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Statistical Wind Data Analysis Based on Weibull Distribution Function for Partial Utility in Agricultural Application (Case Study: Broujerd Province, Iran)

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Abstract

The study presents the statistical analysis of wind data in Broujerd, Iran during a period of 10 years (2012-2021). The wind data have been registered by three-hour intervals at the height of 10 m and it has been taken up a study entitled statistical wind data analysis. In this paper, weibull distribution function has been obtained from the wind data. Two important parameters such as waybill's shape factor and scale factor have also been determined by two methods including the maximum likelihood and least square methods. Judgment criterion for Goodness of fit was performed by chi-square test. The wind speed distribution is represented by the typical two-parameter weibull distribution function for all the months except the 9th month of the year (September). Thus, four-parameter weibull distribution function has been developed to analyze the wind speed frequency distribution for September. The diurnal wind speed curves and wind frequency rose have been drawn and analyzed. Also, mean wind speed and density were calculated. The American schedule classification of wind speed was used to determine the wind speed class. It is found that wind speed has the cycle variation. Peak of wind speed occurs 3 times a day with 8-hour intervals. These peaks are around 5, 12 and 21 GMT. Also the prevailing winds in the region are the winds that blow from the southeast to northwest with some deviation around it and the mean wind speed in winters is greater than for other seasons.

Keywords: Weibull distribution function, Wind direction, Wind power density, Wind speed

آنالیز آماری داده‌های باد با استفاده از تابع توزیع ویبول به منظور تأمین بخشی از انرژی مورد نیاز عملیات کشاورزی (مطالعه موردی: شهرستان بروجرد، ایران)

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چکیده

در این تحقیق تجزیه و تحلیل آماری داده های باد در شهرستان بروجرد مطالعه شده است. اطلاعات مربوطه در یک دوره ۱۰ ساله (۲۰۲۱-۲۰۱۲) و در فواصل سه ساعته در ارتفاع ۱۰ متری ثبت شده اند. در این بررسی از تابع توزیع ویبول به منظور پیشگوئی سرعت باد استفاده شده است. دو پارامتر مربوطه در توزیع ویبول، یعنی پارامترهای شکل و مقیاس توسط دو روش ماکزیمم بزرگ نمائی و حداقل مربعات محاسبه شده اند. به منظور آزمایش نکوئی برازش از آزمون کای اسکوئر استفاده شده است. طبق نتایج حاصل از برازش در ۱۱ ماه از سال، توزیع فراوانی تجربی مطابق با توزیع ویبول دو پارامتره می باشد ولی احتمال تجربی داده های سرعت باد در ماه سپتامبر از تابع ویبول دو پارامتره تبعیت نمی کند، بنابراین برای ماه سپتامبر از تابع توزیع ویبول چهار پارامتره استفاده گردیده است. منحنی روزانه سرعت باد و گلباد هادی مربوطه به تفکیک ماه های مختلف سال ترسیم و بحث شده اند. همچنین میانگین سرعت باد و دانسیته نیز محاسبه شده است. برای مشخص کردن کلاس باد در شهرستان بروجرد از جدول کلاس بندی آمریکائی استفاده شده است. نتایج نشان داد که ماکزیمم سرعت باد در هر روز سه مرتبه و در فواصل زمانی هشت ساعته رخ می دهد و این زمان ها حدوداً در ساعات پنج و ۱۲ و ۲۱ به وقت گرینویچ می باشند. همچنین نتایج نشان داد که جهت باد غالب در منطقه از سمت جنوب شرقی به سمت شمال غربی(با انحراف کمی در اطراف جهات مذکور) می باشد و سرعت متوسط باد در زمستان ها بیشتر از سایر فصول سال می باشد.

