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Characterization of Seasonal Wind Power Density at 10 m Height in Al Khums, Libya

J. F. Alnaas[1], A. M. Sharif[2,*], M. S. Altraiki[3], K. M. Jaballa[4]
[1,2](*Chemical & Petroleum Eng. Dept., Engineering College, Elmergib University, Libya)*
[3](*Department of Chemistry, College of Pharmacy, Elmergib University, Libya)*
[4](*Department of Mechanical Eng., Engineering College, Elmergib University, Libya)*
**Corresponding Author*

ABSTRACT: *In this study, the potential of wind power density alongside with wind speed Weibull distribution in Al Khums city are investigated. The investigation is based on a daily-mean historical data for 10 years from January 2005 to December 2014 at 10 meters height above the ground level. The investigation includes an estimation of the seasonal observed wind power density and Weibull distribution parameters. In order to characterize the wind power in this area, the observed wind power density is first calculated based on the power density equation, then, the two parameters of Weibull distribution are estimated. The observed wind power density is found to be 66.0, 126.8, 100.5, and 48.8 W/m^2 in fall, winter, spring, and summer respectively. The study reveals high potential of wind power density in winter and a very low potential in summer. The estimated shape factor ranges from 2.48 in winter to 3.56 in summer using the power density method, and ranges from 2.55 in winter to 3.78 in summer using the method of moments. On the other hand, the estimated scale factor ranges from 4.47 m/s in summer to 5.73 m/s in winter using the power density method, and ranges from 4.46 m/s in summer to 5.72 m/s in winter.*

KEYWORDS:*Al Khums, Libya, Method of moments, Power density method, Weibull distribution, Wind power density.*

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I. INTRODUCTION

Al Khums is located on the Mediterranean coast in the north about 105 km to the east of Tripoli and resides on 32.66 °N latitude and 14.26 °E longitude with an average 71 m above the sea level. The city ranked the 6th largest in population with an estimated 202,000 people according to the 2004 census. The city and its suburbs are home to two cement plants and a power plant in addition to many other small factories and businesses. The health and environmental effects of the current fossil fuel power plant cannot be ignored. Adding to that population growth and agricultural activity, the need for a sustainable, clean energy source is becoming a necessity. The city's location is in the north and its relative high wind speed profile makes it a good candidate for wind energy feasibility study. In a survey conducted by Alnaas*et al*. [1] on a 25 cities in the country reveals that the city ranks the 7th in wind power density recording 84.8 W/m^2 based on annual averages. In order to make more reliable decision, a detailed study on monthly or at least seasonal basis is needed. Furthermore, a proper method is needed to predict wind data and, hence, power density at least to some probability.

It had been proven in studies done by Jestus*et al*. [2], Stevens and Smulders [3], Seguro and Lambert [4], Lun and Lam [5], and Celik [6] that Weibull distribution gives the best representation of the probability of wind speed data. The two-parameter Weibull distribution includes the calculation of the shape factor and the scale factor. There are many methods available for the estimation of Weibull parameters. A detailed description of these methods can be found in [2-4,7-9]. In this investigation, two methods are used: the power density method and the method of moments as it will be presented later. In this study, the characterization of wind power density is based on satellite data from NASA's Atmospheric Science and Data Center [10] in conjunction with RETScreen International [11]. The datasets are recordings of daily averages for air temperature, barometric pressure, and wind speed from January 1st, 2005 to December 31st, 2014 at 10 meters height above the ground level. Although ground stations would give more accurate assessments, absence of these stations in some places, their influence by local microclimates, intermittent operation, and some missing data [12] may introduce some uncertainty in the assessment. The datasets are interpolated to one-degree latitude by one-degree longitude. A detailed description of the methodologies used to extract these data can be found in NASA [10], RETScreen International [11], and Chandler *et al*. [12].

II. OBSERVED WIND DATA

The data used to characterize wind power potential are retrieved from RETScreen International and NASA's Atmospheric Science and Data Center. The data are daily recordings of ten years for: the daily average air temperature (T_i), the daily average barometric pressure (p_i), and the daily average wind speed (v_i) all of which at 10 m height above the ground level. The seasonal average air temperature ($\bar{T}_k$) in K and the seasonal average barometric pressure ($\bar{p}_k$) in kPa is given by:

