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A critical review of the models used to estimate solar radiation

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ABSTRACT

Solar radiation data is critical to the design and operation of solar energy utilization systems, so a large number of models have been proposed and developed to estimate solar radiation in the past ten years. However, the performances of such models are controversial in different studies, and there is a lack of systematic comparison among them. In addition, few studies pay attention to the time scales and practicability of the models. This paper focuses on solving these questions through a critical literature review and the authors believe it can benefit researchers to perform further investigations about solar radiation. This paper reviews and compares the models from the points of view of time scale and estimation type for the first time. Furthermore, a large amount of data about the evaluation metrics (root mean square error and mean absolute percentage error) from different studies is summarized to clarify the performances of proposed models. The questions arising from the processing of source data are also carefully examined. This paper has presented a novel method to compare the estimation models and has provided a detailed analysis on available models. The results indicate that the sunshine duration fraction models and artificial neural networks have similar performances when used to estimate monthly average daily global radiation and daily global radiation, while more work is needed to study the estimation method on smaller time intervals and the mechanisms of atmospheric attenuation for solar radiation.

1. Introduction

Solar energy is increasingly attractive in the 21st century since the environmental problems caused by burning fossil fuels are becoming severe. During the winter of 2015, the weather condition of smog has covered most of the cities located in the middle and east of China, and then caused great damage to human health and life. Another important reason for valuing solar energy is the excessive consumption of the fossil fuels with limited reserve. The shortage of fossil fuels is a worldwide long-term challenge that needs us striving for renewable and sustainable energy resources.

Solar radiation data is indispensable for designing and assessing solar energy utilization technologies. Practically measured data is the most accurate but not always readily available, which is mainly due to the initial investment and maintenance cost of the measuring instruments and relevant recorders. For instance, there are 756 meteorological stations altogether in China, among which only 122 of them have records of global solar radiation [1]. Consequently, estimating solar radiation data by correlating it with other easily measured meteorological parameters, such as sunshine duration, ambient temperature, cloud cover, humidity, etc., is an alternative method to obtain desired solar radiation data when there is no record of measurement. Many models have been proposed and developed based on this viewpoint. Some of them are concise mathematical formulas, which are convenient for engineering uses and called empirical models. Some of them are artificial intelligence techniques, such as artificial neural network, support vector machine, genetic programming, etc. Meanwhile, there are also many models utilizing satellite data and atmospheric characteristics to estimate solar radiation data, such as Rayleigh scattering, aerosol extinction, ozone absorption, etc.

In reality, the transient solar irradiance at any location, with the unit of W/m^2, keeps changing throughout the daytime, which mainly attributes to the movement of the earth and the chaotic effect of the atmosphere. There is barely any effective way can accurately estimate or predicate transient solar irradiance except practical measurement. The measurements performed in most of the official meteorological stations are for horizontal surface on the time scale of an hour with the unit of $MJ/(m^2hour)$, or a day with the unit of $MJ/(m^2day)$. These two quantities represent accumulative energy during different time spans instead of transient intensity.

In 1924, Angstrom [2] related monthly average daily global radiation to average clear-sky daily global radiation at the location in question and the sunshine duration fraction by using an empirical correlation. Since the uncertainty in the definition of a clear day, Page

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and others [3] have modified the correlation by replacing the clear-sky radiation with average daily extraterrestrial radiation on horizontal surface. In the last decades, Angstrom-Page model has become the most typical empirical model in solar engineering and is cited vastly by peers and researchers. The parameter of sunshine duration fraction in this model is extremely important in estimating solar radiation. Many subsequent studies have added different expressions of it, including quadratic, cubic, square root, logarithmic, exponential, power, etc., to Angstrom-Page model to create new empirical models, as shown in [4,5]. With the development of computer technology, researchers gradually utilize artificial intelligence techniques, statistical methods and satellite-based methods to estimate solar radiation. The incipient research field of solar meteorology has grown considerably by aggregating diverse areas of knowledge. Currently, more research papers about estimation of solar radiation keep emerging in the literature each year. Accordingly, making comparisons between them and giving recommendations are urgently necessary, which are exactly the main purposes of this study.

