Pamukkale Univ Muh Bilim Derg, 23(4), 337-342, 2017

Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi

Pamukkale University Journal of Engineering Sciences

Investigation of long term wind characteristics and wind energy potential in Bandırma, Turkey

Bandırma'nın uzun dönem rüzgar karakteristiğinin ve rüzgar enerjisi potansiyelinin incelenmesi

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Received/Geliş Tarihi: 22.01.2016, Accepted/Kabul Tarihi: 04.08.2016
doi: 10.5505/pajes.2016.99267
Research Article/Araştırma Makalesi
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Abstract

In this study, wind speed characteristics and wind energy potential were analyzed by using the wind speed data from the meteorological station of Bandırma, Turkey. The hourly time-series wind speed data and wind direction were collected for 30 years between 1975 and 2005. The measured wind speed data were processed for 30 years and seasonal. Weibull and Rayleigh probability density functions were obtained from the observed data and Weibull shape parameter c and the scale parameter k were found as 4.55 and 1.66 for 30 years. The wind energy potentials of 30 years were compared according to Weibull distribution and actual data. The most frequent wind direction was found from NNE direction with the highest mean wind speed value of 4.78 m/s. Seasonal wind speed characteristics were also calculated. The highest mean wind speed value was found for summer season with 4.40 m/s.

Keywords: Weibull distribution, Rayleigh distribution, Wind energy

Öz

Bu çalışmada, Bandırma meteoroloji istasyonundan alınan rüzgar hızı verileri kullanılarak Bandırma'nın rüzgar hızı karakteristikleri ve rüzgar enerjisi potansiyeli incelenmiştir. Bir saatlik zaman serileri biçiminde 1975-2005 seneleri arasında alınan rüzgar hızı ve yönü verileri 30 sene için senelik ve mevsimsel olarak işlenmiştir. Elde edilen veriler yardımıyla Weibull ve Rayleigh olasılık yoğunluğu fonksiyonları 30 sene için çıkartılmış, Weibull şekil parametresi c ve ölçek parametresi k sırasıyla 4.55 ve 1.66 olarak bulunmuştur. Rüzgar enerjisi potansiyeli gerçek veri ve Weibull dağılımı için karşılaştırılmıştır. En sık rüzgar yönü KKD ve en yüksek ortalama rüzgar hızı değeri 4.78 m/s olarak belirlenmiştir. Mevsimsel rüzgar karakteristiklerde incelenmiş ve en yüksek ortalama rüzgar hızı yaz mevsimi için 4.40 m/s değeri olarak ölçülmüştür.

Anahtar kelimeler: Weibull dağılımı, Rayleigh dağılımı, Rüzgar enerjisi

1 Introduction

Turkey is a country that lies between two continents (Europe and Asia). Due to the rapid economic and social developments, energy demand of Turkey is also increasing. Unfortunately, Turkey does not possess great amount of fossil fuels. The country obtains electricity via thermal power plants which use fossil fuels.

After the oil crisis in 1970's countries started to search for alternative solutions of dependency on energy import. The negative impacts of fossil fuels on environment and increasing fuel prices forced other countries not only to improve energy efficiency and energy saving systems but also to find new and renewable energy sources. The renewable energy sources are natural, sustainable and they have much more less impact on environment than that of fossil fuels.

The most common renewable energy resources are solar, wind, biomass, geothermal and hydropower. According to the geographical position and conditions the reserve of these renewable energy sources may change.

As an infinitesimal energy source wind energy is one of the other alternative options against conventional power production systems [1]. According to the estimations Turkey has 88.000 MW wind energy potential [2]. Today Turkey has around 4718.3 MW installed wind farm capacity [3].

There are seven regions in Turkey and some of these regions have different climate types. In some of the regions there are mountains and some of the regions are by the sea. Different geographical terrains provide different climate systems and strong winds. Southern parts of Marmara region, western and some middle parts of Aegean region, eastern parts of Mediterranean and locations with bumpy mountains in Eastern Anatolia region have good locations to install wind farms [4].

