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Preliminary communication

Establishing New Regression Equations for Obtaining the Diffuse Solar Radiation in Sakarya (Turkey)

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Abstract: In this paper diffuse solar radiation component is investigated for Sakarya city (Turkey). For this purpose, 17 diffuse solar radiation equations correlating the diffuse fraction with the clearness index and/or the sunshine fraction are selected from the literature. The predictions obtained from the selected equations are utilized to determine the regression constants of the new equations. In conclusion, the best equation for the city is introduced by performing statistical analysis.

Keywords: clearness index; diffuse fraction; diffuse solar radiation equations; statistical analysis; sunshine fraction

1 INTRODUCTION

The latest energy report indicates that Turkey is heavily dependent on imported fossil fuels for meeting its rising energy demands [1, 2]. Thus it is vital to break this dependency for providing a sustainable growth. At this point, solar energy becomes prominent among all the alternative energy sources due to the favourable geographical location of the country.

The accuracy of the solar data measurements is vital in designing and analysing solar energy systems [3]. Today global solar radiation for a specific location is easily recorded in many countries. However diffuse solar radiation measurement is available in only few countries. Diffuse solar radiation data is required for determining the amount of the total solar radiation on an inclined surface which provides information about the system performance [4]. Therefore it is necessary to develop mathematical equations based on meteorological data for estimating the diffuse component. Liu and Jordan developed the first diffuse solar radiation equation defining the diffuse fraction in terms of the clearness index [5]. Then several researchers have developed empirical equations based on this equation [6-31]. In these equations the solar diffuse fraction and/or the solar diffuse coefficient are introduced in terms of the clearness index [7-9], the sunshine fraction [10-14] and both [15-19]. Al-Mohammad calculated solar-radiation components starting from the simple Angström formula [21]. El-Sebaii et al. used the clearness index, the sunshine fraction, the ambient temperature, the cloud cover and the relative humidity as input data in their equation [23]. They divided the input data into two parts. The first part, the data between 1996 and 2004, is used to develop the equation while the second part, the data between 2005 and 2007, is used to evaluate the results of the proposed equations. Elminir et al. utilized artificial neural network (ANN) technique in their work to estimate the diffuse component [24]. They observed that the equations by ANN technique give better results compared to the equations by regression analysis technique.

The solar radiation measurement stations in Turkey are all capable of measuring the global component. But only few of them measure the diffuse component at present. Therefore, many Turkish researchers have developed several equations for investigating the diffuse solar radiation for specific locations of Turkey based on the available solar data [26-31]. Aras et al. established twelve new empirical equations from twenty current equations to determine the best diffuse fraction equation for Turkey's Central Anatolia Region [26]. Tarhan and Sarı analysed solar radiation data over the five provinces of the Central Black Sea Region of Turkey [27]. They developed two new equations: a cubic polynomial equation and a quadratic polynomial equation. They observed that the new equations give good accuracy for the region. Ulgen and Hepbasli established eight new equations for predicting the diffuse component for three big cities of Turkey [28]. Tırıs et al. used measured meteorological data to develop new empirical equations for correlating the solar radiation components for Gebze city, Turkey [29]. Bakırcı analysed the measured solar data for the eight provinces of Turkey to establish new empirical diffuse solar radiation equations [30]. He used fifteen current equations from the open literature and meteorological data of the provinces to develop these equations. By performing statistical analysis he observed that the proposed equations agree with the obtained average values of the selected fifteen equations. Ulgen and Hepbasli recorded the diffuse solar radiation from 1994 to 1998 for İzmir city, Turkey [31]. They observed that the predictions of their new equations fit the measured data better than the current equations.

In this paper available measured solar radiation data and the current diffuse solar radiation equations are analysed to express the diffuse fraction for Sakarya city. Nine new diffuse solar equations by the clearness index and/or the sunshine fraction are developed respectively. In conclusion the estimates of all the equations are compared statistically and the most accurate equation of all is established.