$$\bar{T}_k = \frac{1}{n_k}\sum_{i=1}^{n_k} T_{ik} \tag{1}$$

$$\bar{p}_k = \frac{1}{n_k}\sum_{i=1}^{n_k} p_{ik} \tag{2}$$

where k indicates to the season ($k = 1$ for fall; $k = 2$ for winter; $k = 3$ for spring; and $k = 4$ for summer). The number of data for each season is as follows: $n_1 = 910, n_2 = 900, n_3 = 920$, and $n_4 = 920$ for fall, winter, spring, and summer respectively. The total number of observed data (n) are 3,650 which represent the number of days from January 1st, 2005 to December 31st, 2014 ignoring the extra day in February for leap years. Equations (1) and (2) can be used to estimate the seasonal average air density ($\bar{\rho}_k$) in kg/m^3 according to the equation:

$$\bar{\rho}_k = \frac{M_a}{R}\cdot\frac{\bar{p}_k}{\bar{T}_k} \tag{3}$$

where M_a is the air molecular weight, 29 g/g mol, R is the ideal gas constant 8.314 J/(g mol· K). The seasonal average air density can also be estimated from the daily average air temperature and atmospheric pressure:

$$\bar{\rho}_k = \frac{1}{n_k}\frac{M_a}{R}\sum_{i=1}^{n_k}\frac{p_{ik}}{T_{ik}} \tag{4}$$

Since the daily mean parameters are available, Equation (4) will be used here although both equations give the same results. Similarly, the seasonal average wind speed ($\bar{v}_k$) in m/s can be estimated by:

$$\bar{v}_k = \frac{1}{n_k}\sum_{i=1}^{n_k} v_{ik} \tag{5}$$

Applying the results of Equation (5) to calculate the seasonal standard deviation for wind speed (σ_k):

$$\sigma_k = \left(\frac{1}{n_k - 1}\sum_{i=1}^{n_k}(v_{ik} - \bar{v}_k)^2\right)^{1/2} \tag{6}$$

The standard deviation is given in m/s and will be used later in the method of moments to estimate the shape factor. A summary of applying Equations (1)–(6) on the data extracted from January 1st, 2005 to December 31st, 2014 is shown in Table 1.

Table 1. The seasonal average wind speed data in Al Khums, Libya at 10 m height.

Season		No. of observations	Avg. air temperature	Avg. barometric pressure	Avg. air density	Avg. wind speed	Standard deviation
k		n_k	$\bar{T}_k$, (°C)	$\bar{p}_k$, (kPa)	$\bar{\rho}_k$, (kg/m^3)	$\bar{v}_k$, (m/s)	σ_k, (m/s)
1	Fall (SON)	910	23.4	100.1	1.177	4.20	1.646
2	Winter (DJF)	900	14.0	100.3	1.218	5.08	2.151
3	Spring (MAM)	920	19.8	99.9	1.190	4.87	1.797
4	Summer (JJA)	920	28.3	99.9	1.156	4.03	1.190
Annual		3,650	21.4	100.1	1.185	4.55	1.727

The daily average power density ($P_{D_{ik}}$) in W/m^2 for a specific season carried by a wind moving at a speed of υ_{ik} is given by:

$$P_{D_{ik}} = 0.5\,\rho_{ik}\upsilon_{ik}^3 \tag{7}$$

where ρ_{ik} is the daily air density for a season k in kg/m^3 and is given by:

$$\rho_{ik} = \frac{M_a}{R}\cdot\frac{p_{ik}}{T_{ik}} \tag{8}$$

The seasonal average wind power density ($\bar{P}_{D_k}$) can be easily estimated from Equation (7) as follows:

$$\bar{P}_{D_k} = \frac{1}{n_k}\sum_{i=1}^{n_k} P_{D_{ik}} = \frac{0.5}{n_k}\sum_{i=1}^{n_k} \rho_{ik}\upsilon_{ik}^3 \tag{9}$$

This is the observed seasonal average power density based on the power density equation. A summary of results of applying Equation (9) is illustrated in Fig. 1. Where the highest power density of 126.8 W/m^2 is observed in winter, and the lowest power density is observed in summer with a value of 66 W/m^2.

