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Statistical Analysis of Wind Speed Data and Assessment of Wind Power Density Using Weibull Distribution Function (Case Study: Four Regions in Iraq)

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Statistical Analysis of Wind Speed Data and Assessment of Wind Power Density Using Weibull Distribution Function (Case Study: Four Regions in Iraq)

R. I. Jabbar[1].

[1]College of Material's Engineering, University of Babylon, Babylon, Iraq

rafah.jabbar@yahoo.com

Abstract Assessment of accurate wind power potential is very essential before planning to implement wind power conversion system in a particular site. In order to determine the wind power potential, a statistical analysis of wind speed measurements is required. The main objective of this paper is to analyse the daily measured wind speed data at the height of 10 m and 50 m over the ground for four regions (Al-Rutba, Sinjar, Al- Qa'im and Al-Bayji) in Iraq using the Weibull distribution function. The wind data that is used in this research is collected from NASA surface meteorology. The Weibull parameters for the individual month have also been computed. This statistical analysis is programmed in MATLAB environment to evaluate the monthly and yearly wind power density of the selected areas. In addition, the wind power classes for the four locations will be determined. The results explain the months that have maximum power wind generation in the four regions. According to the calculated yearly wind power density, it can be concluded that the selected areas are between marginal to fair for wind power generation

Keywords: Weibull distribution function, Wind classes, Wind power potential, Wind speed.

1. Introduction
In the last few decades, the dependence of wind energy source to generate electricity has been increased around the world due to the energy shortage and the awareness of climate change [1, 2]. Studying the wind energy characteristics is an important factor to locate the regions that are highly suitable for wind energy applications. In recent years, many studies have been done to study and analyse the wind power density in different countries. Fawzi analysed the wind speed of the Bahrain Kingdom using Weibull probability function whose parameters are evaluated from two different methods; the graphical method and the approximated method. The results show that the approximated method, is more accurate than the other method [3]. In [4], the wind energy potential of 12 locations in coastal regions of Turkey was calculated using Weibull distribution function. The results illustrate that the sites located in the Marmara region are characterized by a good wind potential compared to the other coastal sites. The wind power density and wind power class of Thasala at Thailand are assessed using Weibull distribution function in [5]. It was concluded that the maximum power generation is accrued during the months of January to June and in the month of October.

The wind energy characteristics have been studied by several researchers in Iraq. Researchers in [6] calculated the wind power for four locations in the south of Iraq to select which site is optimal to install wind turbine. Salman site in Iraq is studied using the Weibull distribution function in [7]. It was concluded from the results that the site had sufficient power to install the wind turbines for the electricity production.

In the west and north western of Iraq, there is a wide area that can be invested to generate electricity using renewable energy sources such as wind and solar energy. The project of integration wind turbine in these regions gives economic and political benefits.

In this study, the daily measured wind speed is statically analysed at the height of 10 m and 50 m over the ground for four regions in Iraq using Weibull distribution function. This paper is organized as the following: Section 2 describes the selected sites for studying Section 3 explains how the wind power potential is determined using Weibull distribution function. Results are discussed in Section 4. Section 5 presents the conclusions of this paper.

2. Wind data and site description

In this study, four sites are selected in the west and north-western of Iraq for the statistical analyses of wind speed and are presented in table 1. The daily wind speed data is collected from NASA surface meteorology measured from January 2018 to January 2019 at the height to 10 and 50 meters above the ground [8].

Table 1. Latitude and Longitude of the selected sites.

Site	Latitude	Longitude	State
Al-Rutba	33.038	40.284	Al Anbar
Sinjar	36.322	41.864	Ninawa
Al- Qa'im	34.415	41.498	Al Anbar
Al-Bayji	34.928	43.513	Salah Al-Din

3. Power wind potential and Wiebull distribution function

The wind power density is an indicator that shows the capacity of wind resources. The power density that could be computed using equation (1) is incorrect because the statistical distribution of wind speed is ignored and the wind speed variations are assumed fixed [9].

