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Establishing New Diffuse Solar Radiation Equations for Antalya, Turkey

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Abstract

In this paper new diffuse solar radiation equations were established for Antalya, Turkey. For this purpose current equations from the literature which were functions of the clearness index and/or the sunshine fraction were examined. 9 equations were selected to determine the regression constants of the new equations. In conclusion the best equation among the new equations was introduced on the basis of different statistical indicators.
Key words: Diffuse solar radiation, regression constant, clearness index, sunshine fraction

1. Introduction

Turkey has become prominent as a fast growing country in recent years. Sustainability of this growth is doubtful since the country is heavily dependent on imported fossil fuels for meeting its rising energy demands [1]. The key to break this dependency is to increase the share of renewable energy sources of the country in power generation.

Solar energy potential of Turkey was recorded to be enormous with the annual average solar radiation of 3.6 kW h/m^2 day and the total yearly solar radiation period of 2640 h [2]. Antalya makes the most significant contribution to this enormous potential as one of the sunniest cities of the country with the annual average global solar radiation of 3.93 kWh/m^2 and the annual average sunshine hours of 8.25 h [3].

The efficiency of solar energy systems is directly related to the total solar radiation received on the PV module surface. Therefore it is important to consider this parameter when determining the inclination angle of PV modules [4]. Today the global solar radiation is easily measured almost all over the world. However the diffuse solar radiation which is required to calculate the total solar radiation is available for very few locations.

In this paper the monthly average diffuse solar radiation estimation was carried out for Antalya city, Turkey. For this purpose new diffuse solar radiation equations were developed using the current selected equations from the literature. In this regard the clearness index and sunshine fraction were used to define the diffuse fraction. In conclusion the best equation for the city was established on the basis of different statistical indicators.

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2. Materials and Method

In this paper new diffuse solar radiation equations were developed using the current equations which correlated the diffuse fraction with the clearness index and/or sunshine fraction. The current equations were evaluated in three groups (Table 1). Here the clearness index is the global solar radiation (H) divided by the extraterrestrial solar radiation (H_0), the sunshine fraction is sunshine hours (S) divided by the maximum sunshine hours (S_0) and the diffuse fraction is the diffuse solar radiation (H_d) divided by the global solar radiation (H).

Table 1. Current diffuse solar radiation equations selected from the literature

Group 1: the diffuse fraction (H_d/H) correlated with the clearness index (H/H_0)	
1. $\frac{H_d}{H} = 1.00 - 1.13 \times \left(\frac{H}{H_0}\right)$	[5]
2. $\frac{H_d}{H} = 1.1244 - 1.5582 \times \left(\frac{H}{H_0}\right) + 0.3635 \left(\frac{H}{H_0}\right)^2$	[6]
3. $\frac{H_d}{H} = 1.027 - 1.6582 \times \left(\frac{H}{H_0}\right) + 1.1018 \times \left(\frac{H}{H_0}\right)^2 - 0.4019 \times \left(\frac{H}{H_0}\right)^3$	[7]
Group 2: the diffuse fraction (H_d/H) correlated with the sunshine fraction (S/S_0)	
4. $\frac{H_d}{H} = 0.791 - 0.635 \times \left(\frac{S}{S_0}\right)$	[8]
5. $\frac{H_d}{H} = 0.7434 - 0.8203 \times \left(\frac{S}{S_0}\right) + 0.2454 \times \left(\frac{S}{S_0}\right)^2$	[9]
6. $\frac{H_d}{H} = 0.5562 + 0.1536 \times \left(\frac{S}{S_0}\right) - 1.2027 \times \left(\frac{S}{S_0}\right)^2 + 0.7122 \times \left(\frac{S}{S_0}\right)^3$	[6]
Group 3: the diffuse fraction (H_d/H) correlated with the clearness index (H/H_0) and the sunshine fraction (S/S_0)	
7. $\frac{H_d}{H} = 1.00 - 0.858 \times \left(\frac{H}{H_0}\right) - 0.235 \times \left(\frac{S}{S_0}\right)$	[10]
8. $\frac{H_d}{H} = 0.945 - 0.675 \times \left(\frac{H}{H_0}\right) - 0.166 \times \left(\frac{H}{H_0}\right)^2 - 0.173 \times \left(\frac{S}{S_0}\right) - 0.079 \times \left(\frac{S}{S_0}\right)^2$	[11]

Table 1. (cont.)

