Comparison of Relative Humidity and Temperature Based Models for Estimating Global Solar Radiation in Uyo, Nigeria

*John F Wansah[1], Prisca Innocent[2], Actor J. Ocheje[3], Jacob B. Akeredolu[3], Cookey Iyen[3] and Amaitem J. Iseh[3]

[1]Department of Physics, Modibbo Adama University of Technology Yola, Yola
[2]Department of Physics, University of Uyo, Uyo
[3]Department of Pure and Applied Physics, Federal University Wukari, Wukari
fomunyuydzesinyuy@gmail.com

Abstract: A comparative study has been carried out using four relative humidity-based models to estimate the global solar radiation in Uyo (Longitude 5' 02° N, Latitude 7' 55° E). The values of the measured and the estimated global solar radiation models were tested using the root mean square error (RMSE), the mean bias error (MBE) and the mean percentage error (MPE); and the coefficient of determination, R^2 and correlation coefficient, r were also calculated. From the results obtained, Augustine and Nabuchi; and Ituen *et al* Models are most suitable for estimating monthly average daily global solar radiation for Uyo and locations with similar geographic and climatic conditions. Since the study, design and utilization of solar energy conversion devices depend to a greater extend on the monthly average daily global solar radiation data so determined, then the global solar radiation intensity values obtained by this approach can be used in the design and estimation of performance of solar applications system in Uyo, Nigeria.

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1. Introduction

Solar radiation is the primary source of the Earth's energy, providing about 99.97% of the heat energy required for chemophysical processes in the atmosphere, ocean, land, and other water bodies (Ogolo, 2010). Solar radiation plays an important role as a renewable energy source or alternative energy source as solar radiation measurements could be used to estimate potential power levels that can be generated from photovoltaic cells and also necessary for determining cooling loads for buildings (Gopinathan, 1992). Solar radiation thus has many useful applications in architectural design, evapotranspiration estimates, agriculture, and atmospheric, land, ocean, and hydrologic models (Tahars *et al*., 2006; Falayi and Rabiu, 2011). The acquisition and the development of database on the long term solar radiation will facilitate the evaluation of solar energy potential as an input to the country's energy budget and other modeling applications (Falayi and Rabiu, 2011). Global solar radiation has being studied due to its importance in providing energy for the Earth's climate system. The solar radiation reaching the Earth's surface depends upon climatic conditions of a location, which is essential to the prediction and design of a solar energy system (Burari and Sambo, 2001). However, in developing countries such as Nigeria, it has been very difficult measuring global solar radiation due to the availability of equipment or non-functioning of the existing equipment (Umoh *et al*., 2013).

Many models using some meteorological variables such as air temperature, sunshine hours, relative humidity, etc have been proposed for various locations, but models based on sunshine hours are the most commonly used. Besides the most popular Angstrom-Prescott model (1924) for estimating solar radiation from sunshine hours, some other scientists have developed many empirical equations that determine the relationship between radiation and several other meteorological, geographical and astronomical parameters. The models are developed in ways that combine one, two, three or more parameters. Models such as the ones developed by Glover and McCulloch (1958), Dogniaux and Lemoine (1983), Raja and Twidell (1990a,b) combined the relative sunshine with the station's latitude. Swartman and Ogunlade (1967) developed a model that combined relative sunshine with the mean relative humidity; Gopinathan (1988a,b) developed a model that combined the relative sunshine with the station's latitude in degrees and altitude in km; Abdalla (1994) made a combination of relative sunshine, mean air temperature and relative humidity in his model; Ododo *et al*., (1995) merged the maximum air temperature and mean relative humidity with relative sunshine in a model he developed with co-scientists; Ojosu and Komolafe (1987) used a model that combined the sunshine ratio with temperature ratio and the ratio between the mean relative humidity and maximum relative humidity; and Rehman and Halwani (1997) combined the sunshine ratio with the station's latitude and longitude in degrees and altitude in km. Bristow-Campbell (1984), Hargreaves *et al*., (1985), Allen (1997) and Chen *et al*., (2004) used only air temperature range in their models. Hargreaves and Samani (1982) developed a model that combined air temperature range with a factor of 0.16 for interior regions or 0.17 for coastal regions depending on the station. Annandale *et al*., (2002) did same but also incorporated the station's altitude in his model. Rietveld (1978) used universally accepted regression constants in the Angstrom-Prescott type regression model. Skeiker (2006) produced a model with seven parameters while Ertekin and Yaldiz (1999) used nine parameters. In Nigeria, a number of other studies have been conducted on the measurement and estimation of solar radiation from other meteorological variables and these include: Ezekwe and Ezeilo (1981), Awachie and Okeke (1982), Ideriah (1981, 1983, 1985), Bamiro (1983) and Okogbue and Adedokun (2003). Also Ezekwe and Ezeilo (1981) presented empirical correlations for Nsukka a town located in the southeastern part of Nigeria. On the other hand, Bamiro (1983) presented some empirical correlations for predicting global insolation for Ibadan (Nigeria). Okogbue and Adedokun (2003) in their attempted to improve on the estimation of global solar irradiance for Ondo, a city in south western Nigeria, used daily global radiation, sunshine hours, minimum and maximum temperature and relative humidity data for the periods (1986-1990). These data were used to produce seven additional correlation equations with the Angstrom type equation for estimating global solar irradiance in the location. The correlation equations performed better when long-term monthly average values of the meteorological parameters were used. The objective of this work is to use four relative humidity based models to calculate the monthly average global solar irradiance over Uyo based on the readily measured meteorological variables and to validate which of the models is the most suitable using some statistical methods.

