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Analysis of Wind Speed Data Using Finsler, Weibull, and Rayleigh Distribution Functions

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ABSTRACT

Determining and modeling the wind speed characteristics of a region are important in terms of constructing the wind energy conversion systems. Several distribution functions such as Finsler geometry, two-parameter Weibull, and Rayleigh are proposed for wind speed modeling in the literature. The modeling performance of Finsler geometry method at high and low speeds was not investigated in the literature, although a model proposal was presented in the studies on Finsler geometry. In addition, there is no comparison in terms of power density. This paper presents the comparative performance analysis of Finsler geometry for modeling the wind speed data. The Finsler geometry method allows accurate modeling and describes the ability for chaotic structures like wind speed data. The two-parameter Weibull, Rayleigh, and Finsler Geometry are used to analyze the wind speed data between October 2015 and September 2016 in Bilecik, Gökçeada, and Bozcaada, which are located in the northwest of Turkey. The obtained results show that the novel method based on Finsler geometry is a better alternative to the two-parameter Weibull and the Rayleigh probability density functions to describe wind speed characteristics.

Index Terms—Finsler geometry, Rayleigh distribution, Weibull distribution, wind energy.

I. INTRODUCTION

Today, the usage of renewable energy systems has increased rapidly in parallel with the growing energy demand, in order to produce clean and sustainable energy. Wind energy is one of the most widely used renewable energy sources. In recent years, along with the development of the wind energy industry, the capacity of wind turbines reached approximately 742 GW by the end of 2020 [1]. The installation of wind turbines has seen a rapid increase in Turkey. Fig. 1 shows the cumulative installation for wind power plants in Turkey [2].

The factors of wind characteristics such as speed, direction, and continuity should be investigated in detail while determining the wind energy potential for the selected region [3]. Several distribution functions have been proposed for modeling the wind speed data in the literature. The two-parameter Weibull and Rayleigh distributions are widely used for wind speed data analysis [4-7]. In addition, many different methods such as Finsler geometry-based distribution, the inverse Weibull distribution, the inverse Gaussian distribution, the Burr distribution, etc., were proposed in the literature [8-16]. It is observed that the performance of the methods varies according to different regions.

A novel approach based on Finsler geometry was proposed by Dokur et al. [10,16] for modeling the wind speed data. The chaotic nature of wind speed poses difficulties in terms of modeling. Therefore, the Weibull distribution-based Finsler geometry approach appears to be a powerful method for modeling asymmetric and anisotropic phenomena such as wind speed [17-22]. Although Dokur et al. [16] presented the Finsler geometry method for the two-parameter Weibull distribution, its performance at low and high wind speeds was not compared and was not investigated in terms of power density. They could only investigate non-comparatively the limited research for Bozcaada data in [10]. In this paper, the performance of this model for different regions having low and high wind regimes (Bozcaada, Bilecik, and Gökçeada) has been investigated, in terms of both wind speed modeling and wind power density.