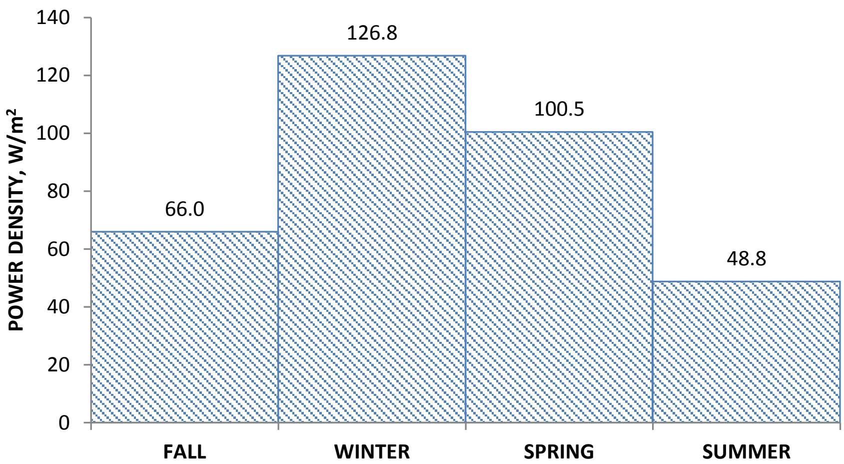


Figure 1. The observed wind power density in Al Khums city at 10 m height.

The observed power density can also be calculated from the observed frequency and the average wind speed range rather than on applying Equation (9). A summary of these results are illustrated in Table 2, Table 3, Table 4, and Table 5 for the seasons fall, winter, spring and summer respectively from January 2005 to December 2014 at 10 m height above ground level. The wind speed is classified to classes (*b*) from 1 m/s to 17 m/s.

Table 2. Observed distribution and the observed power density in fall.

Wind speed class	Wind speed range	Observed occurrence	Observed Frequency	Observed cumulative frequency	Power density
-	(m/s)	-	(%)	(%)	(W/m^2)
1	>0 – ≤1	0	0.00	0.00	0.0
2	>1 – ≤2	41	4.51	4.51	0.1
3	>2 – ≤3	198	21.76	26.26	2.0
4	>3 – ≤4	240	26.37	52.64	6.7
5	>4 – ≤5	172	18.90	71.54	10.1
6	>5 – ≤6	127	13.96	85.49	13.7
7	>6 – ≤7	78	8.57	94.07	13.9
8	>7 – ≤8	32	3.52	97.58	8.7
9	>8 – ≤9	13	1.43	99.01	5.2
10	>9 – ≤10	5	0.55	99.56	2.8
11	>10 – ≤11	3	0.33	99.89	2.2
12	>11 – ≤12	1	0.11	100.00	1.0
13	>12 – ≤13	0	0.00	100.00	0.0
14	>13 – ≤14	0	0.00	100.00	0.0
15	>14 – ≤15	0	0.00	100.00	0.0
16	>15 – ≤16	0	0.00	100.00	0.0
17	>16 – ≤17	0	0.00	100.00	0.0
Total		910	100.00		66.4*

*This value is obtained from: $\bar{P}_{D_k} = 0.5\bar{\rho}_k \sum_{b=1}^{17}[(b-0.5)^3 \text{ Frequency}(b)/100]$.

Table 3. Observed distribution and the observed power density in winter.

Wind speed class	Wind speed Range	Observed occurrence	Observed Frequency	Observed cumulative frequency	Power density
-	(m/s)	-	(%)	(%)	(W/m^2)
1	>0 – ≤1	0	0.00	0.00	0.0
2	>1 – ≤2	30	3.33	3.33	0.1
3	>2 – ≤3	130	14.44	17.78	1.4
4	>3 – ≤4	161	17.89	35.67	4.7
5	>4 – ≤5	175	19.44	55.11	10.8
6	>5 – ≤6	113	12.56	67.67	12.7
7	>6 – ≤7	126	14.00	81.67	23.4
8	>7 – ≤8	75	8.33	90.00	21.4
9	>8 – ≤9	47	5.22	95.22	19.5
10	>9 – ≤10	28	3.11	98.33	16.2
11	>10 – ≤11	7	0.78	99.11	5.5
12	>11 – ≤12	5	0.56	99.67	5.1
13	>12 – ≤13	2	0.22	99.89	2.6
14	>13 – ≤14	0	0.00	99.89	0.0
15	>14 – ≤15	0	0.00	99.89	0.0
16	>15 – ≤16	0	0.00	99.89	0.0
17	>16 – ≤17	1	0.11	100.00	3.0
Total		900	100.00		126.4

Table 4. Observed distribution and the observed power density in spring.

