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Theoretical Assessment and Validation of Global Horizontal and Direct Normal Solar Irradiance for a Tropical Climate in India

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Abstract: Accurate knowledge about solar radiation in a region is of indispensible significance for sizing, designing and monitoring solar energy systems. In case of inaccessibility to measure solar data, proper solar radiation models may be used. This study aims to present the closeness or the relationship between the predicted and measured values of global horizontal irradiance and direct normal solar irradiance in a solar monitoring station located in National Institute of Technology (NIT), Tiruchirappalli. The measured data is promoted under Indo-German Energy programme by the Ministry of New and Renewable Energy, Centre for wind energy technology and federal of German government named GIZ. The data were monitored for the duration of five months from August 2013 to December 2013. The validation is brought out by the significance of the regression coefficient, which approaches to unity declaring the fitness of the model resulting in proposing regression models for the considered region. A statistical approach is also carried out for the validation by the evaluation of mean bias error (MBE) and the root mean square error (RMSE) from the predicted and the model values. Thus the proposed models lead to theoretical assessment of global horizontal irradiance and direct normal irradiance for a particular location.

Key words: Theoretical assessment · Linear quadratic and cubic model · Global horizontal irradiance · Direct normal irradiance · Mean bias error · Root mean square error · Regression coefficient

INTRODUCTION

Solar Energy is the most prevalent renewable energy due to its period of availability, clean and green nature, inexhaustible and free of cost. Many studies have been undertaken to enhance the performance of solar technologies such as solar photovoltaic, concentrating solar power, solar dryers and stills [1-4]. India by its position across the latitude and longitudinal axis along with equator is bestowed with enormous solar energy. The overall annual average of direct normal irradiance in India for a period from 2002-2013 measures up to 4.5 $KWh/m^2/day$ out of which Tiruchirappalli measures individually in the range of 5.0 – 5.5 $KWh/m^2/day$ [5]. Similarly the annual average of global horizontal irradiance for Tiruchirappalli ranges from 5.5 to 6 $KWh/m^2/day$. The International energy agency under photovoltaic power systems programme (PVPS) have framed an objective under task 13 to propose good practices for monitoring of solar photovoltaic systems which includes the solar radiation assessment, under the platform of research and development. As India is not being a member of the International energy agency [6], studies on the availability of solar radiation becomes more imperative. The preliminary input factors such as irradiance, ambient temperature and atmospheric pressure of a particular location determines the existence of solar photovoltaic plant in the same location. The preliminary input factors can also be termed as site survey indicators for the photovoltaic plant. These measurement factors are directly involved in predicting the performance and the yield of photovoltaic plants.

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As an essentiality for the knowledge of solar radiation data becomes imperative, India has initiated a project on solar radiation resource assessment across the nation to access and quantify the availability of solar potential along with the weather parameters in order to develop the solar atlas. The target of phase I started with the installation of 51 solar radiation resource assessment station, including Tiruchirappalli which is presently focused in this paper. The measured parameters include the monthly average global horizontal irradiance, diffuse horizontal irradiance, direct normal irradiance, ambient temperature, station pressure, relative humidity and wind speed.

Extensive researches have been carried out in assessing the global solar radiation data from a few known meteorological parameters. Angstrom [7] developed a basic theoretical model to calculate the global horizontal irradiance which depends on the average sunshine data. Furthermore accuracy was brought by a modified Angstrom model developed by Prescott [8]. Garg and Garg [9] developed linear model for theoretical prediction of global horizontal irradiance for 11 Indian stations. Ogelman et al. [10] developed quadratic model for assessment of global horizontal irradiance. Jain [11] developed a linear model for 31 Italian locations for a period of 10 years. Flocas [12] developed linear regression models for 34 stations in Greece. The regression constants *a* and *b* were obtained from the graphical relationship between clearness index and average sunshine hour duration. Samuel [13] developed the basic form of cubic model. Srivastava *et al*. [14] developed a linear model for Lucknow for annual duration of 1989-1990. Veeran and Kumar [15] developed linear models for Madras and Kodaikanal for a duration of 3 years. Ahmed and Ulfat [16] proposed linear and polynomial models for Karachi in Pakistan. Aras *et al*. [17] developed linear and polynomial regression models for Central Anatolia region in Turkey for a period of 6 years. Katiyar and Pandey [18] proposed quadratic and cubic models for 5 locations in India. Srivastava *et al*. [19] put forth linear and polynomial models for 7 metrological stations in India.

Other successful models for global horizontal irradiance include Glover and McCulloch model [20] involving latitude and average sun shine hour duration (S/S_0), Gopinathan [21] proposed model dealing with latitude, altitude and average sun shine hour duration, Chen [22] developed models incorporating latitude, longitude, altitude and average sun shine hour duration. Artificial neural network were also used for predicting global horizontal irradiance by Alawi and Hinai [23], Mohandess *et al*. [24] and Mubiru and Banda [25].

Research has been collectively less on the estimation of direct normal irradiance. Some of them include some of existing models include the Etmy model proposed by Randell and Whitson [26], Erbs model [27] employing global horizontal irradiance and clearness index for DNI evaluation, Iqbal [28] proposed a model based on scattering transmittances, DISC model proposed by Maxwell [29] employs extraterrestrial DNI and direct clearness index for GHI evaluation, DIRINT model proposed by Perez *et al*. [30], Skartveit and Hinai [31] proposed a model involving Φ which is a function of (Kt, h) to evaluate DNI, Ashare model [32], DIRINDEX model proposed by Perez *et al*. [33] and a model proposed by Janjai [34] employing diffuse horizontal radiation and azimuth angle.

Hence the aim of this paper is to derive theoretically the global horizontal irradiance and direct normal irradiance employing the experimentally measured global horizontal irradiance and direct normal irradiance. This analysis is carried out for the duration of five months from August 2013 to December 2013. A monthly average analysis is presented.

Statistical and regression analysis are also carried out for the period of measured data in order to validate the accuracy of the model. The evaluation of global horizontal radiation is made through basic forms suggested by modified Angstrom Prescott linear model [8], Ogelman [10] quadratic model and Samuel [13] cubic model. These are the most preferred model as they are reliable and feasible for solar energy potential evaluation with different climatic conditions. For the evaluation of direct normal irradiance Erbs model [27], a model proposed by Skartveit and Hinai [31] and Janjai model [34] are discussed and implemented. Erbs model and Skartveit employ clearness index and its coefficients for calculating the direct normal irradiance where as the model proposed by Janjai [34] demands the use of diffuse horizontal irradiance and zenith angle for the station under study in order to evaluate the direct normal irradiance.

