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Comparative analysis of diffuse solar radiation models based on sky-clearness index and sunshine period for humid-subtropical climatic region of India: A case study

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ABSTRACT

In the present work, long-term solar radiation assessment was performed for three years (September 2013 to August 2016) in Humid-Subtropical Climatic Region of India for the city of Aligarh (27.88°N, 78.08°E). Annual average global, beam and diffuse solar radiation values for Aligarh were observed as 21.01 MJ/m^2-day, 13.40 MJ/m^2-day and 7.61 MJ/m^2-day. Annual average sky-clearness index, diffuse fraction and diffusion coefficient were found to be 0.66, 0.37 and 0.24 respectively. Ground based global solar radiation measurements were compared with the available satellite data of the closest coordinate location (27.50°N, 78.50°N). Strong association was found between the ground measurements and satellite data. Further, empirical models for estimation of monthly mean diffuse solar radiation were developed using ground-based measured data. Diffuse solar radiation was modelled in terms of single and two input variables (namely sky-clearness index and relative sunshine period). A total of 42 new models in six different categories were developed. Proposed models were also compared with well-established models from literature. Models were assessed for performance in terms of ten most frequently used statistical indicators. Subsequently, proposed models were ranked in order of suitability of estimation within their respective category as well as among the group of all the developed models using Global Performance Index (GPI). Overall GPI of developed models was found in the range of −1.2677 to 5.5596 with the highest value representing the best model. It was inferred that two input variable models perform much better in comparison to single variable input models. Among the two variable models, diffuse fraction model in terms of sky-clearness index and relative sunshine period (each in order one) was found to be the most accurate. Excellent agreement was affirmed between estimated and measured values from two variable models. The use of single variable models was also suggested within reasonable accuracy.

1. Introduction

Among the available forms of renewable energy resources, solar energy has received considerable attention due to its abundance on the surface of the earth. The use of solar energy can help alleviate the requirement of conventional energy resources. It is therefore for this reason that solar energy is deemed to be a perfect solution to the energy crisis the world is experiencing today. This makes solar energy a sustainable form of energy suitable for varied applications [1]. Knowledge of solar radiation and its components is important to analyze incident solar radiation on horizontal as well as on inclined surfaces as suggested by many researchers in literature [2–4]. Solar surfaces find application in solar thermal as well as PV systems [5]. Particular examples include building integrated photovoltaic modules [6], amorphous and polycrystalline solar PV panels [7], building integrated photovoltaics [8,9], grid-connected photovoltaic system for residential building [10,11] etc.

Therefore, a solar radiation database needs to be established for the region of interest. This is a prerequisite to installation and commissioning of solar energy based establishments. However, it is not always possible to carry out detailed monitoring of local meteorological conditions. This is the case for many developing countries (like India), where although solar radiation potential may be high, but the lack of adequate solar radiation information leads to lesser number of energy schemes being explored and implemented.

The quality of solar radiation is often defined in terms of its components, namely, beam solar radiation and diffuse solar radiation. Among these components, the amount of diffuse solar radiation is always uncertain, since it is mostly affected by many local geographical factors and climatic features in addition to the location parameters.

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Nomenclature

$\overline{H}_0$	monthly mean extraterrestrial solar radiation (MJ/m^2-day)
$\overline{H}_b$	monthly mean daily beam solar radiation (MJ/m^2-day)
$\overline{H}_d$	monthly mean daily diffuse solar radiation (MJ/m^2-day)
$\overline{H}$	monthly mean daily global 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)
$\overline{H}_{e,av}$	average of estimated values of 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	day of the year
n	day of the year
$\overline{S}_o$	maximum possible sunshine period (hours)
$\overline{S}$	monthly mean daily sunshine period (hours)

Greek letters

α	weight factor in GPI
δ	angle of declination (degrees)
ϕ	latitude (degrees)
ω_s	sunset hour angle (degrees)

Abbreviations

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

This makes the estimation of diffuse solar radiation an important task. Most of the available databanks furnish information on global solar radiation and lacks data on diffuse solar radiation due to relatively higher cost incurred in setting up the meteorological facility for monitoring the components. Consequently, diffuse solar radiation is usually estimated by means of the empirical models.

