Energy Conversion and Management 50 (2009) 1761–1766

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A new method to estimate Weibull parameters for wind energy applications

Seyit A. Akdağ [a,*], Ali Dinler [b,1]

[a] Energy Institute, Istanbul Technical University, Maslak, 34469 Istanbul, Turkey
[b] Engineering Sciences Department, Istanbul Technical University, Maslak, 34469 Istanbul, Turkey

ARTICLE INFO

Article history:
Received 23 February 2008
Received in revised form 25 November 2008
Accepted 14 March 2009
Available online 19 April 2009

Keywords:
Weibull distribution
Power density method
Wind energy

ABSTRACT

In recent years, Weibull distribution has been commonly used, accepted and recommended distribution in literature to express the wind speed frequency distribution. In this study, a new method is developed to estimate Weibull distribution parameters for wind energy applications. This new method is called power density (PD) method. In literature most frequently used methods, that are graphic, maximum likelihood and moment methods, are revisited and a comparison between these methods and PD method is carried out. Suitability of these methods is judged based on different goodness of fit tests for different geographical locations. Also to demonstrate the accuracy of PD method, comparisons are carried out based on power density and mean wind estimation results of previous studies. Results of this study indicate that PD method is an adequate method to estimate Weibull parameters and it might have better suitability than other methods. Some superiority of the new PD method are that, it has simple formulation, it does not require binning and solving linear least square problem or iterative procedure. If power density and mean wind speed are available it is very simple to estimate Weibull parameters.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

Energy is one of the essential inputs for economic development and industrialization. Fossil fuels are the main resources and play a crucial role to supply world energy demand. However fossil fuel reserves are limited and usage of fossil fuel sources have negative environmental impacts. Therefore, management of energy sources, rational utilization of energy, and renewable energy source usage are vital.

Since the first oil crisis, renewable energy sources have gained a great importance due to their inexhaustibility, sustainability, ecological awareness and supply of energy security. So, renewable energy sources are expected to play an important role especially in electrical energy generation.

Among the renewable energy sources wind energy is currently viewed as one of the most significant, fastest growing, commonly used and commercially attractive source to generate electrical energy because of the mature and cost effective energy conversation system technology. So, electricity generation cost from wind energy system has become competitive with fossil fuel systems. Installed total wind power capacity has reached over 93 GW and installed wind power capacity generates more than 1% of the global electricity consumption [1].

In order to accurate assessment of wind energy potential and characteristics, it is necessary to carry out long term meteorological observations. Wind speed is a random variable and variation of wind speed over a period of time is represented by probability density functions. Detailed knowledge of wind characteristics and distribution are crucial parameters to select optimum wind energy conversion system to optimize energy output and minimization of electricity generation cost [2]. Wind speed frequency distribution has been represented by various probability density functions such as gamma, lognormal, three parameter beta, Rayleigh and Weibull distributions. However in recent years Weibull distribution has been one of the most commonly used, accepted, recommended distribution to determine wind energy potential and it is also used as a reference distribution for commercial wind energy softwares such as Wind Atlas Analysis and Application Program (WAsP) [3,4]. So, estimation of wind speed distribution parameters correctly is important in terms of selecting wind energy conversation system and obtains correct results about wind energy potential and the economic viability of project. But it is important to note that, Weibull distribution is not suitable to represent wind distribution for all geographical location in the world [5,6]. Therefore, new distributions have been proposed to represent wind speed frequency distribution and wind energy potential assessment of these locations.

Several methods have been proposed to estimate Weibull parameters [7–14]. Graphic method, maximum likelihood method and moment methods are commonly used to estimate Weibull parameters. In literature about wind energy, these methods are

* Corresponding author. Tel.: +90 212 285 38 79.
E-mail addresses: akdagse@itu.edu.tr, akdagseyit@hotmail.com (S.A. Akdağ), dinlera@itu.edu.tr (A. Dinler).
[1] Tel.: +90 212 285 3298.

