Estimation of diffuse component for two locations in Turkey

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Abstract

In analyzing the solar energy systems, the first step is the accurate measurements/estimations of the input in the long term: solar irradiation incident on the panels. The measurements are lacking in many places so the estimation procedures should be developed using the measured data of the locations having similar climates and close in latitudes. In most life cycle assessments, monthly averages of daily values are utilized in the form of typical meteorological year or simply with the averages of a year or for a number of consecutive years. Although the beam component of the solar irradiation is usually higher than total of all diffuse components except in highly cloudy and overcast sky conditions, estimation of diffuse components is vital especially to determine the solar irradiation on tilted solar panels. In this study, with the final aim of developing the best procedures to estimate diffuse solar radiation component for all the locations of Turkey, we carried out a preliminary comparison and reached a best procedure of estimation for two locations in Central Anatolia. Our procedure is to compare a model based on a physical formalism developed before with four methods of estimation appeared in the literature, together with the data obtained by Meteonorm Software. As a result, our model has given one of the two best results together with Meteonorm Software when compared to measured values. It is in fact the best one according to the RMSE value.

Keywords: *Total, beam and diffuse solar radiation; solar energy; Turkey; MBE; RMSE*

1. Introduction

By courtesy of being in solar belt (EPIA, 2010), Turkey is a high potent country to utilize solar energy for daily needs of public body, such as heating, cooling, hot water and in particular electricity, *inter alia*. In that vein, there is an opportunity for developing countries like Turkey to meet their needs in more economical, social and environmental way in parallel to the necessities of sustainable development. Even if the current position of Turkey on solar electricity production is still low with 562 MW PV installed power which was just 249 MW in the beginning of the year (TEIAS, 2016), it carries huge potential when compared to global leaders. For instance, while 1 kW PV system installed at the south part of Germany, a region that has got the highest solar potential in the country, is able to produce 1190 kWh electricity annually, it ranges between 1350-1750 kWh in Turkey from north to south (SMS and Fraunhofer, 2015). Considering the leadership role of Germany throughout the development process of solar energy market, this situation in Turkey is an obvious measure of the potential of Turkey.

As for hot water production via solar energy, Turkey's performance is devastating as being world number 3 together with Germany after China and USA with respect to solar water heating collector capacity (REN 21, 2016).

On the other hand, Turkey has got increasing electricity production demand. Current electricity demand which is around 280 TWh is estimated to be 424 TWh by the year 2023 with more than 50% increase rate (DG for Renewable Energy, 2014). Furthermore, Turkey is obliged to condemn the pledges under Paris Agreement a legally binding document ratified in order to tackle with climate change.

Consequently, solar energy usage in various fields has vital importance for the country. Moreover, its sharply decreasing marginal costs and rapidly increased technological development strengthen the use of solar energy against its counterparts. To look more closely at the development on solar technologies and their prices, together with annual reduction of marginal cost of wafer-based silicon PV modules of about 9% since 1990 (Fraunhofer, 2016) it is expected to be declined 59% more till 2025 (IRENA, 2016). Furthermore, the

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efficiency of them is increased about 5% in the last 10 years (Fraunhofer, 2016).

In this manner, there are two necessities to be known accurately that can be identified by making correct calculations after defining appropriate estimation procedures. The first necessity is to know the solar potential which is directly depended on solar insolation exposure. Second is related to defining the methods/ways to exploit/utilize the potential. In other words, there is a need to make feasible, bankable, technically efficient projects to install solar energy systems for various purposes (Karaveli et al., 2015). In this respect, Karaveli et al. made calculation of monthly mean solar irradiation for horizontal and tilted surface for Konya province Karapinar district which has one of the highest solar potential in the country and owns Energy specialized industrial zone specific to solar energy . Then, solar photovoltaic system designed in an appropriate manner and compared it with nuclear power plant planned to be installed in Turkey. Consequently, this study has lead in showing the appropriate way to define the solar potential and the feasibility of solar energy (Karaveli et al., 2015).

In order to be able to attain these above mentioned two necessities, the most important step is to make accurate estimations of the input of the system with its all components. For solar energy, this input is the solar irradiation falling on tilted surfaces of solar energy systems; mainly its components: beam (direct) and diffuse (scattered) ones.

Of course, the most accurate way to know the solar radiation with its components is long-term measurements of it at each location taken into account. However, this option is not used for a current situation and not possible in a short-run. Moreover, this option may not be economically feasible and physically possible. Therefore, the possibility of using measurements of one location to estimate the irradiation values for another location which has similar coordinate (latitude) and climate features can make it possible to estimate the feasibilities of the applications. Accordingly, by using currently measured long-term solar irradiation values of some locations to attain the best estimation procedures of the solar energy for the other locations, on tilted panels are an important and a possible way to reach feasibilities of the solar systems.

