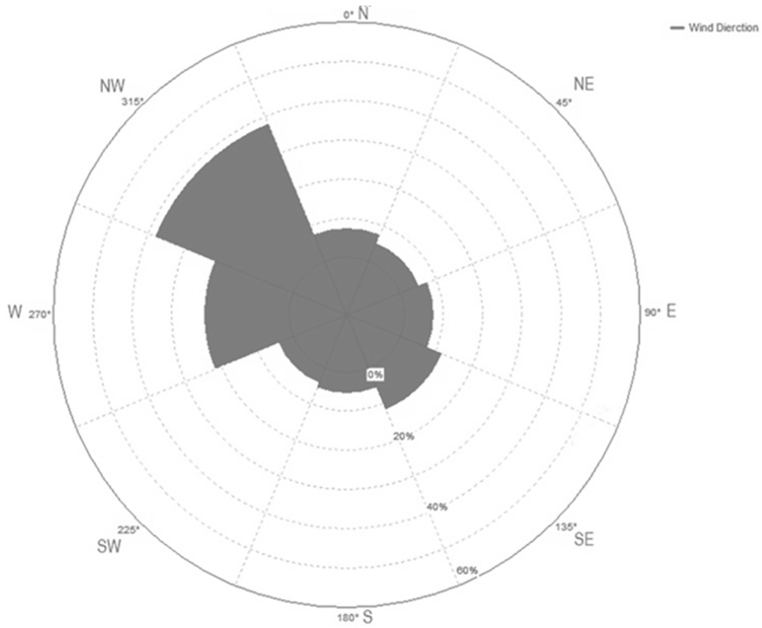

Figure 4. The wind height diagram for RAWA city.

3. Results and Discussions

In this work, the wind data and weather variables for Rawa city, Iraq, were collected and analyzed to explore the accuracy and the time consumed using Mabchour's method (MMab) of Weibull distribution parameters. Most data of this analysis were measured hourly, monthly and annually, based on MERRA-2 meteorological [14].

The accuracy of the results extracted by (MMab) was verified by comparing the results of the Whipple transactions extracted from the site data (2017) at two heights (10 m and

50 m) with the results obtained using the (Weibull parameter estimates) formula, using Matlab software, as shown in Table 2. It was found that the results are very close, and this indicates the accuracy of the results of the (MMab).

Table 2. The Weibull parameters by MATLAB, R^2, *Pw* for RAWA city at 10 m and 50 m height, 2017.

Month	H = 10 m				H = 50 m			
	c (m/s)	Diff%	k	Diff%	c (m/s)	Diff%	k	Diff%
Jan.	3.38	2.45	2.08	1.65	4.247	1.96	1.983	1.18
Feb.	3.45	2.09	1.85	2.37	4.268	2.97	1.749	1.89
Mar.	3.99	2.46	2.2	1.82	5.199	2.25	2.295	1.80
Apr.	4.3	0.99	1.92	1.23	5.370	1.08	1.809	1.74
May	5.2	1.	2.74	1.70	6.472	1.43	2.590	2.37
Jun.	5.53	2.52	3.3	1.93	6.981	1.56	3.218	1.63
Jul.	6.1	1.27	4.09	1.56	7.655	0.88	4.074	2.04
Aug.	4.98	1.87	3.65	2.19	6.297	0.74	3.690	1.12
Sept.	4.17	2.59	2.27	0.70	5.219	2.46	2.193	2.70
Oct.	3.98	2.68	2.45	0.65	5.092	0.41	2.367	2.75
Nov.	3.35	2.44	1.82	0.55	4.158	3.12	1.792	0.99
Dec.	3.87	1.27	2.1	1.20	4.798	2.08	1.890	2.16

Tables 3–8 show the information about the optimal site, based on monthly and annual mean wind speed; several observations in hours, minimum and maximum wind speed, standard deviation, and (*COV*) turbulence intensity at a height of 10 m and 50 m during the period of (2017–2019). The maximum values of hourly mean wind speeds at a hight of 10 m for (2017, 2018 and 2019) were found to be (10.2, 10.2 and 10.5 m/s), respectively, while the minimum values at a height of 10 m were found to be (0.46, 0.43 and 0.27 m/s), respectively, in RAWA city. From Table 3 and Figures 1 and 2, it can be observed that the better results of wind speed appeared at a height of 50 m compared with the height in RAWA city.

