STATISTICAL ANALYSIS OF WIND SPEED DISTRIBUTION BASED ON WEIBULL AND RAYLEIGH METHODS OF ISKENDERUN-TURKEY

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In this study, the statistical analysis of wind power density and wind speed distribution parameters in İskenderun was investigated using the hourly wind speed data measured by the General Directorate of Meteorology between 2005 and 2014. Weibull and Rayleigh distributions were used for modeling and the success of this modeling process was evaluated according to the parameters of R^2, RMSE and χ^2. The result of the study showed that Iskenderun has a mean wind speed of 2.82 m/s with a maximum value of 4.5 m/s in July of 2006 and a minimum value of 1.68 m/s in November of 2012 while the corresponding mean wind power density is approximately 19.16 W/m^2 for the whole year. The Weibull distribution function was found to be more appropriate than the Rayleigh distribution function.

Key Words: *Wind energy, Statistically analysis of the wind energy potential, Weibull distribution, Rayleigh distribution, Iskenderun-Turkey*

1. Introduction

Wind energy is the fastest growing energy source in the world and wind power is one of the most widely used alternative sources of energy today [1]. Wind is popular because it is abundant, cheap, inexhaustible, widely distributed, climate benign, and clean-attributes that no other energy source can match [2-3].

Studies have showed that total wind energy potential of Turkey is higher than its present thermal and hydraulic energy production. Theoretically, Turkey has 160 TerraWatt hours (TWh) a year of wind potential, which is about twice as much as the current electricity consumption of Turkey [1]. In Turkey, the available wind energy power was 433.35 MW by the end of the year 2008; and it became 1503.35 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 [4]. Turkey’s wind energy potential could not be definitely calculated due to the insufficiency of available data. There are a number of regions with relatively high wind speeds in Turkey. The most attractive regions for wind energy utilization are the Marmara, Southeast Anatolian, and Aegean. Potential wind energy areas of Turkey lie generally in the northwestern, northern and Aegean coastal regions. Other fields lie in the Middle Black Sea and East Mediterranean regions of Turkey [5].

The determination of wind energy potential depends on accurately modeling wind speed. Statistical properties of the wind speed are important to predict the output energy of a wind conversion system. There are several distribution functions for wind speed and power density analysis in literature. The log-normal distribution, the inverse Gaussian distribution, the wake, three-parameter log normal, the gamma distribution, two-parameter gamma distribution, hybrid distributions, the three parameter generalized gamma distribution, and similar distribution functions were used to predict regional wind regimes. The two-parameter Weibull density function and the one-parameter Rayleigh distribution is commonly used in wind resource assessment to describe wind speed as a stochastic quantity. There are many different methods for estimating the shape (k) and scale (c) parameters of Weibull and Rayleigh wind speed distribution function [6]. The Weibull and Rayleigh distributions have been employed almost unanimously by researchers involved in wind speed analysis and they have also extensively been used in wind power analysis for many decades. For statistical distribution of wind speed data analysis, Weibull and Rayleigh functions are usually considered as the most qualified function due to its simplicity and high accuracy [7].

In practice, it is very important to describe the variation of wind speeds for optimizing the design of the systems resulting in less energy generating costs. In this context, over the last decade, some researchers have performed the assessments of wind power in Turkey on the basis of individual locations [6-21]. In these studies, much consideration has been given to the Weibull two-parameter (k, shape parameter and c, scale parameter) function because it has been found to fit a wide collection of wind data [22, 9]

The aim of this study was to calculate the wind energy potential for İskenderun and to assess the efficiency of electricity production by using the wind data recorded at the İskenderun meteorological station.

1. Wind speed data

The wind data used in this study were measured and recorded hourly at the İskenderun station of the Turkish State Meteorological Service at 10 m above ground level between 2005 and 2014. The İskenderun station, located in Mediterranean region (Fig.1), is located at 36º 32´ N and 36º 10´ E, and its elevation is 3 m above sea level. The wind data were captured using a cup generator anemometer.

Figure 1. Location of Iskenderun on Turkey map

3. Theory of wind speed and wind power

There are several continuous mathematical functions called 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 [6-21]. 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 Weibull distribution function that is a special case of generalized gamma distribution for wind speed is expressed with Eq. (1).

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

where $f_w(v)$ is the probability of observing wind speed v, k the dimensionless Weibull shape parameter (or factor) and c the Weibull scale parameter, which has its reference value in the units of wind speed [6-21].

The cumulative probability function of the Weibull distribution is calculated as below [8, 12]:

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

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

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

So, a plot of *ln{-ln[1-F(v)]}* versus lnv 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,

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

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

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 [9].

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

$$V_{\mathrm{mod}} = c\left(1-\frac{1}{k}\right)^{1/k} \tag{8}$$

The maximum wind speed is given by [16]:

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

When *k=2* is taken in the above formulas, calculations are performed for Rayleigh distribution [6-21].