Wind speed class	Wind speed range	Observed occurrence	Observed Frequency	Observed cumulative frequency	Power density
-	(m/s)	-	(%)	(%)	(W/m^2)
1	>0 – ≤1	0	0.00	0.00	0.0
2	>1 – ≤2	4	0.43	0.43	0.0
3	>2 – ≤3	110	11.96	12.39	1.1
4	>3 – ≤4	227	24.67	37.07	6.3
5	>4 – ≤5	206	22.39	59.46	12.1
6	>5 – ≤6	156	16.96	76.41	16.8
7	>6 – ≤7	109	11.85	88.26	19.4
8	>7 – ≤8	57	6.20	94.46	15.6
9	>8 – ≤9	30	3.26	97.72	11.9
10	>9 – ≤10	11	1.20	98.91	6.1
11	>10 – ≤11	2	0.22	99.13	1.5
12	>11 – ≤12	4	0.43	99.57	3.9
13	>12 – ≤13	1	0.11	99.67	1.3
14	>13 – ≤14	3	0.33	100.00	4.8
15	>14 – ≤15	0	0.00	100.00	0.0
16	>15 – ≤16	0	0.00	100.00	0.0
17	>16 – ≤17	0	0.00	100.00	0.0
Total		920	100.00		100.8

Table 5. Observed distribution and the observed power density in summer.

Wind speed class	Wind speed range	Observed occurrence	Observed Frequency	Observed cumulative frequency	Power density
-	(m/s)	-	(%)	(%)	(W/m^2)
1	>0 – ≤1	1	0.11	0.11	0.0
2	>1 – ≤2	11	1.20	1.30	0.0
3	>2 – ≤3	151	16.41	17.72	1.5
4	>3 – ≤4	359	39.02	56.74	9.7
5	>4 – ≤5	221	24.02	80.76	12.7
6	>5 – ≤6	116	12.61	93.37	12.1
7	>6 – ≤7	41	4.46	97.83	7.1
8	>7 – ≤8	15	1.63	99.46	4.0
9	>8 – ≤9	4	0.43	99.89	1.5
10	>9 – ≤10	1	0.11	100.00	0.5
11	>10 – ≤11	0	0.00	100.00	0.0
12	>11 – ≤12	0	0.00	100.00	0.0
13	>12 – ≤13	0	0.00	100.00	0.0
14	>13 – ≤14	0	0.00	100.00	0.0
15	>14 – ≤15	0	0.00	100.00	0.0
16	>15 – ≤16	0	0.00	100.00	0.0
17	>16 – ≤17	0	0.00	100.00	0.0
Total		920	100.00		49.1

III. WEIBULL DISTRIBUTION

Weibull distribution is one of the highly recommended methodologies for representing wind speed probabilities. Many methods developed recently to estimate Weibull parameters [13], the two-parameter method is classified among the most suitable method for representing wind speed data because of its simplicity and flexibility [14]. This method is first introduced by Weibull [15] and applied to many research areas. In this paper, the seasonal Weibull probability density function $f_k(v_b)$ for a wind speed class (b) is expressed by:

$$f_k(v_b)\% = \left(\frac{\alpha_k}{\beta_k}\right)\left(\frac{v_b}{\beta_k}\right)^{\alpha_k-1} e^{-\left(\frac{v_b}{\beta_k}\right)^{\alpha_k}} \cdot 100 \qquad (10)$$

where $\alpha_k$is the shape factor for a season (k); and $\beta_k$is the scale factor for a season (k), m/s. The equivalent Weibull cumulative probability function is expressed mathematically by:

$$F_k(v_b)\% = \left(1 - e^{-\left(\frac{v_b}{\beta_k}\right)^{\alpha_k}}\right) \cdot 100 \qquad (11)$$

Both α_k and $\beta_k$in Equation (10) and (11) must be determined first before applying these equations. There are many methods to estimate the shape and scale factors. In this study two methods are used as it is explained in the sections that follow. Weibull distribution from these equations will be called the "estimated" or "fitted" distribution.

3.1 Power Density Method:

The power density method (PDM) is one of the recommended methods for estimating Weibull parameters. This method has a simple formulation that is easy to implement [16] and is recommended by a previous study conducted on the same area by Alnaas*et al*. [1] based on the mean absolute error (MAE) and the root mean squared error (RMSE). A detailed description of this method can be found in [2, 7, 8, 17]. The procedures to estimate the Weibull parameters using this method are explained in [1]. To estimate Weibull distribution parameters, the observed seasonal average power density ($\bar{P}_{D_k}$)in W/m must be calculated first from:

$$\bar{P}_{D_k}\Big|_{\text{observed}} = \frac{1}{n_k}\sum_{i=1}^{n_k} P_{D_{ik}} = \frac{0.5}{n_k}\sum_{i=1}^{n_k} \rho_{ik} v_{ik}^3 \qquad (12)$$

where ρ_{ik} is defined earlier by Equation (8). Depending on the results of Equation (5) and an initial value of α_k, the seasonal scale factor (β_k) can be estimated from:

$$\beta_k = \frac{\bar{v}_k}{\Gamma\left(1 + \frac{1}{\alpha_k}\right)} \qquad (13)$$

