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Analysis of anisotropic and isotropic models for estimation of solar radiation on the inclined surface in New Delhi location

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This content aims to compare several experimental models utilized for the estimation of sunlight based radiation on inclined plane. So, three anisotropic and equal quantities of isotropic models were engaged regularly in New Delhi and their outcomes were analyzed for choice of correct and fitting model for this territory. Three isotropic models to be specific BA (2002), LJ (1960) and KO (1986) and three anisotropic models to be specific HDKR (2006), HD (1980) and RE (1990) model were explored. Here tilt angle was adjusted at 28.58° N (New Delhi latitude). The result of six models had been compared with ground measured data. For this five statistical tests are used for comparison. HD evaluated the most noteworthy measure of occurrence sun oriented radiation in the entire year while BA set up the least among entire models. LJ and KO model showed similar outcomes. The outcomes of statistical analysis gave that HDKR provided smaller MAPE (1.02%), MBE (0.129 kWh/m^2-day), RMSE (0.605 kWh/m^2-day), RMSRE (0.393 kWh/m^2-day) and RRMSE (1.858%) among all six models. Ultimately, HDKR model was favored for estimation of sunlight based radiation occurrence on an inclined plane with least errors. MATLAB has been used for implementation.

Keywords: Anisotropic model, Isotropic model, Inclined plane, Solar radiation, Statistical test

Introduction

Sun oriented radiation information is the best wellspring of data for evaluating normal occurrence radiation essential for appropriate structure and the appraisal of sunlight based energy transformation frameworks[1]. There are a few types of solar radiation data, which could be utilized for an assortment of purposes in the structure and improvement of sun oriented energy frameworks[2]. Hourly radiation may be estimated from day by day information. A few models are created to evaluate the Mg utilizing different climate specifications, for example, daylight length, temperature, moisture and speed of wind[3]. The author utilized the metrological information (1994-2005) of china to evaluate regular global radiation from various parameter like air temperature etc[4]. The author newly projected a straightforward model for evaluation of Mg on flat plane for sixty eight states of Turkey[5]. A model is presented with high aerosol to determine the monthly average hourly global radiation (I_g) by utilizing satellite data[6]. It is somewhat crucial to determine direct and indirect segments of total radiation fact on flat plane. When these segments are solved, it can be converted over tilted plane and thus PV module and other sun based devices can be evaluated. El-Sebaii introduced interaction for evaluating diffuse radiation by interacting (M_d/M_o), (M_d/M_g) and (L/L_{max}) in Egypt[7]. A new method is introduced by the author which might be utilized for evaluating M_b based on the elevation angle[8]. ANN-based satellite data were utilized to evaluate beam and indirect radiation in various town of Turkey[9]. Radiation occurrence on inclined plane comprises three parts: ground reflected, beam and diffuse radiation. Solar radiation directly gains on earth's plane is termed as direct radiation. Radiation attains on earth's surface after having been dispersed by particle in the earth's atmosphere is known as diffuse radiation. Energy of diffuse radiation is uniform over the sky is called isotropic model. While the anisotropic models assume that the energy of diffuse radiation is nonuniform over the sky.

The fundamental destination of this study are:

1. Evaluate the M_g, M_b, M_d on flat plane utilizing several experimental models in New Delhi location.
2. Determine M_T occurrence on inclined plane at tilt angle 28.58° N using six chosen experimental models.
3. Analyze every model with estimated and measured data using five statistical test formula.