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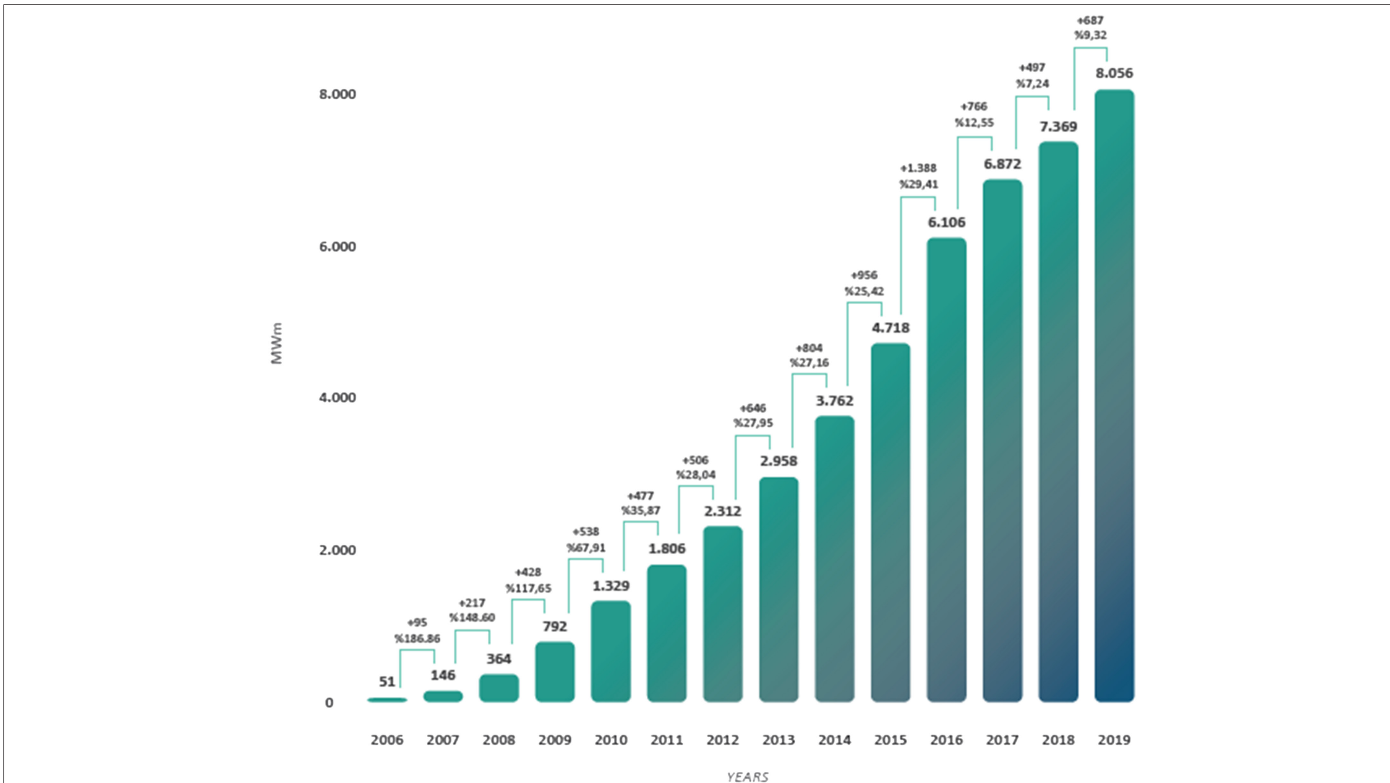

Fig. 1. Cumulative installations for wind power plants in Turkey [2].

In this paper, the wind speed data for three different regions of Turkey have been analyzed using a novel approach based on Finsler geometry. In addition, the Finsler geometry method has been compared with the Weibull and Rayleigh models, which are commonly used for modeling the wind speed data. This paper is structured as follows: the Finsler geometry method and the other methods are explained in Sections II and III, respectively. The comparative modeling results for monthly analysis and power density errors are presented in Section IV. Finally, conclusions are given in Section V.

II. FINSLER GEOMETRY METHOD

In recent years, Finsler geometry is being preferred for various engineering problems as it gives the most accurate solution. Thus, the aim of this paper is to develop more accurate models for determination of wind speed characteristics using the Finsler geometry method.

The Finsler metric functions in (1), presented for the two-parameter family of curves in Finsler space by Matsumoto [21], are calculated for two-parameter Weibull distribution function by Dokur et al. [16], as follows:

$$L_n(x,y,\dot{x},\dot{y}) = \frac{y^{(n+2)}\dot{x}}{x^2}\sum_{k=0}^{n}\binom{n+2}{k+2}\left(-\frac{x\dot{y}}{y\dot{x}}\right)^{(k+2)} \quad (1)$$

The geodesic derived by the Finsler metrics in (1) is the curve that is minimized, of $s=\int_{t_0}^{t} L_n(x,y;\dot{x},\dot{y})dt$ the length integral that it is calculated along a curve and obtained from Euler equations (2) [10],

$$\ddot{x}^i + 2G_n{}^i(x,y;\dot{x},\dot{y}) = 0 \quad (2)$$

where G^i spray coefficients are obtained (3),

$$G^i(x,y;\dot{x},\dot{y}) = \frac{1}{2}g^{il}\left\{\frac{\partial^2 F_n}{\partial x^j \partial y^l}y^j - \frac{\partial F_n}{\partial x^l}\right\}, \quad (3)$$

and $F_n(x,y;\dot{x},\dot{y}) = \frac{L_n{}^2(x,y;\dot{x},\dot{y})}{2}$ refers to the Finsler metric.

