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Research Article

Statistical Analysis of Wind Characteristics and Wind Energy Potential Based on Weibull Distribution in Bingol Province, Turkey

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Abstract : In this study, the statistical analysis of wind energy density and wind speed distribution parameters in Bingol province was examined using hourly wind speed data measured by the General Directorate of Meteorology between 2014 and 2017. Weibull distribution was used for statistical modeling and k and c parameters were calculated for 10 m and 30 m height. According to statistical criteria, in the wind data analysis of Bingol province, it was determined that the months with the highest potential in terms of mean wind speed and wind power densities are March, April and May. In the months when mean wind speeds are the highest, the dominant wind direction is south. As a result, it is concluded that the average monthly and annual power densities in Bingol province are about 100 W/m^2. It is determined that the wind potential of the region can be used for small scale off-grid wind applications. The fact that the average speed is mostly higher than 4 m/s for a 30 m hub height has shown that electrical energy generation from wind energy is promising.

Keywords : Renewable energy; Wind Characteristic; Wind Energy Potential; Weibull Distribution; Wind frequency distribution

1 Introduction

In general, winds that occur because of temperature changes in the atmosphere start with the density difference or pressure variations of the points of equal height [1]. The winds formed because of these effects can be used as an alternative energy source to fossil fuels. Generating electricity using wind energy which is undoubtedly the cleanest among energy resources, provides environmental, social, and economic advantages [2]. The need to research alternative energy sources has arisen with the population and energy consumption in the world. Therefore, many scientific studies have been conducted on wind energy and wind characteristics in recent years [3]–[7]. In addition, wind characteristics are needed to investigate the effects of winds on structures. As a result of the use of fossil fuels which are the most used energy source for increasing energy consumption in today's world, carbon dioxide and greenhouse gases are released, which causes global warming by trapping the heat in the atmosphere. Therefore, the utilization of renewable energy resources has come into prominence. The potential shortages in traditional resources can be compensated by using abundant renewable resources such as wind, solar and biomass energy. Wind energy is a clean energy source, it does not cause environmental pollution and CO2 emission. Today, wind energy is used at increasing rates day by day, although it is not at a level to close the energy gap, which is still needed and becomes a bigger problem day by day. It has been observed in many studies that regional wind energy potentials have been tried to be determined [8]–[13]. First of all, the wind characteristics of the region were revealed to determine the compatibility of the study area regions with wind energy generation. In a site where a wind power plant is planned to be established, the wind characteristics of that region should be analyzed to benefit from the wind energy potential at the maximum level and in the most efficient way. The uncontrollable nature of the wind in unstable fluctuation can lead to various problems in terms of its use as an energy source. Before deciding the wind energy potential of a region, it is necessary to determine wind characteristics such as observed frequency distributions of wind speed, wind energy density, prevailing direction of wind speed, and seasonal changes of wind [14]. Besides, wind data should be analyzed since it is not available to generate energy from every wind speed. To analyze the wind energy potential of any region, hourly wind speed and direction information must be measured for at least one year in the region, and wind measurements are generally made in the range of 10-30 meters [15]. The change in wind speed is characterized by a probability distribution function [4]. In the studies, the wind speed frequency distribution is shown using various probability density functions such as log-normal function, gamma function, beta function, Rayleigh and Weibull distributions [5], [16], [17]. On the other hand, the two-parameter Weibull distribution and one parameter Rayleigh distribution are methods used to represent the wind distribution of many regions of the world [11], [18]–[20]. Since Rayleigh distribution is single parameter, it is less flexible than two-parameter Weibull; however, its parameters are easier to calculate. The Weibull distribution is preferred as the Rayleigh distribution is a special case of the distribution [21]. It can be said that the most suitable probability distribution for wind speeds is the Weibull distribution [3], [4], [22]–[24]. The versatile two-parameter Weibull distribution is widely used to fit the measured wind speed probability distribution. When considering the annual average wind speeds on land and sea, Turkey has more wind power potential compared to many European countries [25]. By determining the average wind speeds and wind power densities in regions with high wind energy potential, companies that will invest in this sector will be encouraged. The purpose of this study is to reveal the wind resource potential of Bingol located in eastern Turkey and to make a preliminary study to determine whether wind energy can be obtained from the region and the areas where this energy can be used. By determining the parameters (k and c) of Weibull distribution, it was ensured that wind characteristics of Bingol were revealed. For this purpose, hourly measured 4-year (2014-2017) wind speeds obtained from a meteorological wind station in Bingol were evaluated within the scope of the study.

