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Suitable model for estimating solar radiation in Tehran province-Iran (Case study: Mehrabad airport station)

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Abstract

The solar radiation received by earth surface is one of the most applicable parameter that is usable in projects and hydrological, agricultural, meteorological, and climatological modeling. This research suggests different experimental equations to estimate solar radiation in different climates, considering very expensive instruments for measuring the solar radiation received by the earth surface. Solar radiation reached to the earth surface (R_s) is the main source of solar energy. Several models have been proposed for its estimation due to its importance. Furthermore, various applications have been represented based on the climate, which most of them have calculated the average daily solar radiation in a month. The aim of this research is to find a way that calculates the amount of daily radiation during a year. Data of sunshine hours, and the maximum and minimum of daily temperature were used in a period of thirty years (1961-1990). The daily measured (R_s) data in the statistical period of 1981-1985 were used for evaluating the model and controlling the results. In the proposed model, the ratio of genuine sunshine hours to possible sunshine hours (during the day) were used to obtain the coefficients of model for calculating the radiation reached to the earth surface. Moreover, adding the maximum and minimum root square of temperature caused to rise

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up the estimation accuracy. The model compared with several popular models such as NSE, MBE, RMSE and correlation coefficient indices and the results showed high accuracy. While the amount of coefficient of correlation in this model is equal to 90%, the correlation coefficient for the Triton, Rietveld, and Yazdan-Panah models are 78%, 76%, and 79%, respectively. The model outcomes showed the highest correlation with the actual amounts of radiation. Therefore, this model can be recommended as the suitable model for estimating solar radiation in this climate.

Keywords: Solar energy; Radiation; Sunshine hours; Atmosphere; Coefficient of determination.

1. Introduction

The estimation of reached radiation to the earth surface (R_s) has many applications in agriculture, hydrology, and architecture sciences, and energy engineering (Majnoni-Heris *et al*., 2009). Solar radiation is a significant factor in estimated equations of plant's moisture-evaporation (Almorox and Hontoria, 2004). The proper estimation is highly important in development of simulation models of plants. Accurate calculation of R_s is an essential principal in designing channels and planning for irrigation.

Considering the importance of the climate change and renewable energies, especially solar energies emphasizes on the measurement of R_s (Safaei *et al*., 2005). Due to high costs of measurement devices and required instruments' maintenance, radiation data is not measured in most of synoptic weather stations or having a short-term of statistical period (Yazdan-Panah *et al*, 2010). In other words, the proportion of radiation data to other ecologic data is very low. Even in developed countries like U.S, this ratio is 1:100 (Badescu, 2008). An actinography device measures the solar radiation reached to the earth surface. There are 21 stations having radiation data with statistical period of ten or eleven years throughout Iran, this is why in most studies, radiation is measured by different methods and models with other metrology data exists in the studied stations. Selection of calculating methods and data source depends on the user's goals and kind of data availability. A model dependant to sunshine hour has the most application in calculation of surface radiation. Angstrom (1924) offered the estimated and proposed model of R_s as bellow:

$$R_s = R_o\left(a + b\,\frac{n}{N}\right) \tag{1}$$

which, R_o is the radiation out of atmosphere based on Mega Jules/square meter per day (MJ/m^2.day). N and n are duration of day and sunshine hour, respectively. The letters "a" and "b" are the constant coefficients. How to measure these coefficients is one of the important issues that lead to variety of these group models. Doorenbos and Pruitt (1977) coefficients "a" and "b" for the northern hemisphere were determined 25% and 50%, respectively. Rietveld (1978) calculated the "a" and "b", accordingly 18%, and 62%. The food and agriculture organization-FAO suggested the coefficients a=25%, and b =50% (Allen *et al.*, 1998). Moreover, Yazdan-Panah *et al.* (2010) calculated the Angstrom model in Esfahan station using the least squares for estimating the radiation.

