A Mathematical Model of Threshold Solar Irradiance for Computing the Quality Hours of Sunshine

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Abstract- This paper proposes a universal mathematical model to compute the number of annual hours that a particular location receives of at least a certain level of Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI). The proposed mathematical model was statistically validated based on actual measured data of various locations in India. A mathematical model is developed using measured solar irradiance data from fifteen different locations in India, and detailed analysis on the quality of the hours of specific solar irradiance using ground measured data, is rarely attempted by researchers in the past, which makes this study a unique one. Statistical analysis is carried out to validate the proposed model using measured data from ten locations in India as well as from five locations globally. The statistical tools used include the Root mean square error (RMSE), Mean absolute percentage error (MAPE), Mean bias error (MBE) and Nash-Sutcliffe Efficiency (NSME). The proposed model gives a best fit to the prediction of over 90% accuracy. It serves as input to designers and policy makers for sizing and feasibility studies in the field solar energy. A statistical analysis was carried out and the model showed excellent performance for GHI calculations for cities in India and the USA.

Keywords Global Horizontal Irradiance; Direct Normal Irradiance; Universal Model; Model Efficiency; Model Evaluation.

1. Introduction

Solar irradiance data is of high importance to the design and operation of solar energy systems [1]. Conventional methods to obtain solar irradiance data include weather stations, solar radiation models, commercial software databases, and field measurements [2]. Yield predictions provide essential information for the design and performance of solar thermal and photovoltaic systems. It can have severe economic consequences for the investor if the predictions of energy yields deviate substantially from the actual field values [3]. The yield predictions are based on solar irradiation data that are derived from meteorological databases. These yield predictions are dependent on the utilizability concept, which is defined as that fraction of the solar radiation incident on a surface that exceeds a specified threshold or critical level [4]. The utilizability of a solar system is dependent on the distribution of solar radiation and the effect of the distribution of solar radiation becomes more defined at higher critical levels. This concept is now extensively used in the evaluation of the performance of flat plate collector systems, concentrating collectors, and photovoltaic, passive and active heating systems [5]. This makes it necessary to calculate the sun hours above a given threshold level. Similarly, solar radiation on tilted surfaces was estimated on different empirical models. Three isotropic and the same number of anisotropic sky models were correlated by using the mean value of monthly average daily basis for the central region of India [6]. A model has been developed using 12 years satellite data on global solar irradiance for 12 cities around the world i.e. Kuala Lumpur, Auckland, Tokyo, Riyadh, London, Accra, Antananarivo, Brasilia, Lima, Quito, Ottawa and Honolulu [7]. Another work reports the modelling of DNI and circum solar normal irradiance (CSNI) using a radiative transfer model and atmospheric measurements and aims to develop a fast and simple model to estimate the CSNI based on more common solar irradiance measurements such as the DNI, global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI)[13]. In another stochastic approach [14], solar radiations and temperatures are converted to quantized number of states and after a training stage that forms the transition probability values of the described states, the hidden Markov model parameters are obtained and tested. There were numerous related studies on the signifance of solar resource assessment for various application in different part of the world, has been carried out in past[15-20].

The output power of any solar system depends on the duration and intensity of the solar irradiance available at any location, and the knowledge of the quality of irradiance hours is very critical in site selection and developing optimal designs. This data can be obtained from online databases which store measured radiation data from different stations. However, due to the high initial investment and maintenance cost of the measuring instruments and relevant recorders, the number of solar radiation stations is too small to achieve accurate global coverage. Most often the raw data supplied by the present databases are not matching to actual users' needs and sometimes data access and correct interpretation is a difficult task as the databases store data in various formats and units using various time idioms. Thus, access is generally complicated by the various type of data, various storage standards, various units, and various way of expressing time. A survey of various solar resource data bases has been investigated in this study. This paper address that challenge by formulating a representative mathematical model (Universally applicable) for quality hours of solar irradiance, which can help evaluate the duration for which a solar system can yield enough power to meet the required load and also for the design of solar thermal storage systems. The detailed analysis on the quality of the hours of specific solar irradiance in India using ground measured data, is rarely attempted by researchers in the past, which makes this study a unique one.

Hence the main objectives of this study are twofold:

- To develop a universal mathematical model to compute the number of annual quality hours of a threshold GHI and/or DNI at any given location.

  Application : This model can be useful when integrated with existing software's that are used in the design of solar systems to predict how much duration a Solar System can yield enough power to meet the required load at a particular location.

- To validate the proposed model with the actual values and quantify the variations.

  Application: Validation facilitates the usability of this model for simulating bankable project and feasibility reports.

2. Methodology

A ground measurement data station, usually called as Solar Radiation Resource Assessment (SRRA) Station consists of a solar tracker, at a height of 2 m, which mounts all the solar radiation sensors. This solar irradiance data is sampled every one second, which is then averaged for one minute and transmitted to the central server at every one minute, via GPRS. The technical details of the Pyranometer sensors used in SRRA are given in Table 1. The geographic information of the 15 Indian Cities are given Table 2. A plan view of the SRRA station for Gurgaon is shown in Fig. 1.

Fig. 1. Plan view of a typical Solar Radiation Resource Assessment Station at National Institute of Solar Energy, India.

Table 1. Specifications of the radiometer used for measurement in SRRA

Sl. No.	**ISO Classification**	**Secondary Standard (Global Radiation and Diffused Irradiance)**
1.	Sensor Type	Circular multi –junction wire wound thermopile
2.	Dome	Glass dome
3.	Sensitivity	7 to 10 microV/W/m^2
4.	Resolution	±1 W/m^2
5.	Spectral Range	300-2800nm
6.	Response time	1second
7.	Temperature Range	-20 ºC to +60 ºC
8.	Tilt Error	± 1 degree
9.	Calibration Certificate (Long and Dutton 2002)	Traceable to WRC/WRR

All the SRRA stations are installed under the solar radiation resource assessment project, which is sponsored by the Ministry of New and Renewable Energy (Govt. of India), and this project is jointly implemented by National Institute of Wind Energy (NIWE) and National Institute of Solar Energy (NISE), both are autonomous institute under Ministry of New and Renewable Energy. Currently, there are 115 SRRA stations uniformly distributed throughout the country. Apart from solar irradiance measurements, these stations also record the ambient temperature, atmospheric pressure, wind speed, humidity, rain fall and wind direction. The details of the plant and the instruments are used in these solar resource station [8].The methodology adopted in this study is as given

in the flowchart in Fig. 2. First, one minute data value for each interval is checked for the quality. In most cases, the lost/missing data is adjusted based on the daily or weekly trend. Further, the data quality is checked for the maximum physical limits. The coherence between the three components of irradiance is also verified in this assessments. The daily averages of the monthly data from the hourly values were calculated for each city, and the trends are represented on a comparative chart. Evaluations and plots are done in MATLAB platform. Further, the irradiance value of each minute is filtered in accordance with the range which extends from 120 W/m^{2}to 1000 W/m^{2}in the intervals of 100 W/m^2.