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 [18],

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

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 Iskenderun. 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

Modeling efficiency (R^2), chi-square (x^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 [13-16].

4. Results and discussion

The monthly mean wind speeds are illustrated in Fig. 2. As can be seen in the Fig. 2, the mean wind speed varies between 2.18 and 3.70 m/s, with yearly mean of 2.82 m/s. The maximum value of the mean wind speed is 4.5 m/s in July of 2006 while the minimum value is 1.68 m/s in November of 2012.

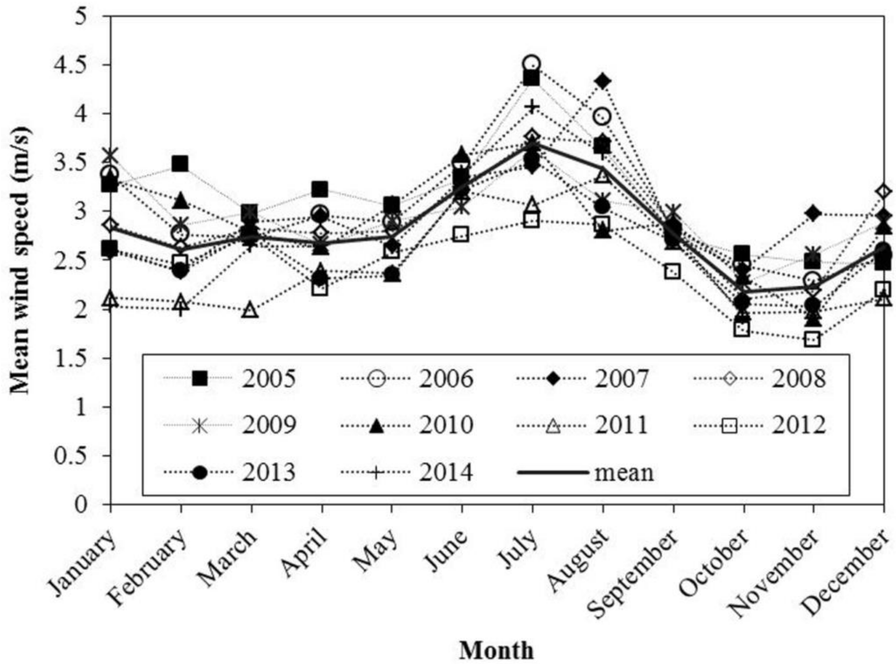

Figure 2. Monthly mean wind speed in Iskenderun

In Fig. 3, the diurnal variation of mean wind speed values is plotted. According to the yearly average results, the wind speed is the lowest as 1.08 m/s between the hours of 04:00 and 05:00 in 2012, and is the highest as 3.81 m/s between the hours of 14:00 and 15:00 in 2005. The maximum and minimum variation of daily wind speed occurs during the afternoon period and the morning period, respectively.

The available time-series data were arranged as frequency distribution format for the period of 2005-2014 in Tab. 1. The wind speed is grouped into classes in the second column of Tab. 1. The mean wind speeds are calculated for each speed class intervals in the third column. The fourth column is given the frequency of occurrence of each speed class. The probability density distribution is presented in the fifth column. In the last columns, the theoretical frequency values calculated from the Weibull and Rayleigh distributions are given, respectively. According to Tab. 1, it is seen that the maximum probability density value is in the range of 1-2 m/s.

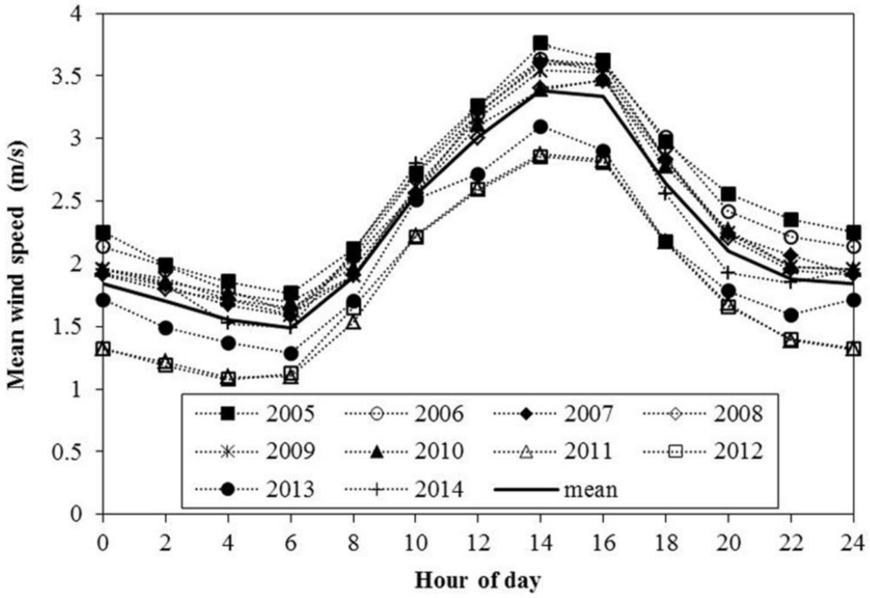

Figure 3. Diurnal variation of mean wind speed for the period of 2005–2014 in Iskenderun