2 Data and Methods

2.1 Data

Time series of hourly wind speed data measured from Bingol Airport station for the period between 2014 and 2017 were provided by Turkish State Meteorological Service. All wind measurements were obtained at an anemometer height of 10 m above ground level. The altitude of the airport in Bingol province located in eastern Turkey is 1063 meters. In addition to analyzing the 4-year wind speed data with the distribution form stated below, the dominant wind directions have been determined using wind roses.

2.2 Probability Distribution Model

Correct determination of the probability distribution of wind speed is a prominent factor in evaluating the wind energy potential in a region. If wind is measured over a year, it is generally seen that very strong winds are seldom, moderate, and strong winds are more likely to occur. In order to determine the wind energy potential, it is necessary to know the distribution of wind speeds at a given site. There are many methods to determine wind speed distributions. In the literature, the Weibull distribution is generally used in the statistical analysis of wind data. Wind distribution for a site is determined either by measuring or by Weibull distribution at different points and heights based on measurements. Many methods such as the method of moments, maximum likelihood estimation (MLE) and least squares are used to determine the Weibull distribution. However, it was stated that the MLE is the most effective method in determining the parameters of the Weibull distribution function [13], [26]–[28]. The probability density function expression of the Weibull distribution is as in Equation (1) and has two parameters. Where k represents the shape parameter and c represents the scale parameter. To determine these parameters, wind speed measurements made at short intervals are required be spread over a long time.

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1}\exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{1}$$

Actually, the scale parameter c indicates how windy a considered wind position is, while the shape parameter k indicates how much the wind distribution peaks [18]. The Weibull distribution can be characterized by the cumulative distribution function $F(v)$ given in Equation (2). As well v represents the wind speed; the parameters k and c in this equation are the same as those in the probability density function. The Weibull cumulative distribution function gives the probability that the wind speed will occur less than or equal to a certain value of v.

$$F(v) = \int_0^v f(v)dv = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

In this study, MLE method was used to determine the k and c parameters. The k parameter of the Weibull distribution is determined iteratively as in the following equation.

$$k = \left[\frac{\sum_{i=1}^{N} v_i^k \ln(v_i)}{\sum_{i=1}^{N} v_i^k} - \frac{\sum_{i=1}^{N}\ln(v_i)}{N}\right]^{-1} \tag{3}$$

Once k parameter is calculated, c parameter is decided with the following equation.

$$c = \left(\frac{\sum_{i=1}^{N} v_i^k}{N}\right)^{\frac{1}{k}} \tag{4}$$

Table 1: Land-cover classes, Hellman coefficient (μ) values [29]

Terrain	Hellmann coefficient (α)
Lake, ocean and smooth hard ground	0.10
Foot high grass on level ground	0.15
Tall crops, hedges, and shrubs	0.20
Wooded country with many trees	0.25
Small town with some trees and shrubs	0.30
City area with tall buildings	0.40

The mean wind power density is used to determine the wind energy potential of a particular site. The mean power density per unit area for the Weibull distribution is expressed in Equation (5). Here ρ is the density of the air ($1.05kg/m^3$ for the given site), Γ is the gamma function.

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

Following the Weibull distribution, Equations 6 and 7 are used in calculating the average wind speed and standard deviation of the wind speed, respectively. Standard deviation is a statistical measure that shows the spread of the most used data for quantitative scaled numbers relative to the mean. The low values of the standard deviation indicate that the data tends to be very close to the mean, thus it reveals the distribution of wind speed values.

$$v_m = c\Gamma\left(1+\frac{1}{k}\right) \tag{6}$$

$$\sigma = \sqrt{c^2\left[\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)\right]} \tag{7}$$

Generally, the wind speed measurements are carried out at a height of 10 m from the earth's surface. The hub's height must be at least 30 m above the ground to obtain the energy from the wind turbines. Thus, it is necessary to estimate wind speeds at higher elevations using wind speed data from lower elevations. Wind speed data measured at a certain height can be transferred to various heights using Equation (8).

$$V = V_{ref}\left(\frac{H}{H_{ref}}\right)^{\mu} \tag{8}$$

The symbols used in this Equation are defined as follows:
V : Wind speed at the desired height (m/s),
V_{ref} : Wind speed at reference altitude (m/s),
H : Desired height (m),
H_{ref} : Reference height (m),
μ : Hellmann coefficient.
Hellmann coefficient (μ) values are given in Table 1 for different terrains.

