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Assessment of wind power potential along the south western Black Sea coasts

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ABSTRACT

Information about wind characteristic together with the analysis of its potential are a key step when it comes to planning and performance estimation of wind energy projects. In the current study, hence, a statistical analysis on wind energy potential and wind characteristics over the coasts of the South Western Black sea is carried out. The aim is to determine fields where wind force is strong and consistent for energy production along south western coasts of the Black Sea. For this purpose, seven meteorological stations (Kumköy, Şile, Akçakoca, Zonguldak, Amasra, Cide, İnebolu) from west to east are selected, and 10 year wind data acquired from TSMS (Turkish Meteorological Service) measured hourly at a height of 10 m were used. Annual, seasonal, monthly and diurnal average wind speed and power density variations are evaluated at all stations, after which conclusions on dominant wind directions and frequency distributions at all sites are made. Based on overall results, Amasra and İnebolu indicated the highest potential of wind power among the other sites with Amasra having about 159 W/m^2 maximum yearly average wind power density and about 1392 kWh/m^2/year maximum yearly average energy density.

Keywords: wind speeds, wind power potential, the south western Black Sea coasts

Güney Batı Karadeniz kıyıları boyunca rüzgar güç potansiyelinin değerlendirilmesi

ÖZ

Bir bölgenin rüzgar karakteristiğinin belirlenmesi ve onun potansiyelinin farklı açılardan analizi, rüzgar enerji projelerinin planlanması ve performans tahminlerinin yapılabilmesi için gerekli olan en önemli adımdır. Bu çalışmada, Karadeniz'in güney batı kıyılarının rüzgar karakteristiğinin ve rüzgar enerji potansiyelinin detaylı istatistiksel analizi gerçekleştirilmiştir. Çalışmadaki hedef, Karadeniz'in Türkiye kıyıları boyunca enerji üretimi için rüzgar gücü yüksek olan uygun alanları belirlemektir. Bu hedef için, bahsedilen kıyı şeridinde rüzgar ölçümlerinin gerçekleştirildiği 7 meteorolojik istasyon seçilmiş ve istatistiksel analiz için Türkiye Meteoroloji Genel Müdürlüğü tarafından arşivlenmiş 10 metre yükseklikteki saatlik rüzgar verisi (hızı ve yönü) 10 yıllık süre boyunca temin edilmiştir. Bütün istasyonlarda hakim rüzgar yönleri ve frekans dağılımları belirlendikten sonra yıllık, mevsimlik, aylık ve günlük ortalama rüzgar hız ve güç yoğunluk değişimleri de irdelenmiştir. Bütün sonuçlara dayanarak, Amasra ve İnebolu lokasyonlarının diğer alanlara kıyasla en yüksek rüzgar güç potansiyeline sahip oldukları, Amasra'nın yaklaşık 159 W/m^2 maksimum yıllık ortalama rüzgar güç yoğunluğuna ve yaklaşık 1392 kWh/m^2/yıl 'lık maksimum yıllık ortalama enerji yoğunluğuna sahip olduğu belirlenmiştir.

Anahtar Kelimeler: rüzgar hızları, rüzgar güç potansiyeli, Karadeniz'in güney batı kıyıları

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1. INTRODUCTION

Supplying quality, consistent and sufficient quantity of energy to communities is challenging. Although the degree of concern differs in developed and undeveloped countries, energy provision is still a big issue globally. To meet demand of the growing world population, efforts have to be put in place to find new ways of energy generation [1]. Fossil fuels, including natural gas, coal, oil and tar are now the basic energy sources worldwide. The problem is that these fuels are non-renewable hence, very limited and they are being depleted at an alarming rate. With an increase in pollution, fossil fuels are also extremely harmful to the environment [2]. The sustainability of these energy resources is questionable since they are finite in nature [1]. Proper management of the available resources, reasonable consumption of energy, and development of alternative energy sources is therefore important to meet demands, reduce air pollution and cut global warming [3].

Wind energy is the fastest growing alternative energy source in the world competing with traditional energy sources. This has been so due to low technology production costs, concerns about energy security and also an effort to solve environmental problems [4]. In order to conserve energy resources and curb damage done to the environment, therefore slowing down climate change, wind power is the best option since it is clean and since wind is free, after the turbines are erected the costs of operation are almost nothing. Making wind energy is the most affordable energy [5]. The kinetic energy in the wind is converted to mechanical power by wind turbines, after which the power can be used to pump water or generate electricity with the use of a generator. The stronger and more consistent the wind is, the more power the turbines will produce [6]. Many countries around the global including Canada, China, Denmark, Germany, India, South Africa, Spain and the USA are using wind energy. The World Wind Energy Association reported that in 2012, wind power generation capacity had reached a staggering 282.3 GW globally. Installed wind power generation capacity in the world had increased from 1,280 MW to 44,799 MW for the period from 1996 to 2012 with a 19.2% growth annually [7].

In Turkey thermal power plants, which run on coal, lignite, natural gas or fuel oil, produce most of the electrical energy. Only a meager supply of electricity is produced from renewable sources [8]. However, with 7.5 m/s in annual average wind speed, Turkey is rich in wind energy potential that there is a possibility of economically investing up to 48000 MW in power from wind energy. Areas where annual wind speeds are 7 m/s and above, possess wind power of at least 48.000 MW based on the 2007-Turkey wind energy potential atlas. Moreover, areas with annual wind speeds of 8.5 m/s and above possess at least 5000 MW wind power. It can therefore be said with confidence that Turkey has 8000 MW available wind energy which could be utilized efficiently and also 40000 MW available at a moderate level [9]. The capacity of wind power in Turkey boomed by 477 MW in 2011 reaching a total of 1806 MW in installed wind power capacity. In 2012 the total capacity reached 2312 MW with 506 MW from newly installed power and in 2013, the total capacity climbed to 2959 MW with 647 MW new installations. Since 2010, the amount of installed capacity grew by approximately 500 MW. The national transmission company estimated that from 2013, annual installations would reach 1000 MW per year [10].

Scientists in many regions around the global have been conducting their studies on wind and its power potential. Their main point of focus is the characteristic of wind speed together with its capability to produce enough power for various uses in a lot of countries [1-7], [11-19]. A study done by Mirhosseini et al. [18] is a good example in which they carried out an evaluation and determination of good locations to establish wind farms. In their study conducted in five towns within Iran's Semnan province, they found out that, among the five locations, the town of Damghan possesses a great potential for wind energy production. The results were derived based on mean wind speeds measured and Weibull distributions fitted at each locations. In a study done by Ohunakin et al. [16], wind characteristics inside the Nigerian North western region's seven meteorological points were examined. They used 36-year wind speed data from 1971 to 2007 which was measured at a height of 10 m and later subjected to Weibull distribution with two parameters. Chandel et al. [4] did an assessment at 12 sites in Himachal Pradesh, a Himalayan Indian city to find potential locations for wind power farm development together with giving vital input data for further studies on wind power potential and mechanical operations to policymakers in the region. Ammari et al. [19] analysed wind power from mean monthly wind speeds knowledge of a typical year, and for five different locations in Jordan. They mentioned that the highly promising sites having good wind energy potential were Aqaba and Ras-Moneef, whereas, the desert sites of Safawi and Azraq South had only moderate potential and Queen Alia Airport had a lower potential. It can therefore be confidently concluded that wind data analyses and good wind energy potential assessment are the main necessities for developing suitable wind power plants at any location.

There haven't been sufficient investigations on locations with wind energy harnessing potential in Turkey despite a few studies conducted in recent years. The aim in this current study is therefore to carry out an assessment and discussion of wind energy potential for stations along south western coasts of the Black sea. In this extent, this study summarizes the comparisons of yearly, seasonal, monthly, and diurnal wind speed variations at various spots over the coasts of south western Black sea at 10 meters above the ground; Weibull parameter variations (yearly, seasonal and monthly), characteristics of wind speed, distributions of wind speed frequency (cumulative frequency and probability density), alongside energy density and wind power; and wind direction analysis for the selected locations.