The ground measured solar irradiance data from fifteen different cities in India collected over a period of last three years were available. However, in this study the data for a specific period of one calendar year is considered for analysis which would provide the monthly trends for a given year. The geographic information of the Indian cities used in this study is given in Table 2. The Annual hours in a year, for the location L, during which I_L (Q_{hL}) is given in the Equation (1) for the proposed model.

$$Q_{hL} = [\{\alpha_1 I_L^2 + \alpha_2 I_L + \alpha_3\} \times H_L] + [\beta_1 I_L^2 + \beta_2 I_L + \beta_3] \quad (1)$$

Where,

I_L : Certain level of irradiance (GHI or DNI) under consideration, for location L (in W/m^2)

Q_{hL}: Annual hours in a year, for the location L, during which I_L is received.

H_L: Annual solar insolation (GHI or DNI) of the location L(in kWh/m^2/year).

α_i, β_i : Statistically derived coefficients as given in Table 3,for GHI and DNI (i=1,2,3).

The methodology of deriving the above values in equation 1 is described below.
The trend is observed to be linear and can be resembled to the equation 1 as,

$$Q_{hL}(I_L) = [f_1 \times H_L] + f_2 \quad (2)$$

Table 2. Geographic information of the 15 Indian Cities

Sl. No.	**Location Name**	**Latitude & Longitude**	**Remarks**	**Elevation (m)**
1.	Gurgaon, Haryana (Near to New Delhi)	28.42N/77.15E	North India, Semi-Arid	259
2.	Chennai, Tamilnadu	12.95 N/ 80.2 E	South India, Near to Sea, Hot and Highly Humid	1
3.	Pune , Maharashtra	18.98N/73.96E	West of India, Tropical	685
4.	Leh, Jammu Kashmir	34.14N/ 77.48 E	Northern India, Cold Dessert climate/Mountain	3252
5.	Indore	22.689 N / 75.874 E	Humid Subtropical climate	565
6.	Erode	11.27 N / 77.604 E	Semi Arid	272
7.	Pondicherry	11.96 N / 79.811 E	Hot and Humid	36
8.	Aurungabad	24.837 N / 84.284 E	Hot and Temperate	104
9.	Pokhran	26.916 N/71.928 E	Hot and Dry	293
10.	Phalodi	27.118 N /72.345 E	Hot and Dry	242
11.	Surat	21.165 N / 74.783 E	Tropical Climate	34
12.	Tezpur	26.699 N/ 92.833 E	Warm and Temperate	83
13.	Gandhinagar	23.155 N / 72.667 E	Hot and Dry	65
14	Kanpur	26.493 N/ 80.272 E	Temperate	130
15	Bhubaneswar	20.349 N/ 85.89 E	Tropical	20

Further, applying the similar logic, a linear trend and corresponding values of f_1 and f_2 is derived for each values of specific irradiance value (I_L)for both DNI and GHI, and the values are as given in Table 3. The detailed derivation of f_1 and f_2 is provided in the result and discussion.

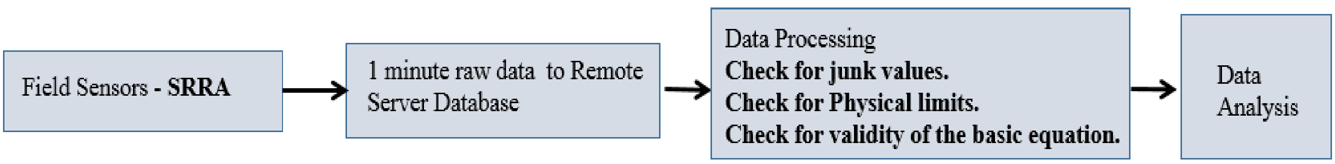


Fig. 2. Methodology adopted for data analysis

Table 3. Derived Values of f_1 and f_2 for GHI and DNI

$I_L(W/m^2)$		100	200	300	400	500	600	700	800	900
DNI	f_1	0.9875	1.0301	1.114	1.2252	1.3279	1.3346	1.0651	0.7962	0.4304
	f_2	1293.1	990.13	571.6	83.735	-442.47	-892.3	-908	-885	-524.22
GHI	f_1	0.836	1.027	1.170	1.2508	1.2698	1.3631	1.3068	0.962	0.5764
	f_2	1872.1	1123.8	419.22	-144.4	-577.35	-1153.4	-1439.9	-1173.5	-808.63

3. Statistical Techniques for Model Evaluation

The accuracy of a mathematical model is determined based on its application. The mostly used statistical indicators used for evaluation of solar radiation models are Mean Absolute Percentage Error (MAPE), Root Mean Square Error (RMSE), and the Mean Bias Error (MBE). The MAPE reflects the mean relative error of the estimation while the RMSE reflects the mean absolute error to some degree, so the combination of them is reasonable. MAPE provide a benchmark to compare identical models and also different models from different studies [9-11]. The mean absolute percentage error (MAPE) represents the mean absolute percentage deviation between the estimated and measured values. MAPE is given by the formula:

$$MAPE = \frac{\left[\sum\left|H_{i,m} - H_{i,c}\right|/H_{i,m}\right]100}{N} \tag{3}$$

Where $H_{i,m}$ is the i^{th} measured value, $H_{i,c}$ is the i^{th} calculated value of solar radiation and N is the total number of observations The smaller the MAPE value, the better the performance of the model [11].

Root Mean Square Error (RMSE) can provide the information about the short-term performance by comparing the actual deviation one by one between the estimated and measured values. RMSE measures systematic error. The smaller the RMSE, the better the performance of the model. The formula is given by:

$$RMSE = \sqrt{\left\{\frac{\left[\sum\left(H_{i,c} - H_{i,m}\right)^2\right]}{N}\right\}} \tag{4}$$

The Mean Bias Error (MBE) is used to measure non-systematic error and it can conceal significant positive and negative biases. The smaller the MBE value, the better the performance of the model [12]. The formula is given by:

$$MBE = \left[\sum\left(H_{i,c} - H_{i,m}\right)\right]/N \tag{5}$$

The Nash-Sutcliffe Efficiency (NSE) is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation. It is calculated as:

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left(H_{i,m} - H_{i,c}\right)^2}{\sum_{i=1}^{N}\left(H_{i,m} - \bar{H}_{i,m}\right)^2} \tag{6}$$

The value of E ranges between $-\infty$ and 1.0 (1 inclusive), with 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values less than 1 indicate unacceptable performance.

