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Estimation of global radiation using clearness index model for sizing photovoltaic system

Ravinder Kumar, L. Umanand*

Centre for Electronic Design and Technology, Indian Institute of Science, Bangalore 560012, India

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Abstract

A methodology for developing a simple theoretical model for calculating global insolation on a horizontal surface is described in this paper. The input parameters to the model are the latitude of the desired location and the amount of total precipitable water content in the vertical column at that location. Both the parameters are easily measurable with inexpensive instrument such as global positioning system (GPS). The principal idea behind the paper is to have a model that could be used for designing a photovoltaic system quickly and within reasonable accuracy. The model in this paper has been developed using measured data from 12 locations in India covering length and breadth of the country over a period of 9–22 years. The model is validated by calculating theoretical global insolation for five locations, one in north (New Delhi), one in south (Thiruvanandapuram), one in east (Kolkata), one in west (Mumbai) and one in central (Nagpur) part of India and comparing them with the measured insolation values for these five locations. The measured values of all these locations had been considered for developing the model. The model is further validated for a location (Goa) whose measured data is not considered for developing the model, by comparing the calculated and measured values of the insolation. Over the range of latitudes covering most parts of India, the error is within 20% of the measured value. This gives the credibility of the model and the methodology used for developing the model for any region in the world.
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Keywords: Modelling; Solar; Insolation; PV

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* Corresponding author. Tel.: +91 80 2293 3088; fax: +91 80 2293 2290.
E-mail address: lums@cedt.iisc.ernet.in (L. Umanand).

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1. Introduction

The energy source for any stand-alone photovoltaic (PV) system is the solar insolation available at the location of the installation. The performance of such a stand-alone PV system is directly affected by the amount of insolation available to the system. Hence, sizing of the system is essential to satisfy the energy demand of the application for the amount of insolation available. The available insolation at any location varies from time to time, caused by the diurnal and seasonal changes in the position of the Sun relative to the Earth. The variations in insolation caused by the position of the Sun can be determined using geometric relations. However, the dependency on the weather conditions cannot be predicted and hence the need to depend on long-term historical records of hourly data for this type of information. These long-term data are available for only a limited number of sites or locations. In the recent years, the utilization of solar energy has increased several folds due to the improvement in the solar panel efficiency and drop in the pricing of the solar panels. This has given a significant boost to applications based on solar photovoltaic (PV) such as lighting, water-pumping systems etc. Traditionally, solar PV has been projected as a de-centralized power source for remote, rural and inaccessible locations. However, now it is a viable alternative even in suburban and urban locations by supplementing the grid energy. With such wide percolation of solar PV applications, the insolation data collection becomes very crucial and critical to PV system design. The procurement of solar insolation data is either by conducting direct measurements of the solar radiation pattern at the location through-out the year and over several years or purchasing the data from meteorological department. Both these methods of insolation data procurement are time consuming and expensive and, therefore, will inhibit the design process of the PV system design for a given location. Therefore, there is need for developing a reasonably accurate mathematical model to estimate the solar insolation at any location for any given day of the year. These models are developed using statistical properties of available long-term records of hourly data over certain locations spread across the country or region.

Measured monthly average values of daily insolation provide a good starting point for developing the solar insolation model. The usefulness of long-term monthly averaged daily insolation can be understood from the fact that at a particular location, these averages are relatively constant so that past values can be used to estimate future ones [1].

Under cloudless skies, solar insolation is essentially due to the direct beam radiation. The accurate prediction of direct radiation is important in most PV applications. This prediction can be performed in various ways depending on the time scale and availability of necessary data [2].

Over the years, several models have been proposed. Some of them have been based on the meteorological parameters and others have been purely statistical in nature. The meteorological parameters that have been used in the models are the following:

(a) Site pressure.
(b) Precipitable water in the vertical column.
(c) Reduced vertical ozone column amount.
(d) Reduced vertical nitrogen dioxide column amount in the stratosphere.