Table 3. The monthly of mean wind speed in (m/s) data for selected wind station at 10 m height. (*COV*) coefficient of variation during the period 2017.

Height 10 m	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Yearly Mean
N(h)	744.0	672.0	744.0	720.0	744.0	720.0	744.0	744.0	720.0	744.0	720.0	744.0	8760
v mean (m/s)	3.03	3.11	3.61	3.80	4.64	5.08	5.62	4.58	3.78	3.59	3.02	3.46	3.94
v max. (m/s)	10.96	11.06	9.22	12.57	10.97	9.57	9.22	8.21	8.2	11.95	9.3	11.17	10.2
v min. (m/s)	0.13	0.17	0.23	0.08	0.72	0.99	1.97	0.72	0.12	0.16	0.02	0.27	0.465
σ (m/s)	1.6491	1.86	1.8432	1.94	1.98	1.75	1.56	1.33	1.68	1.66	1.5	1.88	1.724
P_M	17.03	18.5	28.81	33.8	61.18	80.2	108.7	58.84	33.08	28.3	16.8	25.3	42.5
COV (%)	54.31	60.01	51.02	51.08	42.75	34.63	27.84	29.21	44.59	46.36	49.63	54.38	45.48

Table 4. The monthly of mean wind speed in (m/s) data for selected wind station at 50 m height. *(COV)* coefficient of variation during the period 2017.

Height 50 m	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Yearly Mean
N(h)	744.0	672.0	744.0	720.0	744.0	720.0	744.0	744.0	720.0	744.0	720.0	744.0	8760
v mean (m/s)	3.78	3.52	4.5	4.76	5.8	6.34	7.02	5.72	4.72	4.49	3.77	4.3	4.9
v max. (m/s)	13.7	13.82	11.5	15.71	13.71	11.96	11.52	10.26	10.25	14.93	11.6	13.96	12.75
v min. (m/s)	0.16	0	0.28	0.1	0.9	1.2	2.4	0.9	0.15	0.2	0.02	0.33	0.56
σ (m/s)	2.05	2.49	2.3	2.43	2.48	2.19	1.95	1.67	2.1	2.08	1.87	2.35	2.16
P_M	33.08	26.71	56.18	13.48	119.5	156.08	211.8	114.6	64.4	55.4	32.8	49.7	77.8
COV (%)	54.25	70.6	51.02	51.08	42.75	34.63	27.8	29.21	44.58	46.36	49.63	54.4	46.36

Table 5. The monthly of mean wind speed in (m/s) and (*COV*) coefficient of variation at 10 m height during the period 2018.

Height 10 m	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Yearly Mean
N(h)	744.0	672.0	744.0	720.0	744.0	720.0	744.0	744.0	720.0	744.0	720.0	744.0	8760
v mean	3.66	3.02	4.39	3.33	3.86	5.29	6.25	5.58	3.75	4.7	2.91	3.45	4.18
v max.	9.72	7.94	11.06	8.89	13.38	10.57	10.24	9.56	8.05	12.99	10.73	10.11	10.27
v min.	0.15	0.25	0.34	0.03	0.11	0.22	1.62	2	0.15	0.09	0.02	0.18	0.43
σ	1.75	1.67	2.09	1.76	1.91	2.05	1.64	1.68	1.53	2.15	1.95	1.64	1.82
P_M	30.02	16.87	51.82	22.61	35.22	90.67	149.53	106.41	32.29	63.59	25.15	53.27	56.45
COV (%)	47.7	55.30	47.66	52.92	49.37	38.91	26.25	30.17	40.80	45.89	67.04	47.53	45.79

Table 6. The monthly of mean wind speed in (m/s) and (*COV*) coefficient of variation at 50 m height during the period 2018.