4. Model Evaluation and Validation

The performance of the proposed models for both GHI and DNI is evaluated using the comparison of data from SAM software from 13 cities in India; Gurgaon, Chennai, Pune, Leh, Indore, Erode, Pokhran, Erode, Tezpur, Surat, Pondicherry, Aurungabad and Phalodi. For the validation of the GHI values, 6 cities from the United States of America (USA); Phoenix (Arizona), Los Angeles (Carlifonia), Buffalo (New York), Minot (North Dakota), and Austin (New York) were also considered. The calculated GHI and the DNI quality hours from the proposed model against the data obtained from the System Advisor Model (SAM) database are shown in the Table 4 and Table 5 respectively for GHI and DNI. GHI values are compared for Indian cities and for some USA cities as well. As seen from Table 4 and Table 5, the values derived from the proposed model and the reported values are closely matching with each other. The selection of measured value of DNI and GHI had been considered for maximum operational hours of the utilization of solar technologies as per field conditions i.e. 300 W/m^2 to 700 W/m^2.

5. Result and Discussions

The performance of the proposed models for both GHI and DNI is evaluated using the comparison of data from SAM software from 13 cities in India; Gurgaon, Chennai, Pune, Leh, Indore, Erode, Pokhran, Erode, Tezpur, Surat, Pondicherry, Aurungabad and Phalodi. For the validation of the GHI values, 6 cities from the United States of America (USA); Phoenix (Arizona), Los Angeles (Carlifonia), Buffalo (New York), Minot (North Dakota), and Austin (New York)

were also considered. Fig. 3(a) to 3(c) shows the variation of value of irradiance (GHI) of specific value with the number of hours received in a year for all the 15 locations (Table 2). Fig.4 (a) to 4(c) shows the similar representation, but for DNI values. These representations are based on the actual measured values from the SRRA stations.

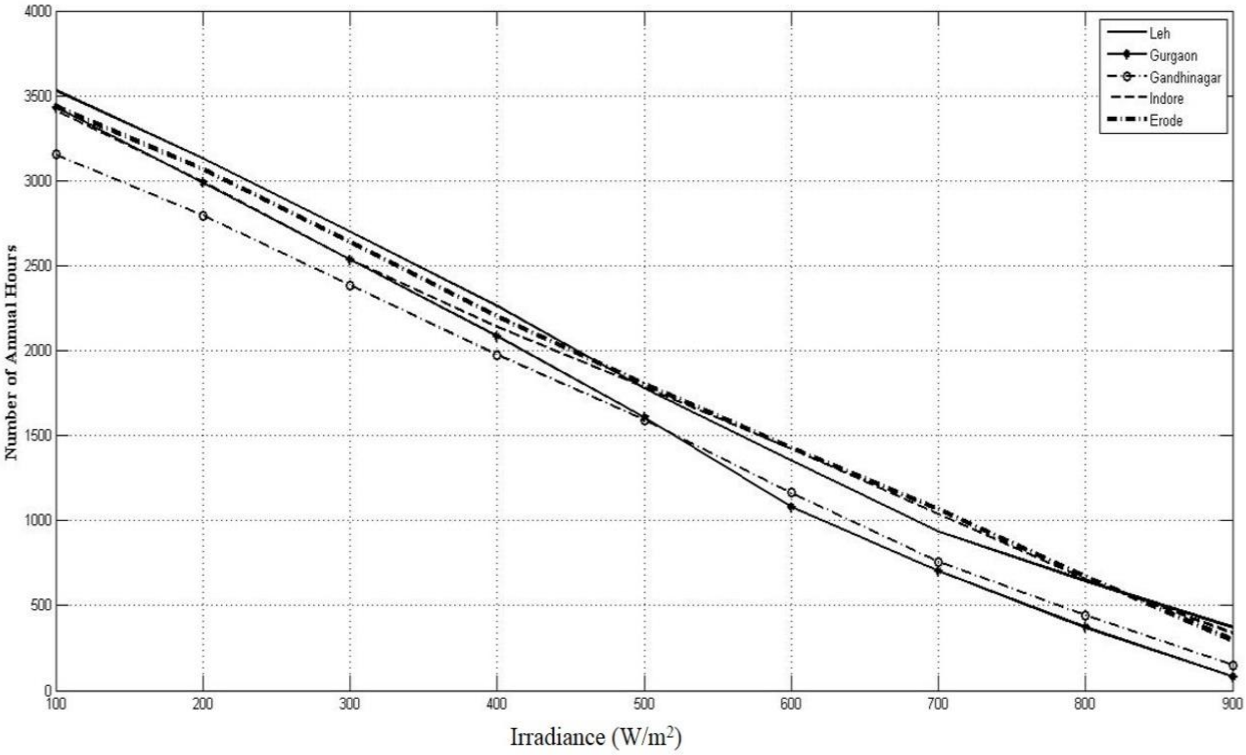
Table 4. Calculated GHI quality hours against measured data from SAM database for cities in India.

CITY	GHI VALUE										
	300 W/m^2		400 W/m^2		500 W/m^2		600 W/m^2		700 W/m^2		YEARLY AVERAGE GHI (kWh/m^2)
	SAM (HRS)	MODEL (HRS)	SAM (HRS)	MODEL (HRS)	SAM (HRS)	MODEL (HRS)	SAM (HRS)	MODEL (HRS)	SAM (HRS)	MODEL (HRS)	
Gurgaon	2500	2402.42	2100	1968.68	1625	1552.73	1100	1154.57	750	774.21	1702.60
Leh	2700	2657.48	2250	2244.69	1800	1832.93	1400	1422.21	950	1012.51	1912.10
Chennai	2500	2567.27	2100	2147.07	1700	1733.83	1400	1327.55	1100	928.23	1838.00
Erode	2650	2624.97	2200	2209.51	1800	1797.22	1450	1388.10	1050	982.14	1885.40
Pokhran	2700	2590.28	2250	2171.97	1850	1759.10	1350	1351.69	950	949.72	1856.90
Tezpur	2200	2175.23	1750	1722.83	1300	1303.15	900	916.19	550	561.95	1516.00
Pune	2600	2629.36	2150	2214.26	1800	1802.04	1450	1392.70	1050	986.24	1889.00
Indore	2550	2594.42	2150	2176.45	1800	1763.65	1400	1356.03	1000	953.59	1860.30
Phalodi	2700	2608.66	2300	2191.86	1900	1779.30	1400	1370.98	950	966.90	1872.00
Surat	2650	2681.71	2300	2270.91	1850	1859.55	1450	1447.63	1100	1035.15	1932
	FOR CITIES IN USA										
Phoenix	2906	2900	2514	2500	2106	2100	1683	1600	1245	1250	2117
Los Angeles	2543	2600	2121	2100	1707	1650	1302	1250	905	910	1818.3
Buffalo (Ny)	2017	1950	1552	1400	1130	1000	751	700	415	400	1386
Minot	2048	2000	1585	1450	1164	1050	783.33	730	443	400	1412
Texas	2500	2500	2074	2030	1660	1600	1257	1250	865	820	1783