واژه‌های کلیدی: تابع توزیع ویبول، جهت باد، دانسیته باد، سرعت باد

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1. Introduction

In recent years, energy and its restrictions may be regarded as one of the most important topics of worldwide problems. Scrutiny about fossil fuels started from the early 1980's. Fossil fuels' utilization causes serious treatments on human health, environment, etc. Therefore, Alternative or Renewable Energies were rapidly improved. Due to the energy demand and growing environmental consciousness, it has become imperative to supplement energy base with alternative energy. Renewable energy is the general name for several kinds of energy that are clean, affordable and durable e.g. sun energy, wind energy and geothermal energy etc.

Wind energy is more effective as it is free and almost available throughout the world. Recently, wind energy has been receiving a lot of attention because of the focus on renewable energies. From many years ago, the utilization of wind power is increasing in many developed countries as well as under developed ones. The wind speed may vary from one location to the others. Nowadays, wind energy conversion system has been extensively used in a lot of countries such as U.S., Germany, Denmark and Netherlands and recently in some regions of Iran and other Asian countries. In the meantime, Iran has already installed some wind turbines for electricity generation in Manjill, Binalood, Qazvin and other suitable sites. According to renewable energy policy of Iran, specific sets of it aim to develop wind energy for electricity generation in various parts of the country. The effective utilization of wind energy entails having a detailed knowledge of the wind characteristics in particular locations. In order to assess the potential of wind energy, the first step is to determine the wind energy potential. These studies have been conducted in many countries. Rehman (2003) performed a study in the east beach of Saudi Arabia and showed that wind energy may be obtained from Small–Scale turbines. He also showd that the long term yearly variation of wind speed provides an understanding of the long term pattern of wind speed and also confidence to an investor on the availability of wind power in coming years. Al Buhairi (2006) studied wind speed in the southwest of Yemen and realized that weibull distribution function is better than Rayleigh distribution function for the estimation of wind density. Sharifi (2005) could estimate wind energy in Qazvin. Satekin (2008) studied wind characterizations in Zabol and determined naught change wind direction as an important advantage of Zabol and It was concluded that this region has a uniform dominant wind from the north-northwest direction also the change in wind direction is not observed abnormally. The distribution of wind speeds is important for the design of wind farms, power generators and agricultural applications like irrigation. In the present scope of study, the weibull distribution function was used. Parameters of weibulll function were estimated by two methods including Maximum likelihood and least square. For the wind speed assessment and the wind class determination, American classification schedule of wind speed has been utilized. In addition to the above, The use of wind turbines in windy areas of the country to replace them with electric pumps, in addition to low maintenance costs, does not impose any social environmental costs on society, is the reason for this research.

2. Material and Methods

2.1. Study area and data set

Broujerd is located in the west of Iran located at 33° 55'N and 48°45'E. Its area is about 1606 km^2 and 1629 m above sea level. It has mountainous climate and is located along Zagros Mountains. The highest peak of it is Valash with 3623 m above sea level. The region is flat with 1500 m above sea level. In this paper, wind data were applied for a period of 10-year. The wind speed and direction were registered by Micherlikh anemometer and wind vane at the height of 10 m from January the 1^{st}, 2012 to December the 31^{st}, 2021. The sampling period is 8 times a day (from 0 to 21 GMT). Wind speeds are frequently measured in integers so that each wind speed is measured many times during the yearling observations .These data were registered in the synoptic station that it has the height of 1629 m with 1012.3 kPaair pressure.

2.2. Continental characteristic and statistic indexes

To analyze the wind characteristics, the first step is to determine the air pressure in the area, and this item obtained from the equation (1) (Manwell, 2002).

$$P = 101.29(0.011837)Z + (4.793 \times 10^{-7})Z^2 \quad (1)$$

Where

Z is the height (m).

Air temperature was obtained from mean monthly so that temperature was determined separately for each month. Air density is different in various months at the special height. The Values of Density Ratio at Altitude (DRA) and Density Ratio at Temperature (DRT) were given by tables (1 and 2) and by Interpolation method.

