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Estimation of Global Solar Radiation on Horizontal Surface in Kano, Nigeria Using Air Temperature Amplitude

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Abstract: The need for a renewable source of energy is inevitable due to globally uneven distribution of the fossil fuel as well as its associated greenhouse effect. For effective implementation of renewable energy resources in a particular location, its potential availability must be investigated. Solar energy studies of a given geographical location require inputs such as solar radiation profile for the performance estimation and development of various solar technologies. Advance solar radiation measuring equipment such as pyranometer and pyrheliometer are normally installed at the selected locations to collect, measure and output data. However, many developing nations could not afford the cost and maintenance of such equipment. The objective of this work is to calibrate, validate and evaluate and compare four empirical air temperature-based models and choose the most appropriate for estimating the global solar radiation at Kano Airport, Nigeria. The methodology used involved the application of four different empirical models namely the Hargreavees, Allen, Bristow-Campbell and the Samani models by adopting monthly average maximum and minimum air temperatures obtained from meteorological stations as the input parameters. The simulations and analysis were performed in R programing software applications. The analysis shows that average global solar radiation can be precisely estimated using air temperature as the only input parameter to the empirical models at locations where solar radiation data are not obtainable. Using statistical performance analysis to compare the estimated global solar radiation values with the measure solar radiation data. The Samani model with RMSE value of 3.5443, coefficient of determination (R^2) value of 0.3508, mean bias error (MBE) of value -3.1506, coefficient residual mass (CRM) of value 0.1448 and mean percentage error (MPE) of value -14.0538 was chosen as the most accurate among the four models. The negative signs in both MBE and MPE indicate non-correlation between the models estimated and observed radiation data. From the simulation and analysis results, simple and non-complex empirical models can be utilized to predict solar radiation with easily obtainable air temperature where sophisticated solar radiation instrument are not readily available. Meanwhile, the accuracy of the estimated solar radiation values of the empirical models using the air temperature can be further improved by using auto- calibration of the models in future works.

Keywords: Air temperature amplitude, Samani model, global solar radiation, meteorological weather data, Latitude, Kano Airport.

1. Introduction

Development and advancement of any nation depend on the accessibility of reliable electric power energy. However, the task of maintaining, upgrading of the existing power system as well as introducing new energy systems in correlation with the increasing energy demand due to population explosion and industrialization has been an important trend worldwide [1]. The necessity to develop a new consistent and permanent source of energy apart from the fossil fuels whose reserve deposit has been expected to be entirely exhausted by the end of the 21st century to be replaced by

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renewable sources of energy that can be manageable, free, eco-friendly and sustainable is highly desirable [1]. The need for the renewable source of energy is inevitable due to uneven distribution of the fossil fuel, its transportation expenses, its political and military invasions to control and manipulate the possession, carbon emission, highly depleted and non-renewable nature [2]. Solar energy is the main source from which all fossil and renewable energy types are derived. Various ancient technologies have been used for harnessing the solar and other renewable energy types since human early civilizations for water irrigations and wind power have been used for milling and navigation purposes [3].

Solar energy studies of a given geographical location require inputs such as solar radiation profile for the performance estimation and development of various solar technologies. Advance solar radiation measuring equipment such as pyranometer and pyrheliometer are normally installed at the selected locations to collect, measure and output data. However, many developing nations could not afford the cost and maintenance of such equipment and hence the need for modeling the global solar radiation using different estimating methods with appropriate daily or monthly climatic data from meteorological stations [4]. The Angstrom – Prescott equation and its variations together with many other linear, polynomial, exponential, logarithmic models are used for various types of solar estimations while stochastic neural network and genetic algorithms models are used for complicated analysis [5, 6]. Different locations vary in meteorological weather data hence methods of solar radiation estimates differ and need to be adapted for that particular location. In Nigeria the most frequently investigated weather parameters are the sunshine hour duration, wind speed, relative humidity, cloud cover, rainfall, and air temperature. Globally, scientists have derived various empirical equations to relate solar radiation with various meteorological parameters [7-13]. Many researchers in Nigeria have modeled global solar radiation using sunshine-based models. [1, 9, 14-18] used the Angstrom model while [19] used the Hargreaves-Samani model to estimate solar radiation for various locations and cities across Nigeria. [20-22] used Hargreaves-Samani models to calibrate and calculate the solar radiation using temperature parameters only, while [23] employed Angstrom, temperature, relative humidity, and precipitation models. Temperature based models utilize air temperature amplitude as a modification of the cloud cover amount in Angstrom and Bristow-Campbell models and thereby measure the state of the sky [3].