The conclusion of this paper projects on the accuracy of prediction of global horizontal and direct normal irradiance models from the actual values, respectively.

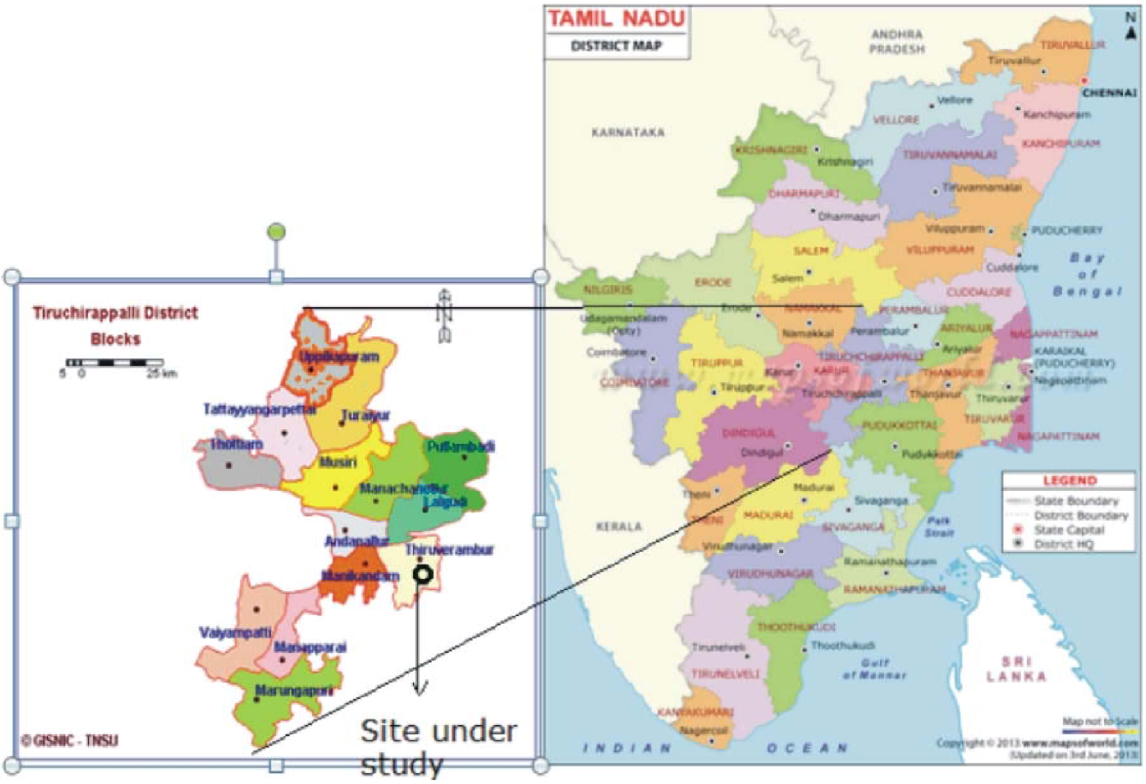

Fig. 1: Map of Tamilnadu state showing an outset of site under study

Table 1: Location under study

Location	Latitude	Longitude	Altitude	Monitored period
Tiruchirappalli	10.76°N	78.81°E	87m	5 months

Study Region and Data Collection: Tamilnadu with an area of 130058 km^2 lies in the southern most part of the Indian peninsular and is neighbored by Kerala, Karnataka and Andhrapradesh. Tamilnadu is divided into 32 Districts out of which Tiruchirappalli occupies an area of 96.9Km^2. Tiruchirappalli lies in the latitudinal and longitudinal belt of 10.76°N and 78.81°E, respectively at an altitude of 89m above the sea level. It experiences tropical savanna climate under the Koppen classification with an annual temperature of 28.9°C. It is further subdivided into 17 blocks out of which NIT Tiruchirappalli locates within the same where the monitoring station is situated. Figure 1 shows the location of monitoring site as an outset on the map of Tamilnadu. The geographical location of the site under study is also separately shown in Table 1.

The solar radiation and resource assessment station consists of two towers of 1.5m and 6m height. The 1.5m tower incorporates a solar tracker equipped with pyranometer, pyranometer with shaded ring and pyrheliometer to measure solar parameters such as global, diffuse and direct normal irradiance, respectively. The 6m height of tower houses equipments capable of measuring rainfall, ambient temperature, relative humidity, atmospheric pressure and wind speed. Each station is powered by 160W solar photovoltaic panel which comprises of 13 equipments paving measurement. The measured data from each SRRA station is transmitted to a central receiving station located at CWET Chennai where it is checked and saved for future research purpose [35].

Study Objective

The Objective of this Work Aims at:

- Proposing Angstrom –Presscot models, Ogelman and Samuel models for theoretical assessment of global horizontal irradiance for Tiruchirappalli with its validation.
- Comparing Erbs, Skarteveit and Janjai model for prediction of direct normal irradiance for Tiruchirappalli with the conclusion of best among the three for DNI assessment.

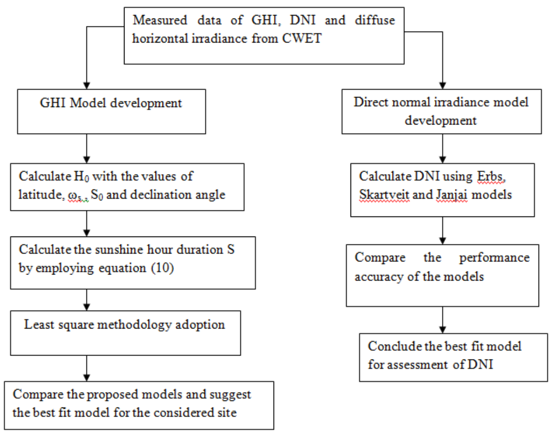

Fig. 2: Flow diagram of objectives in present work

The flow diagram of objectives in this work is illustrated in Figure 2.

Calculation Methodology for Global Horizontal Irradiance: Angstrom [7] predicted that the direct clearness index K_t which is the ratio of measured GHI to the calculated extraterrestrial irradiance is a function of average daily sun shine duration which is expressed below:

$$(H/H_0) = f(S/S_0) \tag{1}$$

The linear modified Angstrom model [7] is given by:

$$(H/H_0) = a + b(S/S_0) \tag{2}$$

The basic form of quadratic and cubic models is given by [10] [13]:

$$(H/H_0) = a + b(S/S_0) + c(S/S_0)^2 \tag{3}$$

$$(H/H_0) = a + b(S/S_0) + c(S/S_0)^2 + d(S/S_0)^3 \tag{4}$$

where H refers to the monthly mean of daily measured global horizontal irradiance, H_0 refers to the monthly mean of the daily calculated extra terrestrial horizontal radiation under the absence of atmospheric scattering. S corresponds to the monthly mean of the daily calculated sunshine hour duration and S_0 is the monthly mean of the daily calculated maximum possible sunshine hour duration. In addition, *a* and *b* are correlation constants.

