Journal of Agrometeorology

ISSN : 0972-1665 (print), 2583-2980 (online)
Vol. No. 26 (3) : 331-338 (September - 2024)
https://doi.org/10.54386/jam.v26i3.2644
https://journal.agrimetassociation.org/index.php/jam

Research Paper

Study and evaluation of wind power density for the use of small wind turbine under Baghdad conditions

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ABSTRACT

The main aim of this research is to analyze the characteristics of the wind speed and wind power density in Baghdad City within micro-scale meteorological conditions at Mustansiriyah University Meteorological Station (MUMS). Temperature, atmospheric pressure and wind speed data were taken for one year (2016) measured at a height of 18 m above the earth's surface. Hourly, monthly, and seasonal changes in wind speed at an altitude of 30 m were estimated using a power law. The mean diurnal and monthly air density was calculated. Different statistical distributions were used, including the Rayleigh, Gamma and Weibull distributions, and the best distribution function was selected to evaluate the wind power density in the study area. The results showed the highest monthly mean of wind speed recorded in June and July. Therefore, these months have the highest wind power density. The lowest monthly mean of wind speed and wind power density was observed in December. The maximum and minimum values of air density were recorded in December, January and July, August, respectively. The monthly variation of the shape parameter (k) ranges between 0.99 - 1.81, while the monthly variation of the scale parameter(c) ranges between 1.07 - 2.3 m s^{-1}. It was also found that the Weibull distribution was more accurate than the Rayleigh and Gamma distributions. The prevailing wind direction is northeast (NE) and east-northeast (ENE) most of the time. The research results showed that the study area is not suitable for using wind energy to generate energy.

Keywords: Wind speed, Weibull distribution, Gamma distribution, Rayleigh distribution, Wind power density, Wind energy.

The urgent need for energy has increased due to the increasing population and industrial development (Herbert *et al.,* 2017). Industrial activity consumes large amounts of fossil fuel including coal, natural gases, oil, and gasoline leading to air pollution (Gul *et al.,* 2019). The use of fossil fuels to generate electricity has a bad side effect on the environment, especially the high emission of greenhouse gases into the atmosphere, leading to climate change and global warming (Al-Knani *et al.,* 2021). The most suitable method to reduce emissions is to reduce the use of fossil fuels, by using renewable energy (Stevens *et al.,* 1979). Renewable energy applications are clean and sustainable sources, such as wind energy, solar energy, geothermal energy, hydropower, and biomass and ocean energy. Among renewable energy sources, wind energy is considered a non-polluting, environmentally safe and inexhaustible resource such as fossil fuels (Al-Qabandi *et al.,* 2014). Wind energy production is best suited to areas with strong wind speeds and moderate turbulence intensity and the highest wind energy density was found under stable condition (Khadir *et al.,* 2024).

The wind pattern in urban areas is very complicated to understand because of surface roughness that leads to low wind velocity and turbulence. Small-scale turbines are known to operate in urban areas and above buildings with low wind speeds and their production capacity is less than 50 kW (Nel *et al.,* 2012). Wind resources are rarely consistent and vary with time of the day, season of the year, height above the ground, and type of terrain, therefore

Article info - DOI: *https://doi.org/10.54386/jam.v26i3.2644*
Received: 29 June 2024; Accepted: 17 July 2024 ; Published online : 01 September 2024

must be investigated carefully (Olaofe *et al.,* 2012). Abdulkarim *et al.,* (2017) performed statistical analysis to determine the probability distribution that best fits the wind speed and showed that the Weibull function was the best amongst the three distribution functions tested (Weibull, Rayleigh and Gamma functions) while Mosetlhe *et al.,* (2018) showed that the Gamma distribution was better than the Weibull and lognormal distributions. Fazelpour *et al.,* (2017) analyzed the wind data of the Kutahya region in Turkey using the Weibull and Rayleigh distribution and found that the Weibull function fitted the data more appropriately than the Rayleigh function. Hadi *et al.,* (2020), used the Weibull distribution function to estimate wind speed and wind energy potential, and showed that the study site was a marginal class and not suitable for installing large wind turbines.

