

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. Nine (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/m² day and the total yearly solar radiation period of 2,640 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/m² 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.

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).

The global solar radiation (H) and sunshine hours (S) were obtained from the solar energy potential atlas

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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. $\frac{H_d}{H} = 1.1244 - 1.5582 \times \left(\frac{H}{H_0}\right) + 0.3635 \times \left(\frac{H}{H_0}\right)^2$	[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. $\frac{H_d}{H} = 0.791 - 0.635 \times \left(\frac{S}{S_0}\right)$	(Iqbal 1979) [8]
5. $\frac{H_d}{H} = 0.7434 - 0.8203 \times \left(\frac{S}{S_0}\right) + 0.2454 \times \left(\frac{S}{S_0}\right)^2$	(Barbaro et al. 1981) [9]
6. $\frac{H_d}{H} = 0.5562 + 0.1536 \times \left(\frac{S}{S_0}\right) - 1.2027 \times \left(\frac{S}{S_0}\right)^2 + 0.7122 \times \left(\frac{S}{S_0}\right)^3$	(Aras et al. 2006) [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. $\frac{H_d}{H} = 1.00 - 0.858 \times \left(\frac{H}{H_0}\right) - 0.235 \times \left(\frac{S}{S_0}\right)$	(Erbs et al. 1982) [10]
8. $\frac{H_d}{H} = 0.945 - 0.675 \times \left(\frac{H}{H_0}\right) - 0.166 \times \left(\frac{H}{H_0}\right)^2 - 0.173 \times \left(\frac{S}{S_0}\right) - 0.079 \times \left(\frac{S}{S_0}\right)^2$	(Jiang 2009) [11]
9. $\frac{H_d}{H} = 0.9593 - 0.8713 \times \left(\frac{H}{H_0}\right) + 0.29191 \times \left(\frac{H}{H_0}\right)^2 - 0.0979 \times \left(\frac{H}{H_0}\right)^3 - 0.28419 \times \left(\frac{S}{S_0}\right) + 0.02653 \times \left(\frac{S}{S_0}\right)^2 - 0.02083 \times \left(\frac{S}{S_0}\right)^3$	(Khorasanizadeh et al. 2014) [12]

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]:

$$H_0 = \frac{24 \times 3600}{\pi} \times G_0 \tag{10}$$

$$S_0 = \frac{2}{15} \times w_s \tag{11}$$

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 Eqs. (12)-(14) were determined by using the predicted data of diffuse solar radiation.

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

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

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

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

Mean bias error:

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

Mean absolute percentage error:

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

Mean absolute bias error:

$$MABE = \frac{1}{x} \sum_{i=1}^x |EV_i - MV_i| \tag{17}$$

Root mean square error:

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

Coefficient of determination:

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

t-statistics:

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

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 Eq. (12)-(14) are shown in Table 2.

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 shown in Table 3.

Table 3 indicates that Eq. (22) gave the best statistical results for the related indicators.

3.3 Monthly Average Daily Diffuse Solar Radiation by Eq. (22)

Monthly average daily diffuse solar radiation by Eq. (22) is shown in Table 4.

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

Table 2 Regression coefficients of the new equations.

Coefficients from Eq. (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 Eq. (13)							
Equation	c_0	c_1	c_2	c_3	c_4	c_5	c_6
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 Eq. (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

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	<i>t</i>
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 4 Monthly average daily diffuse solar radiation by Eq. (22).

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

results of these new equations by means of MBE, MABE, MAPE, RMSE, R² and *t*-statistics. According to the table, Eqs. (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 Eq. (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 Eq. (22). Since the measured data are 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.

5. 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 were no available data. The performance of the equations was evaluated by statistical indicators MBE, MABE, MAPE, RMSE, R² and *t*-statistics. In conclusion Eq. (22), the quadratic function of the clearness index and the sunshine fraction, was selected to be the most accurate equation.

References

- [1] World Energy Council Turkish National Committee; Energy Report 2013. 2014.
- [2] Evrendilek, F., and Ertekin, C. 2003. "Assessing the Potential of Renewable Energy Sources in Turkey." *Renewable Energy* 28: 2303–15
- [3] <http://www.yegm.gov.tr>.
- [4] Aksoy Tirmikçi, C., and Yavuz C. 2018. "Determining Optimum Tilt Angles of Solar Surfaces in Sakarya, Turkey." *Theor Appl Climatol* 133: 15–22.
- [5] Page, J. K. 1961. "The Estimation of Monthly Mean Values of Daily Total Short Wave Radiation on Vertical and Inclined Surface from Sunshine Records for Latitudes 40N–40S." *Proceedings of UN Conference on New Sources of Energy* 4 (598): 378-90.
- [6] Aras, H., Ballı, O., and Hepbaslı, A. 2006. "Estimating the Horizontal Diffuse Solar Radiation over the Central Anatolia Region of Turkey." *Energy Convers Manage* 47: 2240–9.
- [7] Tarhan, S., and Sari, A. 2005. "Model Selection for Global and Diffuse Radiation over the Central Black Sea (CBS) Region of Turkey." *Energy Convers Manage* 46 (4): 605–13.

- [8] Iqbal, M. 1979. "Correlation of Average Diffuse and Beam Radiation with Hours of Bright Sunshine." *Solar Energy* 23 (2): 169-73.
- [9] Barbaro, S., Cannata, G., Coppolino, S., Leone, C., and Sinagra, E. 1981. "Diffuse Solar Radiation Statistics for Italy." *Solar Energy* 26: 429-35.
- [10] Erbs, D. G., Klein, S. A., and Duffie, J. A. 1982. "Estimation of the Diffuse Radiation Fraction for Hourly, Daily and Monthly Average Global Radiation." *Solar Energy* 28: 293-302.
- [11] Jiang, Y. 2009. "Estimation of Monthly Mean Daily Diffuse Radiation in China." *Applied Energy* 86: 1458-64.
- [12] Khorasanizadeh, H., Mohammadi, K., and Mostafaeipour, A. 2004. "Establishing a Diffuse Solar Radiation Model for Determining the Optimum Tilt Angle of Solar Surfaces in Tabass, Iran." *Energy Conversion and Management* 78: 805-14.
- [13] Iqbal, M. 1983. *An Introduction to Solar Radiation*. New York, NY: Academic Press.
- [14] Duffie, J. A., and Beckman, W. A. 2006. *Solar Engineering of Thermal Processes*, 3rd ed. New York: John Wiley & Son.
- [15] Cooper, P. I. 1969. "The Absorption of Solar Radiation in Solar Stills." *Solar Energy* 12: 333-46.