(e) Reduced vertical nitrogen dioxide column amount in the troposphere.
(f) Angstrom's spectral turbidity coefficient.
(g) Angstrom's wavelength exponent.
(h) Unsworth-Monteith's broadband turbidity coefficient.

All the parameters do not contribute equally in calculation of clearness index. Some are more dominant than others. The usages of these parameters in the models have been discussed by Gueymard [2] giving their merits and demerits. Some of the models with their merits and demerits are briefly given in the following paragraphs, chronologically:

1. Hoyt's model [3]: The model is very accurate (95% or better) in estimating direct solar radiation. However, the model depends predominantly on scattering ratios of air and dust, and absorption ratios of water vapor, carbon-di-oxide, ozone, oxygen and dust. These parameters are not directly measurable and in turn depend on several other parameters that are measured and subsequently corrected for various factors such as pressure and path lengths. Further, many of these parameters for a specific location are not readily available. This makes the process of acquiring the parameters both time-consuming and expensive.
2. Atwater and Ball's model [4]: The model is based on two parameters, absorptivity and transmissivity of the radiation. As both the parameters are not the measured ones; they are expressed in terms of other parameters such as the cloud content and optical path length that are difficult and expensive to measure.
3. Excell's model [5]: This model uses Fourier series representation for the daily total global solar radiation. This is simple and appropriate since a plot of the radiation as a function of day of the year results in a sinusoidal waveform. However, Fourier coefficients in the model are dependent only on the latitudes and hence less accurate. The process used for estimation of daily clearness factor is very complex.
4. Bhaskar Choudhury's model [6]: This model is very accurate. However, it uses a complex expression for parameter 'atmospheric transmission function' that uses too many other dependent parameters such as absorption coefficients and scattering coefficients for the calculation of global insolation. The process of obtaining these parameters for a given location can be time consuming and expensive.
5. Chapman's model [7]: This model is purely statistical in nature. At some point of the model, the hour angle and sunset hour angle are used in calculating average hourly clearness index values. The accuracy of the model depends on number of data points available for the locations. Generalization of this model for any location is difficult and hence the model has limited usage.

These are some of the models that have been developed to estimate global solar insolation on a horizontal surface on a clear day taking several meteorological parameters into account. The measurement of some of these meteorological parameters requires very expensive equipment making the whole process expensive. For a preliminary design of a stand-alone PV system, spending enormous amount of money in procuring meteorological data is not justified. This paper addresses this issue of providing a reasonably accurate model using only dominant parameters that are easily measurable or readily available, so that it can be used for quick preliminary PV system design for any given location with reasonable accuracy.

The investigation is aimed:

- At proposing a method to develop a simple and accurate model for clearness index for any location or region in the world, based on minimum number of measurable meteorological parameters.
- At using the model for calculating clearness index for any remote location for any given day from the measured meteorological parameters.
- At estimating direct insolation under clear sky conditions from the clearness index data calculated from the model, so as to enable the design of PV systems at any given location, thereby reducing the design turn around time.
- Validating the proposed modeling method by applying it on measured data in the Indian sub-continent.

The model presented in this paper for predicting direct insolation is based on only two measured factors that are dominant, viz. latitude of the desired location and precipitable water in the vertical column at that location. Latitude of any location can be easily found using a detailed geographical map or by using a GPS (Global Positioning System) receiver. Precipitable water at any location can be found from the daily relative humidity data given by the meteorological department or measured using inexpensive instruments such as radiosonde or GPS receivers [8]. Therefore, a model, based on only these easily measurable parameters will enable quick and easy calculation of insolation for any location for any given day. This paper proposes such a model.

The proposed modeling concepts are introduced in Section 2. The model for the Indian sub-continent is developed in Section 3, using the previously measured data [9] over 12 locations in India. The model is validated in Section 4 with the help of insolation curves for various locations in the Indian sub-continent. Finally the paper is concluded in Section 5.

