Estimation of Solar Radiation on Tilted Surface by Using Regression Analysis at Different Locations in India

Abdul Qadeer[1,*], Mohammad Emran Khan[1] and Shah Alam[2]

[1]*Department of Mechanical Engineering, F/o Engineering & Technology, Jamia Millia Islamia, New Delhi, India*
[2]*University Polytechnic, Jamia Millia Islamia, New Delhi, India*
E-mail: meetqadeer@gmail.com
[*]*Corresponding Author*

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Abstract

This study is to find the regression model for estimation of monthly mean hourly global solar radiation on tilted surface at different locations of India. This study is quite precious due to lack of solar radiation data availability on the tilted surface. Firstly, we have selected some locations having different climatic conditions such as New Delhi, Mumbai, Kolkata, Lucknow and Jaipur to find the solar radiation on tilted surface using Liu and Jordan model, HDKR model and Perez model. The mean values of these models are plotted along with the daytime. Based on regression techniques, four empirical models are developed which are tested to compute the solar radiation on tilted surface for three new stations Ahmadabad, Bangalore and Chennai. The estimated solar radiation by these four developed models are compared with the estimated values using existing models Lie & Jordan, HDKR and Perez based on mean bias error (MBE) and root mean square error (RMSE). It has been found that developed Model-3 has minimum error and the values estimated this model is comparable to existing models. The maximum values

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of RMSE in Model-3 in tested stations are 2.01% with Liu and Jordan, 2.63% with HDKR and 2.10% with Perez. Similarly, maximum values of MBE are −1.79% with Liu and Jordan, −2.27% with HDKR and −1.89% with Perez. Now the Model-3 finally selected to determine the solar radiation on Bhopal, Bhubneshwar, Dehradun, Guwahati and Trivendrum (Thiruvananthapuram).

Keywords: Solar radiation, tilted surface, regression analysis, RMSE, MBE.

1 Introduction

Indian main territory lies between 8.07° N to 37.1° N which has abundant amount of solar radiation. The present situation of environment is quite harsh for living species on earth due to pollution generated by fossil fuels. Hence, it is a challenge to provide clean energy in appreciable amount for human being on earth. Solar energy is one of the cleanest forms of renewable energy which is freely available, and it is advisable to convert solar energy into other useful form. The problem with solar energy is that it is a dilute form of energy, so it is necessary to know how to collect maximum amount of solar energy on the collector surface. For collection of maximum amounts of solar energy, correct tilt angle and orientation must be known [1]. Total solar radiation on tilted surface depends upon its radiation components. Among radiation components, diffuse radiation component plays an important role while specifying quality of incident solar radiation components. For the estimation of diffuse solar radiation many empirical relations have been developed [2]. First ever approach is done by Liu and Jordan [3] for the assessment of diffuse component of solar radiation on horizontal surface. Afterwards many researchers extended the assessment of Liu and Jordan by introducing different climatic data such as ambient temperature, relative humidity, cloudiness and meteorological factors.

Model developed by Liu and Jordan is known as isotropic model for the estimation of diffuse component of solar radiation without azimuth angle and zenith angle considering. Thereafter, extended work considers both isotropic and anisotropic models [4, 5]. Solar radiation on tilted surface has been evaluated [6] by converting the radiation intensities measured on horizontal surface. The intensity of solar radiation on tilted surface depends on tilt angle and orientation [7] but it is impossible to set optimum orientation due to falling shadow on surface for some hours in a day, hence it is advisable to change orientation. Solar radiation was calculated at different tilt angle ($-20^\circ \leq \beta \leq 90^\circ$) and at different orientation ($-90^\circ \leq \gamma \leq 90^\circ$). Increasing demand of energy for domestic and industrial purpose in this rigorous condition of environment makes solar energy a strong contender as it is the cleanest form of energy and available free of cost. Solar radiation availability was calculated for Aligarh and New Delhi (Capital of India) by using measured data over a period of three years and found that annual optimum tilt angle is 27.62° and 27.95° for Aligarh (27.89° N, 78.08° E) and New Delhi (28.61° N, 77.20° E) respectively, which is very close to the latitudes of respective location. The study recommends that the optimum tilt angle must change every month or every season for better collection of solar energy [8].

Takilalte et al. [10] present a method for estimation of global solar radiation on tilted surface in 5-min steps using global irradiance data on horizontal surface. Methodology is based on well-known Perrin Brichambaut and Liu and Jordan models, the results are tested on following scale, normalized root mean square error (nRMSE), relative percentage error (RPE), normalized mean absolute error (nMAE) and coefficient of correlation (R^2).