Theory

The model for estimating the monthly average daily global solar radiation that is simple and widely used is Angstrom-Prescott (1924) model for estimating solar radiation from sunshine hours given as

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) \quad (1)$$

where H is the monthly average global radiation on horizontal surface, S is the monthly average daily bright sunshine hours, S_0 is the maximum possible monthly average daily sunshine hours or day length, a and b are constants, and H_0 is the monthly average daily extraterrestrial radiation (MJ/m^2 day) which can be expressed as:

$$H_o = \frac{24}{\pi} I_{sc}\left[1 + 0.033\cos\left(\frac{360 D_n}{365}\right)\right] \times \left[\frac{\pi}{18\ 0} W_s \sin\emptyset \sin\delta + \cos\emptyset\cos\delta\sin W_s\right] \quad (2)$$

where W_s is sunset hour angle in degree and defined as proposed by Iqbal (1983) as

$$W_s = \cos^{-1}(-\tan\emptyset\tan\delta) \quad (3)$$

The value of 1367 W/m^2 has been recommended for the solar constant I_{sc}, ∅ is the latitude of location under consideration; D_n is the day number of the year starting from January 1 to December 31 and δ is the declination angle of location given as:

$$\delta = 23.45\sin\left(360\left(\frac{28\ 4 + D_n}{365}\right)\right) \quad (4)$$

$$I_{sc} = \frac{1367 \times 3600}{1000000}\ (\text{MJm}^{-2}\text{day}^{-1}) \quad (5)$$

In this work the following models are used: Ituen *et al*., (2012) Models 1 and 2 (equations 6 and 7 respectively) based on relative humidity and maximum temperature.

$$\frac{H_p}{H_o} = -0.589 - 0.280\frac{R}{100} \quad (6)$$

$$\frac{H_p}{H_o} = -0.229 - 0.02T_m \quad (7)$$

Augustine and Nabuchi (2010) developed models for predicting solar radiation in the southern parts of Nigeria given as:

$$\frac{H_p}{H_o} = 0.526 - 0.180\frac{R}{100} \quad (8)$$

Falayi *et al*., (2008) Model

$$\frac{H_p}{H_o} = 1.1974 - 0.00829\frac{R}{100} \quad (9)$$

where H_p is the predicted monthly average global radiation on horizontal surface.

The error or deviation of the estimated values from the measured values is determined based on statistical parameters such as the root mean square error (RMSE), the mean bias error (MBE) and mean percentage error (MPE) (equations 10-12). Coefficient of determination, R^2 (equation 13) is most often seen as a number between 0.0 and 1.0, used to describe how well a regression line fits a set of data. R^2 near 1.0 indicates that a regression line fits the data well, while an R^2 closer to 0.0 indicates that a regression line does not fit the data very well. Coefficient of correlation, r (equation 14) is used to test the linear relationship between estimated and measured values. The value of r is between -1.0 and +1.0, the + and – signs are used for positive linear correlations and negative linear correlations, respectively (Wansah *et al*., 2014).

