Estimation of solar radiation on inclined surfaces for Thailand

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Abstract :

The monthly average daily global radiation on a horizontal surface for selected provinces of Thailand and the isotropic model are both used to estimate the solar radiation on inclined surfaces. The monthly average daily total radiation on south-facing surfaces of various tilt angles for these provinces has been estimated. The ratios of the average daily beam radiation on the tilt surfaces to that on the horizontal surfaces for the month as a function of the latitudes and monthly average daily conversion factors for global radiation on various provinces have also been computed. The results that are presented in this paper can serve a useful data for PV system or solar energy applications in Thailand and other countries that are located at the same latitude angle with a similar climate.

Keywords: Solar radiation-1, Tilt angle-2, Thailand-3.

1. Introduction

Solar radiation incident on Photovoltaic (PV) panels or collection surfaces must be known in order to perform system analysis. In general, only the measurement of the total horizontal (global) radiation is available. At most surfaces of interest are inclined, it is necessary to estimate the radiation on a tilted surface from data of global radiation. Measured radiation data on inclined surfaces are not available for most of the locations in Thailand and have to estimate from theoretical models. There are some methods to compute the total solar radiation on the tilted surfaces from measurements on a horizontal surface. Different mathematical models have been developed by Liu and Jordan [1], Hay and David [2], Klucher [3] and others. Furthermore, the monthly average daily total radiation on the tilted surfaces can be estimated by individually considers the direct beam, diffuse and reflected component of the radiation that incident on the tilted surfaces.

The solar radiation climate of Thailand can be generally stated that [4] during the spring, the weather is fine and the whole of Thailand has from 8 to 9 hours of sunshine per day. This is the season of maximum insolation. In summer, the duration of sunshine is between 5 and 7 hours per day. During the autumn, the duration of sunshine is about 5 to 6 hours per day in many areas. There are more heavy rain and the lowest insolation of the year. In winter, the weather is quite fine and is about 8 to 9 hours of sunshine per day over the most of the country. The seasonal periods of Thailand can be divided into 4 seasons as follows:

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Table 1 The seasonal periods of Thailand

Month	Season
February-April	Spring
May-July	Summer
August-October	Autumn
November-January	Winter

Based on some tables in ref. [5], they give the global solar radiation for selected provinces of Thailand that is estimated fıom mean daily duration of sunshine in each $1\frac{1}{2}$ month period at the 18 stations and sunshine averages over 15 to 20 years. The monthly average daily global radiation on the horizontal surfaces for selected provinces of Thailand has been used in the present study to estimate the solar radiation on the tilted surfaces. It is shown in Table 2, the values of the solar radiation are expressed in kWh/m^2.

2. A model of estimation

Total radiation arriving on an inclined surface has three components, namely beam radiation, sky-diffuse radiation and ground-reflected radiation. The calculation of the monthly average daily total radiation on the tilted surface is needed to use in solar energy design procedures. The method of Liu and Jordan has been widely used and makes calculation of radiation on tilted surface easy [6]. If the diffuse and ground reflected radiation is each assumed to be isotropic. Hence, the results of estimation from this paper are based on the isotropic model. Thus, for a surfaces tilted at a slope angle from the horizontal, the incident total solar radiation can be written as

$$H_T = H_B + H_D + H_G \qquad .....(1)$$

Where H_T is monthly average daily total radiation on a tilted surface, H_B is beam or direct radiation, H_D and H_G are diffuse radiation and ground-reflected radiation on a tilted surface respectively. The beam radiation received on an inclined surface can be expressed as

$$H_B = (H - H_d)R_b \qquad .....(2)$$

Where H and H_d are the monthly average daily total radiation and diffuse radiation on a horizontal surface respectively. R_b is the ratio of the average daily beam radiation on a tilted surface to that on a horizontal surface for the month. Liu and Jordan suggest that it can be estimated by assuming that it has the value that would be obtained if there were no atmosphere. For surfaces that are sloped toward the equator in the northern hemisphere, such as Thailand, with a surface azimuth angle (γ) is to be zero. R_b is given by[6]:

$$R_b = \frac{\cos(L-\beta)\cos\delta\sin\omega'_S + (\pi/180)\omega'_S\sin(L-\beta)\sin\delta}{\cos L\cos\delta\sin\omega_S + (\pi/180)\omega_S\sin L\sin\delta} \qquad .....(3a)$$