In equation (1), the metric function, L_n, defined in n value and the spray coefficients, G_n^i, for arbitrary positive rational numbers of $n=1/2$ and 11/12 are calculated as [10]:

$$L_{1/2}(x,y,p,q) = \frac{15q^2x^2\sqrt{y}}{8x^2p},$$
$$L_{11/12}(x,y,p,q) = \frac{805q^2x^2y^{11/12}}{288x^2p}. \quad (4)$$

The spray coefficients that are associated with Finsler metrics in (4) are found as follows [10]:

$$G_{1/2}^1 = 0, G_{1/2}^2 = \frac{q^2}{8y}, \quad (5)$$

$$G_{11/12}^1 = 0, G_{11/12}{}^2 = \frac{11q^2}{48y}. \quad (6)$$

Then, in equation (2), when calculated for (5) and (6), respectively, we find the second-order nonlinear differential equation of y as follows [10]:

$$y'' = K\frac{y'^2}{y} \tag{7}$$

where a coefficient dependent on n is defined as K. It can be seen easily that the values for K are –1/4,–11/24 for $n = 1/2$, 11/12, respectively. Thus, the relation between n and K is $K = -\frac{1}{2}n$. For all non-negative rational numbers, when the differential equation in equation (7) is solved [10],

$$y = \left(C_2 x + \frac{2}{n+2}C_1\right)^{\frac{2}{n+2}} \tag{8}$$

is found, where C_1 and C_2 are the integration constants for (8). The new two-parameter cumulative function (CDF) is [10,16]:

$$F_f(v; C_1, C_2) = 1 - e^{-\frac{2}{n+2}v^{C_2}e^{\frac{2}{n+2}C_1}} \tag{9}$$

and setting $a = \frac{2}{n+2}$, it is rewritten in the form

$$F_f(v; C_1, C_2) = 1 - e^{-av^{C_2}e^{aC_1}}. \tag{10}$$

The probability density function (PDF) is calculated by $f_f = \frac{dF_f}{dv}$

$$f_f(v; C_1, C_2) = aC_2 e^{a(C_1 - V^{C_2}e^{aC_1})} v^{C_2 - 1}. \tag{11}$$

The new PDF and CDF (10) and (11) respectively are used by the Finsler geometry-based method [10,16].

III. WIND SPEED DISTRIBUTION MODELS

Two-parameter Weibull and Rayleigh distributions are widely used as statistical methods in the modeling of wind speed data. The two-parameter Weibull distribution function is given by equation (12):

$$f_w(v; k, c) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k}, \tag{12}$$

where $f_w(v; k, c)$ is the probability density function of wind speed v according to c and k, which are scale parameter and shape parameter, respectively. The higher value of c indicates that the wind speed is higher, while the value of k shows the wind stability [23].

The cumulative Weibull distribution function $F_w(v; k, c)$ gives the probability of the wind speed exceeding the value v. It is expressed by (13) [24,25]:

$$F_w(v; k, c) = 1 - e^{-\left(\frac{v}{c}\right)^k}. \tag{13}$$

Another distribution function used in the determination of the wind speed potential is the Rayleigh method, which is a simplified case of the Weibull distribution function, in which the dimensionless shape factor of the distribution is a fixed value ($k = 2$). The probability and cumulative probability density functions of the Rayleigh method are given as follows [26]:

$$f_r(v; a) = \frac{v}{a^2} e^{\left(\frac{-v^2}{2a^2}\right)} \tag{14}$$

$$F_r(v; a) = 1 - e^{\left[\frac{1}{2}\left(\frac{v}{a}\right)^2\right]}. \tag{15}$$

There are several parameter estimation methods such as the method of Justus, the method of Lysen, the maximum likelihood method, the moment method, etc. in the literature. In this paper, the maximum likelihood method is used for the Weibull and Rayleigh methods. The scale and shape parameters of the Weibull method can be calculated by:

$$k = \left[\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n}\right]^{-1}, \quad c = \left[\frac{\sum_{i=1}^{n} (v_i)^k}{\sum_{i=1}^{n} v_i^k}\right]^{\frac{1}{k}} \tag{16}$$