The measured data is the best data, but the measurement of solar radiation data is difficult for many developing countries because of high maintenance cost and calibration cost. Hence, it is necessary to develop the models to overcome this problem [11]. Several models have been developed for estimation of solar radiation on horizontal surface based on various climatic conditions like latitude, ambient temperature, cloud cover, sunshine hours, etc. [12–18]. Wu et al. [19] developed global solar radiation model by using ambient temperature, sunshine hours and total precipitation as meteorological data. Sen gave a model to predict global solar radiation by using sunshine hour data [20]. Bulut and Buyukalaca [21] gave a model based on trigonometric functions to predict monthly average daily global solar radiation by using day of the year as only independent parameter. Janjai et al. [22] proposed a model to calculate monthly average hourly global solar radiation by using satellite data for tropical region.

Availability of global irradiation data measurement is an important factor for the assessment of solar potential and the collected data must be accurate and the period of data collection must over than 11 years. Collection of this data is not feasible in many countries; hence, this research proposes numerical models to estimate monthly, seasonally and annually solar irradiance on tilted surface. The measured data is very close to actual data collected from meteorological stations. Optimal tilt angle followed by data validation had been calculated for each year period for best positioning of photovoltaic panel [23].

The Fast, All-sky Radiation Model for solar applications with narrowband irradiances on tilted surface (FARMS-NIT) is enhanced for cloudy sky conditions. Using radiative transfer equation for five independent photon paths, Narrow wavelength band (0.28–4.0 μm) is analytically computed [24].

This study developed a model using back temperature of solar modules having tilt angles 6.7°, 16.8°, 26.8° and 0° in Lagos (6.6080° N, 3.6218° E) Nigeria. These solar modules showed an appreciable amount of energy gain 8.74%, 20.85%, 19.49% respectively as compared to energy generated by horizontally placed modules. Twelve models has been developed based on performance analysis from each module hence total 48 models has been developed and tested on statistical indicators such as Mean Bias Error (MBE), Mean Percentage Error (MPE), Root Mean Square Error (RMSE), Relative Root Mean Square Error (RRMSE), coefficient of determination $(R)^2$ and Global Performance Indicator (GPI). These tests showed that model 44, is the most excellent performing model regarding accuracy as compared to other models [25].

A fixed grid-connected photovoltaic (PV) array, optimum tilt angle not only dependent on geographical location, but also on atmospheric conditions. Impact of long-term variations of solar radiation on optimal tilt angle for fixed grid-connected PV array in Beijing has been considered in this paper. It is found that a considerable decrement in global solar irradiance in past 55 years due to the decreased direct horizontal irradiance. Likewise, there is a downtrend is found in optimal tilt angle. A 2° decrement found in optimal tilt angle in 2011–2015 as compared to 1960s. Therefore, the design and construction of PV power stations must consider the variation of atmospheric conditions [26].

The present work is oriented about to find a new model for effective estimation of monthly mean hourly solar radiation on tilted surface by using regression analysis method based on meteorological data [9]. Based on regression techniques four models are developed by using data of New Delhi (28.57° N, 77.18° E), Kolkata (22.57° N, 88.36° E), Mumbai (19.07° N, 72.88° E), Lucknow (26.85° N, 80.95° E) and Jaipur (26.91° N, 75.79° E). The models are tested for Ahmedabad (23.02° N, 72.57° E) Bangalore (12.97° N, 77.59° E) and Chennai (13.08° N, 80.27° E) India. It is found that model-3 is comparatively more effective.

2 Methodology

2.1 Proposed Models

The solar radiation estimated by Liu and Jordan model, HDKR model and Perez model is analysed, and the mean estimated data of these models are used to develop empirical models. Based on regression analysis we have proposed four models to compute monthly mean hourly solar radiation on tilted surface using meteorological data of five Indian stations viz. New Delhi, Kolkata, Mumbai, Lucknow and Jaipur. The proposed models are given below in Table 1.

Where ω and ω_S are hour angle and hour angle corresponding to sunrise or sunset respectively.

The proposed regression models 1, 2, 3 and 4 are used to predict the solar radiation on tilted surface for Indian locations Ahmadabad, Bangalore and Chennai in different months of the year. The results obtained by these models are compared with three empirical models Liu and Jordan [2], HDKR [2] and Perez [2].

