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STATISTICAL ANALYSIS OF WIND SPEED DISTRIBUTION OF TURKEY AS REGIONAL

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Abstract

In this study, the statistical analysis of wind power density and wind speed distribution parameters of the selected cities from seven region of Turkey was investigated using the hourly wind speed data measured by the Turkish State Meteorological Service between 2005 and 2014. The Weibull and Rayleigh distributions were used for modeling and the success of this modeling process was evaluated according to the criterias of R^2, RMSE and χ^2. The Weibull parameters and the Rayleigh parameters were estimated analytically, and the mean wind speed and energy potential were determined based on these parameters. At the Weibull distribution, the lowest mean wind speed and power density was obtained as 1.73 m/s and 5.78 W/m^2 in Adıyaman, respectively. The highest mean speed and power density was determined as 2.95 m/s and 33.32 W/m^2 in Sinop. At the Rayleigh distribution, the lowest and the highest mean speed and the power density was obtained as 1.72 m/s and 5.63 W/m^2 in Adıyaman, 3.06 m /s and 33.44 W/m^2 in Sinop, respectively. Generally, the highest mean wind speed and power density values were determined in Sinop, and the lowest mean wind speed and power density values in Adıyaman. According to statistical criteria in wind data analysis of Turkey, the Weibull distribution was better than the Rayleigh distribution.

Keywords: Wind energy, statistically analysis of the wind energy potential, Weibull distribution, Rayleigh distribution, Turkey

1. Introduction

Wind energy is regarded as a clean energy resource for the environment with its renewable characteristic. It does not require any sort of transportation or high technology. Renewable wind energy has some other advantages as well. It is abundant and free in the atmosphere, and is a clean energy resource, which is easy to obtain and creates no environmental pollution. Energy is also primary element of economic and social development in the world. Developed and developing countries tend to include the use of renewable energy resources into their future plans. These countries develop new technology in this field and increase their investment in order to utilize their potential more effectively. The world will use renewable energy instead of using fossil fuels in order to meet the demands of the world's energy [1].

Theoretically, yearly wind potential of Turkey is very big, which is about twice as much as the current electricity consumption of country. Turkey's technical wind energy potential is 88,000 MW and its economic wind energy potential is about 10,000 MW. According to the reports of State Electrical Studies Board, wind energy potential of Turkey is estimated as around 120 billion kWh. Studies have showed that total wind energy potential of Turkey is higher than its present thermal and hydraulic energy production. In Turkey, the available wind energy power was 433.35 MW by the end of the year 2008; and it became1503.35 MW at the end of 2010. The strong development of wind energy in Turkey is expected to be continued in coming years. After all, it can be concluded that wind energy generation locations in Turkey are all at low altitudes [2].

In general, wind power prediction methods are categorized into two groups: physical and statistical. The first one implies physical considerations such as topography, terrains, local temperature and pressure to estimate the wind field more accurately and, subsequently, the energy potential. The later one, on the other hand, use statistical models in order to establish the relationship between power and other variables as well as their historical and forecasted values. Weibull distribution provides better fit to probability distributions compared to Rayleigh model and analyzes the wind speed data by using statistical distributions. The Weibull distribution (named after the Swedish physicist W. Weibull, who applied it when studying material strength in tension and fatigue in the 1930s) provides a close approximation to the probability laws of many natural phenomena. It has been used to represent wind speed distributions for application in wind loads studies for some time. For more than half a century the Weibull distribution has attracted the attention of statisticians working on theory and methods as well as various fields of statistics [3]. In this context, over the last decade, some researchers have performed the assessments of wind power in Turkey on the basis of individual locations [4-18]. The wind energy density in many provinces and localities of Turkey; Bilecik [4, 5], the western coast of Anatolia [6], Izmir [7], Iskenderun [8], Nurdağı-Gaziantep [9], Kütahya [10], Maden-Elazığ [11], Agın-Elazığ [12], Keban-Elazığ [13], Elazig and its close regions [14], Akşehir-Konya [15], Kırklareli [16], Maden, Gokceada, Canakkale and Bozcaada [17], Antakya[18], investigated and statistically analyzed using Weibull and Rayleigh distributions. Two parameter Weibull distribution is used to model of many regions of Turkey wind speed in recent year. The reason of using this method is very good fit wind distribution [4, 7, 19].

Turkey is a country surrounded by the sea on three sides, connecting Asia and Europe and therefore having a strategic position. The aim of this study was to calculate the wind energy potential of the selected cities from the seven region of Turkey and to assess the efficiency of electricity production by using the wind data recorded at the meteorological station.

2. Wind speed data

There are 7 regions in Turkey. They are split into climate, location, human activities/communication, etc. Turkey is bounded by four seas on three sides, spans a relatively large region in Asia and Europe. Four regions were named after the seas bordering them the Aegean, Black Sea, Marmara and Mediterranean. Three regions were named in accordance with their location in the whole of Anatolia; Central, Eastern and Southeastern.

The wind data used in this study were measured and recorded hourly at the stations of the Turkish State Meteorological Service at 10 m above ground level between 2005 and 2014. The details of the studied cities (Adıyaman, Bursa, Elazığ, İskenderun, Karaman, Muğla and Sinop) from seven regions of Turkey is given Figure 1 and Table 1. The wind data were captured using a cup generator anemometer.

Figure 1. Location of the studied cities on Turkey map

Table 1. The details of the studied cities

Station	Region	Latitude-Longitude	Height of ground above sea level (m)	Air density (kg/m^3)
Adıyaman	Southeastern Anatolia	38º 17´ N - 37º 46´ E	669	1.145
Bursa	Marmara	40º 15´ N - 29º 05´ E	100	1.213
Elazığ	Eastern Anatolian	38º 37´ N - 39º 14´ E	1015	1.104
Iskenderun	Meditteranean	36º 32´ N - 36º 10´ E	3	1.224
Karaman	Central Anatolian	37º 14´ N - 33º 13´ E	1250	1.076
Muğla	Aegean	37º 15´ N - 28º 22´ E	646	1.148
Sinop	Balack Sea	42º 01´ N - 35º 11´ E	32	1.221

3. Theory of wind speed and wind power

There are several continuous probability density functions that can be used to model the wind speed frequency curve by fitting long time series measured data. In wind power studies, the Weibull and Rayleigh probability density functions are commonly used and widely adopted [4-19]. Herein the Weibull distribution is used since the Rayleigh distribution is only a subset of it.

3.1. Weibull and Rayleigh distribution of wind speed

The probability denstiy function of Weibull distribution that is a special case of generalized gamma distribution for wind speed is expressed with Eq. (1).

$$f_w(v) = (\frac{k}{c})(\frac{v}{c})^{k-1} \exp(-(\frac{v}{c})^k) \quad (1)$$

where $f_w(v)$ is the probability of observing wind speed *v*, *k* the dimensionless Weibull shape parameter and *c* the Weibull scale parameter, which has its reference value in the units of wind speed [4-18].

The cumulative distribution function of the Weibull distribution is calculated as below [7, 11]:

$$F_w(v) = 1 - \exp(-(\frac{v}{c})k) \quad (2)$$

Determination of the parameters of the Weibull distribution requires a good fit of Equation (2) to the recorded discrete cumulative frequency distribution. Taking the natural logarithm of both sides of Eq. (2) twice, gives

$$ln\{-ln[1 - F(v)]\} = k\, ln(v) - k\, ln\, c \quad (3)$$

So, a plot of *ln{-ln[1-F(v)]}* versus ln v presents a straight line. The gradient of the line is *k* and the intercept with the *y*-axis is *–kln c*.

