Comparison of Experimental Data and Isotropic Sky Models for Global Solar Radiation Estimation in Eastern Nigeria

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***Abstract*- This study compared the results of three isotropic sky models for estimating solar radiation on tilted surfaces with experimental data. The three isotropic models considered were Liu & Jordan, Badescu and Koronakis models. Scilab computational tool was used in assessing the performance of each model. The accuracy of the models was determined using mean bias error (MBE), root mean square error (RMSE), mean absolute percentage error (MAPE) and the t-statistics techniques. Liu and Jordan model was recommended for estimating global solar radiation at Nsukka, Nigeria, having recorded the least values of *MBE* and *t-stat* of -0.0127Wh/m^2 and 3.3947 respectively**

***Keywords:* Solar radiation, Isotropic sky models, Statistical error and measured data.**

I. Introduction

On earth, surfaces where solar radiation (SR) are harnessed are mostly tilted for maximum capture of incoming solar radiation. However, more of the measurements of the solar radiation done are reported for horizontal surfaces. Solar radiation data (SRD) on tilted surfaces are still lacking [1]. Adequate control of energy projects demand fitting SR data that are collected from specific solar energy systems [2 - 4].

For the design and evaluation of solar-based energy conversion systems, there should be an all-inclusive SRD that can cater for both active and passive solar energy uses [5-10]. In addition, there are reports of unavailability of SRD in most developing countries. This has been traced to paucity of SR measuring devices as well as huge capital investment involved in procuring the instrument [11, 12].

This has led to the emergence of many theoretical models with the major aim of estimating the amount of global SR on various surfaces, especially for those areas with differing climatic variables. Sunshine duration, ambient temperatures, humidity, cloud cover and wind speed are some of the variables that are normally considered [12 - 19]. Other notable studies include those of Jamil and Akhtar [3] and Guillou et al [20]. Jamil and Akhtar [3] conducted a global and diffuse SR comparison in India. In particular, the case of a typical subtropical climatic region between Aligarh and the neighboring capital city of New Delhi was undertaken. The average annual global radiation of Aligarh was given as 22.12 MJ/m^2 per day, while the average annual diffuse radiation was 7.92 MJ/m^2 per day. The result indicates that good solar energy and energy utilization potentials exist in the area. Guillou et al [20] investigated the accuracy of two commonly used clear sky models based on wet season in South Africa and compared it with experimental data using Fluent software. The average global irradiance for the fair weather condition and measured data correlated appreciably well.

There exist some model dedicated to computing global and diffuse irradiance on horizontal surface [21]. A vast majority of researchers have labored on isotropic models, used for elucidating diffuse radiation on tilted surfaces from their horizontal counterparts [2, 12, 18]. The commonest of isotropic models that can be used when short term data, such as the instantaneous horizontal beam radiation are not available, is due to Liu and Jordan [12, 22]

Among the other isotropic models which have relevance here are the Badescu Model [23] and Koronakis Model [24]. There are ample literatures [13, 15, 25, 26] geared at development of enabling techniques that can be employed in SR estimation in Nigeria. None of the studies explored the suitability of using isotropic models as an alternative to measured SR data in Nsukka, Nigeria. Nsukka is a municipality which is located at 6°51′N 7°23′E. As presented in Mbah [27], while SRD on horizontal surfaces are ubiquitous, the necessity of a viable alternative to full scale experimentation, in SRD acquisition for tilted surfaces in Nsukka cannot be over emphasized. Three isotropic sky

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models have been selected in this paper to address the concern.