0196-8904/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enconman.2009.03.020

Nomenclature

PDM	power density method	Pd_{ts}	power density of time series wind data
R^2	coefficient of determination	Vm_{ts}	time series mean wind speed
RMSE	root mean square error	k_{ref}	Weibull shape parameter of reference article
$f(v)$	Weibull probability density function	c_{ref}	Weibull scale parameter of reference article
CDF	cumulative distribution function	Pw_{ref}	Weibull power density of reference article
k	Weibull shape parameter	Vm_{wref}	Weibull mean wind speed of reference article
c	Weibull scale parameter	k_{pdm}	Weibull shape parameter of PD method
$\overline{V}$	mean wind speed	c_{pdm}	Weibull scale parameter of PD method
v_i	ith wind speed	Pw_{pdm}	power density of PD method
$\overline{V^3}$	mean of cube of wind speeds	Vm_{pdm}	mean wind speed of PD method
E_{pf}	energy pattern factor		

compared several times [12–20] however results and recommendations of the previous studies are different. For this reason, according to the results of the studies, it might be concluded that suitability of the method may vary with the sample data size, sample data distribution, sample data format and goodness of fit tests.

In order to asses the suitability of proposed distributions or methods for wind speed distribution of a region, goodness of fit tests are used. Several goodness of fit tests are used in literature. Celik indicates that judgment of suitability of distribution should be carried out based on power density estimation capability [21].

The main objective of the present study is to propose a new method to estimate Weibull parameters for wind energy applications. The rest of the study is organized as follows. In Section 2, graphic, maximum likelihood and moment methods are revisited and PD method is introduced. In Section 3, suitability of these methods and accuracy of PD method are judged from R^2 (coefficient of determination) and *RMSE* analyses. Also power density and mean wind speed estimation capabilities are compared for Maden, Gökçeada, Çanakkale and Bozcaada regions in Turkey. In Section 4, to prove the accuracy of PD method, the results obtained by this method are compared with the results of previous studies in literature. Section 5 concludes the study.

2. Methods for estimating Weibull parameters

Weibull distribution has been commonly used, accepted and recommended distribution in literature to express the wind speed frequency distribution and estimate wind energy potential. The probability density function of Weibull distribution is given by,

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

where $f(v)$ is the probability of observing wind speed v, k the dimensionless shape parameter and c is scale parameter in units of wind speed. One of the important properties of Weibull distribution which makes this distribution more useful for wind applications is that once these parameters are estimated at one height, it is possible to adjust these parameters to different heights [7]. A literature survey for this study shows that, shape parameter of Weibull distribution range from 1.2 to 2.75 for most wind condition in the world. Cumulative distribution function (CDF) of Weibull distribution is given by

$$F(v) = 1 - e^{-\left(\frac{v}{c}\right)^k}. \quad (2)$$

There are several methods to estimate Weibull parameters. We will discuss four different methods commonly used and one of them is derived by us and firstly represented in this study.

2.1. Graphic method

Graphic method is derived by using cumulative distribution function. Taking twice logarithm of CDF Eq. (2)

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

we obtain $y = ax + b$ form respect to $\ln[-\ln[1 - F(v)]]$ and $\ln v$ and also k is the slope of the straight line. Using cumulative distribution function, we evaluate $(\ln v_i, \ln[-\ln[1 - F(v_i)]])$ pairs and then we solve linear least squares problem to obtain coefficients of straight line *a, b*. Hence

$$k = a \quad (4)$$

$$c = \exp(-b/a) \quad (5)$$

Implementation of this method consists of three stages such that: (i) using wind speed data, calculate cumulative frequency distribution or first evaluate frequency distribution, which requires sorting wind speed data into bins, and then using frequency distribution, obtain cumulative frequency distribution, (ii) calculate $(\ln v_i, \ln[-\ln[1 - F(v_i)]])$ pairs and (iii) solve linear least squares problem and find scale and shape parameters using Eqs. (4) and (5).

2.2. Maximum likelihood method

Maximum likelihood method is a method suggested by Stevens and Smulders [8], details on the development of this method can be found in [18]. Maximum likelihood method requires extensive iterative calculations. Shape and scale parameters of Weibull distribution are estimated by these two equations

$$k = \left(\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n}\right)^{-1} \quad (6)$$

$$c = \left(\frac{\sum_{i=1}^{n} (v_i)^k}{n}\right)^{\frac{1}{k}} \quad (7)$$

where v_i is the wind speed and n is the number of nonzero wind speeds.