2.2 Liu and Jordan Model [2]

This model accounts diffuse radiation from the sky and ground reflected radiation simultaneously and hence it is known as isotropic model. Assumption of this model is the sum of diffuse component and ground reflected component of radiation is independent of surface orientation. The radiation on tilted surface is the sum of beam radiation (Ib), diffuse radiation (I_d) and ground reflected radiation. The total monthly mean hourly radiation on the tilted

Table 1 Regression models

Models	Regression Equations	
Model-1	$I_T = -0.096 I_b e^B + 2.35 I_d B.$	$A = \left\lvert \frac{\omega}{\omega_S} \right\rvert, B = \frac{1}{A^{0.25}}$
Model-2	$I_T = -0.096 I_b e^B + 2.35 I_d B - 1.$	$A = \left\lvert \frac{\omega}{\omega_S} \right\rvert, B = \frac{1}{A^{0.5}}$
Model-3	$I_T = -0.096\sqrt{\left(\frac{I_b}{I}\right)} e^B + 2.35\sqrt{\left(\frac{I_b}{I}\right)} B + \sqrt{\left(\frac{I_b}{I}\right)}\left(\frac{1+\cos\beta}{2}\right),$	$A = \left\lvert \frac{\omega}{\omega_S} \right\rvert, B = \frac{1}{A^{0.5}}$
Model-4	$I_T = -0.215\sqrt{\left(\frac{I_b}{I}\right)}\left(\frac{1+\cos\beta}{2}\right) e^B + 2.68\sqrt{\left(\frac{I_b}{I}\right)} B,$	$A = \left\lvert \frac{\omega}{\omega_S} \right\rvert, B = \frac{1}{A^{0.2}}$

surface can be given as

$$\mathrm{I_T = I_b R_b + I_d}\left(\frac{1+\cos\beta}{2}\right) + \mathrm{I}\rho_\mathrm{g}\left(\frac{1-\cos\beta}{2}\right) \tag{1}$$

Where

$$\mathrm{R_b} = \frac{\cos\theta}{\cos\theta z}$$

$$\cos\theta = \sin\delta\sin(\Phi-\beta) + cos\delta\ cos\omega\ \cos(\Phi-\beta)$$

$$\cos\theta z = \sin\Phi\sin\delta + cos\Phi\ cos\delta\ cos\omega$$

θ is the angle between direct normal irradiance and normal to the surface, θz is the zenith angle, β is tilt angle, Φ is latitude, β is surface tilt angle, ω is hour angle, δ is angle if declenation. I_b is beam solar radiation, I_d is diffuse solar radiation and I is global radiation (I_b + I_d), ρ_g is ground albedo.

2.3 HDKR Model [2]

Some extensions have been done in isotropic model developed by Liu and Jordan. Hay & Device, Klucher and Reindl (HDKR) developed an anisotropic model which also consider the circumsolar diffuse and horizon brightening components of radiation on tilted surface. The total radiation on tilted surface by this model is

$$\mathrm{I_T = (I_b + I_d A_i)\,R_b + I_d\,(1 - A_i)}\left(\frac{1+\cos\beta}{2}\right)\left[1 + \mathrm{f}\sin^3\left(\frac{\beta}{2}\right)\right] + \mathrm{I}\rho_\mathrm{g}\left(\frac{1-\cos\beta}{2}\right) \tag{2}$$

Where A_i is anisotropic index

$$\mathrm{A_i} = \frac{\mathrm{I_b}}{\mathrm{I_0}}$$

I_0 is extraterrestrial radiation, f is modulating factor

$$\mathrm{f} = \sqrt{\frac{\mathrm{I_b}}{\mathrm{I}}}$$

2.4 Perez Model [2]

This model is with more detailed analysis of three diffuse components of radiation. The total radiation on the tilted surface includes five terms: beam radiation, isotropic diffuse, circumsolar diffuse, diffuses from horizon and the ground reflected.

$$I_T = I_b R_b + I_d (1 - F_1) \left(\frac{1 + \cos\beta}{2} \right) + I_d F_1 \frac{a}{b} + I_d F_2 \sin\beta + I \rho_g \left(\frac{1 - \cos\beta}{2} \right) \tag{3}$$

Where F_1 & F_2 are brightness coefficients, a & b accounts incident solid angle for circumsolar radiation on tilted or horizontal surface.

3 Results and Discussion

Given developed models have been tested on Bangalore (12.97° N, 77.59° E), Ahmadabad (23.02° N, 72.57° E) and Chennai (13.08° N, 80.27° E), India with the meteorological data provided by ISHRAE [9]. These models compared with Liu and Jordan model, HDKR model and Perez model on mean bias error (MBE) scale and root mean square error (RMSE) scale [10] as the respective equations are given bellow.

$$MBE = \frac{1}{N} \sum_{i=1}^{N} (x_{f,i} - x_{o,i}) \tag{4}$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_{f,i} - x_{o,i})^2} \tag{5}$$

Where $x_{f,i}$ and $x_{o,i}$ are ith forecast and observation respectively.

The comparison of proposed models and existing standard models are given in Tables 2–4 for these stations. It has been seen in Tables 2–4 that Model-3 has maximum RMSE that is (1.37% with Liu and Jordan, 1.57% with HDKR, 1.46% with Perez) for Ahmadabad, (1.11% with Liu and Jordan, 1.15% with HDKR, 1.16% with Perez) for Bangalore and (0.62% with Liu and Jordan, 0.60% with HDKR, 0.70% with Perez) for Chennai. Based on these errors the Model-3 has been selected best proposed model and now it can be used to estimate the monthly mean hourly solar radiation for unknown Indian stations.

