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SOLAR RADIATION ON INCLINED SURFACES IN LAGOS, NIGERIA

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ABSTRACT

The empirical study evaluates the estimation of monthly average irradiation models, using hourly measurements of total solar irradiation on a surface tilted at 7 degrees and oriented south in Lagos. Three direct solar radiation models, The sky diffuse submodels and one ground-reflected radiation are used with two albedo submodels. The combination of these models were evaluated to estimate the global irradiation on the tilted surface from the measured direct-normal and the global solar radiation on a horizontal surface. Root Mean Square Error (RMSE) and Mean Bias Error (MBE) were used to determine the rank of the models. The Perez 25° circum-solar simplified model for sky diffuse and combined r_b + Perez 25° model, with r_b model for direct radiation are found to have the best overall performances. There is no significant difference in the performance of the sky diffuse models when varying the albedo submodels.

1. INTRODUCTION

The knowledge of incident solar radiation on inclined surfaces are some of the most basic data needed in solar technology. The data of irradiation generally available are those of daily global irradiation on horizontal surfaces. Therefore, estimation methods are required to compute both hourly and daily values of irradiation on inclined surfaces. The flux of radiation incident on an inclined surface consists of that due to the direct solar radiation, diffuse skylight and the radiation reflected from the ground which is incident on the inclined plane. In order to compute the monthly averages of hourly and daily radiation on an inclined surface it is then necessary to separate the diffuse component from the total horizontal radiation. Numerous models have been developed to predict radiation on inclined surfaces from measurements on a horizontal. The difference among these models appears in the assessment of the sky-diffuse component. The most widely used method is the one by Liu and Jordan which uses the simplifying assumption of isotropic distribution of the diffuse radiation which is independent of the Zenith and Azimuth angles.

Perez et. al. (2) is an isotropic model which accounts for the circum-solar radiation, Horizon brightening and the isotropically radiances originating from the main portion of the dome.

Hay (3) considers the anisotropic distribution of the diffuse radiation by accounting for the circum-solar radiation and the isotropically distributed component coming from the rest of the sky dome.

Klucher (4) takes into account the anisotropic distribution of diffuse radiation by taking into account the circum-solar radiation and the horizon brightening and others, to calculate total radiation on inclined surfaces from measurements on a horizontal surface.

Measurement of solar radiation data on inclined surfaces are not available for most of the locations in Nigeria and have to be estimated from the theoretical models. Different mathematical correlations are available in the literature for estimation purposes one has to decide which one of these correlations can be applied accurately to locations in the region.

The object of this study is to select 3 direct solar radiation, 10 sky-diffuse radiation models and 2 ground reflected radiation models associated with different albedo models; a constant reference mean value of 0.2 and anisotropic albedo model dependent on the solar Zenith angle. These three components are then combined to predict monthly mean radiation on inclined surfaces. The comparison of the models with measurement of total solar irradiance on inclined surface facing south is done for the first time in Lagos.

2. THE DATA

Hourly radiation data (global and beam) with global irradiation on tilted surface of 7° facing south were measured, for the year 1992 to 1993 at a site in the University of Lagos, located within the Lagos metropolis. The normal incidence beam radiation is measured using an Eppley normal incidence pyrheliometer. The total and diffuse components on the tilted surface are measured with Eppley Pyranometer with a shade ring to eliminate beam radiation. A middleton pyranometer and recorder were used for the global radiation. Thus, 12,045 data were obtained, only

6,556 data points were used. The data points dropped either had no diffuse component for that hour, or violated the physical limits given by Reindl et al. No albedo data are available for this period.

3. *MODELS OF ESTIMATION*

The total solar radiation received on a tilted surface (H) may be expressed as

$$H_T = H_B + H_S + H_R \qquad (1)$$

where H_B = Beam solar radiation on the tilted surface

H_S = Sky-diffuse radiation on the tilted surface

H_R = Ground-reflected radiation on the tilted surface.

3.1 A model for monthly average of ground reflected Radiation on tilted surfaces

The grounds reflected irradiation varies according to the angle of the sun at its Zenith and the sky-diffuse radiation as a proportion of global radiation. Since there is no measured data for the reflected radiation, the ground reflected model is used, which is defined as

$$H_R = HP\, R_d \qquad (2)$$

where *P* is the ground albedo.

$R_d = (1-\cos\beta)/2$ is the configuration factor between ground and the receiver plane. β is the angle of tilt in degrees and *H* is the global irradiation on the horizontal.