2. Modeling process

The monthly averages of daily global solar insolation data are normally available for several locations in a region. The data should be such that it covers a larger range of latitudes. These data are then reduced to the monthly average daily clearness index (K_T) by taking the ratio of measured global solar insolation to the calculated extra-terrestrial horizontal insolation. The extra-terrestrial horizontal insolation per day at a given place is the insolation on a horizontal surface at the place without the atmospheric effects. This is calculated from the following expression [10]:

$$H_o = \frac{24 I_o}{\pi}[\cos(\phi)\cdot\cos\delta\cdot\sin\varpi_{sr} + \varpi_{sr}\cdot\sin(\phi)\sin\delta]\ \text{kWh/m}^2 \quad (1)$$

Here,

H_o = Extra-terrestrial horizontal insolation in kWh/m^2
I_o = Extra-terrestrial irradiance in kW/m^2

$$I_o = I_{sc}\left[1 + 0.033\cos\left(\frac{360N}{365}\right)\right] \quad (2)$$

I_{sc} = Solar constant = 1.367 kW/m^2 [2]
N = Day of the year (N = 1 on January 1st and N = 365 on December 31st, February 29th is ignored.
ϕ = Latitude of the location in degrees
δ = Declination angle in degrees [5]

$$\delta = 23.45 \sin\left[\frac{2\pi(N-80)}{365}\right] \tag{3}$$

ω_{sr} = Hour angle at Sunrise in radians

$$\omega_{sr} = \cos^{-1}(-\tan\phi\cdot\tan\delta) \tag{4}$$

It can be seen from the above expressions that the extra-terrestrial horizontal insolation is a function of latitude and the day of year only. Hence, it can be calculated for any location for any given day. However, the calculated insolation does not take any atmospheric effects into account.

The clearness index, K_T gives a measure of the atmospheric effects at a place on the insolation. However, the clearness index is a stochastic parameter, which is a function of time of year, season, climatic condition and geographic location. Therefore, to include the atmospheric effects on the insolation at a given place, a model for the clearness index is essential. To develop the model for the clearness index, the insolation on a horizontal surface for a few locations is measured over a period of time encompassing all seasons and climatic conditions. Using Eq. (1), the extra-terrestrial horizontal insolation is calculated for various locations for which the measured global insolation is available. The calculated values are without any atmospheric effects. Based on the calculated values of extra-terrestrial horizontal insolation for locations and the measured global insolation on a horizontal surface for the same locations, K_T for these locations are computed. A plot of K_T versus day of the year indicates that the variation of K_T over a period of one year is a periodic function with a periodicity of one-year. Therefore, the Fourier series are considered as an appropriate curve fitting technique to model K_T.

Let us represent K_T by the following Fourier series:

$$K_T = f(x,w,t) + e \tag{5}$$

where

$$f(x,w,t) = A_1 + A_2\sin t + A_3\sin 2t + A_4\sin 3t + A_5\cos t + A_6\cos 2t + A_7\cos 3t \tag{6}$$

Here, the arguments of the trigonometric terms (t) are functions of the day of the year (N), and the Fourier coefficients $A_1, A_2, \ldots, A_7$ are the functions of latitude (ϕ) & total precipitable water vapor in the atmosphere (w). The Fourier coefficients are calculated from the following expression:

$$A_i = a_{i1} + a_{i2}x + a_{i3}x^2 + a_{i4}w + a_{i5}w^2.$$

Substituting for A_i in the expression for $f(x,w,t)$, we get the following:

$$\begin{aligned} f(x,w,t) = {} & (a_{11} + a_{12}x + a_{13}x^2 + a_{14}w + a_{15}w^2) \\ & + (a_{21} + a_{22}x + a_{23}x^2 + a_{24}w + a_{25}w^2)\sin t \\ & + (a_{31} + a_{32}x + a_{33}x^2 + a_{34}w + a_{35}w^2)\sin 2t \\ & + (a_{41} + a_{42}x + a_{43}x^2 + a_{44}w + a_{45}w^2)\sin 3t \\ & + (a_{51} + a_{52}x + a_{53}x^2 + a_{54}w + a_{55}w^2)\cos t \\ & + (a_{61} + a_{62}x + a_{63}x^2 + a_{64}w + a_{65}w^2)\cos 2t \\ & + (a_{71} + a_{72}x + a_{73}x^2 + a_{74}w + a_{75}w^2)\cos 3t \end{aligned} \tag{7}$$