Nomenclature

M_g: Monthly average daily global radiation on a horizontal surface
C: Solar constant =1.367 kW/m^2
P: Day of the year
M_o : Monthly average daily extra-terrestrial radiation fall on a horizontal surface
a_1, b_1: Angstrom constants (New Delhi a_1 = 0.26, b_1 = 0.05)
L: Monthly average daily hours of bright sunshine (hours)
L_{max}: Monthly average of the maximum possible daily
hours (day length) of bright sunshine
M_d: Monthly average daily defused radiation
C_l : Monthly average clearness index
M_T : Total incident solar radiation on tilted surface
$M_{T,b}$: Tilted surface beam radiation
$M_{T,d}$: Tilted surface diffuse radiation
$M_{T,r}$: Tilted surface ground reflected radiation
M_b: Monthly average daily beam radiation on horizontal surface
T_b: View factor for beam radiation
M_{gm}: Metrological ground measured global solar radiation at horizontal surfaces
M_{gmt}: Metrological ground measured tilted global solar radiation (kWh/m^2-day)
HD: Hay and Davies Model
BA: Badescu Model
LJ: Liu and Jordan Model
KO: Koronakis Model
RE: Reindl et al. Model
HDKR: Hay and Davies, Klucher Model
D: Anisotropy index

Material and method

About New Delhi location

The latitude, longitude and altitude of New Delhi is 28.61oN, 77.21o E and 216 m. The atmosphere of New Delhi is sweltering summer and dry winter. The normal climate is 30°C and 40 °C during May. The overall rainfall of the city is below 1200mm.

Solar radiation on horizontal Surface

The Mo is expressed by given equation

$$M_0 = \frac{24}{\pi} C\left(1 + 0.033\cos\frac{360P}{365}\right) \times \left(\frac{\pi\mu_s}{180}\sin\varphi\sin\lambda + \cos\varphi\cos\lambda\sin\mu_s\right) \quad (1)$$

The declination angle (λ) is calculated from the below equation[10]

$$\lambda = 23.45\sin\frac{360}{365}(284 + P) \quad (2)$$

Where P is total no of day as appear in Table 1.

The sunshine hour angle (μ_s) is determined by[11]

$$L_{\max} = \left(\frac{2}{15}\right)\mu_s \text{ , } \mu_s = \cos^{-1}(-\tan\lambda\tan\varphi) \quad (3)$$

Table 1. Total number of days corresponding to month[12]

Months	Days (P)
Jan.	15
Feb.	46
Mar.	75
Apr.	106
May.	136
Jun.	166
Jul.	196
Aug.	227
Sept.	258
Oct.	288
Nov.	319
Dec.	349

The M_g is given by[13]

$$\frac{M_g}{M_0} = a_1 + b_1\left(\frac{L}{L_{\max}}\right) \quad (4)$$

The L_{max} can be calculated:

$$L_{\max} = \left(\frac{2}{15}\right)\mu_s \quad (5)$$

The M_d is determined by:

$$\frac{M_d}{M_g} = 1.411 - 1.696\left(\frac{M_g}{M_0}\right) \quad (6)$$

Global radiation is obtained by adding diffuse and beam radiation. So, Beam radiation is expressed as

$$M_b = M_g - M_d \quad (7)$$

Solar radiation on inclined plane

The M_T is given as:

$$M_T = M_{T,b} + M_{T,r} + M_{T,d} \quad (8)$$

Beam radiation ($M_{T,b}$)

The radiation on tilted surface is given by:

$$M_T = M_b T_b \quad (9)$$

M_b is calculated by equation 7. The value of R_b is calculated by:

$$T_b = \frac{\sin\lambda\sin(\varphi-\alpha) + \cos\lambda\cos(\varphi-\alpha)}{\sin\lambda\sin\varphi + \cos\lambda\sin\varphi\cos\mu} \quad (10)$$

Where μ is the hour angle and α is the inclination of tilted surface (degree).

Reflected radiation ($M_{T,r}$)

The radiation reflected from earth's surface is called reflected radiation. It ($M_{T,r}$) can be obtained from below equation:

$$M_{T,r} = M_g\eta\left(\frac{1-\cos\alpha}{2}\right) \quad (11)$$

Where η is the constant (ground reflectance). Here consider η = 0.2 which is most commonly used for hot location[14].

Diffused radiation ($M_{T,d}$)

After scattering the radiation gained at the earth's plane from entire parts of the sky in the atmosphere is called diffuse radiation. Condition of cloudiness and atmospheric clearness is the function of this radiation which are extremely unpredictable. Horizon brightening, isotropic and circumsolar are the three components of this radiation.

