Comparative Analysis of Anisotropic Sky Models and Experimental Data in Estimating Solar Radiation on Tilted Surface in Sub Saharan Africa Climate

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Abstract

Comparative analysis of Anisotropic Sky models and measured data in search of a decision support tool in estimating solar radiation on tilted surface is presented. The study investigates the case of a typical sub-Saharan African municipality climate, in South East Nigeria. In the experiment, the solar radiation on a solar energy surface tilted to 15^o and facing southwards was measured with a solarimeter. A second solarimeter was employed to measure solar radiation on horizontal surface. The experiment was conducted during October, 2016 to March, 2017. The anisotropic sky models considered were Perez model as well as Hay, Davies, Klucher and Reindl (HDKR) models. Full analysis of the models with the experimental data was implemented using Scilab computational software, version 5.2.2. The performance criteria for the studied models were based on selected standard statistical error indices, including mean bias error (MBE), root mean square error (RMSE) and mean absolute percentage error (MAPE). The results show that Perez model recorded the least MBE of - 0.005Wh/m^2, least RMSE of 0.0147Wh/m^2 and least MAPE of 0.9587Wh/m^2 than HDKR model. The study reveals that Perez model can be utilized as a good means of estimating solar radiation on tilted surfaces in the studied location.

Keywords: Solar radiation estimation, renewable energy, anisotropic sky models, experimental data

1. Introduction

Availability of Solar radiation data (SRD) is valid not only in promoting solar energy applications, but more importantly in maintaining reliable solar energy system data inventory for energy generation and development as well as environmentally friendly solar energy usage. Prohibitive cost of devices used to collect data for solar radiation on inclined solar collectors and environmental logistics can hinder timely data acquisition for such scenario, especially in technologically less developed countries (TLDC). Solar energy parameters changes with both changes in location and seasonal variations and requires a careful location based analysis to deduce appropriate method for representative data gathering for design and other applications. To optimize the solar radiation (SR) that can be captured by solar radiation collectors, solar conversion systems can be tilted towards the sun at specified angles. The importance of optimal tilt angle has spurred more work aimed at obtaining accurate data for specific solar energy applications. Dedicated significant research effort in chronicling efficient techniques and procedures applied, in recent presentations, on the design considerations, simulations and mathematical methodologies of obtaining tilt angles in various solar energy applications (Hafez et al. 2017). Various techniques can be employed to analyse the diffuse radiation distribution in the sky.

The traditional method of drawing inference from horizontal surface radiation through the use of empirical models is still practiced (Jakhrani et al. 2013). This has spurred more work on investigating the applicability of sky models in estimating SRD for specific locations (Demain et al. 2013, Jamil et al. 2016, Rossi et al. 2018). A proof of concept theoretical model was built and employed to ascertain the anisotropic diffuse radiation on inclined surfaces. Instantaneous diffuse radiation data obtained by 30^0, $45^{\ 0}$ and 60^0 were relied upon to compute the radiation enhancement coefficients in the developed mod. The model compared well with existing models while attributing higher accuracy to Perez and NADR model over Liu and Jordan model for East and North orientations respectively. For the West and South orientations, Liu and Jordan model had more accurate point to point comparison over the Perez model. The result indicates that on a global comparison, NADR model is more accurate than all other models considered (Yao et al. 2015).

Comparisons of anisotropic sky models for irradiance estimation had been implemented in the past, a good example of such study is the building facades in Beijing China. The authors conclude that Iwaga model performs better than six others tested (Li, et al. 2017). Elsewhere, the suitability of selected SR models for approximating global SR on sloping exterior surface was examined. The one-sample statistical test used to evaluate the models led to recommending Klucher model over others (Jakhrani et al., 2011). Other investigative model comparison in estimation of SR for tilted surfaces in various locations of the World are found in literatures (Shukla et al. 2015, Hameed et al. 2017). Despite existence of vast research outputs on solar radiation data acquisition techniques, many developing countries are still grappling with paucity of solar energy data in several locations, to which recent researchers have attributed to high cost of measurement and instrumentation required for reliable solar radiation data collection (Olomiyesan et al., 2017). The implication is that SRD on tilted surfaces for various orientations continues to be scarce in technologically less developed countries of which sub-Saharan Africa is a typical example. This paper attempts to address the situation using the case of Nsukka, South East Nigeria. The municipality experiences all possible climatic conditions representative of Sub Sahara Africa. There is no report or existence of such presentation for known to the authors. A simple model was used in estimating hourly global solar radiation under clear sky condition in Iraq (Al-Jumaily et al., 2012).