$$Power\ Density = \frac{power}{area} = \frac{1}{2}\rho v^3$$

where ρ is mean air density and v is the mean wind speed. Therefore, it's essential to take into account the probability distribution of wind speed in wind power calculations over a certain period of time. There are several statistical distribution functions that have been used to analyze the wind speed measurements and determine the wind potential. Weibull probability distribution function is a common function that is used to analyze wind speed data and estimate power wind generation [10]. It can be expressed by the following equation [11]:

$$P(v) = \frac{k}{a}\left(\frac{v}{a}\right)^{k-1} \ exp\left[\left(\frac{-v}{a}\right)^k\right]$$

where k and a are the shape factor and scalar factor of the Weibull distribution function. There are various methods used to calculate Weibull function parameters. In this paper, approximated method is used to determine the Weibull parameters which are determined using equations (3) and (4) and are given as [12]:

$$k = \left(\frac{S_d}{V_m}\right)^{-1.086}$$

$$a = \frac{V_m}{\Gamma\left(1 + {}^{1}/_{k}\right)}$$

where, V_m is the average wind speed for each month; S_d is the standard deviation; Γ is the gamma function which is evaluated by the following integral:

$$\Gamma(x) = \int_{-\infty}^{\infty} t^{x-1}\, e^{t}\, dt$$

The average wind speed for each month (V_m) can be calculated as follow:

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

where N is the number of records at each month. The standard deviation S_d is also determined for each month using the following formula:

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

The average monthly wind speed and the power density using Weibull distribution are calculated, respectively as follows [13,14,15]:

$$V_{mw} = a\Gamma\left(1 + {}^{1}/_{k}\right)$$

$$P_w = \sum_{i=1}^{N} 0.5\, \rho (V_m)^3\, \Gamma\left(1 + {}^{3}/_{k}\right)$$

The daily wind speed is statistically analysed using Weibull probability distribution function to determine the average wind power for each month. The statistical analysis is programmed in MATLAB environment. The analysis procedure is presented in the following algorithm:

Step 1: Insert the daily measured wind speed data over a specific period.

Step 2: Calculate the number of records at each month (N).

Step 3: Determine the summation of the wind speed per month and divide it on the number of records in order to find the average wind speed V_m.

Step 4: Estimate the Weibull distribution parameters (k, a, Γ, S_d) using equations (3)-(7).

Step 5: Calculate the average monthly Weibull wind speed (V_{mw}) using equation (8).

Step 6: Calculate the average monthly Weibull power wind potential (P_w) using equation (9).

4. **Results and discussions**

4.1. Weibull parameters and average wind speed

The Weibull parameters and Weibull monthly average wind speed at the four sites for two heights (10 and 50 m) are determined using equations (3)-(8) and illustrated in tables 2-5 . The strength of wind at a site is classified based on power density at an elevation of 50 m above the ground level. Table 6 illustrates the definition of wind classes in terms of power density values at 10 and 50 m according to international classification system that are presented in the wind energy resources atlas of the United States [16].

Table 2. Weibull monthly wind speed, and Weibull parameters at 50 and 10 m (Al-Rutba).

Month	50 (m)				10 (m)			
	S_d	k	a	V_{mw}(m/s)	S_d	k	a	V_{mw}
January	2.13	4.76	9.77	8.95	2.18	3.33	7.34	6.59
February	2.10	4.35	8.94	8.14	2.07	3.00	6.36	5.68
March	2.61	3.81	9.88	8.93	2.07	3.00	6.36	5.68
April	2.79	3.22	9.13	8.18	2.63	2.41	6.66	5.90
May	1.72	5.35	8.74	8.05	1.66	4.11	6.70	6.09

June	0.89	11.95	9.15	8.77	1.23	6.39	7.30	6.79
July	0.86	12.89	9.40	9.03	1.14	6.84	7.16	6.69
Aquest	1.16	8.55	8.85	8.36	1.15	6.16	6.59	6.13
September	1.40	6.19	8.08	7.51	1.34	4.45	5.81	5.30
October	2.63	3.57	9.42	8.48	2.66	2.59	7.19	6.39
November	1.84	4.31	7.78	7.08	1.74	3.02	5.41	4.83
December	2.21	4.40	9.51	8.67	2.23	3.08	7.01	6.27

Table 3. Weibull monthly wind speed, and Weibull parameters at 50 and 10 m (Sinjar).