3 Analysis Results and Discussion

In this study, 2014-2017 wind speed data for Bingol, Turkey were analyzed using the Weibull distribution. After deciding on Weibull parameters, mean wind speed, standard deviation and mean power density values were calculated. The wind characteristics of Bingol province were tried to be revealed by evaluating the prevailing wind directions and wind speed data according to months and years and the results obtained were examined under the headings below.

3.1 Statistical Distributions

Using the Weibull distribution, k and c parameters were determined, and mean wind speed and standard deviation values were calculated according to the relevant equations (Table 2). In Table 2; SD defines Standart Deviation, W defines Weibull Distribution. It is seen in Table 2 that Weibull k parameter varies between 1.40 and 2.59, while c parameter varies between 2.25 and 5.34 at 10 m height. At 30 m, the k parameter does not change, but the c parameter varies between 2.74 m/s and 6.51 m/s. As a result of the examination of monthly wind speeds, it was determined that the highest mean wind speeds occurred in March, April and May at 10 m height. Based on 4-year wind speeds, the months with the highest k parameter are July and August at 10 m height. In addition, the c parameter reached its highest value in March, April, May, June, July, and August. When wind speeds for 30 m height are evaluated, the highest mean wind speed, standard deviation, and the k and c parameters were realized in similar months at 10 m height. It has been observed that wind speeds, standard deviation and c parameter increase with increasing height. The lowest mean wind speeds were obtained in the winter months (November, December, January and

Table 2: Monthly mean wind speeds, standard deviations, and Weibull parameters for 10 m and 30 m

Year	Month	Mean WS (m/s) (10m)	SD (m/s) (10m)	W k (10m)	W c (10m)	Mean WS (m/s) (30m)	SD (m/s) (30m)	W k (30m)	W c (30m)
2014	Jan	1.99	1.06	2.01	2.25	2.43	1.29	2.01	2.74
2014	Feb	3.85	3.00	1.40	4.22	4.68	3.65	1.40	5.14
2014	Mar	4.56	2.18	2.14	5.15	5.55	2.66	2.14	6.27
2014	Apr	3.59	2.20	1.73	4.02	4.37	2.68	1.73	4.90
2014	May	3.04	2.06	1.66	3.40	3.71	2.51	1.66	4.15
2014	Jun	3.34	1.82	2.03	3.77	4.07	2.22	2.03	4.59
2014	July	3.47	1.90	2.07	3.92	4.23	2.31	2.07	4.78
2014	Aug	3.26	2.20	1.80	3.67	3.98	2.68	1.80	4.47
2014	Sept	3.39	1.97	1.92	3.82	4.13	2.40	1.92	4.65
2014	Oct	2.78	2.01	1.66	3.11	3.38	2.45	1.66	3.79
2014	Nov	2.25	1.38	1.77	2.53	2.74	1.69	1.77	3.08
2014	Dec	2.41	1.23	2.09	2.72	2.94	1.50	2.09	3.31
2015	Jan	2.75	2.14	1.47	3.04	3.35	2.61	1.47	3.70
2015	Feb	2.94	1.70	1.70	3.29	3.58	2.07	1.70	4.01
2015	Mar	3.78	2.24	1.87	4.26	4.60	2.73	1.87	5.19
2015	April	4.17	2.02	2.12	4.71	5.09	2.46	2.12	5.74
2015	May	3.95	1.98	2.01	4.45	4.81	2.42	2.01	5.43
2015	Jun	4.41	2.03	2.33	4.98	5.38	2.47	2.33	6.07
2015	July	4.14	2.04	2.08	4.67	5.04	2.48	2.08	5.69
2015	Aug	4.00	1.87	2.28	4.52	4.88	2.28	2.28	5.51
2015	Sep	3.78	1.99	2.02	4.27	4.61	2.43	2.02	5.20
2015	Oct	2.97	1.36	2.35	3.36	3.62	1.66	2.35	4.09
2015	Nov	2.98	1.56	2.04	3.37	3.63	1.90	2.04	4.10
2015	Dec	2.81	1.81	1.69	3.15	3.43	2.21	1.69	3.84
2016	Jan	2.29	1.06	1.87	2.58	2.79	1.29	1.87	3.14
2016	Feb	2.32	1.23	1.96	2.61	2.82	1.50	1.96	3.19
2016	Mar	4.07	2.55	1.77	4.58	4.97	3.10	1.77	5.58
2016	Apr	4.20	2.01	2.14	4.74	5.12	2.45	2.14	5.78
2016	May	4.62	2.50	1.97	5.21	5.63	3.05	1.97	6.35
2016	June	4.62	1.81	2.43	5.21	5.63	2.21	2.43	6.35
2016	July	4.21	1.58	2.51	4.75	5.13	1.93	2.51	5.78
2016	Aug	3.53	1.32	2.17	3.98	4.30	1.61	2.17	4.85
2016	Sep	4.08	1.94	2.14	4.60	4.97	2.36	2.14	5.61
2016	Oct	3.18	1.87	1.93	3.59	3.88	2.28	1.93	4.37
2016	Nov	3.59	2.80	1.45	3.96	4.38	3.41	1.45	4.82
2016	Dec	2.55	1.74	1.66	2.85	3.11	2.12	1.66	3.48
2017	Jan	2.81	2.05	1.51	3.11	3.42	2.50	1.51	3.80
2017	Feb	3.19	2.25	1.56	3.55	3.89	2.74	1.56	4.33
2017	Mar	3.92	2.23	1.69	4.39	4.77	2.72	1.69	5.35
2017	Apr	4.70	2.47	2.01	5.31	5.73	3.01	2.01	6.47
2017	May	4.73	2.24	2.29	5.34	5.76	2.73	2.29	6.51
2017	Jun	4.13	1.90	2.34	4.67	5.04	2.31	2.34	5.69
2017	July	4.07	1.96	2.20	4.60	4.96	2.39	2.20	5.60
2017	Aug	4.39	1.84	2.59	4.95	5.35	2.25	2.59	6.03
2017	Sep	3.46	1.84	2.02	3.91	4.22	2.24	2.02	4.76
2017	Oc	3.99	2.09	2.01	4.50	4.86	2.55	2.01	5.48
2017	Nov	2.25	1.34	1.85	2.54	2.74	1.63	1.85	3.09
2017	Dec	2.23	1.30	1.83	2.51	2.71	1.59	1.83	3.06