Where ω'_S is the sunset hour angle for the tilted surface for mean day of the month, it is given by

$$\omega'_S = \min\begin{bmatrix}\cos^{-1}(-\tan L\tan\delta)\\ \cos^{-1}(-\tan(L-\beta)\tan\delta)\end{bmatrix} \qquad .....(3b)$$

Where "min" means the smaller of the two terms in the brackets. L and β are latitude and surface slope from the horizontal, both are expressed in degrees. δ is solar declination that is also expressed in degrees. The ω_S is sunset hour angle in degrees, and it is equal to $\cos^{-1}(-\tan L \tan\delta)$. It is assumed as an approximation that the diffuse-sky radiation is an isotropic, i.e., it is uniform in all directions. The equations of conversion factor for diffuse-sky radiation (R_d) and conversion factor for the ground-reflected radiation (R_g) can be expressed as follows:

$$R_d = \frac{1+\cos\beta}{2} \quad \text{and} \quad R_g = \left(\frac{1-\cos\beta}{2}\right)\rho_g \quad .....(4)$$

Thus, R_d is the ratio of diffuse on a tilted surface to that on a horizontal surface and ρ_g is ground reflectance (albedo). Based on the isotropic model, the monthly average daily total radiation on the tilted surface is given by [6]:

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

When H_T has been determined, the ratio of total radiation on the tilted surface to that on the horizontal surface is given by $R = H_T/H$. In addition, the value of H_d can be determined from the ratio of H_d/H that Erbs at el. [7] derived a seasonal monthly average daily diffuse correlation, where K_T (monthly average daily clearness index) is the ratio of H/H_o. For H_o is the extraterrestrial radiation on a horizontal surface on mean day (n) of the year that is suggested by Klein [8], for example Jan.(17), Feb.(47),..., Dec.(344). The value of the solar constant that is used in this paper is 1367 W/m^2 [9] to calculate the value of H_o on mean day of the year.

3. Results and discussion

In the present study the total solar radiation on tilted surfaces on various slope angles for selected provinces of Thailand that is situated latitude between 6° and 20° N has been done based on the isotropic model. The results in the present study can be concluded as follows:

Firstly, the ratio of the average daily beam radiation on the tilted surface to that on the horizontal surface for the month (R_b), that is a function of transmittance of the atmosphere has been plotted as a function of latitude between 6° and 20° N. For surface that is sloped toward the equator with γ = 0° is shown in Figure 1. As can be seen from Figure 1, the value of R_b of each month is a little different, especially the latitudes that are lower than 8° N. However, they have shown that the effects of sloping to the south for R_b throughout the winter (Nov.-Jan.) are larger than other months of the year. On the other hand, the values of R_b in the summer (May-June) are least.

Secondly, the monthly average daily total radiation on the tilted surfaces (H_T) for selected provinces of Thailand has been estimated. The annual variation of global radiation on horizontal and tilted surfaces for 4 provinces that are both different latitudes and compass points are plotted. In fact, Chiang Mai (18.78°N) is in the north and Roi Et (16.05°N) is in the north-east. For Bangkok (13.73°N) and Phuket (7.88°N) are in the central part and in the south respectively. They are shown in Figures 2-5. Altogether, they show the values of H_T for different surface orientations and the values that are reported in these figures are expressed in kWh/m^2. Due to the fact that no information is available about the ground-reflectance (albedo), ρ_g is assumed to be 0.20 that is suggested by Liu and Jordan [6]. Figure 6 shows variation of average annual radiation, winter (Nov.-Jan.) and summer (May-July) as a function of surface slope for Songkhla province. It indicates a maximum average annual radiation at approximate β = 7°. It also shows a maximum average seasonal radiation in the winter for the months of November, December and January. The slope corresponding to the maximum estimated is about 32°. On the other hand, a maximum point of average seasonal radiation in the summer for the months of May, June and July is about-18°. Furthermore, the variation of average annual and seasonal radiation for other provinces of Thailand is calculated. From the results it can be concluded that the maximum average annual radiation availability, a surface slope that is equal to latitude in question is best. For maximum summer availability, slope should be approximated as L-25° and maximum winter availability, slope should be approximately as L+25°. However, the slope are not critical, deviations of 25° from a latitude, energy can be increased about 6-7% compared with a latitude.