Table 2 Comparison of proposed models with Liu and Jordan, HDKR and Perez model based on MBE and RMSE for Ahmadabad, India

Proposed Models	Std. Models	Errors	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Model-1	Liu and Jordan	MBE	−3.09	−2.64	−3.00	−2.77	−0.99	−0.21	1.59	2.11	0.05	−1.95	−3.09	−2.96
		RMSE	3.53	2.95	3.32	2.96	1.04	0.90	1.88	2.53	0.81	2.33	3.52	3.46
	HDKR	MBE	−3.27	−2.76	−3.06	−2.78	−0.96	0.11	1.61	2.11	0.00	−2.05	−3.23	−3.14
		RMSE	3.67	3.04	3.36	2.98	1.02	0.63	1.90	2.53	0.80	2.40	3.62	3.58
	Perez	MBE	−3.19	−2.73	−3.07	−2.81	−1.01	−0.27	1.59	2.09	−0.04	−2.06	−3.20	−3.08
		RMSE	3.62	3.04	3.38	3.00	1.07	0.96	1.88	2.51	0.79	2.42	3.62	3.56
Model-2	Liu and Jordan	MBE	−5.24	−4.72	−5.53	−5.38	−2.58	−1.05	0.47	0.70	−0.11	−0.85	−1.33	−1.18
		RMSE	6.34	5.68	6.84	6.56	3.00	1.35	0.85	1.04	0.85	1.31	1.71	1.38
	HDKR	MBE	−5.43	−4.84	−5.59	−5.39	−2.56	−0.73	0.49	0.69	−0.16	−0.94	−1.47	−1.36
		RMSE	6.46	5.76	6.88	6.57	2.99	0.99	0.85	1.04	0.85	1.37	1.81	1.51
	Perez	MBE	−5.34	−4.81	−5.60	−5.42	−2.61	−1.12	0.47	0.68	−0.21	−0.96	−1.44	−1.30
		RMSE	6.43	5.77	6.89	6.59	3.03	1.42	0.84	1.02	0.84	1.38	1.80	1.48
Model-3	Liu and Jordan	MBE	−1.15	−0.95	−1.07	−0.86	−0.44	−0.61	−0.21	−0.21	−0.45	−0.86	−1.22	−1.10
		RMSE	1.37	1.14	1.18	0.99	0.65	1.03	0.50	0.46	0.68	0.98	1.34	1.26
	HDKR	MBE	−1.33	−1.07	−1.13	−0.87	−0.42	−0.29	−0.19	−0.22	−0.49	−0.96	−1.37	−1.28
		RMSE	1.57	1.27	1.25	1.00	0.62	0.52	0.48	0.46	0.71	1.07	1.47	1.42
	Perez	MBE	−1.25	−1.04	−1.14	−0.90	−0.47	−0.68	−0.21	−0.23	−0.54	−0.97	−1.33	−1.21
		RMSE	1.46	1.22	1.25	1.02	0.66	1.12	0.49	0.46	0.73	1.08	1.44	1.36
Model-4	Liu and Jordan	MBE	−1.08	−0.90	−1.03	−0.84	−0.42	−0.59	−0.18	−0.18	−0.40	−0.82	−1.16	−1.03
		RMSE	1.37	1.10	1.10	0.91	0.56	0.87	0.48	0.48	0.59	0.91	1.30	1.28
	HDKR	MBE	−1.27	−1.02	−1.10	−0.85	−0.40	−0.27	−0.16	−0.19	−0.45	−0.92	−1.31	−1.20
		RMSE	1.54	1.21	1.16	0.93	0.55	0.47	0.47	0.49	0.63	1.00	1.41	1.41
	Perez	MBE	−1.18	−0.99	−1.10	−0.88	−0.44	−0.65	−0.18	−0.20	−0.49	−0.93	−1.27	−1.14
		RMSE	1.46	1.19	1.17	0.95	0.58	0.96	0.48	0.49	0.66	1.02	1.40	1.38

Table 3 Comparison of proposed models with Liu and Jordan, HDKR and Perez model based on MBE and RMSE for Bangalore, India