Table 3: Annual mean wind speeds, standard deviations and Weibull parameters for 10 m and 30 m

Year	Mean WS (m/s) (10 m)	SD (10 m)	W k (10 m)	W c (10 m)	Mean WS (m/s) (30 m)	SD (30 m)	W k (30 m)	W c (30 m)
2014	3.13	1.92	1.68	3.51	3.82	2.34	1.68	4.27
2015	3.61	1.99	1.88	4.07	4.40	2.43	1.88	4.96
2016	3.77	2.05	1.91	4.25	4.59	2.50	1.91	5.18
2017	3.72	2.14	1.80	4.19	4.54	2.61	1.80	5.10
All data	3.59	2.05	1.81	4.03	4.37	2.50	1.81	4.91

February). Considering the 4-year wind data, the highest mean wind speed was realized in May 2017 with 5.76 m/s at 30 m height. However, the lowest mean wind speed was recorded in January 2014 with 2.43 m/s at 30 m height.

It is seen from Table 3 the yearly mean wind speeds range from 3.13 m/s to 3.77 m/s at 10 m height. (In Table 2; SD defines Standart Deviation, W defines Weibull Distribution.) In addition to this, the average of the standard deviation from 2014 to 2017 is 2.05. At 30 m height, the mean wind speed reaches 4.37 m/s over a period of 4 years. These results show that at higher hub height, the higher the wind speed, standard deviation and scale parameters are obtained. It was also determined that the shape parameter has lower values than the scale parameter at different hub heights. The averages of the k and c parameters required to calculate the energy generated from the wind over a 4-year period are respectively 1.81 and 4.03 for 10 m height, 1.81 and 4.91 for 30 m height, respectively.

The wind speed probability density function obtained by the Weibull distribution of wind speeds on an annual basis using the MLE method is given in Figures 3-7. As the hub heights increase, the peaks of the Weibull distribution decrease in all years

