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Modeling and Analysis of Latitude-Based Solar Radiation Models Suitable for Indian Cities

Sandhya S.[1], Narciss Starbell R.[2], Jims John Wessley G.[3]

[1]*PG student, Renewable and Energy Technologies*
[2]*Department of Electrical and Electronics Engineering*
[3]*Department of Aerospace Engineering*
Karunya University, Coimbatore, Tamilnadu, India

Abstract:* *This paper presents the analysis and comparison of six latitude-based solar radiation estimation models and to choose the suitable model for Indian cities. Three isotropic models proposed by Liu & Jordan, *Badescu and Koronakis and three anisotropic models given by Hay & Davies, Reindl and HDKR are used to estimate the monthly average daily solar radiation on tilted surfaces across eight prominent cities in India.* ***The solar radiation for each day is simulated for solar noon, while the tilt of the receiver is considered to be the same as that of the latitude of the city.*** *The estimated solar radiation using these models are compared w****ith the 22-year monthly averaged solar data obtained from the Surface Meteorology, Atmospheric science data centre, NASA. The anisotropic model based on Hay & Davies is found to be useful in the estimation of available solar radiation on a tilted surface across all Indian cities. The outcome of this study provides a framework to estimate the availability of solar energy across Indian cities for any latitude paving way for extensive research in solar energy utilization to make this freely available energy towards sustainable development.***

Keywords : **Anisotropic, Indian cities, Isotropic, latitude-based, solar radiation, Solar model**

1. INTRODUCTION

The oil and gas reserves of the world are estimated to be adequate to meet our rapidly increasing energy demands only for the next 40-50 years. Ardent efforts by the entire scientific community are now focused towards finding an alternate source of energy that could fill the demand gap. Solar energy is one of the promising and dependable renewable sources of energy obtained from nature which is safe and does not cause an untoward effect on the environment. Though the utilization of solar energy in the everyday application is not new ever since mankind started expanding, a very deliberate effort towards efficient harnessing, utilization and storage of this free energy is the need of the hour. Various researches over the past 50 years have been performed to effectively use solar energy in a variety of applications like heating and cooling of buildings, swimming pools, desalination, to power refrigerators and vehicles, to generate electricity and much more [1]. The enormous availability of the energy from the sun and its clean nature are the main advantages of solar energy while the economic feasibility is a small stumbling block which necessitates more research and developments to make this free energy a viable source towards sustained development of mankind.

2. SOLAR RADIATION ESTIMATION

The availability of solar radiation at any particular location has to be known in order to effectively design and implement solar-powered techniques and applications. Due to the variations in the availability of solar radiation with time and location, the intensity of solar radiation reaching a flat / tilted surface on the earth surface is a primary requirement for optimum design and study of solar energy conversion systems. The solar data for many places are available through Metrological measurements and satellite estimations. These data being accurate and precise however require large investment and are not available for all the locations of the world. For example, in India, the Global solar radiation is measured only at four work stations namely Delhi, Kolkata, Mumbai and Chennai [2]. Hence, it becomes essential to depend on empirical relations for the estimation of solar radiation based on the latitude of the location. Several empirical relations have been developed over the years by various researchers that are available for this purpose. But, it is also essential to pick up the best fitting model among the available ones which can be used to serve any particular purpose.

The mathematical models for the estimation of solar radiation on tilted surface is of two types namely Isotropic and anisotropic. The isotropic models assume that the intensity of diffuse sky radiation is uniform over the sky dome. Some of the isotropic models were given by Hottel and woertz, Liu and Jordan, Jimenz and castro, Koronakis, Tian et al and Badescu. All these methods assumed that the diffuse radiation is isotropic only and could estimate the solar radiation in a uniform sky scenario. In order to improve the accuracy of the isotropic models the anisotropic sky models were developed by various researchers by incorporating the contribution of circumsolar and horizon brightening components into the isotropic models [3]. The estimation of solar radiation using these methods normally yields higher values compared to the isotropic models. Some of the anisotropic models by Hay & Davies, Klucher, Temps & Coulson, Reindl et al, Perez et al, HDKR (Hay-Davies-Klucher-Reindl) are widely known and accepted anisotropic methods [4].

3. LITERATURE BACKGROUND

Some of the investigations on the solar radiation estimation models are presented below. The works of Abdul Qayoom Jakhrani et.al [3] presents the analysis and comparison of solar radiation estimation for Malaysian conditions comparing four models namely Liu & Jordan , HDKR, Klucher and Reindl et.al. The study shows that Reindl model predicted the maximum estimated solar radiation while Liu & Jordan the lowest radiation values. Less SEM (Standard error of the mean) was observed by klucher model, which is an anisotropic model, thus concluding that Klucher model suits best for Malaysian conditions. The works of Akhlaque et al (5) shows the total solar radiation estimated over Hyderabad, India and Sindh, Pakistan using the regression equation of Angstrom. It is observed that sunshine duration is above 70% throughout the year except July-August. The contribution of diffuse solar radiation is found to be very low about 25% throughout the year except during the monsoon months when it is around 40%. Al-Rawahi et al (6) modeled the hourly terrestrial radiation for horizontal and inclined surfaces for Muscat. The results based on isotropic reflection of diffuse radiation, shows that the optimum tilt during January is 40° towards south and for the summer season during June the horizontal orientation is seen to absorb more solar radiation.