Anisotropic and Isotropic models

The models are categorized as anisotropic and isotropic sky models. For this, six models were picked, and their outcomes were analyzed for choice of correct and fitting model for this territory. Three isotropic models to be specific BA (2002), LJ (1960)[15] and KO (1986)[16] and three anisotropic models to be specific HDKR (2006), HD (Hay 1980)[17] and RE (1990)[18] model were explored.

A short portrayal of the anisotropic and isotropic models chose for correlation of evaluated results is given underneath:

LJ model

Here horizontal brightening and circumsolar were considered as zero. The complete expression for calculating M_T is given below:

$$M_T = M_b T_b + M_g \eta \left(\frac{1-\cos\alpha}{2}\right) + M_d \left(\frac{1+\cos\alpha}{2}\right)$$

KO model

For this model the M_T will be

$$M_T = M_b T_b + M_g \eta \left(\frac{1-\cos\alpha}{2}\right) + M_d \left(\frac{2+\cos\alpha}{3}\right)$$

BA model

The M_T for this model is shown below:

$$M_T = M_b T_b + M_g \eta \left(\frac{1-\cos\alpha}{2}\right) + M_d \left(\frac{3+\cos 2\alpha}{4}\right)$$

HD model

The M_T on an inclined plane is given as follows.

$$M_T = (M_b + M_d D) T_b + M_g \eta \left(\frac{1-\cos\alpha}{2}\right) +$$
$$M_d \left(\frac{1+\cos\alpha}{2}\right)(1-D) + A T_b$$

Where D is anisotropy index, is expressed as

$$D = \frac{M_b}{M_0}$$

RE model

Their proposed model is given underneath:

$$M_T = (M_b + M_d D) T_b + M_g \eta \left(\frac{1-\cos\alpha}{2}\right) +$$
$$M_d \left\{ (1-D) \times \left(\frac{1+\cos\alpha}{2}\right) \left[1 + \sqrt{\frac{M_b}{M_g}} \sin^3\left(\frac{\alpha}{2}\right) \right] + D T_b \right\}$$

HDKR model

This model is partner with HD, Klucher and RE models. The model is given underneath:

$$M_T = (M_b + M_d D) T_b + M_g \eta \left(\frac{1-\cos\alpha}{2}\right) +$$
$$M_d \left\{ (1-D) \times \left(\frac{1+\cos\alpha}{2}\right) \left[1 + \sin^3\left(\frac{\alpha}{2}\right) \right] \right\}$$

Methods of models evaluation

Here Indian meteorological department data considered as measured data. Now, estimated global radiation on a flat and inclined plane is compared with measured data. For this, five statistical tests are used for comparison.

- Mean Absolute Percentage Error (MAPE)
- Mean Bias Error (MBE)
- Root Mean Square Error (RMSE)
- Root Mean Squared Relative Error (RMSRE)
- Relative Root Mean Squared Error (RRMSE)

These tests assess the exactness of the connections portrayed previously.

MAPE

This error is a symbol of precision which generally gives exactness as a percentage of the data. It might be communicated as:

$$MAPE = \frac{1}{m} \sum_{j=1}^{m} \left(\frac{V - V_p}{V}\right) \times 100$$

Where V is measured value, V_P is estimated Value, and m is the total number of Perceptions.

MBE

This error is given by:

$$MBE = \frac{1}{m} \sum_{j=1}^{m} \left(V_{pj} - V_j\right)$$

Where V_j is j^{th} measured Value, V_{pj} is j^{th} estimated Value

RMSE

This Error might be computed from the below expression:

$$RMSE = \sqrt{\frac{1}{m}\sum_{j=1}^{m}\left(V_{pj} - V_j\right)^2}$$

Where V_j is j^{th} measured Value, V_{pj} is j^{th} estimated Value

RMSRE

$$RMSRE = \sqrt{\frac{1}{m}\sum_{j=1}^{m}\left(\frac{V - V_p}{V}\right)^2}$$

PRMSE

This error is determined by dividing RMSE with mean value of measured data.