2 REVIEWING CURRENT DIFFUSE SOLAR RADIATION EQUATIONS

In this section the current equations based on the clearness index and/or the sunshine fraction are examined. The clearness index is the global solar radiation (H) divided by the extra-terrestrial solar radiation (H_0), the sunshine fraction is the hours of sunshine (S) divided by the maximum hours of sunshine (S_0) and the diffuse fraction is the diffuse solar radiation (H_d) divided by the global solar radiation (H). Seventeen of the commonly adapted equations from the literature are as follows:

i) Equations expressing (H_d/H) in terms of (S/S_0):

Eq. (1) [14]:

$$\frac{H_d}{H} = 0.6603 - 0.5272 \times \left(\frac{S}{S_0}\right) \quad (1)$$

Eq. (2) [26]:

$$\frac{H_d}{H} = 0.663 - 0.4883 \times \left(\frac{S}{S_0}\right) \quad (2)$$

Eq. (3) [10]:

$$\frac{H_d}{H} = 0.791 - 0.635 \times \left(\frac{S}{S_0}\right) \quad (3)$$

Eq. (4) [14]:

$$\frac{H_d}{H} = 0.7434 - 0.8203 \times \left(\frac{S}{S_0}\right) + 0.2454 \times \left(\frac{S}{S_0}\right)^2 \quad (4)$$

Eq. (5) [26]:

$$\frac{H_d}{H} = 0.6492 - 0.4323 \times \left(\frac{S}{S_0}\right) - 0.0512 \times \left(\frac{S}{S_0}\right)^2 \quad (5)$$

Eq. (6) [26]:

$$\frac{H_d}{H} = 0.5562 + 0.1536 \times \left(\frac{S}{S_0}\right) - 1.2027 \times \left(\frac{S}{S_0}\right)^2 + 0.7122 \times \left(\frac{S}{S_0}\right)^3 \quad (6)$$

ii) Equations expressing (H_d/H) in terms of (H/H_0):

Eq. (7) [7]:

$$\frac{H_d}{H} = 1.00 - 1.13 \times \left(\frac{H}{H_0}\right) \quad (7)$$

Eq. (8) [26]:

$$\frac{H_d}{H} = 1.0212 - 1.1672 \times \left(\frac{H}{H_0}\right) \quad (8)$$

Eq. (9) [28]:

$$\frac{H_d}{H} = 0.6772 - 0.4841 \times \left(\frac{H}{H_0}\right) \quad (9)$$

Eq. (10) [26]:

$$\frac{H_d}{H} = 1.1244 - 1.5582 \times \left(\frac{H}{H_0}\right) + 0.3635 \times \left(\frac{H}{H_0}\right)^2 \quad (10)$$

Eq. (11) [27]:

$$\frac{H_d}{H} = 0.9885 - 1.4276 \times \left(\frac{H}{H_0}\right) + 0.5679 \times \left(\frac{H}{H_0}\right)^2 \quad (11)$$

Eq. (12) [27]:

$$\frac{H_d}{H} = 1.027 - 1.6582 \times \left(\frac{H}{H_0}\right) + 1.1018 \times \left(\frac{H}{H_0}\right)^2 - 0.4019 \times \left(\frac{H}{H_0}\right)^3 \quad (12)$$

iii) Equations expressing (H_d/H) in terms of (H/H_0) and (S/S_0):

Eq. (13) [16]:

$$\frac{H_d}{H} = 1.194 - 0.838 \times \left(\frac{H}{H_0}\right) - 0.446 \times \left(\frac{S}{S_0}\right) \quad (13)$$

Eq. (14) [17]:

$$\frac{H_d}{H} = 1.00 - 0.858 \times \left(\frac{H}{H_0}\right) - 0.235 \times \left(\frac{S}{S_0}\right) \quad (14)$$

Eq. (15) [15]:

$$\frac{H_d}{H} = 0.945 - 0.675 \times \left(\frac{H}{H_0}\right) - 0.166 \times \left(\frac{H}{H_0}\right)^2 - 0.173 \times \left(\frac{S}{S_0}\right) - 0.079 \times \left(\frac{S}{S_0}\right)^2 \quad (15)$$

Eq. (16) [15]:

$$\frac{H_d}{H} = 0.747 - 1.502 \times \left(\frac{H}{H_0}\right) - 4.956 \times \left(\frac{H}{H_0}\right)^2 + 0.173 \times \left(\frac{H}{H_0}\right)^3 - 1.004 \times \left(\frac{S}{S_0}\right) + 1.747 \times \left(\frac{S}{S_0}\right)^2 - 1.226 \times \left(\frac{S}{S_0}\right)^3 \quad (16)$$