Two expressions for the albedo are considered in this study,

1. Isotropic constant model; this is the most commonly used albedo estimate with a constant value of 0.2, (P = 0.2).
2. Climatological anisotropic model; Developed by Nkemdirim (6) and Arnfield (13), this model expresses the albedo as a function of the solar Zenith angle

$$P = a\exp(b\,\theta_z)$$

where a = 0.244 and b = 0.00891 deg^{-1} for afternoon hours for any day of the year.

3.2 Models for Monthly Averages of the Direct Solar Radiation

1. The model

This model predicts the daily hourly direct solar radiation for an inclined surface from direct radiation on a horizontal surface;

$$H_B = \sum^{day} (I-I_d)r_b;\; r_b = \frac{\cos\theta}{\cos\theta_2} \qquad (4)$$

where θ is the incidence angle and is the solar Zenith angle of the solar rays onto the tilted surface, *I* and I_d are the hourly global and diffuse solar radiation on a horizontal surface.

Equation (4) gives accurate results when it is used with daily summation of hourly radiation.

2. The R_b Model

The model is expressed as $H_B = (H-H_d)\, R_b$

R_b is the ratio of average beam radiation on the tilted surface to that on a horizontal surface for each month.

For surfaces facing toward the equator the equation for is given as (1).

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\sin W_s^{1} + (\pi/180)W_s^{1}\sin(\phi-\beta)\sin\delta \;(6)}{\cos\phi\sin\delta\sin W_s + (\pi/180)W_s\sin\phi\sin\delta)}$$

$$W_s^{1} = \text{Min}\,(W_s, \text{ar}\cos(-\tan(\phi-\beta)\tan\delta) \qquad (7)$$

min means the minimum of the two terms in the bracket.

3. The weighted R_b model

Sinmonson (7) used the weighted R_b model instead of R_b in equation (5), in an attempt to correct the assumption made in model (2), also

$$H_B = (H - H_d)\, R_b^{1} \qquad (8)$$

$$R_b^1 = \sum^{day} (\cos\theta / \cos\theta_z) I / \sum^{day} I \quad (9)$$

where H and H_d are the monthly average global diffuse and diffuse radiation on a horizontal surface.

3.3 Models for Monthly Average of the Sky-Diffuse Component on Inclined Surface

The distribution of sky-diffuse radiation on inclined surface can be expressed in two ways. The first uses the simplifying assumption of isotropic distribution of the diffuse radiation, which is independent of the Zenith and Azimuth angles and the second is the anisotropic distribution of the diffuse radiation by taking it to be composed of a circum-solar radiation plus an isotropically distributed component coming from the sky dome.

Of the ten models evaluated, Liu and Jordan method belongs to the isotropic type and the others to the anisotropic one. The monthly averages hourly and daily radiation are used as input data for the ten models.

Bugler (8) Model

This model makes the assumption that circumsolar radiation accounts for 5% of direct radiation on a horizontal surface and that the remaining sky diffuse radiation is uniformly distributed throughout the sky. His model is represented by the following equation:

$$H_b^1 = \sum^{day} (I_d - 0.05 I_b / \cos\theta) R_d + 0.05 I_b \cos\theta \quad (10)$$

Klutcher (4) Model

Klutcher introduced a partly overcast conditions by a factor. $F = I_d / I$. Under completely overcast conditions, $F = 0$ while under clear skies, the value of F is close to 1. It is expressed by the following equation:

$$H_s = \sum^{day} (I_d R_b (1 + F\sin^3(\beta/2))(1 + F\cos^2\theta \sin^3\theta_z) \quad (11)$$

$$F = 1 - (I_d / I)^2$$

Hay (3) Model

This model assumes that a certain proportion of total sky-diffuse radiation is circumsolar radiation, and that the remainder is distributed uniformly throughout the sky

$$H_s = \sum^{day} I_d (k_b \cos\theta / \cos\theta_z + (1 - k_b) R_d) \quad (12)$$

$$k_b = (I - I_d) / I_0 \quad (12a)$$

where I_0 is the extraterrestrial radiation on a horizontal surface.