Table 1. Values of Density Ratio at Altitude in various altitudes

Altitude(m)	0	762	1524	2286	3048
DRA(15.5°C)	1	0.912	0.832	0.756	0.687

Table 2. Values of Density Ratio at Temperature in various Temperatures

Temperature(°C)	-17.78	-6.67	4.44	15.55	26.67	37.78	48.89
DRT	1.30	1.083	1.040	1	0.963	0.929	0.897

Thus, air density was given by equation (2) (Saghafi, 2009).

$$\rho = (DRA.DRT)0.0763 \quad (2)$$

Where

0.0763(lb/ft^3) is the air density at standard condition (15.5°C on the beach of the sea). Then, wind Rose diagrams were drawn. The wind Rose shows the wind frequency in each direction. In this paper, 16 directions of wind rose were used. Actual probability density function was calculated using equation (3) (Rezai, 2005).

$$f_i = \frac{n_i}{N} \quad (3)$$

Where

N is the total number of wind data obtained in a specific month and n_i is the frequency of particular wind speed value.

Then, Skewness Coefficient was given by equation (4) (Rezai, 2005).

$$C.S = \frac{m - Mo}{\delta} \quad (4)$$

Where

C.S is the Skewness Coefficient, m is the mean of wind data (m/s), Mo is the mode, δ is the Standard Deviation (m/s).

Also, Kurtosis Coefficient was given by the use of equation (5) (Rezai, 2005).

$$C.K = \frac{\frac{1}{2}(Q_3 - Q_1)}{P_{90} - P_{10}} \quad (5)$$

Where

Q_1 and Q_3 are the 1st and 3rd quartiles and P_{10} and P_{90} are the 10th and 90th percentiles, respectively.

2.3. Weibull Distribution Function

To predict the probability of each wind speed, the two-parameter weibull distribution function was used. This probability distribution is widely used to describe the long-term records of wind speeds. The probability density function of a Weibull distribution was given according to equation (6) (Eskin, 2007).

$$f(v) = \frac{K}{C}\left(\frac{V}{C}\right)^{K-1} e^{-\left(\frac{V}{C}\right)^K} \quad (6)$$

Where

K is the shape factor (No dimension), C is the scale factor (m/s) and V is the wind speed (m/s).

The cumulative distribution function in which the wind speed will be less than or equal to V is given by equation (7) (Eskin, 2007).

$$F(V) = 1 - e^{-\left(\frac{V}{C}\right)^K} \quad (7)$$

Where:

F (V) represents the probability for the speed V.

There are several methods to determine the shape factor and scale factor. In this paper, two approaches of maximum likelihood method and least squares method have been used. These two methods are subset analytical methods that are preferred to graphical methods.

2.3.1. Least squares method [LSM]

In least squares method, the values of the shape (K) and the scale factors (C) can be determined using least square fitting of the data, i.e. equation (8) (Al-Fawzan, 2000).

$$Y = AX + b \quad (8)$$

Where

X and Y were calculated on the basis of equations (9, 10) (Al-Fawzan, 2000).

$$X = Ln(V_i) \quad (9)$$

$$Y = Ln\{-Ln[1 - P(V)]\} \quad (10)$$

Therefore, regarding K and C factors, it can be calculated using equation (11-13) (Al-Fawzan, 2000).

$$A = \frac{n.\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n.\sum_{i=1}^{n} x_i{}^2 - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i} = k \quad (11)$$

$$B = \frac{1}{n}\sum_{i=1}^{n} y_i - \frac{A}{n}\sum_{i=1}^{n} x_i \quad (12)$$

$$C = \exp\left(-\frac{B}{A}\right) \quad (13)$$

2.3.2. Maximum likelihood estimator [MLE]

In Maximum likelihood method, K factor was determined by equation (14) (Mathew et al, 2002).

$$k = \left[\frac{\sum_{i=1}^{n} v_i{}^k \ln(v_i)}{\sum_{i=1}^{n} v_i{}^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n}\right]^{-1} \quad (14)$$

Where

V_i is the wind speed (m/s) at i time step, and n is the number of time steps.