This method is implemented in two stages such that: (i) using wind speed data, calculate summations in Eqs. (6) and (7) with taking care of zero wind speeds which make logarithm indefinite and than calculate shape parameter with Eq. (7) and (ii) find scale parameter using a numerical technique in order to find the root of Eq. (6) around $k = 2$.

2.3. Moment method

This method is suggested by Justus et al. [7]. When the mean wind speed $\overline{V}$ and standard deviation σ are available, shape and scale parameters can be estimated with this method using

$$k = \left(\frac{\sigma}{\overline{V}}\right)^{-1.086} \quad 1 \leqslant k \leqslant 10 \tag{8}$$

$$c = \frac{\overline{V}}{\Gamma(1+\frac{1}{k})} \tag{9}$$

Since k and c are related to $\overline{V}$ and σ by

$$\overline{V} = c\Gamma\left(1+\frac{1}{k}\right) \tag{10}$$

$$\left(\frac{\sigma}{\overline{V}}\right)^2 = \left[\frac{\Gamma(1+\frac{2}{k})}{\Gamma(1+\frac{1}{k})^2}\right] - 1 \tag{11}$$

where Γ is gamma function.

Also mean wind speed is calculated by

$$\overline{V} = \left(\frac{1}{n}\sum_{i=1}^{n} v_i\right) \tag{12}$$

and standard deviation is calculated by

$$\sigma = \left[\left(\frac{1}{n-1}\sum_{i=1}^{n}(v_i - \overline{V})\right)\right]^{0.5}. \tag{13}$$

This method also requires two stages such that: (i) using wind speed data, calculate summations in Eqs. (12) and (13), calculate mean wind speed $\overline{V}$ and standard deviation σ and (ii) find scale parameter k and shape parameter c using Eqs. (8) and (9). Also Eq. (11) can be solved numerically to obtain Weibull parameters [12].

2.4. Power density method

This is a new method that we suggest and recommend to be used estimating scale and shape parameters since it has simpler formulation, easier implementation and also requires less computation. Power density according to the Weibull distribution can be expressed as

$$P_w = \frac{1}{2}\rho\int_0^{\infty} v^3 f(v)\,dv \tag{14}$$

where ρ is air density of the region.

Using Eqs. (9) and (14)

$$\frac{\overline{V^3}}{(\overline{V})^3} = \frac{\Gamma(1+3/k)}{\Gamma(1+1/k)^3} \tag{15}$$

where $\overline{V^3}$ is mean of wind speed cubes and $\overline{V^3}/(\overline{V})^3$ is known as energy pattern factor (E_{pf}) and according to the literature survey conducted for this study shows that E_{pf} is between 1.45 and 4.4 for most wind distribution in the world. Weibull parameters can be estimated with solving energy pattern factor Eq. (15) numerically [22] or approximately by PD method using this simple formula

$$k = 1 + \frac{3.69}{(E_{pf})^2} \tag{16}$$

Also scale parameter is estimated by Eq. (10). In short PD method needs just mean of cube of wind speeds and mean wind speed. If time series mean wind speed and wind power density

$$Pd_{ts} = \frac{1}{2}\rho\overline{V^3} \tag{17}$$

are available, then using energy pattern factor $\overline{V^3}/(\overline{V})^3$ Weibull parameters can be obtained even without whole time series wind speed data.

Also energy pattern factor for time series wind data can be calculated using Eqs. (12) and (18)

$$\overline{V^3} = \frac{1}{n}\sum_{i=1}^{n} v_i^3 \tag{18}$$

Superiority of the new PD method are that: (i) it has a simple formulation, (ii) it does not require binning and solving linear least square problem or iterative procedure, (iii) If power density and mean wind speed are available it is very simple to estimate Weibull parameters and (iv) also it is more suitable to estimate power density for wind energy applications as shown in Section 3.

