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Prediction of daily average solar radiation on tilted surfaces and the optimum tilt of the receiver for coimbatore using MATLAB

[1]R.Allocious Britto Raj Kumar, [2]R.Ramasamy, [3]S.Bairavi
[1,2,3]Assistant Professor, Department of Aeronautical Engineering
Nehru Institute of Technology, Coimbatore.
nitbritto@nehrucolleges.com[1]

Abstract: This paper presents a model to estimate the available average solar radiation and the influence of the receiver's tilt in absorbing the maximum radiation at Coimbatore, Tamilnadu, India (11.01°N latitude, 73.96°E longitude). The solar radiation estimated using this model is checked for accuracy by comparing with the 22-year monthly averaged data obtained from the Surface Meteorology, Atmospheric science data centre, NASA. The estimated solar radiation is also verified with the actual measured data in the experimental site and the variation is found to lie within reasonable limits. The equation of fit derived from the model will enable quick and easy estimation of the available solar energy in places where measured data is not readily available for potential solar-based applications.

Keywords: angle of tilt, average daily solar, coimbatore, optimum angle, solar radiation

Introduction

The demand of energy for the sustenance and well-being of modern man has increased beyond the availability of commercial sources of energy such as fossil fuels, hydroelectric and nuclear power. The fast depletion of fossil fuels and the awareness of harmful hazards of these fuels on the environment has led humanity to seek for a variety of non-commercial sources of clean energy like solar, wind and geothermal to lead a better and quality life. Sun, being an inexhaustible source of energy, environment-friendly and available in almost every part of world could supply the total energy needed by the entire mankind. However, the dilute nature and large collecting areas needed for its technological utilization and the low efficiencies of conversion results in excessive costs of such systems [1]. An in-depth Knowledge on the availability of solar energy is a must for extensive research to make this freely available energy a viable alternate source.

Literature background

A number of researchers have carried out various studies to estimate the available solar energy and also to determine the optimum tilt angle to receive maximum solar radiation based on the location of the experimental site.

Studies on solar radiation estimation

Kouremenos [2] developed correlations of solar radiation for Athens, Greece to provide average and maximum solar radiation based on the calculation of 3 different solar constants. These constants were used to calculate maximum normal, diffuse and total radiations up to a minimum deviation of 1% compared to the values estimated earlier. The work of Krishnnaiah [3] was an attempt to implement Artificial Neural Network (ANN) for estimating the hourly global solar radiation in Tamilnadu. The model was trained and tested with the data from the meteorological department spanning 4 years. The Mean Percentage Error (MPE) of the proposed model was low and the estimated values were in good agreement with the real-time data obtained from the meteorological stations. The daily total radiation incident on a horizontal surface is calculated by Rodostina [4] using four different formulae and is compared with the measured data. It was found that Angstrom's formula used to estimate total solar radiation was close to the measured data in Bulgaria. The studies of Akhlaque [5] shows the total solar radiation estimated over Hyderabad, India and Sindh, Pakistan using the regression equation of Angstrom. The contribution of diffuse radiation to the global radiation is found to be less than 40 % even in worst sky conditions. Tamer [6] presented the models for global and diffuse radiations using linear, nonlinear, fuzzy logic and artificial neural network (ANN) for five main cities in Malaysia. He concluded that ANN models can be used for accurate prediction of solar energy as compared to the other models studied. Al-Rawahi [7] modeled the hourly terrestrial radiation for horizontal and inclined surfaces for Muscat. The results show that the optimum tilt during January is 40° towards south and for the summer season the horizontal orientation is seen to absorb more solar radiation. KacemGairaa [8] measured and analyzed the global solar radiation and surface temperatures in Ghardaia, Algeria and indicated the promising potential of solar energy in that area. MeitaRumbayan [9] demonstrated the use of ANN to estimate the daily global solar radiation in Indonesia and proposed that the analysis based on day of the year, daily average relative humidity, daily average temperature and sunshine hours as input yielded the best predictions with a Mean Average Percentage Error (MAPE) less than 10%. Sivamadhavi [10] estimated the global radiation using 4-layer Multilayer Feed Forward (MLFF) neural network for Tamilnadu and concluded that the results of this method are in excellent agreement with the measured values and with a MAPE of 5.47%. Abdul [11] examined the accuracy of the radiation models predicted by Reindi et.al and Klucher models. He concluded that the Kulcher model can be preferred for the estimation of radiation on tilted surfaces. He also concluded that the yearly average solar radiation recorded in the meteorological stations were 7% less than the solar data derived from NASA's satellite.

