Renewable and Sustainable Energy Reviews xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

The development of empirical models for estimating global solar radiation on horizontal surface: A case study

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ARTICLE INFO

Keywords:
Solar energy
Global solar radiation
Sunshine duration
Empirical models
Statistical test

ABSTRACT

This paper presents a comparison between empirical models in the literature and the development of new models for estimating global solar radiation on the horizontal surface in the city of Muğla/Turkey. The necessary meteorological data are collected using a Kipp and Zonen pyranometer installed at the University Campus of the Muğla Sıtkı Koçman University and the records are available from 2007 to 2015, inclusive. In total 105 literature models are assessed to estimate global solar radiation in the Muğla Province using MATLAB software program on the basis of statistical tests such as mean bias error (MBE), mean percentage error (MPE), mean absolute percentage error (MAPE), mean absolute bias error (MABE), root mean squared error (RMSE) and coefficient of determination (R^2). The results indicate that only two models (Veeran and Kumar/model 24, Chegaar and Chibani/model 35) are within the ±10% acceptable statistical error limits. In this paper, 7 new models are calibrated in the same manner leading to less than 0.8 error values as high R^2 values. In order to reduce the error values of these models data sets are divided into two semesters (January–June and July–December). In addition, Benson's model is investigated and compared with the previous models. Finally, it is found that the cubic and quadratic models are appropriate for January–June and July–December periods, respectively.

1. Introduction

Solar energy is known as a sustainable, reliable, environmentally friendly, pollution free and abundant energy source at the Earth's surface. This energy is released by the Sun but only part of it reaches the Earth. This situation can be analytically determined by taking into consideration the geometric relationship between the Earth and Sun [1]. In some countries, like Turkey solar radiation intensity is higher than many parts of the world. Accurate information about the solar radiation availability is very important for researchers. Global solar radiation (GSR) data are necessary for the solar energy systems design, to assess their long-term performance and to accurately estimate productivity of photovoltaic modules, which directly convert solar energy into electricity or solar thermal systems [2]. At any location, the best way to know about the availability of solar radiation is possible through the processing of satellite images and measurements from appropriate measuring instrumentations such as pyranometers or pyrheliometers at a set of locations in a region with day-by-day recording, maintenance and calibration. However, in many developing countries, like Turkey, current solar radiation measurements are not easy to obtain due to old/defective measuring devices and rather old techniques.

An alternative approach is to develop a relationship between astronomical, physical, meteorological and geographical parameters that are recorded at a location. The correlation between these parameters and GSR can be used to estimate the GSR at the location and time. Using this approach, empirical models for surface of the earth may be established using a variety of parameters to calculate GSR. These parameters may comprise sunshine duration, extraterrestrial radiation, mean and maximum ambient temperature, relative humidity, soil temperature, altitude, latitude, number of rainy days, evaporation, cloudiness and total precipitation. The most common parameter used to estimate GSR is sunshine duration. In the absence of sunshine duration, the other parameters can be a useful alternative. Sunshine duration may easily and reliably measured as the availability of such data is wide [3]. The first model to estimate solar radiation using sunshine duration was recommended by Angstrom [4] relating GSR to clear day radiation. On the other hand, Prescott [5] suggested the use of the extraterrestrial radiation. Innovations related to the improvement of the Angstrom-Prescott model are related to efficient use of the

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http://dx.doi.org/10.1016/j.rser.2017.06.082
Received 6 October 2016; Received in revised form 20 March 2017; Accepted 22 June 2017
1364-0321/

Nomenclature

a, b	Empirical constants
d	Day of the year
E	Relative percentage error, %
G_{sc}	Solar constant, kW h/m^2
H	Terrestrial global solar radiation on horizontal surface, kW h/m^2
H_i	Calculated global solar radiation value, kWh/m^2
H_m	Measured global solar radiation value, kWh/m^2
$\overline{H}_m$	Average value of measured global solar radiation, kWh/m^2
H_o	Extraterrestrial global solar radiation on horizontal surface, kWh/m^2
K_T	Daily clearness index
$MABE$	Mean absolute biased error, kWh/m^2
$MAPE$	Mean absolute percentage error, %
MBE	Mean biased error,, kWh/m^2
n	Average sunshine duration
N	Cloudless sunshine duration
$RMSE$	Root mean square error, kWh/m^2
δ	Declination angle,
φ	Latitude angle,
ω_s	Sunrise angle,

correlation. Later efforts have concentrated on improving the accuracy of estimations and general validity of this model. Additionally, there are countless studies published in the literature about the estimation of solar radiation in different regions over the Earth based on the Angstrom-Prescott model.

