Estimation of Monthly Average Hourly Global Solar Radiation from the Daily Value in Çanakkale, Turkey

Özge Ayvazoğlu-yüksel and Ümmühan Başaran Filik

Abstract—Solar energy has come into prominence due to its sustainability, emission-free and ease of use considering the harmful nature of fossil resources in recent years. Accurate information on global radiation is essential to achieve the goal of planning and projection of a solar power system. Global solar radiation measurements provided by meteorology lack of reliability and some of the data are missing. At this point, global solar radiation estimation has an important role in designing energy systems that are based on solar energy. In this study, six different global radiation models are considered to estimate the monthly average hourly global radiation from the daily value in Çanakkale, which is located in the northwest of Turkey. The models are validated with hourly global radiation measurements provided by the Turkish State Meteorological Service. Based on the analysis of mean absolute bias error (MABE), root mean square error (RMSE), mean bias error (MBE) and t-statistical test, accuracy of the existing models is obtained. The results indicate that the Collares - Pereira and Rabl model modified by Gueymard (CPRG) is the most accurate one, and this model is proposed to obtain the hourly global radiation averaged over the months in elsewhere that has the similar climate with the northwest of Turkey.

Index Terms—Global solar radiation, hourly radiation estimation, CPRG model.

I. INTRODUCTION

The electrical energy demand is increasing with industrial and technological developments all over the world, and meeting this increasing energy demand has a significant importance. Most of the world's energy demands are provided by fossil sources. However, fossil sources being run out and their harmful impact on environment such as environmental pollution and global warming cause renewable energy resources to gather wide interest [1]. Among renewable energy resources, solar energy is mostly preferred due to being safe, clean, free, limitless and non-polluting.

Global solar radiation data in a particular region are essential for solar energy applications because electricity generation from photovoltaic panel is directly affected by solar radiation [2]. The data must be available, reliable and accurate for planning, projection and continuity of the system [3]. However, due to the maintenance and calibration requirements and the cost of the equipment used for measurements, solar radiation estimation techniques are considered as an important issue [4]. In literature, there are

lots of models performed for estimation of hourly global radiation by using daily radiation values. The existing daily global solar radiation decomposition models are mainly categorized in three groups. The first kind of models considers the effect of time [5]-[11]. In these models, only the time of day is included, which means that varying tendency in weather conditions is not considered. The second kind of models assumes that there is a random variation in weather conditions and axial symmetric distribution between hourly global radiation of morning and afternoon times which results in a normal distribution [12]-[15]. The third kind of models completely considers neither the variability of hourly solar radiation, nor the randomness of weather conditions [16], [17].

In this study, six different models categorized in the first group, Whillier model, Liu and Jordan model, Collares - Pereira and Rabl (CPR) model, CPRG model, Garg and Garg model, Gueymard model, are studied to obtain hourly global radiation values averaged over the months by using measured daily values for Çanakkale, Turkey. Measured monthly average hourly global radiation data are obtained by calculating the arithmetic mean of individual hourly global solar radiation values for each month of the year of 2005. The estimated values of hourly global solar radiation averaged over the months are obtained by performing six different models included in the first group models and the results of these models are compared with the measured hourly global solar radiation data. Thus, with the validation of the considered models, the most accurate one is determined for estimation of the monthly average hourly global radiation from daily values for the northwest coast of Turkey.

II. MATHEMATICAL MODELS

A. Whillier Model

In this model, there is an assumption that proposes constant weather conditions as if there were no atmosphere [5]. The formula of the proposed model is obtained as;

$$\frac{I}{H} = \frac{\pi}{24} \frac{\frac{24}{\pi} \sin \frac{\pi}{24} \cos W - \cos W_s}{\sin W_s - \frac{\pi W_s}{180} \cos W_s}, \quad (1)$$

where

$$\delta = 23.45 \sin \left(360 \frac{(284 + n)}{365} \right), \quad (2)$$

Manuscript received September 14, 2016; revised December 16, 2016. This work was supported by Anadolu University Scientific Research Projects (1505F512/1604F170).

