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Prediction of solar energy gain on 3-D geometries

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ABSTRACT

In this study, the solar energy gain on 3-D geometries and the amounts of energy output from photovoltaic panels fixed on selected geometries were determined using the radiation data collected by the Iranian Meteorological Organization on a horizontal surface. The results can be used in designing solar houses, street and traffic lights, and rail transport systems. The K–T model was used to calculate the daily average solar radiation intensity; the solar radiation data on a horizontal surface in Kerman was used as input in the above mentioned model. The solar energy on 3-D geometries was calculated in different directions throughout the year. Finally, the geometries were compared with each other in terms of solar energy gain in different months of the year. The results show that the solar energy gain on selected geometries in hot season of the year prevails in east–west direction.

1. Introduction

Solar energy is a safe and endless energy source that can be used for heating, cooling and other purposes. Using this clean energy reduces the consumption of fossil fuels and also reduces the environmental pollutants. Besides, solar energy can supply the human energy needs in deprived areas.

Solar radiation can be used in passive designs to aid in reducing energy consumption for space heating and daylight [1]. It can also be used as a source to generate electricity using photovoltaic panels. A passive solar building can supply 40–100% of daily heating necessities [2,3]. The shape of buildings and solar plates play an important role in energy gain [4]. An important necessity in solar building design is selecting the optimal shape and orientation of the building [5].

To estimate the amount of electricity and thermal energy obtained from photovoltaic panels or solar collectors, we need to determine the solar energy gain at different angles. It is necessary to estimate the intensity of solar radiation at different slopes in various directions to predict the amount of heat released in houses and electricity provided by photovoltaic panels and also to design the solar systems [6]. Solar radiation data on a flat horizontal plate is measured in most meteorological stations but there is little data available on tilted surfaces. The amount of solar energy gain on tilted surfaces should be calculated by various models using the radiation data on horizontal plates [7]. There are a lot of studies to predict radiation intensity on tilted 2-D flat surfaces but this work is focused on selected 3-D geometries.

Ahmad and Husain [8] computed the monthly average hourly and daily solar radiation on a tilted, south-facing surface in Karachi, Pakistan. They also compared the hourly and daily values of solar radiation on tilted surfaces. The method of Liu and Jordan [9,10] was applied in that study.

Nijmeh and Mamlook [11] estimated the global solar radiation on a 45° tilted south-facing surface at Amman, Jordan. In their study, the isotropic model of Liu and Jordan [10] and the anisotropic model of Hay [12] were used.

Abdolzadeh and Mehrabian [13] estimated the global solar radiation on inclined south-facing surface in Kerman using a mathematical method, and determined the monthly, seasonal and yearly optimum slope angles for the solar collectors in Kerman, Iran. They also estimated the solar radiation gain on solar collectors in optimum angles for a hot and dry part of Iran [14].

Talebizadeh et al. [15] determined the optimum slope angles of solar collectors fixed at latitudes of 20–40° N based on new correlations.

Notton et al. [16] calculated diffuse radiation on tilted surfaces using various relationships between global radiation and diffuse radiation on horizontal surfaces.

Noorian et al. [17] evaluated the performance of 12 different models to appraise the hourly diffuse solar radiation on tilted surfaces from data on horizontal surfaces. Twelve models were tested against recorded irradiation on south- and west-facing surfaces at Karaj (35°55′ N; 50°56′ E), Iran.

El-Sebaii et al. [18] estimated total solar radiation incident on a tilted south-facing surface with different tilt angles. They used both

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Nomenclature

List of symbols

E_o	irradiation on PV at STC (1000 W/m^2)
E_c	irradiation on PV (W/m^2)
$\overline{H}$	monthly average of daily solar radiation on horizontal surface (J/m^2)
$\overline{H}_d$	monthly average of daily diffuse radiation on horizontal surface (J/m^2)
$\overline{H}_o$	monthly average of daily extraterrestrial radiation on horizontal surface (J/m^2)
$\overline{H}_T$	monthly average of daily solar radiation on tilted surface (J/m^2)
I_{mp}	maximum power current (A)
I_{sc}	short circuit current (A)
$\overline{K}_T$	monthly average clearness index
n	day of the year
$\bar{R}$	the ratio of radiation on tilted surface to that on horizontal surface
STC	standard test conditions
T_{amb}	ambient temperature (°C)
T_c	cell temperature (°C)
T_o	cell temperature at STC (25 °C)
V_{mp}	maximum power voltage (V)
V_{oc}	open circuit voltage (V)
WS	wind speed (m/s)

Greek symbols

α_{mp}	temperature coefficient of I_{mp} (1/°C)
α_{sc}	temperature coefficient of I_{sc} (1/°C)
β	slope (deg)
β_{mp}	temperature coefficient of V_{mp} (1/°C)
β_{oc}	temperature coefficient of V_{oc} (1/°C)
δ	declination (deg)
ϕ	latitude (deg)
γ	surface Azimuth angle (deg)
ρ_g	reflectance of ground
ω_s	sunset hour angle (deg)
ω'_s	sunset hour angle for the tilted surface for the mean day of month (deg)

Liu and Jordan [9] isotropic model and Klucher's anisotropic model [19].

