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Comparative Assessment of Angstrom Sunshine-Base Models for Estimation of Global Solar Radiation in Owerri, Nigeria

[1]Njoku M.C., [2]Anyanwu, E.E., [3]Uwalaka, D.U., [4]Anyadike, C.O., [5]Eyo, M.C., [6]Eze, I.J.,[7]Uchegbu, E.I.

[1,3,4,5,6,7]Department of Mechanical Engineering, Federal Polytechnic Nekede, P.M.B. 1036 Owerri, Imo-State, Nigeria

[2]Department of Mechanical Engineering, Federal University of Technology, P.M.B. 1526 Owerri, Imo-State, Nigeria

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ABSTRACT

Comparative assessment of the average monthly global solar radiation on horizontal surface for Owerri has been carried out with the use of five Angstrom sunshine-base models. Thirty years (1992 - 2022) of average monthly global solar radiation and sunshine hours are sourced from NASA and NIMET, respectively. The sunshine-base models are evaluated with the use of geographical and metrological data of Owerri and comparison is made based on estimated statistical error indices of Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), Coefficient of Determination (R^2) and percentage error to assess the applicability accuracy of the models. Results obtained shows that regression equations of Fagbenle and Page models satisfied viability criterion of MBE, RMSE, and MPE being close to zero, the R^2 values are reasonably close to unity and the percentage error agreed to within $\pm$ 10% of the measured average monthly global solar radiation on a horizontal surface in Owerri. Rietveld model closely followed with less prediction accuracy to those of Fagbenle and Page models, while, Glower and McCulloh and Turton models yield poor estimation of the average monthly global solar radiation on horizontal surface.

Key words: Angstrom model, meteorological data, solar radiation, statistical indices, sunshine

1. Introduction

Energy is a fundamental and valuable commodity that drives the wealth of nations. The economic success of any nation largely depends on the quality and quantity of energy it can produce and successfully distribute to the citizens. Present increase in the concern of environmental hazards cause by the use of carbon-base fuel has led to the pursuit of environmentally friendly energy sources.

Solar energy is harness from the sun; it is clean and abundant in most part of the world with the cost of its utilization coming only from the means of accessing it. Two methods exist for the harvest of solar energy: (i) conversion of solar radiation into electricity through the use of photovoltaic solar collector panel and (ii) conversion of solar energy into heat with the use of solar thermal collectors.

The design and installation of solar conversion devices require information on the amount of solar energy of the location where such devices will be mounted. The most appropriate means to obtain such information is by the measurement of the day-to-day values with the use of instruments like pyrheliometer and pyranometer. This has been reported to be a very tedious and costly exercise [1]. In consideration of the importance of global solar radiation data in architecture design, crop growth models, evapotranspiration models, hydrology, climatology and in the design of solar devices. Global solar radiation data is not readily available in many developing countries because of the affordability of the required equipment for measurement [2]. In some cases, solar radiation is estimated from the measurements of nearby stations with similar geographical characteristic [3]. Few meteorological stations in advance countries measure solar radiation in its required forms in terms of the type (global, direct or diffuse), time basis (hourly, daily, monthly or yearly) and surface placement (horizontal or tilted).

As a result of the importance of solar radiation data in solar energy study applications, different empirical models have been suggested for global solar radiation estimation base on available measurement of meteorological data such as sunshine, temperature, relative humidity, etc.

The Angstrom-Page sunshine-base model has been used by several authors to determine the solar radiation of different locations. Angstrom correlation coefficients of 0.23 and 0.38 were obtained for Onne [4]. For Makurdi, Angstrom correlation coefficients of 0.138 and 0.488 are obtained [5]. In different reports, Angstrom sunshine-base model has been used to estimate global solar radiation for Kebbi, Sokoto and Maiduguri in Northern Nigeria [6, 7 and 8]. Relationships between global solar radiation and relative sunshine for Calabar, Port Harcourt and Enugu have also been reported [9]. Some other sunshine based models have been reported in India [10, 11], Nairobi, Kenya [12], Turkey [13, 14] and Ibadan, Nigeria [15].

The main objective of this study is to evaluate the accuracy of five different sunshine-base Angstrom models when fitted with geographical and measured solar radiation data of Owerri. These models are also compared base on statistical error indices with a view to establish the most accurate model for the study location.

2. Materials

The study location is Owerri. It is a major cosmopolitan tropical city in Imo state, south-eastern part of Nigeria. Owerri is suited on Latitude and Longitude of 5.48^{o}N and 7.05^{o}E, respectively, and on an elevation of 120 m above sea level. Thirty years (1992 - 2022) of measured hours of bright sunshine averaged for a given month is collected from Nigerian Meteorological Agency (NIMET) Oshodi, Lagos [16]. Also, average monthly global solar radiation on a horizontal surface for the same period as that of the sunshine hour data is source from National Aeronautics and Space Agency (NASA) website [17].