$$x = (\varphi - 35), \quad \varphi = \text{Latitude in degrees} \tag{8}$$

w = Total precipitable water vapor in the atmosphere in gm/cm^2

$$t = (2\pi/365)(N - 80) \text{ [5]} \tag{9}$$

e = error

x is proposed based on the best fit for the available data. This would involve some iteration to determine the appropriate function for x. Here, all collected data is for the Indian subcontinent. We find that an offset value of 35 degrees latitude gives the best fit for this region. This led to the determination of function x given in Eq. (8).

Now, the error term ‘e’ is given by:

$$e = K_T - f(x,w,t) \tag{10}$$

The Fourier series representation becomes valid if this error term is zero or at best, minimum. The error term can be minimized by the least squares technique [5].

The sum of the squares of the error E is given by:

$$E = \sum [K_T - f(x)]^2 \tag{11}$$

Performing partial differentiation with respect to $a_{11}, a_{12}, \ldots, a_{75}$ and equating to zero, we get the following:

$$\partial E/\partial a_{11} = 2\sum [K_T - (a_{11} + a_{12}x + \cdots + a_{75}w^2\cos 3t)](-1) = 0 \tag{12}$$

This yields the following expression:

$$\begin{aligned}\sum a_{11} &+ \sum a_{12}x + \sum a_{13}x^2 + \sum a_{14}w + \sum a_{15}w^2 + \sum a_{21}\sin t \\ &+ \sum a_{22}x\sin t + \sum a_{23}x^2\sin t + \sum a_{24}w\sin t + \sum a_{25}w^2\sin t \\ &+ \sum a_{31}\sin 2t + \sum a_{32}x\sin 2t + \sum a_{33}x^2\sin 2t + \sum a_{34}w\sin 2t \\ &+ \sum a_{35}w^2\sin 2t + \sum a_{41}\sin 3t + \sum a_{42}x\sin 3t + \sum a_{43}x^2\sin 3t \\ &+ \sum a_{44}w\sin 3t + \sum a_{45}w^2\sin 3t + \sum a_{51}\cos t + \sum a_{52}x\cos t \\ &+ \sum a_{53}x^2\cos t + \sum a_{54}w\cos t + \sum a_{55}w^2\cos t + \sum a_{61}\cos 2t \\ &+ \sum a_{62}x\cos 2t + \sum a_{63}x^2\cos 2t + \sum a_{64}w\cos 2t + \sum a_{65}w^2\cos 2t \\ &+ \sum a_{71}\cos 3t + \sum a_{72}x\cos 3t + \sum a_{73}x^2\cos 3t + \sum a_{74}w\cos 3t \\ &+ \sum a_{75}w^2\cos 3t = \sum K_{Ti} \end{aligned} \tag{13}$$

Performing similar partial differentiations $\partial E/\partial a_{12}$, $\partial E/\partial a_{13}, \ldots, \partial E/\partial a_{75}$, arranging them in the matrix form and solving, we get the coefficients $a_{11}, a_{12}, \ldots, a_{75}$. These coefficients are used to obtain Fourier coefficients $A_1, A_2, \ldots, A_7$. This leads to the following model for K_T:

$$K_T = A_1 + A_2\sin t + A_3\sin 2t + A_4\sin 3t + A_5\cos t + A_6\cos 2t + A_7\cos 3t \tag{14}$$

The clearness index, K_T for any location for any given day of the year can now be calculated using Eq. (14). From Eq. (1) H_o, the extra-terrestrial horizontal insolation is calculated. The global solar insolation with atmospheric effects included, is obtained from the following expression:

$$H_{tc} = K_T \cdot H_o \tag{15}$$

where H_{tc} is the global solar insolation on a horizontal surface at any location on any given day.