Proposed Models	Std. Models	Errors	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Model-1	Liu and Jordan	MBE	−1.38	−2.70	−1.30	−0.75	0.34	1.21	1.01	2.06	1.26	0.91	−0.34	−0.64
		RMSE	1.70	3.15	1.76	1.25	0.84	1.69	1.22	2.45	1.57	1.26	1.20	1.07
	HDKR	MBE	−1.44	−2.75	−1.32	−0.74	0.36	1.39	1.03	2.07	1.25	0.88	−0.39	−0.70
		RMSE	1.74	3.18	1.78	1.25	0.85	1.78	1.24	2.46	1.56	1.25	1.22	1.10
	Perez	MBE	−1.45	−2.75	−1.34	−0.76	0.35	1.15	1.03	2.06	1.22	0.85	−0.42	−0.72
		RMSE	1.76	3.19	1.79	1.26	0.84	1.68	1.24	2.45	1.53	1.22	1.22	1.12
Model-2	Liu and Jordan	MBE	−2.95	−5.07	−3.12	−2.21	−0.47	1.25	0.63	2.64	1.23	0.71	−1.27	−1.68
		RMSE	3.67	6.37	4.38	3.21	1.29	2.28	1.16	3.82	2.00	1.63	2.12	2.11
	HDKR	MBE	−3.01	−5.11	−3.14	−2.21	−0.45	1.43	0.65	2.65	1.22	0.69	−1.32	−1.74
		RMSE	3.71	6.39	4.39	3.21	1.28	2.31	1.17	3.82	1.99	1.62	2.15	2.16
	Perez	MBE	−3.02	−5.12	−3.16	−2.23	−0.46	1.19	0.65	2.64	1.19	0.65	−1.35	−1.77
		RMSE	3.72	6.40	4.41	3.22	1.29	2.29	1.17	3.82	1.97	1.60	2.16	2.18
Model-3	Liu and Jordan	MBE	−0.55	−1.00	−0.63	−0.56	−0.38	−0.47	−0.25	−0.30	−0.33	−0.21	−0.37	−0.34
		RMSE	0.70	1.11	0.76	0.67	0.52	0.68	0.43	0.44	0.47	0.40	0.54	0.54
	HDKR	MBE	−0.62	−1.05	−0.65	−0.56	−0.36	−0.29	−0.23	−0.29	−0.34	−0.23	−0.41	−0.40
		RMSE	0.76	1.15	0.78	0.67	0.50	0.44	0.42	0.43	0.48	0.41	0.58	0.58
	Perez	MBE	−0.63	−1.05	−0.67	−0.58	−0.37	−0.53	−0.23	−0.29	−0.37	−0.27	−0.44	−0.42
		RMSE	0.76	1.16	0.79	0.69	0.51	0.79	0.42	0.43	0.50	0.43	0.59	0.59
Model-4	Liu and Jordan	MBE	−0.51	−0.96	−0.60	−0.53	−0.36	−0.44	−0.24	−0.26	−0.30	−0.17	−0.33	−0.29
		RMSE	0.67	1.04	0.73	0.63	0.51	0.60	0.45	0.48	0.51	0.40	0.49	0.46
	HDKR	MBE	−0.58	−1.01	−0.62	−0.53	−0.34	−0.25	−0.22	−0.26	−0.31	−0.19	−0.38	−0.35
		RMSE	0.72	1.08	0.75	0.63	0.49	0.46	0.44	0.48	0.52	0.42	0.53	0.50
	Perez	MBE	−0.58	−1.01	−0.64	−0.55	−0.35	−0.50	−0.23	−0.26	−0.34	−0.23	−0.41	−0.37
		RMSE	0.73	1.09	0.77	0.65	0.50	0.69	0.44	0.48	0.54	0.44	0.56	0.52

Table 4 Comparison of proposed models with Liu and Jordan, HDKR and Perez model based on MBE and RMSE for Chennai, India