Studies on optimum collector tilt

The study of Jamil Ahmad [12] examines the theoretical aspects of choosing a tilt angle for solar flat plate collectors to receive maximum radiation. He predicted that the annual optimum angle is equal to the latitude of the place and the loss of energy collected is 15% while using a yearly fixed angle of tilt instead of varying it every month to an optimum tilt. The work of Akachukwu [13] reported the experimental studies of solar radiation measured by a solar radiometer mounted on a telescopic leg rotated at an interval of 1° from the horizontal to vertical position. The optimum angle of tilt for Zaria was studied for all the months and an yearly average tilt was also determined. Oko [14] performed estimations to calculate the optimum tilt for the low latitudes of Nigeria ranging from 4.86-13.02°N and derived expressions for the monthly optimum tilt angle as a function of latitude for all the months in a year. The work reported by Farzad [15] aims at determining the optimum tilt angle for south facing flat-plate collectors across 80 cities in Iran. Keshavarz [16] determined the daily, monthly, seasonal and yearly optimum slope for 30 Iranian cities and provided atlases combining the data with Geographic Information System (GIS). The investigations of Sekar [17] reports the thermal performance of a solar water heater inclined at angles between 0-30° in intervals of 10°. The work indicates that the optimum angle of solar water heaters in Coimbatore is 10± 2° with the horizontal. The mathematical modeling based on four years solar data in 35 sites in different countries of the Mediterranean region by Hassane [18] resulted in a quadratic regression equation based on the site's latitude to calculate the optimum tilt angle for all the cities. Similar works are reported by researchers [19-21] aiming at determining the optimum tilt angles using various regression models in low-latitude tropical regions, Indian cities of Kolkata and New Delhi.

The present work aims at

1. Predicting the monthly average daily radiation for Coimbatore, Tamilnadu, India and comparing with the 22 year solar data obtained from the Science Data Center, Surface meteorological and Solar Energy, NASA and observations on-site.
2. Simulating the variation in the radiation received with respect to tilt angles ranging from 1° to 90° at intervals of 1° and to determine the optimum tilt for every month.
3. Estimating the yearly average tilt from the daily optimum tilt for the specific location and the corresponding loss of solar radiation associated with it.

Modelling of daily average solar radiation and optimum tilt

The estimation of average daily solar radiation based on latitude using standard empirical relations given by Duffie and Beckman [22] is shown below. The constant values assumed as input to the analysis are as follows :

i) The latitude according to the location of the experimental venue Coimbatore, Tamilnadu, India is taken as 11°
ii) The solar constant is assumed as G_{sc} = 1367 W/m^2.
iii) The average day length (N) is taken as 7 and the diffuse ground reflectance (ρ_g)is considered as 0.8.
iv) The values of a and b corresponding to the location are taken as 0.3 and 0.44 respectively.
v) Isotropic diffuse model is used to derive the beam, isotropic diffuse radiations on tilted surface.

Estimation of daily average solar radiation and optimum tilt

The declination δand the sunset hour angle $\omega_s$are calculated as
Declination (δ)

$$\delta = 23.45 \sin\left(360 \text{ x } \frac{284+n}{365}\right) \quad (1)$$

Where n = number of day in the year (1 to 365)

Sunset hour angle (ω)

$$\omega = \cos^{-1}[-\tan(\varphi)\tan(\delta)] \quad (2)$$

Where ϕ = Latitude of the location (11°)

Extraterrestrial radiation (H_o)

$$H_0 = \frac{24*3600*G_{Sc}}{\Pi} * \left(1 + 0.033 \cos\frac{360*n}{365}\right) * \left[(\cos\delta \cos\phi \sin\omega) * \left(\frac{\Pi\omega}{180} \sin\phi \sin\delta\right)\right] \quad (3)$$

The hourly estimate of solar radiation on a tilted collector is estimated by determining the geometric factor R_b, which is the ratio between beam radiations on the tilted surface to that on a horizontal surface at any time.