3. Model for the Indian sub-continent

Validation of the model is done as a two-step process. In the first step, the measured values of daily median values of global insolation data for each month for 12 locations across India are taken [9]. The range of latitudes covered is between 8.48°N and 28.58°N covering most part of India. The data has been collected over long periods of time. The data is averaged over years ranging from 9 to 22 years. The locations for which the data are considered for modeling are given in Table 1 along with their latitude and representative symbol.

Table 2 gives the measured insolation data and the precipitable water vapor data for the twelve locations considered. These data are used as parameters to develop the model for

Table 1
Locations of which the measured insolation data are considered

Sr. no	Location	Latitude (deg)	Symbol
1	Ahmedabad	23.07	A
2	Bhavnagar	21.75	B
3	Mumbai	19.12	C
4	Kolkata	22.65	D
5	Jodhpur	26.30	E
6	Kodaikanal	10.23	F
7	Chennai	13.00	G
8	Nagpur	21.15	H
9	New Delhi	28.58	I
10	Pune	18.53	J
11	Thiruvanandapuram	8.48	K
12	Vishakapattanam	17.72	L

K_T. Based on the model, the theoretical global insolation for each location are calculated and compared with the measured data for its validity.

In the second step, the theoretical global insolation calculated from the proposed model for any station such as Goa, whose latitude lies within the range of latitudes considered for modeling are compared with the measured values of daily median global insolation for Goa. The calculated and measured insolation curves are studied to illustrate the validity of the proposed model. Table 2 gives the measured median values of daily global solar insolation H_m in kWh/m^2 and total precipitable water vapor in the atmosphere, w in gm/cm^2 for the twelve stations mentioned earlier. These are the daily median data for each month of a year.

The starting process for the first step is to calculate the extra-terrestrial (ETR) insolation on a horizontal surface without any atmospheric effects. This is a function of the day of year. Dividing the measured value of global insolation for that day of the year by the ETR insolation value, clearness index data for that day is obtained. The process is done for all the twelve locations for all the months of the year, at the median values of the month. The 'N' values for each month are 15, 46, 74, 105, 135, 166, 196, 227, 258, 288, 319 and 349 for Jan to Dec, respectively. Based on these calculated values of K_T, the coefficients $a_{11}, a_{12}, \ldots, a_{75}$ of Eq. (13) are calculated. They are listed as follows in the matrix form:

$$\begin{array}{cccccc}
 & 1 & 2 & 3 & 4 & 5 \\
1 & 0.5563 & 0.0089 & 0.0002 & 0.0743 & -0.0089 \\
2 & -0.2350 & 0.0119 & 0.0004 & 0.1473 & -0.0237 \\
3 & -0.1011 & -0.0091 & -0.0004 & 0.1029 & -0.0201 \\
4 & 0.0136 & 0.0041 & 0.0002 & -0.0071 & 0.0010 \\
5 & 0.1300 & -0.0133 & -0.0003 & -0.0848 & 0.0098 \\
6 & -0.0600 & 0.0048 & 0.0002 & 0.0733 & -0.0132 \\
7 & 0.0970 & 0.0058 & 0.0002 & -0.0282 & 0.0010
\end{array}$$

