Solar Collector Tilt Angle Optimization for Maximum Solar Irradiation in Lucknow, Uttar Pradesh, India

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Abstract This study is oriented about providing the cleanest form of energy for the living species on earth. Solar energy is the cleanest form of energy. Solar plate collector's tilt angle is the main point of interest in this study. This study is about how to find the optimum tilt angle and at the same time the maximum solar energy. This study shows the solar energy falling on the solar plate increased at the optimum tilt angle. For Lucknow (26.87° N, 80.95° E) India, the optimum tilt angle during winter season is 55° (Latitude +28°) and during summer season it is 0° (Latitude − 27°). Solar energy falling on the collector surface during winter is 31.83 MJ/m^2 and during summer season 22.38 MJ/m^2.

Keywords Tilt angle optimization · Solar radiation · Solar collectors · Beam conversion factor · Reflected conversion factor

Nomenclature

H	Daily global radiation incident on a horizontal surface, MJ/m^2-day
Hd	Daily diffuse radiation incident on a horizontal surface, MJ/m^2-day
Hb	Daily beam radiation incident on a horizontal surface, MJ/m^2-day
HT	Daily global radiation on a tilted surface, MJ/m^2-day

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Rb Ratio of average daily beam radiation incident on an inclined surface to that on a horizontal surface (beam conversion factor).
Rd Ratio of average daily diffuse radiation incident on an inclined surface to that on a horizontal surface (diffused conversion factor).
β Surface slope from the horizontal (degrees)
δ Declination angle (degrees)
ωs Sunrise hour angle (degrees)
ω's Sunrise hour angle for a tilted surface (degrees)
φ Latitude (degrees)
ρ Ground albedo (reflectivity)

1 Introduction

Energy requirement is the key factor for living species survival on earth. Energy is available on earth in both conventional and non-conventional forms. Conventional energy sources are more efficient as compared to non-conventional energy sources but, there is a big hurdle of pollution with conventional energy sources that leads to find some other way to fulfill the need of energy without pollution or with minimum pollution. There is some non-conventional energy sources like: wind energy, solar energy, nuclear energy etc. Solar energy is the cleanest form of energy and mother of all form of energy available on earth. This paper has little approach towards fulfillment of energy requirement by solar energy.

In India, during summer season approximately 90% area receives significant amount of solar radiation of the order of 10.8–23.4 MJ/m^2-day [1]. However, in northern parts of the country this amount reaches up to 27 MJ/m^2-day during summer [2]. Tilt angle of solar plate is the key factor in the performance of the solar system. Remarkable changes can be observed on variation of the tilt angle. To attain the optimum tilt angle, tracking equipment which follow the trajectories of the sun's motion can be installed to get maximum solar radiation on the solar surface [3, 4]. However, according to Vermaak [5] tracking systems are not economical as inclined tracking requires 550% more and 2-axis tracking requires 350% more as compared to static PV panels. Solar radiation data is usually available in the form of global and diffused solar radiation on the horizontal surface at latitude of interest and the problem is how to find the global and diffused form of radiation on the tilted surface. In the northern hemisphere the optimum orientation is due south ($\gamma = 0$) and the optimum tilt angle is dependent upon latitude and day of the year. In winters the optimum tilt is greater (usually latitude $+15^{\circ}$) whereas in summers the optimum tilt is less (usually latitude -15°) [6].

There are many research papers available which offer different recommendations for optimum tilt angle based on the latitude of the station [7, 8]. Practically in the northern hemisphere, solar plates are oriented due south ($\gamma = 0$) with a fixed tilt angle for monthly, seasonaly or annual basis to get maximum solar radiation.

Method of Estimation

As the solar radiation data published on the horizontal surface by IMD Pune (18.52° N, 73.86° E), Maharashtra, India, it is required to find it on the tilted surface. A correlation is developed here to find total solar radiation on the tilted surface.

$$\mathbf{H_T = H_b R_b + H_d R_d + \rho H R_r} \tag{1}$$

H_T is monthly daily solar radiation on the tilted surface whereas H_b, H_d and H are monthly mean daily beam and diffused components of solar radiation respectively. H is the total global solar radiation. R_b, R_d and R_r are known as beam, diffused and reflected conversion factor respectively. ρ is ground albedo, its value is taken as 0.2 for a normal surface.

