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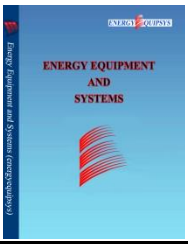

Analysis of prediction models for wind energy characteristics, Case study: Karaj, Iran

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ABSTRACT

Iran is a country completely dependent on fossil fuel resources. In order to obtain a diversity of energy sources, it requires other resources, especially renewable energy. Utilization of wind energy appears to be one of the most efficient ways of achieving sustainable development. The quantification of wind potential is a pivotal and essential initial step while developing strategies for the development of wind energy. This study presents an investigation of the potential of wind power, using two methods—Weibull and Rayleigh—at Karaj, the center of Alborz province of Iran. The wind speed data for a three-hour time interval measured over a 10-year period (2004–2015) was used to calculate and estimate the wind power generation potential. After calculating the factors related to power density and wind energy, it was concluded that data fitting via Weibull distribution was partly better than the Rayleigh distribution function. The RMSE values of Weibull and Rayleigh were respectively 0.018 and 0.013, and R^2 values of Weibull and Rayleigh were 0.95 and 0.97 in Karaj for the years 2004–2015. The wind rose charts of Karaj for the 2004–2015 period show that the most prevalent wind direction is NW (North-West). The wind power density obtained indicates the region is not completely suitable for large on-grid wind farms and related investments. But the region can be suitable for off-grid applications such as water pumping and irrigation, lighting, electric fan, battery charging, and, as hybrid, with other power sources.

Keywords: Wind Power, Wind Energy, Weibull Function, Rayleigh Function.

1. Introduction

Fossil fuel reserves are limited and some negative environmental issues like greenhouse gas emissions, global warming, and environmental pollution have arisen in connection with the utilization of fossil fuels in earlier years, which have led to some undesirable phenomena that have not been previously experienced in known human history. Energy is an essential tool for economic and social development but also poses a lot of environmental challenges. By 2050, the global demand for energy would possibly be double or even triple, as the population rises and developing countries expand their economies. Energy production from renewable energy resources is a part of the solution to the crisis of limited sources of fossil fuels, rapid depletion of their reserves, and the environmental challenges of greenhouse gases [1, 2]. The deleterious impacts of fossil fuels usage have actuated researchers to turn toward clean and renewable energies that are environmentally friendly [3, 4].

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Wind energy—as a major renewable energy—is one of the fastest growing energy sources in the world. Wind energy potential can be enough for more than 35% of the total global energy consumption and is a clean, valuable energy resource in many countries, especially Iran. The total capacity of the installed equipment for harnessing wind energy is more than 282 GW, which is more than 3% of total global energy consumption [5, 6].

The wind energy potential was studied at 45 appropriate locations and it was found that the least potential of wind power in Iran is 6,500 MW [7]. Binalood and Manjil are the leaders in installed wind turbines in the country. In Iran, electrical energy generation via wind power were 47, 82, 91, and 100 MWh in 2006, 2008, 2009, and 2013 respectively [8]. The wind energy potential for three regions, including Chabahar, Kish, and Salafchegan, were studied, based on annual wind speed data, at a height of 10 meters. The annual wind power density of these regions was calculated as 38.88, 111.28, and 114.34 W/m^2 respectively [7]. The wind energy potential was evaluated in Tehran, and it was revealed that the Weibull probability density function could predict the wind speed, and the value of wind power density was calculated in the range of 74–122.48 W/m^2 [9]. The wind energy potential and power density were investigated in Shahre-Babak of Iran. For a four-year period from 2007 to 2010, wind power density and the annual average of wind energy density were estimated at 305.514 W/m^2 and 2676.3 kWh/m^2 at a height of 40 meters [10]. On conducting another study in Booshehr city, the potential of wind energy was assessed, and wind power density was found to be 265 W/m^2 in this region [8]. The wind energy potential and wind energy economic assessment for four different wind turbines were evaluated in Zahedan city. Their results revealed that the Bergey Excel-R turbine—with rated power 7.5 kW—had a maximum rate of electricity production; it is identified as the most economic wind turbine in comparison with Bergey XL.1, Proven 2.5, and Southwest Whisper 500 wind turbines [11].

The aims of this study are to investigate the possibilities of exploitation of wind energy and to calculate the following: The highest probability and optimum wind speeds, comparison and evaluation of Weibull and Rayleigh distribution, wind power and wind energy density, wind energy potential, and assessment of wind direction in Karaj.