As stated earlier, k is generally between 1.20 and 2.75 for most wind conditions in the world and PD method estimates Weibull parameters significantly very well in this interval. In view of the fact that in many studies which deal with many regions k parameter is between these values.

Particularly, we will compare graphic, maximum likelihood, moment and power density methods in Section 3 using three different analyses; first one is R^2,

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i - x_i)^2}{\sum_{i=1}^{N}(y_i - \bar{y})^2} \tag{19}$$

and second is *RMSE*

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2\right]^{0.5} \tag{20}$$

where N is the total number of intervals, y_i the frequencies of observed wind speed data, x_i the frequency distribution value calculated with Weibull distribution, $\bar{y}$ the average of y_i values. It is concluded as "better method" if R^2 magnitude is bigger or *RMSE* value is smaller.

Power density error analysis was carried out by

$$Error\ (\%) = \left|\frac{P_w - Pd_{ts}}{Pd_{ts}}\right| \tag{21}$$

where Pd_{ts} is time series power density and P_w is Weibull distribution power density.

3. Comparison of methods

In order to compare the methods hourly mean wind data used for Maden, Gökçeada, Çanakkale and Bozcaada regions are obtained from Turkish State Meteorological Service cover the period of 1997–2006, 1997–2006, 1997–2000, 2002–2003, respectively. Wind speed measurements were carried out at 10 m above ground level. Information about the regions and mean wind and speeds energy densities are shown in Table 1. In this part of this study air density is assumed to be equal to 1.225 kg/m^3 and constant for Maden, Gökçeada, Çanakkale and Bozcaada regions.

Table 1
Information about regions.

Station	Longitude	Latitude	Mean speed (m/s)	Power density (W/m^2)	Years of wind data	Number of wind data
Maden	29°25′	39°30′	5.04422	199.632	1997–2006	87144
Gökçeada	40°11′	25°54′	3.77985	101.53	1997–2006	87384
Çanakkale	40°08′	26°24′	3.59473	75.6431	1997–2000	35064
Bozcaada	41°58′	34°02′	5.9532	299.558	2002–2003	17520

Table 2
Comparison of methods for different regions.

Regions	Parameters	Graphic method	MLH method	Moment method	Numerical solution of Eq. (15)	PD method
Maden	k (–)	1.59536	1.57016	1.58143	1.57289	1.5722
	c (m/s)	5.45798	5.63616	5.6199	5.61691	5.61666
	R^2	0.98512	0.9862	0.98581	0.98625	0.98628
	RMSE	0.00567	0.00546	0.00554	0.00545	0.00545
Gökçeada	k (–)	1.39653	1.27034	1.36157	1.38776	1.39165
	c (m/s)	3.84854	4.0657	4.1282	4.14139	4.14325
	R^2	0.84609	0.90361	0.87524	0.8652	0.86365
	RMSE	0.02287	0.0181	0.02059	0.0214	0.02153
Çanakkale	k (–)	1.46907	1.57803	1.56044	1.52294	1.52203
	c (m/s)	4.00644	4.01898	3.99964	3.98911	3.98884
	R^2	0.92183	0.92013	0.92155	0.92299	0.923
	RMSE	0.01885	0.01906	0.01889	0.01871	0.01871
Bozcaada	k (–)	1.69875	1.68755	1.70331	1.68471	1.68672
	c (m/s)	6.5515	6.6759	6.67304	6.66795	6.66851
	R^2	0.98795	0.98972	0.98874	0.98984	0.989741
	RMSE	0.0046	0.00425	0.00445	0.00422	0.00424