Geometrical factor (R_b)

$$R_b = \frac{\sin(\varphi-\beta)\sin\delta + \cos(\varphi-\beta)\cos\delta\cos\omega}{\sin\varphi\sin\delta + \cos\delta\cos\omega} \quad (4)$$

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Where β = angle of tilt of the collector

The monthly average daily radiation H_T on a tilted surface is given by

$$\frac{H_b}{H} R_b + \frac{H_d}{H}\left(\frac{1+\cos\beta}{2}\right) + \rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (5)$$

Where H = Monthly average daily radiation on a horizontal surface

$$H = H_o\left\{a' + b'\,\frac{n'}{N}\right\} \quad (6)$$

A Matlabprogramme based on the equations 1-6 is used to estimate the daily average solar radiation with the hour angles ranging from ω = -60°, -40°, -20°, 0°, 20°, 40° and 60°. The daily average solar radiation obtained is used to calculate the monthly average solar radiation by taking the average of daily radiations from the corresponding number of days of the month, say for example n=1 to 31 for the month of January. The same procedure is repeated and the monthly average solar radiation for all the months in a year is simulated. The tilt is also varied from 1 through 90° and the simulations are repeated to calculate the solar radiation on tilted surface at varying angles of tilt.

Results and discussion

The theoretical simulation of the monthly average daily radiation for horizontal and tilted surface is simulated for the location Coimbatore using the Matlabprogramme. The monthly average solar radiation obtained from the simulation is shown in Table 1.

Table 1: Estimated monthly average solar radiation for Coimbatore (11°N)

Month	Average solar radiation (kWh/m^2)
January	5.22
February	5.5
March	5.75
April	5.78
May	5.61
June	5.47
July	5.53
August	5.67
September	5.72
October	5.55
November	5.25
December	5.11

A maximum solar radiation of 5.78 kWh/m^2 is estimated during the month of April and the minimum is observed during the month of December as 5.11 kWh/m^2. The solar radiation is recorded using a pyranometer for all the sunny days from 9 am to 4 pm in an interval of 30 minutes and checked with the estimated data. The comparison of the estimated and absorbed solar radiation on a horizontal surface for selected days is shown in **Figure:** 1. It is seen that the absorbed solar radiation varied between 8.8 -37.8 % when compared with the simulated results. The observed solar radiation data fits into a polynomial equation (Equation. 7) of the order of 6 as shown below. The root mean square (R^2) value for the predicted equation of line is 0.8601.

$$Y = 0.0011x^4 - 0.0371x^3 + 0.4016x^2 - 1.46\,x + 5.1902 \quad (7)$$

Where Y = Solar radiation

x = latitude

The comparison of the estimated solar data obtained using the Matlab equations with the 22-years monthly average of the daily solar radiation obtained from NASA website is shown in **Figure:**. 2.

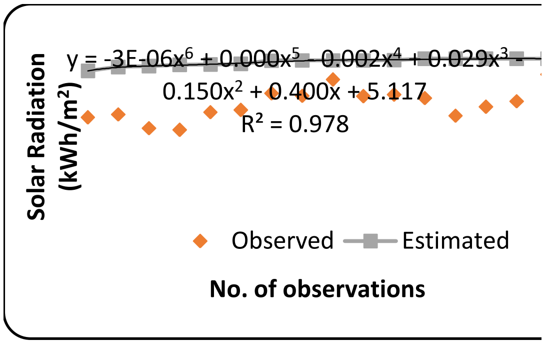

Figure: 1 Comparison of observed and predicted solar radiation on a horizontal receiver

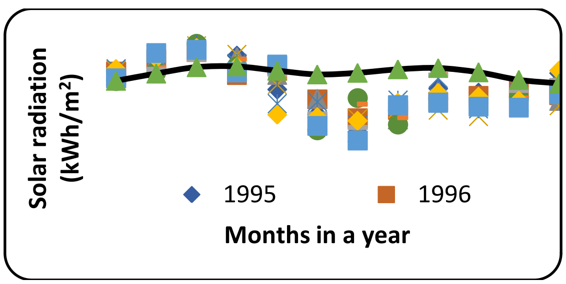

Figure: 2 Comparison of predicted radiation with 22 years actual data

The 22-year (July 1983 through June 2005) average monthly solar radiation corresponding to the latitude of Coimbatore (11.01°N, 76.97°E) is compared with the simulated results.