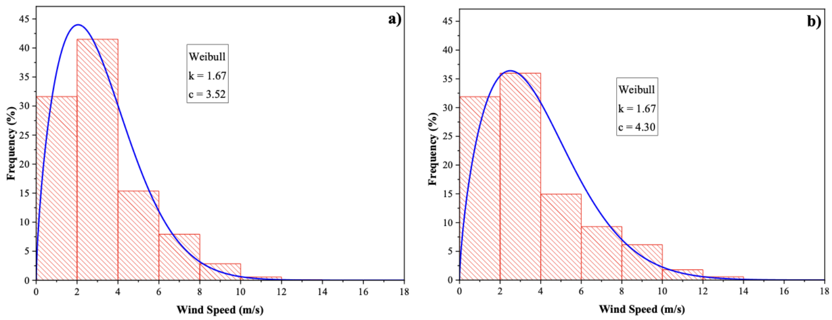

Figure 1: 2014 wind speed profile; a) 10m, b) 30m

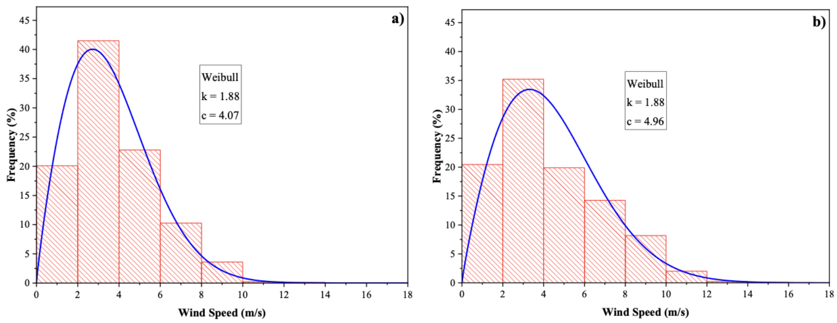

Figure 2: 2015 wind speed profile; a) 10m, b) 30m

and spread towards increasing speed. It can also be said for the determined wind speed ranges, the distributions of wind speeds and Weibull distribution coincide. From the figures, wind speeds are generally between 0 and 4 m/s for 10 m hub height. When the height of 30 m is reached, it has been determined that the frequency of wind dispersion is maintained up to 6 m/s. When all wind speed data are considered at 10 m hub height, it has been determined that the most wind data is around 2 m/s and corresponds to approximately 40% of the data. For a height of 30 m, it was found that this value was around 3 m/s and showed a distribution of approximately 35%.

3.2 Wind Roses

Monthly and annual wind rose charts help explain the variation in wind direction each month and year as shown in the figures below. The monthly wind rose charts obtained from 10 m height in Figure 6 demonstrate that most wind flows from the South during the spring months when average wind speeds are the highest. When all wind data from 2014 to 2017 are examined-again, most of the winds flow from the South (about %14) (Figure 7). Simply, it can be concluded that the prevailing wind direction in the study area is south. It is observed that the winds are generally flowing from the south in the spring, which is the windy season, and that there is no uniform distribution in the other months. Wind roses were generated with WRPlot Software. WRPlot software provides a visual representation of how the wind direction changes in certain periods.