This study aims to investigate the possibility of using the best statistical distribution function (Weibull, Rayleigh and Gamma distributions) to evaluate wind power density at the Mustansiriya University site located in the center of Baghdad city, Iraq.

MATERIAL AND METHODS

Study location

Mustansiriya University is located in the center of Baghdad city, at longitude and latitude (33.36 °N, 44.23 °E). It has an automatic weather station over its building at an altitude of 18 m above ground level. The station records several weather parameters such as temperature, pressure, wind speed, wind direction, solar radiation, humidity, etc. (Fig. 1) shows the location of the station over the building.

The wind speed data at the height of 18m from January to December of 2016 was collected and extrapolated to 30 m using a power law. Mean monthly and seasonal air density was estimated based on temperature and pressure data measurements. Analyzed wind directions to find the prevailing wind direction. Weibull, Rayleigh and Gamma distribution functions were used to investigate the probability distribution of the wind speed data and to choose the best distribution and its estimated parameters, The modified maximum likelihood method was used to estimate the shape parameter (k) and the scale (c, m.s^{-1}) parameter at (30 m). Statistical analysis such as the mean wind speed and Weibull parameters were used to calculate seasonal wind power density. Finally, the effect of air density values on wind power density values was studied, and the studied location can be considered a poor-scale site and unsuitable for installing wind turbines.

Mean wind speed

The mean wind speed indicates the suitability of a wind location for small-scale and large-scale power generation.

$$\bar{u} = \frac{1}{n}\sum_{i=1}^{n} u_i \tag{1}$$

Where ($\bar{u}$) represents the mean wind speed, (u_i) represents the observed wind speed with (ith) time, and *(n)* is the number of wind speed data points (Olaofe *et al.,* 2012).

Fig. 1: Shows the location Mustansiriyah University Meteorological Station (MUMS)

Wind speed variation with height

The most common expression for the change in wind speed with height is known as the power law.

$$u_2 = u_1\left(\frac{z_2}{z_1}\right)^p \tag{2}$$

Whereis the wind speed at a reference height (anemometer height), is the wind speed at a height (hub height), and (p) is the shear exponent (dimensionless parameter).

The shear exponent (p) of the power law profile can be calculated from the roughness length(z_0). It is defined as (Panofsky *et al.,* 1984);

$$P = \left(\frac{1}{\ln\sqrt{\frac{z_2}{z_o}}}\right) \tag{3}$$

Weibull distribution

The Weibull distribution is the most important method for wind speed calculation, so Weibull probability distribution function is expressed as;

$$f_w = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} exp\left(-\left(\frac{u}{c}\right)^k\right) \tag{4}$$

Where *(f_w)* is the Weibull probability density function (PDF). (*c*) is the scale parameter that shows the extent of wind at a location. (*k*) is the shape parameter (dimensionless) that shows how peaked the wind distribution.

Wind power density in Weibull distribution analysis can be written as follows (Mohammed *et al.,* 2019).

$$WPD_{wb} = \frac{1}{2}\rho c^3\Gamma\left(1+\frac{3}{k}\right) \tag{5}$$

Rayleigh distribution

The Rayleigh probability distribution function (PDF) has only one parameter making it the simplest and most widely used distribution. It is known that the Rayleigh distribution is a special case of the Weibull distribution where the shape parameter is (k=2). The Rayleigh probability density function (f_R) is given as (Tizgui *et al.,* 2019);

$$f_R = \left(\frac{2u}{c^2}\right) exp\left(-\left(\frac{u}{c}\right)^2\right) \quad (6)$$

The Rayleigh wind power density is estimated as;

$$WPD_{Ry} = \frac{3}{\pi}\rho c^3 \sqrt{\frac{\pi}{4}} \quad (7)$$

Gamma distribution

The Gamma distribution was applied in the wind speed model, which is a two-parameter distribution (Tizgui *et al.,* 2019).