Table 2
Insolation and precipitable water vapor data for twelve locations

Month	Measured values	A	B	C	D	E	F	G	H	I	J	K	L
Jan	Hm(kwh/m^2)	4.94	5.20	5.08	4.24	4.79	6.81	5.44	5.03	4.15	5.30	6.17	5.51
	w (g/cm^2)	1.67	1.84	2.70	2.10	1.59	0.74	2.73	1.75	1.40	1.77	3.02	2.73
Feb	Hm(kwh/m^2)	5.84	6.07	5.77	5.26	5.68	7.32	6.41	5.78	5.19	6.18	6.58	6.16
	w (g/cm^2)	1.82	1.85	2.55	2.22	1.60	0.77	2.66	2.09	1.38	1.75	3.16	3.21
Mar	Hm(kwh/m^2)	6.78	6.90	6.58	6.09	6.66	7.18	7.03	6.43	6.34	6.87	6.89	6.65
	w (g/cm^2)	2.16	2.30	2.90	2.63	1.83	0.77	2.51	2.08	1.66	2.06	3.49	3.08
Apr	Hm(kwh/m^2)	7.43	7.38	7.13	6.59	7.38	6.60	7.11	6.97	7.13	7.30	6.48	6.83
	w (g/cm^2)	2.73	2.88	3.30	3.49	2.29	1.12	3.25	2.58	1.93	2.45	4.30	3.98
May	Hm(kwh/m^2)	7.67	7.68	7.42	7.01	7.64	6.01	6.86	7.12	7.51	7.58	5.96	6.91
	w (g/cm^2)	3.33	3.42	3.95	4.3	2.86	1.58	4.36	2.99	2.55	2.87	4.47	4.59
Jun	Hm(kwh/m^2)	6.69	6.31	5.80	5.14	7.31	5.23	6.18	6.01	6.76	5.98	5.58	5.45
	w (g/cm^2)	4.66	4.81	5.17	5.62	4.22	1.86	5.07	4.66	4.01	3.94	4.47	5.50
Jul	Hm(kwh/m^2)	5.03	4.76	4.17	4.71	6.24	4.34	5.66	4.41	5.66	4.57	5.20	4.84
	w (g/cm^2)	5.37	5.32	5.36	6.28	5.23	1.88	5.09	5.32	5.56	4.26	4.46	5.55
Aug	Hm(kwh/m^2)	4.67	4.43	4.09	4.36	5.87	4.51	5.86	4.22	5.45	4.58	5.75	5.12
	w (g/cm^2)	5.32	5.16	5.05	6.17	5.25	1.77	4.94	5.41	5.74	4.17	4.29	5.48
Sep	Hm(kwh/m^2)	5.93	5.85	5.20	4.62	6.33	4.69	6.07	5.38	6.07	5.42	6.23	5.65
	w (g/cm^2)	4.40	4.59	4.78	5.69	3.91	1.82	4.82	4.59	4.19	3.86	4.39	5.39
Oct	Hm(kwh/m^2)	5.87	6.05	5.66	4.64	5.86	4.25	5.25	5.87	5.50	5.96	5.59	6.03
	w (g/cm^2)	3.27	3.31	4.01	4.55	2.53	1.63	4.64	3.53	2.67	3.15	4.37	4.91
Nov	Hm(kwh/m^2)	5.15	5.35	5.23	4.30	5.03	4.70	4.69	5.30	4.60	5.41	5.24	5.6
	w (g/cm^2)	2.00	2.29	2.94	2.86	1.71	1.04	3.45	1.99	1.50	2.29	4.02	3.18
Dec	Hm(kwh/m^2)	4.67	4.85	4.83	4.07	4.47	5.71	4.57	4.85	4.02	5.09	5.62	5.25
	w (g/cm^2)	1.91	2.03	2.93	2.06	1.73	0.91	3.12	1.89	1.42	2.09	3.67	2.67

Table 3
Measured and calculated insolation values

Loc	Ins	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
I	Htm	4.15	5.19	6.34	7.13	7.51	6.76	5.66	5.45	6.07	5.50	4.60	4.02
	Htc	4.25	5.33	6.47	7.14	7.39	6.94	5.90	5.69	6.10	5.55	4.61	4.16
K	Htm	6.17	6.58	6.89	6.48	5.96	5.58	5.20	5.75	6.23	5.59	5.24	5.62
	Htc	6.01	6.99	7.75	6.88	5.64	4.87	5.31	6.25	6.00	4.89	4.89	5.59
D	Htm	4.24	5.26	6.09	6.59	7.01	5.14	4.71	4.36	4.62	4.64	4.3	4.07
	Htc	4.78	5.72	6.66	7.14	6.97	5.42	4.63	4.51	4.83	5.48	5.10	4.62
C	Htm	5.08	5.77	6.58	7.13	7.42	5.80	4.17	4.09	5.20	5.66	5.23	4.83
	Htc	5.15	6.04	6.86	7.33	7.06	5.47	4.60	4.67	5.37	5.67	5.23	4.87
H	Htm	5.03	5.78	6.43	6.97	7.12	6.01	4.41	4.22	5.38	5.87	5.30	4.85
	Htc	5.06	5.91	6.88	7.44	7.38	5.99	4.73	4.66	5.50	5.79	5.14	4.81