Month	50 (m)				10 (m)			
	S_d	k	a	V_{mw}(m/s)	S_d	k	a	V_{mw}
January	2.50	2.94	7.56	6.75	2.18	2.37	5.44	4.82
February	1.98	3.05	6.19	5.53	1.42	2.87	4.22	3.76
March	1.82	4.59	8.12	7.41	1.78	3.12	5.68	5.08
April	1.83	3.77	6.88	6.21	1.56	3.28	5.18	4.65
May	2.12	3.55	7.55	6.80	1.85	2.74	5.25	4.67
June	1.29	8.09	9.38	8.84	1.07	6.93	6.83	6.39
July	0.87	10	9.49	9.12	0.96	7.59	6.61	6.21
Aquest	1.15	9.17	9.38	8.89	0.96	7.15	6.29	5.89
September	1.39	6.01	7.83	7.27	0.95	5.28	4.78	4.40
October	1.90	4.49	8.32	7.59	1.88	3.27	6.24	5.60
November	2.36	2.74	6.71	5.97	2.25	2.07	4.97	4.40
December	2.57	2.73	7.27	6.47	2.24	2.25	5.33	4.72

Table 4. Weibull monthly wind speed, and Weibull parameters at 50 and 10 m (Al- Qa'im).

Month	50 (m)				10 (m)			
	S_d	k	a	V_{mw}(m/s)	S_d	k	a	V_{mw}
January	1.99	4.88	9.34	8.56	2.04	3.21	6.66	5.97
February	2.07	4.09	8.34	7.57	1.91	2.85	5.62	5.01
March	2.01	5.37	10.26	9.46	2.03	3.57	7.25	6.53
April	2.00	4.37	8.54	7.78	1.74	3.42	6.01	5.41
May	2.43	3.86	9.33	8.44	2.42	2.81	7.05	6.28
June	1.61	6.68	9.95	9.28	1.66	4.71	7.54	6.90
July	1.03	11.92	10.51	10.07	1.16	7.69	8.10	7.61
Aquest	1.71	6.35	10.09	9.39	1.56	4.92	7.37	6.76
September	1.46	6.03	8.21	7.62	1.48	3.89	5.73	5.18
October	2.30	4.45	9.98	9.10	2.44	3.05	7.63	6.82
November	2.56	2.88	7.59	6.76	2.17	2.24	5.15	4.57
December	2.47	3.67	9.07	8.18	2.12	2.91	6.35	5.67

It is clear from table 6 that the wind power is ranging from class 1 to class 7. Class 1 area is unsuitable for installing wind turbine. Areas under class 2 and class 3 may be viable for wind technology applications. Regions that falls into class 4 and above are suitable for generating electricity with advanced wind turbine technology [17].

Table 5. Weibull monthly wind speed, and Weibull parameters at 50 and 10 m (Al-Bayji).

Month	50 (m)				10 (m)			
	S_d	k	a	V_{mw}(m/s)	S_d	k	a	V_{mw}
January	1.45	4.73	6.62	7.39	2.37	2.25	5.66	5.01
February	1.91	3.54	6.78	6.73	1.52	3.16	4.91	4.39
March	1.92	3.43	6.63	7.76	2.46	2.38	6.16	5.46
April	1.86	3.37	6.34	6.35	1.94	2.55	5.16	4.58
May	1.99	3.30	6.67	7.47	1.43	4.05	5.72	5.19
June	1.98	4.48	8.61	8.94	1.23	5.99	6.90	6.40

July	2.12	4.50	9.26	9.52	1.44	5.39	7.35	6.77
Aquest	2.24	3.58	8.04	8.96	1.18	5.85	6.48	6.00
September	1.98	2.93	5.98	7.73	1.05	5.38	5.36	4.94
October	1.43	4.62	6.39	9.00	2.24	3.16	7.21	6.45
November	1.31	4.03	5.22	6.27	1.93	2.43	4.94	4.38
December	1.93	3.03	6.01	6.70	2.12	2.42	5.40	4.78

Table 6. Classes of wind power density.