The extra terrestrial horizontal global irradiance is given by:

$$H_0 = (24/\pi) * G_0 * ((\cos L \cos \delta \sin \omega_s) + ((\pi/180) * \omega_s \sin L \sin \delta)) \tag{5}$$

$$G_0 = I_{sc}(1 + 0.34\cos((360 * D_n)/365.25)) \tag{6}$$

where L represents the latitude of the location, δ represents the declination angle, ω_s represents the sunset hour angle in degrees and D_n denotes the day of the year.

$$\delta = 23.45 * \sin(360(D_n + 284)/365) \tag{7}$$

$$\omega_s = inv\cos(-\tan\delta \tan L) \tag{8}$$

$$S_0 = (2/15) * \omega_s \tag{9}$$

The daily sun shine duration can be calculated by equation [36]:

$$S = (h/360) * \arccos(\tan(L)\tan(23.5)\cos((360 D_n)/365.25)) \tag{10}$$

where h represents a day in hours = 24 hours.; L corresponds to the latitude of the monitored site;

The correlation constants a, b and c vary with respect to the location. They are much affected by the air pollution stepping out due to urban activity. The values of empirical constants are derived from the direct clearness index and the sun shine hour duration which will be described in the sections below.

Determination of Empirical Constants a, b and c: Employing the linear Prescott Angstrom Model the equation is of the form [7, 8] as given below:

$$(H/H_0) = a + b(S/S_0) \tag{11}$$

The above equation is of the linear form y = ax + b; y is assumed to be $\frac{H}{H0}$ and $\left(\frac{S}{S0}\right)$ Applying the linear fit equation by least square method in statistics we obtain the following correlations:

$$\Sigma y = n * a + \Sigma x \tag{12}$$

$$\Sigma xy + a\Sigma x + b\Sigma x^2 \tag{13}$$

where n represents the number of data points. In this case, n=5 as data is recorded for five months from August to December.

Table 2: Variation of polynomial coefficients for the duration of monitored period

Monitor -ed period	(x)	(y)	x^2	x^3	x^4	x^5	x^6	xy	x^2 y	x^3 y
August	0.5040	0.6395	0.2540	0.1280	0.0645	0.0325	0.0163	0.3223	0.162	0.08
Sep	0.5046	0.5283	0.2546	0.1284	0.0648	0.0327	0.0165	0.2665	0.134	0.06
Oct.	0.5039	0.494	0.2539	0.1279	0.0644	0.0324	0.0163	0.2489	0.125	0.06
Nov	0.5026	0.3701	0.2526	0.1269	0.0638	0.0320	0.0161	0.1860	0.093	0.04
Dec	0.50073	0.3916	0.2507	0.1255	0.0628	0.0314	0.0157	0.1961	0.098	0.04

Applying the above linear first order equation for the month of the monitoring period from August to December we derive the value of the regression coefficients a and b. Table 2.

$$2.4236 = 5\,a + 2.51585\,b \quad (14)$$

$$1.2199 = 2.51585\,a + 1.2659\,b \quad (15)$$

By solving the above equations we get the value of regression or empirical constants to be $a = -0.48$; $b = 1.92$.

Hence the proposed linear model for the latitudinal location of 10.76°N will be:

$$(H/H_0) = -0.48 + 1.92(S/S_0) \quad (16)$$

Proposed Second Order Quadratic Equation Model: Applying the statistical analysis to the quadratic model we get the equation in the form

$$y = a + bx + cx^2 \quad (17)$$

which replicates the actual quadratic model [10, 18].

$$(H/H_0) = a + b(S/S_0) + c(S/S_0)^2$$

On comparing the equations now we get

$$y = (H/H_0) \text{ and } x = (S/S_0) \quad (18)$$

The regression constants are obtained from the least square method by employing the equations shown below:

$$\Sigma y = na + b\,\Sigma x + c\Sigma x^2 \quad (19)$$

$$\Sigma xy = a\Sigma x + b\Sigma x^2 + c\Sigma x^3 \quad (20)$$

$$\Sigma x^2 y + a\Sigma x^2 + b\Sigma x^3 + c\Sigma x_4 \quad (21)$$

The derived equations after the substitution of x and y values gives:

$$2.4236 = 5a + 2.5158b + 1.2659c \quad (22)$$

$$1.2199 = 2.5158a + 1.2659b + 0.6369c \quad (23)$$

$$0.6141 = 1.2659a + 0.6369b + 0.3205c \quad (24)$$

Which solves the values of a, b and c as $a = 7.93$; $b = -31.90$; $c = 33.99$. Hence the proposed Quadratic model for the location under discussion is:

$$(H/H_0) = 7.93 - 31.90(S/S_0) + 33.99(S/S_0)\hat{}2 \quad (25)$$

Proposed Third Order or Cubic Model: The equation for the cubic model [13,18] is of the form as represented below:

$$y = a + bx + cx^2 + dx^3 \quad (26)$$

which represents the actual cubic model given by:

$$(H/H_0) = a + b(S/S_0) + c(S/S_0)^2 + d(S/S_0)^3 \quad (27)$$

The regression or empirical constants a, b, c and d are obtained by least square method on taking the equations (29-32) into account.

$$\Sigma y = na + b\Sigma x + c\Sigma x^2 + d\Sigma x^3 \quad (28)$$

$$\Sigma xy = a\Sigma x + b\Sigma x^2 + c\Sigma x^3 + d\Sigma x^4 \quad (29)$$

$$\Sigma x^2 y = a\Sigma x^2 + b\Sigma x^3 + c\Sigma x^4 + d\Sigma x^5 \quad (30)$$

$$\Sigma x^3 y = a\Sigma x^3 + b\Sigma x^4 + c\Sigma x^5 + d\Sigma x^6 \quad (31)$$

On substitution of appropriate values from Table 2 we get the equations shown below:

$$2.4236 + 5a + 2.5185b + 1.2659c + 0.6369d \quad (32)$$

$$1.2199 = 2.5158a + 1.2659b + 0.6369c + 0.1612d \quad (33)$$

$$036141 = 1.2659a + 0.6369b + 0.3205c + 0.1612d \quad (34)$$

$$0.3061 = 06369a + 0.32056b + 0.1612c + 0.08115d \quad (35)$$

Solving the above equations we get the value of regression coefficients to be:

$a = -16679$; $b = 3272$; $c = -24.75$; $d = 54.679$

Hence the proposed cubic model becomes:

$$(H/H_0) = -16.679 + 32.72(S/S_0) - 24.75(S/S_0)^2 + 54.679(S/S_0)^3 \quad (36)$$

Calculation Methodology for Direct Normal Irradiance: The direct normal irradiance for the Tiruchirappalli location is calculated by selected existing models of DNI in literatures surveyed [26-34]. The employed models of DNI are the Erb's model, Skartveit model and the Janjai model.