The probability density function of a Gamma distribution *(fg)* is defined as;

$$f_g = \frac{u^{k-1}}{c^k\,\Gamma(k)} exp\left(-\left(\frac{u}{c}\right)\right) \quad (8)$$

The wind power density using the Gamma distribution is estimated as (Aidan *et al*., 2010);

$$WPD_{ga} = \frac{1}{2}\rho c^3\,[k(k+1)(k+2)] \quad (9)$$

Where is Gamma wind power density.

Estimating of Weibull parameters by modified maximum likelihood method (MMLM)

The MMLM was solved by numerical iterations to determine the scale parameter (c) and the shape parameter (k), and was estimated by the equations (10) and (11).

$$c = \left(\frac{\sum_{i=1}^{n} u_i^k \cdot f(u_i)}{f\,(u \geq 0)}\right)^{-1} \quad (10)$$

$$k = \left(\frac{\sum_{i=1}^{n} u_i^k \ln(u_i) \cdot f(u_i)}{\sum_{i=1}^{n} u_i^k \cdot f(u_i)} - \frac{\sum_{i=1}^{n} \ln(u_i) \cdot f(u_i)}{f\,(u \geq 0)}\right)^{-1} \quad (11)$$

f (u≥0) , probability of wind speed *(u ≥ 0)* (Kaoga *et al.,* 2015).

Wind power density (WPD)

Wind power density is estimated to evaluate wind resources at a specified site. it is proportional to the cube of average wind speed and air density, which can be calculated following Amaya-Martínez *et al.,* (2014);

$$P_d = \frac{1}{2}\rho u^3 \quad (12)$$

Where (P_d) represents wind power density (W.m^{-2}) and (*u*) represents wind speed (m.sec^{-1}). (ρ) is air density (kg.m^{-3}), which is mostly considered a constant, (1.225 kg.m^{-3}).

Air density greatly affects the performance of a wind power density (Olaofe *et al.,* 2012).

The mathematical equation for the air density is defined as:

$$\rho = \frac{P}{T\,R_d} \quad (13)$$

Table 1: Classes of wind power at a height of 30 m above the ground according to NREL

Wind power class	Resource potential	Wind power density (W.m^{-2})	Wind speed (m.s^{-1})
1	Poor	≤160	≤5.1
2	Marginal	≤240	≤5.9
3	Fair	≤320	≤6.5
4	Good	≤400	≤7.0
5	Excellent	≤480	≤7.4
6	Outstanding	≤640	≤8.2
7	Superb	≤1600	≤11.0

Where (P) is average air pressure (N.m^{-2}) and (T) is average air temperature (K^o) and (R_d) is dry air gas constant (R_d = 287 J.kg^{-1}. K) .

The percentage error of wind power density can be expressed by;

$$Error = \frac{P_{W,G,R} - P_d}{P_d} * 100\,\% \quad (14)$$

Whereis calculated from the measured data; and is calculated from the estimated PDF (Yang *et al.,* 2014).

Goodness of fit

There are many tests used to evaluate the suitability of selected distribution functions to the wind speed data. The more commonly used tests are the root mean square error (RMSE) test and the coefficient of determination (R^2) (Olaofe *et al.,* 2012).

$$RMSE = \sqrt{\left[\frac{1}{N}\sum_{i=1}^{N}(y_i - \bar{x}_i)^2\right]} \quad (15)$$

The value of the root mean square error (RMSE) close to zero indicates that the distribution function is appropriate for evaluating wind power density. The coefficient of determination (R^2) is expressed as;

$$R^2 = \frac{\sum_{i=1}^{N}(y_i-\bar{y}_i)^2 - \sum_{i=1}^{N}(y_i-\bar{x}_i)^2}{\sum_{i=1}^{N}(y_i-\bar{y}_i)^2} \quad (16)$$

Where (y_i) represents the actual data, (x_i) represents data predicted using the distribution, (y_i) is the average value of (y_i), and (N) represents the number of observed or measured wind data (Kaoga *et al.,* 2015).