Wind Classes	Wind Classes Name	Power Density (w/m^2) (10m)	Wind Speed (m/s) (10m)	Power Density (w/m^2) (50 m)	Wind Speed (m/s) (50m)
1	Poor	≤100	≤4.4	≤200	≤5.6
2	Marginal	≤150	≤5.1	≤300	≤6.4
3	Fair	≤200	≤5.6	≤400	≤7.0
4	good	≤250	≤6.0	≤500	≤7.5
5	Excellent	≤300	≤6.4	≤600	≤8.0
6	Outstanding	≤400	≤7.0	≤800	≤8.8
7	Superb	≤1000	≤9.4	≤2000	≤11.9

4.2. Monthly and seasonally wind power density

The calculated Weibull wind speed and Weibull distribution parameters are used in equation (9) to estimate the wind power potential which is shown in figures 1-4 for regions (Al-Rutba, Sinjar, Al- Qa'im Al-Bayji) at 50 and 10 m above the ground. According to the wind power density results, the following observations can be obtained.

- March and October have the highest wind power density values in Al-Rutba site at height 50 m and 10 m above ground respectively. While November has the lowest power density value in two heights as shown in figure 1.
- Figure 2 shows that the highest values of wind power potential in Sinjar region are in July and Jun at 50 and 10 m, respectively while the lowest values belong to February at specific heights.
- In the Al- Qa'im site which are illustrated in figure. 3, the maximum values of wind power wind density belong to July at 50 and 10 m heights. On the other hand, the minimum values of wind power belong to November in this site at two specific heights.
- In figure 4, the minimum values accrued in November and February at 50 m and 10 m above ground, respectively. On the other hand, the maximum values of wind power density occurred in July and October at 50 m and 10 m above ground, respectively.
- In specific months of the year, the consumption of electricity is increased due to the use of a huge number of cooling and heating instruments. Therefore, it’s better to evaluate the amount of power that produced from wind in cold (January, February, December) and warm season (June, July, August). Table 7 illustrates the total wind power density in cold and warm season at four regions. It can be seen from table 7, January and July have the highest values of power density in most locations in cold and warm season, respectively.

Table 7. Total wind power density in cold and warm season at four regions.

Site	50 (m)						10 (m)					
	Total Power Density w/m2 (warm season)			Total Power Density w/m2 (cold season)			Total Power Density w/m2 (warm season)			Total Power Density w/m2 (cold season)		
	Jun	Jul	Aug	Jan	Feb	Dec	June	July	Aug	Jan	Feb	Dec
Al-Rutba	425	462	378	513	396	477	210	199	155	233	157	208
Sinjar	449	476	451	267	144	246	173	156	135	112	47	110
Al- Qa'im	534	644	557	446	325	427	236	289	219	176	111	159
Al-Bayji	468	566	462	371	226	254	178	215	147	131	70	108

4.3. Annual wind power and wind classes

The wind classes in terms of annual wind power generation are explained in table 8 for four sites at an elevation 50 m. From table 8 and according to table 6, it is clear that the wind classes of the selected regions range between 2 to 4. This means that the wind power in these areas is sufficient for generating electricity using wind turbine technology.

Table 8. Annual Wind Power and Wind Classes.

Site	Power Density w/m^2	Wind Class
Al-Rutba	420	Class 4
Sinjar	294	Class 2
Al- Qa'im	454	Class 4
Al-Bayji	359	Class 3

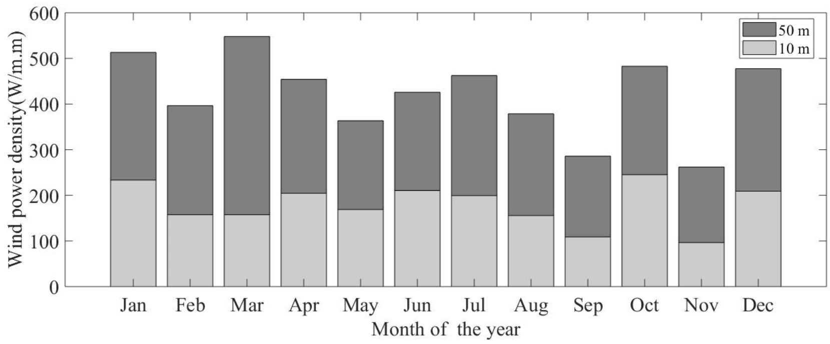

Figure 1. Monthly variation of the mean power density for Al-Rutba site.