Height 50 m	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Yearly Mean
N(h)	744.0	672.0	744.0	720.0	744.0	720.0	744.0	744.0	720.0	744.0	720.0	744.0	8760
v mean	4.58	3.78	5.49	4.15	4.83	6.61	7.82	6.98	4.69	5.87	3.63	4.31	5.25
v max.	12.15	9.92	13.82	11.11	16.72	13.2	12.8	11.95	10.06	16.23	12.78	12.63	12.78
v min.	0.18	0.31	0.42	0.03	0.13	0.27	2.02	2.5	0.18	0.11	0.02	0.22	0.53
σ	2.19	2.09	2.61	2.2	2.36	2.57	2.05	2.1	1.91	2.7	2.41	2.05	2.27
P_M	58.84	33.08	101.34	43.77	69.01	176.89	292.9	208.29	63.18	123.88	29.29	49.03	104.12
COV (%)	47.89	55.34	47.67	53.12	48.84	38.92	26.23	30.17	40.82	45.92	66.58	47.53	45.75

Table 7. The monthly of mean wind speed in (m/s) and (*COV*) coefficient of variation at 10 m height during the period 2019.

Height 10 m	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Yearly Mean
N(h)	744.0	672.0	744.0	720.0	744.0	720.0	744.0	744.0	720.0	744.0	720.0	744.0	8760
v mean	3.91	3.5	4.23	3.88	4.16	4.93	5.54	5.09	4.11	3.04	3.13	3.59	4.09
v max.	13.87	9.76	14.2	10.89	9.93	13.78	9.47	10.17	8.47	8.01	9.45	8.62	10.5
v min.	0.08	0.2	0.17	0.16	0.14	0.2	0.12	0.29	0.77	0.99	0.09	0.09	0.27
σ	2.32	1.88	2.47	1.89	2.04	1.81	1.6	2.17	1.52	1.4	1.57	1.72	1.86
P_M	36.61	26.26	69.06	35.77	44.09	73.39	104.1	126.4	42.52	25.81	18.78	28.33	52.29
COV (%)	59.39	53.75	58.34	48.82	48.97	36.66	28.94	42.79	36.94	45.93	50.28	48.0	46.56

Table 8. The monthly of mean wind speed in (m/s) and (*COV*) coefficient of variation at 50 m height during the period 2019.

Height 50 m	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Yearly Mean
N(h)	744.0	672.0	744.0	720.0	744.0	720.0	744.0	744.0	720.0	744.0	720.0	744.0	8760
v mean	4.89	4.37	5.29	4.85	5.21	6.17	6.92	6.27	5.14	3.81	3.91	4.49	5.11
v max.	17.33	12.2	17.75	13.61	12.41	17.22	11.83	12.71	10.58	10.01	11.81	10.77	13.18
v min.	0.1	0.25	0.21	0.2	0.17	0.25	0.15	0	0.96	0.11	0.11	0.11	0.21
σ	2.9	2.35	3.09	2.36	2.55	2.26	2.0	2.64	1.89	1.75	1.97	2.15	2.33
P_M	71.61	51.11	90.67	69.87	86.62	143.8	202.9	150.9	83.17	33.87	54.75	55.44	91.22
COV (%)	59.27	53.7	58.38	48.82	48.95	36.68	28.93	42.21	36.96	45.95	50.33	48.03	46.52

The results of the statistical analysis of the RAWA site for both heights, 10 m and 50 m, are shown in Tables 9–11, respectively. It was noticed that when using the Mabchour (MMab) method, higher results were obtained, while it was found that values of k and c are close to each other. Furthermore, the values of the Weibell measurement coefficient had values that were very close to the measured values of average wind speed. The value of the correlation coefficient (R^2 = 0.9971) between the Weibull parameters of the scale and the shape parameters were also calculated. In order to obtain high accuracy, the value of the correlation coefficient should be close to 1.