Beam Conversion Factor

According to Liu and Jordan [9] it can be calculated assuming that there is no atmosphere. In the northern hemisphere, it is sloped toward the equator where the equation of R_b can be written as

$$\boldsymbol{R_b} = \frac{\mathbf{\cos(\Phi - \beta)\cos\delta\sin\omega_s^{'} + \omega_s{'}\sin(\varphi - \beta)\sin\delta}}{\mathbf{\cos\varphi\cos\delta\sin\omega_s + \omega_s\sin\varphi\sin\delta}} \tag{2}$$

Here

$$\mathbf{\omega_s^{'} = \min\left\{\cos^{-1}(-\tan\varphi\tan\delta), \cos^{-1}(-\tan(\varphi - \beta)\tan\delta)\right\}} \tag{3}$$

Φ is latitude, δ is declination angle and ω is the hour angle for the local solar noon.

ω_s is the sunrise or sunset hour angle for the mean day of the month. "min" indicates the smaller value among the two in the bracket. The declination angle can be given as

$$\boldsymbol{\delta} = 23.45\mathbf{\sin}\left[\frac{360(284 + \boldsymbol{n})}{365}\right] \tag{4}$$

Diffused Conversion Factor

Diffused component of solar radiation can be estimated on the basis of two theories. Assuming sky is isotropic or sky is anisotropic. Isotropic condition means solar radiation distributed all over the sky dome evenly whereas anisotropic condition means anisotropy all over the sky dome plus isotropic radiation component. There are many isotropic and anisotropic models that are used to estimate the diffused component of solar radiation. Here we assumed the isotropic condition and use the Liu and Jordan model again for the diffused component of solar radiation. Diffused conversion factor can be written as

$$R_d = \frac{1 + \cos\beta}{2} \tag{5}$$

Reflected Conversion Factor

Assuming isotropic reflection from the ground, the reflected conversion factor can be written as

$$R_r = \rho \frac{1 - \cos\beta}{2} \tag{6}$$

The total radiation on the tilted surface can be estimated by using (1). Since, the Eq. (1) is the function of the tilt angle. This paper is oriented toward the estimation of the optimum tilt angle.

2 Methodology

To estimate the optimum tilt angle, it is advised to partially differentiate the Eq. (1) with respect to tilt angle β and put it equal to zero [12]. Then the obtained tilt angle will be the optimum tilt angle

$$\frac{\partial \mathbf{H_T}}{\partial \boldsymbol{\beta}} = 0 \tag{7}$$

$$\beta_{opt} = \tan^{-1}\left[\frac{H_b(\cos\delta \sin\omega_s' \sin\varphi - \omega_s' \sin\delta \cos\varphi)}{H_b\omega_s' \sin\delta \sin\varphi + \cos\delta \sin\omega_s' \cos\varphi + 1/2(H_d - \rho H)(\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s)}\right] \tag{8}$$

Put this optimum value of tilt angle in the Eq. (1) and all the values of radiation factors and angles for any Indian station can give the maximum value of solar radiation on the tilted surface. This research paper is to find the optimum tilt angle and maximum solar radiation on the tilted surface for Lucknow, capital city of Uttar Pradesh, India. By, using MSEXCEL graphic software package value of solar radiation is calculated for each month of the year and graphs are plotted.

3 Result and Discussion

Solar energy is the cleanest form of energy available in Earth's atmosphere. The tilt angle of the solar collector is the key factor for the collection solar energy. Tilt angle must be accurate to get maximum amount of solar energy. Tilt angle optimization has been done in this study in order to approach the maximum amount of solar energy and the values are given in Table 1 (Fig. 1).