In the literature there are researches regarding the wind speed statistics for some locations in Turkey, such as: Turksoy for Bozcaada [5], Tolun et al. [6] and Eskin et al. [7] for Gokceada, Incecik and Erdogmus [8] and Sen and Sahin [9] for western Turkey, Durak and Sen [10] Akhisar in Konya, Karsli and Gecit [11] for Nurdagi in Gaziantep, Bilgili et al [12] for Antakya and Iskenderun, Akpinar [13] for Elazig, Gokcek et al. [14] for Kirklareli, Ucar and Balo [15] for Manisa, Gungor and Eskin [16] for some regions in Turkey, Sahin and Bilgili [17] for Belen in Hatay and Ucar and Balo [18] for six locations in Turkey.

In this article wind energy characteristics and wind energy potential of Bandırma in Balıkesir province were investigated for a period of 30 years between 1975 and 2005. Weibull and Rayleigh probability density distributions were calculated from obtained data. Seasonal and 30 years wind speed characteristics were calculated.

2 Wind speed data

In this study, wind speed of hourly time series for 30 years between 1975 and 2005 was obtained from Turkish State Meteorological Service. Bandırma station is located at 40º 21′ N and 27º 58′ E. In the station wind speed was measured via a cup anemometer on a mast that has a height of 10 m. Figure 1 shows the location of the site in Marmara region.

Figure 1: Bandırma weather station.

3 Calculation and methodology

3.1 Weibull and Rayleigh distributions

In the evaluation of wind speed characteristics and the wind energy potential of a site wind speed distribution, meteorological data and topographical information are needed. Once the wind speed distribution is calculated statistically by using several years of data the power potential of the site can be obtained. There are several methods to describe the characteristics of wind speed data and one of the easiest way is to use a distribution function. In most of the studies Weibull and Rayleigh functions are used.

The Weibull distribution function is written in Eq. (1).

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

Where v is the wind speed, k is the dimensionless Weibull shape parameter and c is the Weibull scale parameter in m/s. The cumulative probability function of the Weibull function can be calculated as below

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

There are several methods of calculating Weibull k and c parameters, such as graphical method, standard deviation method, moment method, maximum likelihood method etc. In this study standard deviation method is used to determine the Weibull k and c parameters. According to standard deviation method Weibull k and c parameters can be found as below [19].

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \tag{3}$$

$$c = \frac{\bar{v}}{\Gamma(1+\frac{1}{k})} \tag{4}$$

Where $\bar{v}$ is the mean wind speed and σ is the standard deviation. The mean wind speed according to Weibull distribution can be calculated as below,

$$\bar{v} = \int_0^\infty v f(v) dv \tag{5}$$

If Weibull distribution function in Eq. 1 is replaced in Eq. 5 the mean wind speed can be obtained as follows,

$$\bar{v} = \int_0^\infty v \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^k\right] dv \tag{6}$$

If we replace $x = \left(\frac{v}{c}\right)^k$ and $dv = \frac{c}{k}x^{(\frac{1}{k}-1)}dx$ Eq. 6 will be

$$\bar{v} = c\int_0^\infty x^{1/k} exp(-x) dx \tag{7}$$

Which is in the form of standard gamma function. Standard gamma function is given by,

$$\Gamma n = \int_0^\infty \exp(-x)\, x^{n-1} dx \tag{8}$$

Rayleigh distribution is a special case of Weibull distribution in which the dimensionless shape parameter is taken as 2.0. Probability and cumulative function of Rayleigh distribution are given in Eqs. 9 and 10.

$$f_R(v) = \frac{\pi v}{2\bar{v}^2} exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{\bar{v}}\right)^2\right] \tag{9}$$

$$F_R(v) = 1 - exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{v}{\bar{v}}\right)^2\right] \tag{10}$$

