

*Full Length Research Paper*

# Precise estimation of total solar radiation on tilted surface

R. K. Aggarwal

Department of Environmental Science, Dr Y S Parmar University of Horticulture and Forestry, Nauni – Solan (HP) – 173 230 India. E-mail: [rajeev1792@rediffmail.com](mailto:rajeev1792@rediffmail.com).

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**A new correction factor (CF) which depends upon the longitude and altitude of the location, has been used for the estimation of hourly and total solar radiation at different orientation and inclination for Delhi. The estimated values of hourly solar radiation have also been compared with 15 years measured data of Delhi to establish the accuracy of the results. The study reveals that hourly and total solar radiation can be estimated using correction factor without applying any meteorological parameters for the locations having longitude range of  $\pm 70$  to  $\pm 125$ .**

**Key words:** Correction factor, meteorological parameters, solar radiation.

## INTRODUCTION

Solar radiation data is necessary for the performance evaluation of solar energy systems, which is not available for many locations. The hourly solar radiation data is rarely available required for precise sizing of energy systems. The total solar radiation at different orientation and slope is needed to calculate the efficiency of the installed solar energy systems. To calculate clearness index ( $K_t$ ) used by Gueymard (2000) for estimating solar irradiation  $H$ , irradiation at the earth's surface has to be measured. It will also be important to estimate solar radiation for the locations where there is no facilities to measure any meteorological data, only geographical parameters are available. Now these days solar energy based systems are in use throughout the world, which generates enough data for their performance evaluation. The estimation of solar radiation without using any meteorological parameters can be achieved by using newly introduced correction factor (CF), which requires only geographical parameters such as longitude and altitude of the location (Aggarwal, 2005). The hourly solar radiation using Gueymard (2000) daily integration method has been estimated for Delhi [Latitude  $28.58^\circ\text{N}$ , Longitude  $77.2^\circ\text{E}$  and Altitude 216 m] in which  $K_T$  has been replaced by CF and compared with 15 years of

measured data (Mani, 1980) for establishing the accuracy of the model. The total solar radiation using Klein (1977) model at different orientations and inclination has also been estimated for Delhi. This technique gives error at true north and true south.

## METHODOLOGY

After passing through the Earth's atmosphere, solar radiation includes both a direct component from the Sun itself and a diffuse component made up from reflections off clouds, moisture vapour and other particulates within the sky. The diffuse component may also contain reflections off the ground and other elements of the local built environment.

Incident solar radiation is calculated directly from the geometry of the model and using hourly recordings of direct beam and diffuse horizontal solar radiation values taken from the currently loaded weather data file. Direct horizontal radiation differs from direct beam in that it is measured incident on a flat horizontal plane.

The diffuse horizontal component is also given in  $\text{W/m}^2$  and is taken as the energy from the entire sky dome that falls on a horizontal surface, minus the effects of direct beam radiation as it hits the horizontal.

This is important as it means that radiation from low in the sky

near the horizon strikes the flat measurement surface at almost grazing incidence - meaning that it contributes much less to the measurement than light from the zenith which strikes the surface at or near normal incidence.

Diffuse horizontal radiation values assume that there are no surrounding obstructions to obscure any part of the sky and, as a result, are typically measured on the top of a tall building or on a pole in a field.

The global horizontal radiation being the sum of both the direct and diffuse components as measured incident on a flat horizontal plane. It is therefore the sum of the direct horizontal and diffuse horizontal values.

The total solar radiation on tilted surface ( $H_T$ ) is the sum of direct or beam solar radiation ( $H_B$ ), sky diffuse solar radiation ( $H_S$ ) and the ground reflected radiation ( $H_R$ ) and given by:

$$H_T = H_B + H_S + H_R \tag{1}$$

The daily beam radiation on an inclined surface is given as:

$$H_B = (H - H_d) R_b \tag{2}$$

where  $H$  is the monthly mean daily global solar radiation,  $H_d$  is diffuse solar radiation on a horizontal surface and  $R_b$  is the ratio of the average daily beam radiation on tilted surface to that on horizontal surface and is given as (Klein, 1977):