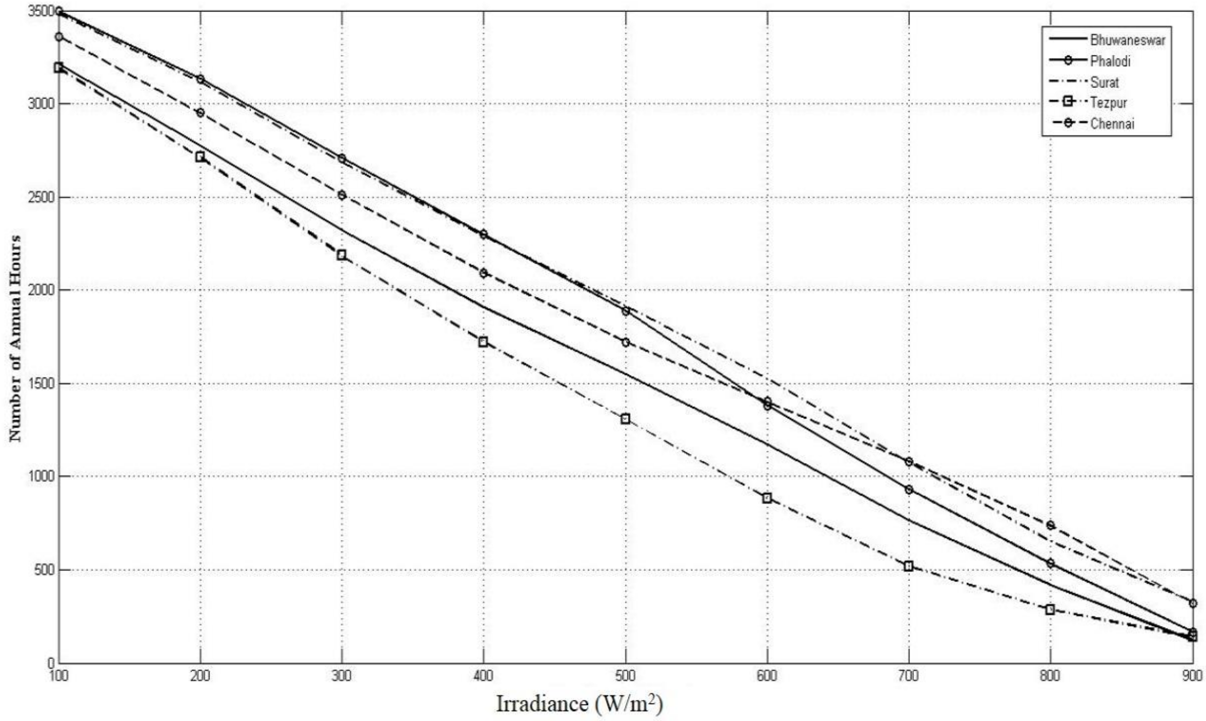
Table 5. Calculated DNI quality hours against measured data from SAM database for cities in India.

CITY	DNI VALUE (W/m^2)												
	300 W/m^2		400 W/m^2		500 W/m^2		600 W/m^2		700 W/m^2		800 W/m^2		YEARLY AVG. DNI (kWh/m^2)
	SAM (HRS)	MODEL (HRS)	SAM (HRS)	MODEL (HRS)	SAM (HRS)	MODEL (HRS)	SAM (HRS)	MODEL (HRS)	SAM (HRS)	MODEL (HRS)	SAM (HRS)	MODEL (HRS)	
Gurgaon	2125	1324	1700	926	1250	566	520	243	0	0	0	0	806.70
Leh	2600	2887	2350	2553	2100	2154	1850	1690	1600	1161	1300	567	2089.00
Chennai	2200	2229	1900	1868	1520	1485	1100	1081	660	654	400	206	1549.00
Erode	2000	1943	1680	1571	1300	1195	790	816	450	434	130	49	1314.70
Pokhran	2800	2611	2400	2266	2100	1874	1600	1435	1000	949	400	416	1863.10
Tezpur	1660	1663	1390	1279	1015	910	710	557	400	219	0	0	1085.00
Pune	2010	2120	1990	1755	1820	1375	1200	980	610	571	195	146	1460.00
Indore	2210	2063	1920	1695	1560	1317	1000	927	440	527	95	115	1413.00
Phalodi	2800	2637	2500	2293	2110	1900	1600	1459	1000	969	420	430	1884.00
Surat	2390	2107	2000	1742	1600	1362	900	969	395	561	95	140	1449.6