3.2 Wind power density

It is important to determine the wind power density of a site which corresponds to the wind power per unit rotor area. The wind power density of the considered site per unit area based on any probability density function can be expressed as,

$$P_m = \frac{1}{2}\rho\int_0^\infty v^3 f(v) dv \tag{11}$$

Where ρ is the density of air, 1.225 kg/m^3, v is the wind speed, m/s. The power of the wind was obtained via Weibull distribution and measured data. The wind power for Weibull distribution can be calculated as below

$$P_{mW} = \frac{1}{2}\rho\bar{v}^3 \frac{\Gamma(1+\frac{3}{k})}{\left[\Gamma(1+\frac{1}{k})\right]^3} \tag{12}$$

3.3 Wind speed variation with height

The wind speed measurements are usually taken from 10 m above ground level which is a standard height for meteorological stations. It is important to know the wind speed at higher elevations which the wind turbines are going to operate. The power law is used to extrapolate the wind measurements that are taken from Bandırma observation station.

$$v = v_0\left(\frac{h}{h_0}\right)^\alpha \tag{13}$$

Where v_0 is the measured wind speed taken from the h_0 height of the anemometer, v is the extrapolated wind speed for the requested height h, α is the power law parameter and changes for the surface roughness. In this study power law parameter α is taken as 0.14.

3.4 Capacity factor and annual energy production

The capacity factor C_f is a performance indicator of a wind turbine. Sum of the energy that is converted within a certain time T via wind turbine E_{out} divided to the maximum available energy output E_r of the wind turbine for the same time. Capacity factor can be found as,

$$C_f = \frac{E_{out}}{TP_r} = \frac{E_{out}}{E_r} \quad (14)$$

Where, P_r is the rated power of the wind turbine.

Annual energy production (AEP) can be calculated if the capacity factor is known [20].

$$AEP = P_r C_f 8760 \quad (15)$$

4 Results

Figure 2 represents yearly average wind speed values of the location for 30 years. The yearly mean wind speed values are changing between 3.19 and 4.68 m/s. The maximum value of annual mean wind speed was observed in 1985 while the minimum mean wind speed is observed in 2002.

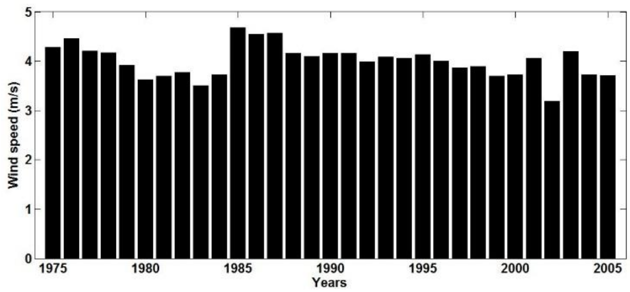


Figure 2: Mean wind speed values of the site for thirty years.

Figure 3 represents the monthly wind speed values of the site for 30 years. As seen from Figure 3 monthly wind speed values vary between 3.22 and 4.94 m/s. The maximum value of monthly wind speed was observed in August while the minimum mean wind speed was observed in April.

Figure 4 shows the wind direction frequency of the site for 30 years. The most wind is coming from the NNE direction with a frequency value of 0.2894 and the least wind is coming from W with a frequency value of 0.0072.

Relative frequency (%) and mean wind speed values are presented in Figure 5a-b respectively. NNE direction has the maximum wind frequency and also the maximum annual wind speed values.

In Figure 6, the mean wind speed values for wind directions are presented. The highest wind speed value was observed from NNE direction with a wind speed value of 4.78 m/s while the least wind speed value was observed for E direction 1.33 m/s.