Skartveit-Olsetz (9) Model

They assumed that under cloudy skies, 30% of the horizontal sky-diffuse irradiance which reaches the earth's surface is due to collimated radiation from the zenith, the remaining 70% being uniformly distributed throughout the sky, and that the value of proportion of diffuse solar radiation from the zenith (z) decreases rapidly when the amount of cloud in the sky decreases. Their model is expressed as follows:

$$H_s = \sum^{day} I_d (k_b \cos\theta / \cos\theta_z + z\cos\beta + (1 - k_b - z) R_d) \quad (13)$$

$$z = 0.3 - 2k_b \quad (13a)$$

Temps and Coulson (10) Model

This model has been developed for clear sky and expresses the maximum intensities of the diffuse radiation near the sun and near the horizon:

$$H_s = \sum^{day} I_d (1 + \cos^2\theta \cos^3\theta_z) + (1 + \sin^3(\beta/2) R_d) \quad (14)$$

Gueymard (11) Model

Consider that the irradiance for partially cloudy skies is a linear combination of values for overcast skies R_{d1} and for clear skies R_{d0}.

$$H_s = \sum^{day} I_d ((1 - N) R_{do} + N R_{d1}) \quad (15)$$

where N is the cloud opacity, for situation in which no coincident cloud opacity information is available: max(min(Y,1), 0)

$$N = \max(\min(Y, 1), 0) \quad (16)$$

where Y is a function of I_d / I.

Y has been obtained by Gueymard from Montreal data and is given by

$$Y = 6.6667\ (I_d / I) - 1.4167 \tag{17}$$

If $I_d / F \leq 0.227$; otherwise,

$$Y = 1.2121\ (I_d / I) - 0.1758 \tag{18}$$

The clear sky's irradiance R_{do} is given by sum of a circumsolar and a hemispherical term.

$$R_{do} = \exp(a_o + a_1 \cos\theta + a_2 \cos^2\theta + a_3 \cos^3\theta) + F(\beta)\ G(Y) \tag{19}$$

a_i being functions of Y. The overcast sky irradiance R_{di} depends on the plane tilt-angle and on a correction factor b $(1.0 \leq b \leq 2.0)$ and is given by

$$R_{dI} = R_d - (\pi^{-1}(\beta\cos\beta - \sin\beta) + {}^1/_2(1-\cos\beta) / (1+3/2b)) \tag{20}$$

Muneer's (12) Model

$$H_s = \sum^{day} I_d T \tag{21}$$

for surfaces in shade and sunlit surfaces under overcast sky, and

$$H_s = I_d (T(1\text{-F}) + F\cos\theta / \cos\theta_z) \tag{22}$$

for surfaces under non-overcast sky, where

$$T = R_d + N_1 N_2 \tag{23}$$

$$N_1 = 0.00263 - 0.7120 - 0.6883\ F^2 \tag{24}$$

$$N_2 = \sin\beta - \beta\cos\beta - \pi\sin^2(\beta/2) \tag{25}$$

$$F = (I - I_d)\cos\theta_z / H_0 \tag{26}$$

Isotropic (1) Model

Assuming direct and diffuse radiation to be isotropic, Liu and Jordan (1) have proposed the following correlation

$$H_s = \sum^{day} I_d R_d \tag{27}$$

Reindl's (22) Model

$$H_s = \sum^{day} I_d ((k-d_b) R_d (1 + F\sin^3(\beta/2) + k_b R_b)) \tag{28}$$

where K_b is defined as in equation.(12a)

Perez (23) Model

Perez model divides the sky dome into three different zones, each one with a characteristic diffuse irradiance, a horizon zone, a circumsolar and an isotropic zone. The horizon zone is considered of zero width and the circumsolar zone alternatively 0^0 (point source) or 25^0 wide to simplify the evaluation of and . For the point source circumsolar model we obtain

$$H_s = \sum^{day} I_d (R_d (1-F_1^1) + F_1^1(\cos\theta / \cos\theta_z) + F_2^1 \sin\beta) \tag{29}$$

where and are expressions for the circumsolar and horizon brightening effects. The 25^0 circumsolar Perez model is less simple but more accurate. Both versions have been applied in this paper.

4. STATISTICAL METHOD

The statistical test root mean square error and the mean bias error were used to evaluate the accuracy of the 3 direct solar radiation, 10 sky-diffuse radiation models times two albedo submodels, and combination of these three components.

$$\text{RMSE} = \left(\sum_{i=1}^{N} (X_i - X_{0i})^2 / N\right)^{1/2} / X_o \times 100 \tag{30}$$

$$\text{MBE} = \sum_{i=1}^{N} (X_i - X_{0i}) / N / X_o \times 100 \tag{31}$$

X is the predicted value. X_0 is the measured value, N is the number of data points, i is the number given to an item of data.