Very little attention has been given to solar radiation potentials of Kano city and its environs The main focus of this work is to calibrate, evaluate and validate four air temperature-based models to estimate global solar radiation potentialities in the Kano using air temperature as the sole parameter as the input because of its easiness in availability and accessibility and can be used for any location in Nigeria without the sunshine hour parameters.

2. Materials and Methods

Kano Airport, Nigeria located at Latitude 12.046o N and Longitude 8.522o E and at 476m above the sea level is the site under considerations for this study. The global solar radiation on horizontal surfaces, air temperature, relative humidity and atmospheric pressure for a period of 22 years were obtained from the archives of National Aeronautics and Space Administration (NASA) [24].

Four air temperature-based model types are investigated in this work. The inputs variables into the models are air temperature amplitude, extraterrestrial solar radiation, declination angle, solar hour angle, latitude and day of the year which except the air temperature defined the extraterrestrial solar radiation parameters. The daily average extraterrestrial global solar radiation H_o is given [23] as:

$$H_o = \frac{24}{\pi} I_{SC}\left(1 + 0.033\,cos\left(\frac{360N}{365}\right)\right) \times \left(cos\,\emptyset\,cos\,\delta\,sin\,\omega + \frac{2\pi}{360} sin\,\emptyset\,sin\,\delta\right) \quad (1)$$

where I_{SC} is the solar constant and the value given as 1.367kW/m2; $\emptyset$ is the latitude of the location (in degrees); δ is the solar declination angle in degrees; ω is the sunset hour angle and N is day ofa the year, starting with 1 for January 1st and 365 for December 31st . The solar declination angle can be determined from equations (2) - (5) [23, 25];

$$\delta = -23.45 \times \cos\left[\frac{360}{365}(N + 10)\right] \quad (2)$$

$$\delta = -23.45 \times \sin\left[\frac{360}{365}(N + 284)\right] \quad (3)$$

$$\delta = \left(\frac{180}{\pi}\right)\begin{pmatrix} 0.006918 - 0.399912\cos\alpha + 0.070257\sin\alpha \\ - 0.006758\cos 2\alpha + 0.0009072\sin 2\alpha \\ - 0.002697\cos 3\alpha + 0.00148\sin 3\alpha \end{pmatrix} \quad (4)$$

$$\alpha = \frac{2\pi \times (N-1)}{365} \tag{5}$$

where α is the day angle (in radians)
The sunset hour angle is given in equation (6):

$$\omega = \cos^{-1}[-\tan\delta \tan\emptyset] \tag{6}$$

$$K_T = \frac{H_m}{H_o} \tag{7}$$

The ratio of average horizontal surface radiation H_m to the average extraterrestrial radiation H_o measures the clearness index at that particular surface, the temperature-based model relate the temperature amplitude to K_T in equation (7).

3. Air Temperature Amplitude Based Models

3.1 Hargreaves and Samani model

Hargreaves and Samani [26] introduced and proposed the estimation of global solar radiation from daily temperature amplitude according to equation (8):

$$H_m = K_r(T_{max} - T_{min})^{0.5} H_o \tag{8}$$

where, H_m represents approximated global solar radiation in (MJ/m2day), H_o represent extraterrestrial solar radiation in (MJ/m2day), T_{max} stand for daily maximum temperature in degree Celsius, T_{min} stand for daily minimum temperature in degree Celsius and K_r stands for empirical the coefficient. K_r was assigned 0.17 for semiarid and arid zones. Hargreaves [27] proposed $K_r =$ 0.16 for inland zones and a value of K_r = 0.19 to coastal areas. It is assumed that this temperature amplitude based equation can supply full information on cloud cover.

3.2 Allen Model

Allen [28] recommended the use of the self-calibrating model to assess the global radiation after the work of Hargreaves-Samani [26] by introducing a correction factor which expressed the empirical coefficient K_r as a function of the ratio of atmospheric pressure at the site location, (kPa) and at sea level (Po, = 101.3kPa) as in equation (9)

$$K_r = K_{ra}\left(\frac{P}{P_o}\right)^{0.5} \tag{9}$$

Allen recommended values of 0.17 for interior regions and 0.20 for coastal regions for the empirical coefficient K_{ra}.

3.3 Samani Model

Samani [29] was able to provide further improvement in the empirical coefficient K_r of equation (8) by analyzing one year average monthly data which reduced the estimated global solar radiation errors. The improved K_r is given in equation (10) [25].

$$K_r = A(T_{max} - T_{min})^2 + B(T_{max} - T_{min}) + C \tag{10}$$

The coefficients A = 0.00185 (oC-2), B = -0.04330 (oC-1) while C = 0.40230.