2. Materials and methods

2. 1. Site location and case study

Karaj city is the provincial capital of Alborz, and located in the northern central region of Iran. It is located in the south part of Alborz (mountains), at 35°31′ N latitude and 50°10′ E longitude at a height of 1,292 meters above the sea level. It was considered the target station for gathering the required data. The vast Karaj plain is the intercommunication link between Tehran, Ghazvin, Zanjan, and Azarbayjan provinces. Based on the 2011 census results of the statistical center of Iran, the population of Karaj was around 1,614,626, the fourth largest population of Iran (Fig. 1). The city has a relatively cool climate; it is necessary for the application of renewable energy resources to supply energy. In this study, the meteorological data of Karaj were processed in the following parts in order to analyze the regional wind power potential [12].

Fig. 1. Map of Iran and Karaj County.

2.2. Wind data collection description

All wind data for this station were measured with an anemometer and weather cock label, placed at a height of 10 meters above the ground. The wind data collected consisted of speed, direction, and time of record (every three hours and averaged over a day). Other studies indicated that the changes in height have a significant effect on wind speed. This variation in wind speed with altitude is called wind shear; therefore, wind speed will increase with the increase in height. It is essential to determine the wind speeds at the corresponding turbine hub height, because the anemometers and the wind turbine hub height are mostly not equal. The hub height for wind turbines in Iran can be more than 40 meters. The relationship between height and wind speed can be described by the power law method, and the extrapolated wind speeds were determined by using the following equation [13]:

$$\frac{V_2}{V_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \quad (1)$$

where

V_1 = wind speed measured at reference height h_1,

V_2 = wind speed estimated at height h_2, and

α = surface friction coefficient. As it is a variable for different terrain conditions, therefore, α for water, ice, and very flat surfaces is 0.1, for forest and woodlands is 0.25, and for neutral stable conditions is 0.143 [14]. The surface coefficient value was selected equal to 0.143 for this study.

There are various models for describing and analyzing wind speed data. These models are different probability distribution functions (PDFs) like Weibull, Rayleigh, Pearson, Gamma, Chi-2 and so on. Wind speed PDFs show the probability that a particular wind speed is observed in a region. In the present study, Weibull and Rayleigh distribution functions were used because of their high precision in calculating and describing wind data. The distribution function has some advantages—for example, it can be used to calculate the time fraction in which the wind turbine will generate power, and produce a description of wind behavior and statistical parameters like uniformity, average, and variance of wind speed data.

Excel software was used to calculate and draw the wind rose diagram. Finding the overall wind direction by applying the wind rose diagram is important for the purpose of specifying the direction of wind power constructions.

2.3. Wind speed data

The mean wind speed (V_{avg} (m/s)) and the standard deviation (σ) of wind speed data can be calculated using Eq. (2) and (3) respectively [15].

$$V_{avg} = \frac{1}{n}\left[\sum_{i=1}^{n} V_i\right] \quad (2)$$

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(V_i - V_{avg}\right)^2} \quad (3)$$

The most probable wind speed (V_{mp} (m/s)) and optimum wind speed (V_{op} (m/s)) (the maximum energy carrying by wind speed) can be calculated by using following equations [15, 16, 17]:

$$V_{mp} = C\left(\frac{K-1}{K}\right)^{1/K} \quad (4)$$

$$V_{op} = C\left(\frac{K+2}{K}\right)^{1/K} \quad (5)$$

2.4. Weibull and rayleigh distribution

There are various statistical distribution functions, such as normal, lognormal, Rayleigh, and Weibull, for describing and modeling wind speed data. In order to estimate the potential of wind in a specific location, Weibull and Rayleigh probability distribution functions (PDFs) can fit the wind speed data better than other distributions such as: Normal, Lognormal, Pearson, Chi2, etc. In fact, the Weibull and Rayleigh PDFs are special cases of Gamma distribution. The Weibull and Rayleigh PDFs are defined based on the following equations [18, 19]:

$$f(V) = \left(\frac{K}{C}\right)\left(\frac{V}{C}\right)^{K-1} \exp\left[-\left(\frac{V}{C}\right)^{K}\right] \quad (6)$$
$$(K > 0, V > 0, C > 1)$$

$$f(V) = \left(\frac{2}{C}\right)\left(\frac{V}{C}\right)^{2-1} \exp\left[-\left(\frac{V}{C}\right)^{2}\right] \quad (7)$$

where $f(V)$ represents the probability of observed wind speed (dimensionless), V is the wind speed (m/s), K is the shape factor (dimensionless), and C is the scale factor (m/s). Rayleigh PDF is the same as Weibull PDF, in which the shape factor equals 2 (K=2).