Erbs Model for Calculation of Direct Normal Irradiance and its Result: Erbs.et.al proposed a model for theoretical evaluation of direct normal irradiance from global horizontal irradiance as:

$$I = (1-G)*(\psi/\cos(z)) \quad (37)$$

where G represents the monthly average global horizontal irradiance; Ψ is a function of clearness index K_t and Z represents the solar zenith angle.

If the value of $K_t \le 0.22$ then $\Psi = 1 - 0.06K_t$
If the value of $0.2 < K_t < 0.8$ then
$\Psi = 0.9511 - 0.1604 * K_t + 4.388 * (K_t)^2 - 16.638 * (K_t)^3 + 12.336 * (K_t)^4$ else:

$\Psi = 0.165$;

Hence employing the equation (3) of Erb's model we get the calculated monthly average of direct normal irradiance.

Skartveit Model for Calculation of Direct Normal Irradiance and its Result: The modified Erbs model resulted in Skartveit model. The functional term Φ is not only the function of clearness index, but also a function of the solar hour angle h.

$$\Phi = 90° - Z; \quad (38)$$

The modeled direct normal irradiance is given by:

$$I = G*(1-\phi)/\cos(z) \quad (39)$$

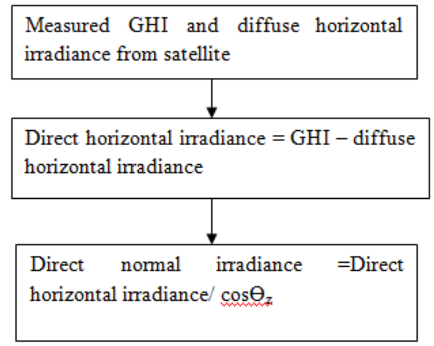

Fig. 3: Flow diagram of Janjai model to calculate direct normal irradiance

If $k_t < k_0$ then $\Phi = 1$.
If $k_0 \le k_t \le \alpha k_1$ then $\phi = 1-(1-d_1)(a\sqrt{k} + (1-a)k^2)$
where $\alpha = 0.9$; $k_1 = 0.87 - 0.65\exp(-0.06h)$; $d_1 = 0.15 + 0.43\exp(-0.06h)$; a=0.27

$k = 0.5(1+\sin(\pi((a`/b`)-0.5)))$

$a` = k_t - k_0$; $b` = k_1 - k_0$.

If $k_t > ak_1$ then $\phi = 1-((\alpha * k_1*(1-\xi))/k_t)$

where $\xi = 1-(1-d_1)(a\sqrt{k`} + (1-a)(k`)^2)$ and

$k` = 0.5(1+\sin(\pi(a``/b` - 0.5)))$

$a`` = ak_1 - k_0$.

In this case $k_t \le \alpha k_1$ hence the case (2) equation applies. Thus, on applying we get the predicted value of direct normal irradiance expressed tabulated as follows

Janjai Model for Calculation of Direct Normal Irradiance and its Results: The methodology involves the measured value of global horizontal and direct normal irradiance.

$$I_{dh} = I_{gl} - I_{df}$$

where I_{dh} refers to direct horizontal irradiation; I_{gl} refers to global horizontal irradiance and I_{df} refers to diffuse horizontal radiation.

The direct normal irradiance $= I_{dh}/\cos(Z)$; (40)

where Z represents the solar zenith angle.

The flow diagram of Janjai model to calculate direct normal irradiance is shown in Figure 3.

RESULTS AND DISCUSSION

Daily Results of the Model Input Parameters: The Figure 4 shows the daily variation of measured global horizontal irradiance and direct normal irradiance in Tiruchirappalli for the monitored duration. The variation of GHI and DNI encounters similar peak and fall during the monitored period. The nature of variation seems to be same for GHI and DNI with respect to the daily duration. The maximum and the minimum value of GHI and DNI correspond to 6.57 and 1.67KWh/m^2/day, 7.73 and 0.04KWh/m^2/day, respectively. The highest value of GHI and DNI occur at October 4th and October 14th, respectively. The monthly average value is highest for the month of August measuring up to 5.19 KWh/m^2/day and least for the month of November corresponds to 3.99 KWh/m^2/day.

The daily calculated sun shine hour for the duration under study is shown below. The sunshine hour decreases as the day of the year progresses. The seasonal change throughout the day affects the sunshine hours as reflected in the Figure 5. The maximum and minimum sun shine hour duration is calculated to be 6.27 and 5.68 hours, correspondingly occurring at 1st August and December 31st, respectively.

Relative humidity is the measure of water vapour in air compared to its maximum withstanding capability at that temperature. The average value of relative humidity is higher for the month of November measuring to 76.8% and least for the month of August measuring to 58.4%.The overall maximum relative humidity amounts to 87% at November 2nd and the minimum amounts to 46% at August 1st. The ambient temperature reduces progressively with the monitored duration. This is related to the decrease in the bright sun shine hour duration which causes the decrease in ambient temperature. The monthly average of the ambient temperature is high for the month of August measuring to 29.6°C and least for the month of December. The daily relative humidity and ambient temperature for the monitored period is shown in Figure 6.

The variation of extra terrestrial global horizontal irradiance over the monitored day of the year is shown in the Figure 7. As the day of the year progresses the extra terrestrial global horizontal irradiance increases significantly. The maximum and the minimum values correspond to 11.08 and 7.56KWh/m^2/day. The extra terrestrial global horizontal irradiance and sunshine hours are inversely proportional with respect to the day of the year which is proved by the model equation and also by the calculated data.

The ratio of measured GHI to the extra terrestrial global horizontal irradiance gives the value of clearness index represented as K_t as displayed in Figure 8. Yousif *et al*. [37] in 2013 proposed four different intervals of K_t which determines the level of clearness of the sky.

For,

Cloudy condition : $0 < K_t < 0.2$
Partly cloudy : $0.2 \leq K_t + < 0.6$
Sunny : $0.6 \leq K_t, 0.75$
Partly sunny : $0.75 \leq K_t < 1$

The overall average of clearness index for the tropical climate of Tiruchirappalli depicts the sky to be partly cloudy according to Yousif's classification.