Then, C factor was given by equation (15) (Mathew et al, 2002).

$$C = (\frac{1}{n}\sum_{i=1}^{n} {v_i}^{k})^{\frac{1}{k}} \quad (15)$$

2.4. The goodness of fit test

The prediction accuracy of the model in the estimation of the wind speeds with respect to the actual values was evaluated based on the Chi-Square Test. This parameter was calculated based on the equation (16) (Mistaya Engineering Inc., 2011).

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i} \quad (16)$$

Where

O_i and E_i are the observation and prospect frequency, respectively.

Specific months when the wind speed distribution is not represented by the typical two-parameter Weibull distribution function and Weibull probability density function is not of a good fit were used with respect to four-parameter Weibull distribution function. The four-parameter Weibull probability distribution function was given by equation (17) (Karta & Ramirez, 2007).

$$fww = \int_0^\infty \frac{K_1}{C_1}\left(\frac{V}{C_1}\right)^{K_1-1} \exp\left[-\left(\frac{V}{C_1}\right)^{K_1}\right] dv + (1 - P)\int_0^\infty \frac{K_2}{C_2}\left(\frac{V}{C_2}\right)^{K_2-1} \exp\left[-\left(\frac{V}{C_2}\right)^{K_2}\right] dv = 1 \quad (17)$$

Where

V is the wind speed (m/s); C_1 and C_2 are the scale factors (m/s) for the right and left in four-parameter Weibull probability function, respectively. K_1 and K_2 are the shape factors (no dimension) for the right and left in the diagram, respectively. P is the weight of probability for the left diagram.

The weight of probability is given by equation (18) (Karta & Ramirez, 2007).

$$V_m = PV_{m_1} + (1 - P)V_{m_2} \quad (18)$$

Where

V_m is the mean wind speed (m/s).

2.5. Estimation of average monthly wind speed and wind power density

The mean velocity can be expressed as equation (19) (Karta & Ramirez, 2007).

$$V_m = c\Gamma(1 + \frac{1}{k}) \quad (19)$$

Where

C is the scale parameter (m/s), K is the shape parameter (no dimension) and Γ is the gamma function (Mathew, 2006).

The mean power density using Weibull probability distributions calculated as follows equation (20) (Celik, 2003)

$$P = \frac{1}{2}\rho c^3 \Gamma[1 + \frac{3}{k}] \quad (20)$$

Where

ρ is the air density (kg/m^3) and Γ is the gamma function given based on equation (21) (Celik, 2003).

$$\Gamma(x) = \int_0^\infty \zeta^{x-1} e^{-\zeta} d\zeta \quad (21)$$

Where

ζ was calculated by the use of equation (22) (Celik, 2003).

$$\zeta = (V_{mi}/c)^k \quad (22)$$

3. Results and Conclusions

3.1 Results

As it has been shown in table 3, the Density Ratio at Temperature in the desired region is 0.959 to 1.049. Also, the Density Ratio at Altitude in Broujerd is 0.821. The air density in the region was shown in table 4.

Table 3. Values of Density Ratio at Temperature in Broujerd

Months	Jan.	Feb.	Mar.	Apr.	Ma.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
DRT	1.049	1.044	1.027	1.014	0.997	0.974	0.960	0.959	0.970	0.986	1.014	1.036

Table 4. Values of air density in Broujerd

Months	Jan.	Feb.	Mar.	Apr.	Ma.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Air density (Kg/m^3)	1.05	1.04	1.03	1.01	1.00	0.97	0.96	0.97	0.97	0.98	1.01	1.03