3.4 Bristow-Campbell Model

Bristow and Campbell [30] introduced a model for estimating daily global solar radiation that exponentially and arbitrarily approaches the value of the air temperature amplitude and is expressed as:

$$H_m = A[1 - exp(-B\Delta T^C)]H_o \tag{11}$$

The coefficients A, B and C are empirical and have some physical explanation. Coefficient A expresses the greatest estimate of the atmospheric transmission, it is a property of the location under consideration, and a function of latitude, (L) and elevation h of the location and A can be expressed as equation (12) [31]

$$A = a + b \tag{12}$$

where a and b could be expressed as equations (13) and (14) respectively as follows:

$$a = -3.517 \times 10^{-3}L - 1.492 \times 10^{-6}h + 0.3263 \quad (13)$$

$$b = 5.042 \times 10^{-4}L + 4.845 \times 10^{-5}h + 0.4644 \quad (14)$$

The coefficients B (oC-1) and C determine the result of the increase in ΔT on the greatest estimate of atmospheric transmission and vary between (0.001945) and (0.007846) from arid zones to humid zones. C = 2.4 while B is calculated as in equation (15):

$$B = 0.036 exp(-0.154\Delta T_{av}) \quad (15)$$

where ΔT_{av} is the monthly average of ΔT.

4. Model Statistical evaluation

Statistical analysis for evaluation of the performance of the estimated model's values and the measured values data was based on measured daily global solar radiation H_m against estimated daily global solar radiation H_c [32]. To evaluate the models performance of goodness extrapolation precision, different statistical evaluation indicators were employed and as follows: root mean-square error $RMSE$, mean bias error MBE, the coefficient of determination R^2, coefficient the of residual mass CRM, and mean percentage error MPE. They are defined in the following equations [22, 25]:

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(H_m - H_c)\right]^{1/2} \quad (16)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(H_m - H_c) \quad (17)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(H_m - H_c)^2}{\sum_{i=1}^{n}(H_m - H_{mav})^2} \quad (18)$$

$$CRM = \frac{\sum_{i=1}^{n} M_m - \sum_{i=1}^{n} H_c}{\sum_{i=1}^{n} H_m} \quad (19)$$

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{H_m - H_c}{H_m}\right) \times 100 \quad \% \quad (20)$$

where H_{mav} is the mean measured solar radiation and n is the number of data.

5. Results and Discussion

Table 1 shows the observed and estimated global solar radiation for the 22 years monthly average daily data analyzed for Kano Airport. It is observed that the estimated global solar radiation vary from one model to another and also from one month to another. The variations in the models estimate were quite expected and this forms the basis for selecting the one that best suits the particular location. From the estimated model results and statistical analysis from Table 1

Table 1- Estimated and Observed global solar radiation for Kano.

Month	**Estimated Radiation (MJm^{-2}d^{-1})**				**Observed Radiation (JMM^{-2}d^{-1})**
	Hargreaves	**Allen**	**Bristow-Campbell**	**Samani**	
Jan	**17.970**	**18.577**	**23.445**	**17.133**	**19.764**
Feb	**20.158**	**20.840**	**25.898**	**19.790**	**22.788**
Mar	**21.443**	**22.168**	**27.803**	**20.675**	**24.444**
Apr	**20.481**	**21.173**	**27.213**	**19.103**	**25.056**

May	**17.950**	**18.557**	**21.877**	**18.580**	**24.336**
Jun	**15.340**	**15.859**	**14.266**	**19.081**	**23.112**
Jul	**13.580**	**14.039**	**9.117**	**19.487**	**20.916**
Aug	**14.149**	**14.627**	**10.591**	**19.464**	**19.476**
Sep	**15.696**	**16.226**	**16.106**	**18.455**	**20.412**
Oct	**18.520**	**19.145**	**24.607**	**17.274**	**21.240**
Nov	**18.407**	**19.029**	**23.918**	**17.678**	**20.592**
Dec	**17.392**	**17.979**	**22.691**	**16.582**	**18.972**
Average	**17.591**	**18.185**	**20.628**	**18.608**	**21.759**

and Table 2, the Samani model has the best fit while Allen model and Hargreaves model follow in that order for solar radiation estimation for the site under considerations. The Bristow-Campbell model with the highest average of 20.628MJm^{-2}d^{-1}, however, has the highest error and the least correlation coefficient hence not suitable for global solar radiation estimation for the site.

