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Full Length Article

Estimation of solar radiation and optimum tilt angles for south-facing surfaces in Humid Subtropical Climatic Region of India

Basharat Jamil *, Abid T. Siddiqui, Naiem Akhtar

Heat Transfer and Solar Energy Laboratory, Department of Mechanical Engineering, Aligarh Muslim University, Aligarh 202002, Uttar Pradesh, India

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ABSTRACT

In the present work, availability of solar radiation for south-facing flat surfaces in Humid Subtropical Climatic Region of India has been estimated. Measurements of global and diffuse solar radiation for Aligarh (27.89°N, 78.08°E) which lies in the Humid Subtropical Climatic Region were performed for over a period of three years. Monthly, seasonal and annual optimum tilt angles were estimated. Comparison of total incident solar radiation was performed between Aligarh and New Delhi (Capital of India, 28.61°N, 77.20°E). Annual optimum tilt angle for Aligarh and New Delhi was found as 27.62° and 27.95° respectively (close to the latitude of the respective location). Estimated gains in annual average solar radiation (based on monthly, seasonal and annual optimum tilt angles) in comparison to a horizontal surface were 12.92%, 11.61% and 6.51% (for Aligarh) and 13.13%, 11.80% and 7.58% (for New Delhi) respectively. A loss of 1.16% and 5.68% energy (for Aligarh) and 1.18% and 4.91% (for New Delhi) were estimated with surface at seasonal and annual optimum tilt angles respectively compared to a surface at monthly optimum tilt angle. Based on the study, it was recommended that the inclined surface must be tilted on monthly or seasonal optimum tilt angle for better utilization of solar energy.

1. Introduction

Increasing demand of energy in domestic and industrial processes has burdened the energy resources to be consumed readily releasing huge amounts of pollutants affecting the environment. Solar energy is deemed to be the perfect solution to the world's dependence on conventional fuels. Solar radiations on the surface of the earth at absolute no cost makes it to be the perfect contender to energy crisis.

In India, during the summer season over 90% of the country receives a significant amount of solar radiations of the order of 3.0–6.5 kWh/m^2-day (10.8–23.4 MJ/m^2-day) (as shown in Fig. 1). However, in northern parts of the country this value can reach a maximum value of 7.5 kWh/m^2-day (27 MJ/m^2-day) in the month of May during summers [2]. This solar radiation potential can be utilized in desalination, solar-thermal collectors, building heating and daylighting and Photovoltaic (PV) Cells etc. Researchers are therefore concerned to maximize the amount of useful energy that can be extracted through the incoming solar radiations. It is believed that proper installation of these devices can make a remarkable change in the observed performance. Predominantly climatology, latitude, orientation, tilt angle, azimuth angles and usage over a period of time in a specific geographical region affect the performance of the above mentioned devices [3].

Tilt of a surface (β) is one of the significant factors that considerably affect the availability of solar radiation on a flat surface. Optimization of performance of solar based devices requires option like solar tracking equipment which follows trajectories of Sun's motion to enhance incident radiation [4,5]. However, these options are not always economical. As estimated by Vermaak [6], the inclined tracking system requires 6.94 ha (550% more) and the 2-axis tracking system requires 4.81 ha (almost 350% more) in comparison to a plant equipped with static PV panels (which requires an area of 1.07 ha). Also, trackers needs periodic maintenance and calibration, requires input energy for their operation which is in the range of 5–10% of the energy produced [7]. Further, trackers are made up of sophisticated mechanical parts which add to capital cost and an increase in cost of absolute power produced from solar PV panels [8]. Other method readily suggested by researchers is to optimize the orientation of flat surfaces at optimum tilt inclination (β_{opt}) [3]. Vieira et al. [9] performed an experimental study which suggested that the sun tracking panel exhibited a low average gain in power generated relative to the fixed panel. In another study performed by Sinha & Chandel [8],

* Corresponding author.
E-mail address: basharatjamil@zhcet.ac.in (B. Jamil).
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Nomenclature

$\bar{H}_B$	beam component of solar radiation on an inclined surface (MJ/m^2-day)
$\bar{H}_d$	diffuse solar radiation on a horizontal surface (MJ/m^2-day)
$\bar{H}_D$	diffuse component of solar radiation on an inclined surface (MJ/m^2-day)
$\bar{H}_g$	global solar radiation on a horizontal surface (MJ/m^2-day)
$\bar{H}_R$	reflected component of solar radiation on an inclined surface (MJ/m^2-day)
$\bar{H}_T$	total solar radiation on an inclined surface (MJ/m^2-day)
k_d	cloudiness index
k_t	sky-clearness index
n	day of the year
$\bar{R}_b$	beam conversion factor
$\bar{R}_d$	diffuse conversion factor = $(1+\cos(\beta))/2$
$\bar{R}_r$	reflected conversion factor = $\rho(1-\cos(\beta))/2$

Greek letters

β	tilt angle (degrees)
β_{opt}	optimum tilt angle (degrees)
γ	surface azimuth angle (degrees)
δ	angle of declination (degrees)
θ	angle of incidence (degrees)
θ_z	zenith angle (degrees)
ρ	ground reflectivity
ϕ	latitude (degrees)
ω	hour angle (degrees)
ω_s	sunset hour angle (degrees)

it was reported that the horizontal axis weekly adjustment and vertical axis continuous adjustment tracking systems produced less energy annually than the existing PV system at fixed tilt. Optimum tilt inclination can be adjusted daily, monthly, seasonally, bi-annually or annually for maximizing the performance of the device in use [10].