The single scale parameter of the Rayleigh method is calculated by the maximum likelihood method using equation (17):

$$a = \sqrt{\frac{1}{2n}\sum_{i=1}^{n} v_i^2} \tag{17}$$

There are several methods based on performance criteria for comparison of models, such as the mean absolute percentage error, the mean square error, the sum square error, etc. The root mean square error (RMSE) method is used in this paper. The performance criteria of analysis are shown by using RMSE in (18):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (y_i - x_i)^2} \tag{18}$$

where y_i is the actual wind speed probability value, x_i is the probability value calculated from distribution methods, and n is the number of observations.

IV. FINSLER GEOMETRY APPLICATION FOR MODELING THE WIND SPEED DATA

In this paper, the wind speed data of the hourly time series between October 2015 and September 2016 for the three different regions of Bozcaada, Bilecik, and Gökçeada are analyzed. Although the wind speed data for Bozcaada are analyzed using Finsler geometry [10], a comparison is made with the data in low and high wind speed

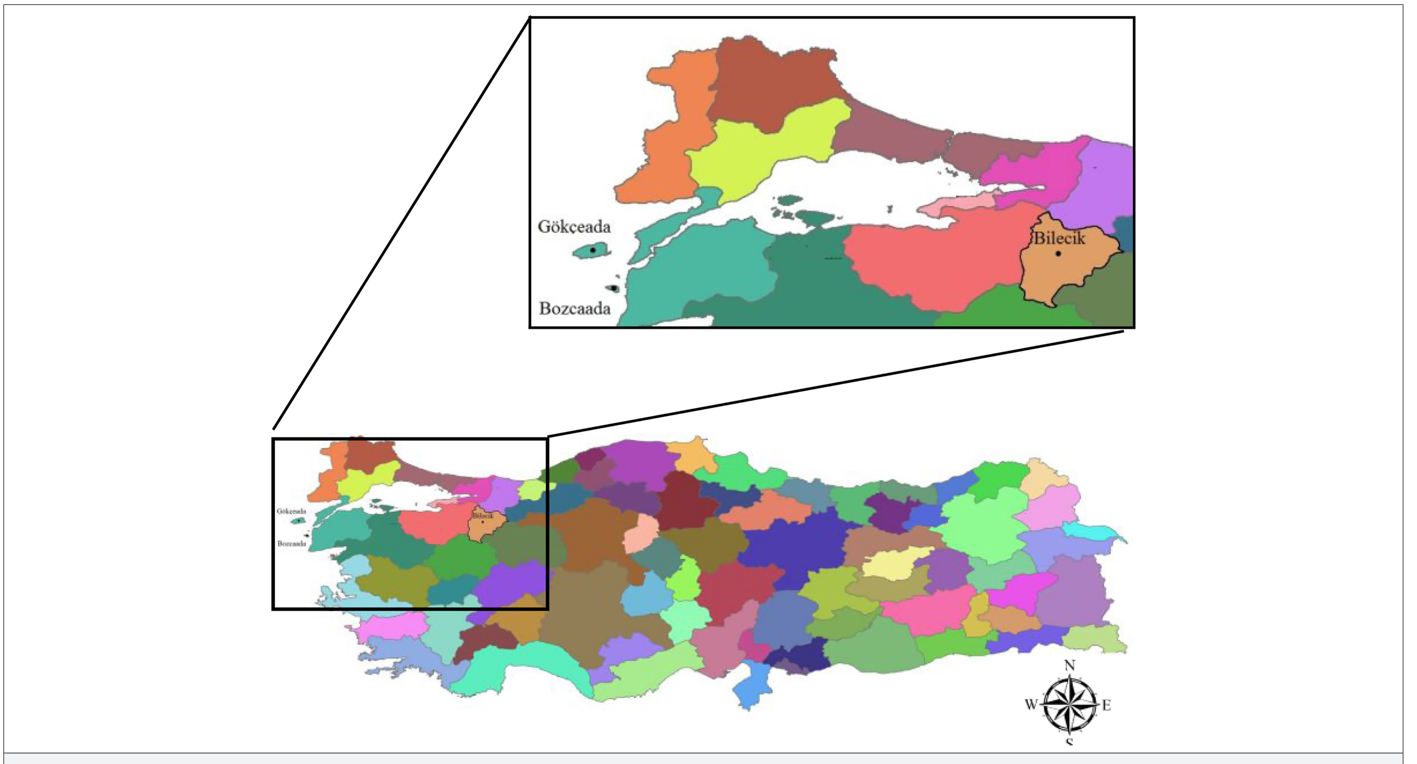

Fig. 2. The geographical data and wind data periods for the regions.