Finally, the ratios of total radiation on a tilted surface to that on a horizontal surface for the month, this is a value of R, for selected provinces of Thailand on a particularly tilt angles have been computed and can be tabulated in Table 3.

Table 2 Monthly average daily global radiation for selected provinces of Thailand.[5]

Province	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Chiang Rai	4.237	4.608	4.997	5.275	5.389	4.717	4.591	4.473	4.636	4.456	4.270	3.765
Chiang Mai	4.469	4.698	5.345	5.491	5.511	4.787	4.571	4.369	4.671	4.694	4.704	4.322
Loei	4.201	4.479	4.857	5.031	5.097	4.636	4.528	4.427	4.125	4.118	4.109	3.997
Nakhon Phanom	4.268	4.284	4.601	4.810	4.887	4.299	4.239	4.183	4.345	4.471	4.578	4.253
Sakon Nakhon	4.523	4.521	4.985	5.075	5.076	4.520	4.477	4.438	4.706	4.711	4.711	4.555
Phitsanulok	4.527	4.625	5.240	5.463	5.540	4.868	4.694	4.532	4.357	4.519	4.665	4.485
Khon Kaen	4.625	4.674	5.008	5.231	5.329	4.857	4.707	4.567	4.427	4.649	4.847	4.578
Roi Et	4.369	4.423	5.124	5.263	5.324	5.031	4.881	4.741	4.520	4.603	4.671	4.369
Nakhon Sawan	4.560	4.661	5.136	5.233	5.238	4.682	4.532	4.392	4.287	4.473	4.643	4.508
Ubon Ratchthani	4.624	4.732	5.229	5.208	5.167	4.915	4.735	4.567	4.404	4.571	4.723	4.567
Nakhon Ratchasima	4.555	4.644	5.054	5.124	5.144	4.892	4.778	4.671	4.404	4.536	4.655	4.508
Surin	4.648	4.746	5.275	5.171	5.074	4.822	4.774	4.729	4.613	4.684	4.747	4.601
Bangkok	4.641	4.713	5.403	5.124	4.906	4.613	4.451	4.299	4.136	4.346	4.545	4.625
Chanthaburi	4.742	4.743	5.089	4.803	4.571	4.183	4.045	3.916	3.811	4.218	4.606	4.764
Phuket	4.844	5.140	5.507	4.907	4.496	4.392	4.362	4.334	4.113	4.268	4.422	4.624
Songkha	4.496	4.990	5.368	5.054	4.824	4.636	4.678	4.717	4.415	4.235	4.068	4.113

4. Conclusions

A method of an isotropic model by Liu and Jordan is used to estimate the solar radiation on an inclined surface for Thailand that is situated latitude between 6° and 20° N. The monthly average daily total radiation on the tilted surfaces (H_T) for selected provinces has been estimated. The optimum tilt angles in different seasons for summer, winter for Thailand are approximately latitude minus 25° and latitude plus 25° respectively. Among all the inclinations studied here, a tilt angle that is equal to latitude at the design location will collect the maximum energy round the year. The ratio of the monthly average daily total radiation on the tilted surfaces to that on the horizontal surfaces (H_T/H) for selected provinces has been computed. The results that are presented here can serve as a useful reference of radiation data on inclined surfaces for the future solar energy and PV system applications in Thailand. They can be applied in other countries that are located at the same latitude angle with a similar climate, not just in Thailand.