$$R_b = \frac{(\cos\beta \sin\delta \sin\phi) (\omega_{ss} - \omega_{sr}) (\pi/180) - (\sin\delta \cos\phi \sin\beta \cos\gamma) (\omega_{ss} - \omega_{sr}) (\pi/180) + (\cos\phi \cos\delta \cos\beta) (\sin \omega_{ss} - \sin \omega_{sr}) + (\cos\delta \cos\gamma \sin\phi \sin\beta) (\sin \omega_{ss} - \sin \omega_{sr}) - (\cos\delta \sin\beta \sin\gamma) (\cos \omega_{ss} - \cos \omega_{sr})}{2 (\cos\phi \cos\delta \sin\omega_s + (\pi/180) (\omega_s \sin\phi \sin\delta))} \tag{3}$$

where  $\gamma$  is the surface azimuth angle, and  $\omega_{ss}$  &  $\omega_{sr}$  are sunrise and sunset hour angles on the tilted surface given by:

$$\omega_{sr} = - \min \left\{ \omega_s, \arccos \left[ \frac{(AB + \sqrt{(A^2 - B^2 + 1)})}{(A^2 + 1)} \right] \right\} \text{ if } \gamma > 0 \tag{4}$$

$$\omega_{ss} = \min \left\{ \omega_s, \arccos \left[ \frac{(AB - \sqrt{(A^2 - B^2 + 1)})}{(A^2 + 1)} \right] \right\} \text{ if } \gamma > 0 \tag{5}$$

$$\omega_{sr} = - \min \left\{ \omega_s, \arccos \left[ \frac{(AB - \sqrt{(A^2 - B^2 + 1)})}{(A^2 + 1)} \right] \right\} \text{ if } \gamma < 0 \tag{6}$$

$$\omega_{ss} = \min \left\{ \omega_s, \arccos \left[ \frac{(AB + \sqrt{(A^2 - B^2 + 1)})}{(A^2 + 1)} \right] \right\} \text{ if } \gamma < 0 \tag{7}$$

The constants A and B are given by:

$$A = \frac{\cos\phi}{\sin\gamma \tan\beta} + \frac{\sin\phi}{\tan\gamma} \tag{8}$$

$$B = \tan\delta \left\{ \frac{\cos\phi}{\tan\gamma\beta} + \frac{\sin\phi}{\sin\gamma \tan\beta} \right\} \tag{9}$$

Using Equation 3, one can estimate the total solar radiation on tilted surface ( $H_T$ ). In this study the total solar radiation on tilted surface using Klein model and CF has been estimated and compared.

### RESULTS AND DISCUSSION

The hourly solar radiation estimated for Delhi using CF has been presented in Table 1 along with 15 years measured values of hourly solar radiation (Mani, 1980) for comparison. The % deviation (N) from measured value is in the range of 0.238 to 28.2 represents new model whereas % deviation (G) represents Gueymard model the deviation is in the range of 1.94 to 23.54. Estimated total solar radiation (kWh/m<sup>2</sup>) for Delhi at different inclination and surface azimuth angle is presented in Table 2. Table 3 shows that the predicted hourly values of solar radiation are in the range of 15% for all the locations except for the months of July and August this is due to the onset of Monsoon which is not accurately predictable in India. This table also shows that the percentage error in estimating hourly solar radiation is similar to as estimated using Gueymard (2000). Hence the hourly solar radiation using CF can be estimated for other stations also.

The total solar radiation at various orientations and inclinations for Delhi has been presented in Table 2. The results show that Equation 3 does not give correct value for true north or true south. However, for other orientation the total solar radiation can be estimated accurately for any location.

### Conclusion

The study reveals that by using CF the total solar radiation can be estimated for locations having longitude range of ± 70 to ± 125. This method does not require any type of measured value which requires costly equipments.

