Estimating daily global solar radiation by day of year in China

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ABSTRACT

In this study, a new empirical model is proposed for estimating daily global solar radiation on a horizontal surface by the day of the year. The performance of the proposed model is validated by comparing with three trigonometric correlations at nine representative stations of China using statistical error tests such as the mean absolute percentage error (MAPE), mean absolute bias error (MABE), root mean square error (RMSE) and correlation coefficients ($r$). The results show that the new model provides better estimation and has good adaptability to highly variable weather conditions. Then the application of the methodology is performed for the other 70 meteorological stations across China.

1. Introduction

Solar energy is one of the most important and promising renewable and sustainable energy. China has abundant solar energy resources and more than two-thirds of areas receive an annual total solar radiation that exceeds 5.9 GJ/m² with sunshine duration more than 2200 h [1]. It is meaningful to substitute solar energy for fossil energy with respect to solar energy resources.

An accurate knowledge of the solar radiation data at a particular geographical location is important for solar energy system design [2]. However, in most areas of the world, solar radiation measurements are not easily available due to cost and techniques involved. There are only 103 solar radiation observation stations until 2008 in Chinese mainland [3]. Long-term data on global solar radiation are not available for most areas in China, especially in remote rural and mountainous areas, where approximately 80% of the Chinese population is living [4]. Therefore, elaborating methods to estimate the solar radiation is of great significance.

Solar radiation can be estimated by means of empirical relations using other available meteorological observations [5–17], interpolating methods [18], geostationary satellite images [19], time series methods [20], stochastic weather models [21], physically radiative transfer models [22], and the artificial neural network method [23,24]. Among the numerous methods, those based on empirical correlations using commonly measured meteorological data are attractive due to lower data requirement and computation cost [10]. Recently, several empirical formulas using some available meteorological parameters have been tested around the world. The meteorological parameters include sunshine hours [5–8], ambient temperature [9–11], cloudiness [12–14], relative humidity [15], precipitation [16] and vapor pressure [17].

In general, although sophisticatedly empirical formulas try to simulate solar radiation with a good prediction, it is on the other hand, very useful to build reliable and easy models to estimate solar radiation.

Simple models to estimate solar radiation without meteorological data have been implemented by using the only one parameter, i.e., the day of the year [25–28]. Bulut [25] developed a model to estimate the daily global solar radiation for Istanbul using long-term measured data with a sine wave equation. Subsequently, Bulut and Büyükalaca [26] tested the model for 68 locations in Turkey and the results showed that the predictions from the model agree well with the long-term measured data. Al-Salaymeh [27] predicted the daily global solar radiation in Amman city in Jordan using the sine wave model. Statistical results showed that the sine wave model gave best fit. Kaplanis and Kaplani [28] used a cosine wave model to calculate the daily global solar radiation in six climatic zones of Greece and the correlation coefficient for all cases is higher than 0.996.

The main advantage of these models is the readily usage of mathematical expressions even by a pocket calculator and thus, do not require tedious inputting work for the variables and database files for simulation [25]. However, there has been a lack of reports in literature about the evaluation of the applicability of these models for estimating daily global solar radiation.

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In the present study, a new trigonometric model in conjunction with a sine and cosine wave for estimating the daily global radiation is proposed. The performance of the proposed model is validated by comparing with three existing trigonometric correlations at nine representative stations of China using statistical error tests, and then the methodology is applied to the other 70 meteorological stations across China.

2. Data and methodology

2.1. Data

Daily measured global solar radiation data of 79 meteorological stations covering all over China are taken from the National Meteorological Information Centre (NMIC), China Meteorological Administration and then are averaged to obtain the annual mean values after processing. There are missing measurements in the data, and they are marked and coded as 32766 in the files. Fig. 1 shows the distribution of the selected stations. The daily global solar radiation data measured during at least 10 years between January 1 1994 and December 31 2008 are used in the calculations.

The quality control of the original solar radiation data is performed to eliminate spurious data and inaccurate measurements, with the clearness index $K_t$ as an indicator. Data will be rejected if the daily global solar radiation were greater than the corresponding extraterrestrial radiation, i.e., $K_t > 1$, or the daily global solar radiation were less than a minimum value expected with continuous overcast conditions. The smallest acceptable value for $K_t$ is set as 0.015, representing a heavy overcast sky for the whole day [29–31]. All excluded and missing data, accounting for approximately 0.58% of the whole data-base, are replaced with the values derived from those of preceding and subsequent days by interpolation.

2.2. Methods

Daily solar radiation is a quasi-periodic phenomenon on a yearly cycle due to seasonal effects [32]. It is convenient to model daily global solar radiation by the day of the year. Among the models estimating daily global solar radiation by the day of the year, trigonometric correlations give excellent fitting. A brief description of the trigonometric models examined is given below.

Bulut [25] proposed a sine wave model:

$$H = a_0 + a_1 \times \left| \sin \left( \frac{\pi}{365} (n + 5) \right) \right|^{1.5}$$  

(1)
Another sine wave correlation used by Al-Salaymeh [27]:

\[ H = a_0 + a_1 \times \sin \left( \frac{2\pi}{a_2} n + a_3 \right) \]  
(2)

Kaplanis and Kaplani [28] suggested a cosine wave correlation:

\[ H = a_0 + a_1 \times \cos \left( \frac{2\pi}{365} n + a_2 \right) \]  
(3)

In addition, a new model in conjunction with a sine and cosine wave correlation is proposed and defined as follows:

\[ H = a_0 + a_1 \times \sin \left( \frac{2\pi a_2}{365} n + a_3 \right) + a_4 \times \cos \left( \frac{2\pi a_4}{365} n + a_5 \right) \]  
(4)

Where \( H \) is the daily global solar radiation and \( n \) is the number of the day of year starting from January 1. For the 1st January, \( n = 1 \), and for 31st December \( n = 365 \). \( a_0, a_1, a_2, a_3, a_4 \) and \( a_5 \) are the empirical coefficients.