2. Materials and Methods

Data were taken from Nigerian Metrological Agency, NIMET Uyo and the monthly mean relative humidity, solar radiation, and temperature readings spanning 13 years (2000-2013) were obtained for Uyo (Longitude 5' 02° N, Latitude 7' 55° E) as shown in Fig. 1. The monthly averages of the data were obtained. The necessary meteorological and solar radiation parameters were calculated from equations (1-5). Four different relative humidity-based solar radiation models (equations 6-9) were selected based on their relationship with geographical information of Uyo and used for the estimation. Assessment and comparison of the four selected models were based on some statistical parameters given by equations (10-14).

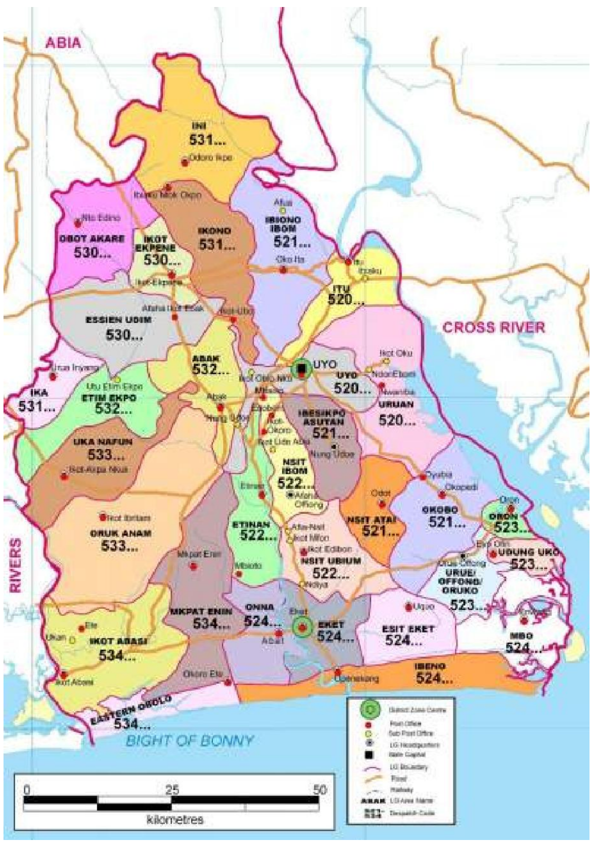

Fig. 1: Uyo, Akwa Ibom State (Anon., 2016)

3. Results and Discussion

The monthly data processed in preparation for the correlation are presented in Table 1. The accuracy of the estimated values was tested by calculating the RMSE (Root Mean square Error, MJ/m^2), MBE (Mean Bias Error, MJ/m^2), and MPE (Mean Percentage Error, %). The results are shown in Table 3. Figure 2 further illustrates the comparison between observed and predicted values of the correlation equation. Microsoft Excel software was used in evaluating model parameters by writing computer programmes for the appropriate formulae.

$$RMSE = \{[\sum(H_p - H_m)^\wedge 2]/n\}^{½} \quad (10)$$

$$MBE = [\sum(H_p - H_m)]/n \quad (11)$$

$$MPE = \frac{1}{n}\left[\sum \frac{(H_m - H_p \times 100)}{H_m}\right] \quad (12)$$

$$R^2 = 1 - \frac{\sum(H_m - H_p)}{\sum(H_m - \bar{H}_m)^2} \quad (13)$$

$$r = \frac{n\sum H_p H_m - \sum H_p \sum H_m}{\sqrt{n(\sum H_p^2) - \sum H_p^2} \times \sqrt{n(\sum H_m^2) - (\sum H_m)^2}} \quad (14)$$