**Table 1.** Estimated hourly global solar radiation (kWh/m<sup>2</sup>) for Delhi.

Hour angle	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
97.5	0.000	0.000	0.000	0.000	0.027	0.047	0.036	0.000	0.000	0.000	0.000	0.000
82.50	0.000	0.002	0.060	0.123	0.170	0.190	0.179	0.138	0.079	0.017	0.000	0.000
67.50	0.097	0.149	0.222	0.292	0.338	0.355	0.345	0.306	0.241	0.167	0.107	0.081
52.50	0.251	0.315	0.397	0.471	0.514	0.527	0.518	0.483	0.416	0.334	0.263	0.231
37.50	0.402	0.472	0.561	0.637	0.675	0.684	0.677	0.646	0.579	0.492	0.415	0.378
22.50	0.522	0.597	0.688	0.764	0.799	0.803	0.798	0.771	0.705	0.616	0.535	0.497
7.50	0.589	0.665	0.757	0.833	0.866	0.868	0.864	0.839	0.774	0.684	0.602	0.563
-7.50	0.589	0.665	0.757	0.833	0.866	0.868	0.864	0.839	0.774	0.684	0.602	0.563
-22.50	0.522	0.597	0.688	0.764	0.799	0.803	0.798	0.771	0.705	0.616	0.535	0.497
-37.50	0.402	0.472	0.561	0.637	0.675	0.684	0.677	0.646	0.579	0.492	0.415	0.378
-52.50	0.251	0.315	0.397	0.471	0.514	0.527	0.518	0.483	0.416	0.334	0.263	0.231
-67.50	0.097	0.149	0.222	0.292	0.338	0.355	0.345	0.306	0.241	0.167	0.107	0.081
-82.50	0.000	0.002	0.060	0.123	0.170	0.190	0.179	0.138	0.079	0.017	0.000	0.000
-97.5	0.000	0.000	0.000	0.000	0.027	0.047	0.036	0.000	0.000	0.000	0.000	0.000
Total (measured)	3.721 (3.987)	4.399 (5.001)	5.370 (6.138)	6.241 (6.935)	6.779 (7.287)	6.948 (6.544)	6.832 (5.334)	6.367 (5.053)	5.590 (5.602)	4.620 (5.355)	3.842 (4.523)	3.498 (3.843)
	% deviation (N)											
	6.677	11.49	12.54	9.785	6.831	6.22	28.2	26.6	0.238	13.44	14.97	9.073
	% deviation (G)											
	4.86	11.24	11.84	8.78	5.27	7.75	23.54	22.30	1.94	13.41	15.20	7.51

**Table 2.** Estimated total solar radiation (kWh/m<sup>2</sup>) for Delhi at different inclination and surface azimuth angle.

Azimuth	INCL	Total solar radiation												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
179	φ -15	3.24	3.89	4.73	5.49	5.90	6.00	5.93	5.59	4.92	4.08	3.36	3.04	4.68
	φ	2.50	3.08	3.79	4.35	4.54	4.51	4.52	4.40	3.94	3.25	2.61	2.31	3.65
	φ + 15	1.88	2.49	3.12	3.53	3.47	3.13	3.35	3.53	3.24	2.65	2.01	1.63	2.84
	φ -15	3.27	3.94	4.81	5.62	6.08	6.21	6.12	5.74	5.02	4.13	3.39	3.06	4.78
150	φ	2.64	3.24	4.02	4.71	5.05	5.11	5.06	4.80	4.20	3.42	2.75	2.44	3.95
	φ + 15	1.93	2.47	3.14	3.68	3.85	3.80	3.83	3.74	3.29	2.63	2.02	1.80	3.01
	φ -15	3.42	4.10	5.03	5.90	6.43	6.60	6.49	6.04	5.25	4.31	3.54	3.20	5.03
120	φ	3.01	3.66	4.55	5.39	5.90	6.07	5.96	5.53	4.76	3.86	3.13	2.81	4.55

