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Comparative study of isotropic and anisotropic sky models to estimate solar radiation incident on tilted surface: A case study for Bhopal, India

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ABSTRACT

The purpose of this study is to compare the different empirical models used for estimation of solar radiation on tilted surface. For this, three isotropic and same number of anisotropic sky models were employed by using average monthly mean value of solar radiation on daily basis at Bhopal, local climatic condition, located in central region of India. The tilt angle was fixed at 23.26° N (latitude of Bhopal). The models results were compared with ground measured data from one sample statistical test. It was found that Hays and Davis model (HD) estimated the highest amount of incident solar radiation in the whole year whereas Badescu model (BA) established the lowest among all isotropic as well as anisotropic models. Finally, Badescu model (BA) was preferred for estimation of solar radiation incident on tilted surface with smallest statistical errors among all models and closed agreement with measured data.

1. Introduction

Solar radiation data are the best source of information for estimating average incident radiation necessary for proper design and the assessment of solar energy conversion systems (Sabziparvar, 2008). There are several forms of solar radiation data, which could be used for a variety of purposes in the design and development of solar energy systems (Jakhrani et al., 2012). Daily data is often available and hourly radiation can be estimated from available daily data. The availability of more comprehensive solar radiation data is invaluable for the design and evaluation of solar-based conversion systems. Particularly, the basic solar radiation data for the surfaces of interests are not readily available in most developing countries (Li et al., 2008; El-Sebaii et al., 2010). Because of not being able to afford the measuring equipments and techniques involved. Therefore, it is necessary to develop methods to estimate the solar radiation on the basis of the more readily available meteorological data (El-Sebaii et al., 2010).

Several models have been developed to estimate the amount of global solar radiation on horizontal surfaces using various climatic parameters, such as sunshine duration, cloud cover, humidity, maximum and minimum ambient temperatures, and wind speed (El-Sebaii et al., 2010).

Wu et al. (2007) used the metrological data from 1994 to 2005 of Nanchang station (China) to predict daily global solar radiation from sunshine hours, air temperature, total precipitation and dew point. Wu et al. (2007) and Bulut and Buyukalaca (2007) recently proposed a simple model for estimation of monthly average of daily global solar radiation on horizontal surface for 68 provinces of Turkey with a high accuracy (Bulut and Buyukalaca, 2007). Janjai et al. (2009) proposed a model for calculating the monthly average hourly global radiation in the tropics with high aerosol load using satellite data. This model was employed to generate hourly solar radiation maps in Thailand (Janjai et al., 2009).

It is rather important to determine the beam and diffuse components of total radiation incident on a horizontal surface. Once these components are determined, they can be transposed over tilted surfaces, and hence, the short as well as the long term performances of tilted flat plate collectors, photovoltaic modules and other solar devices can be estimated. Many authors have presented empirical correlations to estimate the monthly average daily diffuse radiation on a horizontal surface. El-Sebaii and Trabea (2003) proposed correlations for estimating horizontal diffuse radiation in Egypt by correlating (H_d/H_g) and (H_d/H_o) with K_T and $(S/S_{\max})$ (El-Sebaii and Trabea, 2003). Solanki and Sangani (2008)

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Nomenclature

$\bar{H}_o$: Monthly Average daily extraterrestrial solar radiation (kWh/m^2-day)
I_{SC}: Solar constant 1.367 kW/m^2
N: Day of the year
$\bar{H}_g$: Monthly average daily global solar radiation (kWh/m^2-day)
a, b: Angstrom constants (for Bhopal $a = 0.26$, $b = 0.05$)
s: Monthly average daily hours of bright sunshine (hours)
S_{max}: Monthly average of the maximum possible daily hours (day length) of bright sunshine
$\bar{H}_d$: Monthly average daily defused radiation (kWh/m^2-day)
K_T: Monthly average clearness index
$\bar{H}_T$: Total incident solar radiation on tilted surface (kWh/m^2-day)
$\bar{H}_{T,b}$: Beam radiation on tilted surface (kWh/m^2-day)
$\bar{H}_{T,d}$: Defused radiation on tilted surface (kWh/m^2-day)
$\bar{H}_{T,r}$: Ground reflected radiation on tilted surface (kWh/m^2-day)
$\bar{H}_b$: Monthly average daily beam radiation on horizontal surface (kWh/m^2-day)
$\bar{R}_b$: View factor for beam radiation
$\bar{R}_r$: View factor for ground reflected radiation
$\bar{H}_{d,iso}$: Isotropic diffused radiation
$\bar{H}_{d,cs}$: Circumsolar component of diffused radiation
$\bar{H}_{d,hz}$: Horizon brightening component of diffused solar radiation
$\bar{H}_{gm}$: Metrological ground measured global solar radiation at horizontal surfaces (kWh/m^2-day)
$\bar{H}_{gmt}$: Metrological ground measured tilted global solar radiation (kWh/m^2-day)
MAPE: Mean Absolute Percentage Error (%)
MBE: Mean Bias Error (kWh/m^2-day)
RMSE: Root Mean Square Error (kWh/m^2-day)
t-set: t-statistics error
HD: Hay and Davies Model
BA: Badescu Model
LJ: Liu and Jordan Model
KO: Koronakis Model
RE: Reindl et al. Model
HDKR: Hay and Davies, Klucher Model
IMD: Indian Metrological Department
A: Anisotropy index
F: Modulating factor
$F_{c\text{-}s}$: View factor for circum solar diffused radiation
$F_{c\text{-}hz}$: View factor for horizon brightening solar diffused radiation

