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Comparative Analysis of Wind Speed Models Using Different Weibull Distributions

Emrah Dokur[1], Salim Ceyhan[2], Mehmet Kurban[1]

[1]Department of Electrical Electronics Engineering, Bilecik Şeyh Edebali University, Bilecik, Turkey
[2]Department of Computer Engineering, Bilecik Şeyh Edebali University, Bilecik, Turkey

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ABSTRACT

A wide variety of distribution functions are used in the literature for wind speed modelling. It is the most widely used Weibull distribution (WD) function in wind speed modelling. In this paper, two-parameter WD, Rayleigh distribution (RD) which is a special form of WD, and Inverse Weibull distribution (IWD) offered for a new seasonal wind speed modelling are considered and analyzed for six different regions (Gökçeada, Bozcaada, Bandırma, Bilecik, Yalova and Sakarya regions) in the Northwest of Turkey, comparatively. The hourly wind speed data for the period of October 2015 to 30 September 2016 is taken from Turkish State Meteorological Service. As a result of the comparison, it is seen that the WD is generally suitable, although IWD has good seasonal results in some regions. All the comparative results are given in tables.
Keywords: Wind speed modeling, weibull distribution, rayleigh distribution, inverse weibull distribution

Introduction

Energy is one of the most important parts of our life. Clean form of energy production in parallel with the needs of today's growing demand for power is of great importance. Thus, the use of renewable energy resources is increasing rapidly. Consequently, it is foreseen that the renewable energy resources in the generation systems will increase by the year 2020 rapidly and the major part of these resources will be wind energy as 12% [1]. Hence, wind energy conversation systems have great importance among renewable energy sources.

The detailed information of wind data characteristics such as direction, speed and duration should be investigated while determining the wind energy potential for the selected region [2]. Several distribution functions were proposed for wind speed modelling in literature. The two-parameter Weibull [3-5], the log-normal distribution [6-9], the inverse Gaussian distribution [10], the wake by [11, 12], three-parameter log normal [13], the gamma distribution [14, 15], two-parameter gamma distribution [16], hybrid distributions [17, 18], Finsler geometry approach [19], the three parameter generalized gamma distribution [20, 21],and similar distribution functions were used about energy and other research areas.

The use of Inverse Weibull distribution (IWD) function on the purpose of wind speed modeling is proposed by Akgül et al. [22]. Two parameter Weibull distribution (WD) and IWD are compared for the seasonal wind speed data in their study. The aim of this paper is to addresses that monthly and seasonal wind speed data for six different regions of Turkey are modeled using WD,IWD and Rayleigh distributions (RD) function, comparatively. Analyses are made for the regions taken from stations of the Marmara region which have low and high wind speed regimes. Especially, the modelling performance of the IWD is compared with the WD and RD for monthly analysis. This paper is structured as follows: the WD,RD and IWD methods are explained by Section 2. Comparative modelling results for monthly and seasonal analysis are presented in Section 3. Finally, conclusions are given in Section 4.

Corresponding Author:
Emrah Dokur

E-mail:
emrah.dokur@bilecik.edu.tr

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Methods for Wind Speed Modelling

The two-parameter WD function that is suitable for wind speed modelling is given by Equation (1):

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

where f(v) is the probability density function (pdf) of wind speed v, the Weibull scale parameter is c which has with unit equals to the wind speed unit (m/s) and, the shape parameter of WD is k. While the value of k shows the wind speed, higher c indicates more stability [23].

The cumulative distribution function (cdf) of WD, F(v) is expressed by the following Equation (2) [24-25]:

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

The Rayleigh is a special form of WD function in which the shape factor of the WD is a fixed value (k=2).