Eq. (17) [18]:

$$\frac{H_d}{H} = 0.9593 - 0.8713 \times \left(\frac{H}{H_0}\right) + 0.29191 \times \left(\frac{H}{H_0}\right)^2 - 0.0979 \times \left(\frac{H}{H_0}\right)^3 - 0.28419 \times \left(\frac{S}{S_0}\right) + 0.02653 \times \left(\frac{S}{S_0}\right)^2 - 0.02083 \times \left(\frac{S}{S_0}\right)^3 \quad (17)$$

3 DATA AND METHODOLOGY

The global solar radiation (H) and hours of sunshine (S) are obtained from the solar energy potential atlas by Turkey Renewable Energy Head Office (Tab. 1).

The extra-terrestrial solar radiation (H_0) and maximum possible hours of sunshine (S_0) are calculated from mathematical expressions respectively [32-34]:

$$H_0 = \frac{24 \times 3600}{\pi} \times G_{sc} \times \left(1 + 0.33 \times \cos\frac{360 \times n_{day}}{365}\right) \times \times \left(\cos\phi \times \cos\delta \times \sin w_s + \frac{\pi \times w_s}{180} \times \sin\phi \times \sin\delta\right) \quad (18)$$

$$S = \frac{2}{15} \times w_s \quad (19)$$

where G_{sc} is the solar constant (equals 1367 W/m^2), n_{day} is the number of the day of the year and ϕ is the latitude. δ is solar declination and w_s is the sunrise hour angle for horizontal surface defined as:

$$\delta = 23.45 \times \sin\left(\frac{n_{day} + 284}{365} \times 360\right) \quad (20)$$

$$w_s = \cos^{-1}(-\tan\varphi \times \tan\delta) \quad (21)$$

The diffuse solar radiation is obtained by averaging the results of the selected equations for the city. Then the following equations are utilized to develop new diffuse solar equations fitting all the data obtained:

i) Equations expressing (H_d/H) in terms of (S/S_0):

$$\frac{H_d}{H} = c_0 + c_1 \times \left(\frac{S}{S_0}\right) + c_2 \times \left(\frac{S}{S_0}\right)^2 + c_3 \times \left(\frac{S}{S_0}\right)^3 \quad (22)$$

ii) Equations expressing (H_d/H) in terms of (H/H_0):

$$\frac{H_d}{H} = c_0 + c_1 \times \left(\frac{H}{H_0}\right) + c_2 \times \left(\frac{H}{H_0}\right)^2 + c_3 \times \left(\frac{H}{H_0}\right)^3 \quad (23)$$

iii) Equations expressing (H_d/H) in terms of (H/H_0) and (S/S_0):

$$\frac{H_d}{H} = c_0 + c_1 \times \left(\frac{H}{H_0}\right) + c_2 \times \left(\frac{H}{H_0}\right)^2 + c_3 \times \left(\frac{H}{H_0}\right)^3 + c_4 \times \left(\frac{S}{S_0}\right) + c_5 \times \left(\frac{S}{S_0}\right)^2 + c_6 \times \left(\frac{S}{S_0}\right)^3 \quad (24)$$

where c_0, c_1, c_2, c_3, c_4, c_5 and c_6 express the regression constants determined by the regression analysis technique [35].

Finally, the accuracy of all equations including the selected equations from the literature is evaluated using the statistical indicators below:

Mean bias error:

$$MBE = \frac{1}{x}\sum_{i=1}^{x}(EV_i - MV_i) \quad (25)$$

Mean absolute percentage error:

$$MAPE = \frac{1}{x}\sum_{i=1}^{x}\left|\frac{EV_i - MV_i}{MV_i}\right| \quad (26)$$

Mean absolute bias error:

$$MABE = \frac{1}{x}\sum_{i=1}^{x}\left|EV_i - MV_i\right| \quad (27)$$

Root mean square error:

$$RMSE = \sqrt{\frac{1}{x}\sum_{i=1}^{x}(EV_i - MV_i)^2} \quad (28)$$

Coefficient of determination:

$$R^2 = \frac{\sum_{i=1}^{x}(EV_i - EV_a)\cdot(MV_i - MV_a)}{\sqrt{\left[\sum_{i=1}^{x}(EV_i - EV_a)^2\right]\cdot\left[\sum_{i=1}^{x}(MV_i - MV_a)^2\right]}} \quad (29)$$

t-statistics:

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

where x is the sample size, $n - 1$ is the degrees of freedom, EV_i is the i^{th} estimated value, MV_i is the i^{th} measured value, EV_a is the average of the estimated values, MV_a is the average of the measured values. All the indicators except the R^2 take small values around "zero" while the absolute R^2 takes values around "1" in suitable equations. Here the t is used additionally to overcome the inadequacy of the separate utilization of the *MBE* and *RMSE* [36]. It is better to select the equations with smaller t values when the equations give similar results for *MBE* and *RMSE*.

4 RESULTS AND DISCUSSIONS

Based on the data in section 3, the regression coefficients in Eqs. (22), (23) and (24) are obtained by performing the regression analysis technique:

i) Equations expressing (H_d/H) in terms of (S/S_0) :

$$\frac{H_d}{H} = 0.7490 - 0.5512 \times \left(\frac{S}{S_0}\right) \quad (31)$$

$$\frac{H_d}{H} = 0.9795 - 1.4843 \times \left(\frac{S}{S_0}\right) + 0.8848 \times \left(\frac{S}{S_0}\right)^2 \quad (32)$$

$$\frac{H_d}{H} = 0.9903 - 1.5515 \times \left(\frac{S}{S_0}\right) + 1.0193 \times \left(\frac{S}{S_0}\right)^2 - 0.0867 \times \left(\frac{S}{S_0}\right)^3 \quad (33)$$

ii) Equations expressing (H_d/H) in terms of (H/H_0):

$$\frac{H_d}{H} = 0.9576 - 1.0956 \times \left(\frac{H}{H_0}\right) \tag{34}$$

$$\frac{H_d}{H} = 0.4676 + 1.2232 \times \left(\frac{H}{H_0}\right) - 2.6735 \times \left(\frac{H}{H_0}\right)^2 \tag{35}$$

$$\frac{H_d}{H} = 2.7357 - 14.7572 \times \left(\frac{H}{H_0}\right) + 34.9699 \times \left(\frac{H}{H_0}\right)^2 - 29.1629 \times \left(\frac{H}{H_0}\right)^3 \tag{36}$$

iii) Equations expressing (H_d/H) in terms of (H/H_0) and (S/S_0):

$$\frac{H_d}{H} = 0.8695 - 0.5887 \times \left(\frac{H}{H_0}\right) - 0.2711 \times \left(\frac{S}{S_0}\right) \tag{37}$$

$$\frac{H_d}{H} = 0.8782 - 0.6422 \times \left(\frac{H}{H_0}\right) + 0.0638 \times \left(\frac{H}{H_0}\right)^2 - 0.2611 \times \left(\frac{S}{S_0}\right) - 0.0107 \times \left(\frac{S}{S_0}\right)^2 \tag{38}$$

$$\frac{H_d}{H} = 0.8675 - 0.5392 \times \left(\frac{H}{H_0}\right) - 0.1645 \times \left(\frac{H}{H_0}\right)^2 + 0.1660 \times \left(\frac{H}{H_0}\right)^3 - 0.2877 \times \left(\frac{S}{S_0}\right) + 0.0404 \times \left(\frac{S}{S_0}\right)^2 - 0.0314 \times \left(\frac{S}{S_0}\right)^3 \tag{39}$$

Table 1 Monthly mean daily global solar radiation H (MJ/m^2), hours of sunshine S (h) of Sakarya

Months	January	February	March	April	May	June	July	August	September	October	November	December
H	5.112	8.244	11.808	15.876	20.304	21.636	21.024	18.972	15.0840	10.296	6.0840	4.428
S	3.20	4.23	5.01	6.33	8.39	9.72	10.35	9.56	8.01	5.53	4.05	3.09

Table 2 The MBE (MJ/m^2), $MAPE$ (%), $MABE$ (MJ/m^2), $RMSE$ (MJ/m^2), R^2 and t-$stat$ values for the current equations (1)-(17) and the equations developed in this paper (31)-(39)