II. SOLAR RADIATION ON TILTED SURFACES

As presented in Literature [28], for determination of the constituents of total solar radiation on a tilted surface (I_T):

$$I_T = I_{T,b} + I_{T,d} + I_{T,r} \quad (1)$$

where:
$I_{T,b}$= the beam radiation
$I_{T,d}$ = diffuse radiation
$I_{T,r}$ = the ground reflected radiation

Description of the selected isotropic models

1. Liu & Jordan Model [28]: Here the total solar radiation is given as

$$I_T = I_{h,b}R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I_h\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (2)$$

2. Badescu Model [23]: The total solar radiation is given as

$$I_T = I_{h,b}R_b + I_{h,d}\left(\frac{3+\cos 2\beta}{4}\right) + I_h\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (3)$$

3. Koronakis Model [24]: The total solar radiation is given as

$$I_T = I_{h,b}R_b + I_{h,d}\left(\frac{2+\cos\beta}{3}\right) + I_h\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (4)$$

where $I_{h,b}$ is the hourly beam SR on a horizontal surface, $I_{h,d}$ is the hourly diffuse SR on a horizontal surface, ρ_g is the ground reflectance, R_b is the geometric ratio and I_h is the hourly global SR on a horizontal surface.

III. METHODOLOGY

Method and Equipment

The experiment was carried out at the National Center for Energy Research and Development (NCERD) located inside University of Nigeria, Nsukka, Nigeria. The setup is as shown in Plate 1. The data were collected using two KIMO Instruments SAM 20 solarimeters with spectral response of 400-1000 nm and rated sensitivity of 100 mV for 1000 W/m^2. One of the solarimeters was placed on a platform tilted at 15^o facing south while the other was kept on a horizontal platform. The data were recorded at 10 minutes interval each day from 9.00 am to 5.00 pm from October 2016 to March 2017 covering the period of harmattan dry season in Nigeria. Scilab computational software, version 5.5.2 was used to determine the performance of each model.

Models Performance Evaluation Using Statistical Test

In order to compare the experimental data and the predictions of the models, four widely used statistical parameters were used namely: Mean Bias Error *(MBE)*, Root Mean Square Error *(RMSE)* Mean Absolute Percentage Error *(MAPE)* and t-statistics *(t-stat)*.

Fig 1: Experimental setup for measuring data

Mean Bias Error (MBE) provides information on long-term performance of the models.

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(H_{pi} - H_{mi}\right) \quad (5)$$

Root Mean Square Error (RMSE) provides information on short term performance of the models.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(H_{pi} - H_{mi}\right)^2} \quad (6)$$

Mean Absolute Percentage Error (MAPE) is a measure of prediction accuracy.

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{H_{mi} - H_{pi}}{H_{mi}}\right| \times 100 \quad (7)$$

T-statistics (t-stat) is given as:

$$t = \sqrt{\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}} \quad (8)$$

where n is the number of data, H_{pi} and H_{mi} are the i^{th} predicted value and measured value.

IV. RESULTS AND DISCUSSION

The graphs below (Figures 2 - 4) show a comparison between each estimated data obtained from the theoretical models and the measured data. Of the three models, at first look, the Koronakis model, with R^2 value of 0.9882, appears

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to fit the experimental data more than those of the other two models. This assertion can further be studied by considering the data presented in Table 1.

Table 1 presents the values of the statistical performance indices obtained from the analysis. It can be seen that Koronakis model fits the experimental results most when viewed from the fact that it has the highest value of coefficient of determination. This index actually shows how closely the experimental results fit the line of best fit. On this basis, the Koronakis model with 98.82% offers a better fit than the Liu & Jordan model with a corresponding value of 98.06% but the correlative coefficient R^2 was done on short term period. The *RMSE* shows how much error is incurred in the experimentation. The smaller the value of the index, the bettr the model's performance. A look at the error data shows that the Koronakis model has higher absolute value in *MBE* and lower *RMSE* than Liu & Jordan whereas the Liu & Jordan has lower absolute value of *MBE* and higher *RMSE*.

On the basis of the above, Koronakis model seems to give a better estimation of the SRD for tilted surfaces for the considered location. However, these deductions must be quoted with great care. According to [29] and [30], the most reliable assessment tool for evaluation and comparison of such models is the *t-stat* test along with the *MBE* and *RMSE*. The *t-stat* indicator allows models to be compared and at the same indicate whether or not a model estimate is statistically significant at a particular confidence level [29].