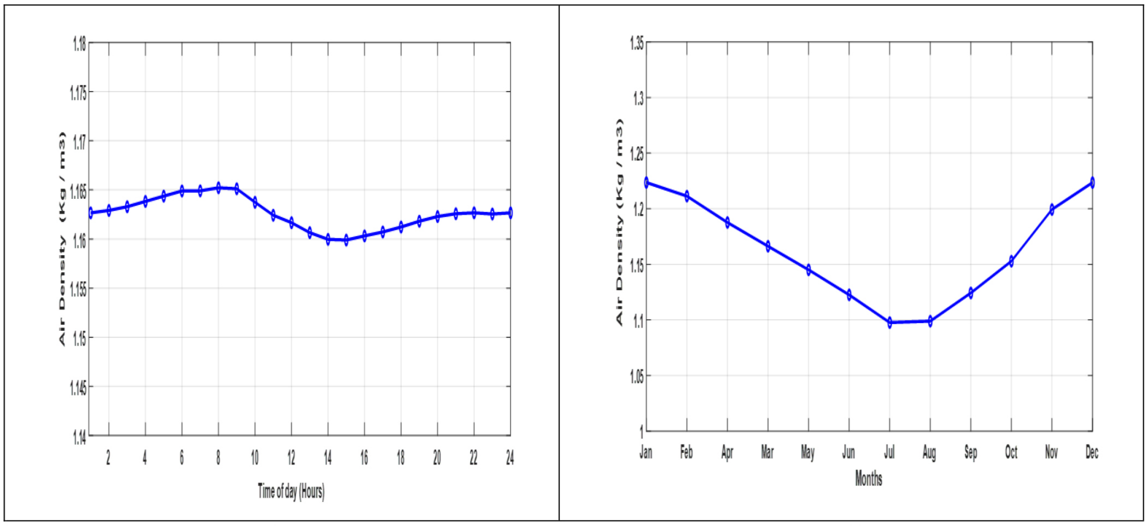
Wind power classifications

According to the renewable energy laboratory (NREL) standard, the wind power categories range from class 1 to 7. Each class represents the average wind speed or average wind power density at specific heights above the surface (Table 1) (Bailey, *et al.,* 1997).

RESULT AND DISCUSSION

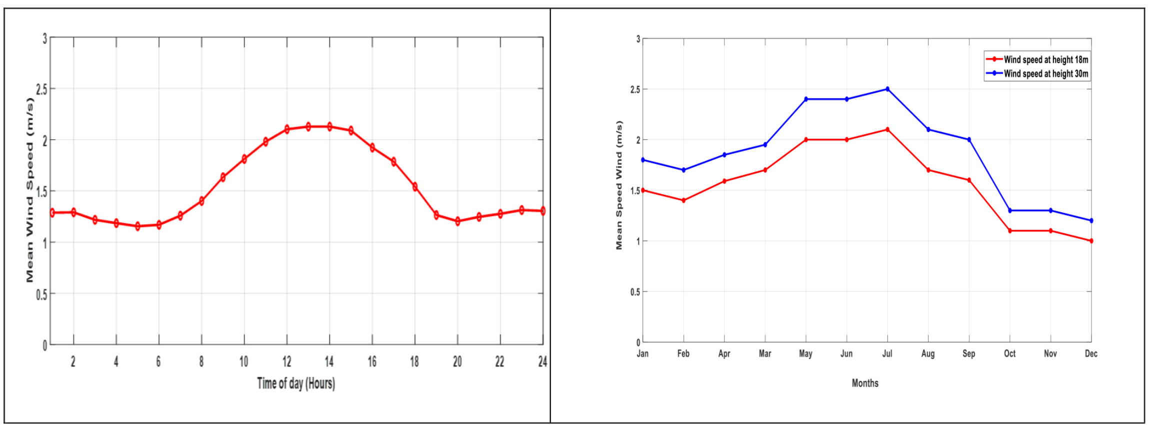
Diurnal and monthly variations of air density

Fig. 2 (a) shows the diurnal variation of the mean air



(a) **(b)**

Fig. 2: (a) Diurnal and (b) monthly variation of mean air density.