Proposed Models	Std. Models	Errors	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Model-1	Liu and Jordan	MBE	−0.07	−0.23	1.06	1.28	0.54	0.40	1.14	0.66	0.72	1.21	1.05	0.51
		RMSE	1.26	1.33	1.85	2.09	1.55	1.28	1.56	1.06	1.36	1.70	1.48	1.20
	HDKR	MBE	−0.12	−0.27	1.04	1.28	0.56	0.59	1.16	0.67	0.71	1.19	1.02	0.46
		RMSE	1.27	1.34	1.84	2.09	1.55	1.35	1.58	1.07	1.35	1.68	1.45	1.18
	Perez	MBE	−0.15	−0.30	1.01	1.27	0.55	0.35	1.16	0.65	0.69	1.15	0.98	0.42
		RMSE	1.26	1.34	1.82	2.09	1.56	1.27	1.58	1.06	1.34	1.65	1.42	1.15
Model-2	Liu and Jordan	MBE	−0.77	−1.19	1.04	1.44	0.01	−0.01	1.05	0.16	0.41	1.28	1.06	0.25
		RMSE	1.84	2.35	2.59	3.09	2.00	1.54	1.94	1.17	1.60	2.51	2.22	1.77
	HDKR	MBE	−0.82	−1.23	1.03	1.44	0.03	0.17	1.07	0.17	0.40	1.26	1.02	0.20
		RMSE	1.86	2.37	2.58	3.09	2.00	1.53	1.95	1.17	1.60	2.50	2.20	1.76
	Perez	MBE	−0.85	−1.26	1.00	1.42	0.02	−0.06	1.07	0.15	0.37	1.23	0.99	0.16
		RMSE	1.87	2.38	2.57	3.08	2.01	1.55	1.95	1.17	1.59	2.47	2.17	1.75
Model-3	Liu and Jordan	MBE	−0.27	−0.44	−0.38	−0.42	−0.36	−0.48	−0.28	−0.35	−0.37	−0.20	−0.05	−0.15
		RMSE	0.48	0.57	0.48	0.53	0.49	0.62	0.41	0.45	0.49	0.35	0.29	0.39
	HDKR	MBE	−0.31	−0.48	−0.39	−0.42	−0.34	−0.29	−0.26	−0.34	−0.37	−0.23	−0.08	−0.20
		RMSE	0.50	0.60	0.49	0.53	0.48	0.41	0.40	0.45	0.50	0.36	0.30	0.41
	Perez	MBE	−0.35	−0.51	−0.42	−0.44	−0.35	−0.53	−0.27	−0.35	−0.40	−0.26	−0.12	−0.23
		RMSE	0.52	0.62	0.51	0.53	0.49	0.70	0.40	0.46	0.51	0.38	0.31	0.42
Model-4	Liu and Jordan	MBE	−0.23	−0.41	−0.35	−0.39	−0.34	−0.45	−0.26	−0.33	−0.34	−0.16	0.01	−0.08
		RMSE	0.41	0.53	0.48	0.50	0.46	0.50	0.43	0.49	0.50	0.39	0.34	0.32
	HDKR	MBE	−0.27	−0.45	−0.36	−0.39	−0.33	−0.26	−0.24	−0.32	−0.35	−0.18	−0.02	−0.13
		RMSE	0.44	0.56	0.49	0.50	0.45	0.40	0.42	0.48	0.51	0.40	0.34	0.34
	Perez	MBE	−0.31	−0.48	−0.39	−0.40	−0.33	−0.50	−0.25	−0.33	−0.38	−0.22	−0.06	−0.17
		RMSE	0.47	0.59	0.52	0.51	0.46	0.56	0.42	0.49	0.53	0.43	0.36	0.37

Tables 2–4 shows that the variation of proposed Model-3 is minimum with standard models. Hence Model-3 is more appropriate to predict the solar radiation data at tilted surface for different Indian locations.

3.1 Validation of Model-3

The validation of Model-3 has been done by putting the meteorological data of Bhopal (23.26° N, 74.41° E), Bhubneshwar (20.3° N 85.82° E), Dehradun (30.32° N, 78.02° E), Guwahati (26.14° N, 91.74° E) and Trivandram (8.52°