4. ESTIMATION OF SOLAR RADIATION IN INDIAN CITIES

India is located in the South Asia that lies entirely on the Indian Plate in the northern portion of the Indo-Australian Plate. It is located to the north of the equator between 8°4' to 37°6' north latitude and 68°7' to 97°25' east longitude. The cities selected for the study are chosen such that they represent the entire stretch of the country between the latitudes 8°4' to 37°6' N. The isotropic models proposed by Liu & Jordan (1963), Badescu (2002) and Koronakis (1986) and anisotropic models given by Hay & Davies (1981), Reindl (1990) and HDKR ie Hay & Davies- Koronakis –Reindl (2006) are chosen for the study. The Indian cities analyzed in the present study are shown in Table 1.

Table 1. Indian cities analyzed and their location with chosen models

Cities	Trivandrum	Bangalore	Goa	Mumbai	Kolkata	Jaipur	New Delhi	Srinagar
Latitude(°N)	8.48°	12.96°	15.49°	18.97°	22.56°	26.92°	28.61°	34.09°

5. METHODOLOGY OF THE SIMULATION

The methodology for the estimation of solar radiation on a tilted surface is detailed below [7]. The inclination of the solar receiver is assumed to be the same as the latitude of the corresponding location. The solar radiation available during noon corresponding to the solar hour angle (ω=0) is estimated for each location for January 1 to December 31 (n=1-365). The declination (δ) is calculated as shown by Equation (1) as below.

$$\delta = 23.45 \sin (360 \text{ x } \frac{284+n}{365}) \quad (1)$$

where n = number of day in the year (1 to 365)

The sunset hour angle (ω_s) is estimated using the relation shown in Equation (2)

$$\omega_s = \cos^{-1} [-\tan(\varphi) \tan(\delta)] \quad (2)$$

where ϕ = Latitude of the location

Extraterrestrial radiation (H_o) which is the intensity of solar radiation outside the earth's atmosphere is estimated using the Equation (3) as given below.

$$H_0 = \frac{24*3600*G_{Sc}}{\Pi} * \left(1 + 0.033 \cos\frac{360*n}{365}\right)* \left[(cos\delta\, cos\phi\, sin\omega) * (\frac{\Pi\omega_s}{180}\ sin\phi\, sin\delta)\right] \quad (3)$$

The monthly average daily radiation on a horizontal surface (H) is given by the relation as in Equation (4)

$$H = H_0 \left[a' + b' \frac{\bar{n}}{N}\right] \quad (4)$$

where a' and b' are constants depending on the location
$\bar{n}$ = average daily hours of bright sunshine (7 hours)
N = Maximum daily hours of bright sunshine

The combination of diffuse and ground-reflected radiation is isotropic, the sum of diffuse from the sky and the ground-radiation on the tilted surface is the same regardless of the orientation.

Table 2. Diffuse components of the solar models

Solar Models	Diffuse component of solar radiation
Liu and Jordan (1963)	$H_d\left(\frac{1+\cos\beta}{2}\right)$
Badescu (2002)	$H_d\left(\frac{3+\cos 2\beta}{4}\right)$
Koronakis (1986)	$H_d\left(\frac{2+\cos\beta}{3}\right)$
Hay and Davies (1981)	$H_d\left(\frac{1+\cos\beta}{2}(1-A)+AR_b\right)$ where A = Anisotropy index = $\frac{H_b}{H_o}$
Reindle et.al (1990)	$H_d\left(\frac{1+\cos\beta}{2}(1-A)*(1+f\,sin^3\left(\frac{\beta}{2}\right)+AR_b)\right)$ where f = Modulating factor = $\sqrt{\frac{H_d}{H}}$
HDKR (2006)	$H_d\left(\frac{1+\cos\beta}{2}(1-A)*(1+f\,sin^3\left(\frac{\beta}{2}\right))\right)$

The diffuse component of the total solar radiation on a tilted surface as estimated by various models is shown below in Table 2.

A Matlab program is developed based on the above equations to estimate the daily average solar radiation on the tilted surface based on the chosen models for all the cities identified. The program is executed for each of the latitude of the cities for n=1 to 365 based on all the six models and the average solar radiation for each month is estimated. The estimated values are compared with the 22-year average maximum monthly solar radiation obtained from NASA SSE for the years from 1983 to 2005. In order to check the accuracy of the prediction and to figure out the best model suitable for Indian climatic conditions, Percentage Error is estimated as given in Equation (5).

$$\text{Percentage Error (PD)} = |X - \bar{X}| / X * 100 \quad (5)$$

6. RESULTS AND DISCUSSION

The variation of the Monthly average daily radiation estimated using various models for New Delhi are shown in Table 3.