2. AREA OF STUDY AND DATA DESCRIPTION

The main area of focus in this study is at analysing wind characteristics and potential of wind power for several coastal locations where meteorological data are collected along the south western Black Sea coasts. Figure 1 shows topographic structure of the area of the interest and distribution of the seven coastal locations (Kumköy, Şile, Akçakoca, Zonguldak, Amasra, Cide, and İnebolu denoted in Figure 1 as W1, W2, W3, W4, W5, W6 and W7) along the south western Black Sea coasts. In the figure, topographic data is presented in the log format to indicate better presentation of orographic effect. A statistical analysis was done on the data used provided by the Turkish State Meteorological Service (TSMS). The data was collected hourly over a span of 10 years for the respective locations. All data at all locations have been recorded using a cup anemometer by the TSMS. Table 1 presents information about the mentioned coastal locations in detail. As seen from the table, data at the locations were recorded at an hourly interval. Most locations have measurements for a 33-year long time period. 10-year long (2004-2013) data, however, is used here for a proper comparison because Cide location include only the data in this range. Data from some hours of some days was missing at almost all the locations with Amasra being the location with the highest value of missing data (12.8%) while Kumköy and İnebolu locations have the lowest missing data (about 0.8%). However, it is observed that all locations have enough data to assess and discuss wind characteristics and wind power potentials of these locations.

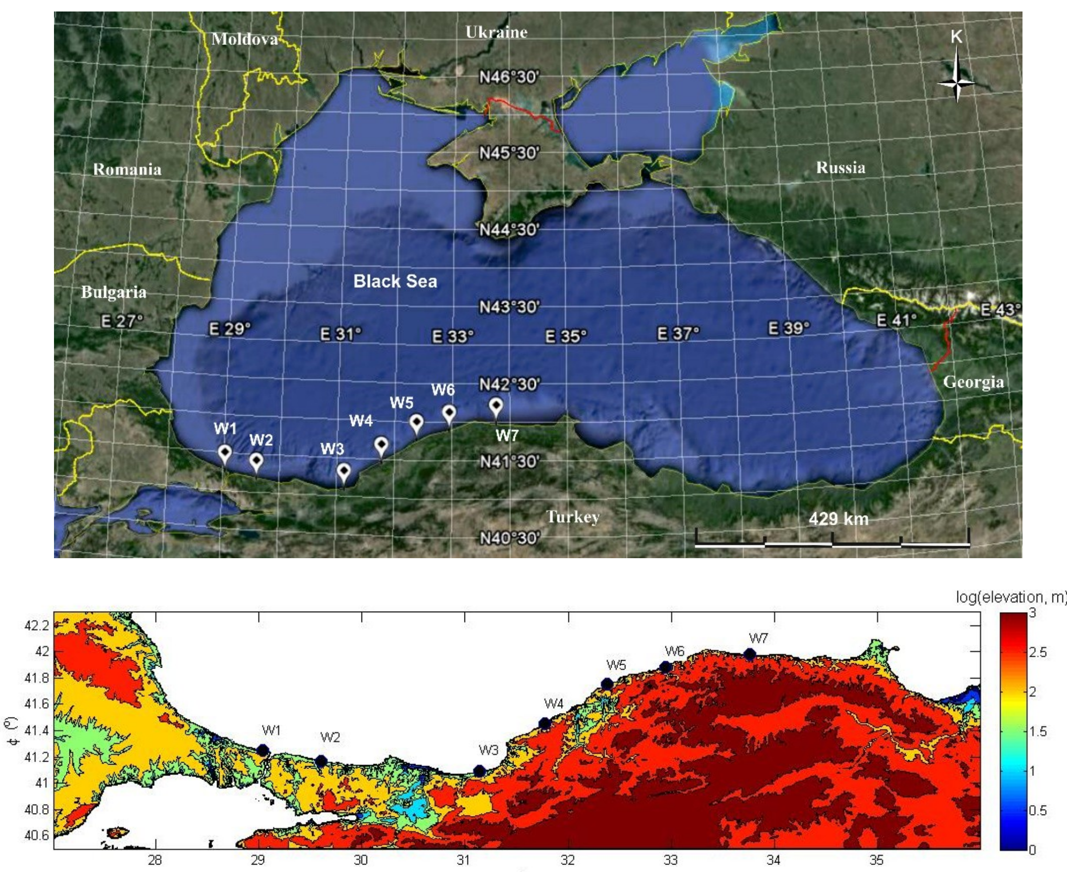

Figure 1. Topografic map of the area of the interest and locations of selected meteorological stations

Table 1. Geographic coordinates and some characteristics of selected locations in the study

Locations	Notation	Latitude	Longitude	Period of record	Temporal resolution of records	Missing data (%)
Kumköy	W1	$41^0$15’01” N	$29^0$02’18” E	1980-2013	1 hourly	0.9
Şile	W2	$41^0$10’07” N	$29^0$36’02” E	1980-2013	1 hourly	4.9
Akçakoca	W3	$41^0$05’22” N	$31^0$08’14” E	1980-2013	1 hourly	2.0
Zonguldak	W4	$41^0$26’57” N	$31^0$46’40” E	1980-2013	1 hourly	2.8
Amasra	W5	$41^0$45’09” N	$32^0$22’57” E	1982-2013	1 hourly	12.8
Cide	W6	$41^0$52’55” N	$32^0$56’51” E	2004-2013	1 hourly	7.2
İnebolu	W7	$41^0$58’44” N	$33^0$45’48” E	1980-2013	1 hourly	0.8

3. THEORETICAL BACKGROUND

To evaluate wind resource availability at a given location, wind power density calculation is commonly used as the best way. It shows the energy amount available at a location which a wind turbine is able to convert into electricity [20]. The power of wind available per unit area is known as the wind power density (P/A). The calculation of P/A is as follows:

$$\frac{P}{A}=\frac{1}{2}\rho\, V^{3} \tag{1}$$

where P is power given in Watts, ρ is average air density in kg/m^3 (1.225 kg/m^3 at average atmospheric pressure at sea level and at 15^{o}C), A is an area perpendicular to wind speed vector in m^2, and V is wind speed given in m/s [18], [21].

For a given time (T), as given in the equation (1) above, density of wind energy can be estimated by using a given wind power density [22]. For any period, wind energy available can be calculated as below [23]:

$$\frac{E}{A}=\left(\frac{P}{A}\right)T \tag{2}$$

In areas that are prone to strong winds, knowledge concerning frequency distribution of wind speeds has importance besides information on wind power and energy densities. If it is known wind speed in any area fits which distribution, it is easy to obtain power potential belonging to that area and also gather information on whether the area is economically feasible or not. Having a couple of important parameters which are able to explain the nature of wind-range wind speed data is necessary in the analysis of wind energy since there are wind ranges in data acquired using different observation methods. Using a function called probability distribution for this process is the most straightforward and useful method. The curve of wind speed frequency can be described in many ways using functions of probability density. Distributions for measured probability of wind speed are generally fitted using Lognormal, Rayleigh, and Weibull functions. Weibull in wind data description is frequently preferred as a statistical distribution describing data [15]. Besides, Akpinar and Akpinar [24] showed that over a period of 12 months, Weibull distribution gave improved power density estimates in all months compared to Rayleigh based on a study conducted in Turkey. Furthermore, they stated that, for the entire year, measured monthly probability density is better in fitting Weibull distribution than Rayleigh distribution. Therefore, the function of Weibull distribution was preferred and used in wind speed frequency distributions assessment at different land-based coastal locations in this study.

Compared to other statistical functions, two-parameter Weibull probability is the most suitable, most used and highly recommended distribution function because it provides best fitting for monthly probability density distributions in the analysis of wind speed data [25], [26]. The functions of cumulative distribution and probability density are two parameters that characterize wind speed variation in the Weibull distribution. Probability of a given wind velocity (V) is indicated by a function called the probability density (f(V)), while the wind velocity’s probability being equal to V (or less than V) or within a provided wind speed extent is given by the velocity’s corresponding cumulative distribution function [17]. The function of Weibull probability density is given below:

$$f(V)=\frac{k}{c}\left(\frac{V}{c}\right)^{(k-1)} e^{-(V/c)^{k}} \tag{3}$$

In which f(V), k, and c values are, respectively, probability of wind speed (V) observed, dimensionless shape parameter of Weibull, and Weibull scale parameter (m/s). Using shape factor (k), a relationship between scale factor (c) and mean wind speed can be established. Thus determining uniformity of wind speed at any given spot [17]. The probability of wind velocity being equal to V (or less than V), on the other hand, is given by the cumulative distribution function of wind velocity (V). As a result, the cumulative distribution (F(V)) comes from an integration of the probability density function [27],

$$F(V) = 1 - e^{-(V/c)^k} \tag{4}$$

Two parameters are required in order to determine the function of Weibull probability density namely: shape and scale factors. To find k and c, analytical and empirical methods shown below such as Justus formulas are used [18], [24]:

$$k = \left(\frac{\sigma}{V_m}\right)^{-1.086} \tag{5}$$

$$c = \frac{V_m\, k^{2.6674}}{0.184 + 0.816k^{2.73855}} \tag{6}$$

Expressions given below can be used in the calculation of mean wind speed (V_m) and the known wind speed data standard deviation (σ).