where n is the number of observations, H_m is the measured global radiation, H_p is the estimated global radiation and $\bar{H}_m$ is the mean measured global radiation. The global solar radiation, estimated and measured solar radiation, and regression and statistical indicators for Uyo are calculated as shown in Tables 1, 2 and 3 respectively. Table 3 contains summaries of various liner regression analyses obtained from the application of equations (10-14) to the monthly mean values for the three variables under study. Equations (1-3) have the highest values of correlation coefficient while equation (4) has the lowest value of *r*. The estimated values of global solar radiation for Uyo along with the measured data are shown in Table 2. The following observations were made from a study of Table 3 based on the RMSE; equation (3) produces the best correlation while equation (1) gives the worst with larger value of RMSE. For MBE the result shows that equation (3) is the best while equation (1) is the worst. With respect to MPE, equation (3) offers the best correlation while equation (1) gives the worst. Since MPE gives information on long term performance of the examined regression equation, a positive MPE value provides the average amount of overestimation in the calculated values while a negative MPE gives underestimation (Umoh *et al.*, 2013). On the whole, a low MPE is desirable. The test on RMSE conveys information on the short term performance of the different equations since it enables a term-by-term comparison of the actual variations between the estimated and measured values. For more accurate estimation, lower values of RMSE are desired (Umoh *et al.*, 2013). Hence it can be concluded that equation 2 and 3 are more suitable for estimating global solar radiation for Uyo as shown in Figs. 2 and 3.

Generally, correlation coefficients (0.791 - 0.298) are high for all the variables. This implies that, there are statistically significant relationships between the clearness index, the relative humidity, the ratio of minimum to maximum daily temperature and the monthly average daily temperature. From Tables 2 and 3 it is concluded that equations 2 and 3 can be used in estimation of global solar radiation for Uyo, the same as also observed from the graphs shown in

Figs. 1 and 2. Therefore, the global solar radiation intensity values obtained by this approach can be used in the design and estimation of performance of solar applications system in Uyo, Nigeria.

4. Conclusion

Data taken from the Nigerian Metrological Agency, NIMET Uyo on the monthly mean relative humidity, solar radiation, and temperature readings spanning 13 years (2000-2013) for Uyo has been compared.

The values of the measured and the estimated global solar radiation models were tested using the root mean square error (RMSE), the mean bias error (MBE) and the mean percentage error (MPE); and the coefficient of determination, R^2 and correlation coefficient, *r* were also calculated. From the results obtained, Augustine and Nabuchi; and Ituen *et al* Models are most suitable for estimating monthly average daily global solar radiation for Uyo and locations with similar geographic and climatic conditions in the design and optimization of the performance of solar energy utilities such as stand-alone photovoltaic systems.

Table 1: Relative Humidity, Maximum Temperature and Global Solar Radiation for Uyo

Month	R (%)	T_m (^{o}C)	H_m (MJ/m^2)	H_o (MJ/m^2)	$K_t = \frac{H_m}{\text{Ho}}$
Jan	73.64285714	33.74285714	14.23	37.42695626	0.380207247
Feb	72.14285714	34.79285714	16.25	38.22424533	0.425122847
Mar	80.35714286	33.60714286	14.67	36.93018651	0.397236012
Apr	82.07142857	32.65000000	14.44	37.0481899	0.389762632
May	82.85714286	31.95000000	14.72	37.57223752	0.391778637
Jun	84.92857143	30.72857143	13.66	37.56243139	0.363661230
Jul	87.78571429	29.92857143	11.65	37.67116892	0.309255070
Aug	88.28571429	29.00000000	10.36	38.35497945	0.270108344
Sep	86.35714286	29.97857143	13.85	38.48210929	0.359907506
Oct	84.14285714	31.20000000	14.63	38.17055043	0.142143989
Nov	81.92857143	32.18571429	16.15	37.42361130	0.180710971
Dec	78.64285714	33.10000000	15.14	37.09835242	0.234280716

Where K_t the clearness index is defined as the ratio of the observed/measured horizontal terrestrial solar radiation (H_m), to the calculated/predicted horizontal extraterrestrial solar radiation (H_0).

Table 2: Comparison of Estimated and Measured Solar Radiation Data for Uyo

Month	H_m	**Eqn 1**	**Eqn 2**	**Eqn 3**	**Eqn 4**
Jan	14.23	-29.7619	16.68708	14.7253686	44.58655
Feb	16.25	-30.2354	17.84526	15.14226176	45.54111
Mar	14.67	-30.0612	16.36535	14.08359041	43.97419
Apr	14.44	-30.3351	15.70843	14.01427172	44.10944
May	14.72	-30.8468	15.40462	14.15936608	44.73092
Jun	13.66	-31.0566	14.48300	14.01561636	44.71279
Jul	11.65	-31.4479	13.92219	13.862452	44.83331
Aug	10.36	-32.0724	13.46260	14.07956503	45.64554
Sep	13.85	-31.9709	14.26037	14.25982047	45.80298
Oct	14.63	-31.4754	15.07737	14.29650702	45.43916
Nov	16.15	-30.6275	15.52011	14.16590612	44.55686
Dec	15.14	-30.0200	16.06359	14.26219660	44.17970