The solar data is obtained from the online services provided by the Science Data Center, Surface meteorological and Solar Energy (SSE) web portal supported by the NASA LaRC POWER Project. The yearly average absorbed solar radiation for all the months in the year from the 22-year data is found to be 4.92 kWh/m^2 against the estimated one of 5.51 kWh/m^2.

The equations 1-6 were used to develop a computer programme in Matlab and the daily average solar radiation was calculated for various tilt angles from β=1° to β=90°. The programme was repeated to estimate the monthly average solar radiation for all the months for various tilt angles and the results are tabulated. **Figure:** 3 shows the variation of daily average solar radiation for the month of January with respect to the tilt angles from 1-90°. It is seen that the daily average solar radiation increases with increase in the tilt angle till β=32° and then starts to decrease with increase in tilt angle. A maximum radiation of 5.6 kWh/m^2 is estimated at the optimum tilt angle of β=32° for the month of January.

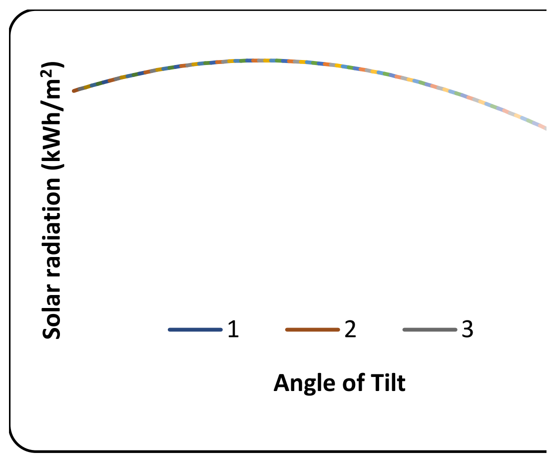

Figure: 3 Variation of daily average solar radiation with angle of tilt for January

The simulation was repeated for each day of the year by varying the tilt angle as above from 1-90° and the optimum tilt angle for each month is determined.

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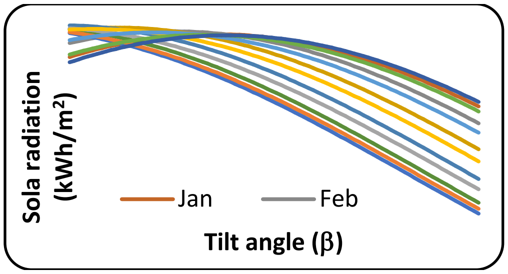

Figure: 4 Variation of daily average solar radiation with angle of tilt for 12 months

The variation of daily average radiation for the individual months of February through December has not been reported here as the same trend is observed for all the months more or less similar to the month of January. The variation of daily average solar radiation for all the months is shown in **Figure:**. 4. The monthly optimum angle corresponding to the maximum solar radiation is obtained from the simulation and shown in Table 2. The yearly average tilt is also estimated from the monthly optimums. The maximum solar radiation as mentioned in Table 2 can be obtained for each month if the receiver orientation is changed every month to the corresponding monthly optimum tilt $(\beta)_{M\text{-}opt}$ as shown.

Table 2: Month-wise optimum tilts

Month	Optimum tilt $(\beta)_{M\text{-}opt}$	Maximum average solar radiation kWh/m^2
January	32°	5.6
February	23°	5.7
March	11°	5.75
April	1°	5.8
May	1°	5.72
June	1°	5.61
July	1°	5.64
August	1°	5.72
September	6°	5.72
October	19°	5.64
November	30°	5.58
December	35°	5.55

In solar-based applications and installations like water heaters, it is highly impossible for the user to vary the angle of tilt every month to obtain the maximum radiation. Hence, an average tilt of the receiver for the whole year irrespective of the months with minimum loss of absorbed solar energy would be a fitting solution.