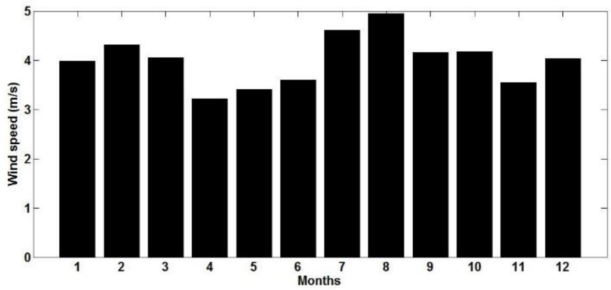


Figure 3: Monthly mean wind speed values of the site.

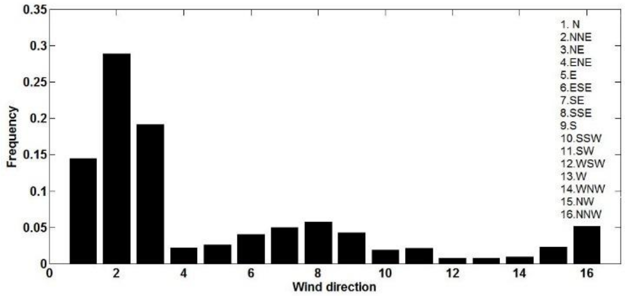
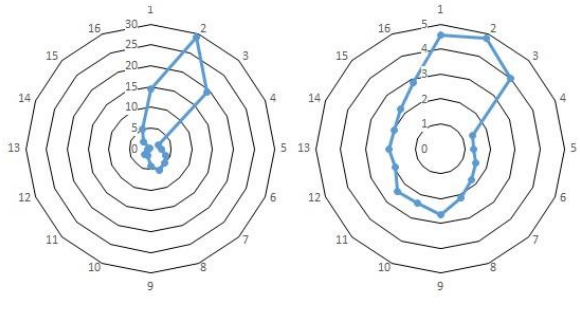


Figure 4: Wind speed frequency values for wind directions.



(a) (b)

Figure 5: Frequency (%) and mean wind speed (m/s) values for wind directions.

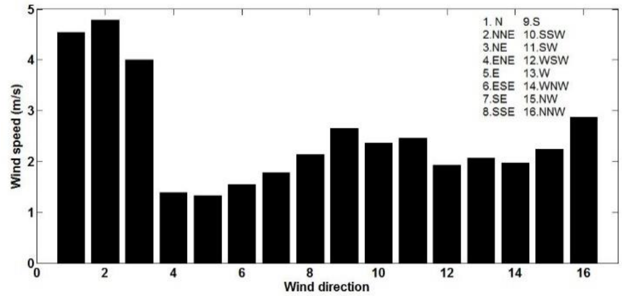


Figure 6: Mean wind speed values for wind directions.

Figure 7 illustrates the comparison of actual data with Weibull and Rayleigh probability density functions of the site. According to Figure 7 it can be seen that the Weibull distribution is closer to actual data that are taken from the site. The Weibull shape parameter c and the scale parameter k were obtained as 4.55 m/s and 1.66. Figure 8 shows the cumulative probability distributions for actual data, Weibull and Rayleigh distributions.

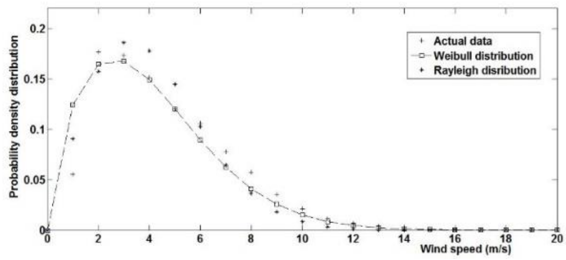


Figure 7: Wind speed frequency distributions of the site.

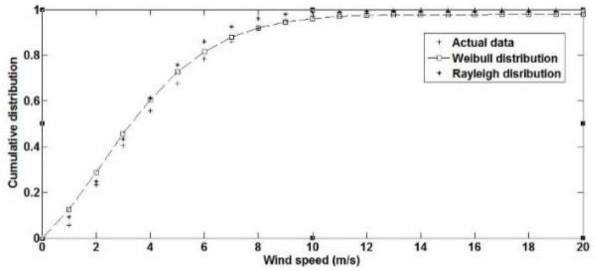


Figure 8: Wind speed cumulative probability distributions of the site.

