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Establishing a diffuse solar radiation model for determining the optimum tilt angle of solar surfaces in Tabass, Iran

H. Khorasanizadeh [a,*], K. Mohammadi [a], A. Mostafaeipour [b]

[a] Faculty of Mechanical Engineering and Energy Research Institute, University of Kashan, Kashan, Iran
[b] Industrial Engineering Department, Yazd University, Yazd, Iran

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ABSTRACT

In this study the optimum tilt angle for south-facing solar surfaces in Tabass, Iran, for the fixed monthly, seasonal, semi-yearly and yearly adjustments were calculated. Due to lack of measured diffuse solar radiation data, to predict the horizontal diffuse radiation nine diffuse models from three different categories were established. Based on some statistical indicators the three degree model, in which both clearness index and relative sunshine duration are variables, was recognized the best. The monthly optimum tilt varies from 0° in June and July up to 64° in December and the yearly optimum tilt is around 32°, which is very close to latitude of Tabass (33.36°). For different adjustments, particularly for a vertically mounted surface, the received monthly mean daily solar radiation components and the annual solar energy gains were calculated and compared. Total yearly extra solar gain for the monthly, seasonal, semi-yearly and yearly optimally adjusted surfaces compared to that of horizontal surface are 23.15%, 21.55%, 21.23% and 13.76%, respectively. The semi-yearly tilt adjustment of 10° for warm period (April–September) and 55° for cold period (October–March) is highly recommended, since it provides almost the same level of annual solar energy gain as those of monthly and seasonal adjustments.

1. Introduction

Renewable energy sources like solar, wind, geothermal and tidal are environmentally friendly, since they have a much lower environmental impact than conventional sources like fossil fuel. Due to serious environmental problems raised by fossil fuels exploitation the current energy situation is unsustainable; thus, better balance between energy security, economic development and environmental issues is unquestionably requisite [1]. Among different kinds of renewable energy sources solar energy is considered as immense source, since it is ubiquitous. Solar energy is a non-depletable source that can provide abundant heat and electricity demands for a long time without polluting the air [2,3]. Despite many efforts conducted by developed and developing countries, solar energy potentials are largely unexploited yet. Among solar energy technologies invented for heat and electricity generation solar collectors and solar panels are extensively employed. The performance of the solar collectors and solar panels is greatly influenced by their orientation and tilt angle. This is due to the fact that both orientation and tilt angle change the amount of solar radiation arriving at a surface. Accurate information about solar radiation received by a solar surface in different tilt angles along with knowledge of the optimal tilt angle are of great importance for solar energy experts and designers. The optimum tilt angle of a solar surface is dependent on the local solar radiation characteristics and climatic condition, the latitude as well as the system utilization period; thus, calculation of the tilt angle should be made for each particular site.

On the optimum tilt angle of solar collectors and solar panels, several studies have come into view in the literature. Hussein et al. [4] examined the influence of tilt angles and orientations on the performance of PV modules in Cairo, Egypt. Their results illustrated that the highest yearly performance of PV is obtained by adjusting the surface toward south direction with a tilt angle between 20° and 30°. Furthermore, by adjusting a PV module toward the west direction, it receives higher annual solar energy compared with east direction. Skeiker [5] used a mathematical model to compute the optimum tilt angle of solar collectors for the major Syrian zones for daily adjustment as well as adjustment for other time periods. The results indicated that changing the tilt angle for 12 times in the year keeps the total amount of solar radiation approximately near the maximum, which is obtained for daily adjustment. In addition, monthly adjustment of the tilt angle increases the solar gain almost 30% compared with that of a solar collector mounted on a horizontal surface. Elminir et al. [6]

* Corresponding author. Address: University of Kashan, Kashan 87317-51167, Iran. Tel.: +98 361 5912449; fax: +98 361 5912424.

E-mail addresses: khorasan@kashanu.ac.ir (H. Khorasanizadeh), kasra278@yahoo.com (K. Mohammadi), mostafaei@yazduni.ac.ir (A. Mostafaeipour).