The *k* values range from 1.5 to 3.0 for most wind conditions. Another distribution function used in determination of the wind speed potential is Rayleigh distribution. This distribution is a special case of Weibull distribution and validate situation where the dimensionless shape parameter k of the Weibull distribution is assumed to be equal to 2. Probability density and cumulative function of the Rayleigh distribution are given by Eqs. (4) and (5), respectively,

$$f_R(v) = (\frac{2v}{c^2}) exp(-(\frac{v}{c})^2) \tag{4}$$

$$F_R(v) = 1 - exp(-(\frac{v}{c})^2) \tag{5}$$

The mean v_m and standard deviation σ of the Weibull distribution can then be computed from,

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

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

where $\Gamma()$ is the gamma function [7].

Based on the Weibull distribution, the wind speed with the largest frequency is calculated from Eq. (8)

$$V_{\text{mod}} = c(1-\frac{1}{k})1/k \tag{8}$$

The maximum wind speed is given by [14]:

$$V_{\max E} = c(\frac{k+2}{k})1/k \tag{9}$$

When *k=2* is taken in the above formulas, calculations are performed for Rayleigh distribution [4-18].

3.2. Calculations of wind power

The wind power per unit area in any windy site is of importance in assessing of the wind power projection for the power plants. The mean wind power density of the considered site per unit area based on any probability density function can be expressed as [16],

$$P_m = \int_0^\infty P(v) f(v) dv \tag{10}$$

It is well known that the power of the wind that flows at speed *v* through a blade sweep area A increases as the cubic of its velocity and is given by

$$P(v) = \frac{1}{2}\rho A v^3 \tag{11}$$

where ρ is the air density for the studied site. The mean power density for the Weibull distribution is obtained from Eq. (12) as follows

$$P_w = \frac{1}{2}\rho c^3 \Gamma(1+\frac{3}{k}) \tag{12}$$

where, Γ is gamma function.

The mean power density for the Rayleigh distribution is determined by Eq. (13):

$$P_R = \frac{3}{k}\rho v^3 m \tag{13}$$

3.3. Statistical analysis of distributions

The coefficient of determination (R^2), chi-square (χ^2) and root mean square error analysis (*RMSE*) and were used as the primary criterion to select the best distribution to account for the variation in the wind speed curves. Chi-square is the mean square of the deviations between the experimental and calculated values for the distributions and was used to determine the goodness of the fit. The lower are the values of chi-square, the better is the goodness of the fit. The RMSE gives the deviation between the predicted and experimental values, and it is required to approach zero. The R^2 also gives the ability of the model, and its highest value is 1. These statistical values can be calculated as follows:

$$R^2 = \frac{\sum_{i=l}^{N}(yi - zi)^2 - \sum_{i=l}^{N}(xi - yi)^2}{\sum_{i=l}^{N}(yi - zi)^2} \tag{14}$$

$$x^2 = \frac{\sum_{i=l}^{N}(yi - xi)^2}{N - n} \tag{15}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=l}^{N}(yi - xi)^2\right]^{1/2} \tag{16}$$

where *yi* is the *ith* experimental data, *zi* is the mean value of the experimental data, *xi* is the *ith* predicted data with the Weibull or Rayleigh distribution, *N* is the number of observations and *n* is the number of constants [11-14].

4. Results and discussion

In this study, wind speed data in the selected cities from seven region of Turkey, over a ten-year period from 2005 to 2014 were analyzed. Based on these data, wind speeds analysed were processed using Statistica statistical software and Fortran computer software. Calculations in the whole regions were then made to obtain the Weibull and Rayleigh distribution parameters in terms of k and c, mean wind speed and mean wind power. The main results obtained from the present study can be summarized as follows:

The monthly mean wind speeds are illustrated in Figure 2. Table 2 shows the maximum and minimum values of the monthly mean wind speed and also the yearly mean values for the period of 2005 and 2014. The monthly and yearly mean wind speed values are mostly between 1.0 and 4.0 m/s for the selected cities. The maximum value of the yearly mean wind speed is 3.36 m/s in Sinop while the minimum value is 1.97 m/s in Adıyaman. In Elazığ, Muğla, Karaman and Bursa, the mean wind speed is mostly on 2 m/s and wind energy potential is suitable for wind energy applications. In Iskenderun and Sinop, it is determined that electricity generation from wind energy is suitable because the monthly mean speed is mostly on 3 m/s. In Adıyaman, the monthly mean wind speed is about 2 m/s, is not suitable for wind energy applications.

Table 2. The monthly and yearly mean wind speed values for the studied cities

The monthly mean wind speeds	The minimum	The maximum	The yearly mean wind speeds
Adıyaman	1.34 m / s in January of 2014	3.09 m/s in June of 2008	1.97 m/s
Bursa	1.50 m/s in November of 2006	3.78 m/s in August of 2013	2.53 m/s
Elazığ	2.18 m/s in October 2009 as	3.85 m/s in March 2012	2.83 m/s
İskenderun	1.68 m/s in November of 2012	4.5 m/s in July of 2006	2.82 m/s
Karaman	1.77 m/s in November 2011	3.91 m/s in March 2008	2.64 m/s
Muğla	1.39 m/s in March of 2013	2.84 m/s in February of 2005	2.23 m/s
Sinop	2.41 m/s in March of 2013	4.28 m/s in February of 2011	3.36 m/s