Seasonal probability density distributions were shown between Figs. 9-12 and seasonal mean wind speed values, Weibull parameters were presented in Table 1. According to Table 1 the highest mean wind speed value was observed in summer with 4.4 m/s where the lowest mean wind speed value was observed in spring with 3.6 m/s.

Table 2 shows the wind speed values, wind power density for Weibull distribution and actual data with wind speed variations of the site.

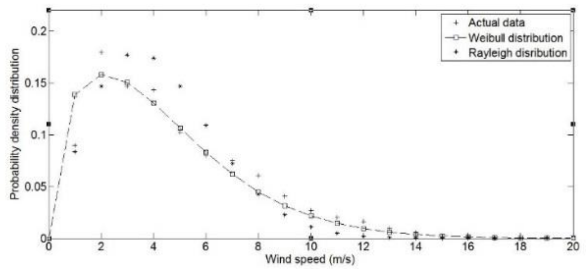


Figure 9: Wind speed frequency distributions of the site for winter.

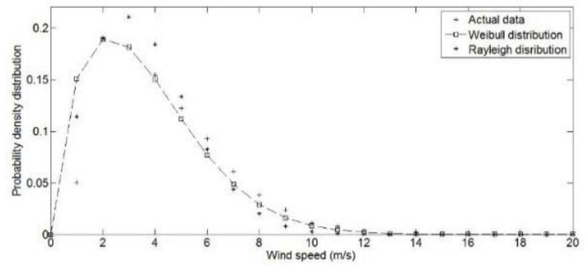


Figure 10: Wind speed frequency distributions of the site for spring.

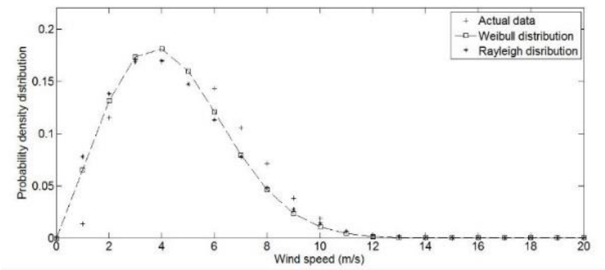


Figure 11: Wind speed frequency distributions of the site for summer.

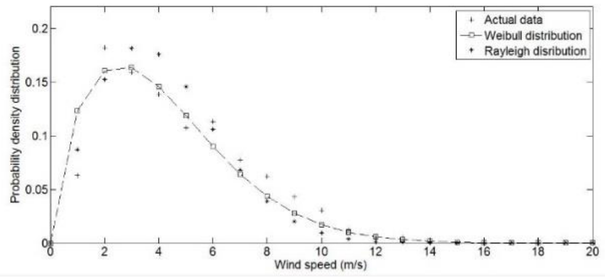


Figure 12: Wind speed frequency distributions of the site for autumn.

Table 1: Seasonal wind speed characteristics of the site.

Parameters	Seasons			
	Winter	Spring	Summer	Autumn
k	1.45	1.64	2.17	1.63
c (m/s)	4.68	4.03	4.97	4.63
V_{mean} (m/s)	4.24	3.60	4.40	4.15

Table 2: Wind speed values, wind power density for Weibull distribution and actual data with wind speed variations.

Height (m)	Wind speed (m/s)	P_{mW} (W/m²)	P_m (W/m²)
10	4.06	97.28	126.04
40	4.93	174.13	212.98
60	5.22	206.46	250.44
80	5.44	232.98	280.76

The main characteristics of three commercial wind turbines are presented in Table 3. The rated power of the turbines are 600 kW, 1300 kW and 2500 kW according to their hub heights and rotor areas.