Type	Equation	*MBE*	*MAPE*	*MABE*	*RMSE*	R^2	*t*
(H_d/H) in terms of (S/S_0)	1	−0.9713	16.7586	0.9713	1.0716	0.9907	7.1178
	2	−0.6396	11.5043	0.6396	0.6884	0.9965	8.3282
	3	−0.0613	3.4770	0.2275	0.2950	0.9901	0.7051
	4	−0.9814	16.6174	0.9814	1.0969	0.9900	6.6438
	5	−0.6298	11.3663	0.6298	0.6786	0.9963	8.2689
	6	−0.6418	11.4520	0.6418	0.7011	0.9952	7.5422
	31	**0.0206**	**2.5827**	**0.1485**	**0.1775**	**0.9966**	**0.3875**
	32	**0.0100**	**0.9857**	**0.0482**	**0.0607**	**0.9996**	**0.5535**
	33	**0.0100**	**0.9869**	**0.0484**	**0.0606**	**0.9996**	**0.5566**
(H_d/H) in terms of (H/H_0)	7	−0.3148	8.9304	0.4126	0.4774	0.9891	0.5670
	8	0.3898	6.8668	0.3898	0.4617	0.9958	5.2239
	9	0.1833	8.4575	0.4835	0.5841	0.9877	1.0958
	10	0.3932	7.2325	0.3932	0.4519	0.9961	5.8605
	11	0.0583	3.4886	0.2207	0.2856	0.9932	0.6916
	12	0.1421	3.4155	0.2330	0.3371	0.9930	1.5418
	34	**0.0041**	**2.4750**	**0.1524**	**0.1864**	**0.9959**	**0.0735**
	35	**−0.0045**	**1.3636**	**0.0891**	**0.1321**	**0.9979**	**0.1135**
	36	**−0.0048**	**1.2446**	**0.0822**	**0.1219**	**0.9982**	**0.1299**
(H_d/H) in terms of (H/H_0) and (S/S_0)	13	1.3787	25.4757	1.3787	1.4283	0.9975	12.2616
	14	0.2887	5.6872	0.2887	0.2924	0.9999	20.8053
	15	0.3224	6.2411	0.3224	0.3288	0.9997	16.6045
	16	0.3161	6.1584	0.3161	0.3226	0.9997	16.2640
	17	0.1081	2.1864	0.1081	0.1098	1.0000	18.6761
	37	**−0.0001**	**0.0247**	**0.0016**	**0.0022**	**1.0000**	**0.1243**
	38	**0.0000**	**0.0047**	**0.0003**	**0.0003**	**1.0000**	**0.0821**
	39	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**1.0000**	**0.6095**

The performance of these new equations (31)-(39): they are all compared with the performance of the seventeen equations selected from the literature (1)-(17) by means of different statistical indicators presented in Tab. 1. The results indicate that the performance of the new equations developed in this paper is better than the performance of the existing equations. However the equations expressing (H_d/H) in terms of (H/H_0) and (S/S_0) give the best results among all. The *t-stat* is used as the determining indicator between these equations since the other indicators are almost the same. Thus, it is determined that the Eq. (38) is the most accurate equation for Sakarya city.

5 CONCLUSION

Solar energy potential in Turkey is adequate to meet all the energy demand of the country. For utilizing this potential efficiently, it is essential to obtain accurate solar data. Unfortunately, it is not possible for most of the cities in Turkey, since only few stations are able to make diffuse solar radiation measurements. To overcome this matter, researchers have proposed mathematical equations for obtaining proper estimates for the diffuse component for some cities. However, there is no measured or predicted diffuse solar radiation data for Sakarya city.

In this paper, new diffuse solar radiation equations are developed for the city by utilizing the current studies from the literature. Based on statistical analysis, the Eq. (38) is introduced as the most accurate equation for the city:

$$\frac{H_{\mathrm{d}}}{H} = 0.8782 - 0.6422 \times \left(\frac{H}{H_0}\right) + 0.0638 \times \left(\frac{H}{H_0}\right)^2 - 0.2611 \times \left(\frac{S}{S_0}\right) - 0.0107 \times \left(\frac{S}{S_0}\right)^2 \tag{38}$$

From this result, it can be concluded that both the clearness index and the sunshine fraction are required for estimating the diffuse solar radiation accurately for Sakarya city and the other cities with the same latitude and meteorological conditions in the world.

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