Many researchers such as Ojosu and Komolafe (1987), Bristow (2003), Akpabio and Etuk (2003), Rivington *et al.* (2005), Burnett *et al.*

(2014), attempted for calculating the solar radiation in order to apply other metrology data additional to the sunshine hours, weather temperature, and radiation outside the atmosphere. Chen *et al*. (2006) developed several models using metrological data for different areas in China. They concluded that this nine variables model offered by Ertekin and Yaldiz (1998) had higher accuracy than the other models. Hargreaves *et al.* (1985) proposed a model which in fact estimates the lack of availability of real sunshine hours based on the radiation outside the atmosphere (R_o) and the square root of maximum and minimum variation of temperature, and the quantities of R_s by the following equation (Hargreaves and Samani, 1982):

$$R_s = R_o \left[c \left(T_{max} - T_{min}\right)^{0.5} + d\right] \quad (2)$$

which, T_{max} and T_{min} are maximum and minimum of temperature in centigrade, c and d are constant coefficients in Equation (2). The studies also were carried out inside the country by Samimi (1986), Kamali and Moradi (2005), Khalili (1889), Khalili *et al*. (1891), Majnoni-Heris *et al*. (2009), Safaei *et al*. (2005) that used the hybrid model for estimating the monthly average of total radiation during a day in Iran.

Thus, given the importance of earth surface radiation and its widespread use in various meteorological, climatological, hydrological, and agricultural projects and studies, this paper presents several models for estimating solar radiation in a semi-arid climate such as Tehran. The results were compared with the values measured by pyranometer to select the most appropriate model to obtain better and more accurate results in this region.

2. Data and Methodology

In order to estimate daily radiation in Mehrabad station in Tehran, the data of metrology including the sunshine hour (n), and the minimum of daily weather temperature for the statistical year of 1961 to 1990 were used. Whole radiation data reached to the earth (R_s) measured from the statistical years 1974 to 1991, which the statistics of 1981 to 1985 were reliable. The eastern altitude of 51° 19’ and northern longitude 35° 41’ and height of 1190.80 from the sea surface are used. In this research, the radiation data during 1981-1983 were used to determine the coefficients of the model constant and the statistics for the years 1984-1985 were investigated to evaluate the validity of the models.

Since there was the probability of error in the existed data, first, the daily measured sunshine hours (n) were compared with day length (N) and the bigger ones were removed. Then, in sunny hours, the closest weather station existed in the region (Dushan-Tapeh weather station) was reconstructed by double mass curves. Minimum and maximum temperature data reconstruction was performed using a double mass curves. Purification of the measured radiation data of these stations based on 100 WMO meteorological Organizations were conducted in two stages as follows:

- When the measured data were bigger than the amount of the net radiation received from the upper atmosphere in a day
- After initial refinement, the methods of double mass curves were applied and data were reconstructed again

The proposed method of radiation calculation, considering the minimum and maximum temperature, sunshine hours, and root square, is as follows:

$$R_s = R_o \left(a' \left(\sqrt{T_{max} - T_{min}}\right) + b\,\frac{n}{N}\right) \tag{3}$$

In this relation, R_s is the amount of radiation energy received by the Earth's surface to the horizontal plane in MJ/m^2.day, and R_o is the amount of daily energy of radiation relation to a horizontal surface over the atmosphere. "a" and "b" are the constant coefficents of model, "n" is the number of the day of year starting from the first of January or the daily sunshine hours, and "N" is the maximum sunshine duration or day length.

To calculate the amount of energy received to the top of atmosphere (R_o) as a function of latitude and day, the following equation was used (Allen *et al.*, 1998).

$$R_o = \frac{3600*24}{\pi} I_0 * \frac{\pi\, hss}{180} (\sin\varphi \sin\delta + \cos\varphi \cos\delta \sin h_{ss}) \tag{4}$$

where, the hourly angle of sun at sunset (h_{ss}) was obtained from the following equation:

$$h_{ss} = \cos^{-1}[-\tan(\varphi)\tan(\delta)] \tag{5}$$

and I_o is the moderate levels of measured radiation outside the atmosphere for every day of the year on a surface perpendicular to the sun angle which can be calculated by the following method.

$$I_o = I_{SC}\,[1 + 0.033 \cos(\frac{360\,n}{365})] \tag{6}$$

which, the number 1 is reffered to the number of first day of year (1st January).