Based on these coefficients, the Fourier coefficients A_1,A_2,…,A_7 for Eq. (14) are calculated which gives the model for the clearness index, K_T. From the clearness index values obtained from the model as given by Eq. (14) and the ETR global insolation values (H_o) given by Eq. (1), the daily global solar insolation (H_{tc}) are calculated for any location and for any given day from the following expression:

$$H_{tc} = K_T \times H_o$$

4. Validation of the model

The measured values and calculated values of insolation for five stations located in north (New Delhi), south (Thiruvanandapuram), east (Kolkata), west (Mumbai) and central (Nagpur) part of India are given in Table 3. In the table, Loc stands for locations given in symbol form, Ins stands for insolation, H_{tm} is the measured insolation in kWh/m^2 and H_{tc} is the calculated insolation in kWh/m^2.

The global insolation charts for these five stations are given in Figs. 1–5. The charts show both measured values of insolation (H_{tm}) and calculated values of insolation (H_{tc}) for comparison. The maximum error seen in the charts are within 20% of the measured value, which is good for a preliminary design of a PV system.

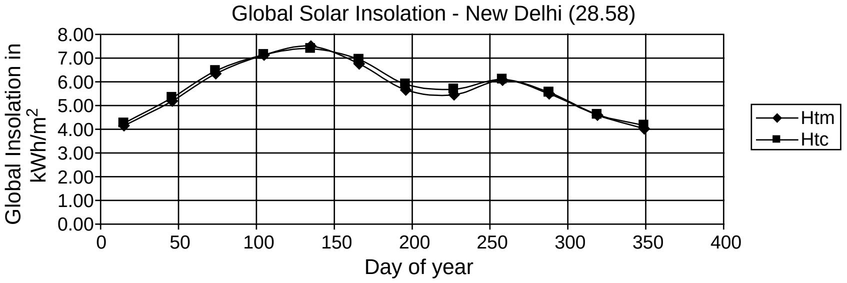

Fig. 1. Insolation chart for New Delhi.

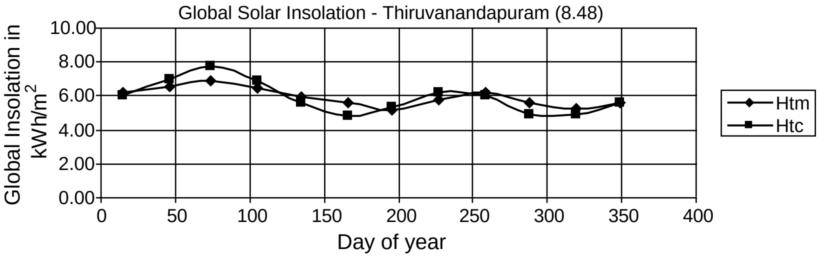

Fig. 2. Insolation chart for Thiruvananthapuram.

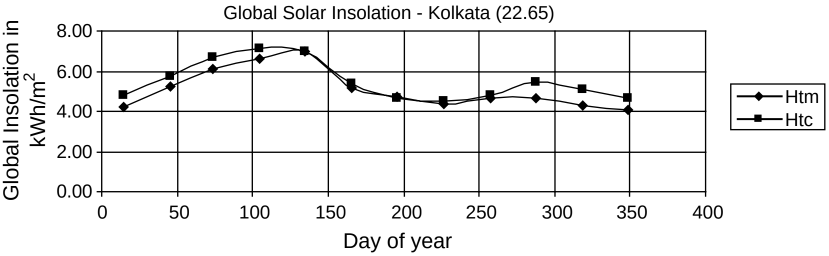

Fig. 3. Insolation chart for Kolkata.