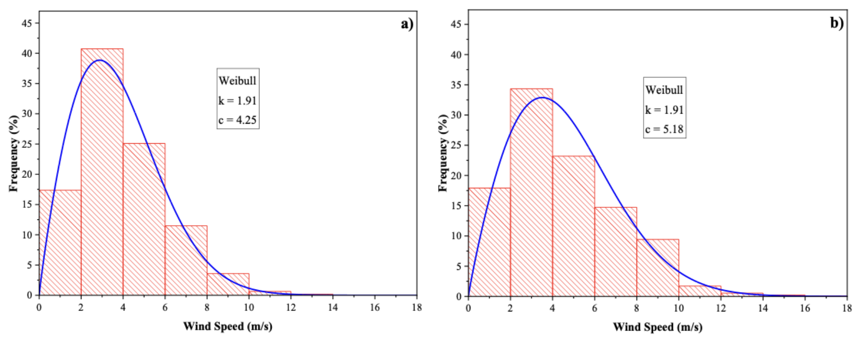

Figure 3: 2016 wind speed profile; a) 10m, b) 30m

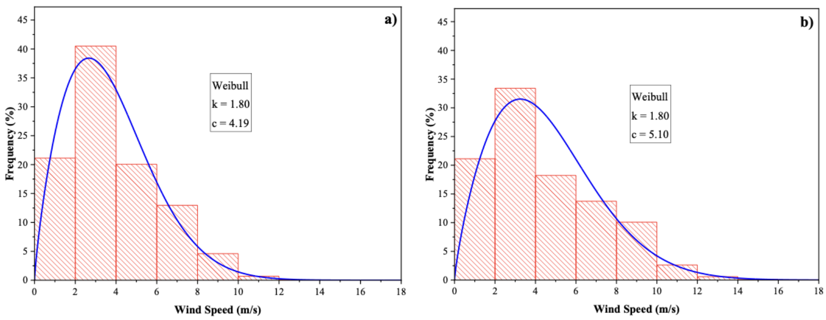

Figure 4: 2017 wind speed profile; a) 10m, b) 30m

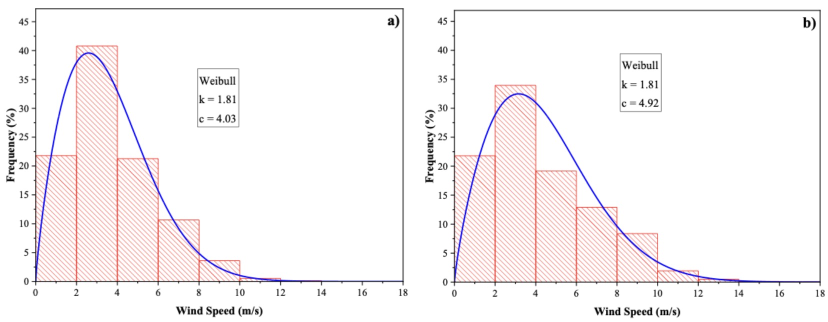

Figure 5: 2014 to 2017 wind speed profile; a) 10m, b) 30m

3.3 Wind Power Density

Calculating wind power density(PD) is an important step in evaluating wind energy potential. The annual values of the Weibull power density(PD) are given in Table 4. In this study, wind power density values are evaluated for 30 m. According to the Weibull distribution, the highest wind power density was achieved as 105.04 W/m^2 in 2017 and the lowest power density as 68.22 W/m2 in 2014. In Bingol province, the average wind power density was approximately $90W/m^2$ in a period of 4 years.

3.4 Evaluation of Wind Data

In Figure 8, the mean wind speeds and wind power densities of Bingol province by months are shown. In the Bingol region, the highest wind power density and mean power speeds is observed in the spring months, while the lowest is observed in the winter months. Generally, both mean wind speeds and wind power densities are high in the spring months. Mean wind speeds in March, April, May, and June are about 5 m/s at 30 m height. The lowest monthly mean wind speeds were obtained in January and February for 10 m and 30 m altitude, respectively, 2.5 m/s and 3.0 m/s. The average wind power density is around $135W/m^2$ in March and April. Accordingly, it can be said that spring months have higher energy potential than other months in terms of average wind speed and wind power density. However, in addition to the mean wind speeds and wind power densities, the data distribution is also important in wind energy. International standards have classified the energy that wind turbines can generate over wind speed (m/s) and power density (W/m^2) [30]. Considering the monthly and annual wind power densities and mean wind speeds the energy potential of region is in Class 1 (Tables 4 and 5) (Fig 8). As a result of these data it was found that wind potential of the region can be used for low-capacity wind turbines in rural and small communities.

The cumulative distribution function shows the ratio of the wind speed when it is below a certain wind speed. The cumulative distribution function can also be used to predict the wind is within a certain speed range [31]. Figure 9 shows the cumulative percentages of monthly wind speeds. The cumulative distribution function in Figure 9 shows that approximately 90% of the wind speed recorded in March, April, May and June is below 8.5 m/s in December and January, and below 4.5 m/s.

In order to determine the wind energy potential of a region, it is necessary to determine the wind speed distribution [32], [33]. Figure 10 shows wind speed Weibull distributions and cumulative probability distributions derived from the measured hourly time-series data of Bingol (2014 to 2017). The cumulative distribution shows that approximately 90% of the wind speed recorded