Table 1: The result of statistical analysis for different isotropic models

S/N	Models	MBE	RMSE	MAPE	t-stat	R^2
1	Liu & Jordan	-0.0127	0.0261	2.42	3.3947	0.9806
2	Badescu	-0.0189	0.0233	3.61	8.4504	0.988
3	Koronakis	-0.0148	0.0200	2.82	6.6966	0.9882

The smaller the value of *t-stat* the better the performance of the model. The *t-stat* has a formula combination of *MBE* and *RMSE* and was used to determine the performance of the models. Among the three models considered, the Liu & Jordan model has the least values of *MBE* and *t-stat* of -0.0127Wh/m^2 and 3.3947 respectively. Hence, the Liu and Jordan model will be the most suitable for estimating SRD in the studied location, based on the overall combination of the error measuring parameters.

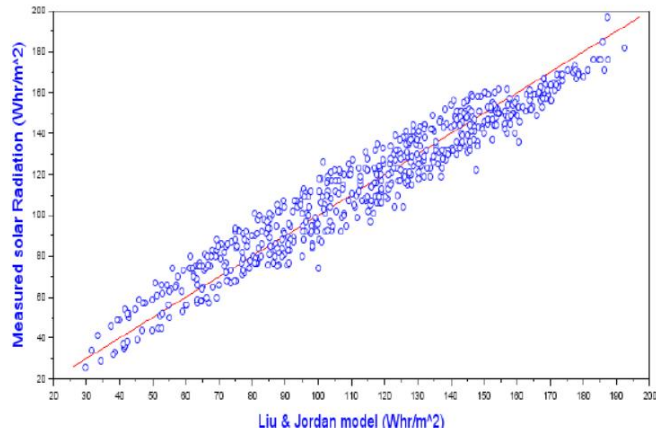

Fig. 2 Measured solar radiation on tilted surface versus Liu & Jordan model.

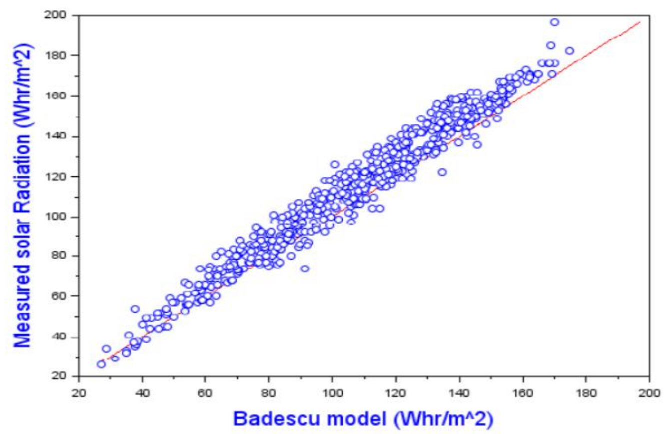

Fig. 3 Measured solar radiation on tilted surface versus Badescu model.

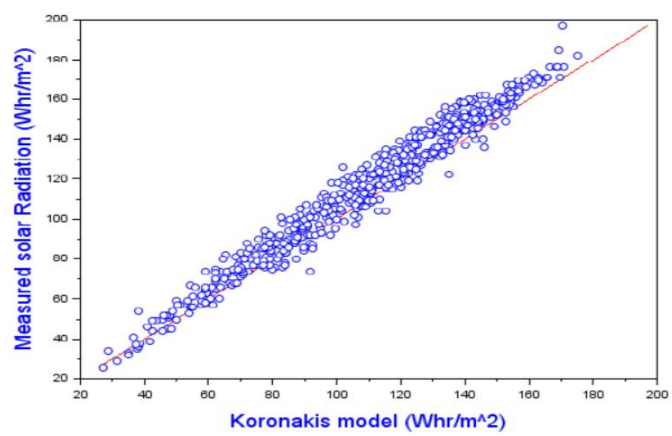

Fig. 4 Measured solar radiation on tilted surface versus Koronakis model.