There are already some review papers [4–11] existing in the literature pool. Kadir [4] listed 60 empirical models developed to estimate monthly average daily global solar radiation, in which many of them had same mathematical expressions just with different regressive constants. However, according to the results of many existing studies, these constants totally depend on the locations in question. Fariba et al. [5] did a similar work to [4], collecting 78 empirical models, in which they were classified into four groups of sunshine-based models, cloud-based models, temperature-based models and other meteorological parameters-based models. Then they respectively selected several models from each group to make a case study for Yazd, Iran, in the end a sunshine-based model with exponential expression gave the best performance. Amit et al. [7] reviewed a large number of studies that had applied ANN (artificial neural network) to estimate solar radiation on horizontal surface, and three studies that had applied ANN to forecast solar radiation. However, they did not clearly consider the time scales that the estimations were made on as well as the types of the solar radiation. They concluded that ANN models were more accurate than empirical models. Rajesh et al. [9] reviewed many studies using linear empirical model and ANN models to estimate monthly average daily global radiation. They also pointed out that the ANN models were better than regression models. In addition, [10,12] and many research papers also concluded that ANN models were better than empirical models.

After examining many review and research papers, we have found several noteworthy questions on estimation of solar radiation. In addition, the author and his team have just finished building a demonstration project of 200 kW solar power plant, and such questions have been verified during the processes of design and operation. Some of above questions are presented here. 1) Few studies pay attention to the time scale of estimation when they compare the accuracy of models. Is the time scale monthly average daily, daily or hourly? It has a great impact on the performances of models and is vital for practical applications. 2) Judgments about which model is the best neglect the intrinsic quality of estimations. Such as in the estimation of monthly average daily global radiation, the monthly average data inherently is very coarse and uncertain to describe the solar radiation distribution, thus, slight improvement of accuracy does not prove the advantage of new developed models, especially when the new developed models are much more complicated than conventional models. 3) Too much work has been spent in collecting the expressions of existing models instead of the values of evaluation metrics. It provides readers with numerous models but cannot show how accurate they are. 4) This paper calls the models' outputs as "estimation" rather than "prediction" or "forecast". The reason is, these models use already measured parameters, such as sunshine duration and air temperature, to recreate the solar radiation condition in the same period. However, the ability of "prediction" or "forecast" is to estimate the solar radiation condition in the coming periods, such as 3 h ahead and 12 h ahead. There are also many papers [13–15] aiming at forecasting solar radiation condition of coming period. Section 5 has briefly introduced two of them to distinguish the difference between the terms of "estimation" and "prediction", but the detailed investigations are out of this paper. This paper specifically focuses on these aforementioned questions. In addition, we have carefully examined the data reduction processes and the rationality of the values of statistical indicators in existing studies. For example, ''monthly average'' commonly means that average the data over a month of a year, but some researchers average the data over a month first, and then they average the previous obtained data over many years for the same month. Despite the latter can result in lower values of estimation errors, the superiority and usability of the model are questionable.

The papers reviewed in this study are all from influential journals with high impact factors. The estimation is only for global solar radiation on horizontal surface, which is the most basic data in the field of measurement about solar radiation. It is noteworthy that the daily radiation and monthly average daily radiation are not very precise records for solar radiation. They can reflect the overall resource situation about solar energy, but cannot give the detailed change of the intensity. They are helpful to select the promising locations for building solar power plants, but are not practical to control an actual solar energy concentrating system. Two familiar statistical indicators MAPE (mean absolute percentage error) and RMSE (root mean square error) have been selected to compare different models, because these two indicators appear most in existing studies. Besides, the former can reflect the relative error while the latter can reflect the absolute error. The combination of them can reasonably assess the performances of models.

The rest of this paper is organized as follows. Section 2 first gives the computations of several common parameters that are often used in the models. Then the evaluation metrics and the method of reviewing and comparing existing studies are explained. Section 3 and Section 4 respectively summarize the models used to estimate monthly average daily global radiation and daily global radiation. Section 5 first describes two studies about the forecast of solar radiation, and then summarizes the models used to estimate hourly global radiation. Section 6 briefly summarizes the comparison results about different types of models and discusses the research gaps in this field.

2. Fundamental considerations

2.1. Basic parameters

The parameters of sunshine duration fraction, hourly and daily extraterrestrial radiation on horizontal surface are important for the estimation of solar radiation. It is necessary to figure out them before building a model. Sunshine duration fraction is the ratio of actual sunshine duration to maximum possible sunshine duration. Hourly extraterrestrial radiation is the solar radiation intercepted by horizontal surface during an hour without the atmosphere, and daily extraterrestrial radiation has similar definition.

The maximum possible sunshine duration S_O is

$$S_0 = \frac{2}{15}\cos^{-1}(-\tan\phi\cdot\tan\delta) \tag{1}$$

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right) \tag{2}$$

where ϕ is the latitude, δ is the declination [16], n is the ordinal number of the day in solar calendar which can be a non-integer.

Hourly extraterrestrial solar radiation on horizontal surface is