Taking into account the geographical location of Turkey, solar energy is one of the most promising renewable energy sources. The annual mean solar radiation for Turkey varies between 1200 and 1700 kWh/m^2/year and sunshine duration is determined at 2640 h/year [6]. Unfortunately, in many developing countries, solar radiation measurements are not easily recorded due to high cost of measuring equipments and requirements for maintenance and calibration. An alternative solution to this problem is to use a modeling approach to estimate solar radiation. In spite of the amount of studies on the development of empirical models to determine GSR for locations in Turkey, in the previous studies there is no empirical correlation found for Muğla. The correlation developed in this study allows for easy estimation of solar radiation necessary for solar device and structure designs with passive solar heating. Some models only with sunshine duration data are validated and statistically compared in the estimation of GSR on a horizontal surface in Muğla, one of Turkey's richest provinces in terms of solar radiation. The statistical evaluation of current and new models in this study uses solar radiation data obtained from a Kipp & Zonen pyranometer located in the Campus of Muğla Sıtkı Koçman University and recorded between 2007 and 2015. Thus a general model is developed for use in areas where there are current solar radiation data including places with missing or unavailable data.

2. A review of empirical sunshine duration based GSR models

There have been numerous studies on the estimation of the GSR on a horizontal surface. An initial empirical correlation was proposed by Angstrom [4], which correlated GSR with sunshine duration and clear sky radiation. The Angstrom correlation was adjusted by Prescott [5] and Page [7], which can be used by replacing clear sky radiation component by the extraterrestrial radiation. Their modifications are being used widely to estimate global irradiance [8], and furthermore machine learning based techniques (artificial neural network [9–14], fuzzy logic [15–18], support vector machine [19–21]) are also used recently for this purpose [22–25].

The studies conducted to estimate only GSR except machine learning based techniques for any place on earth can be summarized as follows: Tiris et al. [26] developed empirical equations for monthly average daily horizontal global, diffuse and beam radiations with the fraction of maximum possible number of sunshine hours in Gebze/Turkey between 1984 and 1992. In another study, Tiris et al. [27] employed a correlation of monthly average hourly global and diffuse solar radiation to clearness-index for a statistical procedure. Monthly-average hourly data of global and diffuse solar radiation on a horizontal surface is used in Gebze/Turkey in the period 1984–1992. A quadratic relationship between solar insolation and sunshine duration in order to estimate monthly average global irradiance was analyzed by Aksoy [28] for Ankara, Antalya, Samsun, Konya, Urfa and Izmir in Turkey with data from 1993 to 1995. An analysis of measured solar radiation at Gebze/Turkey between 1984 and 1992 is mentioned in Tiris and Tiris [29]. They derived the correlation models for calculating the hourly and monthly diffuse radiations. In a very similar study, it was carried out by Kaygusuz and Ayhan [30] for the period from 1990 to 1993 in Trabzon/Turkey

The effect of geographical and meteorological parameters on the monthly mean GSR between 1994 and 1995 years in Elazig/Turkey is analyzed by Togrul and Onat [31]. The monthly average GSR in Elazig was estimated with a −9% average error. In addition, Togrul et al. [32] investigated the usability of clear sky radiation for predicting the average GSR in Antalya, Izmir, Ankara, Yenihisar (Aydın), Yumurtalık (Adana) and Elazig in Turkey. Solar radiation data for Antalya/Turkey was used by Ertekin and Yaldiz [33] to test the applicability of 26 models available for computing the monthly average daily GSR on a horizontal surface. Sen and Tan [34] worked an extensive statistical analysis of hourly, daily and monthly measured solar radiation for Gebze Province in Turkey.

Ogulata and Ogulata [35] used measured monthly mean daily global radiation data of Adana/Turkey for GSR estimation. They determined hourly global, diffuse and direct solar-radiations on a horizontal surface. Ulgen and Hepbasli [36] developed empirical correlations (models) to estimate the monthly average daily GSR based on a clearness index for the period 1993–1999 in the city of Izmir/Turkey. They compared the derived models with 25 models available in the literature for calculating monthly average daily global radiation. The models obtained for Izmir produced better results than others. Togrul and Togrul [37] examined the variation of GSR at the Elazig/Turkey on hourly and monthly average daily basis using daily GSR between 1994 and 1995. Akpabio and Etuk [38] used measurements of GSR and sunshine duration data during the period from 1984 to 1999 at Onne/Nigeria to establish an Angstrom-type correlation equation. A good agreement was observed between the measured and the predicted values.

Ulgen and Hepbasli [39] reviewed 41 solar radiation models for Turkey. Most of them were developed in Turkey in the period 1983–2002 and have the polynomial forms. Ahmad and Ulfat [40] obtained a new set of constants for the Angstrom relationship correlation of first and second order, to estimate the monthly average GSR, employing sunshine duration data recorded at Karachi/Pakistan. Almorox and Hontoria [41] employed several equations (Angstrom–Prescott linear regression and modified functions like quadratic, third degree, logarithmic and exponential functions) to estimate GSR from sunshine duration at 16 meteorological stations in Spain. Tarhan and Sarı [42] analyzed global and diffuse radiations for five Provinces include Amasya, Corum, Ordu, Samsun and Tokat in Turkey to guide future projects. They showed that the developed models were adequate for solar radiation prediction. Jin et al. [43] developed the formula for