(a) (b)

Fig. 3: (a) Diurnal variation of the mean wind speed at 18 m and (b) Monthly mean wind speed at heights at 18 and 30 m.

density during the daily cycle. It was found that the air density varies between a minimum of 1.160 kg.m^{-3} during 14:00 -15:00 h and a maximum of 1.165 kg.m^{-3} during 08:00-09:00 h. Higher values were observed during the early morning and lower during the afternoon. Fig. 2(b) shows the mean monthly air density. The highest mean air density was obtained in January and December, which were characterized by low temperatures and relatively high air pressure. While the lowest air density was recorded in July and August, known for high temperatures and low air pressure. The maximum value of air density is about 1.26 kg.m^{-3}, while the minimum value of air density is around 1.09 kg.m^{-3}.

Diurnal and monthly variations of wind speed

Knowledge the monthly variation in wind speed provides confidence in the availability of energy in different months of the year. Fig. 3(a) shows the diurnal variation of the hourly mean wind speed at a height of 18 m. During the entire period of data collection, the mean wind speed was 1.72 m.s^{-1}. The wind speed increases relatively during the day and reaches its maximum speed of 2.14 m.s^{-1} which occurs at 14 p.m., while the wind speed decreases during the night. This is due to the differential heating of the earth surface during the daily radiation cycle, where the sun heats the ground in the morning hours, which leads to an increase the wind speed Fig. 3(b) shows the monthly variation of wind speed. It can be seen that the monthly mean wind speed increases with increasing height. The highest wind speed was observed in May, June, and July with a value of 2.4 m.s^{-1}, 2.45m.s^{-1} and 2.5m.s^{-1} respectively at a height of 30m.Thus, it can be concluded that the maximum energy production will occur during these three months. While the lowest energy production was recorded in December at a value of 1.3 m.s^{-1} at 30m height. Fig. 4 shows that the prevailing and most frequent wind direction is NE and ENE.

Probability density distribution and choosing the best distribution

Fig. 5 shows a comparison of Weibull, Rayleigh and Gamma probability density functions with histograms of wind speed data. The bars show the relative frequency with each bin of wind speed occurring in 1 m.s^{-1}, which appears along the x-axis and

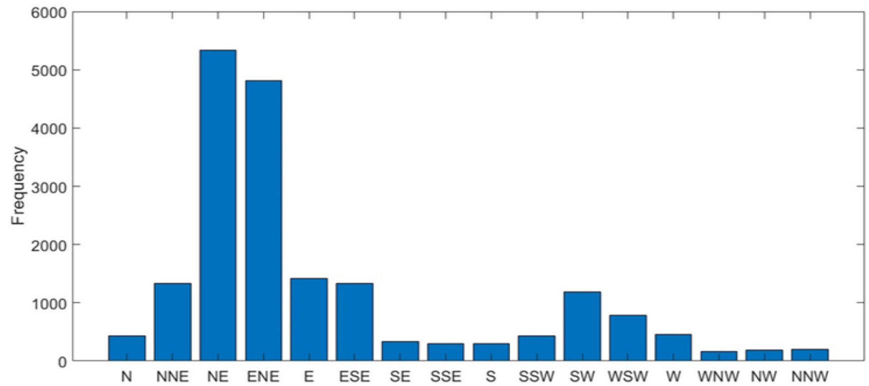


Fig. 4: A histogram of the wind direction at the site.