I_{sc}, the constant of solar radiation, is equal to 1367 (W/m^2), φ latitude of the place, and δ the place angle which can be obtained from the following equation.

$$\delta = 23.45 \sin\,[360\,\frac{284+n}{365}] \tag{7}$$

In this relation, the "n" is the number for the first day of a year (1st January).

The letter "N" or the sunshine hours may be obtained from the Equation (8).

$$N = \frac{2}{15} \cos^{-1}[-\tan(\varphi)\tan(\delta)] \tag{8}$$

which, is the longitude, and σ is the orientation angle of place. For estimating the constant quantities "a" and "b" in the Equation (1), were calculated by the Allen method (Allen *et al.*, 1998) available in the Equations 10 and 11, respectively. Furthermore, "a" in Equation (11) is obtained from Equation (10).

$$a = \frac{\Sigma\frac{R}{R_o}\Sigma(\frac{n}{N_o})^2 - \Sigma\frac{n}{N} * (\Sigma\frac{n}{N} * \frac{R}{R_o})}{M\,\Sigma\left(\frac{n}{N}\right)^2 - (\Sigma\frac{n}{N})^2} \tag{9}$$

$$b = \frac{M\,\Sigma\,\frac{n}{N} * \frac{R}{R_O} - \Sigma\frac{n}{N}\Sigma\frac{R}{R_o}}{M\,\Sigma(\frac{n}{N})^2 - (\Sigma\frac{n}{N})^2} \tag{10}$$

which, M is the amount of data. Then, the root square of temperature is inserted in the following equation:

$$a' = \frac{a}{\sqrt{T_{max} - T_{min}}} \tag{11}$$

The results of this method were compared with the other models' outcomes using following equations:

Rietveld model

$$R_s = R_o\left(0.18 + 0.62\,(\frac{n}{N})\right) \tag{12}$$

Triton model

$$R_s = R_o\left(0.30 + 0.40\,(\frac{n}{N})\right) \tag{13}$$

Yazdan-Panah model

$$R_s = R_o\left(0.28 + 0.39\,(\frac{n}{N})\right) \tag{14}$$

In order to analyze the estimation accuracy of measured relations, the Nash-Sutcliffe (NSE) (Nash and Sutcliffe, 1970), the root mean square error (RMSE), and the mean bias error

(MBE) were calculated from the following equations:

$$NSE = 1 - \frac{\sum_{i=1}^{u}(p_i - O_i)}{\sum_{i=1}^{u}(O_i - \bar{O})^2} \quad (15)$$

$$RMSE = \sqrt{\frac{1}{u}\sum_{i=1}^{u}(p_i - O_i)^2} \quad (16)$$

$$MBE = \frac{\sum_{1}^{U}(P_i - O_i)}{U} \quad (17)$$

which, in the above equations p_i, o_i , o, u are the recommended quantities at the time "i", measured in the time "i", the average of measured data, and the amount of data, respectively. The quantity NSE changes between zero and one. The more nearer the quantity NSE to one, the better compatibility of estimated amounts of measured. If the quantity MBE is positive or negative, this shows that the estimated quantity is more than or less than the measured quantities, respectively. The lower RMSE, the more appropriate accuracy will be obtained in the model estimation.

For evaluating the validity of this model, the measured data in 1984 and 1985 were used. The results related to the validity of these models are shown in Table 1 briefly.

3. Results

For the comparison of model accuracy suggested in this research, statistical data of 1984 and 1985, which has not been applied in the modeling, considered for monitoring the results. The statistical comparison of measured and estimated quantities from different relations, using three statistical indices NSE, MBE, and RMSE obtained from the Equations 15, 16 and 17. The model accuracy is also studied according to the statistical indices in Table 1. It was identified that the suggested model has the best correlation coefficient compared to other models while the quantity of correlation coefficient in our developed model was equal to 90%. The correlation coefficient for the models of Yazdan-Panah, Rietveld and Triton was 0.79, 0.76, and 0.78, respectively. However, a significant level of 5% was considered for the model. The amount of NSE between zero and one modifies and the closer the amount to one, the better compatibility of measured amounts. According to Table 1, the numerical quantity of model is closer to one with 0.7 in relation to other models.