$$RMSRE = \frac{\sqrt{\frac{1}{m}\sum_{j=1}^{m}\left(\frac{V - V_p}{V}\right)^2}}{\sum_{j=1}^{m} V} \times 100$$

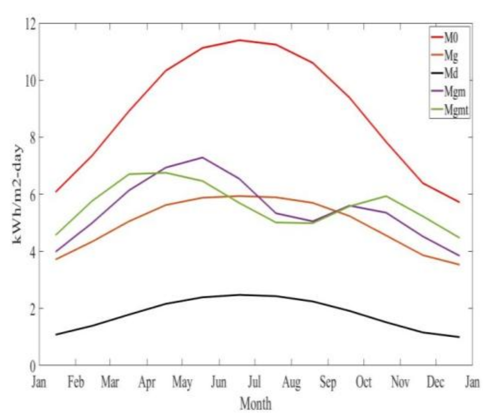

Fig. 1. Variety M_o, M_g, M_d, M_{gm} and M_{gmt} on horizontal surface at New Delhi

Result and Discussions

Solar radiation on horizontal plane

After calculation, the value of λ, μ_s, M_g and M_d is given in Table 2 and the variation of M_o, M_g, M_d, M_{gm} and M_{gmt} on horizontal surface are shown in Fig. 1. Mo is seen to be highest in June 11.395 and least in December 5.719 kWh/m^2-day. Mg is evaluated with the help regression constant for New Delhi (a_1 = 0.25 and b_1 = 0.50)[19].

Sky condition of New Delhi

The clearness index (C_I) is the parameter that demonstrates the straightforwardness of the environment and showed by division of extraterrestrial radiation that arrives at the earth's surface as global sunlight based radiation. C_I is characterized as $C_I = M_g/M_0$. C_I is determined from the estimated value of M_o and M_g. C_I, M_d/ M_o and M_d/ M_g for New Delhi appear in Fig. 2.

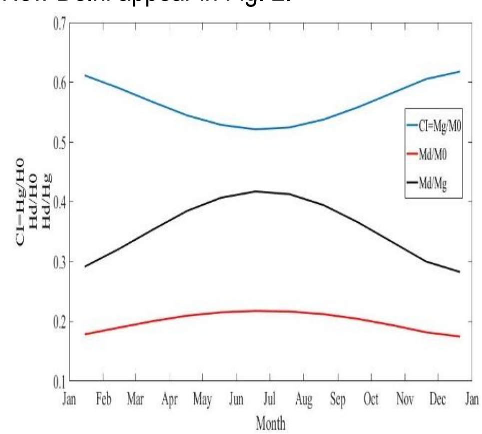

Fig. 2. Monthly variation of $C_I = M_g/M_o$, M_d/M_o and M_d/M_g at New Delhi.

Table 2. Value of λ, μ_s (degree), Mg and M_d (kWh/m^2-day)

Month	λ degree	μ_s degree	M_g(kWh/m^2-day)	M_d(kWh/m^2-day)
Jan.	-21.269	77.741	3.716	1.083
Feb.	-13.289	82.598	4.344	1.394
Mar.	-2.418	88.680	5.053	1.786
Apr.	9.783	95.397	5.623	2.163
May.	19.031	100.844	5.880	2.392
Jun.	23.314	103.596	5.938	2.477
Jul.	21.517	102.418	5.893	2.432
Aug.	13.784	97.688	5.699	2.247
Sept.	2.217	91.210	5.238	1.916
Oct.	-9.599	84.707	4.556	1.517
Nov.	-19.148	79.083	3.866	1.160
Dec.	-23.335	76.390	3.533	0.998

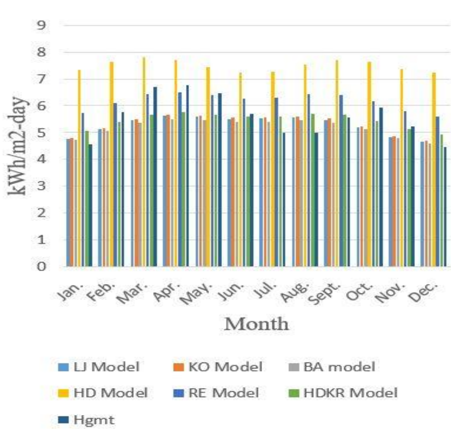

Fig. 3. Analysis of various models with M_T at New Delhi.