Table 3 showing a comparison of relative humidity, ambient temperature, GHI and bright sun shine hours for Trichy to three other locations available in literatures surveyed is as shown below.

Monthly Results of the Model Input Parameters: The calculated monthly mean of the daily sun shine hour duration for the monitored period of five months is predicted below. The monthly mean of the daily sun shine hour duration ranges from a minimum of 5.69 hours/day to a maximum of 6.22 hours/day. The monthly total sunshine hours for the month of August, September, October, November and December is 192.87, 182.45, 183.52, 173.38 and 176.65h, respectively. The Calculated total monthly sunshine hour duration (S) for the monitored period is shown in Figure 9.

The variation of maximum possible sunshine hour duration (S_0) over the monitored period is shown in Figure 10.

The monthly average of the maximum possible sun shine hour duration is high for the month of August 2013 measuring to 12.344 h/d and least for the month of December which happens to be 11.38 h/d. The maximum possible sunshine hour is always higher than the bright sun shine hour duration.

The variation of monthly average of clearness index over relative sun shine hour duration for Tiruchirappalli is shown in Figure 11.

Table 3: Comparison of GHI, RH, AT and sunshine duration (S) for the present site with the surveyed locations in the literature

Measured parameters	Location	August	September	October	November	December	Reference
Global horizontal irradiance	Madras	5.36	5.30	4.82	4.63	4.29	[15]
	Kodaikanal	5.14	4.99	4.81	5.83	5.53	[15]
	Jodhpur	5.24	5.34	5.18	4.26	3.90	[18]
	Trichy	5.19	4.97	5.13	3.99	4.29	Present study
Relative humidity	Madras	64	66	75	76	72	[15]
	Kodaikanal	83	84	83	80	70	[15]
	Trichy	58.45	64.5	66.96	76.86	70.8	Present study
Ambient temperature	Madras	30.5	30.2	28.8	26.6	25.9	[15]
	Kodaikanal	15.1	15.3	14.5	13.8	13.6	[15]
	Trichy	29.6	28.87	28.51	26.17	24.02	Present study
Sunshine hours(S)	Madras	7.1	7.0	7.1	9.8	7.6	[15]
	Kodaikanal	4.3	4.4	4.5	6.6	6.2	[15]
	Trichy	6.2	6.1	5.9	5.8	5.7	Present study

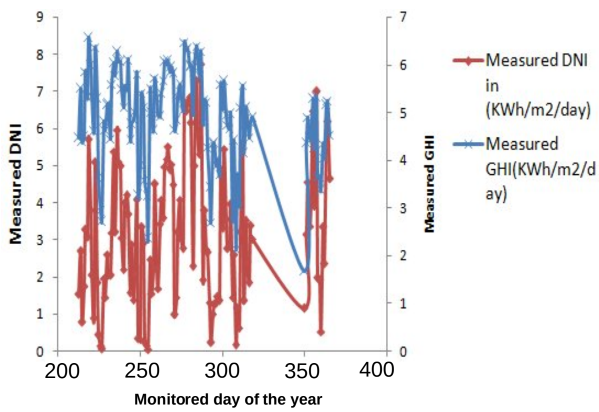

Fig. 4: Variation of daily measured global horizontal irradiance for the monitored period

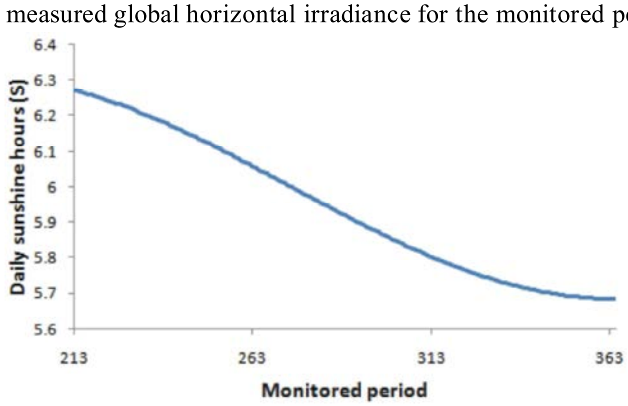

Fig. 5: Daily sunshine duration(S) for the monitored period

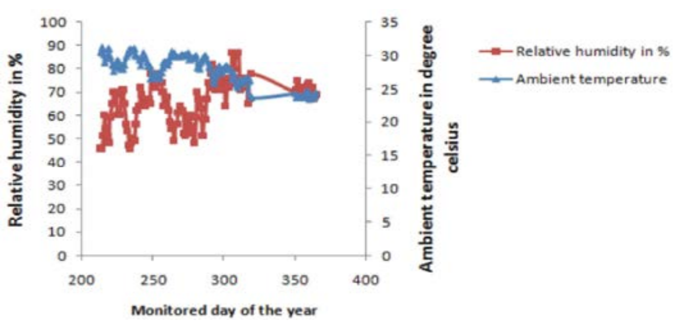

Fig. 6: Daily relative humidity and ambient temperature for the monitored period

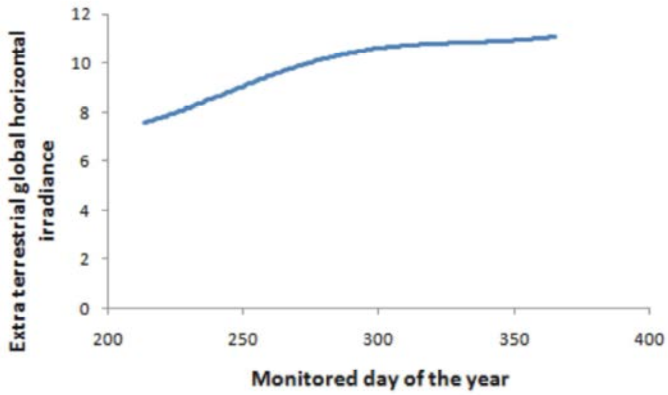

Fig. 7: Evaluated daily extra terrestrial global horizontal irradiance for the monitored period