Different types of models for estimation of horizontal monthly mean diffuse solar radiation have been proposed in literature using input variables such as global solar radiation and sunshine period together with other climatic variables like humidity, pressure, precipitation levels and temperatures etc. Among these, global solar radiation and sunshine period are important variables used in the development of empirical models for diffuse solar radiation [12].

Liu and Jordan [13] established this form of primitive approach. Their correlation is considered one of the pioneering works in the field of solar radiation analysis. Their form of correlation has been used by many researchers over the years by calibrating the coefficients. This can be observed in a number of similar approaches in numerous research works proposed for diversified locations like Al-Mohamad [14], Diez-Mediavilla et al. [15], Tarhan and Sari [16], Aras et al. [17], Noorian et al. [18], Miguel et al. [19] and Khorasanizadeh and Mohammadi [20] to name a few. Such classical practices have been extended by Haydar et al. [21], Boland et al. [22], Boland et al. [23] and Iqbal [24] where diffuse fraction was correlated with sunshine period, while others researchers correlated diffuse fraction with the sky-clearness index (like Oliveira et al. [25], Tarhan and Sari [26], Jacovides et al. [27] and Karatasou et al. [28] etc). Other meteorological factors have also been deployed to evaluate diffuse solar radiation models [29,30].

In recent years, many researchers have explored the possibility of various correlations for estimation of diffuse solar radiation. El Mghouchi et al. [31] evaluated four existing empirical correlations to calculate the global, diffuse and beam solar radiation for Tetuan City, Morocco and described the suitability of model based on the statistical analysis. Jin et al. [32] derived a diffuse solar radiation model with functional form similar to Liu and Jordan model using the measured data of 78 locations in China. MBE and RMSE were used to statistically analyze the application of models under the locations considered. Ulgen and Hepbasli [33] analyzed the hourly global and diffuse radiation measurements monitored for over 5 year period (1994–1998) for Izmir, Turkey. Two new models correlating diffuse fraction with sky-clearness index (first and third-order polynomial) were developed and compared with 16 available models from literature. The developed models were found to have better performance for the region considered. Dervishi and Mahdavi [34] compared eight diffuse solar radiation models using measured data of global solar radiation for Vienna, Austria. They stated that calibration of the models (using new regression coefficients) can slightly improve the performance of the models. Khahro et al. [35] estimated the horizontal diffuse solar radiation using the available models from literature. They developed nine new diffuse solar radiation models correlating diffuse fraction and diffusion coefficient with relative sunshine period and sky-clearness index. Based on statistical test analyses it was reported that cubic model of diffuse fraction in terms of relative sunshine period provide the best estimates. Li et al. [36] discussed the estimation of diffuse solar radiation in regions without measurements of solar radiation. They classified and compared models under different approaches of H-based and non-H methods. It was suggested that non-H method is more accurate for estimation of diffuse radiation. Cao et al. [37] compared solar radiation values obtained from website data, solar radiation model, TRNSYS software and measurements for Northern China. They reported that a combination of sunshine period together with Julian day lead to better accuracy of models for diffuse solar radiation. Jamil and Akhtar [38] explored global, beam and diffuse solar radiation measurement for Aligarh, India and proposed model for diffuse fraction in terms of sky-clearness index with a new set of regression coefficients. Models were proposed by El-sebaii and Trabea [39] correlating diffuse transmittance and diffuse fraction with sky-clearness index and relative sunshine period. Tapakis et al. [40] analyzed the solar radiation measurements performed for the region of Cyprus and developed diffuse radiations correlation based on sky-clearness index and solar altitude. They concluded that introducing solar altitude improved the accuracy of the correlations. It was further reported that separation of the dataset into smaller subgroups resulted in higher accuracies at higher elevation angles. Wattan and Janjai [41] investigated performance of 14 radiation models at two sites in the tropics for predicting hourly diffuse sky irradiation on inclined surfaces. Ulgen and Hepbasli [42] proposed eight new models under four different categories to assess diffuse radiation; and discussed their application and suitability in three major locations in Turkey. They also suggested the use of developed models for locations under similar climatic conditions. Kaygusuz [43] measured data for Trabzon, Turkey and developed seven empirical models to estimates diffuse radiation based on atmospheric parameters. Similar methodology was followed by Bakirci [44], who proposed six new models based on the mean