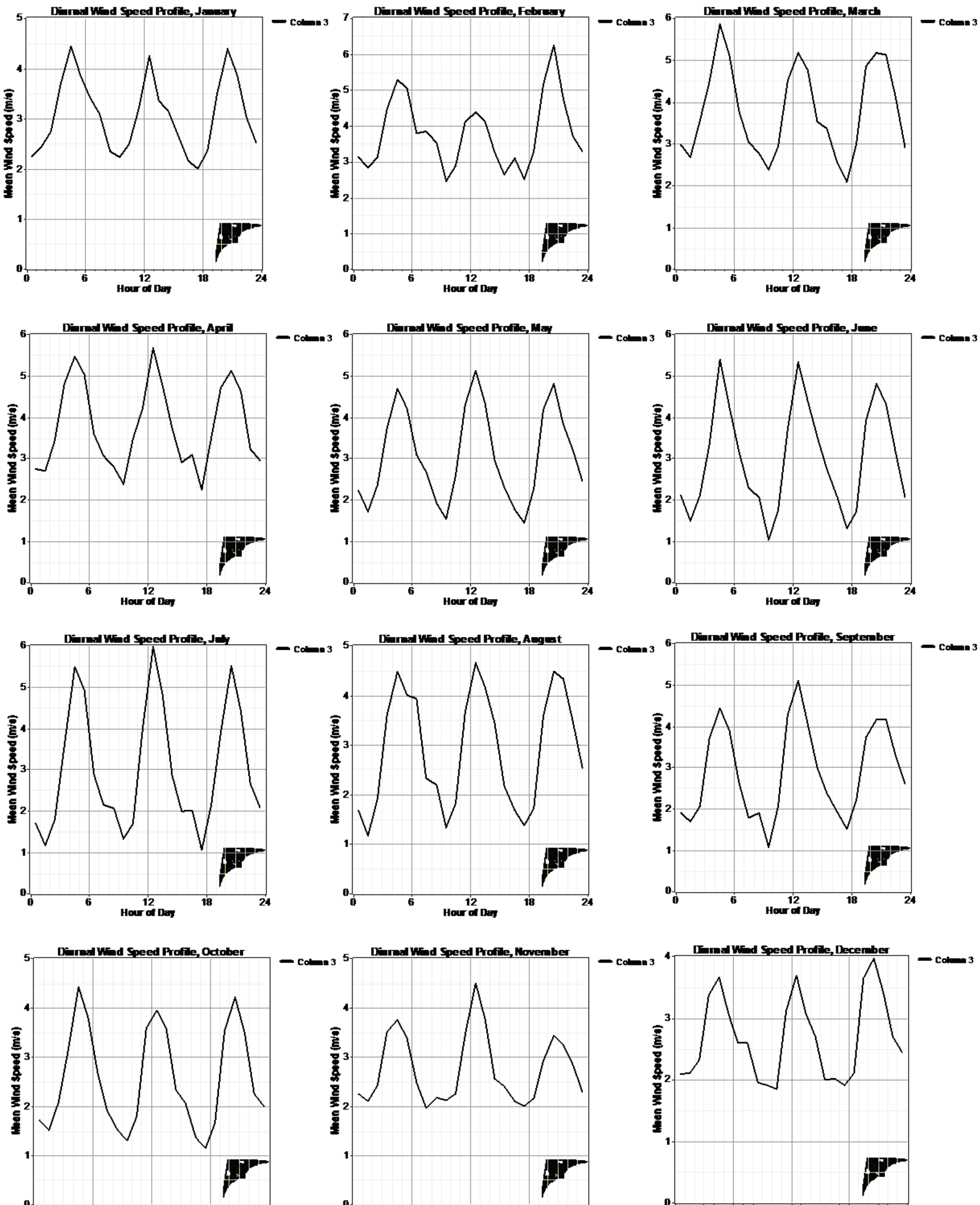

Figure (1) the diurnal wind speed profile concerning the separated months

Figure.1 shows the diurnal wind speed profile concerning the separated months. The diagram shows that wind speed has the cycle variation. Peak of wind speed occurs 3 times a day with an 8-hour interval. These peaks are around 5, 2 and 21 GMT.