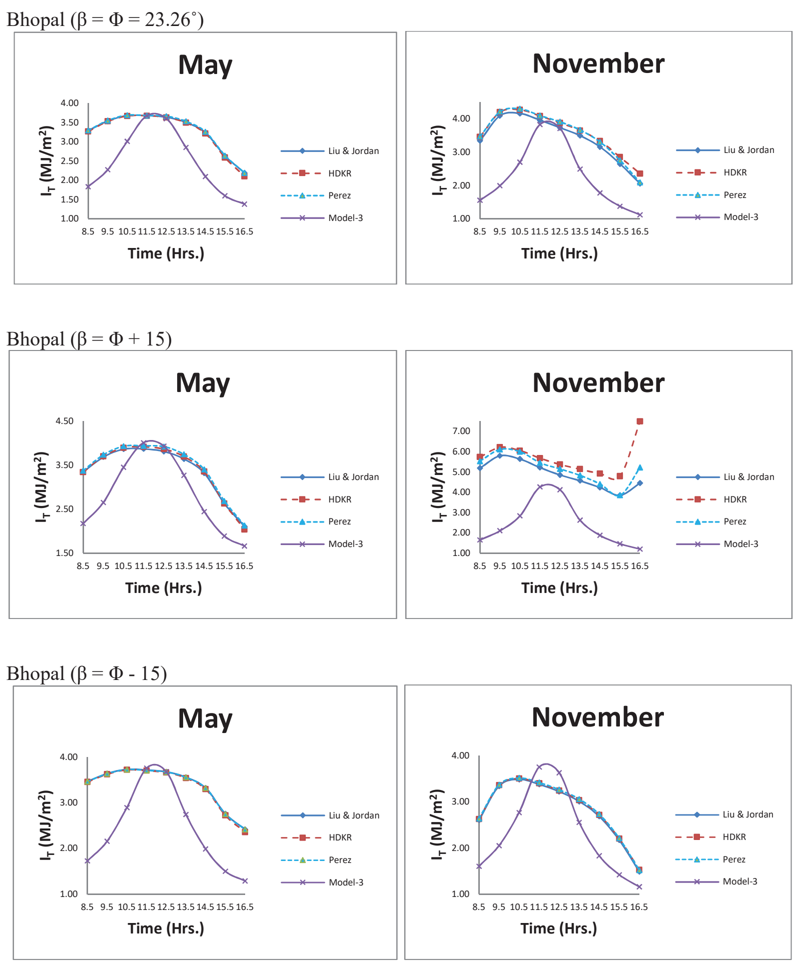

Figure 1 Estimation of solar radiation on tilted surface using Model-3 for Bhopal at $\Phi = \beta$, $\Phi = \beta + 15$ and $\Phi = \beta - 15$.

N, 76.94° E). The estimated data by proposed model is plotted along with daytime in Figure 1 for Bhopal at various tilt angles $\beta = \Phi$, $\beta = \Phi + 15$ and $\beta = \Phi - 15$.

The estimated solar radiation is also compared with Liu and Jordan model, HDKR model and Perez model for these new stations. The MBE and RMSE is given in Table 5.

The Table 5 shows that the maximum Values of RSME at latitude Φ are 1.43% (Bhopal in November), 0.94% (Bhubneshwar in March), 1.31% (Dehradun in November), 0.72% (Guwahati in November), 1.24% (Trivendrum in March).

Table 5 Variation of Model-3 with standard models on MBE and RMSE scale at different stations of India

Cities	Latitude	Std. Models	Errors	Mar	May	Nov
Bhopal	Φ	Liu and Jordan	MBE	−1.15	−0.78	−1.12
			RMSE	1.29	0.92	1.30
		HDKR	MBE	−1.21	−0.76	−1.28
			RMSE	1.35	0.90	1.43
		Perez	MBE	−1.23	−0.80	−1.25
			RMSE	1.35	0.93	1.41
	Φ+15	Liu and Jordan	MBE	−1.46	−0.53	−2.41
			RMSE	1.61	0.69	2.61
		HDKR	MBE	−1.67	−0.55	−3.25
			RMSE	1.81	0.70	3.55
		Perez	MBE	−1.61	−0.60	−2.71
			RMSE	1.74	0.74	2.92
	Φ-15	Liu and Jordan	MBE	−0.91	−0.95	−0.51
			RMSE	1.08	1.12	0.75
		HDKR	MBE	−0.91	−0.93	−0.54
			RMSE	1.09	1.10	0.77
		Perez	MBE	−0.92	−0.95	−0.55
			RMSE	1.09	1.11	0.78
Bhubneshwar	Φ	Liu and Jordan	MBE	−0.74	−0.32	−0.14
			RMSE	0.87	0.47	0.50
		HDKR	MBE	−0.79	−0.31	−0.22
			RMSE	0.91	0.46	0.54
		Perez	MBE	−0.81	−0.33	−0.26
			RMSE	0.94	0.48	0.55
	Φ+15	Liu and Jordan	MBE	−1.09	−0.25	−0.68
			RMSE	1.21	0.38	0.92
		HDKR	MBE	−1.26	−0.28	−1.00
			RMSE	1.36	0.39	1.22

(*Continued*)

Table 5 Continued

Cities	Latitude	Std. Models	Errors	Mar	May	Nov
		Perez	MBE	−1.26	−0.33	−0.91
			RMSE	1.37	0.44	1.09
	Φ-15	Liu and Jordan	MBE	−0.60	−0.45	0.11
			RMSE	0.74	0.61	0.42
		HDKR	MBE	−0.60	−0.44	0.10
			RMSE	0.75	0.60	0.42
		Perez	MBE	−0.61	−0.45	0.08
			RMSE	0.75	0.61	0.41
Dehradun	Φ	Liu and Jordan	MBE	−0.64	−0.36	−0.84
			RMSE	0.76	0.47	1.18
		HDKR	MBE	−0.74	−0.36	−1.00
			RMSE	0.85	0.47	1.30
		Perez	MBE	−0.78	−0.41	−1.01
			RMSE	0.88	0.50	1.31
	Φ+15	Liu and Jordan	MBE	−1.13	−0.33	−2.56
			RMSE	1.22	0.40	2.91
		HDKR	MBE	−1.45	−0.41	−3.52
			RMSE	1.51	0.46	3.74
		Perez	MBE	−1.39	−0.47	−2.90
			RMSE	1.47	0.52	3.26
	Φ-15	Liu and Jordan	MBE	−0.42	−0.46	−0.22
			RMSE	0.60	0.60	0.59
		HDKR	MBE	−0.45	−0.44	−0.26
			RMSE	0.61	0.58	0.61
		Perez	MBE	−0.48	−0.45	−0.28
			RMSE	0.63	0.60	0.62
Guwahati	Φ	Liu and Jordan	MBE	−0.29	−0.15	−0.18
			RMSE	0.50	0.29	0.64
		HDKR	MBE	−0.35	−0.15	−0.30
			RMSE	0.55	0.29	0.72
		Perez	MBE	−0.41	−0.17	−0.32
			RMSE	0.58	0.31	0.70
	Φ+15	Liu and Jordan	MBE	−0.51	−0.06	−0.90
			RMSE	0.70	0.24	1.33
		HDKR	MBE	−0.72	−0.10	−1.38
			RMSE	0.89	0.26	1.85
		Perez	MBE	−0.74	−0.15	−1.10
			RMSE	0.89	0.29	1.44
	Φ-15	Liu and Jordan	MBE	−0.19	−0.25	0.12
			RMSE	0.43	0.38	0.51
		HDKR	MBE	−0.21	−0.24	0.10
			RMSE	0.44	0.37	0.51