2. Materials and Methods

The experimental setup for the SRD collection is shown in figure 1. The case study region-Nsukka is located in Eastern Nigeria (Latitude 6.8º North and Longitude 7.35º East). In its construction, a rigid horizontal reinforced concrete flat slab receives adjustable horizontal and tilted surfaces. The navigating compass as well as two solarimeters and two solarimeter sensors close coupled to the horizontal and tilted surfaces which is inclined at 15^0 to the horizontal, are both coupled to a wooden support base. There is a spirit level used to ensure convenient alignment of the horizontal surface. The compass is basically used to select and maintain a desired polarity of the inclined surface. That is; Northwards or Southwards. The connection of solar sensors to two Kimo SAM 20 solarimeters in the experimental set up made the measurement of the solar radiation at the two surfaces seamless. The two readings are collected daily between 9am and 5pm at 10 minutes' interval with the aid of a data logger. The period of the experimental data collection lasted for six months. Specifically, between October 2016 and March, 2017. This is a period of peak dry season and dry local wind called Harmattan in the area. The analytical tool used in evaluating the models is Scilab Software version 5.5.2.

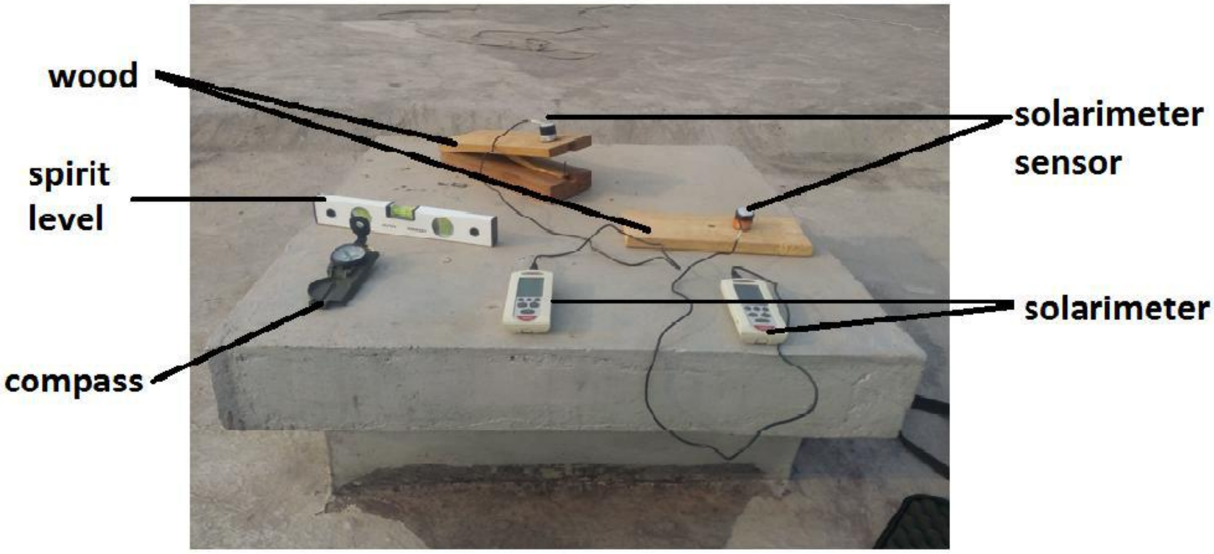

Figure 1: Experimental setup

3. Analysis

The analysis of the models with the collected experimental data was implemented using Scilab computational software, version 5.2.2. The performance criteria for the studied models were based on selected standard statistical error indices, namely; mean bias error (MBE), root mean square error (RMSE) and mean absolute percentage error (MAPE). Equations (1) through (3) present the statistical error indices that can be used to quantify the degree of agreement between a model and experimental data.