The positive amounts in the MBE index show that the model outputs are estimated higher than the real ones. Furthermore, the negative values show that the quantities are lower than the real values. This model's output was about 5 percent lower than the real one. Other models showed that their outputs are higher than the real quantities.

Lower values in RMSE index indicate greater accuracy of the model, as shown in Table 1.

Table 1. The statistical indices for evaluating the validity of models in Mehrabad Airport of Tehran Station (source: The authors)

Index	Triton	Rietveld	Yazdan-Panah	Proposed Model
NSE	0.6	0.47	0.61	0.68
MBE	0.15	0.95	0.39	-0.05
RMSE	4.7	5.4	5.6	4.2
R	0.78	0.76	0.79	0.90

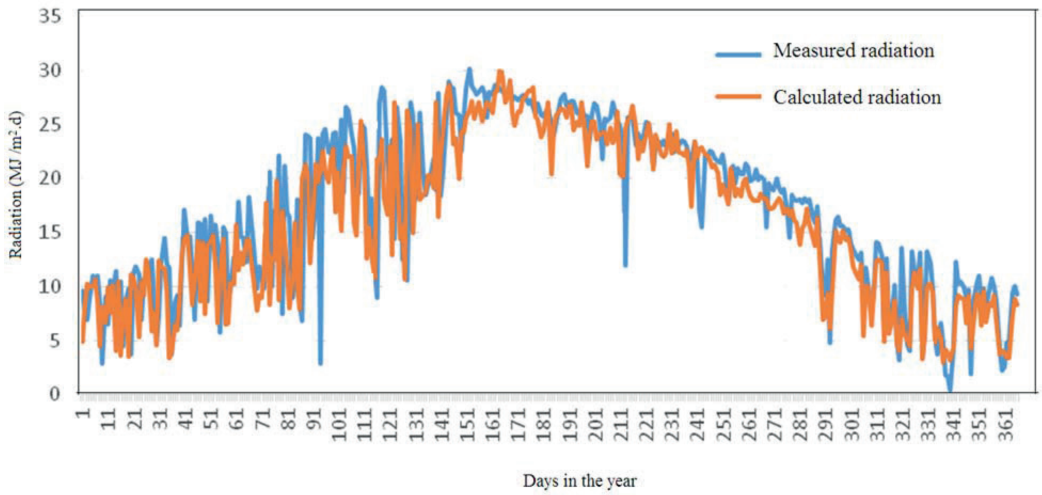

Figure 1. Linear chart for comparison of the measured and calculated daily radiation in MJ/m^2.d Statistical year of Tehran Station in 1990

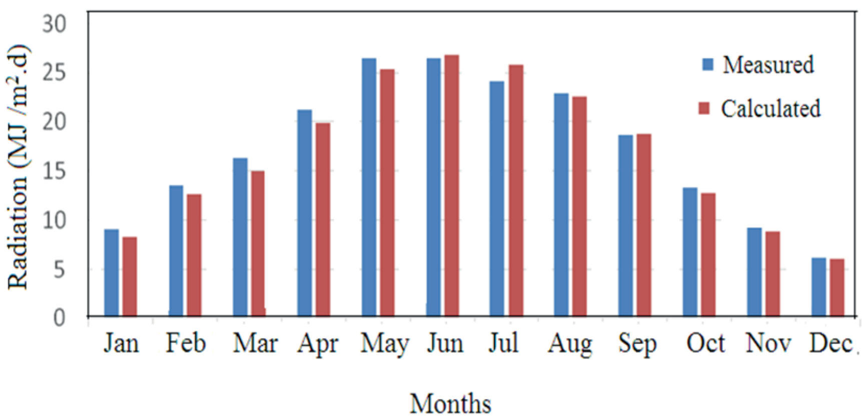

Figure 2. The bar chart of comparison the measured and calculated of radiation at meteorological stations, Mehrabad Airport, Tehran, 1990

Our proposed model has lowest RMSE value compared to the other models.

In addition to indices NSE, MBE, RMSE, and R, a linear graph was used in order to assess the validity the suggested model for statistically comparison of the measured and calculated daily radiation in 1991 at Tehran station.