The minimum value of the coefficient of variation (*COV*) for turbulence intensity that occurred during the months of July over three years were (27.84, 26.25 and 28.94), corresponding to (2017, 2018 and 2019), respectively, at 10 m elevation when the wind speeds were at their maximum. While the values of *COV* during the same months but at 50 m high were found to be (27.80, 26.23 and 28.93), corresponding to (2017, 2018 and 2019) respectively, when the wind speeds were at their maximum. The highest error of wind power density between the measured data and Weibull distribution (P_W) was found to be 4.48% at an elevation of 50 m. It is clear from the obtained results that the turbulence is relatively low at a height of 10 m and less at an elevation of 50 m. Therefore, the winds become more stable at a height above ground level, and this fact led to the lower value of *COV*. Figure 5 shows the variation of the mean *COV* per hour during the selected period (2017–2019).

Table 9. The Weibull parameters by Mabchour's Method (MMab), R^2, *Pw* for RAWA city at 10 m and 50 m height, 2017.

Month	H = 10 m				H = 50 m			
	c (m/s)	*k*	R^2	P_W (W/m^2)	*c* (m/s)	*k*	R^2	P_W (W/m^2)
Jan.	3.396	1.7004	0.9837	18.1	4.332	2.115	0.9837	35.05
Feb.	3.524	1.895	0.9892	19.1	4.399	1.896	0.9890	27.1
Mar.	4.091	2.241	0.9890	29.2	5.319	2.332	0.9883	58.25
Apr.	4.343	1.944	0.9853	35.3	5.429	1.944	0.9853	14.05
May	5.253	2.694	0.9883	64.5	6.566	2.694	0.9883	123.8
Jun.	5.673	3.365	0.9903	84.6	7.092	3.365	0.9903	160.8
Jul.	6.179	4.155	0.9834	113.2	7.723	4.155	0.9834	222.2
Aug.	5.075	3.732	0.9903	60.2	6.344	3.732	0.9903	118.8
Sept.	4.281	2.254	0.9920	34.8	5.351	2.254	0.9920	67.2
Oct.	4.09	2.434	0.9852	29.8	5.113	2.434	0.9852	58.2
Nov.	3.434	1.81	0.9721	17.2	4.292	1.81	0.9721	34.3
Dec.	3.92	2.075	0.9875	26.3	4.9	2.075	0.9875	51.2

Table 10. The Weibull parameters by Mabchour's Method (MMab) for RAWA city at 10 m and 50 m height, 2018.

Month	H = 10 m				H = 50 m			
	c (m/s)	*k*	R^2	*Pw* (W/m^2)	*c* (m/s)	*k*	R^2	P_W (W/m^2)
Jan.	4.185	2.249	0.9868	31.8	5.233	2.248	0.9869	62.3
Feb.	3.406	2.005	0.9876	17.85	4.258	2.004	0.9876	34.5
Mar.	5.003	2.426	0.9852	54.6	6.255	2.425	0.9853	105.2
Apr.	3.799	1.863	0.9853	23.1	4.749	1.862	0.9853	46.2
May	4.38	2.265	0.9919	37.1	5.476	2.263	0.9919	72.3
Jun.	6.018	2.404	0.9740	95.1	7.524	2.402	0.9740	182.2
Jul.	6.854	4.307	0.9950	155.2	8.571	4.307	0.9951	305
Aug.	6.163	3.889	0.9732	110.3	7.706	3.887	0.9732	215.3
Sept.	4.27	2.307	0.9768	33.2	5.336	2.306	0.9768	66.3
Oct.	5.386	2.098	0.9689	66.2	6.733	2.096	0.9690	126.35
Nov.	3.261	1.576	0.9917	26.1	4.062	1.58	0.9919	30.85
Dec.	3.907	2.26	0.9971	55.7	4.888	2.259	0.9971	51.52

Equation (14) was used to calculate the error in the estimation of wind energy density. The monthly errors in the estimation of energy density were checked using Weibull and adjusted by Mabchour's Method (MMab). The results proved that the most efficient and accurate method for estimating Weibull parameters on site is Mabchour's Method (MMab), as shown in Table 12. It can be seen that the maximum error does not exceed 5% for all cases during the whole research period.

Table 11. The Weibull parameters by Mabchour's Method (MMab) for RAWA city at 10 m and 50 m height, 2019.