The estimation procedures of solar irradiation incident on tilted surfaces necessitate the calculation of beam and diffuse components of solar irradiation on horizontal surface (Duffie and Beckman, 2006). There are quite a large number of methods developed in the literature as reviewed by (Khorasanizadeh and Mohammadi, 2016). In addition many comparative studies are carried out using the measured data set of a location or at most a region [see for example (Tasdemiroglu and Sever, 1991)]. The results of our preliminary comparisons showed that it is very important to determine the best procedure(s) for Turkey and for different regions of the country, due to the highly complicated nature of the diffuse component. We present here our preliminary results of these comparisons of various models using the data of two locations in Central Anatolia, as a preliminary work. We also compared a model that we developed based on a physical modeling approach that was outlined before by Akinoglu (1993, 2008) and updated by Karaveli and Akinoglu (2016).

We chose a pair of locations to work on this study located in Central Anatolia: Eskisehir (39.78^{o} N) and Ankara (39.95^{o} N). The climates of the two locations are semi-dry continental and typically similar in terms of mean temperatures, rainfall and hot and cold waves spatial distributions (SMS, 2016). The distance between these two locations is 235 km. and altitudes are 792 m and 938 m, respectively. The data is obtained from State Meteorological Service (SMS) of Turkey.

The correlations that we used for comparisons are as follows: The first expression was derived for twelve locations in Central Anatolia by Aras et al. (2006). They concluded that a cubic expression is relatively better than others. Ulgen and Hepbasli conducted similar analysis and proposes another cubic expression and they both depended on monthly average daily bright sunshine hours per day length ratio (n/N) and monthly average daily solar irradiation on horizontal surface divided by monthly average daily extraterrestrial solar irradiation on horizontal surface, that is clearness index (Ulgen and Hepbasli, 2009). Tasdemiroglu and Sever utilized experimental data of mean solar irradiation on horizontal surface and obtained forth order polynomial function for the diffuse ratio with respect to clearness index (Tasdemiroglu and Sever, 1991). In comparisons, we also used the expression obtained by Erbs et al. who utilized hourly pyrheliometer and pyranometer data of US locations and derived clearness index and sunset hour angle depended equation (Erbs et al., 1982, Duffie and Beckman, 2006).

Moreover, one of the most famous databases/methodologies used by some of the commercial software programs which are heavily used for solar system design in Turkey, namely Meteonorm, is also used for comparisons in this study. The aim is to find the accuracy that this software can reach in their performance calculations of solar energy systems.

Lastly, we obtained linear correlations between monthly average diffuse ratio and monthly average daily fractional bright sunshine hours to estimate the diffuse component of monthly average daily solar irradiation, based on a physical modeling developed by Akinoglu (1993, 2008). In fact, we obtained a linear correlation for one of the locations: Eskisehir, and used this correlation to estimate the diffuse solar irradiation for Ankara.

In the view of above information, this study takes into account all the options to obtain the best estimation method for the diffuse part of solar irradiation. The results will be used in the short term and long term feasibility studies of the solar energy systems to be installed in the mentioned regions of the country.

The data used and exploited in the study provided from State Meteorological Service (SMS) of Turkey is as minute by minute values of total, diffuse solar irradiation and bright sunshine hours. These are the data measured through pyranometers and pyrheliometers in SMS measurement stations in the unit of watts per minute. Then, the measured data taken from the beginning of 2011 till the end of 2015 are analyzed and unreliable data are extracted. Moreover, the unit of the data is converted into MJ m^{-2} d^{-1} as needed for the models used in this study. Finally, the monthly averages of the compiled data are calculated and assigned as the value for monthly mean daily amounts.

In the comparisons, we used Mean Bias Error (MBE) and Root Mean Square Error (RMSE) values for the estimations of each procedure. MBE is a measure of under or over-estimation while RMSE can get high values even if the estimation only for one of the months considerably deviates from its measured value. Therefore, for both error values closer the value to 0 means better the estimation.

2. Solar Radiation Calculations

The study is on the estimation of monthly average daily solar irradiation on horizontal surface. To this aim, we calculated monthly average of daily extraterrestrial solar irradiation on horizontal surface using the equation given in Duffie and Beckman (Duffie and Beckman, 2006). Then, the diffuse component of the solar irradiation reaching the Earth on a horizontal surface after passing through the atmosphere is calculated using the aforementioned models.