regimes (Bilecik and Gökçeada) over the same data set in this paper. The continuously recorded wind speed data were averaged over 1 h at the Bozcaada, Bilecik, and Gökçeada stations (Fig. 2). The geographical data and wind speed periods for these regions are given in Table I.

The biggest island in Turkey is Gökçeada, which is in the Northern Aegean Sea; another island in the Aegean Sea is Bozcaada. Bilecik is a small area located in the same region. Gökçeada and Bozcaada have high wind speed regimes compared to the low wind speed regime of Bilecik. Particularly in this study, both low and high wind regions were selected to compare the behavior of models in different cases (Fig. 3).

The wind speed data are divided into a number of intervals, mostly at a width of 1 m/s, to determine frequency distribution [26]. Therefore, the wind speed data in a time series format are converted into a frequency format for a suitable statistical analysis [27]. The distribution format of this process, for example, according to months and regions, is given in Table II.

In this paper, the most commonly used functions in the wind speed model are compared with the results of the new model for different regions. Accordingly, the calculated parameters of models and their comparative results are given in Tables III and IV. As can be seen in the performance criteria results for all regions, a novel approach based on the Finsler method is promising with respect to accurate modeling.

TABLE I. THE GEOGRAPHICAL DATA AND WIND DATA PERIODS OF REGIONS

Station	Latitude (°N)	Longitude (°E)	Altitude (m)	Wind Data Period
Bozcaada	39° 48'	26° 02'	20	October 2015–September 2016
Gökçeada	40° 10'	25° 50'	48	October 2015–September 2016
Bilecik	40° 05'	30° 05'	850	October 2015–September 2016

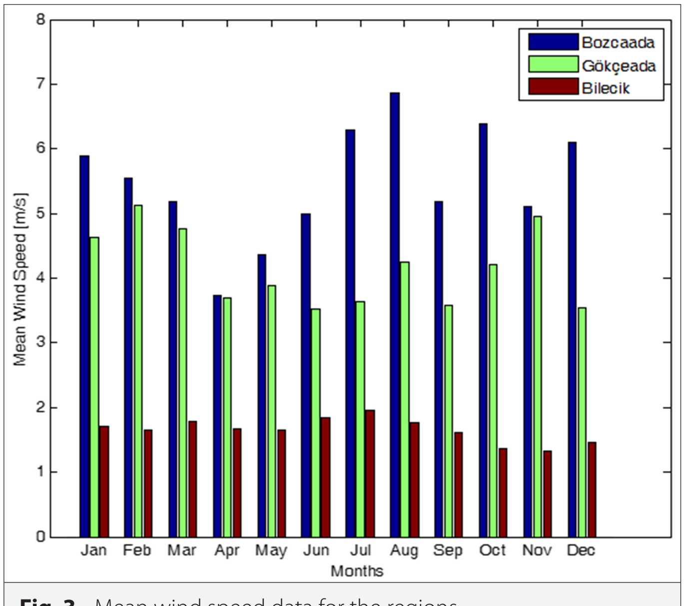

Fig. 3. Mean wind speed data for the regions.

