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Comparison of empirical models to estimate monthly mean diffuse solar radiation from measured data: Case study for humid-subtropical climatic region of India

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ABSTRACT

This study demonstrates the performance comparison of the models to estimate monthly mean diffuse solar radiation on a horizontal surface for Humid-Subtropical Climatic Region of India. Meteorological data (global and diffuse solar radiation) were observed for the city of Aligarh (27.89°N, 78.08°E) at the Heat Transfer and Solar Energy Laboratory, Department of Mechanical Engineering, Aligarh Muslim University, Aligarh. The mean global, beam and diffuse solar radiation values for Aligarh were observed as 22.12 MJ/m^2-day, 14.20 MJ/m^2-day and 7.92 MJ/m^2-day respectively. The mean values of sky-clearness index, diffuse fraction and diffusion coefficient were found to be 0.69, 0.37 and 0.25, respectively. The region exhibits abundant potential for solar energy utilization with favorable sky conditions. Diffuse solar radiation models with single input parameter (in the form of global solar radiation) were analyzed for suitability of estimation. 100 typical models were selected from the literature which correlated diffuse fraction (ratio of horizontal diffuse to global solar radiation) to sky-clearness index (ratio of global to extraterrestrial solar radiation). The objective here was to find the most precise model which is suitable to assess diffuse solar radiation in the region considered. Distinctive statistical evaluation of the models was performed in terms of well-known statistical indicators. Further, the scaled values of statistical indicators were used to calculate Global Performance Indicator (GPI). GPI of the selected models lied in the range of from −4.2987 to 2.6606 with the highest value representing the best performing model. Models were subsequently ranked in order of descending GPI. This study helps to recognize the significance of diffuse solar radiation models where the absence of required equipment as well as high cost of operation and maintenance represents a critical barrier for measurement. The outcomes of the present study are valuable for locations within the developing countries and remote areas with similar climatic conditions.

1. Introduction

Solar energy in the form of radiations received at the ground level on earth is the most preferred sustainable source of renewable energy due to its inexhaustible nature and abundant availability around the world. This clean source of energy can readily be exploited for numerous solar based applications [1,2]. For the better utilization in solar energy system and exploitation in solar energy based devices, it is necessary to assess the availability of solar radiation for the region of interest. Bakirci [3] reported that it is of upmost importance to have accurate information on solar radiation for the development of solar based devices for the desired location. Also this information is useful to create long-term meteorological forecast of the solar energy systems. Based on the area of application, some methodologies of solar radiation assessment will be more appropriate than others depending on the information required and the overall goal set for the system to achieve. However, for large scale solar energy applications, the functionality of the devices is related to monthly mean values of daily incident solar radiation [4]. Estimation of solar radiation using empirical models is a widely adopted technique used to evaluate or assess solar energy at the location of interest prior to setting up the solar based device or equipment [5]. Solar radiation can be estimated by way of processing pictures obtained from satellites or horizontal ground based surface measurements with devices like pyranometers in meteorological stations [6]. Nevertheless, as a result of a sequence of barriers posed due to absence of required equipment as well as high cost of operation and maintenance of these equipment the measurement of solar radiation data are usually not readily accessible. This is the case for many developing countries and even remote areas in many others. In fact, there has been considerable efforts to create solar radiation meteor-

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Nomenclature

$\overline{H}_0$ monthly mean extraterrestrial horizontal solar radiation (MJ/m^2-day)
$\overline{H}_b$ monthly mean daily beam horizontal solar radiation (MJ/m^2-day)
$\overline{H}_d$ monthly mean daily diffuse horizontal solar radiation (MJ/m^2-day)
$\overline{H}_g$ monthly mean daily global horizontal solar radiation (MJ/m^2-day)
H_{sc} solar constant (=1367 W/m^2)
$\overline{H}_{ie}$, $\overline{H}_{im}$ i^{th} estimated and measured monthly mean daily solar radiation (MJ/m^2-day)
$\overline{H}_{m,av}$ average of measured values of solar radiation (MJ/ m^2-day)
$\overline{K}_T$ monthly mean sky clearness index ($=\overline{H}/\overline{H}_o$)
$\overline{K}_d$ monthly mean diffuse fraction($=\overline{H}_d/\overline{H}$)
$\overline{K}_D$ monthly mean diffusion coefficient($=\overline{H}_d/\overline{H}_o$)
m number of observations
n day of the year

Greek letters

α weight factor in GPI (−1 or 1)
δ angle of declination (degrees)
ϕ latitude (degrees)
ω_s mean monthly sunset hour angle (degrees)