$$V_m = \frac{1}{N}\left(\sum_{i=1}^{N} V_i\right) \tag{7}$$

$$\sigma = \left(\frac{\sum_{i=1}^{N}\left(V_i - V_m\right)^2}{N-1}\right)^{0.5} \tag{8}$$

The most probable value of wind speed (V_{mp}) and maximum energy carrying wind speed value (V_{maxE}), on top of the mean wind speed, are important wind speeds for the estimation of wind energy. V_{mp} is the most frequent wind speed for a specific wind probability distribution and easily obtained from Weibull distribution function's scale and shape parameters as below [22], [23]:

$$V_{mp} = c\left(\frac{k-1}{k}\right)^{1/k} \tag{9}$$

Maximum energy carrying wind speed, expressed as below, can also be calculated from Weibull distribution function's scale and shape parameters [23], [26]:

$$V_{\max E} = c\left(\frac{k+2}{k}\right)^{1/k} \tag{10}$$

4. RESULTS AND DISCUSSION

4.1. Wind characteristics

Long-term average wind speed's annual variations gives us a grasp about long-term wind speed pattern, it also provides assurance to investors on amount of wind power to be available for exploitation in coming years [3], [28]. Therefore, wind speed is the most significant feature of wind resource. Not only month-wise or season-wise distributions of wind velocity probability are needed to explain the electricity volume available within a small-sized power system, hourly probability assessment of wind speeds is also required [23]. Consequently, for a 10-year period at the chosen points, diurnal variations of wind speed are essentially discussed. Illustrated in Figure 2 are the results. The diurnal variations of wind speeds observed at Kumköy, Şile, Akçakoca, Zonguldak, and Cide are largely identical while İnebolu is contrary in comparison to the rest of the other locations. The variation range at Amasra is higher compared to the others. From 9 a.m. to 6 p.m., during the day, wind blowing was stronger while at night it was calm at all locations except İnebolu where, conversely, it was windy at night and calm during the day. Hourly average wind speeds show an increase from around 6 a.m. reaching a peak point between 12 noon and 3 p.m. at all locations except İnebolu. Amasra recorded the highest value of average wind speed at 3 p.m. during the study. TEIAS [29] shows that electricity demand load duration curves change significantly from 11 a.m. to 6 p.m. with high energy demand and from 1 a.m. to 11 a.m. with low demand. In addition, Karasu [30] proved that highest demand occurs between 8 p.m. and 11 p.m. especially in summer time. It is therefore concluded that at all locations except İnebolu, wind characteristics comply with the demand curve.

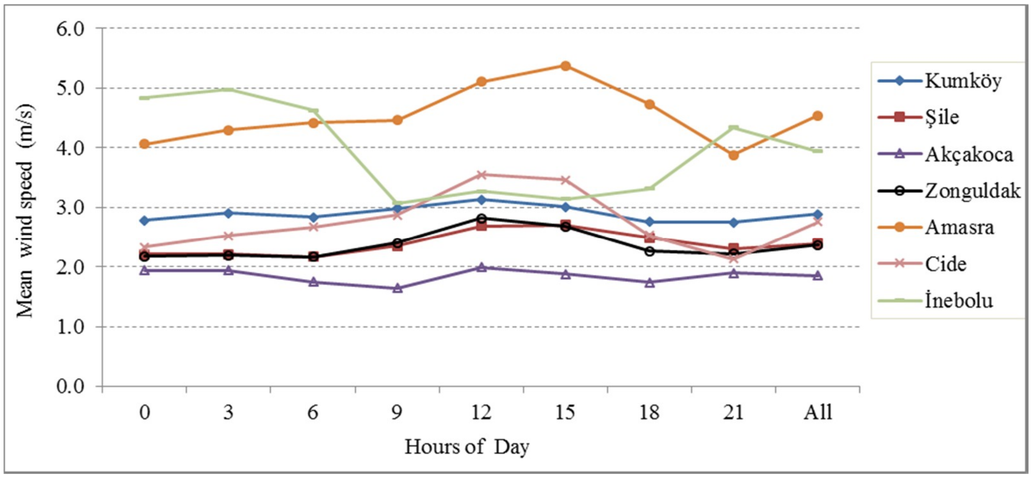

Figure 2. Diurnal variations of mean wind speeds measured at 10 m height for selected locations

After discussing the diurnal wind speeds variations observed at all selected locations, monthly wind speeds variations are examined. The monthly average variations of wind speed at all locations are presented in Figure 3. Monthly average wind speed trends for all locations are almost similar but their ranges are different. At all locations mean wind speed decreases from January to May, and then it increases from May to December. At Kumköy, Şile, Akçakoca, Zonguldak, and Cide, fluctuations of monthly average wind speeds mostly vary between 1.5 m/s and 4 m/s and at Amasra and İnebolu, between 3.5 m/s and 5.5 m/s. It is also seen from Figure 3 for the coastal locations of Kumköy, Şile, Akçakoca, Zonguldak, Amasra, Cide, and İnebolu, maximum values of monthly average wind speed vary between 1.98 m/s and 5.37 m/s. These extremes are seen in January for Kumköy, Akçakoca, Zonguldak, Amasra, and Cide sites, February for Şile location, and December for İnebolu location. It is also very clear from the figure that Amasra has the highest values of wind speed in all months, while the second highest values are at İnebolu location in all months. The location having the lowest monthly mean wind speeds during all months is Akçakoca.

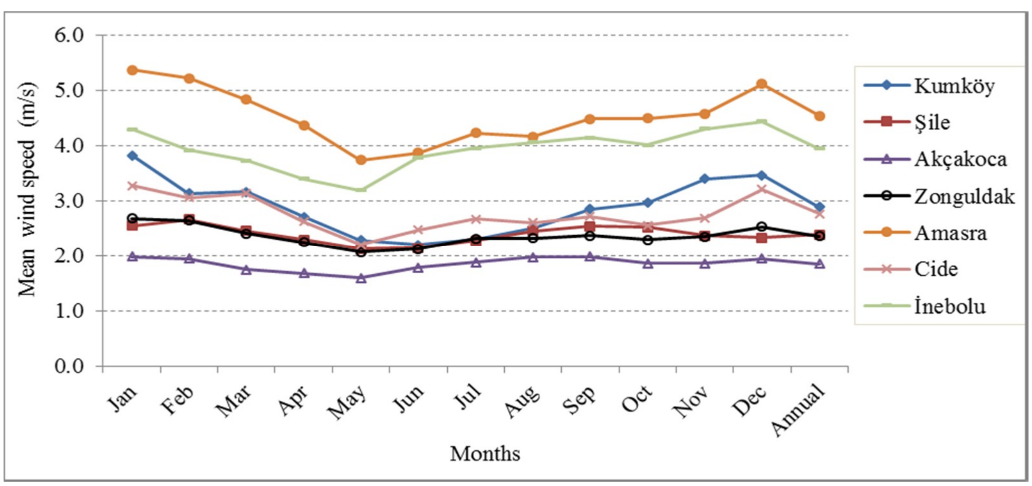

Figure 3. Monthly variations of mean wind speeds measured at 10 m height for selected locations

In the northern hemisphere, months are in most cases split as follows for each of the 4 seasons: winter: December, January and February; spring: March, April and May; summer: June, July and August; and autumn: September, October and November [25]. Therefore, seasonal average wind speeds were computed using data of the months related to each season for each location. Average wind speeds' long-term seasonal trends observed at all selected coastal locations are presented in Figure 4. The figure shows that Amasra, in all seasons, is a spot with the highest wind speeds. It has average wind speeds of 5.24 m/s, 4.33 m/s, 4.09 m/s, and 4.51 m/s in winter, spring, summer, and autumn, respectively. Wind speeds at all locations have highest values in the cold season while having the lowest in summer for Kumköy, Amasra, and Cide sites and the spring for Şile, Akçakoca, Zonguldak, and İnebolu locations. The same figure shows that Amasra is very windy, with 5.24 m/s in maximum seasonal average wind speed measured at 10 m above the ground in winter while having a minimum of 4.09 m/s in summer.