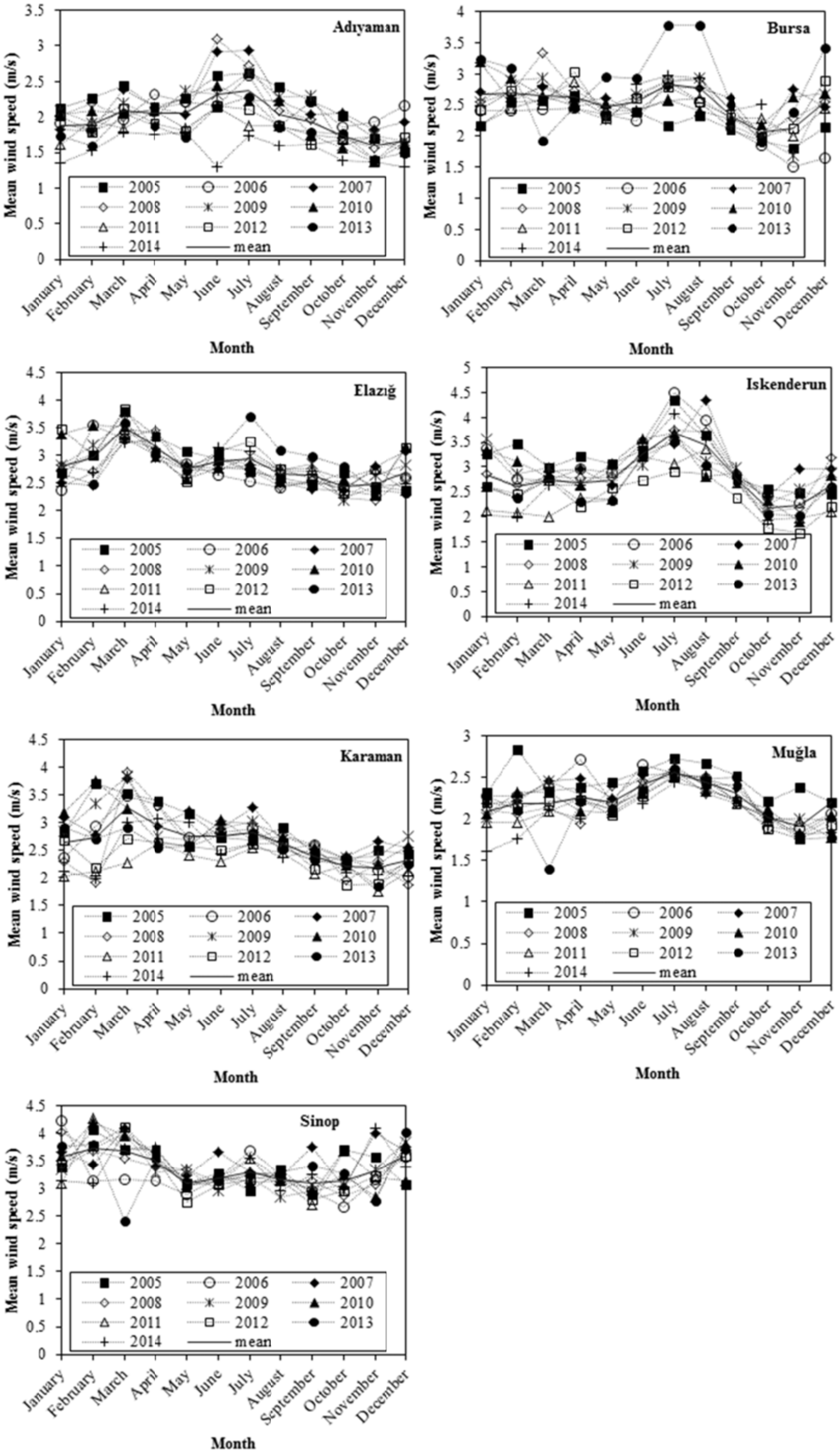


Figure 2. Monthly mean wind speed for the period of 2005–2014

In Figure 3, the diurnal variation of mean wind speed values is plotted. The lowest and highest mean wind speed values at the diurnal variation are given Table 3. According to the yearly average results, the wind speed is the lowest in Adıyaman, and is the highest in Sinop. The diurnal wind speed has its minimum during the morning hours and its maximum during the afternoon hours.

Table 3. The diurnal variation of mean wind speed

The diurnal variation of mean wind speed	The lowest	The highest	The mean of whole year
Adıyaman	0.59 m/s between the hours of 04:00 and 05:00 in 2014 year	2.29 m / s between the hours of 14:00 and 15:00 in 2005 year.	1.48 m/s
Bursa	0.97 m/s between the hours of 05:00 and 06:00 in 2005 year	3.71 m / s between the hours of 14:00 and 15:00 in 2013 year.	2.06 m/s
Elazığ	1.47 m/s between the hours of 06:00 and 07:00 in 2014 year	3.35 m / s between the hours of 14:00 and 15:00 in 2009 year.	2.36 m/s
İskenderun	1.08 m/s between the hours of 04:00 and 05:00 in 2012 year	3.81 m / s between the hours of 14:00 and 15:00 in 2005 year.	2.35 m/s
Karaman	0.89 m/s between the hours of 07:00 and 08:00 in 2006 year	3.55 m / s between the hours of 15:00 and 16:00 in 2005 year.	2.04 m/s
Muğla	1.12 m/s between the hours of 22:00 and 23:00 in 2014 year	2.82 m / s between the hours of 13:00 and 14:00 in 2005 year.	1.74 m/s
Sinop	2.15 m/s between the hours of 05:00 and 06:00 in 2006 year	3.89 m / s between the hours of 13:00 and 14:00 in 2007 year.	2.93 m/s

The wind speed data in time-series format is usually arranged in the frequency distribution format since it is more convenient for statistical analysis. Therefore, the available time-series data were translated into frequency distribution format. The probability density distribution of actual data and the theoretical frequency values calculated from the Weibull and Rayleigh distributions are determined [8, 11-14]. The yearly probability density and the cumulative distributions are seen in Figure 4 for ten years. It is seen that all the curves have a similar tendency of wind speeds on probability and cumulative density.

The Weibull and Rayleigh approximations of the actual probability distribution of wind speeds are shown in Figure 5, while a comparison of the two approximations is given in Table 4. In Figure 5, the probability distribution of the actual data, the Weibull probability distribution, and the Rayleigh probability distribution are plotted versus the wind speed according to the average of ten years data.