Greek symbols

γ: Azimuth angle (degree)
β: Tilted angle (degree)
ω: Hour angle (degree)
ω_s: Sunset hour angle for mean day of month (degree)
Φ: Latitude angle (degree)
θ: Angle of incidence (degree)
θz: Zenith angle (degree)
ε: Elevation angle (degree)

proposed a new method which may be used for estimating H_b on the basis of calculation of the elevation angle constant (ε) for a given location and time (Solanki and Sangani, 2008). Ozan and Tuncay (2009) proposed artificial neural-network using satellite data were also used to estimate monthly mean daily average of horizontal direct and diffuse radiation in different cities of Turkey (Ozan and Tuncay, 2009).

Furthermore, meteorological stations usually measure solar global and diffuse radiation intensities on horizontal surfaces. Measured solar radiation data on tilted surfaces are rarely available. Consequently, the solar radiation incident on a tilted surface must be determined by converting the solar radiation intensities measured on a horizontal surface to that incident on the tilted surface of interest in order to design the system size and estimate its long term performance.

It is generally known that in the northern hemisphere, the optimum collector orientation in south facing ($\gamma = 0$) and the optimum tilt depend upon the latitude and the day of the year. In winter month, The optimum tilt is greater (usually latitude + 15) whilst in summer months the optimum tilt is less (usually latitude − 15). There are many papers in the literature which make different recommendations for the optimum tilt based only on the latitude Sudhakar et al. (2013). In practice the collector plate is usually oriented south facing and latitudinal fixed tilt angle which is set to maximize the average energy collected over a year (Ahmad and Tiwari, 2009).

Total radiation incident on a tilted surface consists of three components: beam radiation, diffuse radiation and ground reflected radiation. The beam radiation on a tilted surface can be computed by the relatively simple geometrical relationship between the horizontal and tilted surfaces. The ground reflected radiation can be estimated with good accuracy with the aid of an isotropic model using a simple algorithm. This is not the case regarding the diffuse component, since diffuse radiation has no define or (singular) angle of incidence on a horizontal surface. There exist a relatively large number of models that attempt to correlate the diffuse radiation on a tilted surface to that measured on a horizontal surface. Generally, these models may be classified as isotropic and anisotropic sky models.

The isotropic models assume that the intensity of diffuse sky radiation is uniform over the sky dome. Hence, the diffuse radiation incident on a tilted surface depends on a fraction of the sky dome seen by it. The anisotropic models on the other hand, presume that the anisotropy of the diffuse sky radiation in the circumsolar region (sky near the solar disk) plus the isotropically distributed diffuse component from the rest of the sky dome (horizon brightening fraction) (Noorian et al., 2008). In general, the diffused fraction of radiation on inclined surfaces is composed of isotropic, circum solar and horizon brightening factors.

The main objectives of this paper are:

1. To estimate the monthly average daily global, diffused and beam solar radiation on horizontal surface in Bhopal using the different empirical relations.
2. To calculate the total solar radiation incident on tilted surface at tilt angle 23.26°N (latitude of Bhopal) using 6 selected empirical models.
3. Compare each model with measured data using statistical tests which includes namely MAPE, MBE, RMSE, and t-stat.

Measured solar radiation data comprising of monthly average daily global solar radiation for Bhopal have been collected average of last several years from Indian Meteorological Department (IMD) for horizontal and latitudinal tilted surface (Karakoti et al., 2012).