The pdf and cdf of IWD are given in below [22]:

$$f_{IWD}(\mathrm{v}) = \frac{k}{c}\left(\frac{v}{c}\right)^{-k-1} e^{-\left(\frac{v}{c}\right)^{-k}} \quad (3)$$

and

$$\mathrm{F}_{IWD}(\mathrm{v}) = e^{-\left(\frac{v}{c}\right)^{-k}}. \quad (4)$$

There are several methods for estimating of k and c parameters, such as maximum likelihood method, graphical method, method of Justus, method of Lysen, power density method, information geometry method etc. [26-29]. In this paper, maximum likelihood methods is used for parameter estimation [30].

k and c parameters are calculated for WD by Equation (5, 6). Where n is number of observed wind speed data.

$$k = \left(\frac{\sum_{i=1}^{n} v_i^k \ln(\mathrm{v}_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(\mathrm{v}_i)}{n} \right)^{-1} \quad (5)$$

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

The determination of scale and shape parameter for IWD are given in below;

$$k = \frac{n\sum_{i=1}^{n} v_i^{-k}}{\sum_{i=1}^{n} \ln \mathrm{v}_i \sum_{i=1}^{n} v_i^{-k} - n\sum_{i=1}^{n} v_i^{-k} \ln v_i} \quad (7)$$

$$c = \left(\frac{n}{\sum_{i=1}^{n} v_i^{-k}} \right)^{1/k} \quad (8)$$

Performance criteria of analysis is shown by using Root Mean Square Error (RMSE) in Equation (9).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (\mathrm{y}_i - \mathrm{x}_i)^2} \quad (9)$$

Where, y_i and x_i are observed and estimated wind speed probability value, respectively. And the number of observations is expressed as n.

Comparative Analysis of Wind Speed Models

In this paper, the six different regions which have low and high wind speed characteristics are comparatively analyzed by the three different methods. Wind speed data, consisting of hourly wind speed records between October 2015-September 2016 were obtained from the Gökçeada, Bozcaada, Bandırma, Bilecik, Yalova and Sakarya Meteorological Stations. They are located in Northwest of Turkey, Marmara region, as shown in Figure 1.

The biggest island of Turkey is Gökçeada which is in the Northern Aegean Sea and also another island in Aegean Sea is Bozcaada. Bandırma, Bilecik, Yalova and Sakarya in Marmara region are located close to each other as shown in Figure 1. The geographical data and wind speed period for these region are given in Table 1.

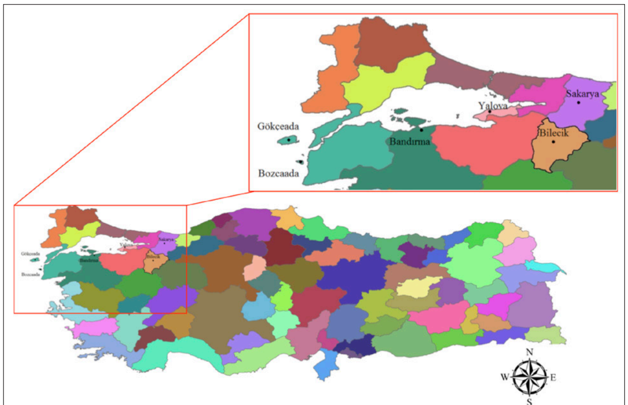

Figure 1. Locations of the sample wind speed data regions in Turkey

Table 1. The geographical data and wind data period of six different regions

Station	Latitude (oN)	Longitude (oE)	Altitude (m)	Wind Data Period
Bandırma	40° 21'	27o 58'	20	October 2015-September 2016
Sakarya	40° 46'	30o 22'	31	October 2015-September 2016
Yalova	40° 39'	29o 15'	30	October 2015-September 2016
Bozcaada	39° 48'	26o 02'	20	October 2015-September 2016
Gökçeada	40° 10'	25o 50'	48	October 2015-September 2016
Bilecik	40° 05'	30o 05'	850	October 2015-September 2016

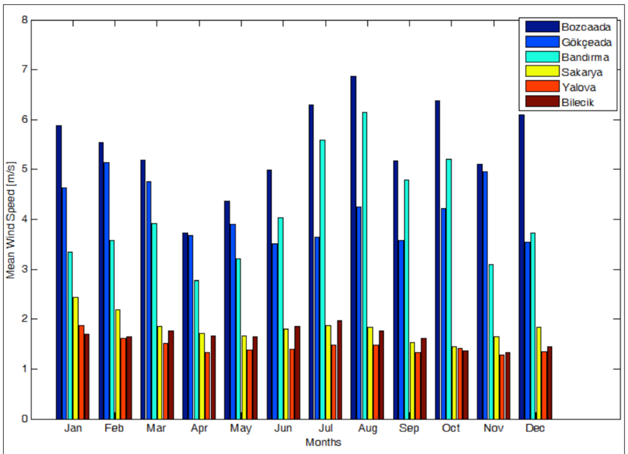

Figure 2. Mean wind speed data for six region

Mean wind speed data for six regions are given in Figure 2. Bozcaada, Bandırma and Gökçeada have higher wind speed profile than Sakarya, Bilecik and Yalova.