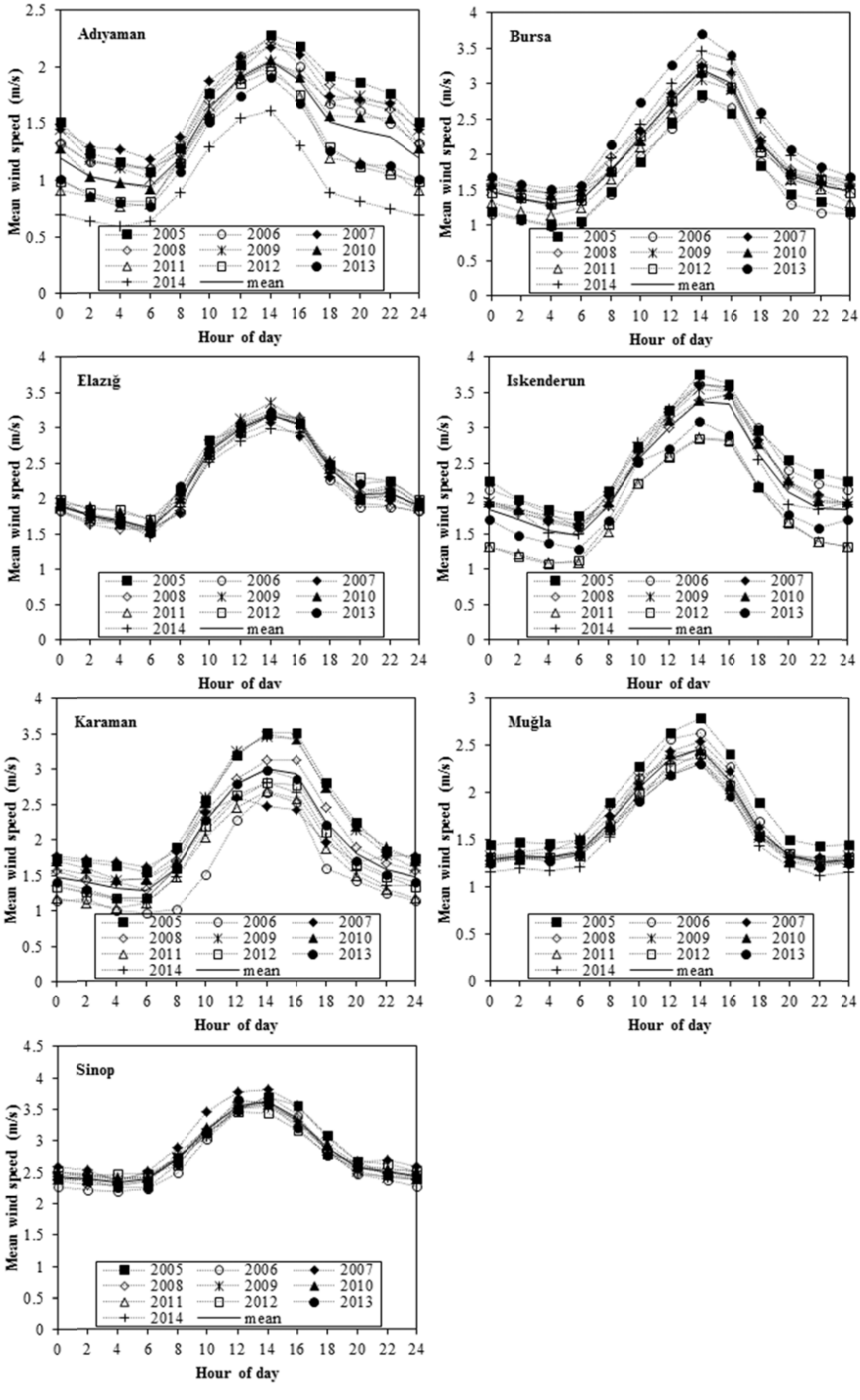


Figure 3. Diurnal variation of mean wind speed for the period of 2005–2014

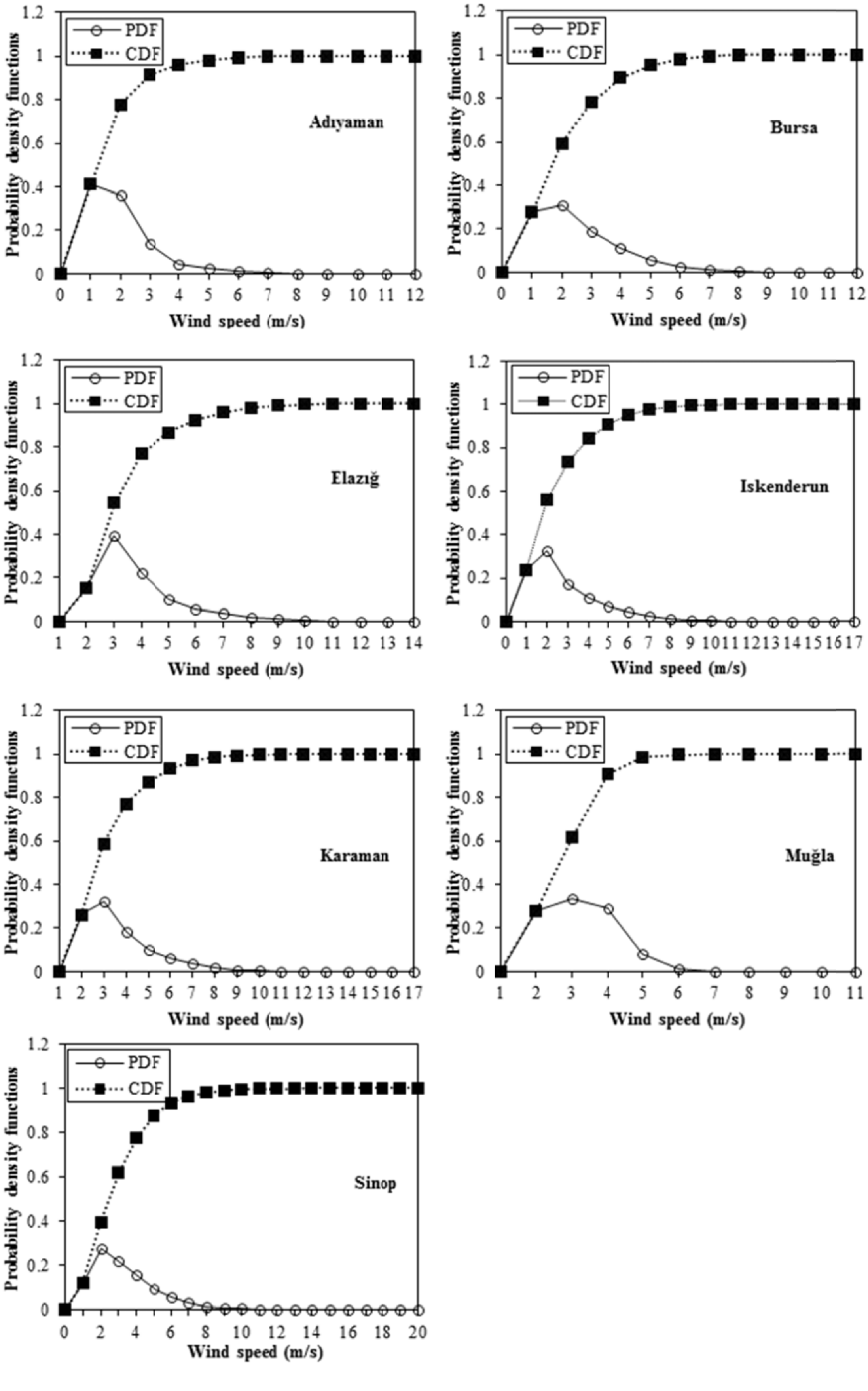


Figure 4. The wind speed probability density and cumulative probability distributions for whole years, derived from the measured hourly time-series

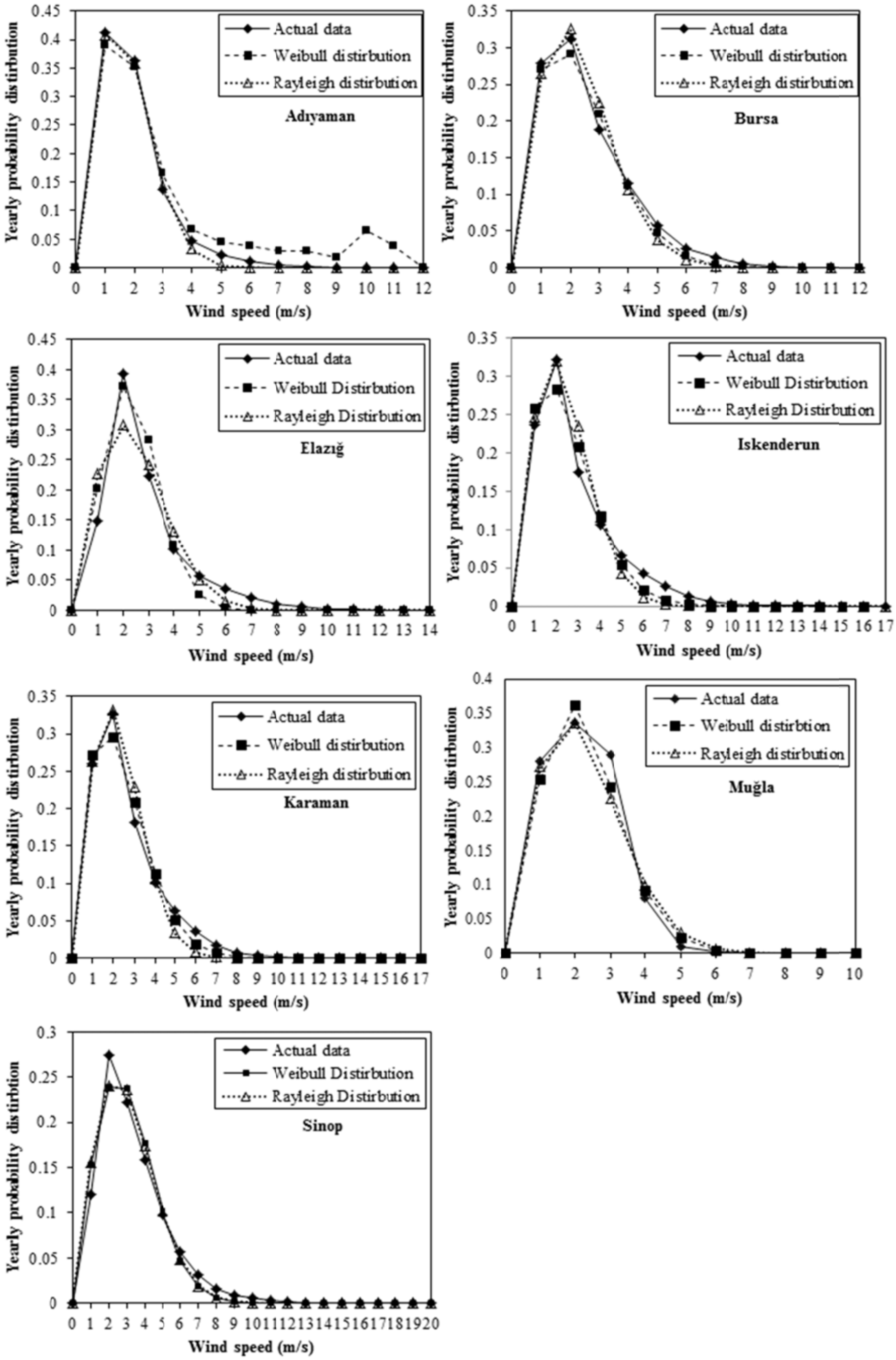


Figure 5. The comparison of Weibull and Rayleigh approximations with the actual probability distribution of wind speeds