Table 4: Annual PDw based on Weibull distribution at 30 m height

Years	2014	2015	2016	2017
PDw (W/m^2)	68.22	91.02	101.87	105.04

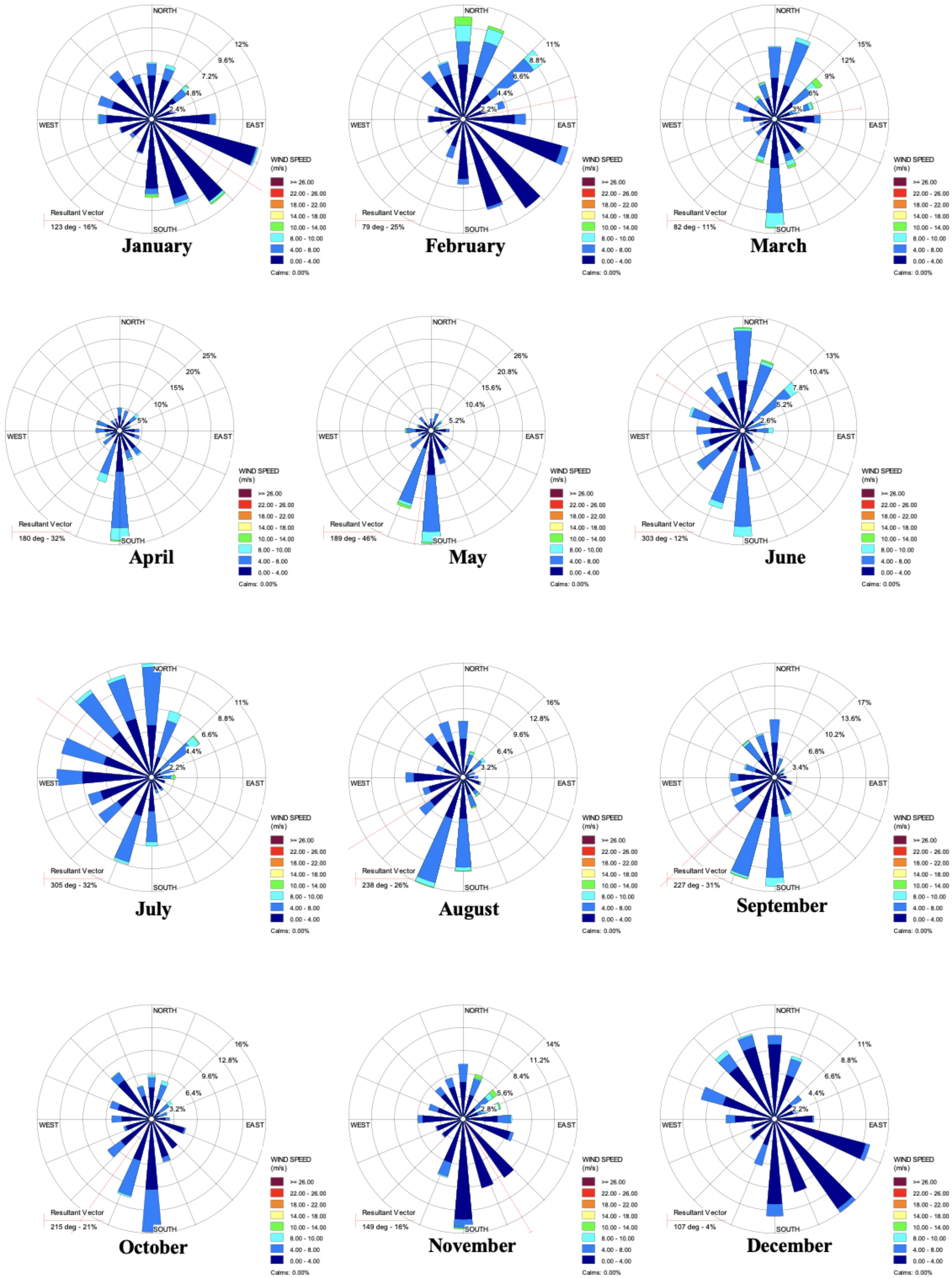

Figure 6: Monthly wind roses 2014 to 2017

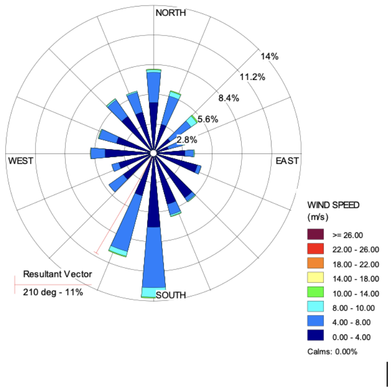

Figure 7: Average Wind rose 2014 to 2017

Table 5: Annual PDw based on Weibull distribution at 30 m height

Wind Power Class	m/s$(10m)$	W/m$^2(10m)$	m/s$(30m)$	W/m$^2(30m)$
1	0-4.4	0-100	0-5.1	0-160
2	4.4-5.1	100-150	5.1-5.9	160-240
3	5.1-5.6	150-200	5.9-6.5	240-320
4	5.6-6.0	200-250	6.5-7.0	320-400
5	6.0-6.4	250-300	7.0-7.4	400-480
6	6.4-7.0	300-400	7.4-8.2	480-640
7	> 7.0	>400	8.2-11	640-1600