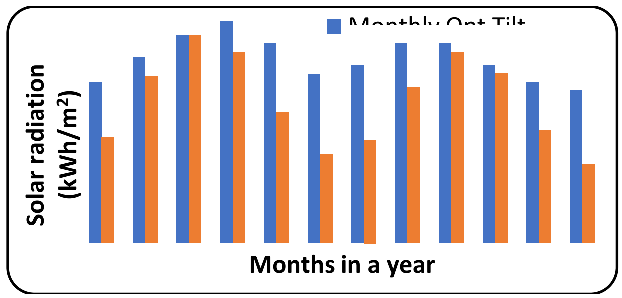

Figure: 5 Comparison of solar radiation for horizontal, monthly optimum tilt and yearly optimum tilt

The yearly optimum tilt angle is $(\beta)_{Y\text{-}opt}$ estimated from the monthly optimum tilts and it was found to be 13.4° for the present location of study. The comparison of the average solar radiation simulated for every month with reference to the monthly optimum tilt and the yearly fixed optimum tilt is shown in **Figure:**. 5. The monthly optimum tilt is seen to attract maximum solar radiation for all the months and there is a slight decrease in the absorbed radiation while fixing the receiver according to a fixed tilt throughout the year. The percentage change in the absorbed solar radiation with respect to monthly optimum tilt and yearly optimum tit is shown in **Figure:** 6.

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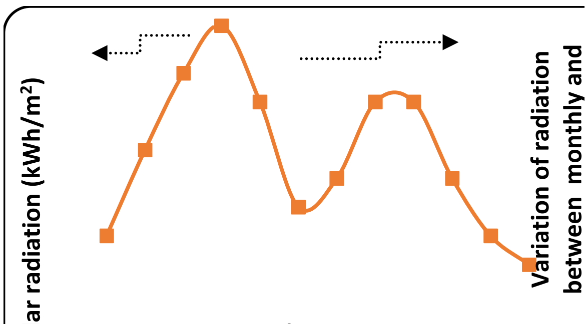

Figure: 6 Variation of solar radiation based on fixed monthly and yearly tilts

The percentage of solar radiation loss when the receiver is fixed all through the year at the yearly optimum tilt varies from 0.017 – 5.17%. The deviation is negligible during the months of March and September, whereas the loss is more during the summer in June and July. However, the yearly average of the monthly radiation received while using monthly optimum tilts is found to be 5.665 kWh/m^2 and while adopting a fixed optimum tilt for the year is found to be 5.512 kWh/m^2. Thus the yearly loss of solar radiation while fixing the collecting surface at an optimum yearly tilt of $(\beta)_{Y\text{-}opt}$ = 13.4° is found to be 2.7 %. This could be a practically feasible and economical solution as the loss of radiation is almost negligible.

Conclusions

In this paper, the daily average solar radiation on a horizontal surface is estimated for various solar angles of a day using the Matlabprogramme and the monthly average solar radiation is obtained for the location Coimbatore (11°N latitude). The maximum average solar radiation estimated is 5.78 kWh/m^2 for the month of April and a minimum of 5.11 kWh/m^2during December. These values were compared with that of the 22-years average solar data obtained from the Surface meteorological and Solar Energy (SSE) and found to be within reasonable limits. The effect of tilt angles on the incident solar radiation is also presented for the same location by varying the tilt angles of the collector surface from horizontal to vertical (1-90°). The monthly optimum tilt is found for all the months and the yearly optimum tilt is estimated. The yearly optimum tilt for the present location is estimated to be 13.4° and the loss of solar radiation while using the yearly tilt orientation is 2.7%. Hence, it is seen that the yearly average tilt can be used for domestic and general applications so that the manufacturing, installation and operating costs of collectors can be as low as possible. Further the predictions are based only on the latitude of the location and so this study can be extended to any region where solar data is not readily available.

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