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$$W_s = \arccos(-\tan \delta \tan \phi), \quad (3)$$

$$W = \frac{360(h-12)}{24}. \quad (4)$$

B. Liu and Jordan Model

Liu and Jordan provided a simplification to the radiation formula of the Whillier model [6]. Since $(24/\pi) \sin(\pi/24)$ is approximately equal to 1, the Whillier and Liu & Jordan models nearly give the same results [17]. Therefore, Liu and Jordan model may be known as Whillier - Liu and Jordan model and is defined as;

$$\frac{I}{H} = \frac{\pi}{24} \frac{\cos W - \cos W_s}{\sin W_s - \frac{\pi W_s}{180} \cos W_s}. \quad (5)$$

C. CPR Model

CPR model gives a significant correction to the Whillier - Liu and Jordan model by adding atmospheric effect as shown [7];

$$\frac{I}{H} = \frac{\pi}{24} (a + b \cos W) \frac{\cos W - \cos W_s}{\sin W_s - \frac{\pi W_s}{180} \cos W_s}, \quad (6)$$

where a and b are linear functions defined as [18]:

$$a = 0.4090 + 0.5016 \sin(W_s - 60^\circ), \quad (7)$$

$$b = 0.6609 - 0.4767 \sin(W_s - 60^\circ). \quad (8)$$

D. CPRG Model

CPRG model provides a modification to CPR model, which results in the following relation for global solar radiation on a horizontal surface as [8];

$$\frac{I}{H} = \frac{(a + b \cos W) r_o}{f_c}, \quad (9)$$

where

$$a = 0.4090 + 0.5016 \sin(W_s - 60^\circ), \quad (10)$$

$$b = 0.6609 - 0.4767 \sin(W_s - 60^\circ), \quad (11)$$

$$f_c = a + 0.5b \frac{\frac{\pi W_s}{180} - \sin W_s \cos W_s}{\sin W_s - \frac{\pi W_s}{180} \cos W_s}, \quad (12)$$

$$r_o = \frac{\pi}{24} \frac{\cos W - \cos W_s}{\sin W_s - \frac{\pi W_s}{180} \cos W_s}. \quad (13)$$

E. Garg and Garg Model

Garg and Garg modified Liu and Jordan model to obtain hourly global radiation values for four Indian stations [9]. The developed model is shown as;

$$\frac{I}{H} = \frac{\pi}{24} \frac{\cos W - \cos W_s}{\sin W_s - \frac{\pi W_s}{180} \cos W_s} - 0.008 \sin 3 \left(\frac{\pi W_s}{180} - 0.65 \right). \quad (14)$$

F. Gueymard Model

Gueymard proposed his own model on the basis of CPR model. In the model, it is observed that asymmetries of morning and afternoon could affect the performance of the model result [10]. The model is described as;

$$\frac{I}{H} = r_o \frac{1 + q \frac{a_2}{a_1} kA(W_s) r_o}{1 + q \frac{a_2}{a_1} \frac{B(W_s)}{A(W_s)}}, \quad (15)$$

where

$$k = 24 / \pi, \quad (16)$$

$$S_o = kW_s, \quad (17)$$

$$q = \cos \phi \cos \delta, \quad (18)$$

$$A(W_s) = \sin W_s - \frac{\pi W_s}{180} \cos W_s, \quad (19)$$

$$B(W_s) = \frac{\pi W_s}{180} (0.5 + \cos^2 W_s) - 0.75 \sin 2W_s, \quad (20)$$

$$r_o = \frac{(\cos W - \cos W_s)}{kA(W_s)}, \quad (21)$$

$$\sin(h_o) = \frac{qA(W_s)}{\frac{\pi W_s}{180}}, \quad (22)$$

$$H_o = kW_o RI_{sc} \sin(h_o), \quad (23)$$

$$K_t = H / H_o, \quad (24)$$

$$a_1 = 0.41341K_t + 0.61197K_t^2 - 0.01886K_t S_o + 0.00759S_o, \quad (25)$$

$$a_2 = \max \left(\begin{array}{l} 0.054, 0.28116 + 2.2475K_t - 1.76118K_t^2 \\ -1.84535 \sin(h_o) + 1.6811 \sin^3(h_o) \end{array} \right). \quad (26)$$

III. CLIMATE DATA OF THE AREA AND METHODOLOGY

Çanakkale is located in the northwest coast of Turkey. The city is located under 25° 40' - 27° 30' east longitude and 39° 27' - 40° 45' north latitude and has an area of 9.887 km². Most of the city is included in Marmara Region and a small part of the city is under the boundaries of Aegean Region. The city that has a transition climate between the Mediterranean Climate and the Black Sea Climate is mostly under the effect of Mediterranean Climate. The annual average rainfall of the region is between 600 – 700 mm. The temperature varies from -10°C to 38 °C, which results in an annual average temperature value of almost 15 °C [19].

In this study, measured hourly and daily global radiation data of the considered region are obtained from Turkish State Meteorological Service from January 2005 to December 2005. The hourly global solar radiation values averaged over the months are estimated from the daily values by using six different models. Selected statistical comparison methods are used to compare recorded and estimated values of monthly average hourly global solar radiation to find the most accurate model for solar radiation estimation of coastal regions that have similar climate characteristics with Çanakkale in Turkey.