Table 1. The measured hourly time-series data in frequency distribution format for the period of 2005-2014 and the probability density distributions calculated from the Weibull, *($f_W(v_j)$)*, and Rayleigh *($f_R(v_j)$)* functions

j	v_j	$v_{m,j}$	f_j	$f(v_j)$	$f_w(v_j)$	$f_R(v_j)$
1	0-1	0.5	19386	0.237035	0.2583538	0.246992
2	1-2	1.5	26797	0.322080	0.28322252	0.319957
3	2-3	2.5	14301	0.174329	0.20880076	0.234864
4	3-4	3.5	8757	0.106378	0.1188635	0.117163
5	4-5	4.5	5491	0.066436	0.05500391	0.042434
6	5-6	5.5	3508	0.042292	0.02132916	0.011554
7	6-7	6.5	2221	0.026378	0.00709704	0.002415
8	7-8	7.5	1083	0.012818	0.00206958	0.000393
9	8-9	8.5	568	0.006576	0.00053935	5.02E-05
10	9-10	9.5	253	0.002911	0.00012785	5.08E-06
11	10-11	10.5	131	0.001508	2.7194E-05	4.13E-07
12	11-12	11.5	63	0.000743	5.5975E-06	2.69E-08
13	12-13	12.5	19	0.000219	1.0851E-06	1.42E-09
14	13-14	13.5	13	0.000155	1.8227E-07	5.79E-11
15	14-15	14.5	3	3.96E-05	2.437E-08	4.2E-13
16	15-16	15.5	4	6.29E-05	4.3102E-09	9.66E-15
17	16-17	16.5	3	1.12E-05	4.0759E-12	1.61E-16

The yearly probability density and the cumulative distributions derived from the time-series data of Iskenderun are presented in Figs. 4 and 5, respectively. The yearly probability density and the cumulative distributions are illustrated in Fig. 6 for whole years. It is seen that all the curves have a similar tendency of wind speeds on probability and cumulative density.

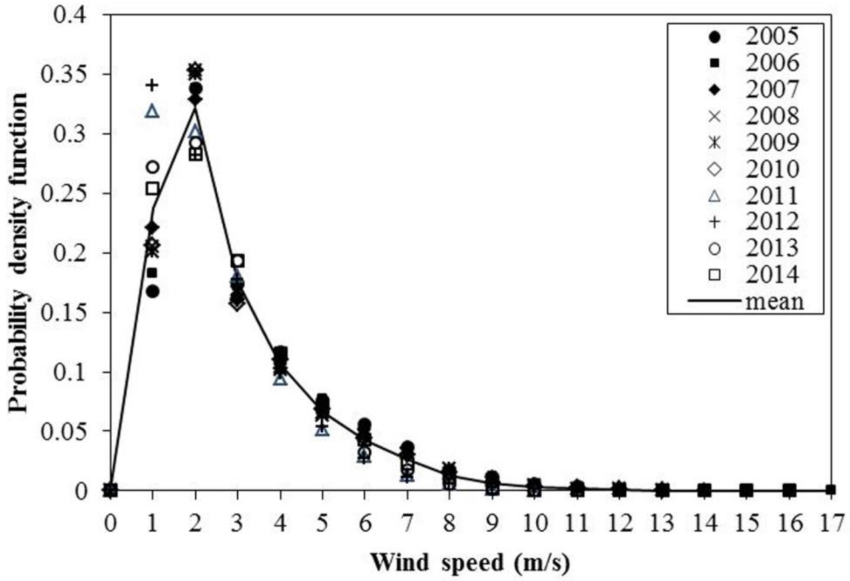

Figure 4. Yearly wind speed probability density distributions, derived from the measured hourly time series