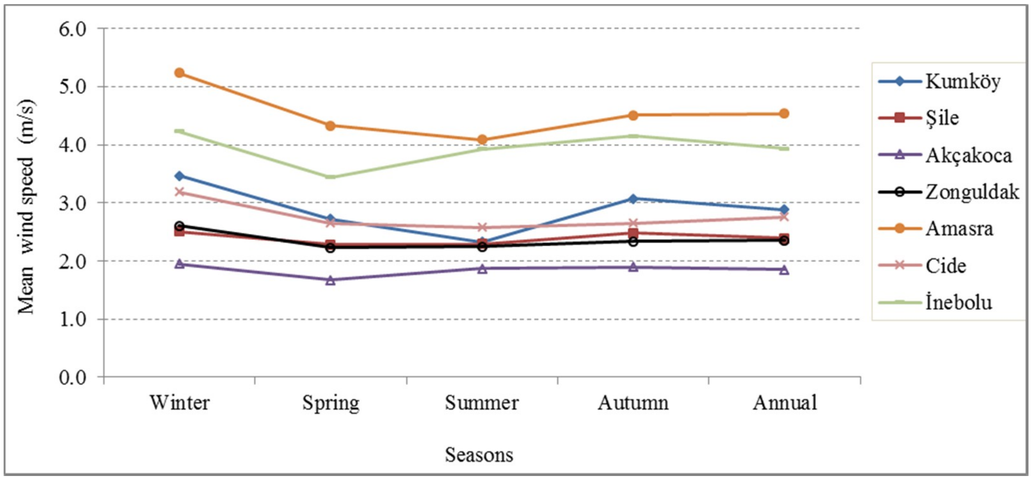

Figure 4. Seasonal variations of mean wind speeds measured at 10 m height for selected locations

Annual average wind speed variations measured at 10 m for the chosen locations are presented in Figure 5. As seen, for Amasra, Kumköy, Cide, Şile, and Zonguldak locations there are decreasing trends while annual trends of İnebolu and Akçakoca locations increase. The maximum mean wind speeds are observed as 3.93 m/s in 2005 for Kumköy, 2.85 m/s in 2004 for Şile, 2.08 m/s in 2011 for Akçakoca, 2.53 m/s in 2010 for Zonguldak, 5.05 m/s in 2005 for Amasra, 3.08 m/s in 2005 for Cide, and 4.16 m/s in 2007 for İnebolu. Yearly mean wind speeds during the period of 2004-2013 vary between 1.85 m/s and 4.59 m/s for these sites. These values are higher than the mean values recorded for 7 years in Kumköy and Şile, for 6 years in Amasra and Cide, for 4 years in Zonguldak, and for 3 years in Akçakoca and İnebolu.

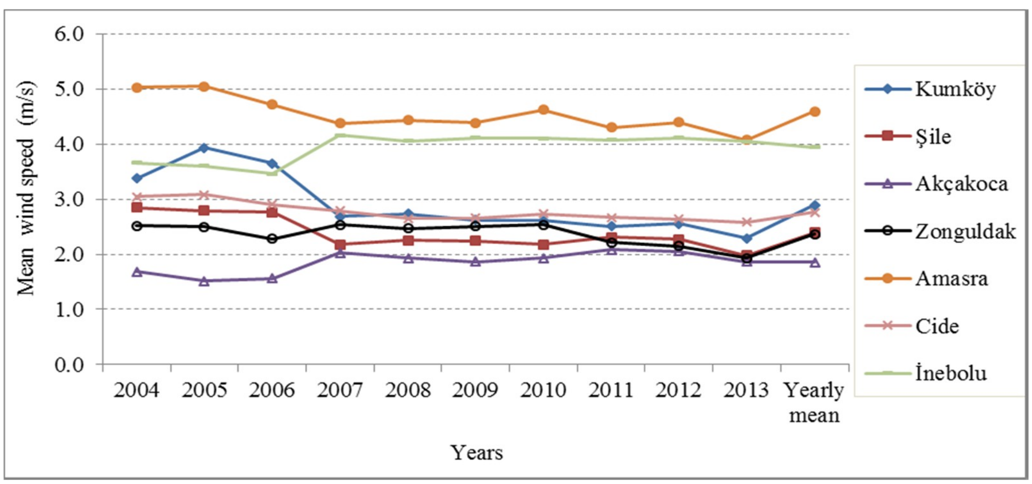

Figure 5. Annual variations of mean wind speeds measured at 10 m height for selected locations

4.1.1. Weibull parameters and characteristic wind speeds

Table 2 presents variations of Weibull parameters (k and c), both monthly and annual at heights of 10 m at the selected locations. Monthly Weibull shape parameter (k) value is the lowest (1.23) at Cide in October and July. This value is highest in June at Akçakoca with a value of 2.70. At Akçakoca, the lowest value (1.82 m/s) of monthly scale parameter (c) is seen in May while Amasra has the highest value of 6.34 m/s in January. There was a fluctuation in yearly shape parameter values between 1.32 in Cide and 1.94 in Akçakoca while the yearly scale parameter fluctuated between 2.16 m/s in Akçakoca and 5.40 m/s in Amasra. Based on these results, it is therefore conspicuous that the shape parameter values have relatively low variations compared to scale parameter values (c). Table 3 shows variations of Weibull parameters, both seasonal and annual for the picked sites. The highest value of k, 2.59, is observed at Akçakoca in summer while the lowest value, 1.26, is at Cide in autumn as per the table. It is seen from the same table that the highest value of c is 6.19 m/s at Amasra in winter while in spring, at Akçakoca, the lowest value of 1.95 m/s is seen. Table 4 presents Weibull parameters' yearly average variations that clearly show Akçakoca has the highest value of k in 2013 which is 2.33 while the lowest is 1.21 seen in 2006 at Cide. In 2005 c has the highest value of 6.02 m/s at Amasra and its lowest being 1.78 m/s, noted at Akçakoca in 2005.

Table 2. Monthly variations of Weibull parameters for selected locations

Months	**Kumköy**		**Şile**		**Akçakoca**		**Zonguldak**		**Amasra**		**Cide**		**İnebolu**	
	k	**c (m/s)**	**k**	**c (m/s)**	**k**	**c (m/s)**	**k**	**c (m/s)**	**k**	**c (m/s)**	**k**	**c (m/s)**	**k**	**c (m/s)**
January	1.55	4.54	1.66	3.01	1.64	2.34	1.75	3.16	1.69	6.34	1.47	3.90	1.87	5.03
February	1.27	3.77	1.62	3.15	1.53	2.31	1.60	3.13	1.61	6.18	1.40	3.67	1.61	4.64
March	1.60	3.75	1.77	2.88	1.67	2.05	1.75	2.83	1.59	5.73	1.41	3.74	1.54	4.43
April	1.70	3.19	1.94	2.68	2.14	1.96	1.74	2.64	1.48	5.21	1.33	3.14	1.51	4.05
May	1.79	2.68	2.07	2.46	2.60	1.82	1.90	2.41	1.43	4.47	1.42	2.63	1.54	3.80
June	1.98	2.56	2.36	2.47	2.70	2.03	1.97	2.48	1.48	4.61	1.34	2.96	1.80	4.44
July	2.02	2.68	2.46	2.61	2.66	2.15	1.84	2.71	1.32	5.08	1.23	3.22	1.92	4.62
August	1.91	2.93	2.53	2.81	2.49	2.26	1.96	2.71	1.59	4.93	1.29	3.13	1.96	4.74
September	1.79	3.35	2.28	2.93	2.25	2.29	1.93	2.77	1.60	5.31	1.27	3.28	1.96	4.83
October	1.77	3.49	1.97	2.95	2.02	2.17	1.80	2.69	1.47	5.35	1.23	3.08	1.96	4.68
November	1.43	4.06	1.82	2.78	1.96	2.17	1.69	2.78	1.64	5.42	1.29	3.24	1.98	5.02
December	1.77	4.07	1.69	2.75	1.60	2.30	1.69	2.99	1.71	6.04	1.41	3.83	1.95	5.19
Annual	1.55	3.44	1.91	2.80	1.94	2.16	1.76	2.78	1.53	5.40	1.32	3.32	1.77	4.63

Table 3. Seasonal variations of Weibull parameters for selected locations

Months	**Kumköy**		**Şile**		**Akçakoca**		**Zonguldak**		**Amasra**		**Cide**		**İnebolu**	
	k	**c (m/s)**	**k**	**c (m/s)**	**k**	**c (m/s)**	**k**	**c (m/s)**	**k**	**c (m/s)**	**k**	**c (m/s)**	**k**	**c (m/s)**
Winter	1.50	4.14	1.64	2.97	1.59	2.32	1.68	3.09	1.67	6.19	1.43	3.81	1.80	4.97
Spring	1.62	3.22	1.89	2.67	2.00	1.95	1.77	2.63	1.48	5.16	1.34	3.17	1.52	4.10
Summer	1.95	2.73	2.43	2.63	2.59	2.14	1.91	2.64	1.45	4.89	1.28	3.11	1.89	4.60
Autumn	1.60	3.64	2.00	2.89	2.07	2.21	1.80	2.75	1.56	5.36	1.26	3.20	1.96	4.85
Annual	1.55	3.44	1.91	2.80	1.94	2.16	1.76	2.78	1.53	5.40	1.32	3.32	1.77	4.63