IV. APPLICATIONS AND RESULTS

The considered models that estimate hourly global solar radiation averaged over the months are validated and analyzed depending on the measured global radiation data of the city, and the results are shown in Table I. To compare the accuracy of the considered models, different statistical analysis methods as RMSE, MBE, MABE and t-statistical analysis are used, which are defined by the equations:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (c_i - m_i)^2}, \quad (27)$$

$$MBE = \frac{1}{n} \sum_{i=1}^n (c_i - m_i), \quad (28)$$

$$MABE = \frac{1}{n} \sum_{i=1}^n (|c_i - m_i|), \quad (29)$$

$$t\text{-statistic} = \sqrt{\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}}. \quad (30)$$

where c_i is the i^{th} calculated global radiation data, m_i is the i^{th} measured global radiation data and n is the number of data. In these statistical test methods, the results should be closer to zero for better performance of the considered models used for global solar radiation estimation [20].

Table I indicates that the CPRG model is more accurate than the other considered global solar radiation estimation models. The CPRG model has minimum MBE, MABE, RMSE and t-statistical values in July, and in other months, the model has minimum statistical parameters or smaller relatively. RMSE values of the CPRG model differ from

almost 6 to 12. The model has the maximum RMSE values in August and September as 16.0854 and 15.0176 respectively and gives the minimum RMSE value in December as 3.8436. The Whillier model has the maximum RMSE generally, followed by Garg and Garg model. Comparison between the recorded and estimated hourly global solar radiation values from six different models of July and December are shown in Fig. 1 (a) and (b) respectively.

The MBE values are also significant to analyze the accuracy of the global solar radiation estimation models. The global solar radiation values estimated from the Whillier model are always less than the measured values, which results in negative MBE values. Garg and Garg model gives an overestimation in all months except November due to the results of positive MBE values. The maximum MBE values belong to the CPR model and Garg and Garg model generally. In Table I, MBE values indicate that the CPRG model mostly leads to the best results.

In addition, the MABE statistical method is used to analyze the accuracy of the considered models. According to Table I, the CPR model and CPRG model have minimum MABE values generally. These models have almost MABE values of between 2 and 9. Also, the MABE analysis points out that the Whillier model has maximum values mostly differ from 4 to 14.

Finally, t-statistical analysis is carried out to evaluate statistical importance of the results of the considered models. As in other statistical analysis methods, the CPRG model has minimum values generally. In addition, Table I indicates that the t-statistical analysis values of the CPR model are maximum mostly.

As a result of the statistical comparison methods, the CPRG model has the best accuracy among the considered models. Therefore, the CPRG model is strongly proposed to perform for the monthly average hourly global solar radiation estimation.

Fig. 1. Measured and estimated radiation values of the considered global solar radiation models: (a) July, (b) December.