Table 4. R^2, RMSE and χ^2 values according to Weibull and Rayleigh distributions

Adıyaman	Weibull Dağılımı			Rayleigh Dağılımı		
Year	R^2	RMSE	χ^2	R^2	RMSE	χ^2
2005	0.992	0.000103	0.000253	0.984	0.000104	0.000229
2006	0.989	0.000049	0.000122	0.968	0.000081	0.000181
2007	0.992	0.000073	0.000178	0.985	0.000125	0.000276
2008	0.995	0.000074	0.000181	0.984	0.000124	0.000273
2009	0.986	0.000101	0.000243	0.959	0.000128	0.000279
2010	0.971	0.000037	0.000091	0.918	0.000065	0.000143
2011	0.951	0.000011	0.000028	0.916	0.000080	0.000182
2012	0.985	0.000032	0.000085	0.971	0.000036	0.000082
2013	0.990	0.000040	0.000113	0.981	0.000042	0.000097
2014	0.992	0.000025	0.000112	0.981	0.000106	0.000248

Bursa	Weibull Dağılımı			Rayleigh Dağılımı		
Year	R^2	RMSE	χ^2	R^2	RMSE	χ^2
2005	0.977	0.000182	0.000455	0.884	0.000940	0.002090
2006	0.976	0.000187	0.000458	0.886	0.000915	0.002012
2007	0.986	0.000082	0.000197	0.981	0.000110	0.000240
2008	0.665	0.002046	0.005001	0.658	0.002090	0.004599
2009	0.988	0.000077	0.000193	0.984	0.000106	0.000236
2010	0.983	0.000105	0.000256	0.967	0.000200	0.000441
2011	0.997	0.000018	0.000046	0.984	0.000114	0.000257
2012	0.990	0.000059	0.000144	0.976	0.000145	0.000320
2013	0.965	0.000179	0.000447	0.947	0.000269	0.000597
2014	0.950	0.000305	0.000784	0.950	0.000309	0.000695

Elazığ	Weibull Dağılımı			Rayleigh Dağılımı		
Year	R^2	RMSE	χ^2	R^2	RMSE	χ^2
2005	0.927	0.000509	0.001204	0.862	0.000971	0.002104
2006	0.909	0.000707	0.001697	0.844	0.001205	0.002630
2007	0.941	0.000429	0.001015	0.871	0.000941	0.002039
2008	0.934	0.000479	0.001150	0.884	0.000852	0.001860
2009	0.909	0.000588	0.001410	0.885	0.000744	0.001624
2010	0.901	0.000638	0.001489	0.853	0.000950	0.002046
2011	0.975	0.000140	0.000332	0.954	0.000263	0.000570
2012	0.943	0.000302	0.000713	0.938	0.000332	0.000720
2013	0.958	0.000168	0.000397	0.962	0.000202	0.000437
2014	0.960	0.000236	0.000558	0.947	0.000313	0.000679

Iskenderun	Weibull Distribution			Rayleigh Distribution		
Year	R^2	RMSE	χ^2	R^2	RMSE	χ^2
2005	0.906	0.004171	0.009732	0.900	0.000443	0.000954
2006	0.924	0.000312	0.000707	0.917	0.000340	0.000722
2007	0.939	0.000282	0.000659	0.919	0.000374	0.000806
2008	0.922	0.000403	0.000952	0.919	0.000419	0.000908
2009	0.922	0.000395	0.000933	0.919	0.000412	0.000891
2010	0.916	0.000435	0.001029	0.910	0.000470	0.001017
2011	0.994	0.000041	0.000103	0.957	0.000295	0.000654
2012	0.994	0.000037	0.088290	0.940	0.000372	0.000806
2013	0.995	0.000022	0.051670	0.966	0.000175	0.000377
2014	0.994	0.000026	0.059140	0.959	0.000177	0.000378

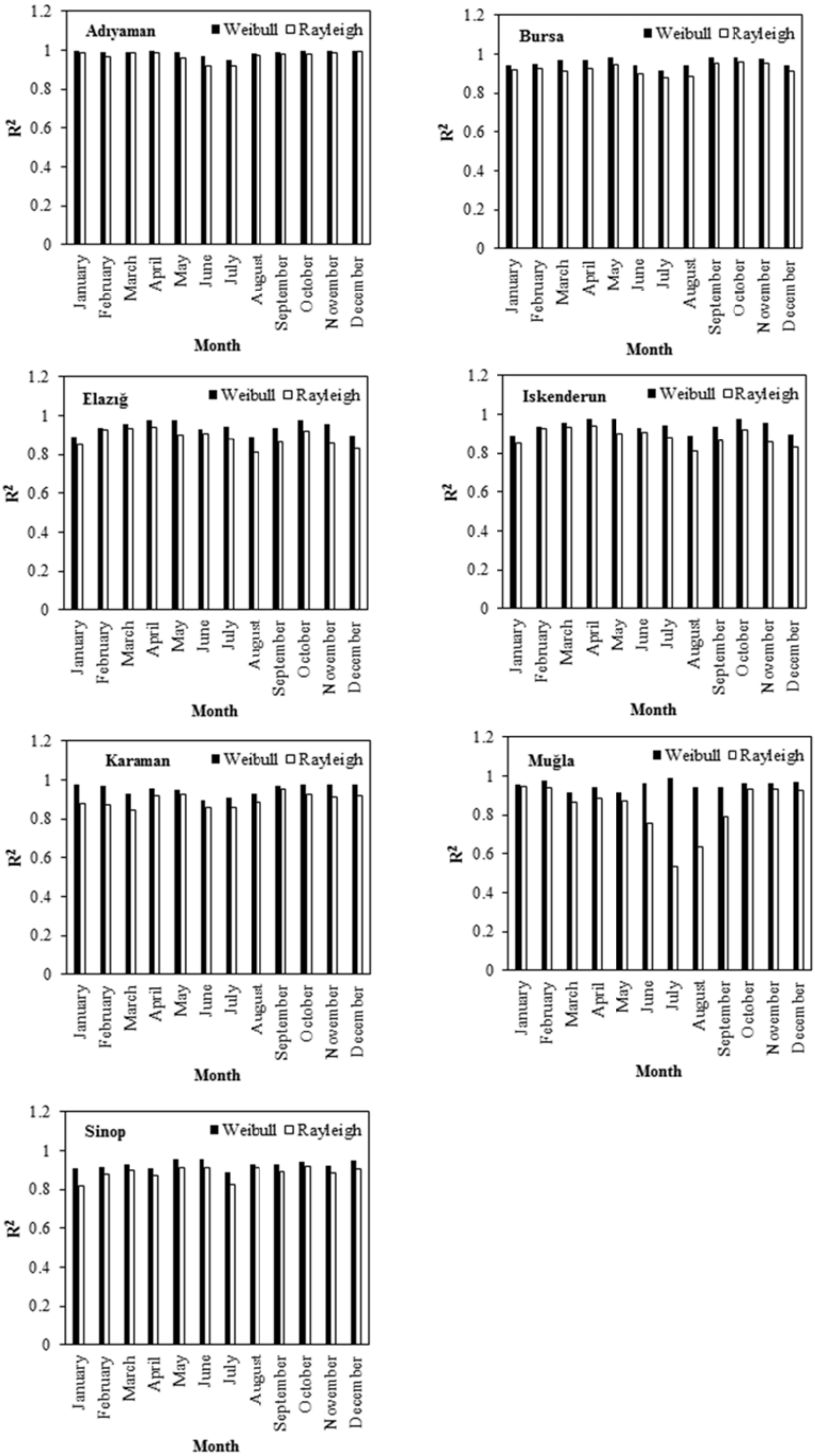
Karaman	Weibull Dağılımı			Rayleigh Dağılımı		
Year	R^2	RMSE	χ^2	R^2	RMSE	χ^2
2005	0.992	0.030950	0.070160	0.942	0.000249	0.000529
2006	0.972	0.000150	0.000349	0.969	0.000165	0.000356
2007	0.939	0.000313	0.000741	0.936	0.000366	0.000705
2008	0.963	0.000190	0.000444	0.952	0.000251	0.000542
2009	0.965	0.000169	0.000394	0.944	0.000270	0.000582
2010	0.974	0.000128	0.000299	0.969	0.000150	0.000324
2011	0.981	0.000161	0.000413	0.980	0.000173	0.000389
2012	0.988	0.000085	0.000217	0.969	0.000221	0.000497
2013	0.993	0.000041	0.099160	0.963	0.000215	0.000470
2014	0.989	0.066030	0.000158	0.970	0.000192	0.000419