Table 3. Variation of the estimated month average solar radiation of New Delhi

MONTHS / MODELS	NEW DELHI (28°38') MONTHLY AVERAGE SOLAR RADIATION IN Kwh/m^2					
	LIU & JORDAN	BADESCU	KORONAKIS	HAY & DAVIES	REINDL	HDKR
JAN	5.10	5.04	5.12	6.07	5.73	5.35
FEB	5.31	5.22	5.35	6.39	6.06	5.56
MAR	5.63	5.50	5.68	6.69	6.38	5.81
APR	5.83	5.68	5.89	6.77	6.51	5.93
MAY	5.84	5.67	5.91	6.65	6.44	5.88
JUN	5.80	5.62	5.86	6.54	6.35	5.81
JUL	5.79	5.62	5.86	6.57	6.36	5.82
AUG	5.80	5.64	5.86	6.68	6.44	5.87
SEP	5.66	5.53	5.71	6.67	6.38	5.82
OCT	5.35	5.24	5.39	6.44	6.11	5.58
NOV	5.14	5.08	5.17	6.13	5.78	5.39
DEC	4.99	4.94	5.01	5.93	5.59	5.25

It is seen that the maximum monthly average solar radiation estimated for New Delhi based on all the models is during the month of April and the minimum solar radiation is during the month of December. The maximum solar radiation estimated for New Delhi is 6.77 Kwh/m^2 and minimum is 5.59 Kwh/m^2 based on Hay and Davie model. A summary of the average solar data obtained using the chosen models and NASA SSE are shown in Table 4. It is evident from the table that the solar radiation estimated by all the isotropic models and the anisotropic model based on HDKR predicted almost similar values whereas the values predicted by the other two anisotropic models Hay Davies and Reindl are little higher. The average values of solar radiation estimated for Trivandrum using Liu Jordan, Badescu, Koronakis and HDKR ranges from 5.95 to 5.96 Kwh/m^2 whereas the solar radiation estimated using Hay Davies and Reindl ranges from 6.54-6.44 Kwh/m^2. Hence, the values predicted by Hay Davies and Reindl are 8.8 to 12.8% higher than the solar radiation estimated using other models in this study for New Delhi. Almost similar results are obtained for all the cities analyzed.

Table 4. Summary of the average solar radiation based on chosen models and SSE

INDIAN CITIES	ESTIMATED YEARLY AVERAGE RADIATION (Kwh/m^2)						NASA SSE (Kwh/m^2)
	ISOTROPIC MODELS			ANISOTROPIC MODELS			
	LIU JORDAN	BADESCU	KORONAKIS	HAY DAVIES	REINDL	HDKR	
TRIVANDRUM	5.95	5.93	5.95	6.84	6.54	5.96	6.44
BANGALORE	5.45	5.42	5.47	6.25	6.04	5.49	6.10
GOA	5.69	5.65	5.71	6.58	6.31	5.74	6.58
MUMBAI	5.79	5.72	5.81	6.72	6.42	5.86	6.68
KOLKATA	4.99	4.90	5.03	5.75	5.58	5.08	5.57
JAIPUR	5.62	5.51	5.67	6.58	6.28	5.76	6.25
NEW DELHI	5.52	5.40	5.57	6.46	6.18	5.67	6.41
SRINAGAR	5.39	5.23	5.45	6.38	6.09	5.60	6.20

To compare the estimated and NASA values the Percentage Error between these two values is estimated. The percentage error of values estimated using Hay and Davies model is seen to be the minimum for all the cities in this study except for Trivandrum and Srinagar. In these two cities the Reindl model has the lowest values of percentage error. A comparison of the percentage errors of Hay Davies and Reindl models for Trivandrum and Srinagar shows that the variation is very less ranging from 0.26% to 1.45%. Hence it is evident from the study that Hay Davies model is found to be the suitable model for solar radiation estimation in Indian cities.

7. CONCLUSIONS

The isotropic models based on Liu & Jordan, Badescu and Koronakis and anisotropic models by Hay & Davies, Reindl and HDKR were used to estimate the monthly average daily solar radiation on tilted surfaces in eight cities namely Trivandrum, Bangalore, Goa, Mumbai, Kolkata, Jaipur, Srinagar and New Delhi across India. The following conclusions were obtained.

1. The Isotropic models predicted lower solar radiation values up to a maximum of 12% when compared to the anisotropic models used in the study.
2. The anisotropic model suggested by HDKR also estimated lower values similar to the other isotropic models in the analysis for the Indian cities in this present study.
3. The percentage error of values estimated using Hay and Davies model is seen to be the minimum for all the cities in this study except for Trivandrum and Srinagar where there is a difference in the marginal in the range of 0.26% to 1.45%.
4. Hence it may be concluded from the study that, Hay & Davies model is found to be the suitable model for solar radiation estimation in Indian cities.

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