The cumulative distribution function $F(V)$ of Weibull can be calculated using Eq. (8). This function represents the probability that the wind speed is less or equal to a specific wind speed [25]:

$$F(V) = 1 - \exp\left[-\left(\frac{V}{C}\right)^{K}\right] \quad (8)$$

The Weibull shape and scale factors (k and c) can be calculated by using the following equations [8]:

$$K = \left(\frac{\sigma}{V_{avg}}\right)^{-1.086} \quad (1 \le K \le 10) \tag{9}$$

$$C = \frac{V_{avg}}{\Gamma(1 - 1/K)} \tag{10}$$

Here, Γ(x) is the gamma function, which is given by [20]:

$$\Gamma(x) = \int e^{-u} u^{x-1} du \tag{11}$$

2.5. Evaluation of weibull and rayleigh distributions

To evaluate the accuracy and performance of Weibull and Rayleigh distributions, the coefficient of determination (R^2), the root mean error (RMSE), mean percentage error (MPE), and mean absolute percentage error (MAPE) must be calculated.

Generally, to calculate the difference between predicted and observed values, Eq. (12) can be used. The RMSE always has a positive value; it is represented as [21]:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(V_{obs} - V_{pre}\right)^2}{N}} \tag{12}$$

The MPE is the mean of all percentage deviations between the observed (actual) and the predicted values. The MPE can be calculated using Eq. (13):

$$MPE = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{V_{pre} - V_{obs}}{V_{obs}}\right) \times 100 \tag{13}$$

The MAPE shows the mean or average percentage difference between the predicted and observed data. The MAPE is represented as [22]:

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{V_{pre} - V_{obs}}{V_{obs}}\right| \times 100 \tag{14}$$

The performance of Rayleigh and Weibull distributions can be evaluated where the model with the lowest values—RMSE, MPE, and MAPE—are validated using Eqs. (12) and (14).

The coefficient of determination (R^2) is the square of the Pearson correlation coefficient. When the R^2 parameter value is close to one, Rayleigh and Weibull perform very well. The R^2 can be represented as [23]:

$$R^2 = \frac{\left(\sum_{i=1}^{n}\left(V_{obs} - \overline{V_{abs}}\right) \times \left(X_{pre} - \overline{V_{pre}}\right)\right)^2}{\sum_{i=1}^{n}\left(V_{obs} - V_{obs}\right)^2 \times \sum_{i=1}^{n}\left(V_{pre} - \overline{V_{pre}}\right)^2} \tag{15}$$

$$\left(0 \le R^2 \le 1\right)$$

The R^2 provides a measure of the linear relationship between the observed and predicted values. Inverse of the RMSE, MPE, and MAPE, the performances of the Weibull and Rayleigh distributions can be evaluated, where the model with the highest value R^2 is validated using Eq. (15).

2.6. Wind power density (PD) and wind energy density (ED)

In order to assess and evaluate the available resource at a specific location, it is necessary to calculate the wind power density. The PD at a specific site shows that how much energy and power are available for conversion to electricity.

Wind power (P) can be calculated as [13]:

$$P = \frac{1}{2}\rho A V_{avg}^3 \tag{16}$$

The PD (wind power per unit area (A)) that A is the area swept by turbine) can be represented as [20]:

$$PD = \frac{P}{A} = \int_0^{\infty} \frac{1}{2}\rho V^3 f(V) dV = \frac{1}{2}\rho C^3 \Gamma\left(\frac{K+3}{K}\right) \tag{17}$$

The air density (ρ) (kg/m^3) in this study was calculated by Eq. (18) [4–9]:

$$\rho = \frac{P}{RT} \tag{18}$$

Here, P is the average air pressure (Pa), T is the average air temperature (K), and R is the gas constant, with a value of 287 J/kgK.

The wind energy density (ED) for a desired duration of time (*T*) can be calculated as [24]:

$$ED = \frac{E}{A} = \frac{1}{2}\rho C^3 \Gamma\left(\frac{K+3}{K}\right) T \tag{19}$$

where *ED* represents the wind energy per unit area swept by the wind turbine (J/m^2) and T is the time of period (h).

2.7. Wind rose

A wind rose diagram gives information about the frequency of wind speeds and distributions of the varying wind directions at a specific site. The evaluation of wind direction in a specific direction order for the purpose of wind energy assessment is essential, playing a very important role in the optimal positioning of a wind farm at the specific site. The wind rose diagram presents the ratio of the number of winds to the total number in a certain direction with the help of several concentric circles, and any wind speed range in each direction is shown by certain colors [25]. In this study, the wind rose diagrams were drawn by Excel. The compass has been divided into eight sectors, 45 degrees for each sector of the horizon. Wind speeds less than 0.5 m/s (1 knot/s) were considered calm winds.