As seen in Figure 1, the Hargreaves, Allen, and Samani model showed good correlation coefficient at the beginning and at the end of year and poor correlation coefficient between the months of May and September each while Bristow-Campbell model had a poor correlation coefficient from the month of May to late September, the Samani model has disparities from the months of August to late November. From Figure 1 it could be observed that the highest global solar radiation on the horizontal surface occurred in the month of March and this coincides with the transition from Harmattan – Hot seasons often with clear sky hot temperature. With the exception of Samani model, the lowest global solar radiation was recorded in the month of July which coincides with peak Rainy season accompanied with total cloud cover.

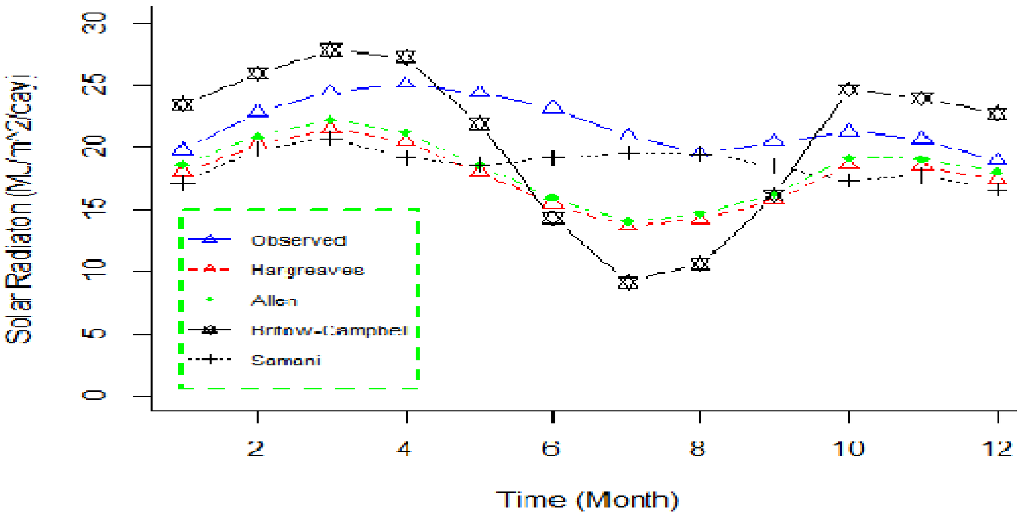

Fig. 1 - Observed and Estimated Model Solar Radiation

Table 2 - Computed Statistical Indicators between Observed and Estimated Models.

Model	**RMSE**	**MBE**	**R^2**	**CRM**	**MPE**
Hargreaves	4.6579	-4.1685	0.3188	0.1916	-19.0246
Allen	4.1595	-3.5740	0.3188	0.1643	-16.2882
Bristow-Campbell	5.7473	-1.1313	0.1750	0.0520	-5.4397

Samani	3.5443	-3.1506	0.3508	0.1448	-14.0538

Statistical performance analysis of each model was evaluated and shown in Table 2. The performance parameter values vary from one model to another with correlation coefficient R2 ranging between 0.1750 to 0.3508 with Samani model indicating the best correlation coefficient of 0.3508 followed by Allen and Hargreaves models with a value of 0.3188 each while the Bristow-Campbell showed the least correlation. The RMSE of Samani model was the least indicating the best performance model followed by Allen and Hargreaves models respectively while the Bristow-Campbell had the highest error. The negative signs in the statistical performance measurement indicate non-correlation between the observed and estimated radiation data.

6. Conclusion

Global solar radiation on horizontal surface assessment of Kano Airport, Nigeria and its environs was carried out in this work. Air temperature, relative humidity, solar radiation data were taken from the National Aeronautics and Space Administration (NASA) website and these data were analyzed statistically using R programming Air temperature was used to calibrate, validate and evaluate four models namely Hargreaves model, Allen model, Bristow-Campbell model and Samani model for estimating global solar radiation on horizontal surface. The Samani model has the least RMSE = 0.3508 and the highest R^2 of 0.3508 is recommended amongst the four models, although Allen model and Hargreaves model could also be considered in that order. The MBE and MPE indicated the level of non-correlation between the observed and the estimated solar radiation levels. The CRM shows the level of underestimation of the empirical models with the Hargreaves model being the most underestimated. Air temperature-based models could be subjected to temperature variations that might lead to error in estimating daily global solar radiation; daily air temperature could easily be sourced from any meteorological station in the absence of sunshine hour data. In the future works, the accuracy of the estimated solar radiation values of the empirical models using the air temperature can be further improved by using auto-calibration of the models in future works.

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