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(H_{pi} - H_{mi}) \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(H_{pi} - H_{mi})^2} \quad (2)$$

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{H_{mi} - H_{pi}}{H_{mi}}\right| * 100 \quad (3)$$

Where:

n = sample size of data

H_{pi} and H_{mi} are the ith predicted and measured values respectively

Duffie and Beckman (2006) present a global model for Solar radiation incident on a tilted surface (I_T).

$$I_T = I_{T,b} + I_{T,d} + I_{T,r} \quad (4)$$

Where:

$I_{T,b}$ = beam radiation

$I_{T,d}$ = diffuse radiation

$I_{T,r}$ = ground reflected radiation

$$I_{T,d} = I_{T,d,iso} + I_{T,d,cs} + I_{T,d,hz} \quad (5)$$

Where the subscripts d, iso, cs and hz refers to the diffuse component, isotropic, circumsolar and horizon brightening respectively

3.1 Anisotropic models (Duffie and Beckman, 2006).

Perez Model

$$I_T = I_{h,b} + R_b + I_{h,d} + I_d\left(\frac{1+cos\beta}{2}\right) + I_d * F_1 * \frac{a}{b} + I_d * F_{2*sin\beta} + I_{h\rho}\left(\frac{1-cos\beta}{2}\right) \quad (6)$$

HDKR Model

$$I_T = \left(I_{h,b} + I_{h,d}A\right)R_b + I_{h,d}(1-A)\left(\frac{1+cos\beta}{2}\right) * \left[1 + f sin^3\left(\frac{\beta}{2}\right)\right] + I_{h\rho}\left(\frac{1-cos\beta}{2}\right) \quad (7)$$

Where:

$I_{h,b}$ = hourly beam solar radiation on horizontal surface
$I_{h,d}$ = hourly diffuse solar radiation on horizontal surface
R_b = geometric ratio
I_d = hourly global solar radiation on horizontal surface
F_1 = Circumsolar coefficient
F_2 = brightness Coefficient
A = anisotropic index
B = angle of tilt
P = ground reflectivity

4. Results

Examination of Anisotropic Sky models and experimental data recorded in this study indicates that the overall goodness of fit of the models can be compared on the basis of some statistical error indices. The indices of comparison in this work are the root mean square error (RMSE), mean bias error (MBE) and mean absolute percent error (MAPE). As presented in equation (1) through (3), the statistical error indices can be used to quantify the degree of agreement between a model and experimental data. More efficient models give lower values of the selected performance criteria. The indices are calculated for the models and results presented in table 1. The results of the various anisotropic models versus measured data were also plotted to provide a better visual appreciation of the relationships. Figure 2 shows a plot of measured solar radiation on tilted surface versus the Perez model while a similar plot for the HDKR plot is displayed in figure 3.