Abbreviations

erMAX Maximum absolute relative error
GPI Global Performance Indicator
HSCR Humid-Subtropical Climatic Region
MAE Mean Absolute Error (MJ/m^2-day)
MARE Mean Absolute Relative Error
MBE Mean Bias Error (MJ/m^2-day)
MPE Mean Percentage Error (%)
RMSE Root Mean Square Error (MJ/m^2-day)
RRMSE Relative root mean squared error
R^2 Coefficient of determination
SD Standard Deviation (%)
$t-stats$ t-statistics
U_{95} Uncertainty at 95% (MJ/m^2-day)

ological stations in current years, but still the data monitored are not adequate and do not suffice the requirements of proper measurement. This is typically true for the case of diffuse solar radiation since the nature of these radiations are quite erratic depending on the geography, local environment and characteristic features of the location. As a result, estimation techniques have widely been adopted to quantify horizontal diffuse solar radiation.

Global solar radiation is an important independent and useful parameter deployed in the development of empirical models used to assess horizontal mean diffuse solar radiation [7]. Diffuse solar radiation in non-dimensional form is described as diffuse fraction (ratio of diffuse to global solar radiation) or diffusion coefficient (ratio of diffuse to extraterrestrial radiation). These non-dimensional forms are then related in terms of sky-clearness index (ratio of global to extraterrestrial solar radiation) for the development of models. Liu and Jordan [8] established this form of primitive approach. Their correlation is considered one of the pioneering works in the field of solar radiation analysis. This method of correlation has been used by many researchers over the years by modification in the coefficients while others have utilized the correlation as such for estimation purposes. This has also been observed in the recent years that a number of similar methods or correlations by numerous researchers in diverse locations exists (like Al-Mohamad [9], Diez-Mediavilla et al. [10], Tarhan and Sari [11], Aras et al. [12] and Noorian et al. [13] to name a few). Therefore one can consider utilizing these existing diffuse solar radiation models for estimation instead of developing new correlations at the location of interest [14]. Other practices have been developed by Haydar et al. [15], Boland et al. [16], Boland et al. [17], Iqbal [18] where diffuse fraction was correlated with sunshine duration, while some others correlated diffuse fraction with the clearness index like Oliveira et al. [19], Tarhan and Sari [20] and Jacovides [21] etc. Factors such as maximum, minimum and average ambient temperatures, cloud cover, relative humidity etc. have also been deployed to evaluate diffuse solar radiation models [22].

El Mghouchi et al. [23] evaluated four empirical models available in literature to predict the global, direct and diffuse solar radiation for Tetuan City, Morocco and describe the suitability of model based on the statistical analysis. Cao et al. [24] compared solar radiation from website data, solar radiation model, TRNSYS software and measurements for Northern China. They reported that a combination of sunshine duration and day of the year together can lead to better accuracy models for estimation of diffuse solar radiation. Božnar et al. [25] developed a simple method using neural network-based technique for diffuse solar radiation. They further tested the model on two locations under different climates and reported that the model was transferable between the two locations.

Jamil and Akhtar [26] explored global, direct and diffuse solar radiation measurement for Aligarh, India. And developed new model by correlating diffuse fraction and clearness index. Models were proposed by El-sebaii and Trabea [27] correlating diffuse fraction and diffuse transmittance with sky-clearness index and relative sunshine period. Few investigators like Soares et al. [28] also utilized neural-network technique to assess diffuse solar radiation using global solar radiation and other meteorological parameters. Şenkal and Kuleli [29] adopted a similar technique of neural-network by calculating diffuse and direct solar radiation for clear-sky as a function of turbidity factor, Rayleigh optical thickness and optical air mass. Chaiyapinunt et al. [30] discussed the use of shadow ring device for measurement of diffuse solar radiation on vertical surfaces. They studies the effect of location for installation and ground reflectance on the performance of shadow-ring device and concluded that the performance was satisfactory. Wattan and Janjai [31] investigated performance of 14 radiation models at two sites in the tropics for predicting hourly diffuse sky irradiation on inclined surfaces. Ulgen and Hepbasli [32] proposed eight new models under four different categories to estimate the diffuse solar radiation in Turkey and discussed their application and suitability in three major locations. They also suggested the use of developed models for locations under similar climatic conditions. Kaygusuz [33] measured data for Trabzon, Turkey and developed seven empirical models to estimates diffuse radiation based on atmospheric parameters. Similar methodology was followed by Bakirci [34], who proposed six new models based on the average solar radiation values obtained out of 10 models available in the literature to estimate the monthly average daily diffuse solar radiation for Erzurum, Turkey. Shamshirband et al. [35] demonstrated the estimation of diffuse solar radiation by support vector machine-wavelet transform (SVM-WT) model. Ruiz-Arias et al. [36] and Furlan et al. [37] proposed new regressive model based on the sigmoid function for the estimation of