Table 3: Equation with Regression and Statistical Indicators for Uyo

Equations	R	R^2	RMSE	MBE	MPE
$\frac{H_p}{H_o} = -0.589 - 0.280\frac{R}{100}$	0.653500150	-16.26899500	12.42033589	-3.212268550	-22.97941775
$\frac{H_p}{H_o} = -0.229 - 0.02Tm$	0.791497691	1.481593979	0.426911036	0.089583049	0.689124449
$\frac{H_p}{H_o} = 0.526 - 0.180\frac{R}{100}$	0.506538395	1.042141000	0.394567378	0.007838822	0.1547839100
$\frac{H_p}{H_o} = 1.1974 - 0.00829\frac{R}{100}$	-0.298464656	12.78749000	8.219490000	2.192634182	15.859740000

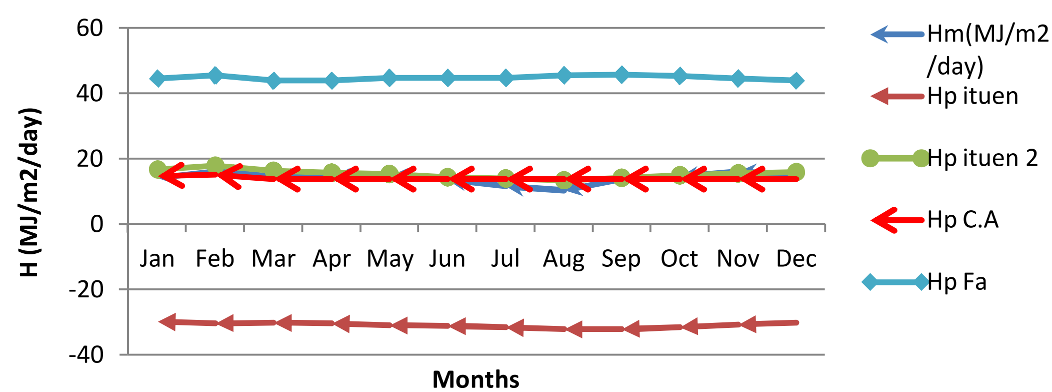

Fig. 2: Comparison of Monthly Average Daily Global Radiation for Different Models

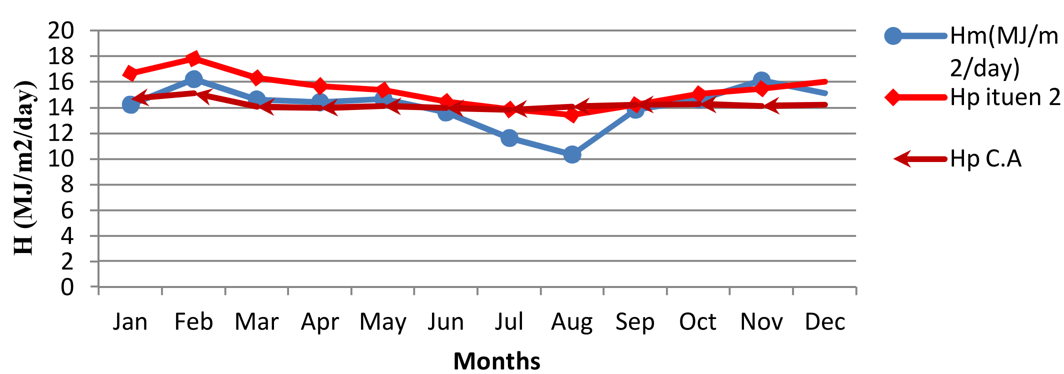

Fig. 3: Solar Radiation, Ituen 2 and Augustine Models Estimated Results

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Corresponding Author
John F. Wansah
Department of Physics
Modibbo Adama University of Technology, Yola
Yola, Nigeria
E-mail: fomunyuydzesinyuy@gmail.com

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