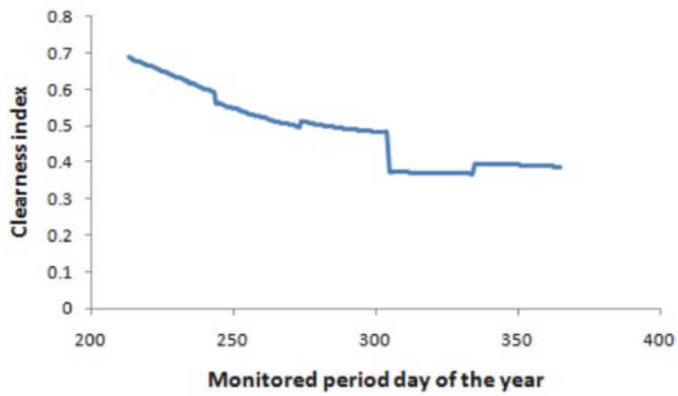

Fig. 8: Pictorial variation of direct clearness index over the monitored period

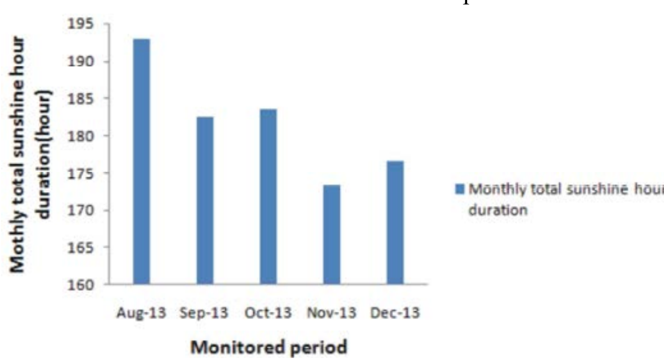

Fig. 9: Calculated total monthly sunshine hour duration (S) for the monitored period

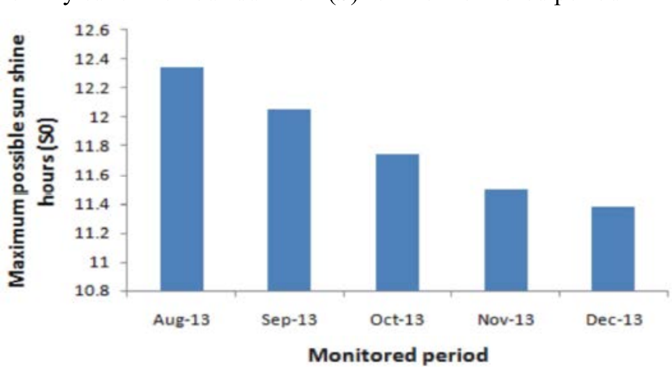

Fig. 10: Variation of monthly average of maximum possible sunshine hour duration (S_0) over the monitored period

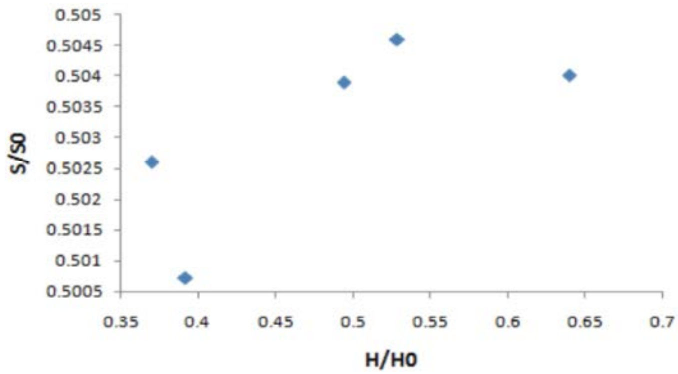

Fig. 11: Variation of monthly average of clearness index over relative sun shine hour duration for Tiruchirappalli

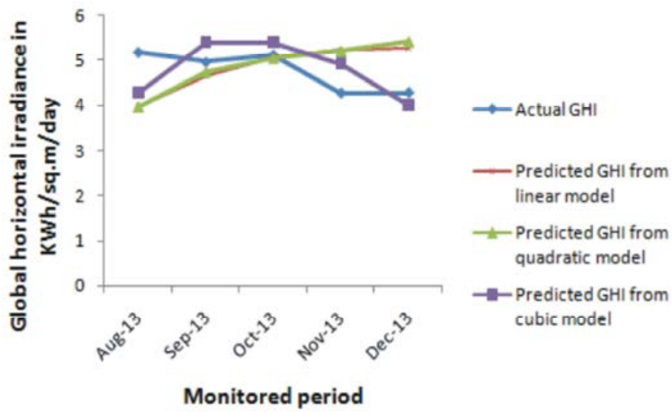

Fig. 12: Variation of actual value of monthly average GHI over the proposed models

The classifications of relative sun shine hours [38] predict the weather condition for a particular location as given by the World Metrological Organization [39] as:

For Cloudy sky : $0 \le (S/S_0) < 0.3$

Scattered clouds : $0.3 \le (S/S_0) < 0.7$

Fair weather : $0.7 \le (S/S_0) \le 1$

In this case the average value of relative sun shine hour duration is 0.503 suggesting the weather to have scattered clouds.

Results for the Proposed GHI Models: A comparison of predicted linear, quadratic and cubic model values of GHI with the measured GHI is represented graphically to understand the considerable agreement between them. The remarkable accuracy of the models is concluded by the value of statistical indicators as calculated below. The variation of actual value of monthly average GHI over the proposed models is shown in Figure 12.

The statistical mean bias error and root mean square error depicts the agreement between the predicted model and the actual values which can be calculated by employing the equations specified below.

$$\text{MBE}= (1/N)\sum_{i=1}^{N} H(pred) - H(meas)) \quad (41)$$

$$\text{RMSE}= \sqrt{(1/N)\sum_{i=1}^{N}(H(pred) - H(meas))^{\wedge}2} \quad (42)$$

where H (pred) represents the predicted or calculated GHI and H (meas) refers to the measured or actual GHI.

The RMSE test gives the information on the short-term performance of the proposed model by allowing a term-by-term comparison of the actual deviation between the predicted and measured values. The lower the RMSE, the more accurate is the correlation. A positive value of MBE shows an over-estimate by the model while a negative value gives an under-estimate by the model [40].The average value of mean bias error and the root mean square error for the proposed linear global horizontal irradiance model amounts to 0.0152 and 0.3166 KWh/m^2/day, respectively. The best fit R^2 for the proposed linear model is shown in Figure 13.