9.	$\frac{H_d}{H} = 0.9593 - 0.8713 \times \left(\frac{H}{H_0}\right) + 0.29191 \times \left(\frac{H}{H_0}\right)^2 - 0.0979 \times \left(\frac{H}{H_0}\right)^3$ $-0.28419 \times \left(\frac{S}{S_0}\right) + 0.02653 \times \left(\frac{S}{S_0}\right)^2 - 0.02083 \times \left(\frac{S}{S_0}\right)^3$	[12]

The global solar radiation (*H*) and sunshine hours (*S*) were obtained from the solar energy potential atlas by Turkey Renewable Energy Head Office. The extraterrestrial solar radiation (H_0) and maximum possible sunshine hours (S_0) were calculated from mathematical expressions below [13-15]:

$$H_0 = \frac{24 \times 3600}{\pi} \times G_0 \quad (10)$$

$$S_0 = \frac{2}{15} \times w_s \quad (11)$$

where G_0 and w_s are the corrected solar constant and the sunrise hour angle for horizontal surface respectively.

Measured monthly average data of *H* and *S* and calculated monthly average data of H_0 and S_0 were used in the equations presented in Table 1 to predict the monthly average diffuse solar radiation. Then the regression coefficients for Equations (12)-(14) were determined by using the predicted data of diffuse solar radiation.

$$\frac{H_d}{H} = c_0 + c_1 \times \left(\frac{H}{H_0}\right) + c_2 \times \left(\frac{H}{H_0}\right)^2 + c_3 \times \left(\frac{H}{H_0}\right)^3 \quad (12)$$

$$\frac{H_d}{H} = c_0 + c_1 \times \left(\frac{S}{S_0}\right) + c_2 \times \left(\frac{S}{S_0}\right)^2 + c_3 \times \left(\frac{S}{S_0}\right)^3 \quad (13)$$

$$\frac{H_d}{H} = c_0 + c_1 \times \left(\frac{H}{H_0}\right) + c_2 \times \left(\frac{H}{H_0}\right)^2 + c_3 \times \left(\frac{H}{H_0}\right)^3 + c_4 \times \left(\frac{S}{S_0}\right) + c_5 \times \left(\frac{S}{S_0}\right)^2 + c_6 \times \left(\frac{S}{S_0}\right)^3 \quad (14)$$

In conclusion the performance of the new equations were evaluated in terms of the statistical indicators below:

Mean bias error:

$$MBE = \frac{1}{x} \sum_{i=1}^{x} (EV_i - MV_i) \quad (15)$$

Mean absolute percentage error:

$$MAPE=\frac{1}{x}\sum_{i=1}^{x}\left|\frac{EV_i-MV_i}{MV_i}\right| \quad (16)$$

Mean absolute bias error:

$$MABE=\frac{1}{x}\sum_{i=1}^{x}\left|EV_i-MV_i\right| \quad (17)$$

Root mean square error:

$$RMSE=\sqrt{\frac{1}{x}\sum_{i=1}^{x}(EV_i-MV_i)^2} \quad (18)$$

Coefficient of determination:

$$R^2=\frac{\sum_{i=1}^{x}\left(EV_i-EV_a\right)\cdot\left(MV_i-MV_a\right)}{\sqrt{\left[\sum_{i=1}^{x}\left(EV_i-EV_a\right)^2\right]\left[\sum_{i=1}^{x}\left(MV_i-MV_a\right)^2\right]}} \quad (19)$$

t-statistics:

$$t=\sqrt{\frac{(n-1)MBE^2}{RMSE^2-MBE^2}} \quad (20)$$

where EV_i and MV_i express the i^{th} and EV_a and MV_a express the average of the estimated and measured values, respectively.