3. Results and discussion

In this study, hourly wind speed data were used to evaluate and analyze the wind energy potential of the Karaj city. A cup anemometer was used to continuously measure wind speed at a height of 10 meters above ground level at the Karaj Meteorological Station. Analyses were then made to obtain the Weibull distribution parameters, including the terms *k* and *c*, mean wind speed, and measured and predicted mean power of wind. The main results can be summarized as follows.

3.1. Monthly and yearly mean wind speed

The calculation of the wind potential was undertaken by analyzing the collected wind data characteristics, such as the wind speed, direction, duration, and availability. The time series have been analyzed by grouping the hourly data month by month. The reason for subdividing the yearly data into monthly periods is that the wind has relatively homogenous behavior within a month. The following Figures and Tables show the results of the wind data analysis.

The yearly and monthly standard deviations (σ) and mean wind speeds (V_{avg}) for Karaj (2004–2015) are depicted in Table 1 and Fig. 2. In Fig. 2, the trends of mean wind speeds are considered. The results showed that the mean wind speeds values ranged between 0.85 and 4.24 m/s. The highest and lowest value of mean wind speed were in July 2009 and November 2010. The standard deviation values are variable from 0.54 to 1.88 m/s. The maximum and minimum standard deviation values belonged to July 2014 and May 2015. The whole year values of mean wind speeds ranged from 1.86 to 3.37 m/s. The highest and lowest monthly wind speed values belonged to July and December respectively, with values of 3.37 and 1.86 m/s.

Table 1. Yearly mean wind speeds and standard deviations in Karaj, Iran

Month	Parameter	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Whole year
January	V_{avg}	-	1.56	1.79	1.49	2.19	2.74	2.63	2.19	2.98	2.10	2.75	2.55	2.27
	σ	-	1.03	1.23	0.95	0.94	1.18	1.04	0.91	1.54	1.31	0.93	0.98	1.09
February	V_{avg}	-	2.10	2.83	2.75	3.00	3.38	2.48	3.00	2.91	2.33	2.62	2.83	2.75
	σ	-	1.53	1.20	1.31	1.45	1.36	1.06	1.25	1.70	1.25	0.89	1.17	1.29
March	V_{avg}	-	3.27	3.50	3.65	3.50	3.52	2.72	2.48	3.76	2.80	3.56	3.06	3.26
	σ	-	1.85	1.71	1.04	1.21	1.11	1.09	1.29	1.22	1.26	1.41	1.15	1.30
April	V_{avg}	3.28	3.3	3.24	2.53	3.13	3.27	2.82	2.92	2.94	2.55	3.47	3.24	3.06
	σ	1.63	1.56	1.26	1.03	1.30	1.04	1.22	1.32	1.11	0.80	1.01	0.78	1.17
May	V_{avg}	3.96	2.31	3.08	2.88	3.40	3.10	2.39	3.47	3.55	3.10	3.27	2.64	3.09
	σ	1.37	1.88	0.91	1.13	0.89	1.15	0.93	1.24	1.17	1.08	0.97	0.77	1.12
June	V_{avg}	3.02	2.78	2.63	3.75	4.12	3.01	2.03	3.89	3.13	3.52	3.57	3.48	3.24
	σ	1.23	1.21	1.09	1.06	0.91	0.95	0.84	1.12	0.91	1.17	0.84	0.79	1.01
July	V_{avg}	2.58	2.88	3.58	4.10	3.55	4.24	2.82	3.14	3.65	3.41	3.60	2.87	3.37
	σ	1.53	0.88	1.11	1.01	1.06	1.05	0.96	1.07	1.12	1.15	0.54	0.84	1.03
August	V_{avg}	2.04	2.81	1.99	2.91	2.54	4.04	2.12	3.44	2.18	2.69	2.68	2.65	2.68
	σ	0.98	0.89	0.77	0.82	0.77	1.22	0.93	1.31	1.10	1.13	0.79	0.82	0.96
September	V_{avg}	1.68	2.34	2.47	2.29	2.83	3.03	1.75	2.74	2.03	2.07	2.75	2.32	2.36
	σ	0.98	0.97	1.16	0.98	0.975	1.12	0.97	0.97	1.09	0.86	0.70	0.65	0.95
October	V_{avg}	1.57	1.90	2.31	2.10	2.72	2.00	1.61	2.63	1.17	1.86	2.71	-	2.05
	σ	1.32	1.34	1.02	1.15	0.97	0.87	0.70	1.40	0.69	1.29	0.85	-	1.06
November	V_{avg}	2.42	1.88	1.96	1.35	2.46	2.65	0.85	2.63	1.45	1.35	2.27	-	1.94
	σ	1.18	1.59	0.88	0.92	0.72	1.22	0.71	1.39	1.10	0.80	0.75	-	1.02
December	V_{avg}	1.71	1.94	1.67	1.22	2.34	1.98	1.69	1.84	1.50	2.55	2.01	-	1.86
	σ	1.11	1.22	0.95	0.82	0.99	0.89	0.97	0.93	1.04	0.82	0.74	-	0.95
Yearly	V_{avg}	2.47	2.42	2.59	2.59	2.98	3.08	2.17	2.86	2.60	2.53	2.96	2.85	2.67
	σ	1.45	1.40	1.23	1.28	1.11	1.23	1.09	1.29	1.39	1.20	0.97	0.94	1.21