Pandey and Katiyar [20] presented a statistical approach to estimate the diffuse/global radiation on various tilted surfaces using the measured radiation data on a horizontal flat surface. They considered six different models to estimate solar radiation on tilted surfaces at Lucknow, India.

Safaripour and Mehrabian [21] predicted the direct, diffuse, and global Radiation fluxes on a horizontal surface using various models and compared their predictions with the measured solar radiation data.

Hachem et al. [3] studied the solar potential of various geometries of two-storey family housing units in mid-latitude climate. Seven plan geometries – square, rectangle, trapezoid, L, U, H and T shapes – were investigated. They studied the effect of those shapes on solar radiation on equatorial-facing facades.

Ling et al. [22] presented the effect of geometry on total solar energy gain in high-rise buildings. They studied buildings with square and circular shapes.

Kampf et al. [23] considered the effect of urban settlement design on solar irradiation availability. The design parameters were the height of buildings up to façade and the orientation of roofs.

Ouarghi and Krarti [24] optimized the selection of office building shape. In their analysis, they optimized the footprint dimensions of the office building while its volume and height were fixed.

Hachem et al. [25] considered the effect of three parameters: geometric shape, density, and site layout in design of two-storey housing units in different neighborhood arrangement, on solar energy gain. They also studied the solar electricity production and energy requirement for heating and cooling of the same housing units in a more recent investigation [26].

Hwang et al. [27] studied various photovoltaic system installations (inclination and direction) and the effects of the installation distance on the module length ratio to maximize electricity production for two different office buildings. They showed that the electric energy provided by the photovoltaic system can supply 1–5% of electric energy consumption of a typical office building in Korea.

Esch et al. [28] studied the effects of building design parameters such as roof shapes and building envelope design on the solar energy gain.

In this study, the amount of monthly, seasonal and yearly average of daily solar radiation incident on seven different geometries as solar collectors and also the amount of output energy from photovoltaic panels fixed on selected geometries in various directions has been determined using the K–T method [29] and the measured radiation data on a horizontal surface at Kerman (30.25° N, 56.96° E), Iran; and then compared with each other.

2. Model Equations

2.1. South-facing surfaces

Since the selected geometries are 3-D and symmetric, when one side is faced to the North the other side will be faced to the South. For the South-facing surfaces, the K–T method can be expressed as:

$$\overline{R} = \frac{\cos(\phi-\beta)}{d\cos\phi}\left[\frac{b}{2}\left(\frac{\pi\omega'_s}{180}+\sin\omega'_s(\cos\omega'_s-2\cos\omega''_s\right) + \left(a-\frac{\bar{H}_d}{\bar{H}}\right)\left(\sin\omega'_s-\frac{\pi\omega'_s}{180}\cos\omega''_s\right)\right]+\frac{\bar{H}_d}{\bar{H}}\left(\frac{1+\cos\beta}{2}\right) + \rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (1)$$

where β, ϕ and ρ_g are surface slope angle, latitude of the site, and reflectance of the ground respectively. The value of ρ_g is assumed 0.25 for the meteorological conditions of Kerman. The monthly average of daily diffuse radiation ($\bar{H}_d$) can be obtained using the following relation:

$$\begin{cases} \omega_s \le 81.4^\circ \rightarrow \dfrac{\bar{H}_d}{\bar{H}} = 1.391 - 3.560\bar{K}_T + 4.189\bar{K}_T^2 - 2.137\bar{K}_T^3 \\ \omega_s \ge 81.4^\circ \rightarrow \dfrac{\bar{H}_d}{\bar{H}} = 1.311 - 3.022\bar{K}_T + 3.427\bar{K}_T^2 - 1.821\bar{K}_T^3 \end{cases} \quad (2)$$

$$\overline{K}_T = \frac{\overline{H}}{\overline{H}_o} \quad (3)$$

The other coefficients are obtained from the following equations:

$$\omega'_s = \min\begin{bmatrix} \cos^{-1}(-\tan\phi\tan\delta) \\ \cos^{-1}(-\tan(\phi-\beta)\tan\delta) \end{bmatrix} \quad (4)$$

$$\omega''_s = \cos^{-1}(-\tan(\phi-\beta)\tan\delta) \quad (5)$$

$$a = 0.409 + 5016\sin(\omega_s - 60) \quad (6)$$

$$b = 0.6609 - 0.4767\sin(\omega_s - 60) \quad (7)$$