Muğla	Weibull Dağılımı			Rayleigh Dağılımı		
Year	R^2	RMSE	χ^2	R^2	RMSE	χ^2
2005	0.930	0.000506	0.001349	0.929	0.000513	0.001173
2006	0.900	0.000799	0.002236	0.875	0.000993	0.002316
2007	0.981	0.000185	0.000493	0.952	0.000478	0.001092
2008	0.976	0.000252	0.000704	0.961	0.000418	0.000975
2009	0.985	0.000147	0.000378	0.964	0.000344	0.000774
2010	0.975	0.000257	0.00072	0.964	0.000420	0.000979
2011	0.981	0.000212	0.000635	0.934	0.000757	0.001816
2012	0.983	0.000163	0.000407	0.963	0.000367	0.000815
2013	0.977	0.000243	0.000647	0.970	0.000317	0.000725
2014	0.983	0.000188	0.000528	0.976	0.000271	0.000632

Sinop	Weibull Dağılımı			Rayleigh Dağılımı		
Year	R^2	RMSE	χ^2	R^2	RMSE	χ^2
2005	0.982	0.000060	0.000140	0.969	0.000107	0.000231
2006	0.994	0.000016	0.000036	0.930	0.000209	0.000439
2007	0.969	0.000110	0.000256	0.966	0.000120	0.000257
2008	0.969	0.000066	0.000155	0.981	0.000069	0.000149
2009	0.962	0.000146	0.000340	0.962	0.000147	0.000316
2010	0.966	0.000128	0.000298	0.965	0.000135	0.000290
2011	0.937	0.000258	0.000597	0.931	0.000284	0.000608
2012	0.957	0.000191	0.000446	0.937	0.000284	0.000612
2013	0.961	0.000140	0.000314	0.955	0.000164	0.000345
2014	0.941	0.000237	0.000547	0.936	0.000258	0.000552

The values obtained according to Weibull and Rayleigh distributions of the statistical parameters as R^2, RMSE, and χ^2 are given in Table 4. At the Weibull distribution, the R^2 value is between 0.66-0.99 and at the Rayleigh distribution is between 0.65-0.98. As can be seen in Table 4, the highest R^2 value is obtained by using the Weibull distribution. However, the results have shown that the RMSE and χ^2values of the Weibull distribution are lower than the values obtained for the Rayleigh distribution. As a result, the Weibull approximation is found to be the most accurate distribution according to the highest value of R^2 and the lowest values of RMSE and χ^2.

Figure 6 shows the monthly change in the R^2 obtained from the Weibull and Rayleigh distributions for the selected cities using the ten-year data. The R^2 values are ranged from 0.89 to 0.99 in the Weibull distribution and 0.54 to 0.98 in the Rayleigh distribution. Because the R^2 value is closer to 1 in the Weibull distribution, it is understood that the Weibull distribution is more suitable for modeling the wind data for the studied cities.


Adıyaman
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R²
Month
January
February
March
April
May
June
July
August
September
October
November
December
0
0.2
0.4
0.6
0.8
1
1.2

Figure 6. The change of R^2 values obtained from Weibull and Rayleigh distribution to months

The Weibull distribution parameters and the Rayleigh distribution parameters are given in Table 5 and Table 6 according to years, respectively. Table 5 shows the yearly values of the two Weibull parameters, the scale parameter c (m/s) and shape parameter k (dimensionless), calculated from the long term wind data for the studied site. The values of c and k were determined using the method described in *Section 3.1* [6-18]. It is clear that the parameter k has a much smaller, temporal variation than the parameter c. In Weibull distribution, the range of k is between 1.167 (Muğla in 2014) and 2.702 (Elazığ in 2007), while the c value varies from 1.58 (Adıyaman in 2014) to 3.69 m/s (Sinop in 2007). In Rayleigh distribution, the values of c changed to 1.563 from 3.717 m/s. In Weibull and Rayleigh distribution, the lowest value of the scale parameter is found in 2014 at Adıyaman, while the highest value is occurred in 2007 at Sinop. The mean wind intensity and standard deviation values are important in predicting shape and scale parameters. The monthly mean wind speed values v_m and standard deviations σ are presented in Table 5 and 6 for the studied sites. Most of the yearly mean wind speed values are between 2 and 3 m/s, but only a few are over 3.0 m/s and under 2.0 m/s. While Sinop in 2007 has the highest mean wind speed value with 3.276 m/s, at Adıyaman in 2014 exhibits the minimum mean wind speed value of 1.40 m/s. The maximum mean velocity (V_{max}) in the Weibull distribution ranges from 2.131 to 5.464 m/s and the mean power density (P) ranges from 2.737 to 39.203 W/m^2. In the Rayleigh distribution, V_{max} and P varies from 2.210 to 5.257 m/s and 2.873 to 41.656 W/m^2, respectively. The mean wind velocity is determined between 1.725 and 2.95 m/s for Weibull distribution and 1.723 and 3.055 m/s for Rayleigh distribution. At the Weibull distribution, the highest mean power density is 33.317 W/m^2 in Sinop and the lowest mean power density is 5.777 W/m^2 in Adıyaman. At the Rayleigh distribution, the highest power density is determined as 33.443 W/m^2 in Sinop and the lowest mean power density as 5.629 W/m^2 in Adıyaman. Generally, the highest mean wind speed and power density values was determined in Sinop, and the lowest mean wind speed and power density values in Adıyaman.