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V. Conclusion

The paper studied the behavior of three different isotropic models formulated for determination of solar radiation in tilted surfaces. The work compared results from the theoretical models with measured data on solar radiation specifics in a solar system located in Nsukka, Nigeria. Based on the statistical error indices, the Liu and Jordan model manifested significant superiority over the other models tested. It recorded the least *MBE* as well as the least *t-stat* values. These impose more confidence on the result hence the recommendation for estimating the global solar radiation in tilted surfaces at Nsukka, Nigeria.

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References

[1] C. K. Pandey and A. K. Katiyar, "A note on diffuse solar radiation on tilted surface," *Energy*, vol. 34, pp. 1764 – 1769, Jul. 2009.

[2] F. Besharat, A. A. Dehghan and A. R. Faghih, "Empirical models for estimating global solar radiation: A review and case study," *Renewable and Sustainable Energy Reviews*, vol. 21, pp. 798–821, May 2013.

[3] B. Jamil and N. Akhtar, "Empirical models for estimation of diffuse solar radiation based on measured data for humid-subtropical climatic region of India," *Journal of Renewable and Sustainable Energy*, vol. 9, pp. 033702-19, May 2017.

[4] D. H. W. Li and J. C. Lam, "Solar heat gain factors and the implications to building designs in subtropical regions," *Energy and Buildings*, vol. 32, no.1, pp. 47–53, Jun. 2000.

[5] C. Gueymard and F. Vignola, "Determination of atmospheric turbidity from the diffuse-beam broadband irradiance ratio," *Solar Energy*, vol. 63, no. 3, pp.135–146, Sept. 1998.

[6] G. N. Tiwari, H. N. Singh and R. Tripathi, "Present status of solar distillation," *Solar Energy*, vol. 75, no. 5, pp. 367–373, Nov. 2003.

[7] J. M. Chang, J. S. Leu, M. C. Shen and B. J. Huang, "A proposed modified efficiency for thermosyphon solar heating systems," *Solar Energy*, vol. 76, no. 6, pp. 693–701, Jun. 2004.

[8] M. K. Ghosal, G. N. Tiwari, D. K. Das and K. P. Pandey, "Modeling and comparative thermal performance of greenhouse air collector and earth air heat exchanger for heating of greenhouse," *Energy and Buildings*, vol. 37, no. 6, pp. 613–621, Jun. 2005.

[9] T. Muneer, S. Younes, N. Lambert and J. Kubie, "Life cycle assessment of a medium-sized photovoltaic facility at a high latitude location," *Proc. the Institution of Mechanical Engineers, Part A, Journal of Power and Energy*, vol. 220, no. 6, pp. 517–524, Jan. 2006.

[10] S. K. Kharol, K. V. S. Badarinath, D. G. Kaskaoutis and H. D. Kambezidis, "Impact of dust storm over Indian region on ground reaching solar radiation: a case study using multi-satellite data and ground measurements," in *Proc. SOLARIS 2007, 3rd International Conference on Solar Radiation and Day Lighting, Indian Institute of Technology Delhi, New Delhi, India, Feb. 7–9, 2007*, pp. 169–179.

[11] D. H. W. Li, T. N. T. Lam and V. W. C. Chu, "Relationship between the total solar radiation on tilted surfaces and the sunshine hours in Hong Kong," *Solar Energy*, vol. 82, no. 12, pp. 1220-1228, Jul. 2008.

[12] A. El-Sebaii, F. S. Al-Hazmi, A. A. Al-Ghamdi and S. J. Yaghmour, "Global, direct and diffuse solar radiation on horizontal and tilted surfaces in Jeddah, Saudi Arabia," *Applied Energy*, vol. 87, pp. 568-576, Jul. 2009.

[13] J. O. Ojosu and L. K. Komolafe, "Models for estimating solar radiation availability in south western Nigeria," *Nigerian Journal of Solar Energy*, vol. 6, pp. 69–77, Jan.1987

[14] T. Khatib, A. Mohamed, M. Mahmoud and K. Sopian, "Modeling of daily solar energy on a horizontal surface for five main sites in Malaysia," *International Journal of Green Energy*, vol. 8, no. 8, pp. 795-819, Nov. 2011. DOI: 10.1080/15435075.2011.602156

[15] D. I. Egeonu., H. O. Njoku, P. N. Okolo and S. O. Enibe, "Comparative assessment of temperature based ANN and Angstrom type models for predicting global solar radiation," in *Abraham A., Krömer P., Snasel V. (eds) Afro-European Conference for Industrial Advancement. Advances in Intelligent Systems and Computing*, vol. 334, 2015, Springer, Cham.

