Renewable and Sustainable Energy Reviews 94 (2018) 168–182

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Evaluation of sunshine-based models for predicting diffuse solar radiation in China

Lan Feng[a], Aiwen Lin[a,*], Lunche Wang[b,*], Wenmin Qin[b], Wei Gong[c]

[a] School of Resource and Environmental Sciences, Wuhan University, Wuhan 430079, China
[b] Laboratory of Critical Zone Evolution, School of Earth Sciences, China University of Geosciences, Wuhan 430074, China
[c] State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing (LIESMARS), Wuhan University, Wuhan 430079, Hubei, China

ARTICLE INFO

Keywords:
Sunshine-based models
Diffuse solar radiation
China

ABSTRACT

Accurate observation and understanding of diffuse radiation is of vital importance for solar energy applications. Numerous empirical models have been developed for estimating solar radiation in regional and global scales, owing to the relatively sparse radiation measurements. The main objective of this study was to conduct a comprehensive evaluation of 15 typical empirical models for estimating diffuse radiation in different climate zones over mainland China. The result showed that the model in form of second order polynomial performed superior than other models, with mean MBE, MAE, MARE, RMSE, RRMSE, t-stat, STD, and R at all 17 CMA stations were $-0.125\ \mathrm{MJ\,m^{-2}day^{-1}}$, $1.331\ \mathrm{MJ\,m^{-2}\ day^{-1}}$, $0.208\ \mathrm{MJ\,m^{-2}\ day^{-1}}$,$1.807\ \mathrm{MJ\,m^{-2}\ day^{-1}}$, 24.889%, 10.866, $0.941\ \mathrm{MJ\,m^{-2}\ day^{-1}}$, and 0.792, respectively. By contrast, the model in form of fractional first order polynomial showed the poorest performance than other models, with mean MAE, MARE, RMSE, RRMSE, t-stat, STD, and R of $-0.699\ \mathrm{MJ\,m^{-2}day^{-1}}$, $2.508\ \mathrm{MJ\,m^{-2}day^{-1}}$, $0.397\ \mathrm{MJ\,m^{-2}\ day^{-1}}$, $6.779\ \mathrm{MJ\,m^{-2}\ day^{-1}}$, 102.716%, 6.709, $1.773\ \mathrm{MJ\,m^{-2}\ day^{-1}}$, and 0.519, respectively. All models generally showed poor accuracies in arid areas with warm-temperate climate, due to the frequent dust occurrences in the air. The estimation errors in Qinghai-Tibet Plateau were also relatively larger, owing to the strong heating atmosphere there. This study would assist in the selection of the most appropriate models for solar energy applications.

1. Introduction

Solar radiation is the source of energy for everything on planet earth, all life, all weather, and all activity that we know, determining the surface processes and distribution patterns [1–3]. The spatio-temporal distribution of solar radiation are closely related to the climate, landform pattern, physical, chemical and biological processes of the terrestrial ecosystem, agricultural pattern and yield, and the energy structure and industrial mix. The solar energy is clean, environmentally friendly and inexhaustible in most places throughout the year and is important especially at the time of high fossil fuel costs and degradation of the atmosphere by the use of these fossil fuels, which can be effectively utilized for many applications, including atmospheric energy-balance studies, analysis of the thermal load on buildings, designing, sizing, operation and economic assessment of energy and renewable energy systems and environmental impact analysis [4–8]. Therefore, clear understanding of regional and global solar energy distribution is of vital importance for many fields such as energy, climatology, geography, environment, ecology, industry and agriculture [9–12].

The global solar radiation on a horizontal surface consists of two parts: direct radiation and diffuse radiation (H_d). It is known that the solar radiation passing through the atmosphere is partly subjected to variations due to atmospheric scattering by air molecules, water and dust, and above scattered radiation eventually arrives at the earth surface in the form of diffuse radiation [13–16]. Changes in cloud properties, water vapor and atmospheric aerosol loadings including dust, volcanic or anthropogenic emissions greatly alter the radiation components, which directly affect the plant and crop productivity, land carbon sink and solar energy applications, it is necessary to quantitatively map the spatial-temporal characteristics of H_d at global/regional scale [17–19].

Ideally, the H_d information should be obtained from a dense network of observing stations. Despite worldwide continuous effort to establish solar radiation measurement stations in recent years, such measurements with reliable and calibrated pyranometer are either absent or only available for a very limited number of locations, especially for some developing countries [20–22]. Meanwhile, measurement of H_d data is relatively more tedious and more expensive than that for global solar radiation, and it is carried out at relatively few stations [23–25]. As a consequence, it is of great significance to determine the amount of

* Corresponding authors.
E-mail addresses: awlin@whu.edu.cn (A. Lin), wang@cug.edu.cn (L. Wang).

https://doi.org/10.1016/j.rser.2018.06.009
Received 26 November 2017; Received in revised form 5 May 2018; Accepted 4 June 2018
1364-0321/

Nomenclature

G_{sc}	solar constant (1367 Wm^{-2})
H	daily global solar radiation on horizontal surface ($MJ\,m^{-2}$)
H_d	daily diffuse solar radiation on horizontal surface ($MJ\,m^{-2}$)
H_0	daily extraterrestrial solar radiation on horizontal surface ($MJ\,m^{-2}$)
n	daily sunshine duration hours (hr)
N	daily maximum possible sunshine hours(hr)
MBE	Mean bias error ($MJ\,m^{-2}$)
MAE	Mean absolute error ($MJ\,m^{-2}$)
RMSE	Root mean square error ($MJ\,m^{-2}$)
T_a	daily averaged air temperature
T_M	daily maximum air temperature
T_m	daily minimum air temperature
R_H	daily averaged relative humidity
α	solar altitude angle (deg.)
δ	solar declination angle (deg.)
φ	latitude of the location (deg.)
ω_s	sunset hour angle (deg.)