Table 5. Weibull distribution parameters

Adıyaman

Year	k	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{max} (m/s)	P_w (W/m^2)
2005	1.980	2.120	1879	0.990	1.486	3.015	7.245
2006	1.865	2.037	1809	1.007	1.350	3.011	6.890
2007	1.814	2.019	1795	1.024	1.299	3.041	6.943
2008	1.819	1.997	1775	1.010	1.288	3.002	6.694
2009	2.142	2.074	1837	0.902	1.547	2.822	6.280
2010	1.870	1.913	1698	0.943	1.270	2.822	5.683
2011	2.170	1.957	1733	0.841	1.472	2.644	5.211
2012	1.959	1.900	1685	0.897	1.320	2.722	5.283
2013	1.978	1.848	1638	0.864	1.294	2.631	4.805
2014	2.182	1.581	1400	0.677	1.194	2.131	2.737
mean	1.978	1.945	1725	0.916	1.352	2.784	5.777

Bursa

Year	k	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{max} (m/s)	P_w (W/m^2)
2005	1.443	2.047	1857	1.302	0.903	3.740	11.185
2006	1.431	1.989	1807	1.281	0.860	3.664	10.424
2007	1.862	2.630	2335	1.302	1.739	3.891	15.871
2008	2.177	3.125	2768	1.340	2.356	4.216	22.623
2009	1.874	2.554	2697	1.257	1.700	3.763	14.428
2010	1.760	2.563	2282	1.338	1.591	3.944	15.789
2011	1.786	2.503	2227	1.288	1.582	3.811	14.421
2012	1.781	2.634	2343	1.360	1.658	4.019	16.873
2013	1.770	2.869	2554	1.490	1.793	4.399	21.999
2014	2.048	2.825	2503	1.280	2.037	3.940	17.704
mean	1.793	2.574	2337	1.324	1.622	3.939	16.132

Elazığ

Year	k	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{max} (m/s)	P_w (W/m^2)
2005	2.662	2.598	2309	0.934	2.176	3.206	10.107
2006	2.691	2.509	2231	0.893	2.111	3.084	9.053
2007	2.702	2.548	2266	0.904	2.147	3.127	9.456
2008	2.579	2.534	2250	0.936	2.095	3.166	9.562
2009	2.377	2.658	2356	1.054	2.113	3.436	11.650
2010	2.600	2.568	2281	0.942	2.131	3.199	9.905
2011	2.324	2.882	2553	1.166	2.263	3.764	15.098
2012	2.166	2.835	2511	1.221	2.130	3.834	15.237
2013	2.166	2.898	2566	1.248	2.177	3.919	16.271
2014	2.258	2.739	2426	1.137	2.114	3.627	13.264
mean	2.453	2.677	2375	1.043	2.146	3.436	11.960

Iskenderun

Year	k	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{max} (m/s)	P_w (W/m^2)
2005	1.846	2.991	2657	1.493	1.960	4.452	23.877
2006	1.823	2.914	2590	1.472	1.884	4.375	22.428
2007	1.710	2.771	2471	1.488	1.658	4.358	21.018
2008	1.878	2.719	2414	1.335	1.814	4.001	17.566
2009	1.877	2.748	2439	1.350	1.832	4.045	18.142
2010	1.840	2.743	2436	1.373	1.791	4.091	18.477
2011	1.636	2.367	2118	1.327	1.329	3.855	13.997
2012	1.543	2.300	2069	1.369	1.169	3.942	14.157
2013	1.665	2.658	2375	1.465	1.532	4.269	19.309
2014	1.6378	2.781	2488	1.558	1.563	2.527	22.679
mean	1.745	2.699	2406	1.423	1.653	3.991	17.016

Muğla

Year	k	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{max} (m/s)	P_w (W/m^2)
2005	1.941	2.823	2.504	1.344	1.945	4.065	17.537
2006	1.741	2.599	2.315	1.371	1.591	4.032	15.676
2007	2.363	2.583	2.289	1.030	2.046	3.348	11.209
2008	2.246	2.466	2.185	1.029	1.897	3.275	10.157
2009	2.309	2.533	2.244	1.031	1.981	3.318	10.755
2010	2.244	2.497	2.211	1.042	1.920	3.316	10.542
2011	2.416	2.459	2.180	0.961	1.971	3.156	9.515
2012	2.327	2.458	2.178	0.993	1.931	3.209	9.778
2013	2.172	2.399	2.124	1.031	1.806	3.239	9.615
2014	1.167	2.328	2.061	1.895	1.750	3.147	8.805
mean	2.093	2.514	2.229	1.173	1.884	3.411	11.359

Karaman

Year	k	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{max} (m/s)	P_w (W/m^2)
2005	1.552	2.632	2.366	1.556	1.353	4.485	18.102
2006	1.882	2.621	2.326	1.284	1.753	3.849	13.526
2007	1.897	2.797	2.482	1.360	1.885	4.086	15.422
2008	1.766	2.602	2.310	1.275	1.740	3.822	13.239
2009	1.707	2.715	2.442	1.606	1.396	4.628	19.883
2010	1.859	2.746	2.437	1.345	1.836	4.033	15.556
2011	1.920	2.276	2.047	1.346	1.170	3.879	11.712
2012	1.745	2.430	2.157	1.191	1.625	3.570	10.788
2013	1.672	2.578	2.318	1.524	1.325	4.393	17.009
2014	1.715	2.440	2.166	1.195	1.632	3.584	10.919
mean	1.772	2.584	2.305	1.368	1.571	4.033	14.616

Sinop

Year	k	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{max} (m/s)	P_w (W/m^2)
2005	1.791	3.295	2.931	1.692	2.088	5.007	33.049
2006	1.527	3.158	2.845	1.900	1.574	5.096	37.213
2007	2.092	3.698	3.276	1.644	2.711	5.464	39.203
2008	1.949	3.499	3.103	1.660	2.419	5.027	35.745
2009	2.027	3.485	3.088	1.594	2.492	4.889	33.855
2010	2.078	3.518	3.116	1.573	2.566	4.866	33.975
2011	2.151	3.461	3.065	1.500	2.588	4.698	31.309
2012	2.287	3.405	3.016	1.397	2.648	4.481	28.298
2013	2.167	3.383	2.996	1.457	2.543	4.574	29.046
2014	2.137	3.460	2.064	1.509	2.576	4.7140	31.482
mean	2.020	3.436	2.950	1.593	2.420	9.124	33.317

Table 6. Rayleigh distribution parameters

Adıyaman

Year	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{max} (m/s)	P_R (W/m^2)
2005	2.119	1.878	0.981	1.498	2.997	7.162
2006	2.038	1.806	0.944	1.441	2.883	6.377
2007	2.021	1.791	0.936	1.429	2.859	6.218
2008	1.999	1.772	0.926	1.413	2.827	6.014
2009	2.081	1.844	0.964	1.472	2.944	6.786
2010	1.918	1.700	0.888	1.356	2.713	5.312
2011	1.953	1.731	0.905	1.381	2.763	5.612
2012	1.902	1.686	0.881	1.345	2.691	5.184
2013	1.849	1.638	0.856	1.307	2.615	4.757
2014	1.563	1.385	0.724	1.105	2.210	2.873
mean	1.944	1.723	0.900	1.375	2.750	5.629

Bursa

Year	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{max} (m/s)	P_R (m/s)
2005	2.121	1.879	0.982	1.499	2.999	7.674
2006	2.063	1.828	0.955	1.458	2.917	7.062
2007	2.615	2.317	1.211	1.849	3.698	14.385
2008	3.219	2.853	1.491	2.276	4.553	26.846
2009	2.543	2.254	1.178	1.798	3.597	13.240
2010	2.541	2.251	1.177	1.796	3.593	13.194
2011	2.501	2.216	1.158	1.768	3.536	12.580
2012	2.627	2.328	1.217	1.858	3.716	14.593
2013	2.824	2.503	1.308	1.997	3.994	18.125
2014	2.835	2.512	1.313	2.004	4.009	18.330
mean	2.589	2.294	1.199	1.830	3.661	14.603