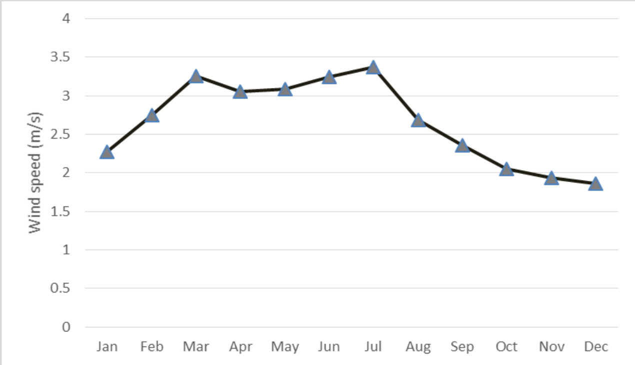

Fig. 2. Monthly wind speed in Karaj.

Table 2. Shape and scale factors and characteristic wind speed in Karaj.

Year	K (dimensionless)	C (m/s)	V_{mp} (m/s)	V_{op} (m/s)
2004	1.71	2.56	1.61	3.90
2005	1.81	2.53	1.62	3.81
2006	2.23	2.89	2.22	3.85
2007	2.14	2.85	2.13	3.88
2008	2.90	3.58	3.10	4.29
2009	2.70	3.63	3.06	4.46
2010	2.07	2.36	1.72	3.28
2011	2.36	3.25	2.58	4.22
2012	1.97	2.80	1.96	3.98
2013	2.24	2.83	2.18	3.76
2014	3.36	3.68	3.32	4.23
2015	3.31	3.54	3.18	4.08
Average	2.41	3.04	2.39	3.98

Table 2 shows the shape and scale factor, most probable wind speed, and optimum wind speed parameters in Karaj for 2004 to 2015. The K parameter value ranged between 1.71 and 2.90, with an average value of 2.41. The C parameter is variable from 2.36 to 3.68 m/s. The V_{mp} and V_{op} parameters values are dependent completely on the K and C parameter values. The results showed that the highest K, C, V_{mp}, and V_{op} parameter values were obtained in 2014, while the lowest values of K and V_{mp} parameters appeared in 2004, and the C and V_{op} parameter values were seen in 2010 (Table 2). The V_{mp} parameter value is a variation between 1.61 and 3.32 m/s. The highest and lowest the V_{op} parameter values are between 4.23 and 3.28 m/s.

3.2. Diurnal wind speed variations

Diurnal speed variation is one of the interesting outcomes of wind energy analysis. The diurnal wind speed variations of all seasons are showed in Fig. 3. It is obvious that the maximum wind speed occurs at noon and the daytime is windy for all years and seasons, while it is very calm at midnight. The wind speed starts to increase around 3 a.m. and peaks at noon. After that, the afternoons are characterized by decreasing wind speeds. If the energy demand is higher in the daytime, there is a good coincidence between the energy demands and the characteristics of the Karaj wind speed, since normally the energy demand is higher in the daytime.

3.3. Evaluation of weibull and rayleigh distributions

Figure 4 shows the comparison of two predicted models (Weibull and Rayleigh) and observed wind speeds in Karaj for 2004 to 2015. The RMSE, MPE, MAPE, and R^2 parameters were considered to evaluate the observed mean wind speed for the Weibull and Rayleigh PDFs. The RMSE values for Weibull and Rayleigh are respectively 0.018 and 0.013. The MPE parameter values for the two predicted models are 54.33% and 60.55%, while the MAPE parameters for the two predicted models mentioned above are 84.30% and 77.12% respectively. Table 3 shows that R^2 values for the Rayleigh and Weibull are 0.97 and 0.95 respectively. Therefore, the Rayleigh distribution is better for fitting the observed wind speeds than Weibull.