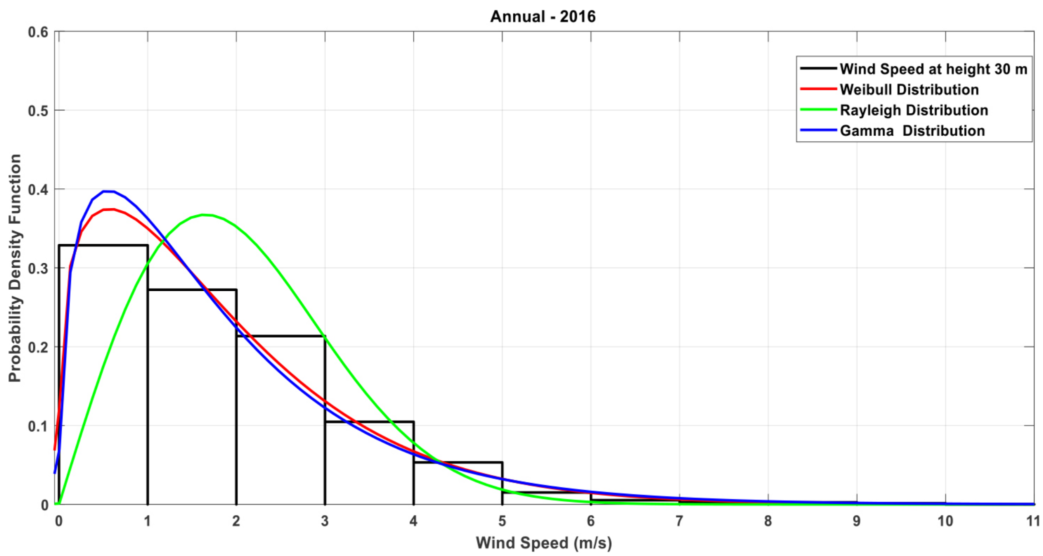


Fig. 5: Probability density distribution of mean wind speed using Weibull, Rayleigh and Gamma distributions with wind speed data histogram.

is based on the results obtained by wind speed analysis. It can be noticed that there is a clear difference in the peaks of the probability density function due to different values of the shape parameter (k). Also, it can be seen that the most frequent wind speeds in the Weibull and Gamma distributions range from 0.1–1 m.s^{-1}, while the Rayleigh distribution shows that the most frequent wind speed is between 1–2 m.s^{-1}.

Fig. 6 compares measured wind speed data and wind speed estimated by Weibull, Rayleigh and Gamma distributions. It shows that the most closely fit distribution for wind speed data was the Weibull distribution followed by the Gamma distribution. While the Rayleigh distribution does not match the measured values of wind speed. Therefore, the Weibull distribution fits best, followed by the Gamma distribution at the studied site. This is also evident from the RMSE and R^2 values (Table 2). Finally, these distributions are very important for estimating wind power density.

Modified maximum likelihood for calculating Weibull parameters

Wind speed variation is often described using the Weibull scale parameter (c), and shape parameters (k). The values of the Weibull parameter provide more explanation about the wind speed distribution behavior at a given location. The Modified Maximum Likelihood Method (MMLM) was used to estimate the shape parameter (k) and the scale (c, m.s^{-1}) parameter at 30m.The year is divided into four seasons. The period, from 21 December to 20 March is considered the winter season, while the spring season is from 21 March to 20 June. The summer season begins on 21 June and ends on 20 September, while the autumn season begins on 21 September and ends on 20 December.

Table 3 shows the highest value of seasonal shape parameter was 1.82 in summer, and the lowest value was 0.99 during the winter season, this parameter represents the nature of wind variability or stability. While the highest value of the scale parameter was 2.45 m.s^{-1} occurred in summer and the lowest value of 1.55 m.s^{-1} was in winter. Fig 7 shows the seasonal probability density functions, based on Weibull parameters at 30 m. It illustrates that the most frequent wind speed was in summer between 1-2 m.s^{-1}, followed by 0.5-1.5 m.s^{-1} in the spring. Probability density functions are introduced to fit the wind speed distribution and conduct the wind energy potential analysis on site.