It is evident that for a region in northern hemisphere, the surface orientation should be set due south i.e. $\gamma = 0$, where γ is the surface azimuth angle. It has been readily reported that the relation of optimum tilt inclination i.e. β_{opt} is purely with latitude and azimuth [11,12]. In the scenario of unavailability of information on optimization of tilt, various rules of thumb are generally adopted [13]. According to these, maximum solar radiation is achieved by making changes in azimuth angles in range of 10–20° and equalizing the tilt angle to latitude for the region [3]. However such rules are not reliable as estimates can be far from actual values. Different authors have suggested an extensive range of optimum tilt angle correlations in literature.

Optimization of tilt angle has been performed for various location in European countries like Bakirci [14] and Ertekin [15] for Turkey; Stanciu et al. [16] for Romania; Hartner et al. [17] for Austria and Germany; Calabrò [18] for Italy; Mehleri et al.[19] for Greece. For Middle Eastern countries Kazem et al. [20] for Oman; Jafari & Javaran [21], Jafarkazemi et al. [22] and Moghadam et al. [23] for Iran; Jafarkazemi & Saadabadi [24] for Abu Dhabi, UAE; Tamimi & Sowayan [25] for Riyadh, Saudi Arabia; Benghanem [26] for Madinah, Saudi Arabia; Elminir et al. [27] for Egypt; Altarawneh et al. [28] and Shariah et al. [29] for Jordan; Kamal Skeiker [30] for Syria. For Asian Countries, by Khahro et al. [31] for Pakistan; Krishna et al. [32] for Bangkok; Handoyo et al. [33] for Indonesia; Li & Lam [34] for Hong Kong; Tang & Wu [35] for China; for Nigeria by Akachukwu Ben Eke [36]; and Siraki & Pillay [37] for Canada.

For India, Ahmad & Tiwari [10,12] estimated optimum tilt angles using Liu & Jordan model and suggested that yearly optimum tilt angle is approximately equal to the latitude. For winters, optimum tilt angle was proposed as $\phi + 19°$ and for summers as $\phi - 16°$. Shukla et al. [38] compared the measured solar radiation data with six different isotropic and anisotropic models to estimate solar radiation on inclined surfaces in Bhopal, India (23°17′ N, 77°36′ E). They concluded Badescu model gives the best estimation of solar radiation on inclined surfaces with least statistical errors. Pandey and Katiyar [39,40] performed comparative study of diffuse solar radiation on tilted surface using different models for Lucknow, India (26.75°N, 80.50°E) and compared with the measurements for the location. Based on the statistical analysis performed they concluded that Klucher's model gives best estimation. It is observed from the literature that Liu & Jordan isotropic model is the most widely used approach for estimation of solar radiation on inclined surfaces.

The present work aims at exploring the availability of solar radiation on south-facing inclined flat surfaces (non-concentrating) in humid subtropical climatic region of India. Horizontal solar radiation measurements were performed for the city of Aligarh. The estimation procedure is based on Liu & Jordan (isotropic) model. The optimum values for tilt angles and solar radiation availability for New Delhi (the capital of India) have also been reported and compared with the estimations made for the city of Aligarh. Monthly, seasonal and annual optimum tilt angles have been suggested for both the locations. Gain in the availability of solar radiation at monthly, seasonal and annual optimum tilt angle as compared to horizontal surface has been stated. Also losses in solar energy at seasonal and annual optimum tilt angles in comparison to a surface at monthly optimum tilt angle have been reported.

1.1. Location under study

Aligarh city (27.89°N, 78.08°E, and 178 m above msl) is located in Northern part of India in the state of Uttar Pradesh 140 km southwest of Capital of India, New Delhi (28.61°N, 77.20°E, 216 m above msl). This region comes under the humid-subtropical climatic region with dry-winters (classified as "*CWa*" according to Köppen-Geiger climate classification system) [41] and receives a good amount of solar radiation throughout the year. Although the potential of solar energy utilization in this region is high, but the precise information on solar radiation on horizontal and inclined surfaces is rarely available.

2. Methodology

2.1. Solar radiation data

For Aligarh, the solar radiation data (global and diffuse radiation) used in this study were observed at Heat Transfer and Solar Energy Laboratory, Department of Mechanical Engineering, Aligarh Muslim University, Aligarh. The data were recorded using high quality meteorological equipment (two Kipp & Zonen CMP-11 secondary standard pyranometers, shadow ring CMP121-B and a Logbox-SD datalogger) as shown in Fig. 2. The method of solar radiation measurement using pyranometers is quite popular for