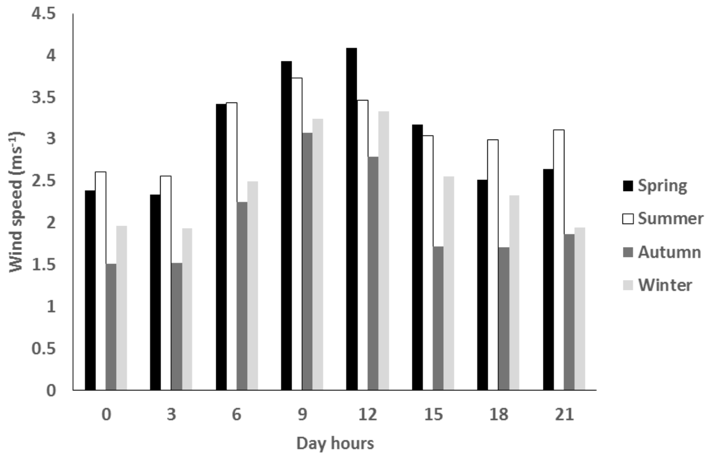

Fig. 3. Diurnal wind speed variations of Karaj

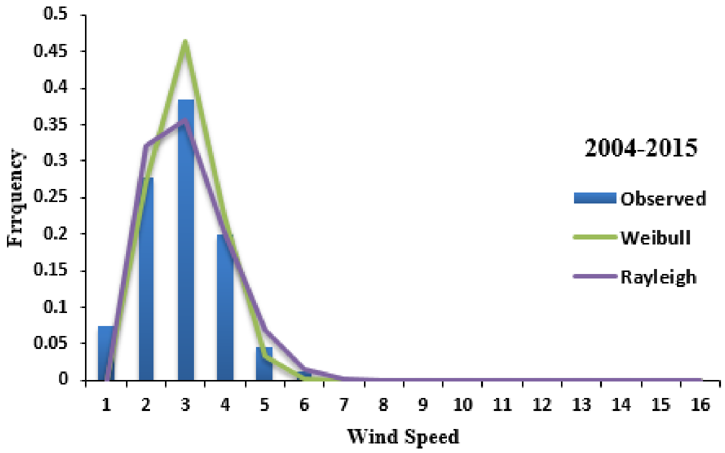

Fig. 4. Comparison of predicted and observed wind speed frequencies of Karaj

Table 3. Evaluation of Weibull and Rayleigh distributions

Indicator	Weibull	Rayleigh
RMSE	0.018	0.013
MPE	54.33%	60.55%
MAPE	84.30%	77.12%
R^2	0.95	0.97

3.4. Wind power and wind energy density

The wind power density (PD) and wind energy density (ED) were calculated for observed wind speed and two predicted models at a height of 10 meters in Karaj. The highest of the produced PD and ED parameter values, using observed wind speeds, were 30 W/m^2 and 261.5 kWh/m^2; these were recorded in 2009 (Table 4). Table 4 also shows that the predicted PD values by the Weibull and Rayleigh models ranged from 9 to 27 W/m^2 and 10 to 35 W/m^2, with average values of 18 and 22 W/m^2 respectively. The average predicted PD value for the Rayleigh distribution is closer to the observed PD value than the Weibull distribution. The ED values for the observed wind speed, and predicted by the Weibull and Rayleigh distributions, ranged from 118.72 to 261.5, 80.46 to 239.2, and 83.48 to 302.49 kWh/m^2. The highest and lowest PD and ED values belonged to 2009 and 2010. Figures 4 and 5 show diagrams of observed and predicted the PD and ED values in Karaj for all the years from 2004 to 2015.

Table 4. Wind power and wind energy density in Karaj

Year	Observed PD (w/m^2)	Predicted PD		Observed ED (kWh/m^2)	Predicted ED	
		Weibull	Rayleigh		Weibull	Rayleigh
2004	23	14	12	154.84	91.31	79.78
2005	22	13	12	194.05	114.17	101.93
2006	22	16	17	193.00	137.08	152.32
2007	21	16	17	187.85	136.57	146.27
2008	26	25	33	228.00	221.20	289.81
2009	30	27	35	261.50	239.20	302.49
2010	14	9	10	118.72	80.46	83.48
2011	26	21	25	230.20	186.98	216.96
2012	24	16	16	213.56	139.77	138.24
2013	20	15	16	170.94	128.66	143.54
2014	23	26	36	198.63	223.74	310.07
2015	20	23	32	133.69	151.22	208.64
Average	23	18	22	190.00	154.00	181.00