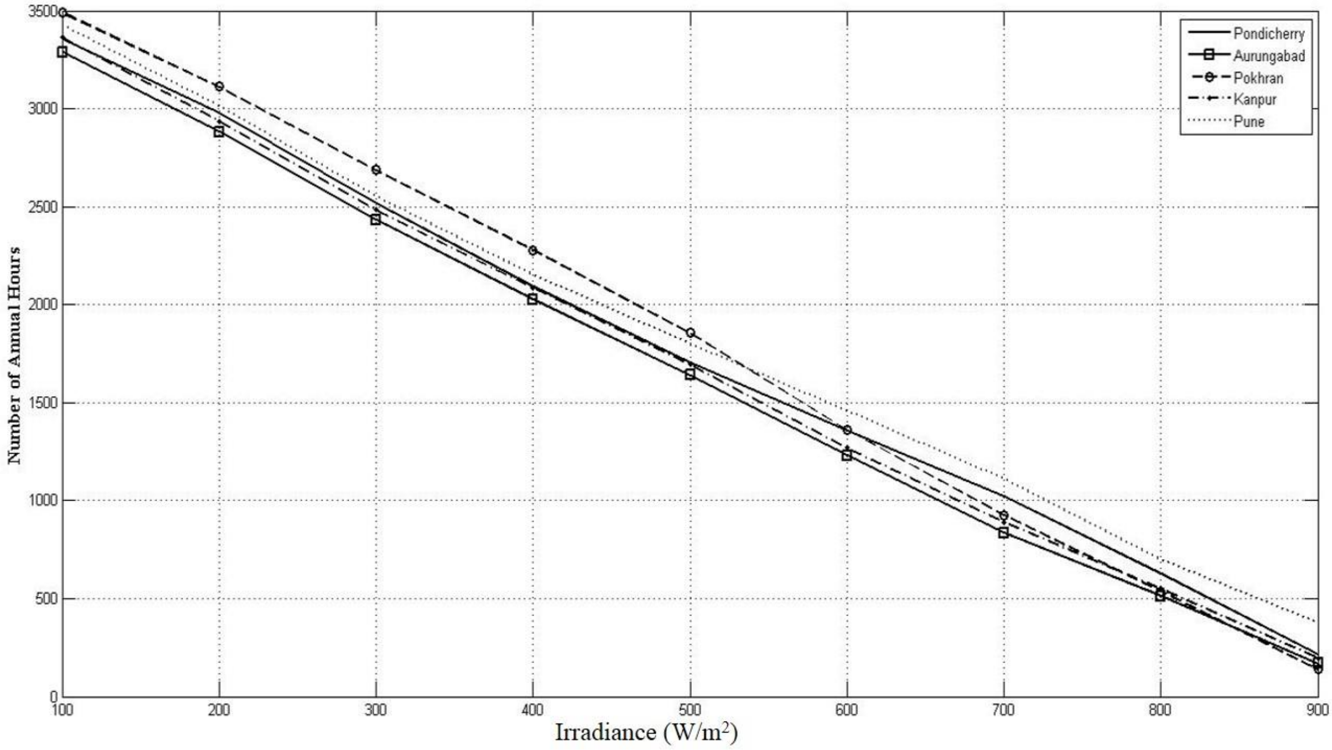
From these graphs and specific values, a relational function is developed for H_L of the location and the quality hours of specific irradiance (I_L) received (Q_{hL}). One such example is given in Fig. 5 for a GHI value 500 W/m². The observed variation of the *f1* and *f2* values with irradiance as shown in Fig. 6 and Fig. 7 indicates that f1 value increases as a function of irradiance, and drops in between 400 W/ m² and 600 W/ m². It signifies, most of the irradiance values that occurs in a year is between 400 W/m² to 500 W/m². The value of *f2*, throughout the analysis, is decrement in nature, but it represents only the constant value in the equation 1. The variation of *f1* and *f2*, statistically fits with approximate accuracy of 90 %. Similarly, the investigation on direct normal irradiance have been carried out and shown in the Fig. 8 and The derived coefficients αi, βi is given in Table 6. The validation of the proposed model was carried out using the statistical techniques which are MAPE, RMSE, MBE and the NSE. For GHI calculations using the model, it was noted that the MAPE values are all within the acceptable level, which is less than 10 % (Table 7 and Table 8). This means that the mean absolute percentage deviations between the estimated and measured values are very low which indicates excellent performance of the model for GHI in all the cities for India and USA. The MBE values for GHI calculations in Indian cities are mostly negative whereas in USA they are mostly positive. This shows that the model tends to slightly overestimate the GHI for the locations in USA and slightly underestimate for most Indian cities. Furthermore, the Nutt Sutcliff Efficiencies (E) are very close to unity, which indicates excellent performance of the model for GHI calculations for all the locations



3(a)

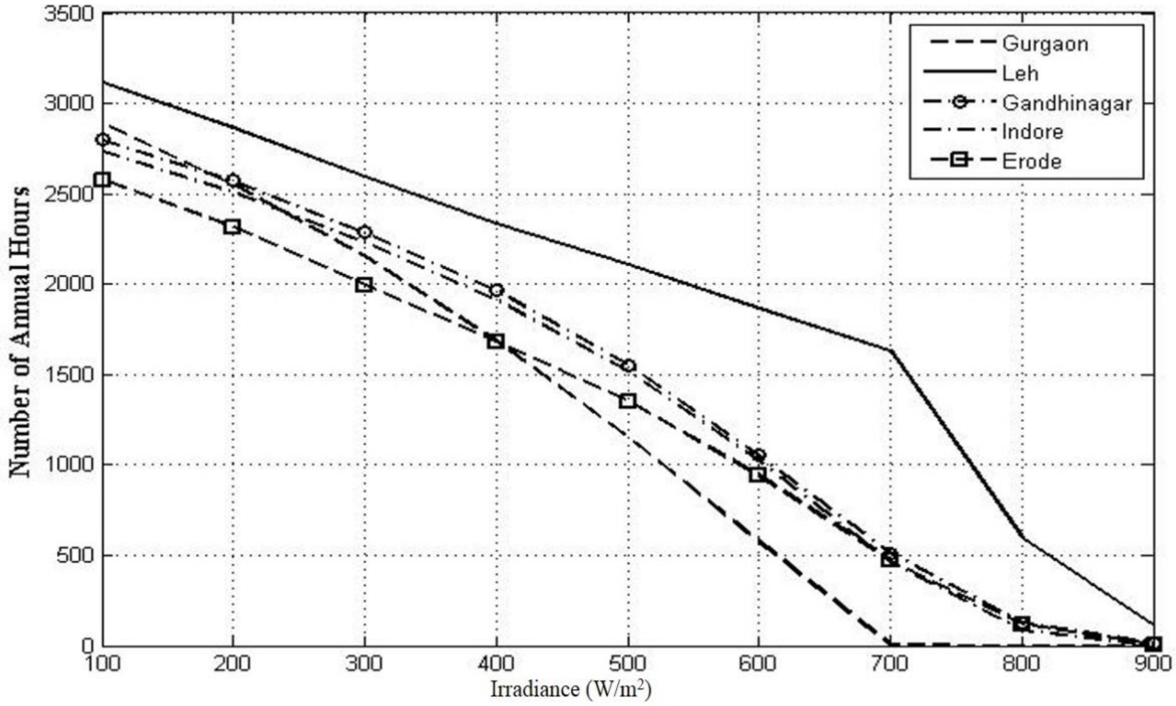


3(b)