### 3. Performance evaluations

In this study, the performance of the models is evaluated in terms of the mean absolute percentage error (MAPE), mean absolute bias error (MABE), root mean square error (RMSE) and correlation coefficients (\( r \)). These error terms can be calculated using the following equations:

\[
MAPE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{H_{ci} - H_{mi}}{H_{mi}} \right| \times 100
\]  
(5)

\[
MABE = \frac{1}{n} \sum_{i=1}^{n} \left| H_{ci} - H_{mi} \right|
\]  
(6)

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (H_{ci} - H_{mi})^2}
\]  
(7)

\[
r = \frac{\sum_{i=1}^{n} (H_{ci} - H_{ca}) \cdot (H_{mi} - H_{ma})}{\sqrt{\sum_{i=1}^{n} (H_{ci} - H_{ca})^2 \cdot \sum_{i=1}^{n} (H_{mi} - H_{ma})^2}}
\]

where \( H_{ci} \) and \( H_{mi} \) are the nth calculated value and measured value, respectively; \( H_{ca} \) and \( H_{ma} \) are the average of the calculated and measured values, respectively.

### 4. Results and discussion

The performance of the above four models, Eqs. (1)–(4), are evaluated at nine meteorological stations over China, namely Minqin, Shantou, Leting, Harbin, Ganzhou, Lasa, Kashi, Tulufan and Mengzi, which represent geographical and climatic conditions of their regions suggested by Lam et al. [31].

According to MAPE, MABE, RMSE and \( r \) as shown in Table 1, the proposed model, Eq. (4), has the best accuracy based on the measured data at nine stations, with the MAPE, MABE, RMSE and \( r \) in
the range of 4.004–11.999%, 0.752–1.348 MJ/m², 1.039–1.660 MJ/m² and 0.776–0.988, respectively. This indicates that we can obtain reasonably accurate data of daily global solar radiation from the proposed model. Eqs. (2) and (3) yield sound estimations, and the estimation differences among them are very slight, but their performance is second to Eq. (4); Eq. (1) yields relatively large errors with maximum MAPE value of 19.393% at Ganzhou and minimum r value below 0.6 at Mengzi. To be obvious, the MAPE, MABE, RMSE and r of the four models for the nine typical stations are shown in Fig. 2.

In terms of r, the stations with the best and worst value, i.e., Tulufan and Mengzi station are selected for further comparative investigation. Fig. 3 shows apparently that the performance of Eqs. (1)–(4) following the variation of the daily global solar radiation throughout the year at Tulufan station (Fig. 3a) is better than that at Mengzi station (Fig. 3b), mainly due to different weather conditions in these two regions, which can be seen apparently from the solar radiation variation in Fig. 3. The interest we focus is that the performance degradation of the four models according to the weather conditions is much different, and the minimum degradation of r, 0.2 (Table 1), is obtained by Eq. (4). This illustrates that Eq. (4) has better adaptability to the complicated weather conditions than the other models.

Overall evaluation, the relative performance of the four models at nine stations is that the Eq. (4) is best, followed by Eqs. (2) and (3), and Eq. (1) shows poor performance. So, for China, the daily global solar radiation can be estimated by the proposed model with better accuracy.

Based on the data at the other 70 stations, the regression coefficients and errors of the proposed model are generated for each station, as shown in Table 2. The results showed that the regression coefficients of Eq. (4) are site dependent. For most of the stations, the best performance, based on MAPE, MABE, RMSE and r is achieved by Eq. (4). The errors resulting from Eq. (4) for the 70 stations are such that the MAPE at about 77% of the stations does not go beyond 10% and has an average value of 7.960%, the MABE lies between 0.737 and 1.417 MJ/m², the RMSE stays well below 1.832 MJ/m² and the mean value of r at all stations is up to 0.937. This result is considered acceptable.

5. Conclusions

Empirical modeling is an essential and economical tool for estimating solar radiation. A trigonometric model in conjunction with a sine and cosine wave for estimating daily global solar radiation is proposed in this study. The model is compared with three existing models at nine representative stations of China by using statistical indicators such as the mean absolute percentage error (MAPE), mean absolute bias error (MABE), root mean square error (RMSE) and correlation coefficients (r). It is found that the new model can be used for estimating daily values of global solar radiation with a higher accuracy and has good adaptability to highly variable weather conditions. Then the regression coefficients and errors of the proposed model are generated at the other 70 meteorological stations of China, and the statistical indicators are at acceptable levels.

The model is very simple, fast, effective and reliable, and estimations can be derived even by a pocket calculator without tedious inputting work for meteorological measurements. There-
Fig. 3. Comparison between daily measured global solar radiation data and estimated values from Eqs. (1)–(4) at (a) Tulufan and (b) Mengzi station.
fore, the proposed model is recommended for estimating the daily global solar radiation for a specific location, which helps in evaluating the long-term performances of solar energy systems.
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