TABLE II. FINSLER, WEIBULL, AND RAYLEIGH WIND SPEED PROBABILITIES FOR A SAMPLE MONTH, FOR BOZCAADA

i	v_i	f_i	$f(v_i)$	$f_w(v_i)$	$f_r(v_i)$	$f_f(v_i)$
1	0–1	11	0.0147	0.0163	0.0386	0.0134
2	1–2	54	0.0725	0.0513	0.1072	0.0451
3	2–3	51	0.0685	0.0825	0.1529	0.0754
4	3–4	72	0.0967	0.1059	0.1693	0.0996
5	4–5	82	0.1102	0.1190	0.1593	0.1149
6	5–6	97	0.1303	0.1215	0.1318	0.1202
7	6–7	64	0.0860	0.1148	0.0975	0.1160
8	7–8	66	0.0887	0.1013	0.0651	0.1045
9	8–9	74	0.0994	0.0840	0.0395	0.0883
10	9–10	63	0.0846	0.0657	0.0218	0.0702
11	10–11	38	0.0510	0.0486	0.0110	0.0528
12	11–12	40	0.0537	0.0341	0.0051	0.0375
13	12–13	17	0.0228	0.0226	0.0021	0.0252
14	13–14	5	0.0067	0.0143	0.0008	0.0160
15	14–15	2	0.0026	0.0086	0.0003	0.0097
16	15–16	6	0.0080	0.0049	0.0001	0.0055
17	16–17	1	0.0010	0.0026	0.0000	0.0030
18	17–18	1	0.0010	0.0013	0.0000	0.0015

TABLE III. ANALYSIS RESULTS OF PARAMETER ESTIMATION AND PERFORMANCE METRICS FOR GÖKÇEADA

	Gökçeada								
	Weibull			Finsler				Rayleigh	
Months	k	C	RMSE	n	C_1	C_2	RMSE	c	RMSE
January	1.3428	5.0590	0.0118	1/1000	−2.1908	1.3021	0.0115	4.1057	0.0383
February	1.3051	5.5598	0.0223	1/1000	−2.2118	1.1552	0.0184	4.4978	0.0460
March	1.5189	5.2773	0.0102	1/1000	−2.3991	1.3851	0.0099	4.0362	0.0244
April	1.2784	3.9648	0.0324	1/1000	−1.5512	1.0564	0.0238	3.2268	0.0638
May	1.5118	4.3269	0.0143	1/2	−2.6435	1.5010	0.0130	3.3112	0.0329
June	1.5583	3.9031	0.0320	1/2	−2.5541	1.5058	0.0286	2.9463	0.0405
July	2.0412	4.0798	0.0645	11/12	−4.1512	2.1210	0.0564	2.8753	0.0650
August	2.2721	4.7470	0.0396	11/12	−4.6235	2.1502	0.0363	3.2937	0.0454
September	2.0404	4.0454	0.0397	11/12	−4.2025	2.1500	0.0322	2.8505	0.0401
October	1.7396	4.7091	0.0267	1/2	−2.9210	1.5558	0.0264	3.4331	0.0280
November	1.5134	5.5156	0.0150	1/2	−2.9896	1.5156	0.0150	4.2350	0.0279
December	1.1198	3.7053	0.0362	1/1000	−1.3400	0.9021	0.0280	3.2546	0.0838

The probability density distributions of some regions and models are given for sample months in Fig. 4 and Tables III and IV.

As seen in Fig. 4 and Tables III and IV, the Finsler geometry approach allows more accurate modeling. The new method based on Finsler geometry provides better results than the other methods in the overshoot points of probability density. In addition, the Finsler geometry approach gives more precise results with respect to both high and low wind speed regimes. The Rayleigh distribution method has good results for only some months of low wind speed regime, such as April and May, in Bilecik. Although the results of Weibull distribution are close to those of Finsler geometry, the novel approach is a better alternative according to all RMSE results.

The other important parameter is the power of wind for energy conversion systems. The power of wind per unit area is given by (19):

$$\frac{P(v)}{A} = \frac{1}{2}\rho v^3 \tag{19}$$

where ρ (kg/m³) is air density and A (m²) is swept area. The reference mean power density can be calculated by (20):

$$P_{Ref} = \frac{1}{2}\rho \sum_{i=1}^{n} v_i^3 f(v_i) \tag{20}$$

The general equation for mean wind power density is:

$$P = \int_0^\infty f(v)\,dv. \tag{21}$$

Accordingly, the power of wind can be calculated by integrating the probability density functions for each model. The errors of wind power obtained by models are presented in Fig. 5, using the following equation for power density error (21):