Table 5 summarises values of the wind speed carrying maximum energy (V_{maxE}) and most probable wind speed (V_{mp}), both monthly and yearly. Highest V_{mp} and V_{maxE} yearly values, 2.89 m/s and 9.36 m/s, are seen at İnebolu and Amasra, while the lowest, 1.12 m/s and 3.11 m/s are observed at Cide and Akçakoca, respectively. A fluctuation between 0.80 m/s and 3.73 m/s is seen in the most probable wind speed value (V_{mp}), while the maximum energy carrying wind speed (V_{maxE}) fluctuates between 2.27 m/s and 28.84 m/s. The lowest value for most probable wind speed (V_{mp}) is 0.80 m/s seen at Cide in October while its highest value is in January at Amasra. V_{maxE} has its highest value of 28.84 m/s in September at Amasra and its lowest is 2.27 m/s in May at Akçakoca.

Seasonal characteristic wind speed values for the picked sites are given Table 6. Per the table, Amasra possesses the highest value of V_{mp} in winter measuring 3.57 m/s, on the other hand Cide has the lowest value in autumn measuring 0.92 m/s. From the same table, it is clear that Amasra has highest V_{maxE} value in winter at 9.93 m/s and has the lowest value of 2.67 m/s in summer at Akçakoca. Presented in Table 7 are yearly mean variations of characteristic wind speed values for locations selected. At 3.06 m/s, İnebolu saw the highest value of V_{mp} in 2012, the lowest was 0.84 m/s at Cide in 2006. The table also shows Amasra in 2005 having the highest value of V_{maxE} at 10.95 m/s, while Akçakoca having the lowest value in 2006 at 2.72 m/s.

Table 4. Yearly mean variations of Weibull parameters for selected locations

Months	Kumköy		Şile		Akçakoca		Zonguldak		Amasra		Cide		İnebolu	
	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)
2004	1.28	4.07	2.02	3.32	1.83	1.97	1.63	2.98	1.50	5.99	1.28	3.66	1.93	4.28
2005	1.48	4.68	2.01	3.25	1.71	1.78	1.58	2.96	1.45	6.02	1.33	3.70	2.01	4.19
2006	1.49	4.35	1.94	3.23	1.84	1.83	1.51	2.71	1.38	5.65	1.21	3.50	1.94	4.05
2007	1.99	3.14	2.00	2.54	2.07	2.35	2.01	2.96	1.62	5.18	1.32	3.35	1.75	4.90
2008	1.97	3.19	1.62	2.67	1.97	2.26	1.90	2.89	1.61	5.24	1.30	3.19	1.78	4.77
2009	2.01	3.06	1.92	2.62	2.18	2.15	1.94	2.94	1.61	5.24	1.42	3.18	1.77	4.83
2010	1.80	3.07	2.06	2.54	1.97	2.25	1.91	2.97	1.62	5.20	1.36	3.27	1.66	4.85
2011	1.95	2.93	2.12	2.68	1.97	2.43	1.88	2.59	1.58	5.49	1.36	3.19	1.72	4.80
2012	1.94	2.98	2.14	2.64	2.11	2.38	1.84	2.52	1.57	5.22	1.37	3.16	1.79	4.83
2013	2.00	2.68	2.19	2.29	2.33	2.15	1.98	2.26	1.55	4.85	1.32	3.10	1.70	4.77
Mean	1.55	3.44	1.91	2.80	1.94	2.16	1.76	2.78	1.53	5.40	1.32	3.32	1.77	4.63

Table 5. Average monthly values of the characteristic wind speeds for selected locations

Months	Kumköy		Şile		Akçakoca		Zonguldak		Amasra		Cide		İnebolu	
	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}
January	2.33	7.74	1.73	4.85	1.32	3.81	1.95	4.88	3.73	10.05	1.81	6.98	3.33	7.43
February	1.10	7.95	1.74	5.17	1.15	3.99	1.69	5.20	3.37	10.22	1.50	6.90	2.55	7.64
March	2.03	6.23	1.80	4.42	1.18	3.30	1.74	4.37	3.07	9.55	1.55	7.01	2.25	7.59
April	1.90	5.04	1.85	3.85	1.46	2.66	1.61	4.09	2.42	9.30	1.11	6.25	1.96	7.10
May	1.70	4.08	1.79	3.41	1.51	2.27	1.63	3.52	1.93	8.24	1.12	4.87	1.91	6.54
June	1.80	3.64	1.95	3.20	1.71	2.49	1.73	3.54	2.16	8.20	1.06	5.86	2.83	6.74
July	1.91	3.77	2.11	3.32	1.80	2.66	1.76	4.05	1.74	10.20	0.82	7.07	3.14	6.71
August	1.98	4.26	2.30	3.53	1.84	2.86	1.88	3.89	2.64	8.22	0.97	6.50	3.29	6.78
September	2.13	5.08	2.27	3.86	1.76	3.04	1.90	4.01	2.87	28.84	0.96	6.92	3.35	6.93
October	2.17	5.36	2.06	4.21	1.55	3.05	1.72	4.07	2.47	9.57	0.80	6.74	3.25	6.71
November	1.76	7.48	1.79	4.18	1.51	3.11	1.64	4.40	3.06	8.81	1.01	6.72	3.52	7.14
December	2.54	6.23	1.61	4.38	1.24	3.82	1.75	4.75	3.61	9.51	1.60	7.17	3.59	7.46
Annual	1.76	5.87	1.90	4.06	1.49	3.11	1.72	4.28	2.68	9.36	1.12	6.69	2.89	7.10

Table 6. Average seasonal values of the characteristic wind speeds for selected locations

Months	Kumköy		Şile		Akçakoca		Zonguldak		Amasra		Cide		İnebolu	
	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}
Winter	1.99	7.27	1.68	4.81	1.24	3.87	1.80	4.93	3.57	9.93	1.64	7.03	3.17	7.51
Spring	1.77	5.29	1.80	3.91	1.38	2.75	1.64	4.02	2.42	9.17	1.15	6.25	2.02	7.12
Summer	1.89	3.92	2.12	3.37	1.78	2.67	1.79	3.85	2.16	8.91	0.94	6.50	3.09	6.74
Autumn	1.96	6.06	2.04	4.08	1.61	3.07	1.75	4.16	2.79	9.08	0.92	6.79	3.37	6.94
Annual	1.76	5.87	1.90	4.06	1.49	3.11	1.72	4.28	2.68	9.36	1.12	6.69	2.89	7.10

Table 7. Yearly mean variations of the characteristic wind speeds for selected locations

Months	Kumköy		Şile		Akçakoca		Zonguldak		Amasra		Cide		İnebolu	
	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}
2004	1.23	8.51	2.37	4.67	1.28	2.95	1.66	4.88	2.88	10.53	1.13	7.59	2.94	6.18
2005	2.18	8.34	2.31	4.58	1.06	2.81	1.57	4.98	2.69	10.95	1.29	7.40	2.98	5.91
2006	2.05	7.72	2.23	4.65	1.19	2.72	1.32	4.73	2.20	10.86	0.84	7.80	2.78	5.84
2007	2.21	4.45	1.80	3.59	1.71	3.26	2.10	4.16	2.86	8.52	1.14	6.75	3.01	7.58
2008	2.22	4.56	1.47	4.39	1.57	3.22	1.95	4.23	2.88	8.64	1.02	6.54	3.00	7.28
2009	2.17	4.31	1.78	3.80	1.63	2.90	2.02	4.23	2.87	8.55	1.35	5.92	3.01	7.42
2010	1.95	4.65	1.84	3.54	1.57	3.22	2.01	4.32	2.90	9.23	1.24	6.35	2.77	7.82
2011	2.03	4.20	1.98	3.67	1.70	3.47	1.72	3.81	2.90	8.22	1.21	6.19	2.89	7.53
2012	2.05	4.29	1.96	3.59	1.76	3.27	1.64	3.76	2.72	8.82	1.21	6.12	3.06	7.34
2013	1.90	3.78	1.73	3.08	1.69	2.80	1.58	3.21	2.48	8.28	1.05	6.25	2.84	7.53
Mean	1.76	5.87	1.90	4.06	1.49	3.11	1.72	4.28	2.68	9.36	1.12	6.69	2.89	7.10