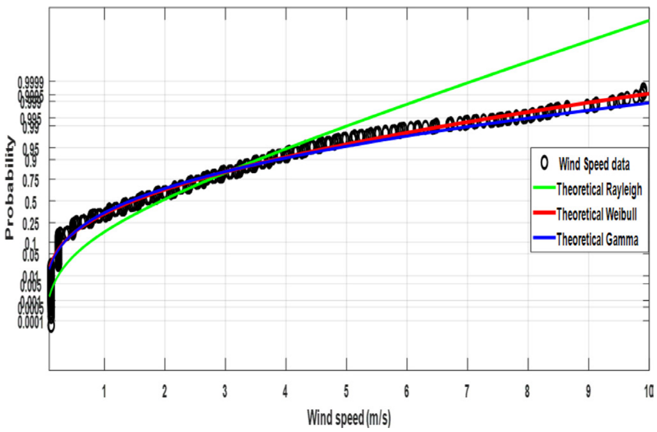


Fig. 6: Comparison of measured wind speed data and wind speed estimated by Weibull, Rayleigh and Gamma distributions.

Table 2: Evaluation of probability distribution functions (PDFs)

Probability distribution functions	RMSE	R^2
Weibull	0.0052	0.982
Gamma	0.0076	0.971
Rayleigh	0.0172	0.891

Table 3: Seasonal values of the Weibull parameters

Weibull parameters	seasons			
	Winter	Spring	Summer	Autumn
Shape parameter (k)	0.99	1.41	1.82	1.22
Scale parameter (c $m.s^{-1}$)	1.61	2.28	2.45	1.55

Calculation of wind power density

The seasonal wind power density was calculated using measured data of wind speed and Weibull parameters, using equations (13) and (5). Table 4 shows the seasonal variation of wind power density and percentage error between the measured and estimated by Weibull parameters. It can be seen that the lowest wind power density and the highest error rate were in the autumn season, while the highest wind power density and the lowest error rate were in the summer season. Also, it can be noticed that values of wind power density evaluated according to Weibull parameters were larger than the wind power density values estimated from the measured wind speed data.

The effect of air density on wind power density

Table 5 shows the values of wind power density when the air density is constant, as well as when the air density was calculated