(*Continued*)

Table 5 Continued

Cities	Latitude	Std. Models	Errors	Mar	May	Nov
		Perez	MBE	−0.23	−0.24	0.07
			RMSE	0.45	0.38	0.50
Trivendrum	Φ	Liu and Jordan	MBE	−1.10	−1.01	−0.88
			RMSE	1.22	1.11	1.00
		HDKR	MBE	−1.11	−0.99	−0.92
			RMSE	1.23	1.09	1.03
		Perez	MBE	−1.12	−1.00	−0.92
			RMSE	1.24	1.11	1.03
	Φ+15	Liu and Jordan	MBE	−1.38	−0.84	−1.57
			RMSE	1.47	0.92	1.66
		HDKR	MBE	−1.45	−0.82	−1.79
			RMSE	1.54	0.89	1.88
		Perez	MBE	−1.45	−0.85	−1.70
			RMSE	1.53	0.93	1.78
	Φ-15	Liu and Jordan	MBE	−1.04	−1.42	−0.54
			RMSE	1.16	1.52	0.68
		HDKR	MBE	−1.04	−1.45	−0.53
			RMSE	1.16	1.55	0.67
		Perez	MBE	−1.03	−1.43	−0.52
			RMSE	1.15	1.53	0.66

4 Conclusion

In this study monthly mean hourly global solar radiation on tilted surface for different Indian stations is evaluated. Many locations of India are selected having different climatic conditions to develop empirical relation. Based on least errors, regression equation named Model-3 is selected and validated at Bhopal, Bhubneshwar, Dehradun, Guwahati and Trivendrum. While validating Model-3 for given cities it is found that MBE lies between 0.14% to 1.28% and RMSE lies between 0.29% to 1.43% at $\beta = \Phi$. Hence, the Model-3 can be effectively and confidently be applied in anywhere for calculating Solar radiation on tilted surface.

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Biographies

Abdul Qadeer is a Ph.D student at Jamia Millia Islamia, New Delhi, India since 2017. He attended Maharshi Dayanand University, Rohtak, Haryana, India where he received M.Tech in Thermal Engineering in 2015. He attended Chandra Shekhar Azad University where he completed his B.Tech in Mechanical Engineering in 2009. He also served as lecturer in mechanical engineering department in Al-Falah School of Engineering and Technology (AFSET) from 2011 to 2013. Thereafter he is serving as assistant professor in mechanical engineering department in Al-Falah University from 2015.

Mohammad Emran Khan received his Ph.D degree in mechanical engineering in 1997 from Delhi University, New Delhi, India. He completed his M.Tech in energy studies from I.I.T Delhi, New Delhi, India in 1992. He also completed his B.Sc engg (Mechanical) from A.M.U Aligarh, Aligarh, India in 1984. He served Jamia Millia Islamia as a lecture 1985 to 1995, as a reader from 1995 to 2003, now he is working as a professor in Jamia Millia Islamia 2003 to till date. He also served as member of task force on "Waste to energy project" by Planning Commission of India. Also served as member of National Board of Accreditation (NBA) of AICTE as expert for mechanical engineering discipline.

Shah Alam received his Ph.D degree from I.I.T Delhi in 2006. He also received his M.Sc. and B.Sc. Engineering degree from A.M.U Aligarh in 1993 and 1990 respectively. he also served as lecture from 1995 to 2000, Sr. lecture from 2000 to 2005 and Sr lecturer (SG)/reader from 2005 to 2007 at university polytechnic Jamia Millia Islamia. He also served as assistant professor in International Islamic University Malaysia from 2007 to 2008. He returned back to University polytechnic, Jamia Millia Islamia as Associate Professor from 2008 to till date.