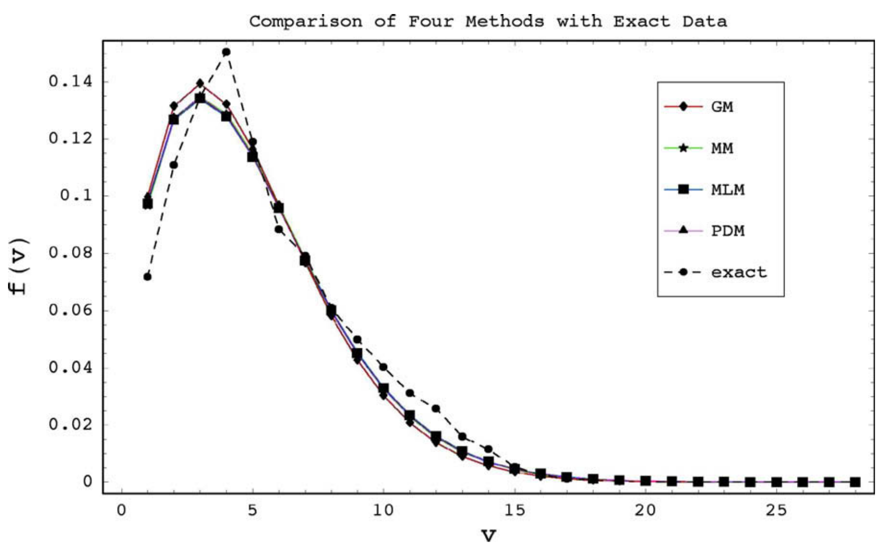

Fig. 1. Comparison of probability density distributions for Maden. GM: graphic method, MM: moment method, MLM: maximum likelihood method, PDM: power density method.

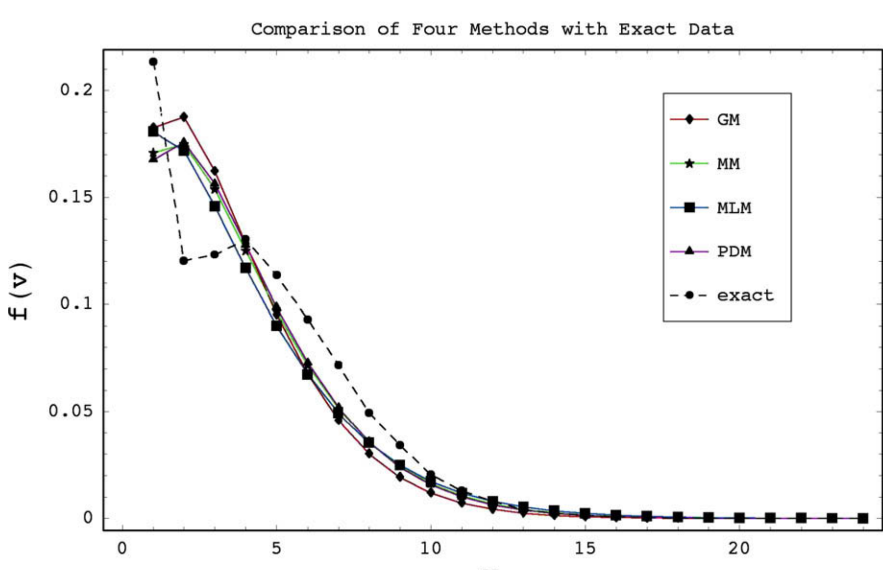

Fig. 2. Comparison of probability density distributions for Gökçeada. GM: graphic method, MM: moment method, MLM: maximum likelihood method, PDM: power density method.

Weibull parameters according to the four methods have been calculated and shown Table 2 with R^2 and $RMSE$ analyses results. Figs. 1–4 show comparison of the probability density distributions.

According to the results, PD method gives satisfactory according to R^2 and $RMSE$ analyses, consistently with numerical solution of energy pattern factor equation for three regions except Gökçeada. Result of analyses shows that, all methods have a better than 0.92 R^2 magnitude and the differences occur after third decimal point except Gökçeada. Estimated scale parameters are close, however graphic method generally estimates smaller value for scale parameter.

4. Comparison with previous studies

In order to show the accuracy of the PD method, the results obtained by PD method were compared with the results of previous studies in literature [23–26], to carry out further and extensive comparison. Firstly we show that PD method has more satisfactory results than other methods according to estimations of power density and mean wind speed for monthly base. Table 3 shows the result of this comparison. To evaluate the accuracy of the method for yearly base is shown in Table 4 for different locations. According to the results in Tables 3 and 4 this method is more suitable than others for calculating power density and mean wind speed. Air density used in previous studies is calculated as follows:

$$\rho = \frac{P_w}{\frac{1}{2}c^3\Gamma\left(1+\frac{3}{k}\right)} \quad (22)$$

According to the Tables 3 and 4, introduced method gives more accurate results based on power density and mean wind speed estimation. As shown in Table 4, PD method makes smaller error in calculating wind power density except April and August, so it is obvious that this method calculates mean power density sensitively than other methods.