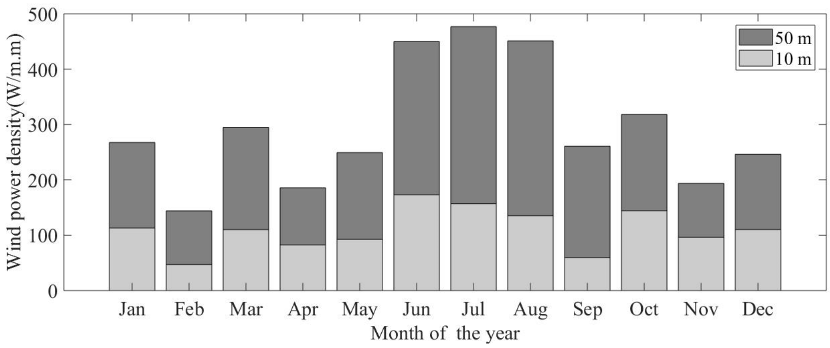

Figure 2. Monthly variation of the mean power density for Sinjar site.

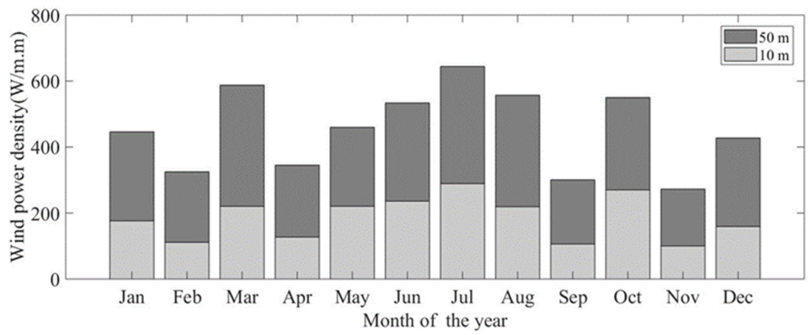

Figure 3. Monthly variation of the mean power density for Al-Qi'am site.

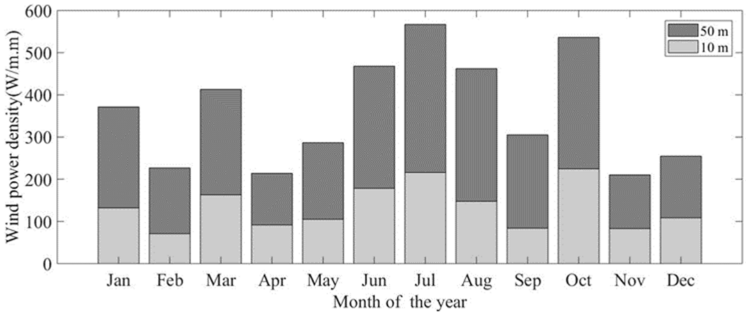

Figure 4. Monthly variation of the mean power density for Al-Bayji site.

5. Conclusions

Wind speed data have been statistically analyzed for 4 regions in Iraq (Al-Rutba, Sinjar, Al- Qa'im and Al-Bayji) over one year (2018-2019) at height 10 and 50 meters above the ground using Weibull distribution function. The monthly, seasonal and yearly power wind potential are determined in this study. The statistical analyses are programmed in MATLAB environment. From analysis, it was found that the months that have the maximum power density values are October and July, while November and February have the lowest wind power potential, respectively. It can be seen from results, the power that extracted from wind in warm season is greater than cold season in each selected site expect Al-Rutba site. In addition, the annual power density in all four regions are between 200 w/m^2 and 500 w/m^2. The wind classes corresponding to yearly wind power density are determined in this research. The results show that the wind power classes range between class 2 to class 4. Finally, it can be concluded from the above that the wind turbine can be installed for generating electricity in the present and future time for almost all selected sites.

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