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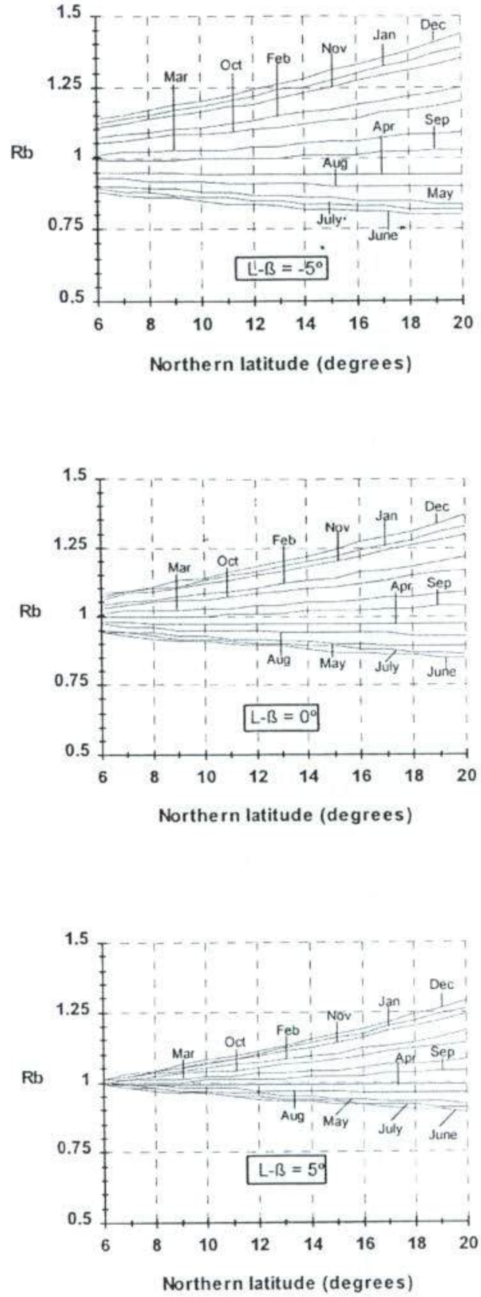

(a)

(b)

(c)

Figure 1 (a) Rb as a function of various latitudes for $L-\beta = -5^o$

(b) For $L-\beta = 0^o$ and

(c) For $L-\beta = 5^o$

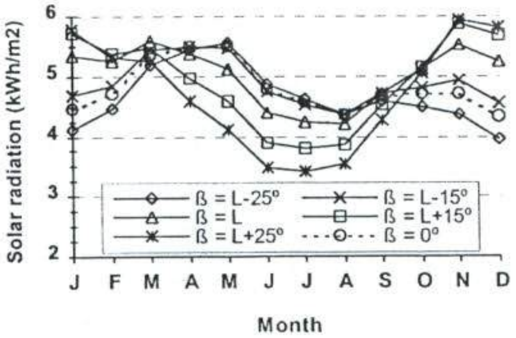

Figure 2 Annual variation of solar radiation on tilted and horizontal surface for Chaing Mai (18.78°N) of Thailand

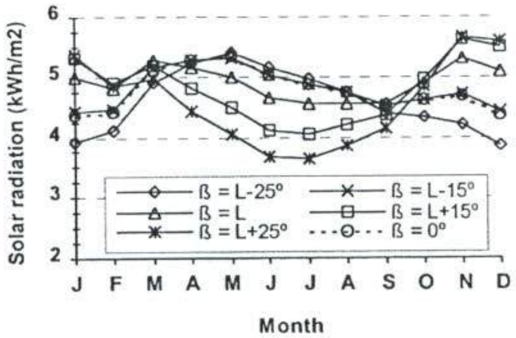

Figure 3 Annual variation of solar radiation on tilted and horizontal surface for Roi Et (16.05°N) of Thailand