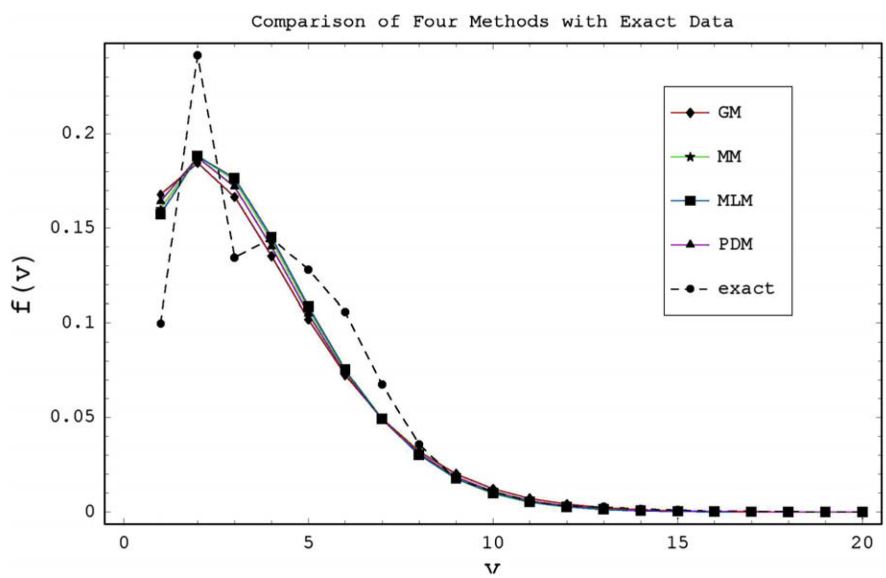

Fig. 3. Comparison of probability density distributions for Çanakkale. GM: graphic method, MM: moment method, MLM: maximum likelihood method, PDM: power density method.

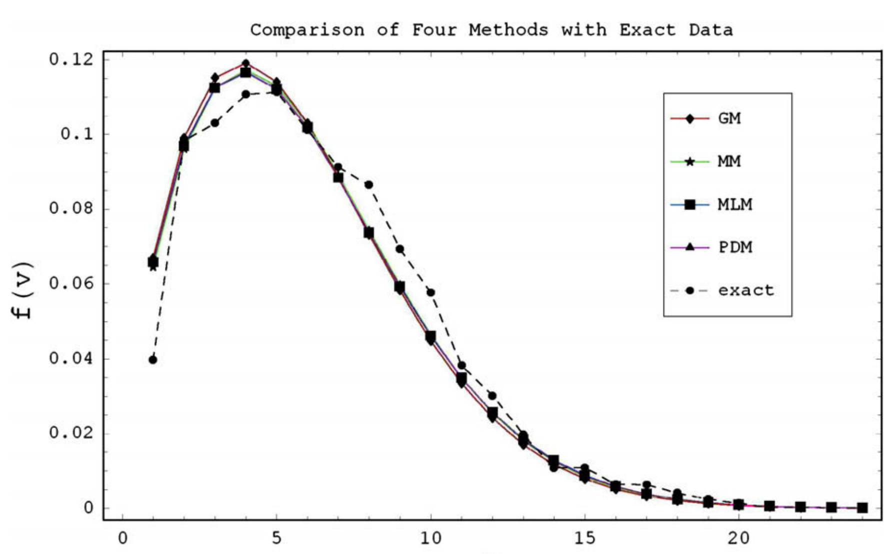

Fig. 4. Comparison of probability density distributions for Bozcaada. GM: graphic method, MM: moment method, MLM: maximum likelihood method, PDM: power density method.

Table 3
Comparison of different regions according to the power density and mean speed [23–25].