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Nomenclature

G_{sc}	solar constant (equal to 1367 W/m^2)
$\overline{H}$	monthly mean daily global radiation on a horizontal surface (MJ/m^2)
$\overline{H}_b$	monthly mean daily beam radiation on a horizontal surface (MJ/m^2)
$\overline{H}_{bT}$	monthly mean daily beam radiation on a tilted surface (MJ/m^2)
$\overline{H}_d$	monthly mean daily diffuse radiation on a horizontal surface (MJ/m^2)
$\overline{H}_{dT}$	monthly mean daily diffuse radiation on a tilted surface (MJ/m^2)
$\overline{H}_o$	monthly mean daily extraterrestrial on a horizontal surface (MJ/m^2)
$\overline{H}_{rT}$	monthly mean daily ground reflected radiation on a tilted surface (MJ/m^2)
$\overline{H}_T$	monthly mean daily global radiation on a tilted surface (MJ/m^2)
$\overline{H}_{di,c}, \overline{H}_{di,m}$	*i*th calculated and measured values of $\overline{H}_{di}$ (MJ/m^2)
$\overline{H}_{dc,avg}, \overline{H}_{dm,avg}$	average calculated and measured values of $\overline{H}_{di}$ (MJ/m^2)
$\overline{K}_T$	clearness index
MABE	mean absolute bias error (MJ/m^2)
MAPE	mean absolute percentage error (%)
$\bar{n}$	monthly mean daily sunshine hours (h)
n_{day}	number of day counted from first of January
$\overline{N}$	monthly mean daily maximum possible sunshine hours (h)
RMSE	root mean square error (MJ/m^2)
R^2	coefficient of determination
$\overline{R}_b$	ratio of monthly mean beam radiation on a tilted surface to that on a horizontal surface
$\overline{R}_d$	ratio of monthly mean diffuse radiation on a tilted surface to that on a horizontal surface
t	*t*-statistic

Greek letters

β	surface slope angle (deg)
δ	solar declination angle (deg)
ρ_g	ground reflectivity coefficient
φ	latitude of the location (deg)
ω_s	sunrise hour angle (deg)
ω'_s	sunrise hour angle for the tilted surface (deg)

performed a study on the optimum slope angle of flat-plate solar collectors to receive maximum solar radiation in Helwan, Egypt. They tested the performance of three anisotropic models proposed by Tamps–Coulson, Perez and Bugler to find out the best model for calculating the solar radiation received on inclined surfaces and finding the optimum tilt angles. They also compared the obtained tilt angle values with the results obtained utilizing several other models, which were functions of declination, daily clearness index and ground reflectivity. Benghanem [7] determined the optimum slope angle of solar panels to receive maximum solar radiation in the city of Madinah in Saudi Arabia. The results showed that optimal tilt angle for the yearly adjustment was around latitude of Madinah. Furthermore, by employing this adjustment, the surface radiation lose of 8% would be achieved compared with that of monthly adjustment. Lave and Kleissl [8] calculated the optimal tilt and azimuth angles of solar panels in the continental United States. They compared the annual global radiation incident on a panel at different optimum orientations with that of a flat horizontal panel as well as a 2-axis tracking panel. They found that irradiation at optimum fixed tilted panel increases between 10% and 25% with increasing latitude. Also irradiation incident on a 2-axis tracking panel was between 25% and 45% higher than irradiation on the panel at optimum fixed orientation. Bakirci [9] carried out a study to determine the optimum tilt angle of solar panels in eight provinces of Turkey. His results showed that the optimum tilt angle varied between 0° and 65° throughout the year. Furthermore, he developed three general models for Turkey to correlate the optimum tilt angle with the declination angle. Jafarkazemi and Saadabadi [10] investigated the effect of orientation on the optimum tilt angle of solar collectors and solar panels in Abu Dhabi, UAE. They also calculated the optimum tilt angle for different orientations of tilt either toward north or south. Their results showed that the annual optimum tilt angle was 22° toward south, which is close to latitude of Abu Dhabi (24.4°). Also to receive more radiation they suggested adjusting the tilt angle at least twice a year.

In line with increased tendency toward solar energy exploitation in Iran, in this study the optimum tilt angles of south-facing solar collectors and solar panels in the city of Tabass have been obtained for the monthly, seasonal, semi-yearly and yearly adjustments. For this purpose, long term daily global solar radiation on a horizontal surface as well as sunshine hours for the period of 1988–2000, taken from Iranian Meteorological Organization (IMO), have been utilized. Since diffuse solar radiation is not measured in the Iranian meteorological stations, in this study a proper model has been established to estimate it in Tabass. Owing to the great potential of solar energy in Tabass and lack of solar studies in this region, this study provides helpful information for installation of solar surfaces.

2. Study region and data collection

Tabass, a city located in the central and sunny desert region of Iran in south-Khorasan province, is situated at geographical location of 33°36/N and 56°55/E with elevation of 711 m above the sea level. Fig. 1 shows the location of Tabass on the Iranian map. Tabass enjoys hot summers and rarely snowfall is seen in the winter. The monthly average temperature varies from 7.7 °C to 34.8 °C with the yearly average of 21.7 °C. The monthly average relative humidity varies between 20% and 57% with annual average of 33%. According to the Köppen classification the Tabass climate condition is categorized as BWh, which relates to arid desert hot [11]. The data provided by IMO consisted from long-term daily global solar radiation on a horizontal surface and daily sunshine duration for the period of 1988–2000. The global solar radiation data contained some missing and incorrect values. Because of instruments malfunction, the missing values relate to some days and even few months. To enhance the quality of global solar radiation data by eliminating invalid data as well as to achieve more accurate data, the following method was used:

1. The concept of daily clearness index was used as a benchmark to find which daily global solar radiation values were not correct. For this purpose all daily values which produced the daily clearness index out of range ($0.015 < K_T < 1$) were eradicated [12].