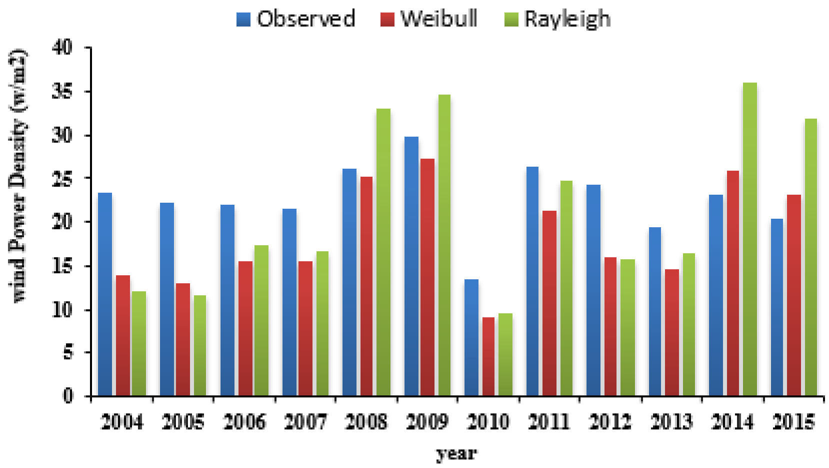

Fig. 5. Wind power density in Karaj

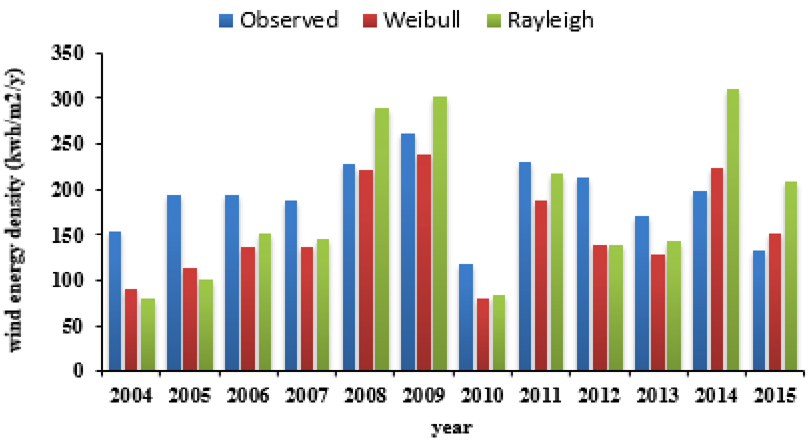

Fig. 6. Wind energy density in Karaj

In order to use ensure that suitable wind turbines are used for the production of electricity in a specific region, the calculation of the wind speed and the power density at greater heights is essential. Table 6 and Fig. 7 show variations in the trend of wind speed at different heights.

Table 5. Wind speed and wind power density at different the heights.

	Height (m)	V_{avg} (m/s)	PD (W/m^2)
2004–2015	10	2.67	23
	20	2.95	40
	30	3.14	47
	40	3.26	59
	50	3.38	65

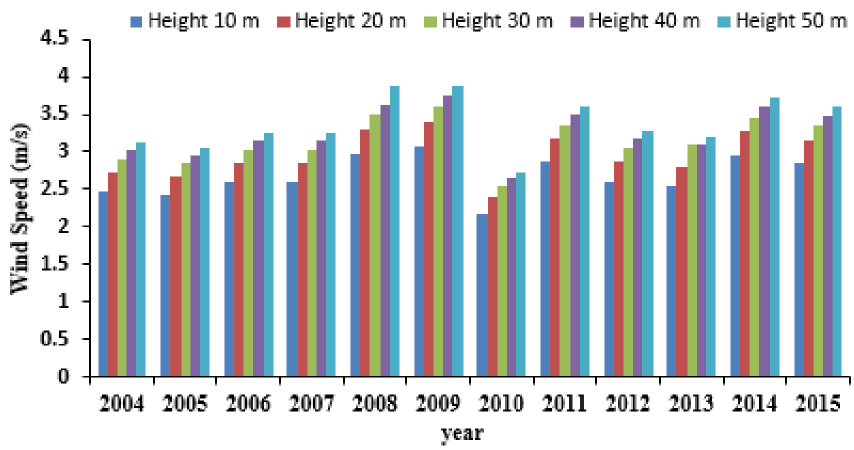

Fig. 7. Wind speeds at different heights in Karaj

3.5. Wind rose

In order to find out the overall wind direction frequency, the wind rose diagram was drawn for Karaj (for the period 2004 to 2015). Figure 8 shows the prevailing wind direction in Karaj: It can be seen that the prevailing wind direction is from 270° north clockwise to 315°. The WNW (west-north-west) direction—with 18.56% frequency—has the highest frequency. The other directions are: West with 16.4% frequency, NW (north-west) with 14.01% frequency, and SSE (south-south-east) with 11.37% frequency. Figure 9 shows the wind direction frequency in Karaj for all years (2004–2015). The results indicated that the highest and lowest wind frequencies belonged to west-north-west and north-east respectively.