Variety of estimated solar radiation on inclined plane with various models

The observation declared that LJ, KO and BA model exhibited around same outcomes. RE and HDKR Model execute large value than LJ, BA and KO model as shown in Fig. 3. HD model showed the highest values among all models. BA exhibited the lowest value than all models. It was established from inspection that all models forecast higher incident solar energy irradiation on inclined plane (M_T) than on horizontal plane (M_g) because of the slope optimization. The value of M_T for six models are given in Table 3.

Table 3. M_T (kWh/m^2-day) by six models and measured data at New Delhi.

Month	M_{gmt}	LJ	KO	BA	HD	RE	HDKR
Jan.	4.57	4.78	4.80	4.72	7.35	5.72	5.06
Feb.	5.77	5.13	5.15	5.05	7.62	6.10	5.38
Mar.	6.7	5.46	5.49	5.36	7.79	6.42	5.67
Apr.	6.75	5.62	5.66	5.50	7.70	6.51	5.77
May.	6.46	5.58	5.63	5.46	7.42	6.39	5.68
Jun.	5.70	5.51	5.56	5.39	7.22	6.27	5.59
Jul.	5.01	5.52	5.57	5.40	7.28	6.30	5.61
Aug.	4.99	5.56	5.61	5.45	7.53	6.42	5.69
Sept.	5.58	5.48	5.52	5.38	7.70	6.42	5.67
Oct.	5.94	5.20	5.23	5.12	7.63	6.17	5.44
Nov.	5.23	4.85	4.87	4.79	7.38	5.80	5.12
Dec.	4.47	4.66	4.68	4.61	7.24	5.60	4.95

Statistical Analysis of models

The outcomes of this analysis are shown in Figs. 4–6. It tends to be seen from Fig. 4. MAPE for BA and HD models are 6.18% and -35.87% respectively while for different models: LJ 4.53%, KO 3.91%, RE −11.82% and HDKR Model 1.02%. MBE is less for HDKR and KO model. From fig 5, value of these two models are 0.1288 and 0.2838 kWh/m^2-day respectively. LJ and BA showed similar value with 0.319 and 0.411 kWh/m^2-day respectively. HD and RE Model scored 0.189 and 0.580 kWh/m^2-day MBE error. RMSE gives data on short term execution of the models. As appeared in Fig. 6, HD model provided the largest value 1.994 kWh/m^2-day of RMSE whereas HDKR creating a least RMSE 0.605 kWh/m^2-day which is closed to KO 0.658 kWh/m^2-day. Other models LJ, RE and BA Model values are 0.674, 0.815 and 0.723 kWh/m^2-day. From Fig.7, HDKR gives the lowest RMSRE error among the models and value is 0.104 kWh/m^2-day. LJ and KO model gives same values (0.109 and 0.108 kWh/m^2-day respectively). HD model gives the highest RMSRE error (0.393 kWh/m^2-day). From Fig.8, HDKR provides the least RRMSE error among the models and value is 1.858%. HD model scored the highest RRMSE error

(7.020%). Table 4 gives the Statistical Evaluation of six different models.