H_d using different estimating methods.

Many empirical/semi-empirical models have been used to estimate H_d using different meteorological and geographical parameters in literature, including sunshine duration, air temperature, latitude and longitude, precipitation, relative humidity and cloudiness [26–30]. For example, Katsoulis [31] compared several H_d models for Greece; Pandey and Katiyar [32] conducted the correlations between diffuse fraction (H_d/H) and the sunshine fraction (n/N) using regression analysis method in India; Ulgen and Hepbasli [33] established a relationship between the monthly average daily cloudness index and monthly average daily diffuse coefficient with the monthly average daily clearness index and monthly average daily n/N for three big cities in Turkey (Istanbul, Ankara and Izmir); Yao et al. [34] proposed a new anisotropic diffuse radiation model and compared the model accuracy with existing Perez models based on the measured values; Park et al. [35] proposed a approach to estimate the spatial distribution of solar radiation using topographic factor and sunshine duration in South Korea; Magarreiro et al. [36] assessed the clearness index regression models and clearness index and additional parameters regression models for cloudy atmospheric conditions, the Boland-Ridley-Lauret model was shown to be the most adequate for estimating H_d in the Azores region. Jamil and Akhtar [37] analyzed the H_d models based on sky clearness index and sunshine period for humid-subtropical climatic region of India, the results showed that the diffuse fraction model in terms of sky-clearness index and relative sunshine period was found to be the most accurate. Jamil and Akhtar [22] compared 100 models which correlated diffuse fraction to sky clearness index for estimating H_d in Aligarh. Badescu et al. [38] tested 54 models for computing hourly H_d on clear sky in Romania; Wattan and Janjai [39] investigated the performance of 14 models for estimating hourly H_d on inclined surfaces at tropical sites, the results show that the Muneer and Gueymard models have comparable performances.

In recent years, various artificial intelligence (AI) methods have been used for predicting solar energy around the world [40–43]. Mellit et al. [44] proposed a adaptive model for predicting solar radiation in Saudi Arabia, which was further compared with Feed-Forward Neural Network using input combinations of sunshine duration, air temperature and relative humidity; Mohammadi et al. [45] evaluated the potential of adaptive neuro-fuzzy system for prediction of daily global solar radiation by day of the year. Mohanty et al. [46] further reviewed a number of predictive models for estimating solar radiation based on soft computing applications, such as Multilayer perceptron, radial basis function, generalized regression, genetic algorithm, back propagation, Levenberg–Marquardt, and also recommended appropriate techniques for solar energy predictions. There were also many publications regarding the H_d estimation using AI models in literature, for example, Soares et al.[40] estimated the hourly H_d in the city of São Paulo using a neural-network technique, the results showed that the inclusion of atmospheric long-wave radiation as input improves the neural-network performance; Alam et al.[47] assessed the diffuse solar energy under

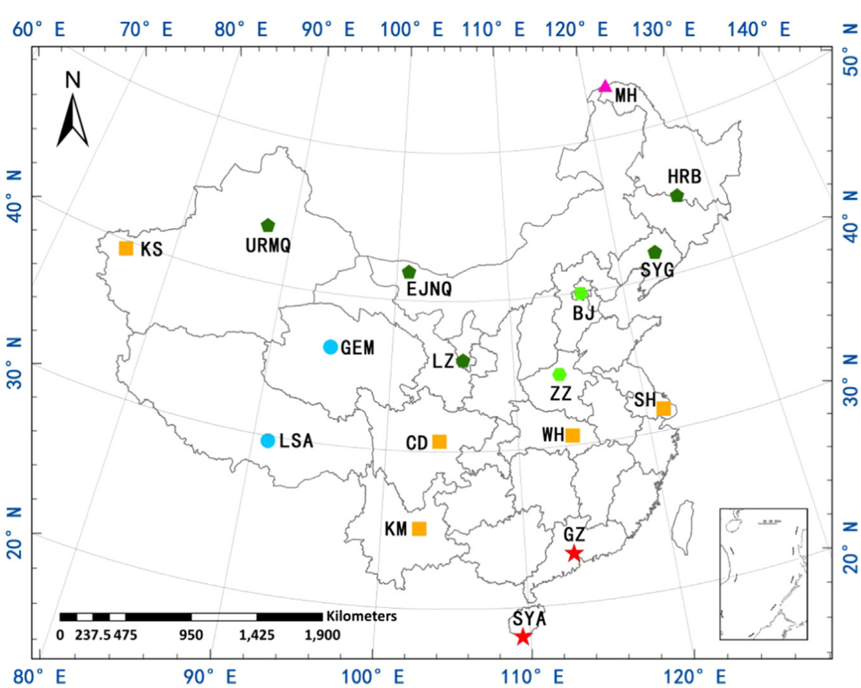

Fig. 1. The geographical distributions of radiation stations used in this study. (BJ, CD, EJNQ, GEM, GZ, HRB, KM, KS, LSA, LZ, MH, SH, SYA, SYG, URMQ, WH and ZZ are representing Beijing, Chengdu, Ejinaqi, Geermu, Guangzhou, Harbin, Kunming, Kashi, Lhasa, Lanzhou, Mohe, Shanghai, Sanya, Shengyang, Urmuqi, Wuhan and Zhengzhou sites, respectively).