Table 1 Tilt angle (degree) for different cities of India in each month of the year

Month	New Delhi	Lucknow	Ahmedabad	Bangalore
Jan	57.3197	54.061	52.2915	41.21
Feb	46.9807	46.686	42.1194	32.6
March	31.9795	30.192	27.3238	15.99
April	12.9589	11.329	7.98034	0
May	0	0	0	0
June	0	0	0	0
July	0	0	0	0
Aug	5.27292	2.9557	0.70146	0
Sep	23.6002	19.422	17.2945	7.039
Oct	42.4501	39.31	36.7792	21.64
Nov	54.7698	52.509	49.9173	36.63
Dec	59.5922	58.272	54.5878	42.21

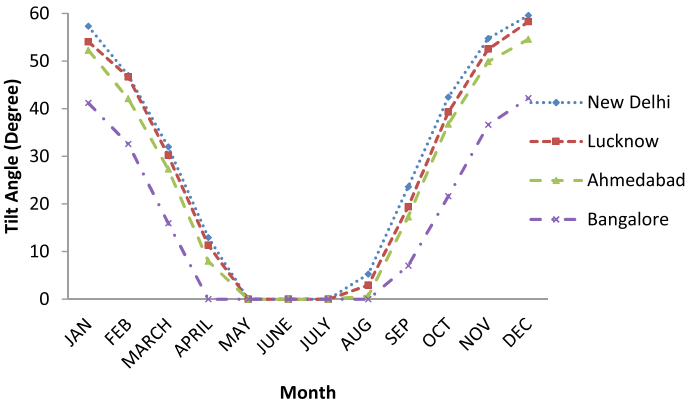

Fig. 1 Values of tilt angle for each month of a year at different stations of India

Research study compares the solar energy falling on flat plat collector for the Liu & Jordan model based on the previous tilt angle vs optimized tilt angle and the result shown in Table 2. H_T is the value of monthly mean daily solar radiation on the tilted surface by the Liu and Jordan model based on the previous tilt angle and H'_T is the same radiation on the optimized tilt angle.

Average value of solar radiation for winter months (November, December and January) is 31.83 MJ/m^2 and for summer (May, June, July) it is 22.38 MJ/m^2 (Fig. 2).

The results show that the tilt angle during winter season is about 55° which is higher (Latitude +28°) and during summer months it is 0° which is lesser (Latitude −27°). These values corroborate well with other studies [10–12].

Table 2 Comparison of monthly mean daily solar radiation (MJ/m^2) falling on tilted surface by Liu and Jordan model at Lucknow

Month	H_T at $\beta = \varphi$	H'_T at $\beta = \beta_{opt}$
Jan	23.38	26.92
Feb	35.62	38.57
March	27.98	28.14
April	28.28	28.56
May	24.40	26.14
June	23.91	24.79
July	15.18	16.21
Aug	16.18	16.80
Sep	19.10	19.16
Oct	23.48	24.41
Nov	26.34	30.03
Dec	31.68	38.54

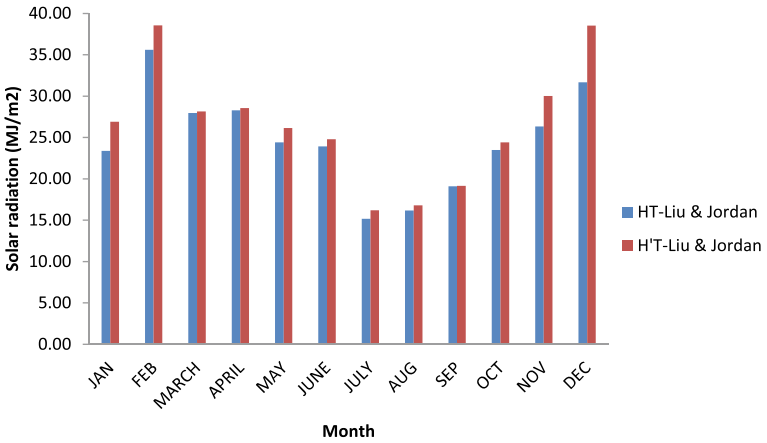

Fig. 2 Comparison of monthly mean daily solar radiation on Liu and Jordan model based on previous tilt angle ($\beta = \phi$) and optimized tilt angle ($\beta = \beta_{opt.}$)

4 Conclusion

This study shows, nearly 1% loss of energy if β_{opt} is adjusted seasonally rather than monthly. If β_{opt} is selected for yearly basis the loss of energy is about 14%. It is concluded that the seasonal optimum tilt angle must be used for power plants and annual optimum tilt angle should be selected for domestic purposes (water heating).

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