The RMSE is the error in the individual predicted values obtained from the models, as compared with the measured values and is expressed as a percentage. The MBE is the average difference between the predicted and measured values. The error is expressed as a percentage of the predicted value.

5. RESULTS AND DISCUSSION

5.1 OVERALL ASSESSMENT

1. The direct component models

The r_b model is the best, the weighted R_b and the R_b models are inferior to the r_b model.

2. Sky diffuse and ground reflected radiation models

Table 2 gives the RMSE and MBE for the 10 models as estimated form the hourly values. From this, it is seen that the RMSE is in the range of 0.026 to 0.83 and MBE -0.003 to 3,192 for all sky diffuse albedo submodel combinations.

In terms of the statistical estmators RMSE and MBE only the Perez (25^0 and 0^0 circumsolar); Skartveit-Olseth and Klutcher models improve the isotropic model. The largest RMSE and MBE obtained with Gueymard, Temps-Coulson's Bugler and Reindl performs worse than the isotropic model, while there is no improvement of Hay's model over the isotropic. The best is Perez 25^0 model with the two statistics exhibiting consistently lower values for the two albedo submodels than those of the isotropic model. Demonstrating its increased precision for the description of the diffuse component.

Table 3 shows the evaluation of the sky diffuse model using the R_b and weighted R_b, MBE values show that Bugler, Hay, Skertveit, Klutcher, isotropic and Reindl under-predict the sky diffuse radiation while Muneer over-estimates the sky diffuse model. All models have their MBE values lower than 1%. On the basis of RMSE and MBE all models except Klutcher improve on the isotropic values.

The (r_b + Perez 25^0) model was the best for models of total irradiation on inclined surface. The two relevant statistics exhibiting consistently lower value than the isotropic.

Table 1. Evaluation of Root Mean Square Errors (RMSE) and Mean Bias Errors (MBE) in percent of the measured average tilted irradiation for the 10 sky diffuse submodels and two albedo submodels.

Model	RMSE	MBE
Bugler	0.3270.336	-0.004-0.004
Klutcher	0.3310.280	-0.004-0.004
Hay	0.3280.331	-0.004-0.004
Skartveith-Olseth	0.3080.316	-0.004-0.004
Temp's and Coulson's	0.2800.260	3.5113.192
Gueymard	0.8010.803	-0.010-0.010
Muneer	0.5100.530	-6.253-6.562
Isotropic	0.3280.331	-0.004-0.004
Reindl	0.3910.394	-0.005-0.005
Perez 0^0	0.2270.230	-0.003-0.003
Perez 25^0	0.2030.205	-0.003-0.003

Table 2. Evaluation of direct component models

	Model	RMSE	MBE
	Bugler	0.328	-0.004
	Klutcher	0.332	-0.004
	Hay	0.329	-0.004
	Skartveith-Olseth	0.309	-0.004
	Temp's and Coulson's	0.275	-0.010
	Gueymard	0.8017	-0.010
	Muneer	0.515	-0.063
	Isotropic	0.329	-0.004
	Reindl	0.392	-0.005
	Perez 0^0	0.228	-0.003
	Perez 25^0	0.204	-0.003
	Bugler	2.691	-0.091
	Klutcher	2.923	-0.098
	Hay	2.673	-0.090
Weighted	Skartveith-Olseth	2.757	-0.093
	Isotropic	2.903	-0.098
	Muneer	2.448	-0.082
	Reindl	2.904	-0.098
	Bugler	2.646	-0.089
	Klutcher	2.846	-0.096
	Hay	2.640	-0.088
	Skartveith-Olseth	2.693	-0.091
	Isotropic	2.846	-0.096
	Muneer	2.845	-0.096
	Reindl	2.847	-0.099

6. CONCLUSION

The Perez (25⁰) model may be used to obtain sky diffuse submodels and (+ Perez 25^0) describes the irradiance on inclined planes more accurately than some other models designed, and therefore may be used to predict monthly average radiation on inclined surface in Lagos. The result presents strong indication that the Perez model is more accurate than any other model for any climatic conditions. The model is recommended for the estimation of beam radiation due to its smaller mean bias errors. Most of the surface used for the evaluation were south facing surfaces, for East or West. Facing surfaces the result may be different. Further work will be necessary for evaluation of various sky diffuse models, this could be achieved by considering more tilt, possible measurement of ground albedo and reflected radiation measurements.

Utrillas et al. (13) shows that the Perez 25^0 model gives the more accurate result.

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