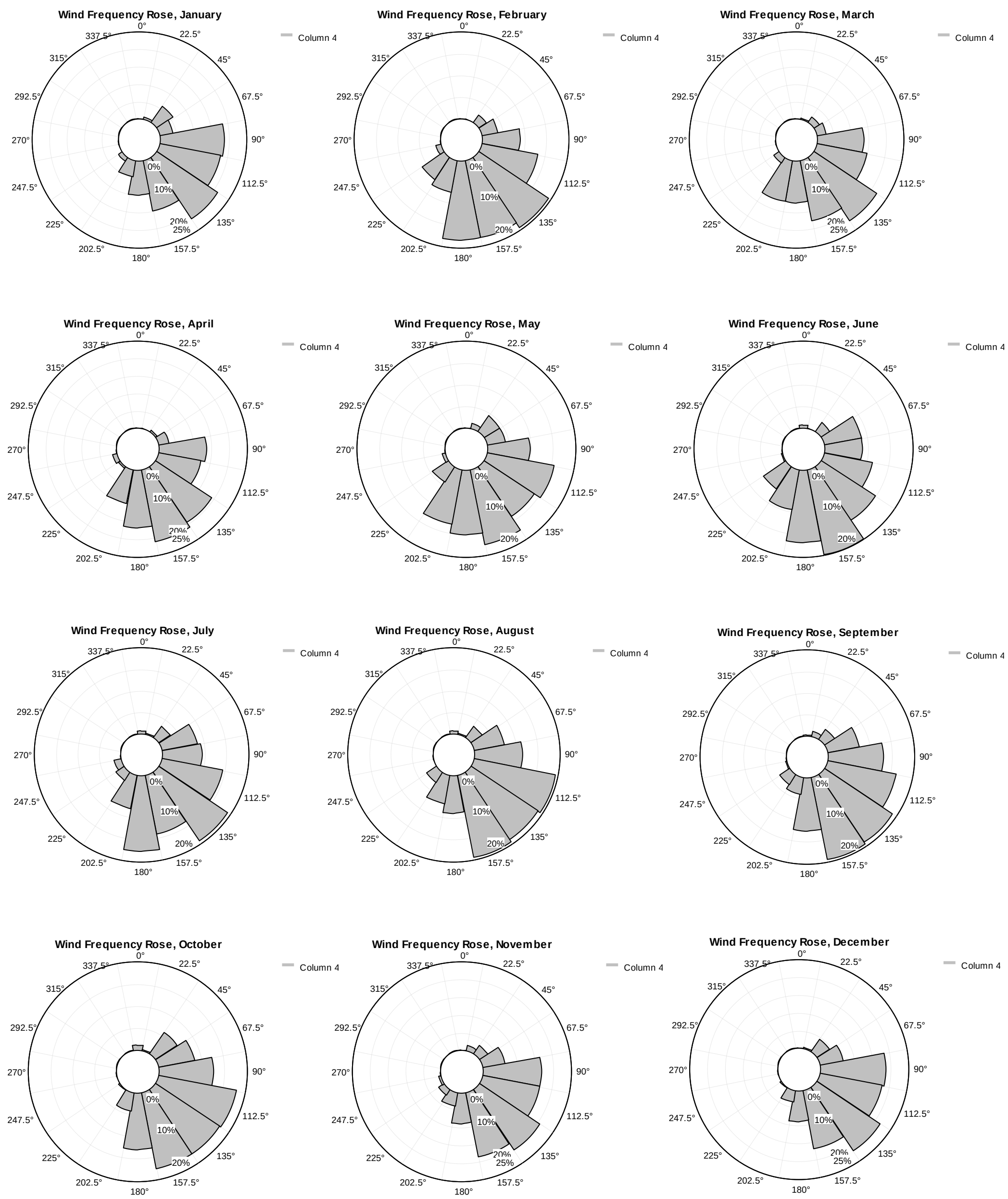

Figure (2) wind direction frequency

Figure (2) shows that the Prevailing Winds in the region are the winds that blow from the southeast to northwest with some deviation around it. Most of these winds have 90°-180° angles. Results of this paper show that the fastest winds in the region often blow from the spectrum of southeast to northwest. Time variations of wind speed show that wind speed at 12GMT (15:30 Tehran time) is maximum and this time wind speed is at least 5 m/s. Minimum wind speed rate is observed at 0GMT (03:30 Tehran time) calculated as 3 m/s. In winter, wind speed is greater than other seasons. The probability of winds blowing between 3-5m/s is around 37% during a specific year. The results of estimating the scale and shape parameters using two methods are shown in table (5).