Table I: Statistical error indices of anisotropic models with experimental data

S/N	MODELS	MBE	RMSE	MAPE
1	PEREZ	-0.005	0.0147	0.9587
2	HDKR	-0.0109	0.0177	2.0865

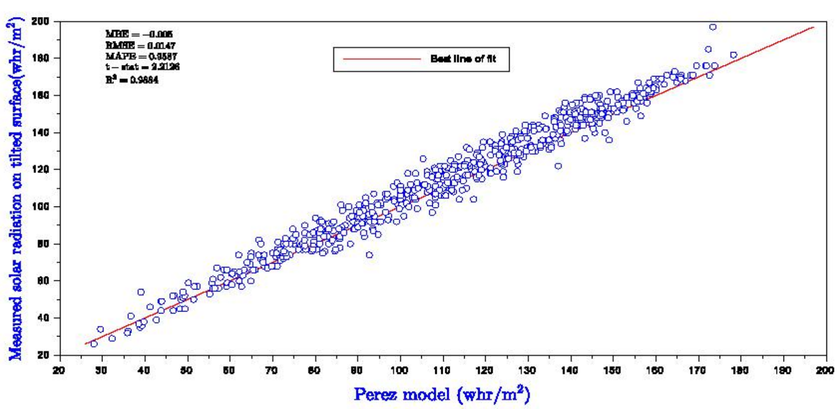

Figure 2: Measured solar radiation on tilted surface versus Perez model

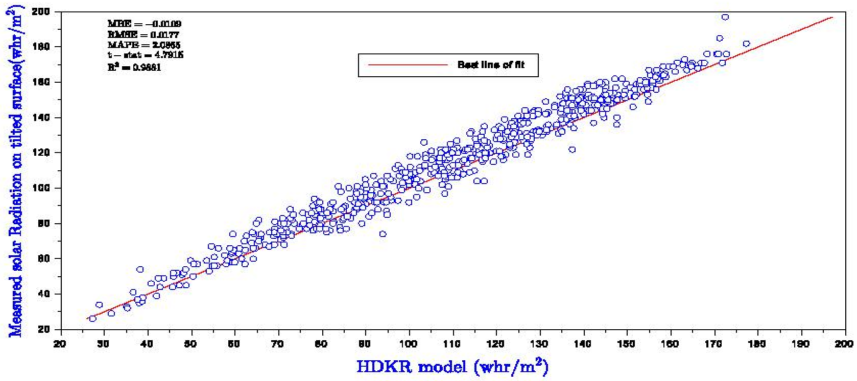

Figure 3: Measured solar radiation on tilted surface versus HDKR model

It can be observed that Perez model had lower values of MBE (-0.005Wh/m^2), RMSE (0.0147Wh/m^2) and MAPE (0.9587Wh/m^2) than HDKR model in all instances.

Conclusion

Based on this study, the following conclusions can be drawn on the comparative analysis of Anisotropic Sky models and measured data to provide a decision aid, for use in estimating global solar radiation on tilted surface, such as obtainable in Nsukka Nigeria. All the Anisotropic models considered provide a good means of predicting solar radiation on tilted surface in the location. Surface comparison of the Perez model and HDKR model based on overall graphical presentation would suggest that there exists no significant difference between the two models in predicting solar radiation variables of the studied location. A point by point calculation of deviations of the models from the field data contradicts the conclusion on similarity and visual equality of the models. Further analysis of the models and measured data based on standard statistical error indices indicate that the Perez model is actually more accurate than the HDKR model, given that it maintained a constantly lower values of MBE, RMSE and MAPE from the combination of numerical parameters. This result show that the Perez model is a good anisotropic model that can be used to estimate solar radiation on tilted surface in the case study location and is hereby recommended for this purpose.

A major contribution of this work is that it has saved a lot of time and resources invested by students and other users of solar radiation data in the studied area that had relied upon measured data when any decision involving solar radiation data on tilted surface becomes necessary. It has further revealed that conducting this type of experiment in areas with paucity of data is still a valid exercise. This is because different Sky models perform better in different environment as deduced from existing literatures, some of which are mentioned in this work.

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References

Al-Jumaily, K. J., Al-zuhairi M.F., and Mahdi, Z.S., Estimation of clear sky hourly global solar radiation in Iraq, *International journal of energy and environment*, vol.3, Issue 5, pp.659 – 666, 2012

Demain, C., Journee, M., and Bertrand, C., Evaluation of different models to estimate the global solar radiation on inclined surfaces, *Renewable Energy*, Elsevier, vol.50, pp. 710 – 721, 2013

Duffie, J.A., and Beckman, W.A., Solar Engineering of Thermal process 3rd edition, John Willey and sons, Inc. New York, USA, pp. 1-125, 2006

Hafez, A.Z., Soliman, A., El-Metwally, K.A. and Ismail, I.M., Tilt and azimuth angles in solar energy applications - A review Renewable and Sustainable *E*nergy Reviews, vol.77, issue C, pp. 147–168, 2017

Hameed, A.A., Mohsen, N.M. and Al-Salihi, A.M., Estimation of hourly Global Solar Radiation incident on Inclined surfaces in Iraq at different Sky condition, *Impact Journal*, vol.5, no.2, pp.13 – 28, 2017

Jakhrani, A. Q., Samo, S., Rigit, A.R.H. and Kamboh, S.A., Selection of Models for Calculation of Incident Solar Radiation on Tilted Surfaces, *Word Applied Sciences Journal*, vol.22, no.9, pp.1334-1343, 2013