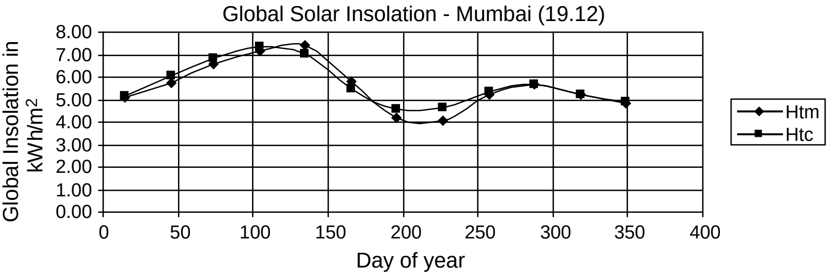

Fig. 4. Insolation chart for Mumbai.

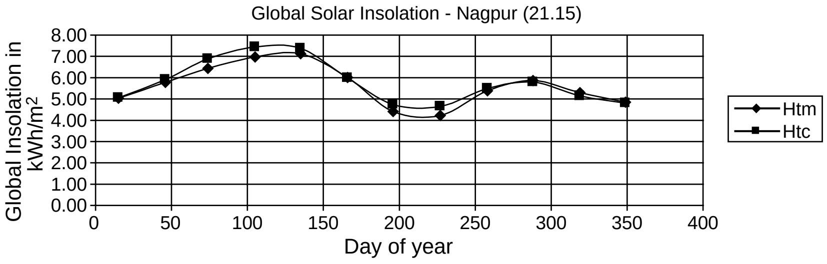

Fig. 5. Insolation chart for Nagpur.

Table 4
Measured and calculated insolation values for Goa

Loc	Ins	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Goa	Htm	5.75	6.41	6.83	7.03	7.00	5.04	3.93	5.05	5.81	5.91	5.85	5.58
	Htc	5.47	6.38	7.20	7.22	6.58	5.34	4.59	4.89	5.35	5.30	5.26	5.12

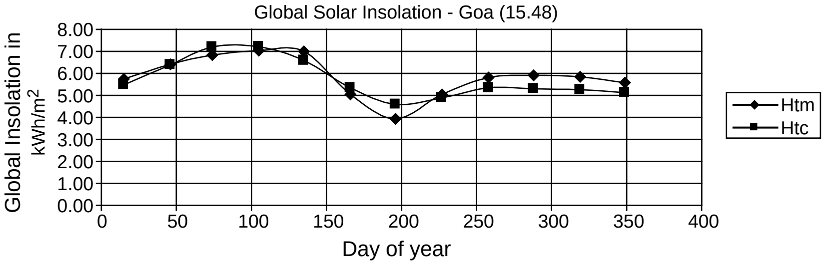

Fig. 6. Insolation chart for Goa.

It can be seen in the charts that the calculated insolation values follow the measured values very closely for most of the locations. These results validate the model. However, since the model itself is based on the data from these five locations among other locations, the closeness in the above results need to be further validated. This is done by considering the measured values and calculated values of insolation for a location whose data has not been used in developing the model and comparing the closeness of these values.

Goa is one such location whose latitude falls within the range of latitudes for the model and whose measured data are not used in the model building. The measured and calculated insolation values for Goa for a year are given in Table 4.

We can see that the measured values and calculated values are very close to each other. This can also be seen from the chart shown in Fig. 6.

These results definitely validate not only the model but also the methodology of modeling.

5. Conclusion

A generic method of developing a solar insolation model for a specific region is explained. The modeling approach has been done for the Indian sub-continent and then validated to verify the model and the methodology. It can be seen from the results that the error in calculated insolation values are within 20% of the measured values. Hence, the proposed methodology of building a model can be used not only for the Indian sub-continent but any region in the world. For the model to be more accurate, the measured data should be available for locations that are well spread across the region covering large range of latitudes. Further, the data available should be as accurate as possible to obtain a low error model that can be used to calculate global solar insolation for any location and for any given day. Today, with the help of satellites, data over specific region can be measured with good accuracy by the meteorological departments. With these accurate data, models with more accurate Fourier coefficients can be constructed which can be used to estimate global solar insolation within a region using easily measurable parameters.

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