4.1.2. Weibull Parameters And Characteristic Wind Speeds

The chunk of time for which given wind speed possibly prevails at a location is illustrated using the probability density function. Based on Figure 6, the peak of frequency values for density function slanted toward higher average wind speed values at all sites as expected. It must be noted that the most frequent speed is indicated by the peak of the curve of probability density function [17]. It is observed from Figure 6 that the most frequent wind speed which is expected at locations selected vary between 1 and 3 m/s. The same figure shows that Amasra and İnebolu, among the rest of the stations, show the highest spread values of wind speed toward high wind speeds. Time when wind speed is in a certain speed interval can be estimated by cumulative distribution function [16]. The frequency of annual probability density and cumulative distributions of wind speed for the picked locations obtained using the Weibull distribution functions are illustrated in Figure 6. For cut-in wind speeds lower or equal to 2.5 m/s, Kumköy, Şile, Akçakoca, Zonguldak, Amasra, Cide, and İnebolu have frequencies of about 46%, 55%, 74%, 56%, 27%, 50% and 29%, while for 3.5 m/s cut-in wind speed, the same locations have frequencies of about 64%, 78%, 92%, 78%, 40%, 66%, and 46%, respectively.

Figures 7 and 8 represent seasonal wind speed probability density and cumulative distributions obtained by using 10-year time series data for the locations selected, respectively. Based on the curves, Şile and Zonguldak seem to share the same tendency in cumulative density and probability frequency. The same applies for Kumköy and Cide loations as well as İnebolu and Amasra, with an exception at Akçakoca which is totally different from the rest. It is concluded from these figures that Amasra site is exposed to higher winds, followed by İnebolu. This tells us that wind farms to be established at these locations, compared to the other locations, are therefore expected to harness more energy. Wind availability percentage of speeds above 3 m/s is observed at Kumköy, Şile, Akçakoca, Zonguldak, Amasra, Cide, and İnebolu, respectively, in summer season with 30%, 25%, 19%, 28%, 61%, 38%, and 64%, in spring season with 73%, 54%, 32%, 28%, 64%, 39%, and 54%, in autumn season with 48%, 34%, 15%, 31%, 67%, 40%, and 68%, and in winter season with 54%, 36%, 22%, 39%, 74%, 49%, and 67%.

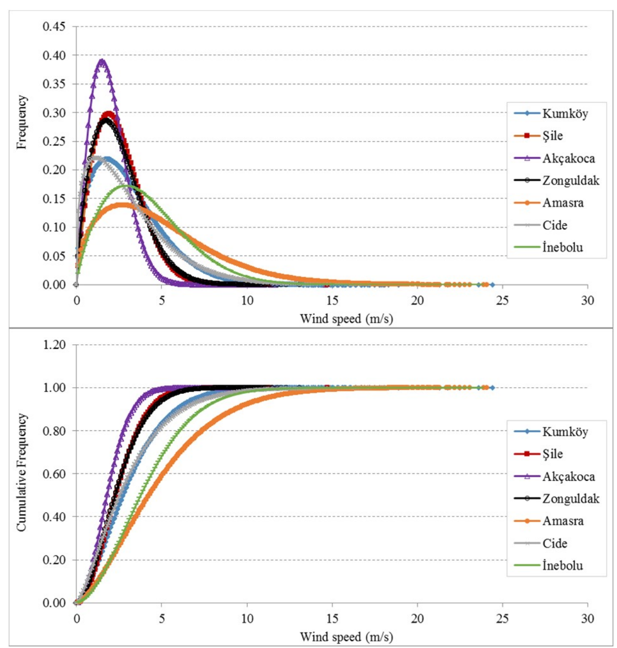

Figure 6. Frequency and cumulative frequency distributions of wind speeds measured at 10 m height at selected locations

4.2. Wind Power And Energy Characteristics

Diurnal wind power density variations shown in Figure 9 for the locations are the similar to that of average wind speed presented in Figure 2. Trends of wind power density variations at Kumköy, Şile, Akçakoca, Zonguldak, and Cide are very much alike while different at İnebolu compared to the other locations. The wind blowing at all locations, for all years, was strong between 9 a.m. and 6 p.m during the day except at İnebolu. Over the study period, 246.32 W/m^2 was the highest value in average wind power density observed at Amasra at 3 p.m., throughout the day, this site has the highest power generation potential.