Table 5. Estimation of shape and scale factors by two methods, maximum likelihood and least square

Months	Maximum likelihood		Least squares	
	K	C	K	C
January	2.764	3.448	2.815	3.441
February	3.047	5.251	3.258	4.227
March	2.800	4.259	2.871	4.239
April	3.153	4.213	3.302	4.192
May	2.471	3.469	2.529	3.452
June	2.217	3.392	2.167	3.400
July	1.930	3.398	1.972	3.379
August	2.199	3.280	2.102	3.299
September	2.212	3.283	2.286	3.261
October	2.199	2.874	2.166	2.884
November	2.730	3.093	2.758	3.096
December	2.949	3.006	3.150	2.989

Correlation coefficient for the parameters with regard to two methods is very high as r is 0.99 and 0.93 for K and C parameters, respectively. It means that there is no significant difference between two methods. The goodness of fit tests was shown in table (6).

Table 6. Goodness of Fit by Chi-Square

Months	Statistics	Critical	Acceptance	Rejection
January	18.744	33.409	*	
February	24.509	37.566	*	
March	22.715	41.638	*	
April	15.888	34.805	*	
May	17.866	32.000	*	
June	24.556	33.409	*	
July	16.468	30.578	*	
August	22.886	33.409	*	
September	37.921	34.805		*
October	27.557	29.141	*	
November	20.790	32.000	*	
December	14.694	30.578	*	

To predict the probability of each wind speed, the two-parameter Weibull function was used. Goodness of fit test given by Chi-Square test has shown that the Wind speed distribution is not represented by the typical two-parameter Weibull function for all the months. Weibull probability density function has a good fit for eleven months but for the 9^{th} month of the year (September), it is not fit. Thus, four-parameter Weibull probability function has been developed to analyze the Wind speed frequency distribution for the mentioned month.

The mean monthly wind speed and mean monthly wind power density were demonstrated in table (7).

Table 7. Mean monthly wind speed, mean wind power density and mean monthly wind power density

Months	Mean monthly wind speed (m/s)	Mean wind power density (W/m^2)	Mean monthly wind power density (KWh/m$^{2/}$/mo)
January	3.07	26	19.34
February	3.80	47	31.58
March	3.79	49	36.45
April	3.77	45	32.40
May	3.07	28	20.83
June	3.00	29	20.88
July	3.00	33	24.55
August	2.91	26	19.34
September	2.90	26	18.72
October	2.55	18	13.39
November	2.75	19	13.68
December	2.68	17	12.64
Total		363	

As table (7) has already shown, the mean wind speed in winters is greater than for other seasons.

Minimum mean power density in the studied region will be obtained in summer and autumn and its maximum will be observed from winter to the outset of spring.

In American schedule classification of wind speed, Broujerd is ranged as the 6th class (300-400) W/m^2 in a year at the height of 10 m.

3.2. Conclusions

Detailed statistical study of wind speed and power is presented at the height of 10 m in Broujerd, Iran. Wind speeds are modeled using Weibull probability function whose parameters are estimated from two different approaches including Maximum likelihood approach and Least squares. It is shown that considering the weibull probability functions, there is no significant difference between two methods in this region. Using Weibull parameters, the mean monthly wind speed and the mean power density in each square meter as well as mean monthly power density are calculated. As the same procedure has been followed in this paper, the region has a suitable position for harnessing wind energy.

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