The initial shape factor and scale factor can, then, be used to estimate the average seasonal power density from Weibull distribution. This will be named the "estimated" power density.

$$\bar{P}_{D_k}\Big|_{\text{estimated}} = 0.5\bar{\rho}_k \sum_{b=1}^{N} v_b^3 \cdot f_k(v_b) \qquad (14)$$

Now in order to find the final values of $\alpha_k$and β_k, Equations (11)–(14) must be repeated several times. The final values of shape and scale factors that satisfy Equation (15) are the final solutions. These solutions are summarized in Table 6.

$$\bar{P}_{D_k}\Big|_{\text{estimated}} - \bar{P}_{D_k}\Big|_{\text{observed}} = 0 \qquad (15)$$

3.2 Method of Moments:

Method of moments (MM) is a very simple technique, yet an effective, for estimating Weibull parameters. It was first proposed by [2]. The method requires the use of the average wind speed and the standard deviation. In this method the seasonal shape factor (α_k) can be easily estimated from:

$$\alpha_k = \left(\frac{\sigma_k}{\bar{v}_k}\right)^{-1.091} \qquad (16)$$

The result of applying Equation (16) can be applied directly to Equation (13) to determine the scale factor. A summary and discussion of this method are presented in the section that follows.

IV. RESULTSAND DISCUSSIONS

After performing a simple statistical analysis on the raw wind speed data in Al Khums city, the initial results indicate that the wind speed profile ranges between 4.03 m/s in summer and 5.08 m/s in winter. The average air temperature varies between 14.0 °C in winter and 28.3 °C in summer. The barometric pressure varies between 99.90 kPa in summer and spring and 100.27 kPa in winter. The combined effect of high wind speed and air density (1.218 kg/m^3) in winter results in high wind power density in winter (126.8 W/m^2) followed by spring (100.5 W/m^2) and fall (66.0 W/m^2) with the minimum in summer (48.8 W/m^2) as illustrated in Fig. 1. Fitting of the observed distribution of wind speed to a two-parameter Weibull distribution is then performed using PDM and MM. The estimated seasonal Weibull parameters are presented in Table 6.

Table 6. The estimated values of the seasonal Weibull parameters at 10 m height.

Season	PDM		MM	
k	α_k	β_k, (m/s)	α_k	β_k, (m/s)
1	2.66	4.73	2.78	4.72
2	2.48	5.73	2.55	5.72
3	2.80	5.47	2.97	5.46
4	3.56	4.48	3.78	4.46
Annual *	2.63	5.12	2.78	5.11

* Theses data are adopted from a previous study [1].

The estimated parameters in Table 6 are, then, used to construct the Weibull probability density curves, Fig. 2, by applying Equation (10), and the equivalent Weibull cumulative probability curves, Fig. 3, by applying Equation (11).