[16] S. Olayinka, "Estimation of global and diffuse solar radiations for selected cities in Nigeria," *International Journal of Energy and Environmental Engineering*, vol. 2, no. 3 pp.13-33, Aug. 2011.

[17] M. S. Okundamiya, J. O. Emagbetere and E. A. Ogujor, "Evaluation of various global solar radiation models for Nigeria," *International Journal of Green Energy*, vol. 13, no.5, pp.505-512, Jan. 2015. DOI: 10.1080/15435075.2014.968921

[18] K. N. Shukla, S. Rangnekar, K. Sudhakar, "Comparative study of isotropic and anisotropic sky models to estimate solar radiation incident on tilted surface: A case study for Bhopal, India, *Energy Reports*, vol. 1, pp. 96–103, Apr. 2015.

[19] M. Alia-Martinez, J. Antonanzas, R. Urraca, F. J. Martinez-de-Pison, and F. Antonanzas-Torres, "Benchmark of algorithms for solar clear-sky detection," *Journal of Renewable and Sustainable Energy*, vol. 8, pp. 033703, May 2016.

[20] P. Guillou, D. M. Madyira, O. Marc and E. T. Akinlabi, Comparison of Experimental Data and Two clear Sky models, in *2016 Proc. International Conference on Competitive Manufacturing COMA '16*, pp. 445-450.

[21] V. Badescu, C. A. Gueymard, S. Cheval, C. Oprea, M. Baciu, A. Dumitrescu, F. Iacobescu, I. Milos and C. Rada, "Computing global and diffuse solar hourly irradiation on clear sky. Review and testing of 54 models," *Renewable and Sustainable Energy Reviews*, vol. 16, pp. 1636– 1656, Jan. 2012.

[22] F. Kreith and J. F. Kreider, *Principles of Solar Engineering*, Washington, D.C Hemisphere Publishing Corp. 1978, Chap. 2.

[23] V. Badescu, "3D isotropic approximation for solar diffuse irradiance on tilted surfaces," Renewable Energy, vol. 26, no. 2, pp. 221-233, Jan. 2002.

[24] P. S. Koronakis, "On the choice of the angle of tilt for south facing solar collectors in the Athens basin area," *Solar Energy*, vol. 36, no. 3, pp. 217-225, Jan. 1986.

[25] C. I. Ezekwe and C. O. Ezeilo, "Measured solar radiation in a Nigerian environment compared with predicted data," *Solar Energy*, vol. 26. pp. 181-186, Jan. 1981.

[26] M. S. Okundamiya and A. N. Nzeako, "Empirical model for estimating global solar radiation on horizontal surfaces for selected cities in the six geopolitical zones in Nigeria," *Research Journal of Applied Science, Engineering and Technology*, vol. 2, no. 8, pp. 805-812, Dec. 2010.

[27] O. M. Mbah, "Performance evaluation of sky models for estimating global solar radiation on tilted surfaces in Nsukka," M.Eng Project Report, Dept. Mech. Eng. Univ. of Nigeria, Nsukka, Nigeria, 2017.

[28] J. A. Duffie and W.A. Beckman, *Solar Engineering of Thermal Process 3rd Ed*, New York: John Willey and Sons Inc., 2006, pp.1-125.

[29] R. J. Stone, "Improved statistical procedure for the evaluation of solar radiation estimation models," *Solar Energy*, vol. 51, no. 4, pp. 289-291, Jan 1993.

[30] A. Kocer, M. Gokcek and A. Gungor, "Comparison of Empirical Models for the Estimation of Monthly Global Solar Radiation at Nigde in Turkey," British Journal of Applied Science & Technology, vol. 11, no. 2, pp. 1-8, Aug. 2015.