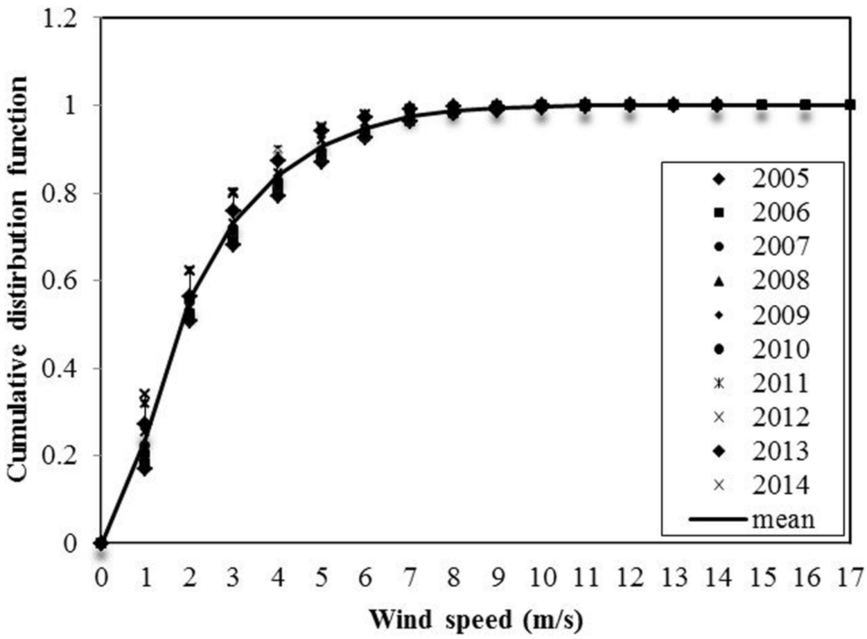

Figure 5. Yearly wind speed cumulative probability distributions, derived from the measured hourly time-series

The monthly mean wind speed values (v_m) and standard deviations (σ) are given in Tab. 2 to Weibull distribution for Iskenderun, the period of 2005–2014. Most of the monthly mean wind speed values are between 2.0 and 4.0 m/s, but only a few are over 4.0 m/s and under 2.0 m/s. While August of 2007 has the highest monthly mean wind speed value with 4.78 m/s, October of 2012 shows the lowest monthly mean wind speed value of 1.44 m/s. Generally, it is determined that the highest mean wind speed values are in July and August, and the lowest mean wind speed values are in October and

November. Having analyzed the 114 months of wind speed data, it can be concluded that the wind speed distribution differs remarkably from one month to the next. The monthly and yearly standard deviation values are mostly between 1.0 and 3.0 m/s, with only a few under 1.0 m/s and on 3.0 m/s.

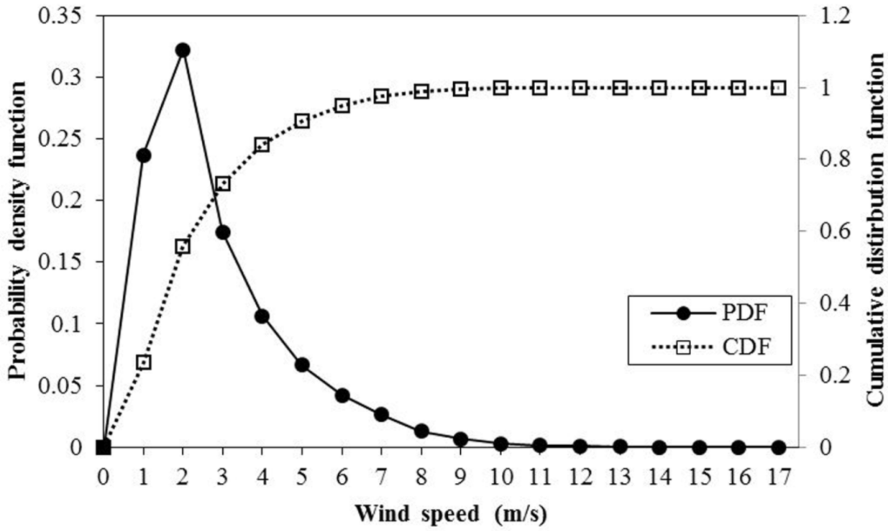

Figure 6. The wind speed probability density and cumulative probability distributions for whole years, derived from the measured hourly time-series

Table 2. Monthly mean wind speed and standard deviations to Weibull distribution

Month	Parameters	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
January	v_m	2.510	2.796	2.091	2.302	2.860	2.782	1.924	2.327	2.446	1.844
	σ	1.093	1.335	0.648	0.874	1.553	1.390	0.864	1.263	1.280	0.811
February	v_m	2.919	2.382	2.192	2.080	2.653	2.732	1.851	2.124	2.112	1.869
	σ	1.560	1.143	1.178	0.861	1.336	1.458	0.875	0.896	1.303	0.878
March	v_m	2.295	2.245	2.112	2.290	2.204	2.207	1.780	2.049	2.238	2.171
	σ	1.142	1.158	1.399	1.259	1.016	1.164	1.016	1.342	1.577	1.209
April	v_m	2.747	2.546	2.496	2.118	2.017	2.152	1.901	1.660	1.933	2.438
	σ	1.800	1.483	1.500	1.406	1.230	1.114	1.241	1.181	1.146	1.308
May	v_m	2.763	2.595	2.252	2.402	2.538	2.768	2.098	2.064	2.165	-
	σ	1.752	1.803	1.436	1.629	1.702	1.696	1.378	1.616	1.358	-
June	v_m	3.120	3.396	3.076	2.798	2.693	3.301	3.059	2.623	3.310	3.354
	σ	2.340	2.393	2.353	2.057	1.875	2.045	2.242	1.835	1.755	2.104
July	v_m	4.464	4.539	3.211	3.743	3.379	3.643	3.071	2.830	3.662	4.226
	σ	2.402	2.613	2.107	2.376	2.094	2.475	1.848	1.871	2.042	1.952
August	v_m	3.691	4.098	4.779	3.618	2.790	2.595	3.381	2.766	3.136	3.706
	σ	2.390	2.259	3.459	2.187	1.994	2.011	2.363	1.913	1.687	1.723
September	v_m	2.394	2.406	2.038	2.483	2.238	2.381	2.674	1.952	2.495	2.560
	σ	1.266	1.549	1.542	1.720	1.024	1.656	1.786	1.506	1.494	1.613
October	v_m	2.021	2.047	1.950	1.859	1.963	1.955	1.732	1.439	1.772	1.715
	σ	0.666	0.844	0.986	0.665	0.955	0.684	0.869	0.814	0.773	0.831
November	v_m	2.055	1.954	2.080	1.938	2.031	1.835	1.769	1.493	1.676	-
	σ	0.747	0.693	0.828	0.628	0.653	0.642	0.786	0.790	0.996	-
December	v_m	2.161	2.010	2.514	2.652	2.336	2.023	1.901	2.043	2.082	-
	σ	0.932	0.584	1.052	1.261	1.091	0.716	0.939	0.926	0.805	-