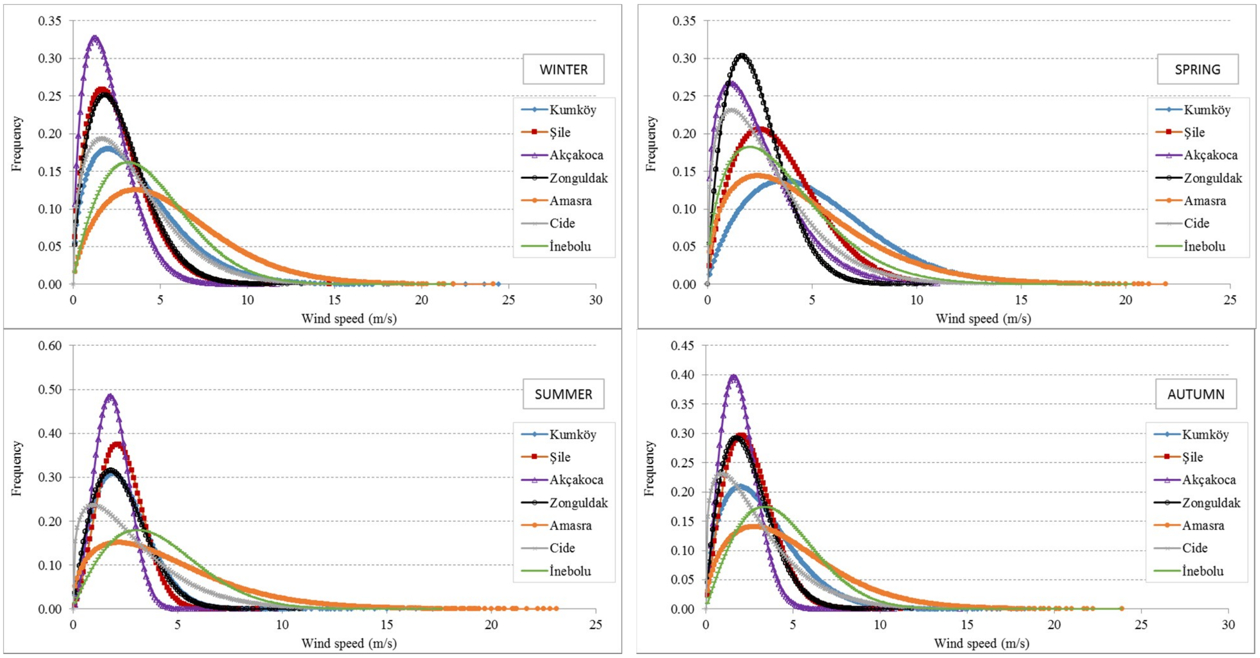

Figure 7. Seasonal wind speed frequency distributions for selected locations

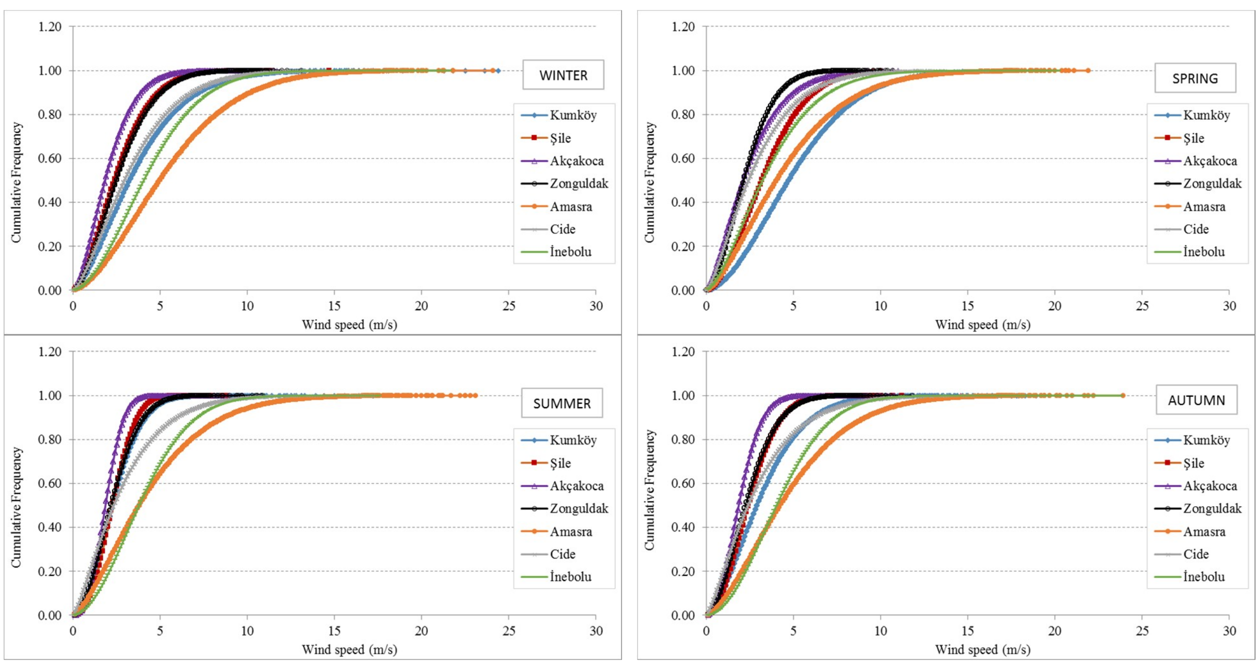

Figure 8. Seasonal wind speed cumulative probability distributions for selected locations

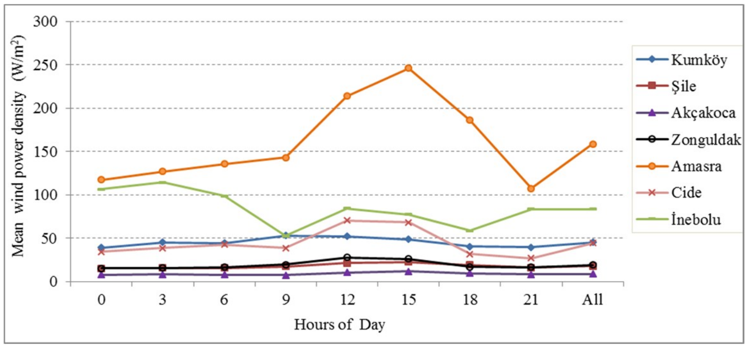

Figure 9. Diurnal variations of mean wind power density for selected locations

Shown in Figure 10 and Figure 11 are monthly and variations of seasonal average power density measured at 10 m above the ground. These variations, as assumed, have similar trends as the average wind speed presented in Figure 3 and 4. In this region, monthly average power density extends from 3.87 W/m^2 in May at Akçakoca to 222.92 W/m^2 in January at Amasra. Followed by İnebolu in terms of wind power density, in all seasons throughout the year, Amasra has the highest. Generally, there is a similarity in wind power potential for Zonguldak, Akçakoca and Şile in all months of the year and seasons. However, Akçakoca is one location that show the lowest energy potential.

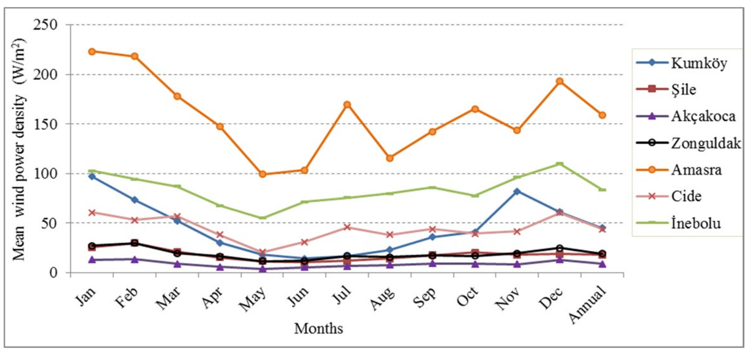

Figure 10. Monthly variations of mean wind power density for selected locations

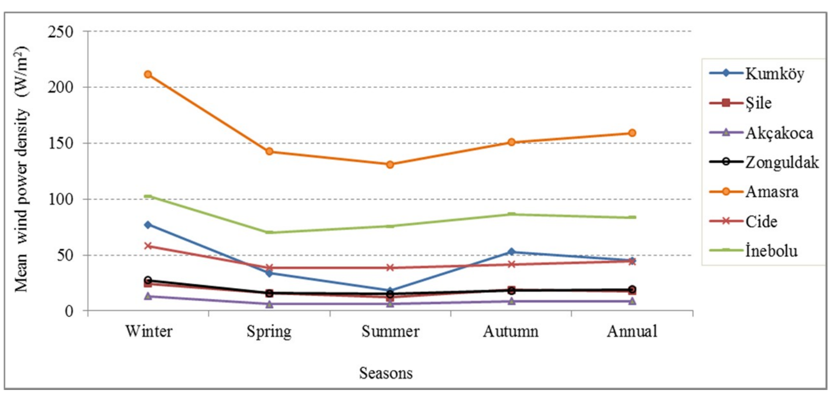

Figure 11. Seasonal variations of mean wind power density for selected locations

The characteristic pattern of the average monthly energy density and power density seem to follow the same path. In this region, there is a range from 2.88 kWh/m^2 in May at Akçakoca to 165.85 kWh/m^2 in January at Amasra in monthly average power density. Table 8 shows that among the seven stations, Akçakoca shows the lowest wind energy density while Amasra has the highest. There is a range from 8.69 W/m^2 at Akçakoca to 158.86 W/m^2 at Amasra in yearly average wind power density, and 1.85 m/s at Akçakoca and 4.54 m/s at Amasra in yearly average wind. Likewise, Amasra has 1391.61 kWh/m^2, which is the highest yearly average energy while Akçakoca has the lowest value of 76.12 kWh/m^2 as per Table 9. Akpınar [11] demonstrated that the wind energy potential increases from east to west in the north-east part of Turkey, and also, Sinop is the most convenient spot for wind energy farm establishment in this region. Mean wind energy density of Sinop site is reported to be 374.38 kWh/m^2. This trend does not continue in the north western Turkey, but there are available higher potential areas than that in the north eastern Turkey.

Table 8. Monthly variations of mean wind energy density (kWh/m^2)

Months	Kumköy	Şile	Akçakoca	Zonguldak	Amasra	Cide	İnebolu
January	72.15	19.12	9.72	20.32	165.85	45.15	76.36
February	49.36	19.94	9.11	20.13	149.49	35.57	63.34
March	38.81	15.57	6.49	14.60	132.62	42.34	64.63
April	21.86	11.06	4.10	11.93	106.26	27.51	48.74
May	13.53	8.55	2.88	8.48	73.73	15.32	40.88
June	10.32	7.45	3.86	8.69	74.54	22.35	51.26
July	12.34	8.73	4.87	12.68	126.34	34.18	56.21
August	17.14	10.65	5.85	11.74	86.12	28.47	59.38
September	25.99	12.74	6.52	12.44	102.56	31.72	61.87
October	30.35	15.11	6.47	12.51	122.82	29.40	57.70
November	59.03	12.89	6.22	14.12	103.19	29.99	69.21
December	45.36	13.91	9.84	18.48	143.53	44.81	81.78
Annual	395.08	156.10	76.12	166.79	1391.61	385.70	731.72

Table 9. Annual wind characteristics for selected sites over the period of 10 years

Locations	Annual mean wind speed (m/s)	Annual mean power density (W/m^2)	Annual energy (kWh/m^2)
Kumköy	2.90	45.10	395.08
Şile	2.39	17.82	156.10
Akçakoca	1.85	8.69	76.12
Zonguldak	2.36	19.04	166.79
Amasra	4.54	158.86	1391.61
Cide	2.76	44.03	385.70
İnebolu	3.94	83.53	731.72

Mean power density yearly variations at 10 m height for the sites are given in Figure 12. The annual mean power density variations, expected, follow a trend similar to the average wind speed (see Figure 5). As can be seen, for Amasra, Kumköy, Cide, Şile, and Zonguldak locations there are decreasing trends while annual trends of İnebolu and Akçakoca locations increase. The maximum mean wind power densities are observed as 113.12 W/m^2 in 2005 for Kumköy, 28.21 W/m^2 in 2004 for Şile, 12.48 W/m^2 in 2011 for Akçakoca, 25.01 W/m^2 in 2005 for Zonguldak, 231.95 W/m^2 in 2005 for Amasra, 58.66 W/m^2 in 2006 for Cide, and 103.53 W/m^2 in 2010 for İnebolu. Yearly mean wind power densities during the period of 2004-2013 vary between 8.69 W/m^2 at Akçakoca and 158.86 W/m^2 at Amasra. All these results indicate that Amasra site possesses the highest wind energy potential, followed by İnebolu site.