Elazığ

Year	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{max} (m/s)	P_R (W/m^2)
2005	2.749	2.436	1.273	1.944	3.888	15.019
2006	2.685	2.379	1.243	1.898	3.797	13.986
2007	2.693	2.387	1.247	1.904	3.809	14.117
2008	2.662	2.359	1.233	1.882	3.765	13.636
2009	2.766	2.451	1.281	1.956	3.912	15.300
2010	2.738	2.427	1.268	1.936	3.873	14.846
2011	2.940	2.606	1.362	2.079	4.159	18.377
2012	2.880	2.552	1.334	2.036	4.073	17.266
2013	2.931	2.598	1.358	2.073	4.146	18.208
2014	2.794	2.476	1.294	1.975	3.951	15.765
mean	2.784	2.467	1.289	1.9688	3.9376	15.652

Iskenderun

Year	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{max} (m/s)	P_R (W/m^2)
2005	2.934	2.600	1.359	2.075	4.150	20.564
2006	2.853	2.529	1.747	2.017	4.035	18.906
2007	2.690	2.384	1.553	1.902	3.805	15.848
2008	2.683	2.378	1.545	1.897	3.795	15.721
2009	2.711	2.402	1.577	1.917	3.834	16.216
2010	2.695	2.388	1.558	1.905	3.811	15.924
2011	2.363	2.094	1.199	1.671	3.342	10.744
2012	2.322	2.058	1.157	1.642	3.284	10.189
2013	2.645	2.344	1.502	1.870	3.741	15.066
2014	2.753	2.440	1.627	1.947	3.894	16.983
mean	2.665	2.362	1.482	1.884	3.769	15.616

Muğla

Yıl	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{max} (m/s)	P_R (W/m^2)
2005	2.831	2.509	1.311	2.002	4.004	17.124
2006	2.653	2.351	1.229	1.876	3.752	14.091
2007	2.572	2.279	1.191	1.818	3.637	12.837
2008	2.454	2.175	1.137	1.735	3.471	11.158
2009	2.521	2.235	1.168	1.783	3.566	12.100
2010	2.484	2.202	1.151	1.757	3.514	11.575
2011	2.446	2.168	1.133	1.729	3.459	11.044
2012	2.445	2.166	1.132	1.728	3.457	11.027
2013	2.388	2.117	1.106	1.689	3.378	10.284
2014	2.319	2.055	1.074	1.639	3.279	9.411
mean	2.511	2.226	1.163	1.776	3.552	12.065

Karaman

Yıl	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{max} (m/s)	P_R (W/m^2)
2005	2.605	2.309	1.207	1.842	3.684	12.413
2006	2.600	2.304	1.204	1.838	3.677	12.344
2007	2.767	1.772	0.926	1.957	3.914	5.615
2008	2.556	2.265	1.184	1.807	3.615	11.728
2009	2.654	2.352	1.229	1.876	3.753	13.127
2010	2.719	2.409	1.259	1.922	3.845	14.111
2011	2.270	2.011	1.051	1.605	3.210	8.2109
2012	2.416	2.141	1.119	1.708	3.417	9.904
2013	2.565	2.273	1.188	1.813	3.627	11.848
2014	2.433	2.147	1.122	1.713	3.426	9.987
mean	2.558	2.198	1.149	1.808	3.617	10.929

Sinop

Yıl	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{max} (m/s)	P_R (W/m^2)
2005	3.252	2.882	1.506	2.299	4.599	27.893
2006	3.105	2.751	1.438	2.195	4.391	24.273
2007	3.717	3.294	1.722	2.628	5.257	41.656
2008	3.490	3.093	1.616	2.468	4.936	34.479
2009	3.490	3.093	1.617	2.468	4.936	34.489
2010	3.537	3.135	1.638	2.501	5.002	35.899
2011	3.499	3.101	1.621	2.474	4.949	34.757
2012	3.466	3.072	1.606	2.451	4.903	33.791
2013	3.427	3.037	1.587	2.423	4.847	32.646
2014	3.492	3.095	1.618	2.469	4.939	34.546
mean	3.447	3.055	1.597	2.438	4.876	33.443

5. Conclusion

In this study, the wind power density and wind speed distribution parameters of Turkey's seven regions were statistically analyzed using wind speed data measured between 2005 and 2014 years. Two probability density functions were fitted to the measured probability distributions on a yearly basis. Performances of the probability models were compared to the measured monthly and yearly wind speed values. Weibull and Rayleigh distributions were used for modeling and the success of this modeling process was evaluated according to R^2, RMSE and χ^2 parameters. The results can be summarized as follows:

(a) The yearly mean wind speed values were mostly between 1.97 and 3.36 m/s for selected cities. The maximum value of the yearly mean wind speed was 3.36 m/s in Sinop while the minimum value was 1.97 m/s in Adıyaman.

(b) At monthly basis, the lowest and the highest wind speed was determined as 1.34 m/s at Adıyaman in January of 2014 and as 4.28 m/s in February of 2011 at Sinop, respectively.

(c) At daily basis, the lowest and the highest wind speed was obtained as 0.59 m/s between 04:00 and 05:00 hours in 2014 year at Adıyaman, as 3.89 m/s between 14:00 and 15:00 hours in 2007 year at Sinop, respectively.

(d) The Weibull model was generally better in fitting the measured yearly probability density distributions than the Rayleigh model, to the statistical criteria such as R^2, RMSE and χ^2. Therefore, it was concluded that it would be better to use the Weibull distribution in the analysis of wind data of the selected cities.

(e) At mean yearly basis, according to the Weibull distribution, the lowest mean wind speed and power density was obtained as 1.725 m/s and 5.777 W/m^2 in Adıyaman, respectively. The highest mean speed and power density was determined as 2.95 m/s and 33.317 W/m^2 in Sinop. According to the Rayleigh distribution, the lowest and the highest mean speed and the power density was obtained as 1.723 m/s and 5.629 W/m^2 in Adıyaman, 3.055 m /s and 33.443 W/m^2 in Sinop, respectively.

(f) As a result, monthly average power and yearly mean power densities in studied cities were as small as 100 W/m^2, so that it was not possible to support directly to the network by wind energy systems, it can be used in applications where there was no network access or in rural areas where low power density was required. It has been decided that electricity generation from wind energy was suitable because the mean speed on daily and monthly basis was usually 3 m/s.

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Nomenclature

ρ : Air density (kg/m^3)
σ : Standard deviations (m/s)
Γ : Gamma function
c : Weibull scale parameter (m/s)
$f(v)$: Probability density function
f_j : Frequency of occurrence of each speed class
$f_R(v)$: Rayleigh probability density function
$f_W(v)$: Weibull probability density function
$F_R(v)$: Rayleigh cumulative distribution function
$F_W(v)$: Weibull cumulative distribution function
k : Weibull shape paramater
n : Number of wind speed classes
N : Number of hours in the period of time considered
P_m : Mean power density (W/m^2)
P_R : Mean power density calculated from the Rayleigh function (W/m^2)
P_W : Mean power density calculated from the Weibull function (W/m^2)
$RMSE$: Root mean square error
R^2 : Determination coefficient
χ^2 : Chi-square
V : Wind speed (m/s)
V_m : Mean wind speed (m/s)
V_{max} : Maximum wind speed (m/s)
V_{mod} : Wind speed with the largest frequency (m/s)