Tab. 3 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 Iskenderun. In addition, Tab. 3 shows monthly values of *k* and *c*. The values of *c* and *k* are determined using the method described in *Section 3.1*. It is clear that the parameter *k* has a much smaller, temporal variation than the parameter *c*. The range of *k* is between 1.29 and 3.84, while the *c* value varies from 1.62 to 5.24 m/s. The lowest value of the scale parameter is 1.62 m/s and is found in October of 2012, while the highest value is 5.24, which occurred in August of 2007. The highest *k* value is in December of 2006 and the lowest is found in May of 2012. The mean *k* and *c* vales is 1.75 and 2.70 m/s, respectively. The reason of lack shape and scale parameters in May, November and December of 2014, the data cannot be obtained of for various reasons from the Turkish State Meteorological Service. The mean wind intensity and standard deviation values are important in predicting shape and scale parameters.

Table 3. Monthly shape parameter (*k*) and scale parameter (*c*) values according to the Weibull distribution for period of 2005-2014

Month	Parameters	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
January	k	2.451	2.210	3.578	2.858	1.917	2.101	2.367	1.911	1.996	2.424
	c	2.830	3.157	2.321	2.584	3.224	3.141	2.171	2.624	2.760	2.080
February	k	1.950	2.199	1.938	2.593	2.084	1.954	2.237	2.538	1.664	2.252
	c	3.292	2.690	2.471	2.342	2.995	3.081	2.090	2.393	2.364	2.110
March	k	2.111	2.029	1.540	1.890	2.299	1.979	1.814	1.559	1.440	1.864
	c	2.591	2.534	2.347	2.580	2.488	2.489	2.002	2.280	2.465	2.445
April	k	1.559	1.773	1.713	1.536	1.686	2.022	1.566	1.426	1.739	1.942
	c	3.057	2.861	2.799	2.353	2.259	2.429	2.116	1.826	2.170	2.749
May	k	1.616	1.462	1.606	1.501	1.519	1.677	1.554	1.287	1.635	-
	c	3.086	2.865	2.513	2.662	2.815	3.099	2.333	2.230	2.419	-
June	k	1.347	1.440	1.319	1.376	1.459	1.657	1.381	1.452	1.969	1.635
	c	3.402	3.742	3.340	3.062	2.973	3.693	3.349	2.894	3.734	3.749
July	k	1.936	1.796	1.556	1.613	1.657	1.498	1.710	1.544	1.860	2.294
	c	5.033	5.103	3.572	4.178	3.780	4.035	3.443	3.145	4.124	4.771
August	k	1.579	1.884	1.400	1.702	1.419	1.301	1.453	1.470	1.937	2.278
	c	4.112	4.617	5.244	4.055	3.068	2.811	3.731	3.056	3.536	4.183
September	k	1.974	1.589	1.334	1.467	2.318	1.461	1.527	1.307	1.720	1.627
	c	2.701	2.682	2.218	2.743	2.526	2.629	2.969	2.117	2.798	2.860
October	k	3.342	2.606	2.074	3.053	2.166	3.126	2.093	1.832	2.447	2.174
	c	2.252	2.305	2.201	2.081	2.216	2.186	1.956	1.620	1.998	1.937
November	k	2.996	3.082	2.709	3.407	3.435	3.126	2.394	1.972	1.734	-
	c	2.302	2.185	2.339	2.157	2.260	2.051	1.996	1.684	1.881	-
December	k	2.476	3.846	2.563	2.220	2.267	3.090	2.129	2.344	2.801	
	c	2.436	2.222	2.832	2.994	2.637	2.263	2.147	2.306	2.339	

In Fig. 7, the variation of Weibull probability distribution with wind speed is plotted according to years. The highest probability value according to the Weibull probability distribution function was obtained in 2012 as 0.32.