The IWD function for wind speed modeling was proposed for seasonal analysis by Akgül et al. [22]. In this paper, the performance of Inverse Weibull Distribution function not only in seasonal analyzes but also in monthly analyzes is realized for different regions. The monthly analysis for six different regions using IWD, WD and RD methods are given in Table 2. Root Mean Square Error (RMSE) that is given in Equation (9) is selected for performance criteria.

As seen in Table 2, Two-parameter Weibull distribution is suitable model for Bandırma region. However, Rayleigh distrubition is better than WD for January and February of Bandırma region. The IWD and WD methods are shown to be suitable for Sakarya region. In particular, the IWD method for monthly analysis seems more appropriate for the Sakarya and Yalova regions than other regions. Especially, the performance of IWD method is good fit for eight months in Yalova. WD method has better performance than the other methods for other regions that are Bilecik, Gökçeada and Bozcaada.

The methods are compared in terms of seasonal analysis perspective in the Table 3. When the analyzes are considered as seasonally, it can be seen that the two-parameter WD method is generally more appropriate than the other methods. The IWD method gives good fit only winter and summer that have Sakarya and Yalova, respectively.

It is important that to determine the wind characteristics of wind resource in site where the wind energy system will be adapted. In order to achieve a feasible project, many observations, analyses and calculations must be done. For the wind resource analysis the wind characteristics of the site must be determined. Important performance criterion for the wind energy conversion system is energy output calculations. Energy production of a wind turbine is predicted by monitoring its energy output over long time periods. At the design stage of wind energy system, for energy calculations conventional approaches are followed such as Weibull or Rayleigh. In addition, IWD which is the special form of Weibull is proposed in the literature. In this study focuses specifically on matching the structure and performance of different Weibull distributions.

As a result of the comparison, it is seen that the WD is generally suitable, although IWD has good seasonal results in some regions in Table 3.

Conclusion

In this paper, the six different regions of Turkey are analysed for wind speed data records between October 2015-September 2016 using WD, IWD and RD comparatively. The following conclusions of this study can be obtained as:

The IWD method was newly proposed for seasonal wind speed modeling in literature. In this study, monthly and seasonal analysis for six different regions that have different wind speed profiles are presented using three different methods, comparatively. In this context, the IWD appears to be a suitable method for some regions that are Yalova and Sakarya which have low wind speed profile.

Table 2. The results of comparative monthly analysis of six regions using WD, IWD and RD