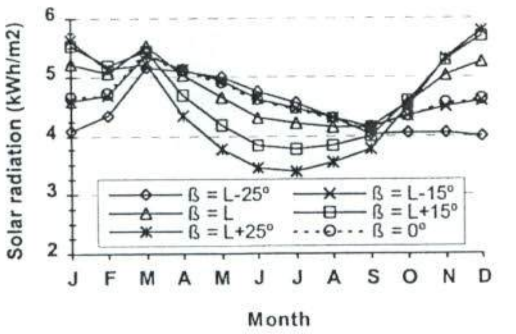

Figure 4 Annual variation of solar radiation on tilted and horizontal surface for Bangkok (13.73°N) of Thailand

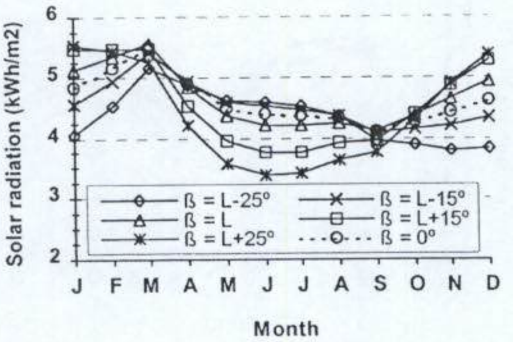

Figure 5 *Annual variation of solar radiation on tilted and horizontal surfaces for Phuket (7.88°N) of Thailand*

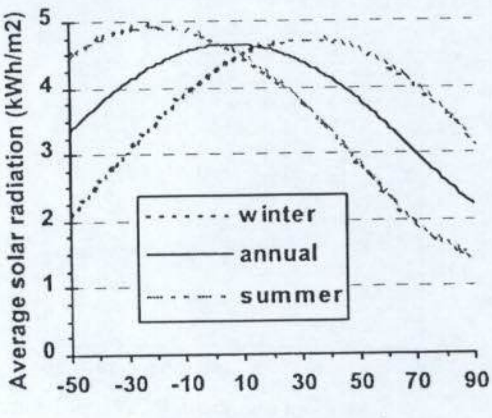

Figure 6 *Variation of average annual, winter (Nov.-Jan.) and summer (May-Jury) solar radiation as a function of various tilt angles for Songkhla ($L=7.23^{\circ}, \gamma=0^{\circ}, \rho_g=0.20$) of Thailand*

Nomenclature

H Monthly average daily total radiation incident on a horizontal surface, kWh/m^2

$\mathbf{H_d}$ Monthly average daily diffuse radiation incident on a horizontal surface, kWh/m^2

$\mathbf{H_B}$ Beam radiation incident on a tilted surface

$\mathbf{H_D}$ Diffuse radiation incident on a tilted surface

$\mathbf{H_G}$ Ground-reflected radiation incident on a tilted surface

$\mathbf{H_T}$ Monthly average daily total radiation incident on a tilted surface, kWh/m^2

L Latitude, degrees

$\mathbf{R_b}$ Ratio of average daily beam radiation incident on a tilted surface to that on a horizontal surface for the month

ρ_g Ground-reflectance

β Tilt angle or surface slope from the horizontal, degrees

γ Surface azimuth angle, degrees

δ Solar declination, degrees

Table 3 Monthly average daily conversion factor that is ratio of total radiation on a tilted surfaces to that on a horizontal surface (H_T/H) for selected provinces of Thailand. (where $\gamma = 0^{\circ}$)

Month	Chiang Rai (19.88° N) Tilt angle (β)					Loei (17.45° N) Tilt angle (β)				
	L+25°	L+15°	L	L-15°	L-25°	L+25°	L+15°	L	L-15°	L-25°
Jan.	1.300	1.284	1.203	1.060	0.935	1.247	1.232	1.156	1.022	0.906
Feb.	1.140	1.153	1.124	1.040	0.955	1.109	1.122	1.095	1.015	0.934
Mar.	0.979	1.022	1.046	1.020	0.975	0.971	1.013	1.034	1.007	0.963
Apr.	0.837	0.906	0.976	1.002	0.993	0.846	0.912	0.978	1.000	0.990
May	0.746	0.829	0.928	0.989	1.006	0.763	0.844	0.938	0.995	1.010
Jun.	0.727	0.811	0.914	0.985	1.011	0.741	0.824	0.926	0.994	1.017
Jul.	0.745	0.826	0.924	0.987	1.008	0.758	0.838	0.934	0.995	1.013
Aug.	0.808	0.879	0.958	0.996	0.999	0.819	0.888	0.963	0.998	0.999
Sep.	0.916	0.970	1.014	1.011	0.984	0.915	0.966	1.007	1.004	0.977
Oct.	1.075	1.100	1.092	1.031	0.963	1.048	1.072	1.066	1.011	0.948
Nov.	1.253	1.245	1.180	1.054	0.941	1.200	1.194	1.135	1.019	0.916
Dec.	1.348	1.323	1.226	1.066	0.929	1.283	1.260	1.172	1.024	0.899