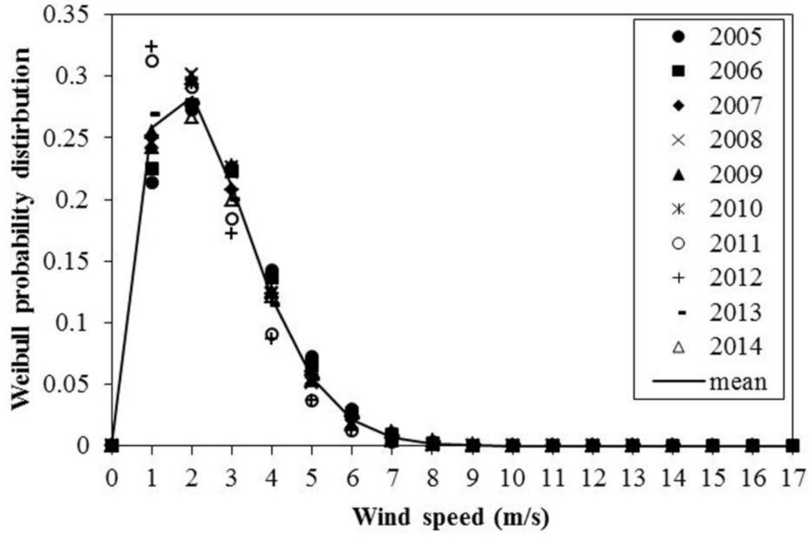

Figure 7. Yearly Weibull probability density distributions for the period of 2004-2005 in Iskenderun

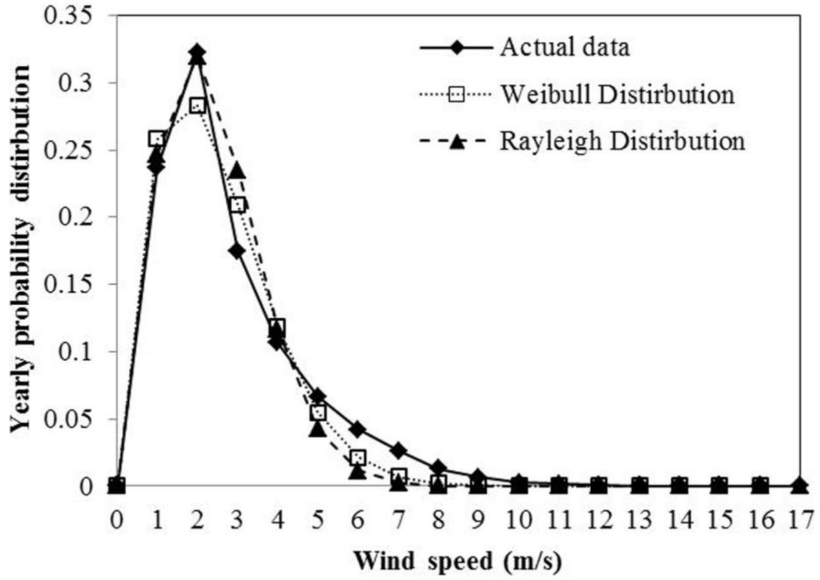

Figure 8. The comparison of Weibull and Rayleigh approximations with the actual probability distribution of wind speeds

The Weibull and Rayleigh approximations of the actual probability distribution of wind speeds are shown in Fig. 8, while a comparison of the two approximations is given in Tab. 4. In Fig. 8, 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. The probability ratio of the Rayleigh distribution is higher than the Weibull distribution.

Table 4. R^2, RMSE and χ^2 values obtained from Weibull and Rayleigh distributions

Years	Weibull Distribution			Rayleigh Distribution		
	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	0.0000413	0.000103	0.957	0.000295	0.000654
2012	0.994	0.0000374	0.000088	0.940	0.000372	0.000806
2013	0.995	0.0000221	0.000051	0.966	0.000175	0.000377
2014	0.994	0.0000259	0.000059	0.959	0.000177	0.000378

The values of the statistical parameters (R^2, *RMSE*, and χ^2) obtained from Weibull and Rayleigh distributions are given in Tab. 4. The R^2 value is found between 0.91-0.99 in the Weibull distribution and 0.90-0.97 in the Rayleigh distribution. The *RMSE* values range from 2.21×10^{-5} to 4.17×10^{-4} in the Weibull distribution and from 1.75×10^{-5} to 4.7×10^{-5} in the Rayleigh distribution. The χ^2 values vary between 5.1×10^{-6} and 9.7×10^{-4} in the Weibull distribution and between 3.77×10^{-5} and 1.01×10^{-4} in the Rayleigh distribution. As can be seen in Tab. 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.

Fig. 9 shows the monthly change in the R^2 obtained from the Weibull and Rayleigh distributions for Iskenderun using the ten-year data. The range of R^2 values change from 0.88 to 0.98 in the Weibull distribution and 0.81 to 0.93 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 Iskenderun.