These models (equations) are depended on H_0, H, H_d, n and N where H_o symbolizes daily value of the extraterrestrial (outside the atmosphere) irradiation incident on a horizontal surface; H is the estimated daily global solar irradiation; H_d is the daily values of diffuse component; n is daily bright sunshine hours (sunshine duration) and N is day length. The over-bar of the mentioned symbols refers to monthly average values. The models used in comparisons are given in Table 1.

In addition to these equations, to retrieve data from Meteonorm, the software is installed on the desktop. Ankara is selected from the tool bar. The diffuse solar radiation data for Ankara is given in the following screen that is revealed in Figure 1.

Tab. 1: Defined equations to find diffuse component of solar irradiation

Equation	**Reference**
$\frac{\bar{H}_d}{\bar{H}} = 1.6932 - 8.2262(\frac{\bar{H}}{\bar{H}_0}) + 25.5532(\frac{\bar{H}}{\bar{H}_0})^2 - 37.8070(\frac{\bar{H}}{\bar{H}_0})^3 + 19.8178(\frac{\bar{H}}{\bar{H}_0})^4$	Tasdemiroglu and Sever, 1991
$\frac{\bar{H}_d}{\bar{H}} = 1.7111 - 4.9062\frac{\bar{H}}{\bar{H}_0} + 6.6711\left(\frac{\bar{H}}{\bar{H}_0}\right)^2 - 3.9235\left(\frac{\bar{H}}{\bar{H}_0}\right)^3$ and $\frac{\bar{H}_d}{\bar{H}_0} = 0.2427 - 0.0933\left(\frac{n}{\bar{N}}\right) + 0.1846\left(\frac{n}{\bar{N}}\right)^2 - 0.2184\left(\frac{n}{\bar{N}}\right)^3$	Aras et al., 2006
$\frac{\bar{H}_d}{\bar{H}} = 0.981 - 1.9028(\frac{\bar{H}}{\bar{H}_0}) + 1.9319(\frac{\bar{H}}{\bar{H}_0})^2 - 0.6809(\frac{\bar{H}}{\bar{H}_0})^3$ and $\frac{\bar{H}_d}{\bar{H}_0} = 0.1437 + 0.2151\left(\frac{n}{\bar{N}}\right) - 0.1748\left(\frac{n}{\bar{N}}\right)^2 + 0.0697\left(\frac{n}{\bar{N}}\right)^3$	Ulgen and Hepbasli, 2009
$\frac{\bar{H}_d}{\bar{H}} = 1.391 - 3.560(\frac{\bar{H}}{\bar{H}_0}) + 4.189(\frac{\bar{H}}{\bar{H}_0})^2 - 2.137(\frac{\bar{H}}{\bar{H}_0})^3$	Erbs et al., 1982

From the table revealed in Figure 1, monthly mean daily diffuse solar radiation amount, as needed, is reckoned by dividing irradiation in the second column in the Table with the number of days in the specific month. The results are given in Table 3.

ANKARA TU

Radiation | Temperature | Precipitation | Sunshine duration
Daily global radiation | Daily temperature | Data table

	Gh kWh/m²	Dh kWh/m²	Bn kWh/m²	Ta °C	Td °C	FF m/s
January	52	28	63	-0,5	-3,9	1,9
February	66	37	66	1,5	-3,4	2,2
March	98	58	72	6,2	-1,3	2,7
April	140	66	121	11	2,5	2,5
May	164	72	138	16,1	6,2	2,3
June	192	82	165	20,5	8	2,6
July	201	78	189	24,1	9,2	2,9
August	176	76	153	24,1	9,7	2,7
September	127	64	107	18,5	6,9	2,2
October	89	46	90	12,8	4,6	1,9
November	65	31	91	6,3	1,5	1,6
December	55	28	77	1,3	-1,9	1,8
Year	1422	665	1332	11,8	3,2	2,3