$$PDE = \left(\frac{P_{model} - P_{Ref}}{P_{Ref}}\right) * 100 \tag{22}$$

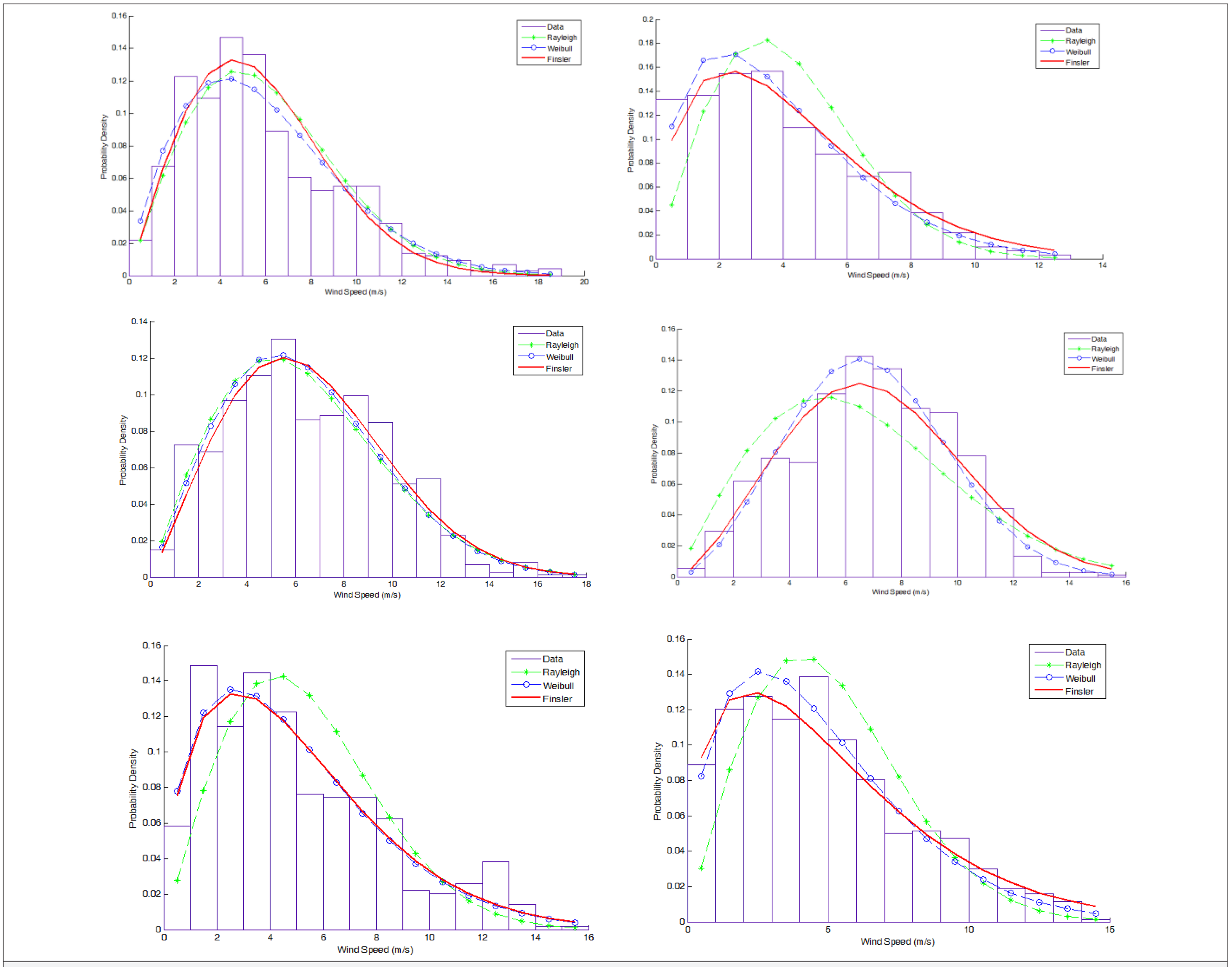

Fig. 4. Probability density distributions for some sample months.