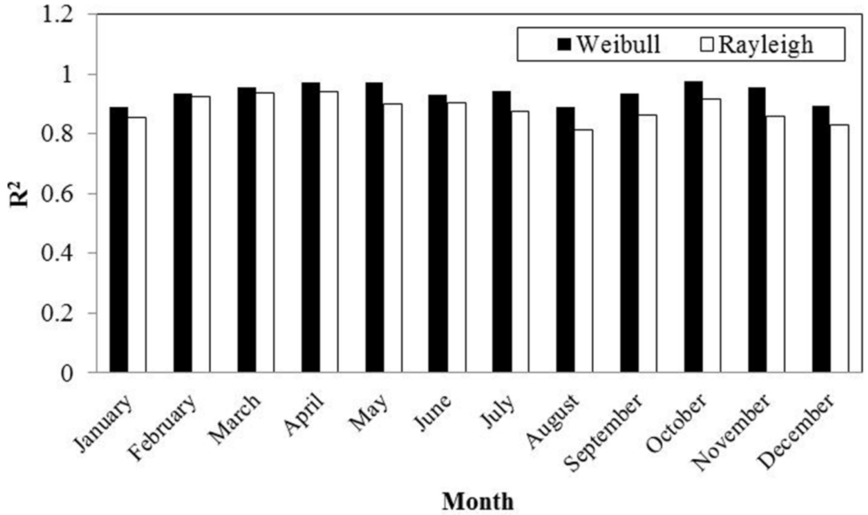

Figure 9. The change of R^2 values obtained from Weibull and Rayleigh distribution to months

The Weibull distribution parameters and the Rayleigh distribution parameters are given in Tab. 5 and Tab. 6 according to years, respectively. The maximum mean velocity (V_{max}) in the Weibull distribution ranged from 2.52 to 4.45 m/s and the mean power density (P_w) ranged from 13.99 to 23.87 W/m^2. In the Rayleigh distribution, V_{max} varied from 3.28 to 4.15 m/s and P_R varied from 10.18 to 20.56 W/m^2.

Table 5. Weibull distribution parameters

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	2.657	1.493	1.960	4.452	23.877
2006	1.823	2.914	2.590	1.472	1.884	4.375	22.428
2007	1.710	2.771	2.471	1.488	1.658	4.358	21.018
2008	1.878	2.719	2.414	1.335	1.814	4.001	17.566
2009	1.877	2.748	2.439	1.350	1.832	4.045	18.142
2010	1.840	2.743	2.436	1.373	1.791	4.091	18.477
2011	1.636	2.367	2.118	1.327	1.329	3.855	13.997
2012	1.543	2.300	2.069	1.369	1.169	3.942	14.157
2013	1.665	2.658	2.375	1.465	1.532	4.269	19.309
2014	1.637	2.781	2.488	1.558	1.563	2.527	22.679

Table 6. Rayleigh distribution parameters

Year	c (m/s)	V_m (m/s)	σ (m/s)	V_{mod} (m/s)	V_{maxE} (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

The variation of mean wind speed with Weibull power density and Rayleigh power density are showed in Fig. 10 and in Fig. 11 with respect to years, respectively. The mean wind velocity is determined as 2.40 m/s for Weibull distribution and 2.36 m/s for Rayleigh distribution. In the Weibull distribution, the highest power density is 23.88 W/m^2 in 2005 and the lowest power density is 14.15 W/m^2 in 2011 and the mean power density is 19.16 W/m^2. In the Rayleigh distribution, the highest and the lowest power density is determined as 20.56 W/m^2 in 2005 and 10.19 W/m^2 in 2012, respectively, and but also the mean power density is obtained as 15.64 W/m^2.

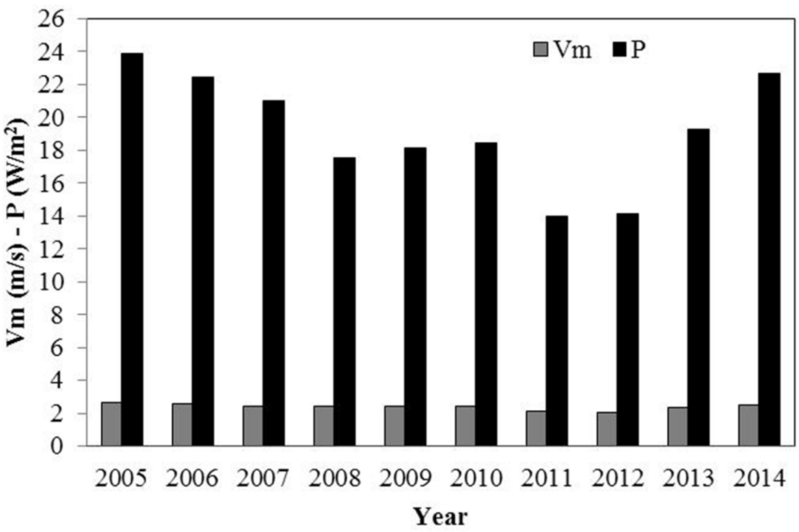

Figure 10. Yearly mean power density and wind speed according to Weibull distribution