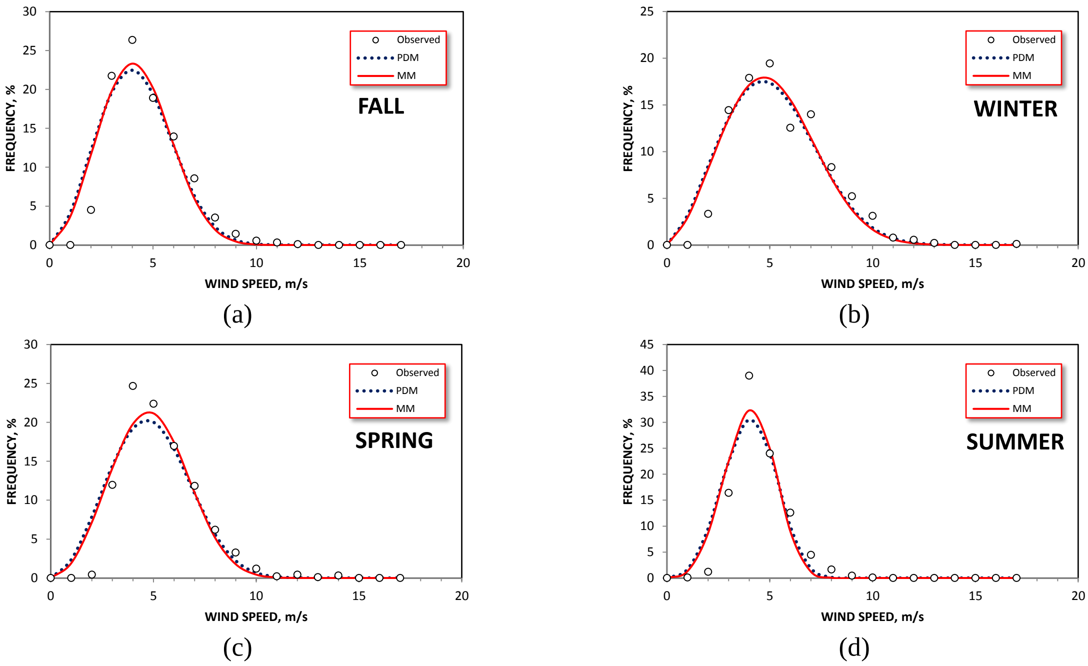
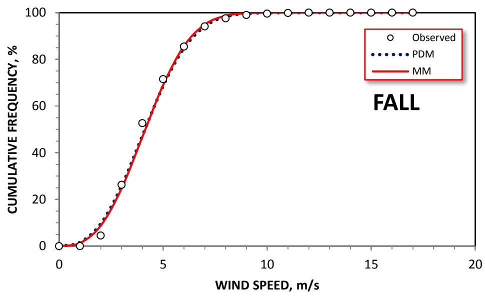
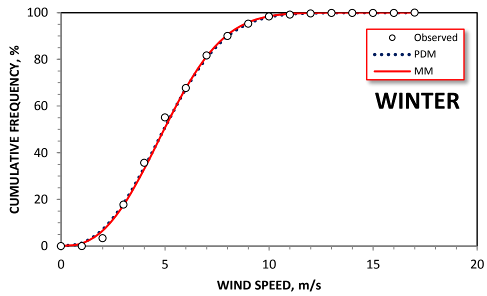


Figure 2. Weibull probability density function in: (a) fall, (b) winter, (c) spring, and (d) summer.

In Fig. 2, fitted Weibull distributions from PDM and MM are compared to the observed distribution for the four seasons. The most probable wind speed occurs around the averages (4.20, 5.08, 4.87, and 4.03 m/s in fall, winter, spring, and summer respectively).



(a)



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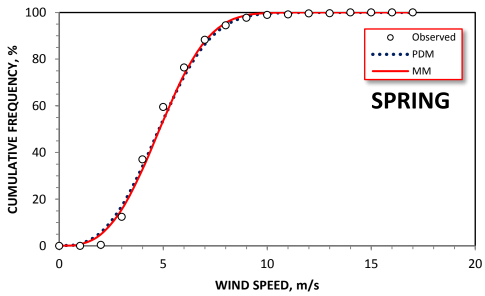
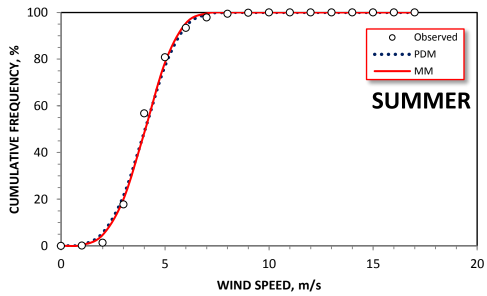


(c)



(d)

Figure 3. Weibull cumulative distribution function in: (a) fall, (b) winter, (c) spring, and (d) summer.

V. CONCLUSIONS

Characterization of wind power density has been performed on Al Khums city by applying simple statistical analysis techniques on a collected data from NASA through RETScreen for 10 years. The initial seasonal analysis reveals that the average wind speed reaches the maximum in winter (5.08 m/s) and the same for the average barometric pressure (100.3 kPa). The average air temperature, however, reaches the minimum (14 °C) in winter. The combined effect of these parameters resulted in high observed power density values in winter reaching 126.8 W/m^2 and low values in summer reaching 48.8 W/m^2. The estimated Weibull parameters by PDM are very close to that estimated by MM, however, the curves show a deviation from the observed curve especially at peak frequencies. It should be noted that this analysis has been performed at 10 meters above the ground level. In order to apply these results in assessing the potential of commercial wind turbines, proper methods must be applied to transform these data into the proper height.

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