		BANDIRMA			SAKARYA			BOZCAADA			YALOVA			GÖKÇEADA			BILECIK		
Months	**Methods**	**k**	**c**	**RMSE**	**k**	**c**	**RMSE**	**k**	**c**	**RMSE**	**k**	**c**	**RMSE**	**k**	**c**	**RMSE**	**k**	**c**	**RMSE**
January	WD	1.5623	3.7486	0.0582	1.9682	2.7627	0.0919	1.8045	6.6232	0.0307	1.7410	2.3207	0.0880	1.3428	5.0590	0.0418	1.6461	1.9157	0.0953
	IWD	1.1515	2.9619	0.0600	1.1924	1.8577	0.0823	0.9265	3.7083	0.0475	1.0463	1.4903	0.0794	0.8861	3.2446	0.0445	1.0408	1.4973	0.1001
	RD	2.0000	2.8730	0.0544	2.0000	1.9608	0.1013	2.0000	4.8133	0.0418	2.000	1.7013	0.1090	2.0000	4.1057	0.0609	2.000	1.4372	0.1138
February	WD	1.4723	3.9865	0.0526	1.9261	2.4819	0.0755	1.6015	6.1965	0.0367	2.1647	1.8286	0.1189	1.3051	5.5598	0.0428	1.8733	1.8738	0.0837
	IWD	1.0543	3.0466	0.0542	1.3922	1.9224	0.0726	0.9071	3.6235	0.0407	1.5447	1.5618	0.1301	0.7942	3.0087	0.0459	1.2361	1.4339	0.0861
	RD	2.0000	3.1593	0.0497	2.0000	1.7710	0.0744	2.0000	4.6698	0.0521	2.000	1.2713	0.1369	2.0000	4.4978	0.0666	2.000	1.3470	0.1008
March	WD	1.4180	4.3319	0.0450	2.0228	2.1096	0.0826	1.7867	5.8550	0.0325	2.1652	1.7105	0.1569	1.5189	5.2773	0.0401	1.9676	2.0109	0.0586
	IWD	1.0324	3.3361	0.0483	1.3296	1.6490	0.0890	1.1443	3.8262	0.0365	1.5903	1.4862	0.1680	0.7970	2.8500	0.0495	1.0602	1.3871	0.1043
	RD	2.0000	3.4856	0.0544	2.0000	1.4878	0.1089	2.0000	4.2631	0.0433	2.000	1.1888	0.1615	2.0000	4.0362	0.0581	2.000	1.4274	0.1136
April	WD	1.4740	3.0964	0.0656	1.9425	1.9414	0.1078	1.6364	4.1676	0.0460	2.1101	1.5135	0.1542	1.2784	3.9648	0.0544	1.9534	1.8862	0.0809
	IWD	1.1083	2.5888	0.0753	1.3709	1.5494	0.1102	0.8152	2.2832	0.0601	1.4875	1.3092	0.1703	0.8169	2.3124	0.0629	1.2219	1.4635	0.1021
	RD	2.0000	2.4504	0.0685	2.0000	1.3825	0.1190	2.0000	3.1097	0.0702	2.000	1.0575	0.1692	2.0000	3.2268	0.0931	2.000	1.3414	0.1189
May	WD	1.8045	3.6287	0.0507	2.1874	1.8982	0.1076	2.0583	4.9181	0.0413	2.4932	1.5593	0.1907	1.5182	4.3269	0.0460	2.0486	1.8816	0.0769
	IWD	1.2190	2.6545	0.0528	1.4121	1.4535	0.1083	0.8346	2.5515	0.0804	1.6508	1.1059	0.1504	0.9244	2.5723	0.0553	1.2414	1.4124	0.1036
	RD	2.0000	2.6356	0.0606	2.0000	1.3171	0.1434	2.0000	3.4576	0.0710	2.000	1.0614	0.2423	2.0000	3.3112	0.0692	2.000	1.3234	0.1301
June	WD	1.6328	4.5150	0.0477	2.0188	2.0526	0.1027	1.6549	5.5660	0.0355	2.4608	1.5837	0.1890	1.5583	3.9031	0.0855	2.1354	2.0912	0.0619
	IWD	1.1530	3.1024	0.0520	1.3476	1.5468	0.0891	0.8038	2.6544	0.0554	1.7143	1.3308	0.1866	0.8461	1.7734	0.1209	1.2414	1.4124	0.1011