Sites	Vm_{ts}	Pd_{ts}	k_{ref}	c_{ref}	Pw_{ref}	Power density error (%)	Vm_{wref}	Mean speed error (%)	E_{pf}	k_{pdm}	c_{pdm}	Pw_{pdm}	Power density error (%)	Vm_{pdm}
Keban-Elazig	2.258	15.603	1.518	2.522	17.731	13.640	2.274	0.687	2.399	1.641	2.481	15.610	0.042	2.258
Kirklareli	4.68	142.75	1.75	5.25	138.850	2.732	4.680	0.000	2.274	1.714	5.248	142.450	0.210	4.68
Kıst	4.07	84.03	2.25	5.22	80.060	4.725	4.624	13.600	2.636	1.531	4.519	84.104	0.088	4.07
Al-Taweel	5.33	105.99	2.64	6.79	150.500	41.995	6.034	13.204	1.551	2.533	6.005	106.751	0.718	5.33
Rawdation	3.87	45.02	2.21	5.26	80.930	79.765	4.658	20.374	1.688	2.295	4.368	44.949	0.157	3.87
Ras As-Subiyah	4.76	98.9	2.08	5.36	103.940	5.096	4.748	0.259	1.736	2.225	5.374	98.574	0.329	4.76
Umm Omara	4.88	97.94	2.19	5.83	123.420	26.016	5.163	5.802	1.648	2.358	5.507	97.973	0.034	4.88
Al-Wafra	5.52	122.71	2.7	7.18	166.680	35.832	6.385	15.671	1.705	2.270	6.232	122.436	0.223	5.52

Table 4
Comparison of different regions according to the power density [26].

Months	V_{mts}	P_{mts}	k_{ref}	c_{ref}	Pw_{ref}	Power density error (%)	E_{pf}	k_{pdm}	c_{pdm}	Pw_{pdm}	Power density error (%)
January	2.71	28.46	1.66	3.04	29.58	3.935	2.288	1.705	3.038	28.406	0.191
February	1.62	7.54	1.49	1.8	7.34	2.653	2.838	1.458	1.785	7.538	0.026
March	2.14	18.79	1.37	2.35	19.35	2.980	3.068	1.392	2.346	18.705	0.452
April	2.28	31.02	1.17	2.41	31	0.065	4.188	1.210	2.429	29.077	6.264
May	2.22	25.38	1.21	2.37	26.89	5.950	3.712	1.268	2.391	24.572	3.183
June	3.38	63.69	1.46	3.73	68.39	7.379	2.639	1.530	3.753	63.746	0.088
July	3.35	62.84	1.42	3.69	70	11.394	2.674	1.516	3.716	62.893	0.084
August	2.74	56.74	1.1	2.84	61.22	7.896	4.413	1.189	2.906	52.248	7.918
September	1.87	16.35	1.23	2	15.43	5.627	4.000	1.231	2.000	15.537	4.976
October	2.43	30.23	1.36	2.66	28.52	5.657	3.371	1.325	2.641	29.782	1.482
November	1.91	9.77	1.79	2.15	9.45	3.275	2.243	1.733	2.143	9.745	0.252
December	2.07	11.63	1.89	2.34	11.37	2.236	2.098	1.838	2.330	11.578	0.450

5. Conclusions

In this study, PD method is developed and represented. Its superior features are shown over other methods. This new method is compared with three most common methods, graphic, maximum likelihood and moment methods and numerical solution of energy pattern factor. Suitability of these methods and accuracy of PD method is judged based on different goodness of fit tests for different geographical locations. Furthermore, PD method is compared with previous studies considering power density and mean wind speed estimation capability. It is worth to indicate that superiority of PD method over other methods can be obviously seen with estimation capability of power density. Then it is concluded that PD method is very suitable and efficient in order to estimate Weibull parameters for wind energy applications.

References

[1] World Wind Energy Association. Press Release, February 2008. Wind turbines generate more than 1% of the global electricity; 2008. <http://www.wwindea.org> [accessed 22.02.08].