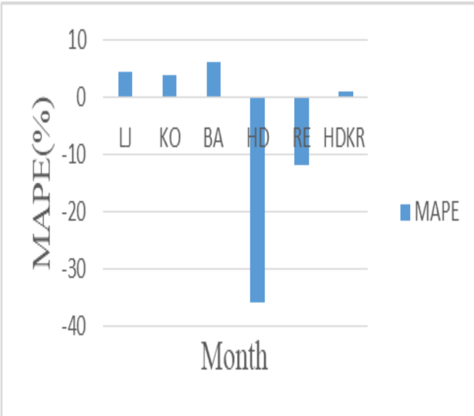

Fig. 4. MAPE for Six models

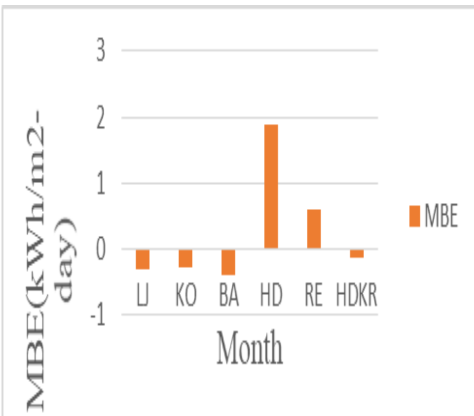

Fig. 5. MBE for Six models

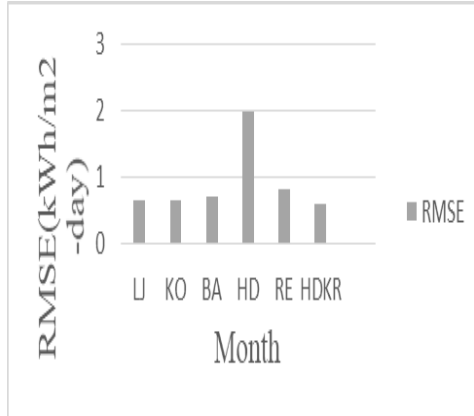

Fig. 6. RMSE for Six models

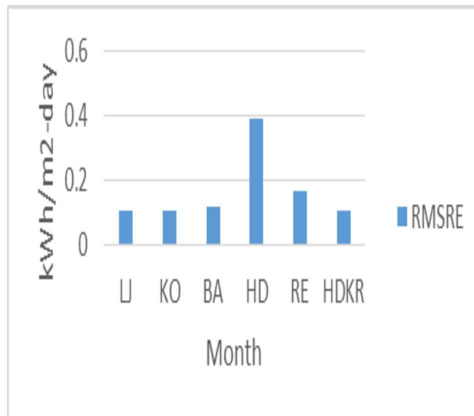

Fig. 7. RMSRE for Six models

Table 4. Statistical Evaluation of six models

Model	MAPE	MBE	RMSE	RMSRE	RRMSE
LJ	4.53	-0.319	0.674	0.109	1.954
KO	3.91	-0.284	0.658	0.108	1.929
BA	6.18	-0.411	0.723	0.116	2.072
HD	-35.87	0.189	1.994	0.393	7.020
RE	-11.82	0.580	0.815	0.165	2.947
HDKR	1.02	-0.129	0.605	0.104	1.858

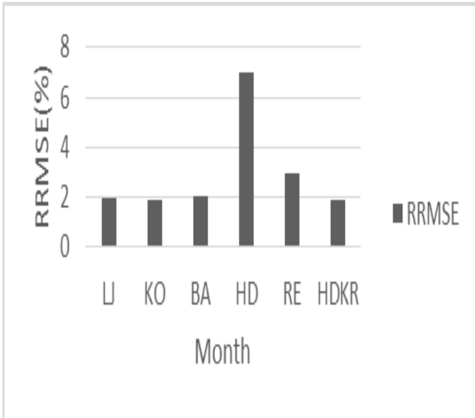

Fig. 8. PRMSE for Six models

Conclusions

The following outcomes are obtained from the analysis of six distinct models at an incline angle of 28.58° N (New Delhi latitude).

1. M_o, M_g and M_d were calculated to be 8.86, 4.94 and 1.8 kWh/m^2-day on horizontal plane respectively.
2. HD gave the highest and BA showed the least values of M_T among entire models.
3. LJ and KO model showed similar outcomes 5.28 and 5.31 kWh/m^2-day.
4. The outcomes of statistical analysis gave that HDKR provided smaller error among all six models.
5. HDKR evaluated radiation more near to the measured value and lowest errors. Subsequently, HDKR can be favored for the evaluation of solar radiation on the inclined plane in New Delhi.
6. These six models can be executed all over the nation where ground measured data is accessible. This can be utilized in solar photovoltaic applications in future.

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