As seen from the Table 4 the maximum AEP and capacity factor values were found for NORDEX N90/2500 model with 2397976 kWh/year and %12 respectively.

Table 3: Characteristics of wind turbines [21].

Characteristics	Nordex N43/600	Nordex N62/1300	Nordex N90/2500
Hub height (m)	40	60	80
Rated power (kW)	600	1300	2500
Swept area (m²)	1453	3020	6362
Cut-in speed (m/s)	3	3	3
Rated speed (m/s)	14	14.5	13.5
Cut-off speed (m/s)	25	22.5	25
Power control	Stall	Stall	Pitch

Table 4: Annual energy production (AEP) and capacity factor (C_f) values of wind turbines.

	AEP (kWh/year)	C_f (%)
Nordex N43/600	420090	8
Nordex N62/1300	979211	9
Nordex N90/2500	2397976	12

5 Conclusions

Long term wind speed characteristics and wind power density were investigated for Bandırma which is located in south of Marmara region. Actual measurement data were compared with Weibull and Rayleigh probability distribution functions. From this study these results can be drawn:

1. The average wind speed for Bandırma weather station at the 10 m height for 30 years was calculated 4.06 m/s and the maximum value of wind speed was observed as 21 m/s.
2. The highest annual mean wind speed value was recorded in 1985 with 4.68 m/s while the minimum annual mean wind speed was recorded in 2002 with 3.19 m/s.
3. The highest monthly mean wind speed value was recorded in August with 4.94 m/s while the minimum monthly mean wind speed was recorded in April with 3.22 m/s.
4. The most frequent wind direction was recorded from NNE direction with the highest mean speed value of 4.78 m/s.
5. The Weibull shape and scale parameters of the site were calculated as 4.55 m/s and 1.66, respectively.
6. The highest mean wind speed value was observed in summer season with 4.60 m/s while the lowest mean wind speed value was observed in spring with 3.6 m/s.
7. The seasonal Weibull shape and scale parameters vary between 1.45 and 2.17, 4.03 m/s and 4.97 m/s, respectively.
8. The mean power density values of the site at 10 m above ground level for measured data and Weibull function were found 126.04 W/m^2 and 97.28 W/m^2, respectively.
9. Maximum *AEP* and capacity factor values among three commercial wind turbines were found for NORDEX N90/2500 model with 2397976 kWh/year and %12 respectively.
10. According to the prevailing wind directions when installing a wind farm in this region, wind turbine arrays should be placed towards NW to SE to harvest more energy and also to reduce wake effects that created by wind turbines.
11. Calculated *AEP* and capacity factors will be higher for site specific measurements and geographical conditions. Surface roughness, terrain type directly affects the energy output of wind turbines.
12. Consequently, it's seen that the location is suitable for wind energy conversion systems in all seasons and the winds coming from NNE, N and NE directions.

6 Nomenclature

AEP	:	Annual Energy Production [MWh/year],
c	:	Weibull scale parameter [m/s],
C_f	:	Capacity factor [dimensionless],
E_{out}	:	Energy output [kWh/year],
E_r	:	Rated energy output [kWh/year],
$F_R()$	:	Rayleigh cumulative distribution function,
$f_R()$	:	Rayleigh distribution function,
$F_W()$	:	Weibull cumulative distribution function,
$f_W()$	:	Weibull distribution function,
h	:	Height [m],
h_0	:	Anemometer height [m],
k	:	Weibull shape parameter [dimensionless],
P_m	:	Power density [W/m^2],
P_r	:	Rated power [kW],
P_{mW}	:	Power density calculated by Weibull distribution [W/m^2],
v	:	Wind speed [m/s],
v_0	:	Wind speed at anemometer height [m/s],
$\bar{v}$	:	Mean wind speed [m/s],
α	:	Power law exponent [0.14],
σ	:	Standard deviation,
Γ	:	Gamma function.

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