TABLE I: THE ACCURACY OF THE CONSIDERED MODELS FOR ÇANAKKALE

Month	Statistical Analysis Method	Whillier Model	Liu and Jordan Model	CPR Model	CPRG Model	Garg and Garg Model	Gueymard Model
January	MABE	6.1121	6.0556	4.1776	4.0541	6.0908	6.0207
	MBE	-0.1795	0.0275	-0.2174	0.0290	0.1322	0.0275
	RMSE	10.9551	10.9087	7.5101	7.4488	11.0038	10.8399
	t-static	0.0786	0.0121	0.1389	0.0186	0.0576	0.0122
February	MABE	5.4500	5.3984	4.0876	4.0016	5.5343	5.3486
	MBE	-0.2584	-0.0013	-0.5444	-0.0080	0.1914	-0.0014
	RMSE	11.1414	11.0624	6.7889	6.7472	11.2018	10.9520
	t-static	0.1112	0.00055	0.3858	0.0057	0.0820	0.00064
March	MABE	6.6621	6.4658	6.7107	6.9308	6.5781	6.3891
	MBE	-0.4648	-0.1452	-1.0021	-0.0920	0.2006	-0.1442
	RMSE	11.8547	11.7401	10.5962	10.8293	12.1743	11.5870
	t-static	0.1882	0.0593	0.4556	0.0407	0.0790	0.0597
April	MABE	8.2501	8.1014	7.4250	7.4415	8.0408	7.8729
	MBE	-0.1445	0.2146	-0.7243	0.1447	0.7650	0.2133
	RMSE	12.1808	11.9560	11.3990	11.7109	11.8060	11.6810
	t-static	0.0569	0.0861	0.3053	0.0592	0.3114	0.0876
May	MABE	13.2874	13.1206	5.9283	5.9781	12.6495	12.9198
	MBE	-0.4976	-0.2068	-0.3509	-0.1436	0.4299	-0.2055
	RMSE	19.0596	18.8246	10.0743	10.0617	18.5266	18.5237
	t-static	0.1253	0.0527	0.1671	0.0685	0.1113	0.0532
June	MABE	14.6570	14.4433	8.6074	8.5273	14.1904	14.1783
	MBE	-0.0437	0.2806	0.4834	0.1898	1.0942	0.2788
	RMSE	20.0725	19.7605	12.6067	12.5790	19.6565	19.4099
	t-static	0.0104	0.0681	0.1840	0.0724	0.2674	0.0689
July	MABE	12.7056	12.5229	7.1585	7.1528	12.6514	12.3007
	MBE	-0.2677	0.0416	0.0475	0.0218	0.7848	0.0412
	RMSE	18.8364	18.5724	10.9539	10.9514	18.8780	18.2384
	t-static	0.0682	0.0107	0.0208	0.0096	0.1996	0.0108
August	MABE	10.8707	10.7565	9.8696	9.9938	10.4440	10.5734
	MBE	-0.3936	-0.0289	-0.7071	-0.0147	0.5987	-0.0286
	RMSE	15.6347	15.4472	15.8552	16.0854	15.1113	15.2134
	t-static	0.1208	0.0090	0.2141	0.0044	0.1902	0.0090
September	MABE	10.3865	10.2689	8.9781	9.4117	9.8330	10.1485
	MBE	-0.4844	-0.1144	-1.1382	-0.0793	0.3486	-0.1137
	RMSE	15.0474	14.9255	14.7003	15.0176	14.3525	14.7559
	t-static	0.1545	0.0368	0.3724	0.0253	0.1165	0.0370
October	MABE	9.9032	9.8134	7.7895	7.6590	9.5745	9.7259
	MBE	-0.1684	0.1843	-0.7206	0.1195	0.4745	0.1832
	RMSE	16.1211	16.0411	11.9678	12.0608	15.7398	15.8997
	t-static	0.0501	0.0551	0.2893	0.0475	0.1446	0.0553
November	MABE	6.5849	6.5849	6.4572	6.5165	6.5153	6.5576
	MBE	-0.4131	-0.1766	-0.4616	-0.1146	-0.0412	-0.1756
	RMSE	11.9530	11.9250	10.5433	10.5759	11.7657	11.8752
	t-static	0.1658	0.0710	0.2101	0.0520	0.0168	0.0709
December	MABE	4.1371	4.1225	2.0621	2.0696	4.1161	4.0825
	MBE	-0.0270	0.1727	-0.0501	0.1271	0.2656	0.1719
	RMSE	7.4081	7.3617	3.9011	3.8436	7.3351	7.2946
	t-static	0.0175	0.1125	0.0616	0.1587	0.1738	0.1131

V. CONCLUSION

In this study, six different models are carried out to estimate hourly global radiation averaged over the months from the daily values for Çanakkale, which is located in the northwest of Turkey. The models are evaluated based on the statistical analysis methods of MBE, MABE, RMSE and t-statistical analysis. The results indicate that the CPRG

model yields the best accuracy. Thus, this model is recommended to carry out for the coastal regions that have similar weather conditions and climate characteristics with the considered city in this study.

NOMENCLATURE

- I hourly global solar radiation on horizontal surface (W/m^2)
- H daily global solar radiation on horizontal surface (W/m^2)
- H_0 daily extraterrestrial global solar radiation on horizontal surface

	(W/m ²)
I/H	the ratio of hourly to daily global solar radiation on horizontal surface (without any unit)
W	solar hour angle (degree)
W _s	sunset hour angle (degree)
W _o	sunrise hour angle (degree)
I _{sc}	solar constant (W/m ²)
a	intermediate variable (without any unit)
b	intermediate variable (without any unit)
h	solar altitude angle (degree)
h _o	daily average solar elevation outside of the atmosphere (degree)
δ	solar declination angle (degree)
φ	latitude (degree)
S _o	day length (h)
R	monthly mean sun-earth distance correction factor (without any unit)
K _t	daily clearness index (without any unit)

ACKNOWLEDGMENT

The authors would like to thank the Turkish State Meteorological Service, Turkey for providing the measured global radiation data of the considered region for this study. This work is funded by Anadolu University Scientific Research Projects with project number: 1505F512/1604F170.

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