	$\phi + 15$	2.58	3.18	4.00	4.79	5.29	5.45	5.35	4.93	4.20	3.36	2.69	2.39	4.02
	$\phi -15$	3.61	4.32	5.29	6.22	6.81	7.00	6.87	6.38	5.52	4.54	3.73	3.38	5.31
90	$\phi$	3.41	4.12	5.09	6.05	6.68	6.90	6.76	6.22	5.33	4.33	3.54	3.19	5.13
	$\phi + 15$	3.13	3.81	4.75	5.71	6.37	6.62	6.46	5.89	4.99	4.02	3.25	2.92	4.83
	$\phi -15$	3.79	4.52	5.52	6.48	7.10	7.30	7.16	6.64	5.76	4.74	3.92	3.56	5.54
60	$\phi$	3.74	4.48	5.50	6.51	7.19	7.43	7.27	6.69	5.75	4.70	3.87	3.50	5.55
	$\phi + 15$	3.53	4.25	5.26	6.28	6.97	7.23	7.06	6.46	5.51	4.47	3.66	3.30	5.33
	$\phi -15$	3.77	4.50	5.50	6.48	7.12	7.35	7.20	6.65	5.74	4.72	3.90	3.54	5.54
30	$\phi$	3.96	4.71	5.74	6.74	7.39	7.61	7.46	6.91	5.99	4.94	4.09	3.72	5.77
	$\phi + 15$	3.93	4.67	5.67	6.64	7.25	7.45	7.31	6.79	5.91	4.89	4.06	3.69	5.69
	$\phi -15$	4.00	4.74	5.73	6.67	7.25	7.44	7.31	6.82	5.96	4.96	4.13	3.77	5.73
0	$\phi$	4.09	4.83	5.82	6.76	7.35	7.54	7.41	6.91	6.05	5.05	4.22	3.85	5.82
	$\phi + 15$	3.92	4.63	5.57	6.46	7.00	7.17	7.05	6.59	5.79	4.84	4.05	3.69	5.56
	$\phi -15$	3.18	3.84	4.73	5.56	6.05	6.20	6.10	5.69	4.94	4.04	3.30	2.97	4.72
-150	$\phi$	2.21	2.79	3.60	4.38	4.87	5.02	4.92	4.52	3.80	2.98	2.31	2.02	3.62
	$\phi + 15$	1.07	1.45	2.05	2.73	3.27	3.50	3.36	2.89	2.23	1.59	1.13	1.01	2.19
	$\phi -15$	3.23	3.90	4.80	5.67	6.21	6.38	6.26	5.81	5.02	4.10	3.35	3.02	4.81
-120	$\phi$	2.28	2.82	3.57	4.32	4.82	5.00	4.89	4.46	3.76	2.99	2.38	2.12	3.61
	$\phi + 15$	1.20	1.50	1.93	2.40	2.74	2.88	2.80	2.50	2.05	1.59	1.25	1.11	2.00
	$\phi -15$	3.43	4.10	5.02	5.89	6.44	6.62	6.50	6.04	5.24	4.31	3.55	3.21	5.03
-90	$\phi$	2.72	3.26	3.99	4.69	5.13	5.28	5.18	4.81	4.16	3.42	2.81	2.55	4.00
	$\phi + 15$	1.80	2.12	2.54	2.93	3.14	3.19	3.15	2.98	2.64	2.22	1.86	1.69	2.52
	$\phi -15$	3.69	4.39	5.33	6.22	6.78	6.96	6.84	6.37	5.55	4.60	3.82	3.47	5.34
-60	$\phi$	3.36	3.96	4.75	5.48	5.91	6.05	5.95	5.59	4.93	4.13	3.46	3.17	4.73
	$\phi + 15$	2.77	3.20	3.72	4.16	4.36	4.39	4.36	4.21	3.83	3.31	2.84	2.63	3.65
	$\phi -15$	3.92	4.64	5.61	6.54	7.11	7.29	7.17	6.68	5.84	4.86	4.05	3.69	5.62
-30	$\phi$	3.92	4.60	5.50	6.34	6.84	6.99	6.88	6.46	5.71	4.80	4.04	3.70	5.48
	$\phi + 15$	3.69	4.27	5.00	5.64	5.96	6.03	5.97	5.71	5.15	4.43	3.79	3.50	4.93