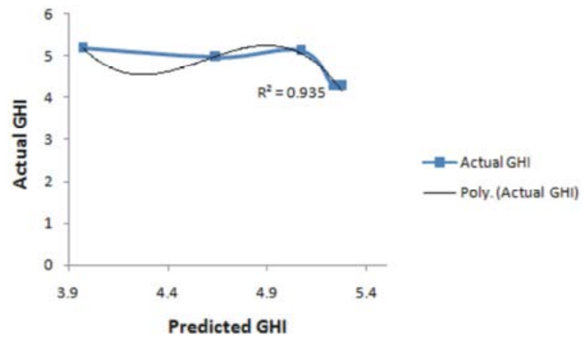

Fig. 13: Best fit R^2 for the proposed linear model

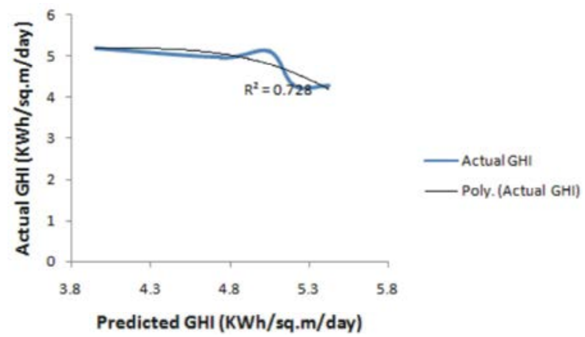

Fig. 14: Best fit R^2 for the proposed quadratic model

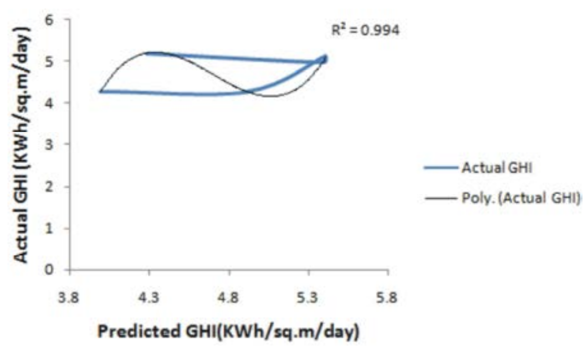

Fig. 15: Best fit R^2 for the proposed cubic model

The cubic fit value of R^2 for the quadratic model, which validates the predicted model is around 0.935 proving a lesser difference in closeness between the predicted GHI derived from the proposed model and the actual GHI values measured experimentally. This accuracy is also reflected in the mean bias error and root mean square error obtained from the linear model.

Similarly the average value of the mean bias error and the root mean square error for the predicted and actual values obtained from the quadratic model are 0.0211 and 0.3246KWh/m^2/day, respectively. The percentage increase in the mean bias error in comparison with the linear model is 27.96%. The best fit R^2 for the proposed quadratic model is shown in Figure 14.

Similarly the best cubic fit R^2 derived for the proposed quadratic model is around 0.728 proving a decrease in accuracy on comparison to the linear model. Thus as the R^2 value decreases from 0.935, the statistical indicators such as the mean bias error and root mean square error are also on rise for the proposed quadratic model in comparison with the other models.

The proposed cubic model for Tiruchirappalli turns out to be the best assessment model for theoretical evaluation of GHI for it. This is being justified by the average values of mean bias error and the root mean square error for the proposed cubic model which are 0.0060 and 0.2280 KWh/m^2/day, respectively. These values are much lesser than those of the above proposed linear and quadratic model which is highly reflected in the R^2 value. The best fit R^2 for the proposed cubic model is shown in Figure 15.

The R^2 value for the third order proposed cubic model is 0.994 justifying the model's accuracy in correctly predicting the global horizontal irradiance. Table 4 is showing an overall comparison of MBE, RMSE and regression coefficient values made for the current study with the existing literature results.

Results for the Comparison of DNI Models: or the calculation of DNI from Janjai model the measured value of diffuse horizontal irradiation is essential. Hence a chart is shown for the daily variation of diffuse horizontal irradiation over the monitored period. The daily variation of diffuse horizontal irradiance over the monitored period is shown in Figure 16.

The overall maximum and minimum value of diffuse horizontal irradiation is 3.81 and 1.03KWh/m² /day occurring at 28th September and 14th of October, respectively.

Erbs, Skarteveit and Janjai model are compared for the conclusion of remarkably accurate model for the present location under study. The Figure 17 represents the comparison of the measured DNI with the model DNI values for the monitored duration. As seen the Janjai model approaches approximately closer towards the measured DNI than the Erbs model and Skartveit model which is seen to be accurate at the start but later displaces from the actual measured values.

The collective average of the mean bias error and the root mean square error for the Erbs, Skartveit model are -1.38 and 3.085, -1.48 and 3.309, -0.704 and 0.314 KWh/m^2/day, respectively; suggesting the model to be more accurate than Erbs model for theoretical evaluation of DNI for the latitudinal and longitudinal location of

Table 4: Comparison of MBE, RMSE and regression constants of the present site with the past cited locations in literatures

Location	Degree of Correlati-on	Regression Constants a	b	c	d	MBE	RMSE	Monitor-ed duration	Reference
Jodhpur	1st	0.227	0.510			0.001	0.43	5 years	[18]
	2nd	-0.19	1.77	-0.91		-1.60	1.70	5 years	[18
	3rd	2.722	-11.0	17.4	-8.65	-2.11	2.30	5 years	
Calcutta	1st	0.262	0.395			-0.03	0.73	5 years	[18]
	2nd	0.129	0.933	-0.50		-0.03	0.66	5 years	
	3rd	1.378	-6.33	12.7	-7.66	0.04	0.50	5 years	[18
Bombay	1st	0.229	0.512			-0.08	0.8	5 years	
	2nd	0.234	0.465			-0.07	0.8	5 years	[18]
	3rd	0.294	0.085	0.77	-0.43	-0.07	0.79	5 years	
Pune	1st	0.228	0.503			-0.05	0.56	5 years	[18]
	2nd	0.293	0.284			0.03	0.28	5 years	
	3rd	0.511	-0.99	2.53	-1.33	-0.05	0.5	5 years	[18]
Delhi	1st	0.131	0.604			-0.105	1.1243	Annual	[19]
Jaipur	1st	0.335	0.332			-0.058	2.1703	Annual	[19]
Ahmedab-ad	1st	0.121	0.582			-0.051	1.4768	Annual	[19]
Goa	1st	0.278	0.513				0.0144	1963-1978	[9]
Madras	1st	0.340	0.339				0.0322	1957-1978	[9]
Nagpur	1st	0.293	0.459				0.024	1960-1978	[9]
Vizag	1st	0.286	0.467				0.0134	1961-1978	[9]
Trivandru-m	1st	0.278	0.513				0.0166	1959-1978	[9]
Trichy (present study)	1st	-0.48	1.922			0.0152	0.316	5 months	Present study
	2nd	7.932	-31.9	33.9		0.0211	0.324		
	3rd	-16.6	32.72	-24.7	54.67	0.0060	0.228		