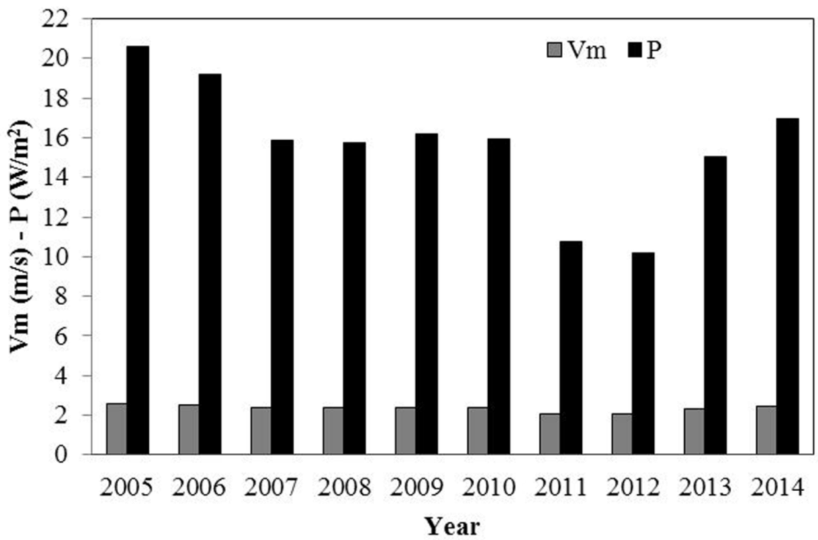

Figure 11. Yearly mean power density and wind speed according to Rayleigh distribution

5. Conclusion

In this study, the wind power density and wind speed distribution parameters of Iskenderun were statistically analyzed in the period of 2005-2014. Two probability density functions were fitted to the measured probability distributions on a yearly and monthly 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 $\chi 2$ parameters. The results can be summarized as follows:

- ✓ At daily basis, the lowest and the highest wind speed was obtained as 1.08 m/s in 2012 year between 04:00 and 05:00 hours as 3.81 m/s in 2005 between 14:00 and 15:00 hours, respectively. At monthly basis, the lowest and the highest wind speed was determined as 1.68 m/s in November of 2012 and as 4.5 m/s in July of 2006, respectively. The mean wind speed was found as 2.82 m/s for all years between 2005 and 2012.
- ✓ At yearly basis, according to the Weibull distribution, the lowest mean wind speed and power density was obtained as 2.07 m/s and 14.15 W/m^2 in 2012, respectively. The highest mean speed and power density was determined as 2.66 m/s and 23.88 W/m^2 in 2005. According to the Rayleigh distribution, the lowest and the highest mean speed and the power density was obtained as 2.06 m/s and 10.19 W/m^2 in 2012, 2.60 m /s and 20.56 W/m^2 in 2005, respectively. The mean power densities were calculated 19.16 and 15.64 W/m^2, respectively for Weibull and Rayleigh distribution for the whole year.
- ✓ The Weibull model is 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 İskenderun.
- ✓ The values of the shape parameter (k) and scale parameter (c) at Iskenderun were examined. The yearly mean values of k and c for Weibull distribution were determined 1.75 and 2.70 m/s over a 10 year period of 2005-2014. The yearly mean c value for Rayleigh distribution was found 2.67 m/s. The Weibull shape parameter follows very closer to the Raleigh function k=2 for Iskenderun which means that the characteristics of wind wave is regular and uniform.
- ✓ As a result, monthly average power and annual average power densities in Iskenderun are as small as 100 W/m^2, so that it is not possible to support directly to the network by wind energy systems, it can be used in applications where there is no network access or in rural areas where low power density is required. It has been decided that electricity generation from wind energy is suitable because the average speed on daily and monthly basis is usually 3 m/s.

Nomenclature

A : Blade sweep area (m^2)

c : Weibull scale parameter (m/s)

f(v) : Probability density function

f_j : Frequency of occurrence of each speed class

F(v) : Cumulative distribution function

k : Weibull shape parameter

n : Number of wind speed classes

N : Number of hours in the period of time considered, number of observations

P : Power density (W/m^2)

RMSE : Root mean square error

R^2 : Correlation coefficient

V : Wind speed (m/s)

x_i : ith measured value

y_i : ith calculated value

zi : mean value of the experimental data

Greek letters

ρ : air density, (kg/m^3)

σ : standard deviations (m/s)

$\Gamma(\,)$: the gamma function of ( )

χ^2 : chi-square

Subscripts

m : mean

maxE : maximum

mod : largest frequency

R : Rayleigh

W : Weibull

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