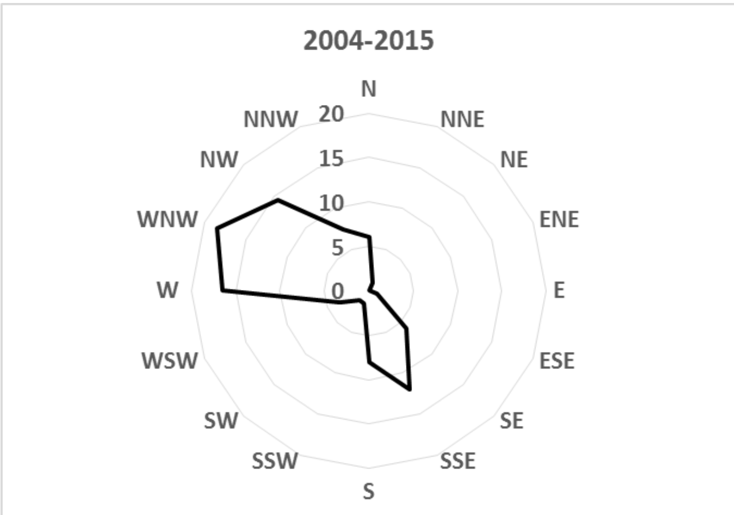

Fig. 8. Wind rose diagram.

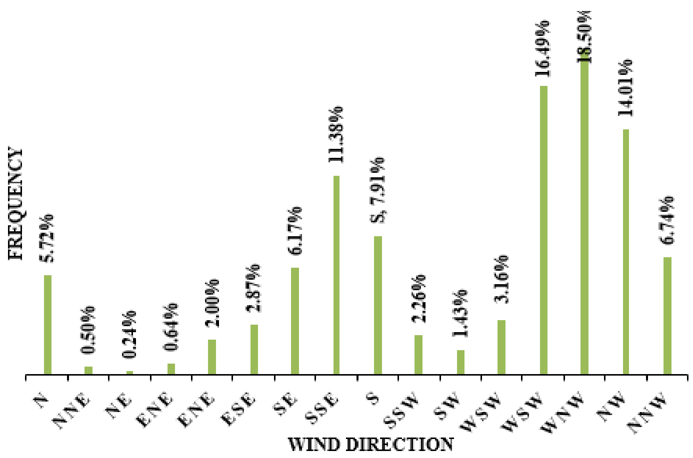

Fig. 9. Wind direction frequency in Karaj (2004–2015)

4. Conclusion

The measured wind speed data—with the interval period of three hours for Karaj city at a height of 10 meters—were evaluated from January 2004 to December 2015; the most important outcomes from the statistical analysis are presented as follows. The shape factor (K) and the scale factor (C)—as the parameters of Weibull and Rayleigh PDFs—were calculated. The observed power density (PD) and energy density (ED) values with the predicted values by Weibull and Rayleigh PDFs for all years (2004 to 2015) in Karaj County were compared. In addition, the directions and percentages of the prevailing wind were determined for Karaj County, using Excel, for all years from 2004 to 2015. The most important results are as follows:

- The average of yearly wind speed is in the range of 1.61 to 3.32 m/s. The maximum wind speed was related to several months, including March, April, May, June, and July, with vales higher than 3 m/s, whereas the minimum wind speed was related to November and December, with values lower than 2 m/s in this period. Since the minimum required speed to launch turbine blades is about 4 to 5 m/s, this wind speed range is not enough to supply electricity. In the studies carried out in some Iranian cities, the average wind speed of Karaj is in the same range with Zahedan, Tabriz, and Chabahar commercial regions, but in comparison with other cities, including Tehran (Iran's capital), Binalood, Booshehr, Ardebil, Kish, Salafchegan, and Shahre-Babak, it has lower wind speeds.
- The average power density values of real, Weibull, and Rayleigh were 23, 18, and 22 W/m^2. Also, the average energy density values were 190, 154, and 181 kWh/m^2 respectively.
- Diurnal speed variation analysis showed that the maximum wind speed occurs at noon and the daytime is windy for all years and seasons, while the midnight time is very calm. If the energy demand is higher in the daytime, there is a good coincidence between the energy demands and the wind energy.
- The Weibull and Rayleigh distribution functions predicted the observed data with 95% and 97% probability. The RMSE, MPE, and MAPE for Weibull distribution were 0.018, 54.33%, and 84.33%, whereas those for Rayleigh distribution were 0.013, 60.55%, and 77.12% respectively.
- The prevailing wind in Karaj is in west-north-west (WNW) direction in the statistical period of study from 2004 to 2015.

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