Table 5: Comparison of DNI models for Tiruchirappalli to the other available sites in literature

Location	Models for direct normal irradiance	MBE (KWh/m² /day)	RMSE (KWh/m² /day)	Monitored period	Reference
14 sites in Europe and United states	Erbs Model	2.064	3.288	60,000 data points (combination of a year, 3years and 6 months of all 14 sites)	[27]
Trichy	Erbs model	-1.38	3.085		Present study
14 sites in Europe and United states	Skartveit model	0.336	2.52	60,000 data points (combination of a year, 3years and 6 months of all 14 sites)	[31]
Trichy	Skartveit model	-1.48	3.309		Present study
Thailand	Janjai model	-0.016	0.16	June 2005 to December 2008	[34]
Trichy	Janjai model	-0.704	0.314	August 2013 to December 2013	Present study

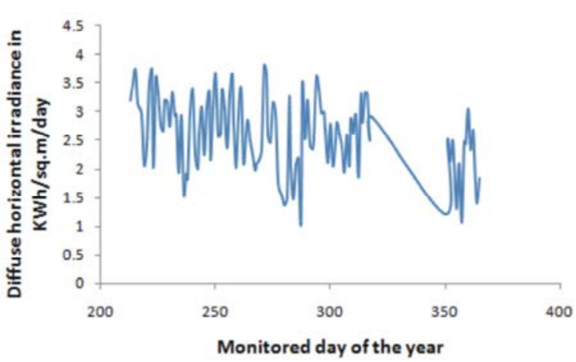

Fig. 16: Measured daily average of diffuse horizontal irradiance over the monitored period

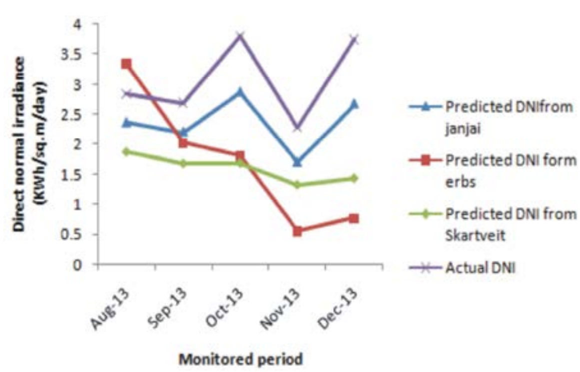

Fig. 17: Comparison of monthly average of predicted and actual DNI from Erbs, Skartveit and Janjai models

10.76°N and 78.81°E respectively. Table 5 is displaying the comparison of model's MBE and RMSE values for the present location with the available surveyed locations is given below. Janjai model seems to be the accurate model for predicting the direct normal irradiance for the present as well as the past studied locations of Europe and United states.

CONCLUSION

Thus the above work projects with the theoretical evaluation of global horizontal irradiance and direct normal irradiance. Modified angstrom, quadratic and cubic models are proposed for the theoretical assessment of global horizontal irradiance with the derivation of empirical constants by least square method. The measured direct normal irradiance are also compared with the selected existing DNI models such as Erbs, Skartveit and Janjai model with the justification of statistical analysis. The actual values of GHI and DNI are obtained from receiving station at CWET as described above. The following strategic conclusions are obtained for the location under study with the latitude and longitudinal angles measuring 10.76°N and 78.81°E, respectively.

- For the evaluation of global horizontal irradiance the proposed cubic model holds good as justified by the statistical analysis and the regression coefficient of best fit. The average mean bias error and the root mean square error for the proposed cubic model is 0.006 and 0.228 KWh/m^2/day, respectively. The regression coefficient or the best fit R^2 turns to be very close to 1 which is 0.994 thus validating the model. The prediction of the most accurate model for GHI varies with location. As seen in reference [17] the accurate model for prediction of Jodhpur, Calcutta, Bombay was linear.
- Three existing DNI models were selected based on the year of existence. Two proposed in late 1990's and one the recently proposed Janjai model in 2010. On comparison, the actual DNI values with the predicted values from the existing model it is inferred that the Janjai model holds good for the theoretical determination of DNI as the MBE and RMSE values are -0.704 and 0.314 KWh/m^2/day, respectively.
- The inferred results may vary with respect to the location's latitude and longitude.

ACKNOWLEDGEMENT

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Nomenclature:

GHI	:	Global horizontal Irradiance
DNI	:	Direct horizontal irradiance
DHI	:	Diffuse horizontal irradiance
MBE	:	Mean Bias error
RMSE	:	Root mean square error
H	:	Measured global horizontal irradiance, KWh/m^2/day.
H_0	:	Extraterrestrial global horizontal irradiance, KWh/m^2/day.
S	:	Sunshine hour duration
S_0	:	Maximum possible bright sunshine hours
RH	:	Relative humidity, %
AT	:	Ambient temperature, °C

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Persian Abstract

چکیده

داشتن دانش صحیحی از تابش های خورشیدی در یک ناحیه برای برآورد ، طراحی و نظارت بر سیستم های انرژی خورشیدی به میزان قابل توجهی ضروری است. این پژوهش می کوشد تا میزان ارتباط و قرابت میان مقادیر پیش بینی شده و اندازه گیری شده از تشعشعات افقی زمینی و تشعشعات مستقیم خورشیدی در یک ایستگاه رصد خورشیدی که در موسسه ملی تکنولوژی Tiruchirappalli قرار دارد، را بیان نماید. اطلاعات اندازه گیری شده بر طبق برنامه انرژی هندی-آلمانی و تحت حمایت وزارت انرژی های نو و تجدید پذیر و مرکز تکنولوژی انرژی بادی و دولت فدرال آلمان با نام GIZ انجام شده است. اطالاعات به مدت ۵ ماه از ماه آگوست ۲۰۱۳ تا دسامبر ۲۰۱۳ ثبت شده است. تایید صحت اطلاعات بدست آمده با استفاده از معنی دار بودن ضریب رگرسیون انجام شد که به ۱ نزدیک بود و این قضیه بیانگر انطباق مدل ارائه شده است که به این نتیجه منجر می شود که مدل خطی در ناحیه مفروض پیشنهاد شود. علاوه بر این یک روش آماری نیز برای تایید صحت اطلاعات بدست آمده استفاده شد. این روش با اندازه گیری خطای بیاس متوسط (MBE) و خطای متوسط مربع ریشه (RMSE) از اطلاعات اندازه گیری شده تا مقادیر پیش بینی شده انجام شد. بنابر این مدل پیشنهاد شده به تخمین تئوریک تشعشعات افقی زمین و تشعشعات طبیعی مستقیم در یک ناحیه خاص بدل شد.