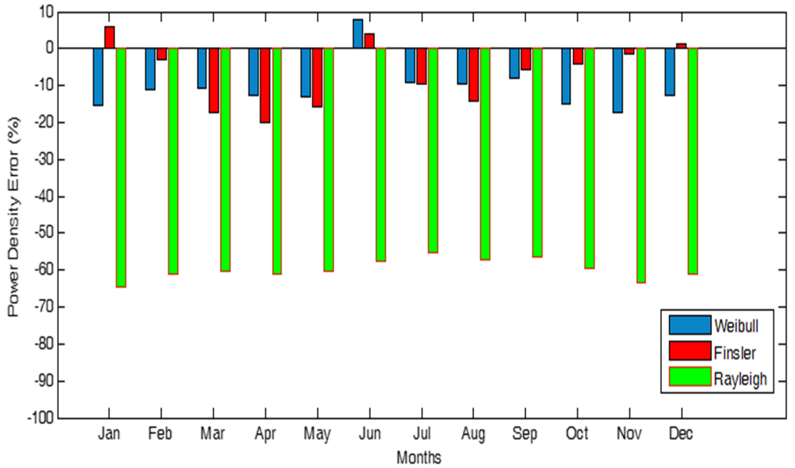

Fig. 5. Power density errors of the models.

TABLE IV. ANALYSIS RESULTS OF PARAMETER ESTIMATION AND PERFORMANCE METRICS FOR BILECIK

	Bilecik								
	Weibull			Finsler				Rayleigh	
Months	***k***	***C***	**RMSE**	***n***	C_1	C_2	**RMSE**	***c***	**RMSE**
January	1.6461	1.9157	0.0185	1/2	−0.9987	1.5107	0.0137	1.4372	0.0458
February	1.8733	1.8738	0.0232	1/2	−1.2015	1.8301	0.0225	1.3470	0.0289
March	1.9676	2.0109	0.0192	11/12	−1.6305	2.1350	0.0187	1.4274	0.0177
April	1.9534	1.8862	0.0155	11/12	−1.3408	2.0707	0.0147	1.3414	0.0134
May	2.0486	1.8816	0.0202	11/12	−1.3415	2.0751	0.0197	1.3234	0.0230
June	2.1354	2.0912	0.0088	11/12	−1.7519	2.1101	0.0086	1.4590	0.0196
July	2.6047	2.2152	0.0261	11/12	−2.2104	2.4307	0.0225	1.5039	0.0561
August	2.3304	2.0004	0.0454	1/2	−1.6310	2.2815	0.0447	2.0004	0.0624
September	2.2881	1.8204	0.0119	11/12	−1.5595	2.3511	0.0108	1.2556	0.0457
October	2.3304	1.5460	0.0273	1/2	−1.1058	2.2815	0.0145	1.0632	0.0528
November	1.8810	1.5050	0.0189	1/2	−0.8621	1.9210	0.0169	1.0814	0.0184
December	1.9703	1.6487	0.0245	1/2	−0.8681	1.7923	0.0204	1.1699	0.0262

The Finsler geometry method has smaller error values in calculating the power density compared to the Rayleigh and Weibull models. The highest error value occurs in April, with 19.8% for the Finsler geometry model. The wind power is estimated by the Finsler model with a very small error value of 1.1% in December. The monthly analysis shows that the error values in calculating the wind power using the Rayleigh model are relatively higher, at over 50%. The Weibull and Finsler models have better results than the Rayleigh model. Although in some months such as March and August, the Weibull models give accurate results, the Finsler geometry approach gives generally better results.

V. CONCLUSIONS

In this paper, the wind speed data for three different regions of Turkey were analyzed using a novel approach based on the Finsler geometry method. In addition, a new model based on the Finsler geometry method was compared with the Weibull and Rayleigh models which are commonly used for wind speed modeling. The Finsler geometry method has been found to allow accurate modeling of wind speed, which is chaotic and unstable. According to results of the monthly analysis, the Finsler geometry model has been seen to have a better fit with the measured probability density distributions than the Weibull and Rayleigh models. Furthermore, the Finsler geometry method has small error values in terms of power density estimation for 12 months. The Rayleigh distribution method has been found to have high error rates in both monthly wind speed models and power density estimation. The Weibull distribution method has been found to provide results similar to those of the Finsler approach in some months in the monthly figures for power density. As a result, it seems that the Finsler geometry method gives more accurate modeling ability, in terms of modeling both wind speed data and power density.

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