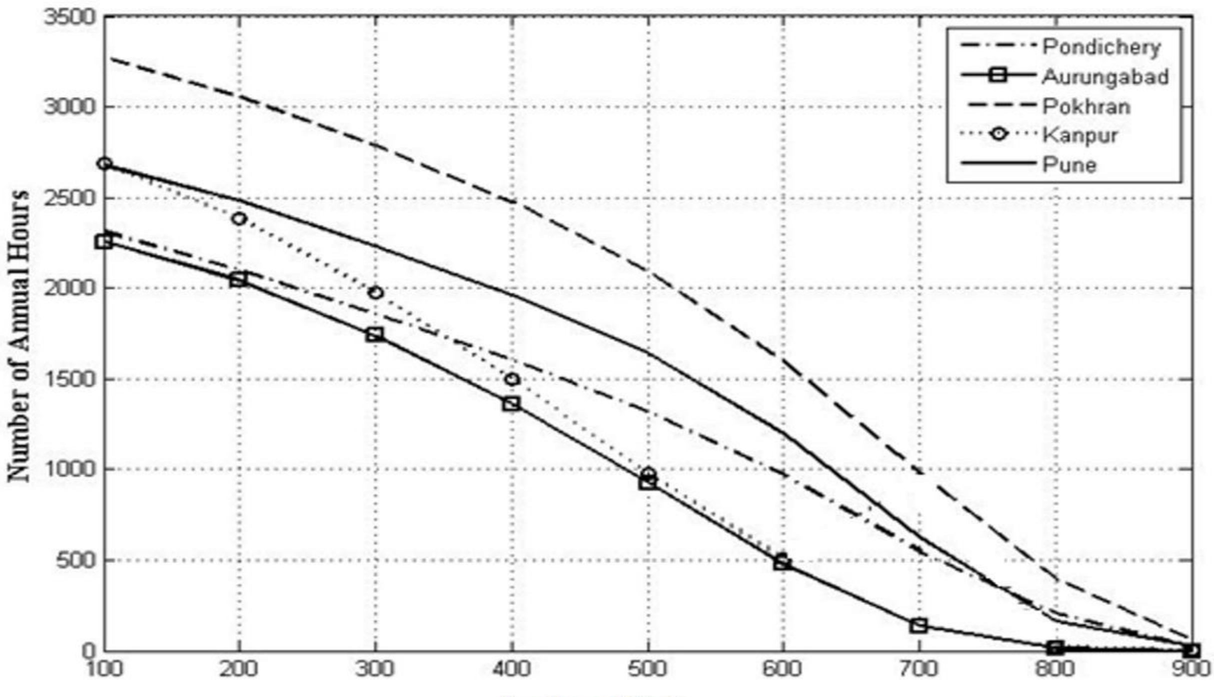


3(c)

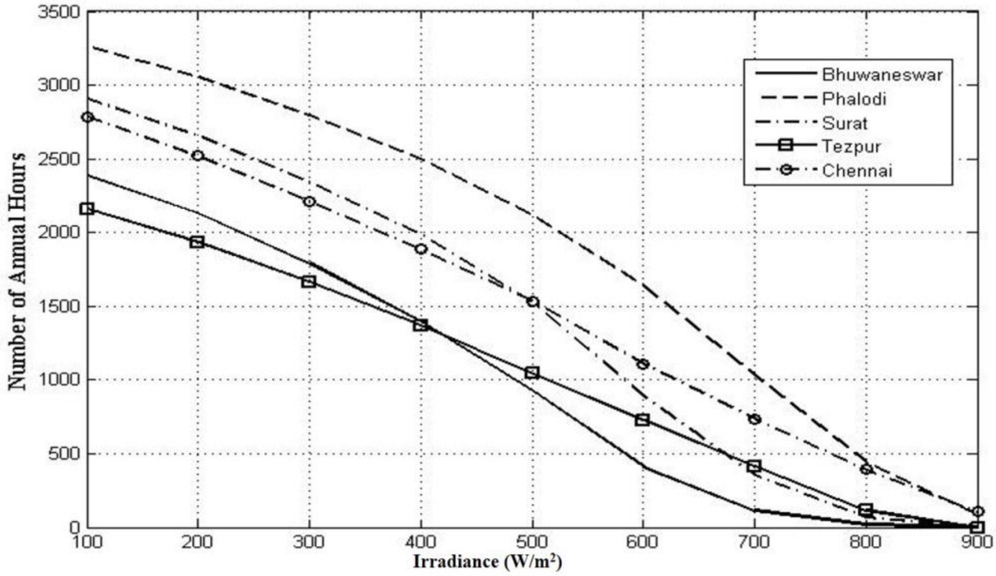
Fig. 3 (a) to 3 (c). Number of Annual hours of Various Global irradiance value for 15 locations


Gurgaon
Leh
Gandhinagar
Indore
Erode
Number of Annual Hours
Irradiance (W/m2)

4(a)


Pondichery
Aurungabad
Pokhran
Kanpur
Pune
Number of Annual Hours
Irradiance (W/m2)

4(b)



4(c)

Fig. 4(a) to 4(c). Number of Annual hours of Various Global irradiance value for 15 locations

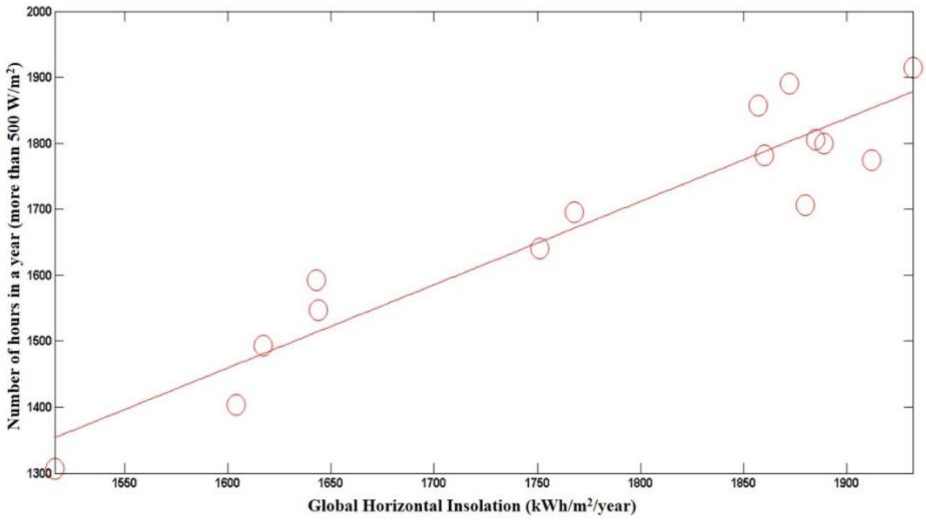


Fig. 5. Relational function of number of hours of irradiance above 500 W/m^2 for different GHI