**Table 3.** Percentage variation in estimation of solar radiation in different locations of India.

Location	Parameter	Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ahmedabad	% variation (G)	11.33	13.58	12.95	9.964	8.529	-10.1	-43.8	-47.9	-8.96	10.17	10.92	10.02
	% variation (N)	11.33	13.58	12.95	9.964	8.529	-10.1	-43.8	-47.9	-8.96	10.17	10.92	10.02
Bhavnagar	% variation (G)	13.58	14.74	13.9	9.062	8.984	-15.5	-49.7	-55	-11.3	10.93	12.82	11.42
	% variation (N)	12.73	13.91	13.07	8.205	8.138	-16.6	-51.0	-56.4	-12.4	10.06	11.97	10.56
Chinnai	% variation (G)	7.34	15.09	14.00	9.61	4.40	-5.73	-14.41	-11.50	-4.91	-12.62	-13.42	-9.66
	% variation (N)	3.86	11.90	10.82	6.31	0.92	-9.58	-18.57	-15.56	-8.77	-16.83	-17.69	-13.78
Jodhpur	% variation (G)	9.087	9.703	8.366	4.824	2.283	-6.17	-23.9	-26.4	-1.92	10.09	9.947	8.655
	% variation (N)	15.03	15.6	14.27	10.81	8.318	0.353	-16.2	-18.5	4.605	15.95	15.84	14.63
Kodaikanal	% variation (G)	23.94	22.4	17.3	8.405	0.889	-7.46	-25.8	-24.0	-19.0	-19.3	-2.033	11.36
	% variation (N)	27.14	25.67	20.76	12.21	5.003	-2.99	-20.6	-18.9	-14.1	-14.3	2.265	15.08
Nagpur	% variation (G)	14.07	15.19	11.50	8.27	6.02	-15.78	-47.96	-52.21	-12.18	11.32	15.78	13.58
	% variation (N)	12.08	13.21	9.45	6.17	3.90	-18.38	-51.29	-55.67	-14.77	9.25	13.82	11.58
New Delhi	% variation (G)	4.631	9.541	10.61	7.84	4.859	-8.45	-30.9	-29.3	-1.95	11.52	13.1	7.084
	% variation (N)	6.677	11.49	12.54	9.785	6.831	-6.22	-28.2	-26.6	0.238	13.44	14.97	9.073
Puna	% variation (G)	13.20	15.99	13.00	9.31	8.55	-13.45	-46.56	-42.37	-14.18	5.77	10.32	10.61
	% variation (N)	13.94	16.70	13.73	10.06	9.30	-12.52	-45.36	-41.19	-13.23	6.57	11.08	11.37
Shillong	% variation (G)	18.60	25.37	20.07	9.46	-5.69	-36.75	-30.46	-24.71	-20.62	2.03	15.02	25.49
	% variation (N)	10.74	17.95	11.97	0.34	-16.22	-50.30	-43.42	-37.22	-32.85	-7.80	6.75	18.37
Trivandrum	% variation (G)	14.12	13.20	10.83	1.12	-8.14	-10.31	-16.30	-8.11	-0.50	-7.02	-4.05	3.58
	% variation (N)	8.65	7.70	5.27	-5.00	-14.85	-17.18	-23.53	-14.81	-6.75	-13.77	-10.68	-2.57
Visakhapatnam	% variation (G)	16.39	17.12	11.77	6.04	3.94	-23.60	-36.70	-26.87	-13.50	1.85	11.31	14.90
	% variation (N)	13.85	14.59	9.11	3.26	1.12	-27.24	-40.72	-30.62	-16.91	-1.14	8.61	12.32

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## Nomenclature

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$H_T$	Total solar radiation on tilted surface	(kWh/m <sup>2</sup> )
$H_B$	Beam solar radiation	(kWh/m <sup>2</sup> )
$H_S$	Sky diffuse solar radiation	(kWh/m <sup>2</sup> )
$H_R$	Ground reflected radiation	(kWh/m <sup>2</sup> )
$H_d$	Diffuse solar radiation on a horizontal surface	(kWh/m <sup>2</sup> )
$H$	Monthly mean daily global solar radiation	(kWh/m <sup>2</sup> )
$K_t$	Clearness index	dimensionless
$R_b$	Ratio of the average daily beam radiation on tilted surface to that on horizontal surface	
$\gamma$	Surface azimuth angle	degrees
$\omega_{ss}$	Sunrise sunset hour angles on the tilted surface	degrees
$\omega_{sr}$	Sunset hour angles on the tilted surface	degrees
$\omega_s$	Hour angle	degrees
$\beta$	Tilt angle	degrees
$\varphi$	Latitude	degrees
$\delta$	Declination angle	degrees
$A$	Constant	dimensionless
$B$	Constant	dimensionless

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