Fig. 1: Meteonorm data for Ankara

3. Linear Equation Derivation

As mentioned in previous parts of this article, the physical formalism derived and applied in this study was developed in Akinoglu (1993 and 2008) and adopted for the diffuse component by Karaveli and Akinoglu (2016). The development of the aforementioned model is launched by the consideration of the instantaneous fractional clear sky period n_i. Then the beam solar irradiation directly reaching the Earth's surface during n_i period, I_B, can be given as:

$$I_B = I_0 \tau n_i \quad \text{(eq. 1)}$$

where I_0 is the extraterrestrial solar irradiation falling on horizontal surface during that certain time interval and τ is atmospheric transmission coefficient for clear-sky. In the mentioned time interval, there is not only beam but also diffuse part (sky and circumsolar) reaching to the surface that can be expressed as:

$$I_{D1} = I_0 (1-\tau) \beta' n_i \quad \text{(eq. 2)}$$

where β' is the atmospheric forward scattering coefficient. The time remaining after n_i period is called as cloudy period. This period, as is nature, has diffuse radiation, I_{D2}, that can be expressed as:

$$I_{D2} = I_0 \tau \tau' (1-n_i) \quad \text{(eq. 3)}$$

where τ' is a transmission coefficient of the clouds.
Then the linear model expression for the global solar irradiation [Akinoglu, 1993, 2008] is attained by adding Eqns. (1) to (3). Moreover, adding Eqns. (2) and (3) results in a linear expression for the diffuse part as:

$$I_D = I_0 (1-\tau) \beta' n_i + I_0 \tau \tau' (1-n_i) \ . \quad \text{(eq. 4)}$$

We may then write equation (4) for daily integrated and then monthly averaged values of diffuse solar irradiation by assuming that the forms would not change and by replacing the coefficients with their effective monthly counterparts (Akinoglu, 1993, 2008 and Karaveli and Akinoglu, 2016). While structuring this approach, we should also consider that the ratio of monthly average of daily sunshine duration to day-length n/N will replace the fractional time period n_i. Accordingly, I_D and I_0 will be replaced with their monthly average daily values of $\overline{H}_D$ and $\overline{H}_0$. If these replacements are carried out, a linear correlation for the monthly average of daily diffuse irradiation from Eqn. (4) can be reached as:

$$\overline{H}_D / \overline{H}_0 = a_1 + a_2 (\overline{n} / \overline{N}) \quad \text{(eq. 5)}$$

where $\overline{H}_D$ is monthly average daily diffuse solar irradiation, $\overline{H}_0$ is extraterrestrial solar irradiation, $\overline{n}$ is the monthly average daily bright sunshine hours and $\overline{N}$ is monthly average day length. In this approach, the parameters a_1 and a_2 can be written as:

$$a_1 = \tau_e \tau_e' \quad \text{and} \quad a_2 = \beta_e' (1-\tau_e) - \tau_e \tau_e' \ .$$

The sub-index e stands to indicate that the coefficients are monthly effective counterparts of the coefficients defined before. Accordingly, τ_e and τ_e' are effective monthly parameters of the transmission coefficient of the atmosphere during clear-sky condition and the transmission coefficients of the clouds, respectively, and β_e' is effective monthly forward scattering coefficient of the clear atmosphere.

In this modeling approach, knowing the value of the global and diffuse component for a location and by assigning a value to β_e' one can reach the monthly values of a_1 and a_2. Thus, in the present study we also used the calculated monthly values of a_1 and a_2 for one location to estimate the diffuse component of solar irradiation of the other location.

In fact, linear equation for the monthly-mean daily total solar irradiation, and monthly average daily fractional bright sunshine hours can also be obtained using this physical modeling approach as presented in ref. Akinoglu, 1993.

Applying above mentioned procedure and using measured SMS values for Eskisehir, we have found the constants specific to Eskisehir to calculate diffuse solar irradiation falling on a horizontal surface, namely a_1, and a_2 as presented in Table 2.

Tab. 2: Monthly specific constants for linear equations

Months	Constants	
	a_1	a_2
January	0.41	-0.26
February	0.28	-0.13
March	0.32	-0.18
April	0.33	-0.19
May	0.35	-0.21
June	0.28	-0.15
July	0.37	-0.24
August	0.33	-0.19
September	0.38	-0.24
October	0.39	-0.22
November	0.37	-0.21
December	0.28	-0.10

Then by using constants given in Table 3, we calculate diffuse solar radiation of Ankara as given in Table 3. Table 2 also gives the estimated values by the models together with the measured SMS data.

4. Results

The diffuse solar radiation values for Ankara calculated by using all the options to be compared are compiled in Table 3. So as to ease the comprehension of Table 3, models are numbered. Model 1 is reserved for the first equation coming from reference Aras et al. (2006), while Model 2 is the second equation of the same reference. Model 3 is the result of the first equation coming from reference Ulgen and Hepbasli (2009), while Model 4 is the second equation of the same reference. Model 5 and 6 constitutes the methodology of the references Tasdemiroglu and Sever (1991) and Erbs et al. (1982), respectively. Model 7 is reserved for Meteonorm values and finally Model 8 for the results coming from the procedure developed and used in this study.