Month	H = 10 m				H = 50 m			
	c (m/s)	*k*	R^2	P_W (W/m^2)	*c* (m/s)	*k*	R^2	P_W (W/m^2)
Jan.	4.412	1.891	0.9923	37.2	5.518	1.89	0.9930	75.75
Feb.	3.974	2.011	0.9863	27.2	4.96	2.013	0.9923	54.09
Mar.	4.815	1.989	0.9940	70.85	6.025	1.991	0.9863	95.35
Apr.	4.402	2.179	0.9901	36.3	5.503	2.178	0.9940	73.64
May	4.742	2.037	0.9609	45.2	5.93	2.036	0/9902	90.2
Jun.	5.573	3.078	0.9239	77.2	6.964	3.077	0.9608	148.55
Jul.	6.231	3.403	0.9906	105.9	7.791	3.401	0.9239	214.3
Aug.	5.667	2.638	0.9884	128.2	7.078	2.619	0/9910	155.84
Sept.	4.624	2.968	0.9917	43.82	5.786	2.972	0.9881	87.32
Oct.	3.468	2.255	0.9903	28.2	4.335	2.254	0.9918	35.2
Nov.	3.568	2.063	0.9937	19.2	4.458	2.062	0.9903	56.3
Dec.	4.072	2.048	0.9937	30.2	5.091	2.046	0.9912	57.2

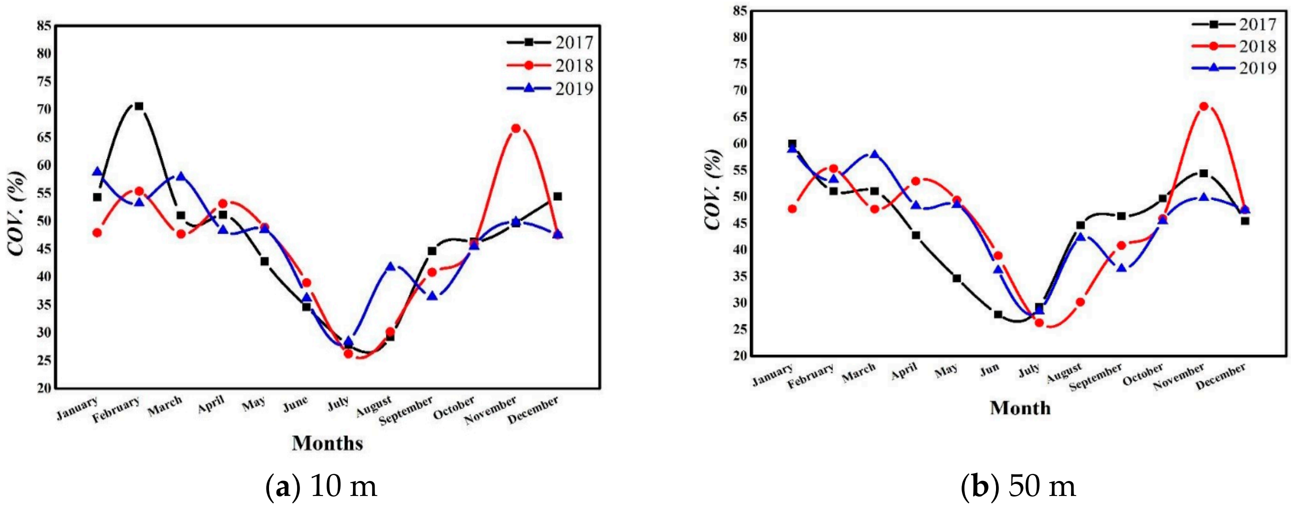

Figure 5. Hourly of mean (*COV*) of turbulence at 10 and 50 m height.

Table 12. The average error between the annual wind power densities calculated using measured data and those estimated by Weibull distribution function.

Year		2017		2018		2019	
Height		10 m	50 m	10 m	50 m	10 m	50 m
Power density (W/m^2)	P_W	44.35	80.91	58.85	108.16	54.12	95.31
	P_M	42.5	77.82	56.45	104.12	52.59	91.22
Error (%)		4.35	3.97	4.25	3.88	2.9	4.48

4. Conclusions and Remarks

Wind energy density is a key element in evaluating the potential of wind energy in any proposed site, and it provides an accurate view of the suitability of the proposed site for wind energy exploitation.