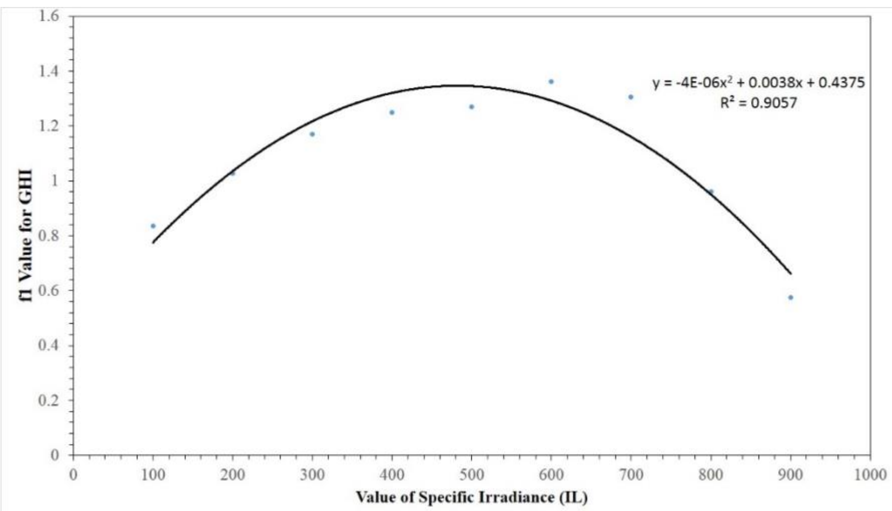


Fig. 6. Variation of f1 for GHI for various values of irradiance

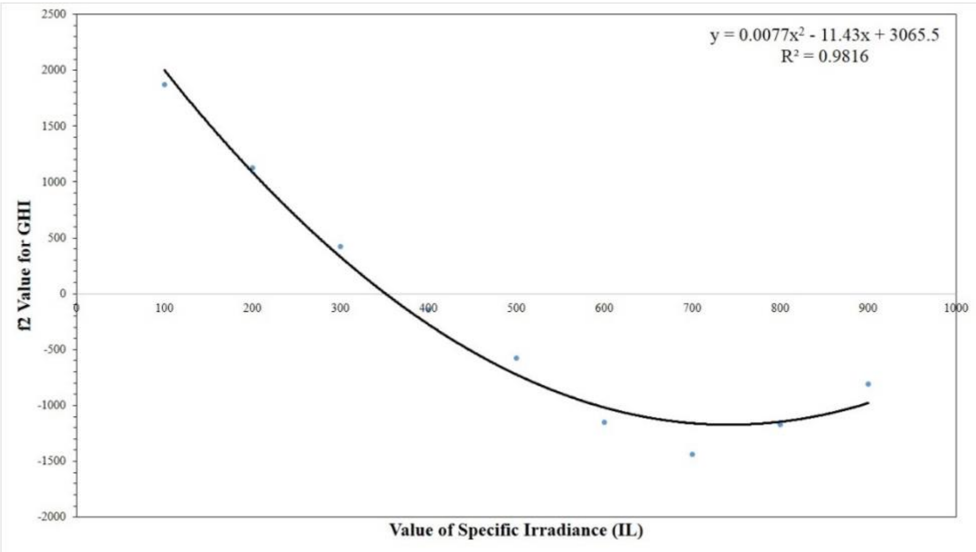


Fig. 7. Variation of f2 for GHI for various values of irradiance

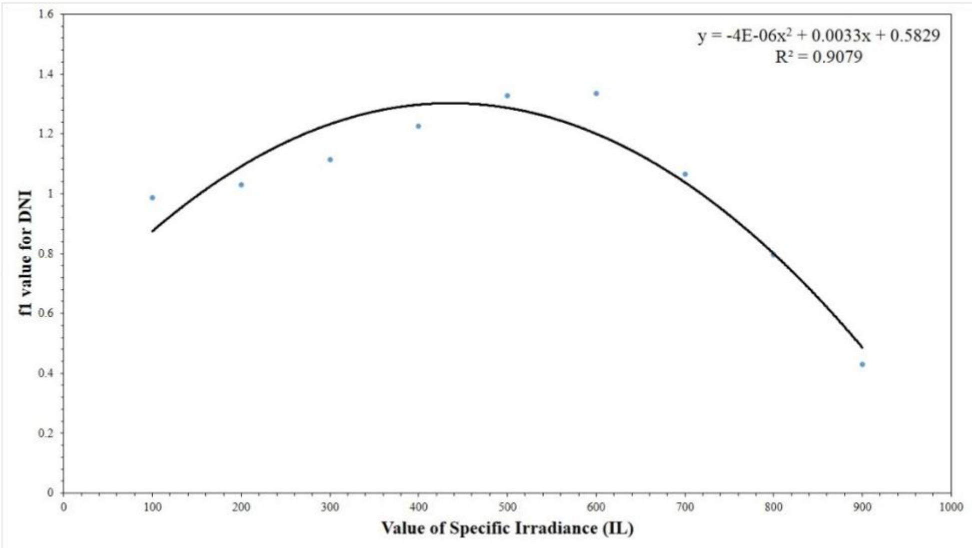


Fig. 8. Variation of f1 for DNI for various values of irradiance

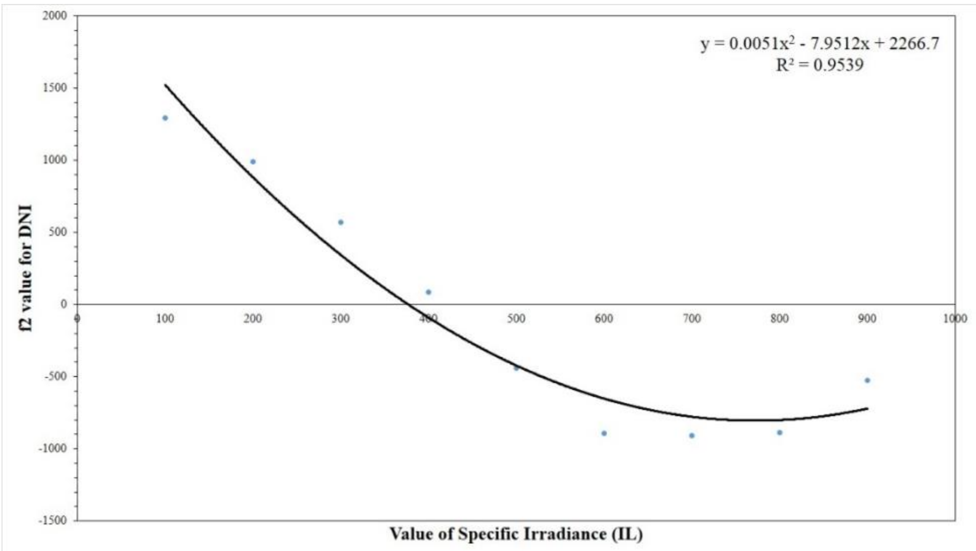


Fig. 9. Variation of f2 for DNI for various values of irradiance

Table 6. Derived Values of α_i, β_i for GHI and DNI

	α_1	α_2	α_3	β_1	β_2	β_3
GHI	-0.000004	0.0038	0.4375	0.0077	-11.43	3065.5
DNI	-0.000004	0.0033	0.589	0.0051	-7.9512	2266.7

Table 7. Model performance on GHI calculations for cities in India

Indian Cities	MAPE	NSE
Gurgaon	4.56%	0.98
Leh	2.36%	0.99
Chennai	5.54%	0.96
Erode	2.45%	0.99
Pokhran	2.52%	0.98
Tezpur	1.38%	0.99
Pune	2.85%	0.99
Indore	2.55%	0.99
Phalodi	3.66%	0.98
Surat	1.81%	0.99

Table 8. Model performance on GHI calculations for cities in USA.