	RD	2.0000	3.3790	0.0639	2.000	1.4483	0.1167	2.000	4.1143	0.0629	2.000	1.0798	0.2177	2.0000	2.8753	0.1340	2.000	1.4590	0.1336
July	WD	2.5125	6.2834	0.0453	1.8042	2.1176	0.1294	2.5944	7.0754	0.0375	2.0939	1.6823	0.1659	2.0412	4.0798	0.0453	2.6047	2.2152	0.0725
	IWD	1.1490	3.1454	0.0837	1.3756	1.5461	0.1063	0.9914	3.0676	0.0816	1.5833	1.1814	0.1477	1.1490	3.1454	0.0837	1.2783	1.3162	0.1720
	RD	2.0000	4.3024	0.0864	2.000	1.5390	0.1210	2.000	4.8267	0.0756	2.000	1.1535	0.2202	2.0000	4.3024	0.0864	2.000	1.5039	0.1897
August	WD	2.6025	6.9199	0.0353	1.9255	2.0917	0.1211	2.7271	7.7120	0.0349	2.3836	1.6882	0.1506	2.2751	4.7470	0.0537	2.3304	2.0004	0.0934
	IWD	1.1677	3.4542	0.0732	1.5350	1.6011	0.1116	0.9470	3.5991	0.0743	1.5166	1.2609	0.1452	0.8318	2.0100	0.1113	1.3071	1.2458	0.1523
	RD	2.0000	4.7124	0.0734	2.000	1.4928	0.1171	2.000	5.2297	0.0702	2.000	1.1575	0.2093	2.0000	3.2934	0.1062	2.000	1.3751	0.1750
September	WD	1.8575	5.3794	0.0542	1.7849	1.7416	0.1427	2.0247	5.8461	0.0336	2.3544	1.5084	0.1599	2.0404	4.0454	0.0615	2.2881	1.8204	0.0722
	IWD	1.0928	2.8811	0.0678	1.4073	1.4738	0.1509	0.8056	2.7155	0.0683	1.5706	1.1682	0.1547	0.8435	1.7806	0.1060	1.1278	1.1483	0.1646
	RD	2.0000	3.8617	0.0833	2.000	1.2716	0.1211	2.000	4.1237	0.0608	2.000	1.0351	0.2196	2.0000	2.8505	0.1115	2.000	1.2556	0.1816
October	WD	1.8129	5.8586	0.0479	1.9550	1.6481	0.1177	2.0730	7.2087	0.0353	2.2958	1.6051	0.1568	1.7396	4.7091	0.0459	2.3304	1.5460	0.0683
	IWD	1.1690	3.5906	0.0580	1.4277	1.4271	0.1419	1.1342	3.9799	0.0519	1.5495	1.2293	0.1313	0.8177	2.2914	0.0726	1.1850	0.9874	0.1680
	RD	2.0000	4.2331	0.0717	2.000	1.1719	0.1245	2.000	5.0678	0.0554	2.000	1.1052	0.1891	2.0000	3.4331	0.0787	2.000	1.0632	0.2048
November	WD	1.4656	3.4498	0.0640	1.6827	1.8591	0.1344	1.6233	5.7244	0.0464	2.0936	1.4494	0.2007	1.5134	5.5136	0.0398	1.8810	1.5050	0.0939
	IWD	1.1569	2.9564	0.0755	1.3118	1.7153	0.1580	1.1590	3.7346	0.0485	1.4843	1.3278	0.2201	0.8072	2.9672	0.0507	0.9168	0.9942	0.1740
	RD	2.0000	2.7327	0.0704	2.000	1.3879	0.1094	2.000	4.2814	0.0623	2.000	1.0139	0.1977	2.0000	4.2350	0.0531	2.000	1.0814	0.1301
December	WD	1.2553	4.0254	0.0945	1.5851	2.0589	0.1222	1.9482	6.8862	0.0365	2.1847	1.5250	0.1879	1.1198	3.7053	0.0597	1.9703	1.6487	0.0893
	IWD	1.0727	2.9619	0.0977	1.2511	1.8612	0.1408	1.0950	4.0143	0.0408	1.5062	1.2830	0.1824	0.8141	2.4122	0.0713	1.1334	1.1267	0.1112
	RD	2.0000	3.3966	0.1185	2.000	1.5742	0.1079	2.000	4.8969	0.0508	2.000	1.0584	0.1977	2.0000	3.2546	0.1087	2.000	1.1699	0.1371