Tab. 3: Diffuse solar radiation in MJ m^{-2} reckoned through all the models

Months	Models								Measured
	1	2	3	4	5	6	7	8	
January	3.45	3.47	2.88	2.87	3.43	3.05	3.25	5.24	3.93
February	4.53	4.54	4.31	4.23	4.96	4.05	4.76	4.73	5.68
March	5.94	6.06	5.92	5.68	6.59	5.88	6.74	6.79	8.14
April	7.29	7.49	7.65	7.43	8.13	7.33	7.92	8.21	9.52
May	8.20	8.57	8.90	8.54	9.15	8.33	8.36	10.06	11.17
June	7.85	8.55	9.82	9.43	8.76	8.37	9.84	7.73	9.02
July	6.64	7.76	9.99	9.50	7.60	7.62	9.06	8.13	9.32
August	5.88	6.79	9.02	8.62	6.77	6.80	8.83	7.02	8.15
September	5.07	5.58	7.31	7.07	5.74	5.71	7.68	6.22	7.13
October	4.60	4.72	5.10	5.02	5.13	4.70	5.34	5.99	5.70
November	3.52	3.54	3.60	3.56	3.91	3.18	3.72	4.41	4.89
December	3.12	3.11	2.72	2.71	3.24	2.77	3.25	3.41	3.98

Then, the results of the comparisons with respect to MBE and RMSE statistical comparison methods are tabulated in Table 4.

Tab. 4: The results of the comparisons for diffuse solar radiation values

Option	MBE	RMSE	Reference
1	-1.71	1.87	Aras et al., 2006
2	-1.37	1.51	Aras et al., 2006
3	-0.78	1.36	Ulgen and Hepbasli., 2009
4	-1.00	1.44	Ulgen and Hepbasli., 2009
5	-1.10	1.22	Tasdemiroglu and Sever., 1991
6	-1.57	1.68	Erbs et al., 1982
7	-0.66	1.20	Meteonorm value
8	-0.72	**1.05**	Procedure derived in this study

5. Outcomes and Discussions

On the way to structure a formalism to determine specific equations for Turkey, the preliminary steps are carried out in this study by identifying equations for diffuse solar irradiation calculations for Eskisehir and estimating the diffuse component for Ankara by utilizing obtained monthly coefficients a_1 and a_2 for Eskisehir. Then, its accuracy is examined by comparing its results with other options in order to get estimations with the least error values.

Checking the results of the comparisons tabulated in Table 4, it can be clearly observed that the procedure used in this study is one of the two best methods. In fact, pursuant to RMSE comparison the procedure derived and used in this study is the best one. The larger value of RMSE for Meteonorm is due to quite high deviation of its estimation for the month May with the measurement as can be seen from Table 3.

The rationale behind this result can be identified with following reasons: The two previous methods (Aras et al., 2006 and Ulgen and Hepbasli, 2009) proposed for the estimation of diffuse irradiation was not derived using measured data of diffuse irradiation. And, the method proposed by Erbs et al. was derived using hourly pyrheliometer and pyranometer data from four U.S. locations and therefore, its lesser accuracy for locations in Turkey is reasonable. Although the model proposed by Tasdemiroglu and Sever was derived from the measured data of five different locations from various climates in Turkey, it is not better than the procedure explained and used in this study. This is because the equation of Tasdemiroglu and Sever, using regression analysis, obtained one equation that fits all the months however the linear equation derived in this study provides an opportunity to assign month-specific correlations.

Therefore, we concluded that better results we obtained by the procedure we used are reasonable and may be the procedure we should choose at the end. The results of Meteonorm Software are also good for diffuse values but our observations showed that global solar irradiation values of Meteonorm considerably deviate from the measured values. Nevertheless, some further analysis should be carried out to reach concrete conclusions.

As a result, our formalism has given one of the two best results together with Meteonorm Software when compared to measured values. It is in fact the best one according to the RMSE comparison. By sticking to the method derived in this study if this study is applied to all regions/locations/provinces in Turkey, the most accurate total and diffuse solar radiation results can be gathered/acquired for all over the Turkey. This paves the way for us to see the exact potential and enables to define the most feasible ways to utilize solar radiation.

Our further prospects are first to extend the present analysis to different locations covering all the climates/regions of Turkey to reach the best procedure(s) to be used in estimation of diffuse component of solar irradiation. Secondly, we will use these procedures to estimate the solar irradiation on tilted panels and evaluate the long term performances of solar energy systems.

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