[2] Pallabazzer R. Parametric analysis of wind siting efficiency. J Wind Eng Indus Aerod 2003;91:1329–52.

[3] Carta JA, Ramírez P, Velázquez S. A review of wind speed probability distributions used in wind energy analysis. Renew Sust Energy Rev, in press, doi:10.1016/j.rser.2008.05.005.

[4] Petersen LE et al. Wind power meteorology. Roskilde (Denmark): Risoe National Laboratory Press; 1997.

[5] Jaramillo OA, Borja MA. Wind speed analysis in La Ventosa, Mexico: a bimodal probability distribution case. Renew Energy 2004;29:1613–30.

[6] Ramirez P, Carta JA. The use of wind probability distributions derived from the maximum entropy principle in the analysis of wind energy. A case study. Energy Convers Manage 2005;47:2564–77.

[7] Justus CG, Hargraves WR, Mikhail A, Graber D. Methods for estimating wind speed frequency distributions. J Appl Meteorol 1978;17:350–3.

[8] Stevens MJM, Smulders PT. The estimation of the parameters of the Weibull wind speed distribution for wind energy utilization purposes. Wind Eng 1979;3:132–45.

[9] Christofferson RD, Gillette DA. A simple estimator of the two-parameter Weibull distribution. J Clim Appl Meteorol 1987;26:323–5.

[10] Al Hasan M, Nigmatullin RR. Identification of the generalized Weibull distribution in wind speed data by the Eigen-coordinates method. Renew Energy 2003;28:93–110.

[11] Tar K. Some statistical characteristics of monthly average wind speed at various heights. Renew Sust Energy Rev 2008;12:1712–24.

[12] Dorvlo ASS. Estimating wind speed distribution. Energy Convers Manage 2002;43:2311–8.

[13] Seguro JV, Lambert TW. Modern estimation of the parameters of the Weibull wind speed distribution for wind energy analysis. J Wind Eng Indus Aerod 2000;85:75–84.

[14] Mathew S. Wind energy. Fundamentals, resource analysis and economics. 1st ed. New York: Springer; 2006.

[15] Cook JN. Discussion on modern estimation of the parameters of the Weibull wind speed distribution for wind speed energy analysis by Seguro JV, Lambert TW. J Wind Eng Indus Aerod 2001;89:867–9.

[16] Shata ASA, Hanitsch R. The potential of electricity generation on the east coast of Red Sea in Egypt. Renew Energy 2006;31:1597–615.

[17] Basumatary H, Sreevalsan E, Sasi KK. Weibull parameter estimation – a comparison of different methods. Wind Eng 2005;29:309–16.

[18] Genc A et al. Estimation of wind power potential using Weibull distribution. Energy Sources, Part A: Recov, Utiliz Environ Eff 2005;27:809–22.

[19] Pérez IA, García MA, Sánchez ML, Torre B. Analysis and parameterisation of wind profiles in the low atmosphere. Sol Energy 2005;78:809–21.

[20] Bagiorgas HS, Mihalakakou G, Matthopoulos D. A statistical analysis of and speed distributions in the area of Western Greece. Int J Green Energy 2008;5:120–37.

[21] Celik AN. On the distributional parameters used in assessment of the suitability of wind speed probability density functions. Energy Convers Manage 2004;45:1735–47.

[22] Raichle BW, Carson WR. Wind resource assessment of the Southern Appalachian Ridges in the southeastern United States. Renew Sust Energy Rev, in press, doi:10.1016/j.rser.2007.12.005.

[23] Gökçek M, Bayülken A, Bekdemir S. Investigation of wind characteristics and wind energy potential in Kirklareli, Turkey. Renew Energy 2007;32:1739–52.

[24] Al-Nassar W, Alhajraf S, Al-Enizi A, Al-Awadhi L. Potential wind power generation in the State of Kuwait. Renew Energy 2005;30:2149–61.

[25] Akpinar EK, Akpinar S. A statistical analysis of wind speed data used in installation of wind energy conversion systems. Energy Convers Manage 2005;46:515–32.

[26] Celik AN. A techno-economic analysis of wind energy in southern Turkey. Int J Green Energy 2007;4:233–47.