Table 3 (Continued)

Month	Khon Kean (16.45° N) Tilt angle (β)					Ubon Ratchathani (15.25° N) Tilt angle (β)				
	L+25°	L+15°	L	L-15°	L-25°	L+25°	L+15°	L	L-15°	L-25°
Jan.	1.255	1.236	1.154	1.011	0.890	1.234	1.216	1.137	1.000	0.883
Feb.	1.107	1.119	1.090	1.007	0.926	1.098	1.109	1.081	1.000	0.920
Mar.	0.970	1.011	1.032	1.004	0.958	0.969	1.009	1.029	1.000	0.954
Apr.	0.845	0.912	0.978	1.000	0.989	0.846	0.912	0.978	1.000	0.989
May	0.760	0.842	0.939	0.998	1.013	0.765	0.847	0.942	1.000	1.014
Jun.	0.737	0.822	0.926	0.997	1.021	0.736	0.822	0.929	1.000	1.025
Jul.	0.755	0.837	0.935	0.997	1.016	0.756	0.838	0.937	1.000	1.019
Aug.	0.818	0.888	0.964	0.999	0.999	0.819	0.889	0.965	1.000	1.000
Sep.	0.916	0.967	1.007	1.002	0.974	0.915	0.965	1.005	1.000	0.972
Oct.	1.057	1.079	1.068	1.006	0.938	1.047	1.069	1.060	1.000	0.934
Nov.	1.226	1.213	1.142	1.011	0.896	1.200	1.190	1.124	1.000	0.891
Dec.	1.304	1.275	1.175	1.013	0.878	1.278	1.251	1.155	1.000	0.871

Table 3 (Continued)

Month	Chanthaburi (12.60° N) Tilt angle (β)					Songkhla (7.23° N) Tilt angle (β)				
	L+25°	L+15°	L	L-15°	L-25°	L+25°	L+15°	L	L-15°	L-25°
Jan.	1.198	1.182	1.109	0.980	0.870	1.123	1.111	1.047	0.935	0.839
Feb.	1.075	1.088	1.063	0.987	0.911	1.050	1.059	1.030	0.953	0.878
Mar.	0.958	0.999	1.020	0.994	0.950	0.955	0.992	1.009	0.977	0.931
Apr.	0.849	0.914	0.979	1.000	0.990	0.861	0.924	0.986	1.004	0.990
May	0.781	0.859	0.951	1.005	1.017	0.794	0.875	0.969	1.023	1.033
Jun.	0.762	0.843	0.942	1.006	1.027	0.766	0.854	0.962	1.032	1.053
Jul.	0.779	0.857	0.948	1.005	1.021	0.779	0.864	0.965	1.028	1.044
Aug.	0.834	0.900	0.970	1.002	1.000	0.835	0.905	0.980	1.012	1.007
Sep.	0.912	0.960	1.000	0.997	0.972	0.919	0.965	0.999	0.989	0.958
Oct.	1.023	1.047	1.042	0.990	0.931	1.007	1.027	1.019	0.966	0.908
Nov.	1.158	1.152	1.094	0.982	0.883	1.087	1.084	1.038	0.945	0.863
Dec.	1.240	1.215	1.125	0.977	0.855	1.135	1.118	1.049	0.933	0.836

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