Jakhrani, A.Q., Othman, A.K., Rigitand, A.R.H., and Samo, S., Comparison of Solar Photovoltaic Module Temperature Models, *World Applied Sciences Journal (Special Issue of Food and Environment)*, vol.14, pp.1-8, 2011

Jamil B., Siddiqui, A.T. and Akhtar, N., Estimation of solar radiation and optimum tilt angles for south-facing surfaces in Humid Subtropical Climatic Region of India, *Engineering Science and Technology, an International Journal*, vol.19, pp.1826–1835, 2016

Li, Z., Xing, H., Zeng, S., Zhao, J. and Wang, T., Comparison of Anisotropic Diffuse Sky Radiance Model for Irradiance Estimation on Building Facades, 10th International Symposium on heating, Ventilation and Air Conditioning, ISHVAC2017, 19 – 22 October 2017, Jinan, China *Procedia Engineering*, vol. 205, pp.779 - 786, 2017.

Olomiyesan, B.M., Oyedum, O.D., Ugwuoke, P.E., and Abolarin, M.S., Evaluation of some Global Solar Radiation Models in Selected locations in Northwest, Nigeria", *Open Access journal of Photoenegy*, vol.1, no. 1, 2017

Rossi. T. J., Escobedo, J..F, Santos, C.M. and Pai, E.D., Global, diffuse and direct solar radiation of the infrared spectrum in Botucatu/SP/Brazil, *Renewable and Sustainable Energy Reviews*, vol.82, pp. 448–459, 2018

Shukla, K.N., Rangnekar, S. and Sudhakar, K., Comparative study of Isotropic and Anisotropic sky models to estimate solar radiation inclined on tilted surface: A case study of Bhopal, India, *Energy Report*, vol.1, pp. 96-103, 2015

Yao, W., Li, Z., Zhao, Q. and Lu, R., A new anisotropic diffuse radiation model, *Energy Conversion and Management*, vol. 95, pp. 304–313, 2015

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Samuel Ogbonna Enibe is a Professor of Mechanical Engineering at the University of Nigeria, Nsukka, Nigeria, (UNN). He obtained the B.Eng degree from UNN, the MSc from the University of Reading, England, and the PhD from UNN. He has over 30 years of University-level teaching and research experience, with specialization in the areas of Energy & Power, Renewable Energy, Thermodynamics, Heat Transfer, Numerical Analysis \& Modeling of Engineering systems, etc. He has successfully supervised 4 PhD, 24 M.Eng and numerous PGD and BEng degree candidates. **Prof. Enibe** has published over 70 research papers or book chapters, many of which appeared in top-level international journals in his area of research. He has served as External Examiner for undergraduate and postgraduate degree projects in several Nigerian and Ghanaian Universities and has assessed candidates for appointment into Professorial positions in many Universities in Nigeria and Ghana. He has held many administrative positions in UNN, such as Head of Department, Dean of Faculty, Director of Centre, etc. He is widely traveled within Nigeria, the rest of Africa, Europe and Asia.

Professor Charles Mbohwa is the Ag, Executive Dean of Faculty of Engineering and the Built Environment, University of Johannesburg. He obtained B. Sc. Honours in Mechanical Engineering in 1986 from Department of Mechanical Engineering, University of Zimbabwe, Harare, Zimbabwe. He later bagged M. Sc. in Operations Management and Manufacturing Systems in 1992, with a distinction from Department of Manufacturing Systems Engineering, University of Nottingham, UK. He obtained PhD in Engineering (Production Systems focusing on Energy and life cycle assessment) from Tokyo Metropolitan Institute of Technology, Tokyo, Japan in 2004. Professor Mbohwa is an NRF-rated established researcher. In January 2012 he was confirmed as an established researcher making significant contribution to the developing fields of sustainability and life cycle assessment. In addition, he has produced high quality body of research work on Southern Africa. He is an active member of the United Nations Environment Programme/Society of Environmental and Toxicology and Chemistry Life Cycle Initiative, where he has served on many taskforce teams.