USA Cities	MAPE	NSE
Phoenix	1.33%	0.99
Los Angeles	2.27%	0.99
New York	7.67%	0.96
Minot	8.12%	0.97
Texas	2.39%	0.99

However, the model performs well for all the other cities and gives a best fit to the prediction in the range of above 90 % NSE. The value derived from the proposed model is compared with the values from SAM software for 10 locations in India and, 5 locations in USA. The comparative chart is presented in Fig. 10 and Fig. 11.

Table 9. Model performance on DNI calculations for cities in India.

City	MAPE	NSE
Gurgaon	47.83%	-0.26
Leh	19.11%	0.24
Chennai	9.39%	0.98
Erode	14.39%	0.99
Pokhran	7.07%	0.97
Tezpur	17.07%	0.92
Pune	15.23%	0.89
Indore	13.67%	0.96
Phalodi	6.39%	0.97
Surat	22.69%	0.94

For DNI calculations, all statistical analysis also shows excellent performance of the model for all the cities except for Gurgaon and Leh (Table 9). The MBE and RMSE values for Gurgaon and Leh are quite high and the MAPE values are much higher than 10 which indicates very poor performance of the model in these 2 cities. The NSE for Gurgaon is negative (-0.26) which indicates unacceptable model performance in this location due to nonlinear nature of the data measured for the specific year. For Leh, the efficiency is very low (0.24) which shows very poor performance of the model in this area for DNI calculations. This may be attributed to the fact that these cities are classified as microclimates in India. Leh has a relatively higher altitude (3252 meters) than the other cities in India and it has a higher clearness index hence it receives unusually more DNI radiation. Although the mathematical model was developed using the ground measured solar irradiance data, the model validation is performed using the data from SAM database, which is a satellite based source. The deviations would be further less when compared to the ground based solar irradiance data.

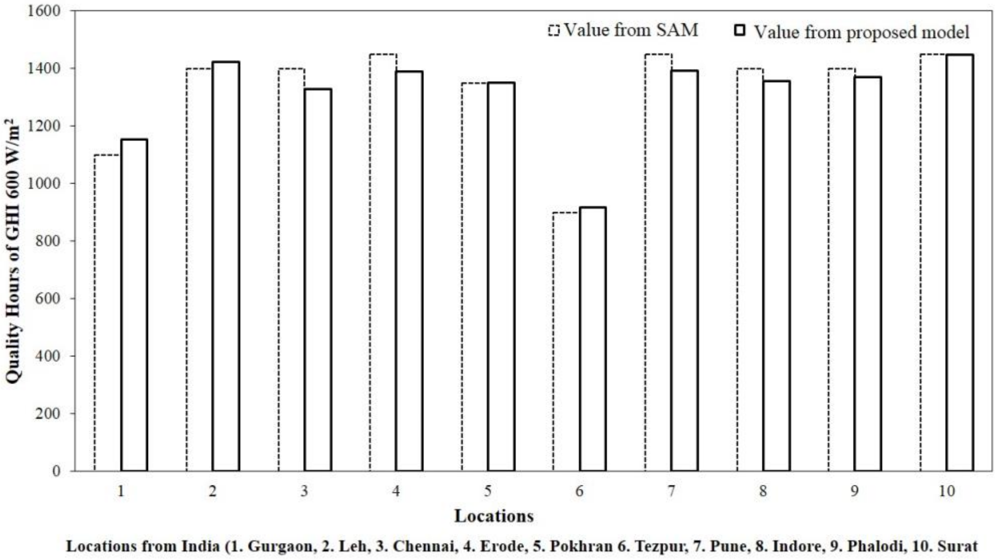


Fig. 10. Validation of the Proposed Model with Exiting Values from SAM Software for 10 Locations in India

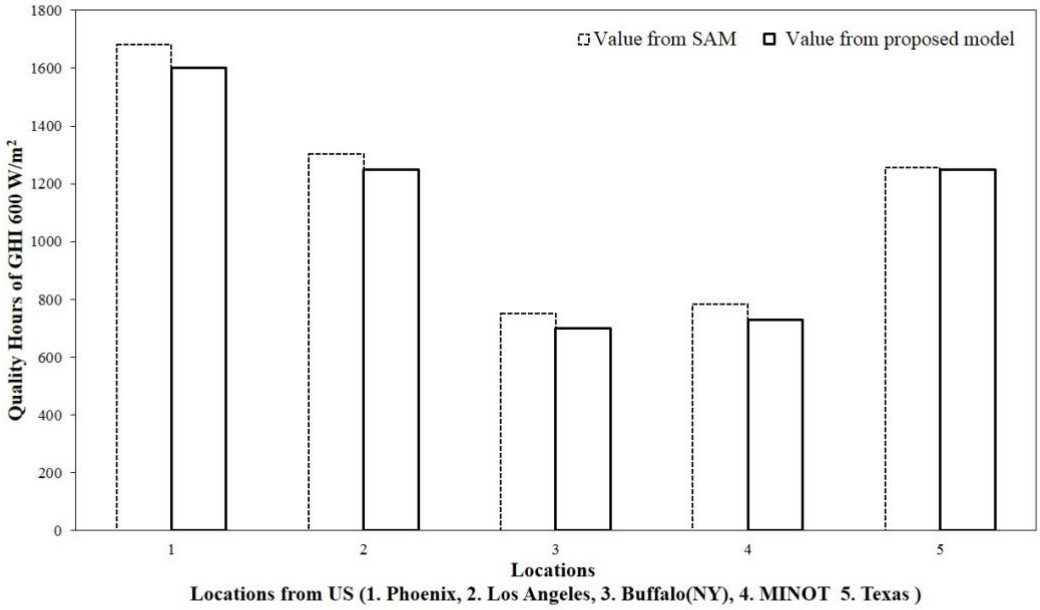


Fig. 11. Validation of the Proposed Model with Exiting Values from SAM Software for 5 Locations in US

6. Conclusion

A universal mathematical model to calculate quality hours of GHI and DNI for a location was developed. A statistical analysis was carried out and the model showed excellent performance for GHI calculations for cities in India and the USA. The proposed model is recommended for use since it gives best fit to the prediction and shows excellent performance in the range above 90 % efficiency. For DNI calculations, the model shows excellent performance for all cities in India except for microclimates such as Gurugram and Leh where it showed some relatively poor performance. This is so because the model is generated based on the correlation of data from 15 unique locations in India. It is then difficult to in cooperate the unique characteristics of the microclimates within the model. This, however, can be subjected to further research to incorporate location specific constants to the model.

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