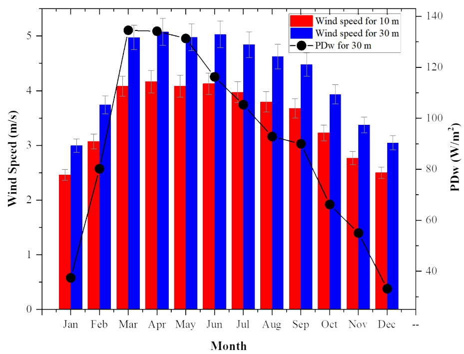

Figure 8: Monthly average wind speeds and PDw

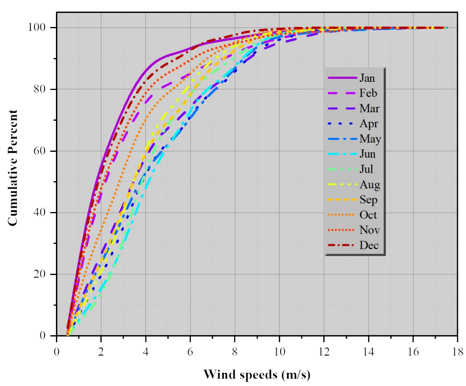

Figure 9: 2014 to 2017 cumulative distribution at 30 m height (hourly average)

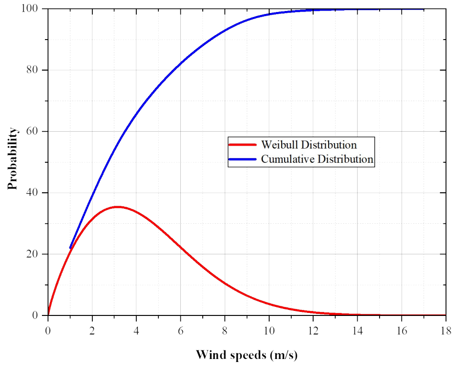

Figure 10: Wind speed Weibull distributions and cumulative probability distributions, derived from the measured hourly time-series data of Bingol (2014 to 2017)

in 2014 to 2017 is below 6.5 m/s. When 4-year wind data were examined, it was determined that approximately 35% of the Weibull distribution was composed of 2.5 m/s wind speed.
To promote renewable energy, examining only the wind energy potential of a region may be insufficient. For this reason, renewable energy studies carried out in a region should be evaluated together in a comprehensive manner [34], [35]. It may be useful to make a solar energy potential assessment for Bingöl province in the future.

4 Conclusion

In this paper, hourly long-term wind speed data of Bingöl province between 2014 and 2017 were analyzed statistically. Probability density distributions are derived from long-term wind speed data and distribution parameters are defined. The dominant wind directions and energy potential of the region were determined, and the data obtained are given below.

- In this study, where the wind characteristics of Bingol province were examined with the Weibull distribution, when all wind data were taken into consideration, it was determined that the shape parameter (k) and scale parameter (c) were 1.81 and 4.03 for 10 m height, 1.81 and 4.91 for 30 m respectively.
- Mean wind speeds from 2014 to 2017 were 3.59 m/s and 4.37 m/s for 10 m and 30 m height, respectively.
- Mean wind speeds reached their highest value with about 5.0 m/s in March, April, May and June. The lowest wind speeds were in the winter months.
- In the spring months when average wind speeds are the highest, the prevailing wind direction is south
- These results show that the potential of generating electricity from wind in general is low in Bingol. As a result, it has been concluded that since the average monthly and annual power densities in Bingol province are 100 W/m^2, it is not possible to directly support the electrical grid by wind energy systems, and it can be used particularly for electrical applications that do not require low power density in rural areas. The fact that the average speed is mostly higher than 4 m/s for 30 m hub height has shown that electrical energy generation from wind energy is promising. However, this study can help to encourage the use of small-scale wind energy projects in Bingol, especially in applications that require electricity, such as the use of internet infrastructure, traffic signs, street lighting, charging stations and irrigation in the rural areas.
- It also shows that the hub heights of the wind turbines to be installed should be as high as possible.
- It is recommended to take long-term measurements at different heights in different regions to make a better decision about the wind characteristics and wind energy potential of the province.
- In this way, the average wind speeds and wind power densities in regions with high wind energy potential will be determined and companies that will invest in this sector will be encouraged.

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Authors' Contributions

In this study, Authors contributed equally to the study.

Competing Interests

The authors declare that they have no conflict of interest.

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