Table 3. The results of comparative seasonal analysis of six regions using WD, IWD and RD

Years	Methods	Bandırma			Sakarya			Bozcaada		
		k	c	RMSE	k	c	RMSE	k	c	RMSE
Winter	WD	1.4113	3.9266	0.0490	1.7849	2.4241	0.0773	1.7735	6.5834	0.0192
	IWD	1.0441	3.3531	0.0575	1.1231	1.8980	0.0759	0.8758	4.0794	0.0321
	RD	2.0000	3.1500	0.0586	2.0000	1.7674	0.0805	2.0000	4.7969	0.0364
Spring	WD	1.4923	3.6876	0.0375	2.0330	1.9842	0.0781	1.7500	4.9851	0.0201
	IWD	1.0247	3.5010	0.0558	1.3079	1.7188	0.0996	0.7914	3.0610	0.0462
	RD	2.0000	2.8972	0.0425	2.0000	1.3977	0.1007	2.0000	3.6484	0.0427
Summer	WD	2.0652	5.9418	0.0306	1.9877	1.8021	0.1177	2.1758	6.8172	0.0250
	IWD	1.1310	3.3237	0.0528	1.3756	1.5461	0.1351	0.7948	2.9871	0.0641
	RD	2.0000	4.1763	0.0636	2.0000	1.2762	0.1333	2.0000	4.7532	0.0595
Autumn	WD	1.6017	4.8877	0.0398	1.8630	1.7863	0.0981	1.8516	6.2764	0.0233
	IWD	1.0411	3.4317	0.0435	1.3118	1.7153	0.1384	0.7867	3.2689	0.0442
	RD	2.0000	3.6696	0.0631	2.0000	1.2872	0.0933	2.0000	4.5157	0.0457

Years	Methods	Yalova			Gökçeada			Bilecik		
		k	c	RMSE	k	c	RMSE	k	c	RMSE
Winter	WD	2.1817	1.8227	0.1123	1.2276	4.7335	0.0328	1.7828	1.8118	0.0745
	IWD	1.2558	1.3670	0.1153	0.7885	3.2038	0.0407	1.0384	1.5177	0.0973
	RD	2.000	1.2660	0.1514	2.0000	3.9763	0.0648	2.000	1.3222	0.0939
Spring	WD	2.3103	1.6026	0.1227	1.4162	4.5515	0.0317	1.9833	1.9267	0.0511
	IWD	1.4690	1.3528	0.1338	0.7968	2.8871	0.0419	1.0481	1.4708	0.0978
	RD	2.000	1.1022	0.1684	2.0000	3.5706	0.0596	2.000	1.3651	0.1050
Summer	WD	2.4038	1.6524	0.1494	1.8835	4.2572	0.0526	2.3310	2.1039	0.0541
	IWD	1.5007	1.2856	0.1418	0.8177	2.2732	0.0808	1.2414	1.4124	0.1192
	RD	2.000	1.1313	0.2014	2.0000	3.0452	0.0944	2.000	1.4469	0.1497
Autumn	WD	2.2305	1.5224	0.1445	1.6613	4.6731	0.0207	2.1075	1.6247	0.0489
	IWD	1.4516	1.3792	0.1692	0.7950	2.9146	0.0517	0.9098	1.0730	0.1692
	RD	2.000	1.0527	0.1705	2.0000	3.4659	0.0547	2.000	1.1361	0.1464

-Two-parameter WD function calculated for the investigated locations is more suitable than IWD and RD function according to RMSE controls.

-The RD is not suitable method for six regions that are located in the Northwest of Turkey, Marmara region.

As a result, it is considered that IWD and two-parameter WD are generally more suitable methods than RD for modelling the wind speed of the Marmara region.

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Emrah Dokur received the B.Sc. in Electrical and Electronics Engineering, Istanbul University, Turkey in 2010 and M.Sc. degrees in Electrical Engineering, Istanbul Technical University, Turkey in 2013. He received the Ph.D. degree at Energy System Engineering in Bilecik S.E. University. Since 2017, he has been assistant professor in the same University. His research areas include high voltage engineering, renewable energy systems, and power system analysis.

Salim Ceyhan received the B.Sc. M.Sc. and Ph.D. degrees in Mathematical Engineering at Istanbul Technical University (ITU) in 1987, 1991 and 1994, respectively. Since 2011, he has been assistant professor in the Bilecik S.E. University. His research areas include applied mathematics, differential geometry, and metric spaces.

Mehmet Kurban graduated from Istanbul Technical University (ITU) in Turkey as an Electrical Engineer from Faculty of Electrical and Electronics Engineering in 1991. He got M. Sc and Ph.D. degree from ITU in 1994 and 2001, respectively. Since 2015, he has been professor in the Bilecik S.E. University. His research areas include renewable energy and power system analysis.