This research paper focused on statistical analyses in order to conduct an in-depth investigation of Weibull distribution methods for wind data. Wind data were collected for three years (2017–2019) for four different sites in Iraq in order to determine the optimal site in the first stage of this work. It was found that the RAWA city is the optimal site and can be considered as a promising site. The monthly mean of wind speed was found to be higher in RAWA city compared with other sites that were investigated.

Additionally, the values of scale factor c and shape factor k were computed using Mabchour's method (MMab). The results were verified based on the compression between the obtained results with results from a different method to show the most optimal method in terms of the accuracy of the calculations and the minimum time needed to perform the calculation. The results showed that the error is very small to estimate the Weibull factors and Mabchour's method can be considered the more efficient approach.

Further research will study the possibility of establishing new wind farms in several promising sites in Iraq. In addition to studying the details of designing the wind farms, future research will also use more than one method to determine the optimal design of the farm.

Author Contributions: Formal analysis, S.J.A.-S. and O.I.A.; Methodology, A.I.A. and S.J.A.-S.; Software, A.I.A.; Writing—review and editing, O.I.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. IEA. Global Energy Review 2020, IEA, Paris. Available online: https://www.iea.org/reports/global-energy-review-2020 (accessed on 22 April 2021).
2. Gielen, D.; Boshell, F.; Saygin, D.; Bazilian, M.D.; Wagner, N.; Gorini, R. The role of renewable energy in the global energy transformation. *Energy Strategy Rev.* **2019**, *24*, 38–50. [CrossRef]
3. Shaban, A.H.; Resen, A.K.; Bassil, N. Weibull parameters evaluation by different methods for windmills farms. *Energy Rep.* **2019**, *6*, 188–199. [CrossRef]
4. Altmimi, A.; Ceekhan, A. Calculate and compare five of Weibull distribution parameters to estimate wind power in Iraq. In Proceedings of the 2017 8th International Renewable Energy Congress (IREC), Amman, Jordan, 21–23 March 2017; pp. 1–5.
5. Resen, A.K.; Mahmood, A.A.; Nmr, J.S. Statistical calculations of wind data utilizing WAsP model. *AIP Conf. Proc.* **2019**, *2123*, 020029. [CrossRef]
6. Akdağ, S.A.; Dinler, A. A new method to estimate Weibull parameters for wind energy applications. *Energy Convers. Manag.* **2009**, *50*, 1761–1766. [CrossRef]
7. Asghar, A.B.; Liu, X. Estimation of wind speed probability distribution and wind energy potential using adaptive neuro-fuzzy methodology. *Neurocomputing* **2018**, *287*, 58–67. [CrossRef]
8. Ahmed, S.A.; Mahammed, H. A statistical analysis of wind power density based on the Weibull and Ralyeigh models of "Penjwen Region" Sulaimani/Iraq. *Jordan J. Mech. Ind. Eng.* **2012**, *6*, 135–140.
9. Davis, C.J. Computational modeling of wind turbine wake interactions. Ph.D. Thesis, Colorado State University, Fort Collins, CO, USA, 2012.
10. Azad, K.; Rasul, M.; Alam, M.; Uddin, S.A.; Mondal, S.K. Analysis of Wind Energy Conversion System Using Weibull Distribution. *Procedia Eng.* **2014**, *90*, 725–732. [CrossRef]
11. Tong, W. *Wind Power Generation and Wind Turbine Design*; WIT Press: Southampton, UK, 2010.
12. Sukkiramathi, K.; Seshaiah, C. Analysis of wind power potential by the three-parameter Weibull distribution to install a wind turbine. *Energy Explor. Exploit.* **2019**, *38*, 158–174. [CrossRef]
13. Tizgui, I.; El Guezar, F.; Bouzahir, H.; Benaid, B. Comparison of methods in estimating Weibull parameters for wind energy applications. *Int. J. Energy Sect. Manag.* **2017**, *11*, 650–663. [CrossRef]
14. Solar radiation Data, Merra-2 Meteorological Re-analysis. Available online: http://www.soda-pro.com/web-services/meteo-data/merra (accessed on 10 March 2021).