4.3. Wind Direction Analysis

When it comes to wind farm establishment locating in an area, wind direction plays a very important role in wind energy use possibility assessment and optimal positioning of a wind farm. The estimation done and mentioned above has been made without inducing wind direction impact in the wind speed distribution. Wind roses are plotted showing wind data which is collected after evaluating wind direction frequency falling within individual directional sectors in this section [18]. A wind rose show a brief and clear view of the frequency distribution of wind speed and direction at a specific location. It gives information about a period of time in hours within which wind remained in a specific direction and wind speed bins. That is to say, respective wind speed information in various directions is given by the wind rose. In order to plot the wind roses, wind speed measurements along with their matching directions are used. Wind roses are also referred to as meteorological fingerprints because just like the speed of wind, they change from one point to another. For this reason, wind roses have to be carefully read and understood before installation of wind power generating machines. The machines have to be installed against the direction which has largest share of wind [12].

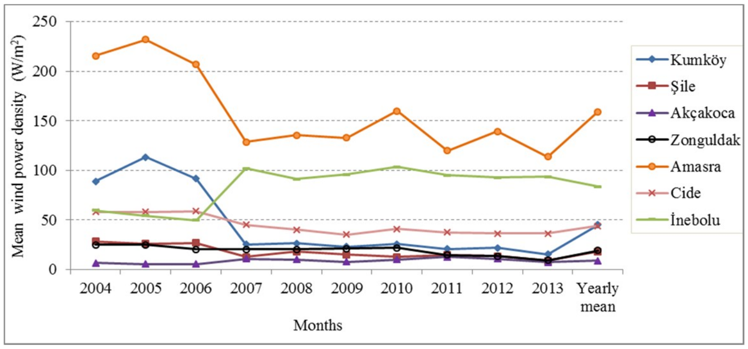

Figure 12. Annual variations of mean wind power density for selected locations

Wind roses and frequency distribution were plotted and analysed using all wind speed time series data and wind direction for each and every station. Figure 13 shows that wind speed roses stayed at various speed pins at 10 m above the ground for all seven locations. As the figures illustrates, there is a predominant blow of wind from southeast (SE), north (N), south-southeast (SSE), southeast (SE), south-southeast (SSE), south-southwest (SSW), and south (S) at Kumköy, Şile, Akçakoca, Zonguldak, Amasra, Cide, and İnebolu, respectively.

5. CONCLUSION

The potential of wind power and its characteristics for coastal areas along the south western Black sea are investigated in this study. Using the function of 2-parameter Weibull distribution, for the purpose of characterizing wind energy resource, a detailed analysis has been carried out on 10-year wind data for each station. Firstly, an investigation on diurnal, monthly, seasonal, and yearly average wind speed was carried out. Then power and energy densities were also investigated at the seven selected locations in north-west Turkey. Weibull parameters have been discussed followed by characteristic wind speeds and then seasonal and annual wind speed frequency distribution variations, after which an analysis of wind direction has been conducted. Summarized below are crucial outcomes from the current study.

- ✓ During the period of 2004-2013, annual average wind speeds vary between 1.85 m/s and 4.59 m/s for locations selected. Yearly maximum energy carrying wind speed values for the above locations vary between 3.11 and 9.36 m/s.
- ✓ Weibull shape parameter's (k) average yearly value is between 1.32 and 1.94, while the yearly scale parameter (c) value is between 2.16 and 5.40 m/s.
- ✓ The yearly average wind power density fluctuates from 8.69 W/m^2 at Akçakoca to 158.86 W/m^2 at Amasra, while the yearly average wind ranges between 1.85 m/s at Akçakoca and 4.54 m/s at Amasra. The resource of wind energy in south western coasts of the Black Sea is therefore considered weak based on the data used in this study. However, generation of energy from wind is still promising in this region for small-scale applications which operates at wind speeds below 5 m/s [31] at the moment and large-scale applications in the future with the development of advanced technology in wind turbine industry.
- ✓ Winds blowing from the southeast (SE), north (N), south-southeast (SSE), southeast (SE), south-southeast (SSE), south-southwest (SSW), and south (S) at Kumköy, Şile, Akçakoca, Zonguldak, Amasra, Cide, and İnebolu, respectively, throughout the years of study were predominant.

In conclusion, a wind farm established at Amasra would likely produce more power compared to the other sites. Moreover, Amasra is able to consider, followed by İnebolu, the most suitable for the development of wind energy among the rest of locations on the northern coasts of Turkey in the Black sea (Table 9).

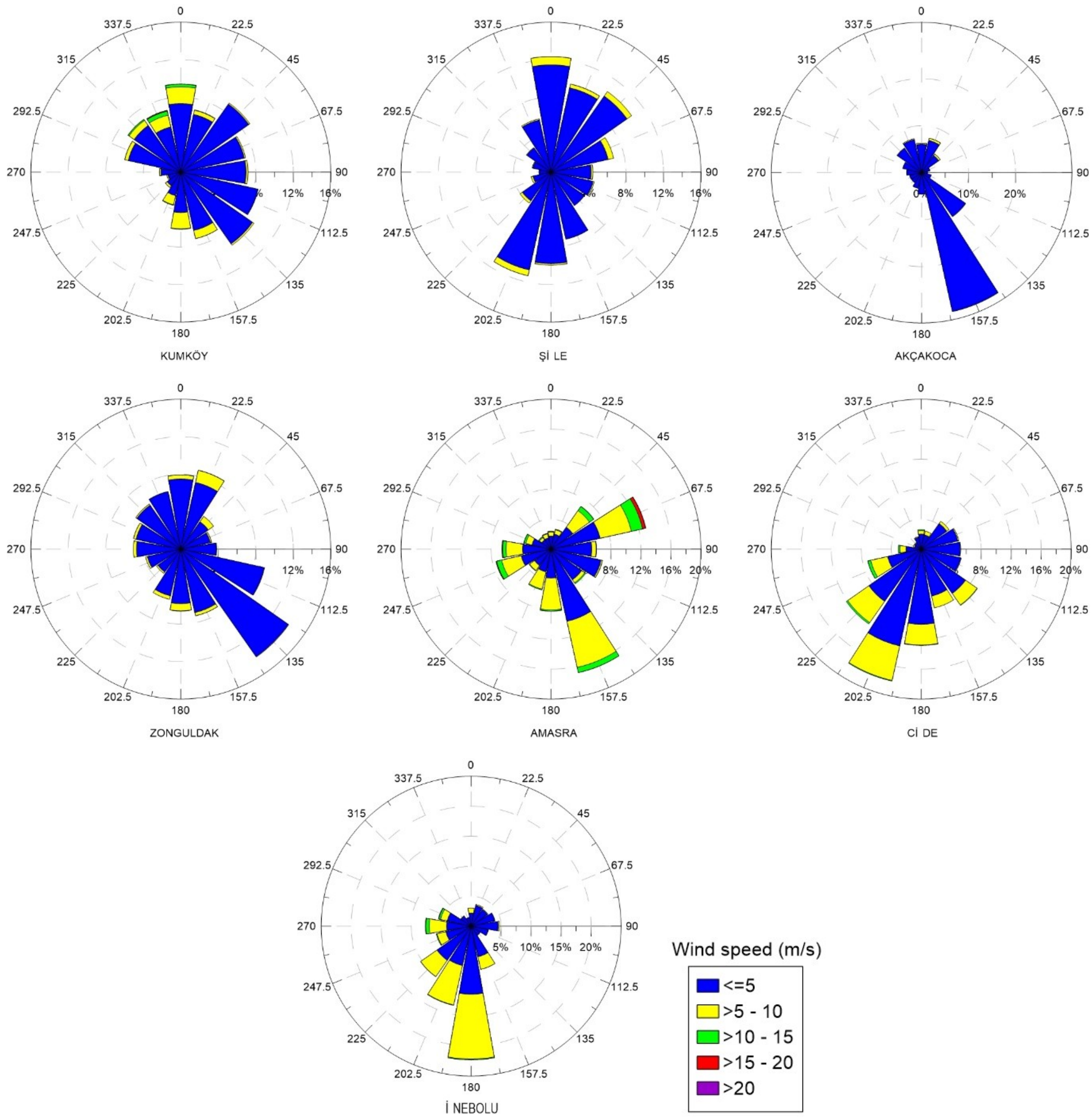

Figure 13. Wind roses for selected locations

6. ACKNOWLEDGEMENTS

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