According to Figure 1, the general trend of the measured and estimated radiation is the same. In the cold days of year with a high fluctuation of the measured radiation, the amount of estimated radiation is also fluctuated. Very intense fluctuations, especially minimization in true radiation exposure were estimated higher than from the estimated values that are less than the real values in some days of the year.

In addition to daily comparison of calculated and measured radiation based on the proposed model of the monthly mean radiation for a statistical period of five years has been examined which the results offered in Figure 2 have no differences regarding the chart, and measured or estimated radiation. In the early five months of the year, the estimated values

Table 2. A briefly estimated statistical parameters for radiation energy (MJ/m^2) in Equation (3) during 1961-1990 at Mehrabad Airport, Tehran (Source: authors)

Month	Avaerage	Minimum	Maximum	Variance	Standard deviation	Total	Percentage
Jan	2.6	0.5	3.7	0.5	0.7	77.1	4.3
Feb	2.8	0.7	4.7	0.8	0.9	83.6	4.7
Mar	3.6	0.6	6.2	1.5	1.2	109.2	6.1
Apr	4.6	0.9	7.4	1.8	1.4	136.7	7.6
May	5.7	1.6	8.2	2.1	1.5	169.9	9.5
June	6.7	1.9	8.6	1.5	1.2	201.0	11.2
July	7.4	3.9	8.8	0.5	0.7	223.1	12.4
Aug	7.2	5.5	8.3	1.3	0.6	216.6	12.1
Sep	6.5	3.3	8.1	0.5	0.7	195.7	10.9
Oct	5.5	1.6	7.1	0.8	0.9	163.8	9.1
Nov	4.2	0.7	6.2	1.0	1.0	124.6	6.9
Dec	3.1	0.6	5.0	0.7	0.9	91.8	5.1
Spring	19	29	2.8	37	6	1774	28
Summer	25	30	12	8	2.8	2329	37
Autumn	15	22	3.25	28	5.3	1367	22
Winter	9	17	0.5	15	3.9	417	13

are almost one majole lower than the measured values, and the estimated values are higher than the measured values almost 1 MJ in June and 2 MJ in July, in the remaining months of the year, the amounts are equal.

After compaing the models, the radiations reached to the surface was estimated by the Equation (3) for a statistical years of 1961-1990 and its brief statisticcal parameters have been given in Table 2.

According to Table 2, Tehran Mehrabad Airport station in January has an average radiation of 2.6 and the maximum 3.7 and the minimum 0.5 in MJ /m^2.day, and a total of 77.1 (MJ / m^2.month) and 4.3% annual radiation. July is the most radiation month of the year, with an average radiation of 7.4, the maximum 8.8, and the minimum 3.9 (in MJ /m^2.day) and a total of 223.1 (MJ /m^2.month), and 12.4% annual radiation.

The maximum fluctuation of radiation at this station is in May with a standard deviation of 1.5, and the minimum variance in January, July and September are 0.5 (MJ /m^2.day).

Annual radiation during 1961-1990 at Tehran Mehrabad Airport showes that summer season (June, July, August) had maximum radiation (37%) and winter season (December, January, February) had minimum radiation (13%), spring season (March, April, May) with 28%, and autumn season (September, October, November) with 22%.

Conclusion

In this work, the modeling of the solar radiation using four approaches was presented. These models could be used as a reference model for the first category of procedures. The results showed good estimation in the four models for the global solar radiation in Tehran. The proposed model gave the most favorable estimated results. It was concluded that using the methods of global solar radiation estimation is a suitable tool because the meteorological data can be estimated easily.

Comparing the measured values and those estimated by the models in literature and our proposed model, represented that better results with highest correlation coefficients (R=0.90) were obtained from the suggested model. The values of mean bias error (MBE= -0.05 MJ/m^2), root mean square error (RMSE= 4.2 MJ/m^2) and the Nash-Sutcliffe error (NSE=0.68) were in acceptable ranges. This indicated the validity of using this model to estimate the global solar radiation intensity in Tehran.

The global solar radiation estimated by this model can be suitable in designing and estimating the performance of solar applications, which are gaining increasing attention in Tehran.

It is expected that the model developed for daily global solar radiation will be useful to the engineers of solar energy related systems as well as those who need to have good estimates of yearly variations of daily global solar radiation for specific location.

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