3. Results

3.1. Regression coefficients of the new diffuse solar radiation equations

Regression coefficients of the new equations obtained from Equation (12)-(14) are as follows:

Table 2. Regression coefficients of the new equations

Coefficients from Equation 12							
Equation	c_0	c_1	c_2	c_3	c_4	c_5	c_6
15.	0,932	-1.045	0	0	0	0	0
16.	-0.062	2.873	-3.789	0	0	0	0
17.	0.241	1.086	-0.313	-2.236	0	0	0
Coefficients from Equation 13							
Equation	c_0	c_1	c_2	c_3	c_4	c_5	c_6

Table 2. (cont.)

18.	0.746	-0.564	0	0	0	0	0
19.	1.091	-1.623	0.7889	0	0	0	0
20.	-1.339	9.922	-17.123	9.079	0	0	0
Coefficients from Equation 14							
Equation	c_0	c_1	c_2	c_3	c_4	c_5	c_6
21.	0.879	-0.626	-0.259	0	0	0	0
22.	0.912	-0.683	0.0660	-0.316	0.038	0	0
23.	0.905	-0.750	0.177	-0.056	-0.222	-0.112	0.077

3.2. Statistical test results of the new diffuse solar radiation equations

Statistical test results of the new equations with regression coefficients in Table 2 are as follows:

Table 3. Statistical test results of the new equations

Equation	*MBE* (MJ/m^2)	*MABE* (MJ/m^2)	*MAPE* (MJ/m^2)	*RMSE* (MJ/m^2)	R^2	*t*
15	0.0193	0.2133	3.6143	0.2524	0.9873	0.2548
16	0.0122	0.1318	2.4375	0.1706	0.9942	0.2386
17	0.0126	0.1314	2.4363	0.1701	0.9943	0.2467
18	0.0271	0.2322	4.0052	0.2912	0.9850	0.3098
19	0.0183	0.1448	2.8047	0.1841	0.9937	0.3305
20	0.0111	0.1467	2.5454	0.1871	0.9929	0.1971
21	0.0001	0.0048	0.0937	0.0056	1.0000	0.0852
22	0.0000	0.0008	0.0125	0.0009	1.0000	0.0444
23	0.0000	0.0000	0.0000	0.0000	1.0000	0.0830

Table 3 indicates that Equation 22 gave the best statistical results for the related indicators.

3.3. Monthly average daily diffuse solar radiation by Equation 22

Monthly average daily diffuse solar radiation by Equation 22 is as follows:

Table 4. Monthly average daily diffuse solar radiation by Equation 22

Month	H_d [kWh/m^2]
January	0.9942
February	1.1975

Table 4. (cont.)

March	1.6432
April	1.9894
May	2.1506
June	2.0511
July	1.9528
August	1.7477
September	1.5183
October	1.2868
November	1.0336
December	0.9192

4. Discussion

Table 2 indicates the regression coefficients of the new diffuse solar radiation equations developed for Antalya, Turkey. Table 3 indicates the statistical test results of these new equations by means of *MBE, MABE, MAPE, RMSE,* R^2 and *t-statistics*. According to the table, Equation (21)-(23) where the diffuse fraction (H_d/H) was correlated with the clearness index (H/H_0) and the sunshine fraction (S/S_0) gave the best results among all. Here *t-statistics* values of these equations came to the front as the determining indicator since the values of other indicators were observed to be almost equal. Thus Equation 22 was introduced to be the most appropriate equation for the city with a very small *t-statistics* value.

Table 4 indicates the monthly average daily diffuse solar radiation values which were calculated by using Equation 22. Since the measured data is unavailable, these values can be used in further studies to calculate the monthly average daily total solar radiation, optimum tilt angles and many parameters related to the radiation received on the surface of PV modules.
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Conclusions

In this paper nine new diffuse solar radiation equations were developed for Antalya, Turkey. The predicted results of the selected current equations were used as measured diffuse solar radiation values since there was no available data. The performance of the equations were evaluated by statistical indicators *MBE, MABE, MAPE, RMSE,* R^2 and *t-statistics.* In conclusion Equation 22, the quadratic function of the clearness index and the sunshine fraction, was selected to be the most accurate equation.

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