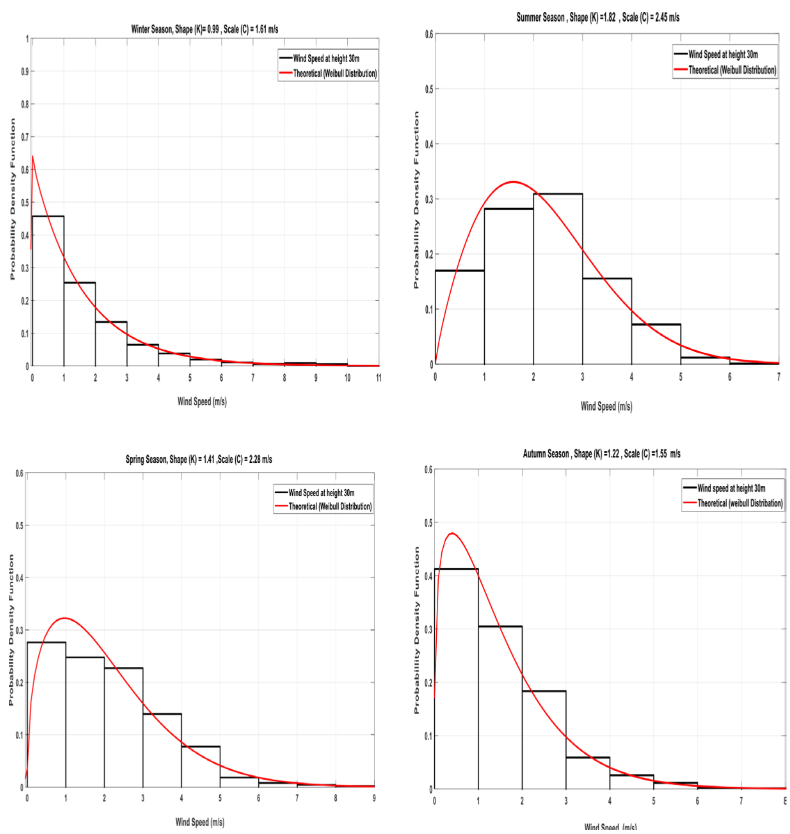


Fig. 7: Weibull fit and seasonal frequency distribution of wind speed

by the equation 13. It shows that the wind power density values are close to each other. According to the wind power density class, the wind power density of the study site at 30m can be considered as a class 1 corresponding to the values in the Table 5 which can be considered as a poor scale site and not suitable for the installation of wind turbines or considered unsuitable for energy production.

CONCLUSIONS

Table 4: Estimated seasonal wind power density using the measured data for wind speed and Weibull parameters

Season	Shape parameter (k)	Scale parameter (c, m.s^{-1})	Mean wind speed (m.s^{-1})	Wind power density using Weibull parameters (W.m^{-1})	Wind power density using measured wind speed data (W.m^{-1})	Error (%)
Winter	0.99	1.61	1.78	15.93	3.45	3.62 %
Spring	1.41	2.28	2.27	16.39	7.20	1.27 %
Summer	1.82	2.45	2.33	13.36	7.75	0.72%
Autumn	1.22	1.55	1.20	7.25	1.10	5.59 %
Annual	1.40	2.00	1.90	13.23	4.88	1.71%

Table 5: Seasonal calculated wind power (W.m^{-1}) density with calculated air density (kg.m^{-3})

Seasons	Calculated air density (kg.m^{-3})	Wind power density when air density is calculated (kg.m^{-3})	Air density constant (kg.m^{-3})	Wind power density when air density is constant (W.m^{-1})
Winter	1.207	15.69		15.93
Spring	1.178	15.30	1.225	16.39
Summer	1.106	12.06		13.36
Autumn	1.191	7.05		7.25

Among the most important results of the study, it was observed that mean air density increases during the early morning and decreases during the afternoon. The highest monthly mean air density was obtained in January and December, and the lowest air density was recorded in July and August. While analysis of the variation in daily wind speed showed that wind speed increases during the day, and decreases during the night. in addition, the mean wind speed increases with increasing height, the highest monthly mean wind speed was in July and the lowest monthly mean wind speed was in December. The most probable wind directions were NE and ENE. It was found that the Weibull distribution is the best in modeling and describing wind speed variation, followed by the Gamma distribution. The highest value for the seasonal shape parameter was 1.82 in the summer, and the lowest value 0.99 during the winter, while the highest value for the scale parameter was 2.45 m.s^{-1} in the summer and the lowest value was 1.55 m.s^{-1} in the winter. As for the wind power density values evaluated according to Weibull parameters were greater than those estimated from measured wind speed data, and the wind power density class at the study site is considered a poor site (Class I) and unsuitable for installing wind turbines for generate electricity.

ACKNOWLEDGEMENT

We thank the Department of Atmospheric Sciences at Mustansiriya University for its cooperation and for providing the appropriate environment for scientific research.

Conflict of Interests: The authors declare that there is no conflict of interest related to this article.

Funding: The authors did not receive support from any organization for the submitted work.

Data availability: Wind speed, direction, pressure and temperature data for the year 2016 were obtained from the Mustansiriya University, Department of Atmospheric Sciences, through the meteorological station installed in the study area (Mustansiriya University) and stored in their repository

***Author contribution*: B. A. Al-Knani:** Data checked, processed, and analyzed, **Hussain A. Nemah:** presented, Investigation, **S. A. Ahmed:** Writing-original draft; **Asdaf A. Raeed:** writing review, and editing.

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