3.0 Methodology

3.1 Prediction Models

The Angstrom sunshine-base model [18] is the first and commonly use model for the estimation of average monthly global solar radiation on a horizontal surface. Its modification by Page [19] resulted in the so-called Angstrom-Page model. Angstrom-Page model is a linear correlation between the ratio of global solar radiation on a horizontal surface to the corresponding extraterrestrial radiation on a horizontal surface at a given location and the ratio of average sunshine duration to the maximum possible sunshine duration. The Angstrom-Page sunshine-base model is given as [19]

$$\frac{\bar{H}}{\bar{H}_O} = a + b\left(\frac{\bar{n}}{\bar{N}}\right) \quad (1)$$

Where $\bar{H}$is the average monthly global solar radiation on a horizontal surface $(MJm^{-2}day^{-1})$; $\bar{H}_O$ is the average monthly extraterrestrial solar radiation on a horizontal surface $(MJm^{-2}day^{-1})$, $\bar{n}$ is the average monthly daily number of hours of bright sunshine, $\bar{N}$ is the day length and a and b are climatologically determine regression constants. From Equ. (1), the ratios on the left hand side and right hand side are called the clearness index $(K_T = \bar{H}/\bar{H}_o)$ and relative sunshine $(\bar{n}/\bar{N})$, respectively. The average monthly extraterrestrial solar radiation $(\bar{H}_O)$ can be computed from the following equation [19]

$$\bar{H}_O = \frac{24\ x3600\,G_{sc}}{\pi}\left(1 + 0.033cos\frac{360n}{365}\right)\ x\ \left(cos\emptyset\ cos\delta\ sin\omega_s + \frac{\pi\omega_s}{180}\ sin\emptyset\ sin\delta\right) \quad (2)$$

Where G_{sc} is the solar constant given as 1367W/m^2 [19], n is the day of the year, $\emptyset$ is the latitude of study location, δ is the solar declination and ω_s is the sunset hour angle.

The solar declination (δ) and sunset hour angle (ω_s) can be computed from the following equations [19]

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

$$\omega_s = cos^{-1}(-tan\emptyset\ tan\delta) \quad (4)$$

For a given month, the average monthly day length can be computed from the following equation [19]

$$\bar{N} = \frac{2}{15}cos^{-1}(-tan\emptyset\ tan\delta) \quad (5)$$

3.2 Models Studied

The following five sunshine-base Angstrom models proposed by different authors for the estimation of global solar radiation are studied

Model 1: Glower and McCulloch Model

Glower and McCulloch proposed a model which takes into account the effect of the latitude of the study location$(\emptyset)$ as an additional input and is valid for $(\emptyset < 60^0)$ [20]. The model is given as:

$$\frac{\bar{H}}{\bar{H}_o} = 0.29\ Cos\emptyset + 0.52\left(\frac{\bar{n}}{\bar{N}}\right) \quad (6)$$

Model 2: Page Model

The Page model is the same as the Angstrom-Page model, except that the coefficients were recalculated by Page for use anywhere in the world [21]. The model is given as:

$$\frac{\bar{H}}{\bar{H}_o} = 0.23 + 0.48\left(\frac{\bar{n}}{\bar{N}}\right) \quad (7)$$

Model 3: Rietveld Model

Rietveld proposed a unified correlation to calculate the average monthly solar radiation on a horizontal surface. This he developed from measured data obtained from 42 metrological stations in different countries. According to him the model is applicable anywhere in the world [22]. The model is given as:

$$\frac{\bar{H}}{H_O} = 0.18 + 0.62\left(\frac{\bar{n}}{\bar{N}}\right) \quad (8)$$

Model 4: Fagbenle Model

Fagbenle proposed a model for the rain forest zone of Nigeria [23] as

$$\frac{\bar{H}}{H_O} = 0.28 + 0.39\left(\frac{\bar{n}}{\bar{N}}\right) \quad (9)$$

Model 5: Turton Model

Turton developed a model for humid tropical countries [24] as

$$\frac{\bar{H}}{H_O} = 0.38 + 0.40\left(\frac{\bar{n}}{\bar{N}}\right) \quad (10)$$

3.3 Evaluation Methods

It is important to evaluate the accuracy and performance of the estimated average monthly global solar radiation from each of the Angstrom sunshine-base models (Equations 6 - 10) and compare the values obtained to the measured average monthly global solar radiation. The following statistical error tests which generally provide reasonable assessment criteria for evaluation of solar radiation estimation models are used: Mean Bias Error (MBE), Root Mean Square Error (RMSE) and Mean Percentage Error (MPE). The RMSE values gives information about the short term performance of the correlations by using a term by term comparison of the deviations between the estimated and measured values of average monthly global solar radiation. MBE and MPE give information on the long-term performance of the model. Positive and negative values of MBE and MPE indicate overestimation and underestimation, respectively.

For a model to be viable, it is desirable that the values of RMSE, MBE and MPE statistical indices should be close to zero. These statistical indices are defined as [25]

$$RMSE = \left[\frac{\sum(H_{est} - H_{mea})^2}{n_p}\right]^{1/2} \quad (11)$$

$$MBE = \frac{\sum(H_{est} - H_{mea})}{n_p} \quad (12)$$

$$MPE = \frac{\left[\sum\left(\frac{H_{est} - H_{mea}}{H_{mea}} X\ 100\right)\right]}{n_p} \quad (13)$$

Where H_{est} and H_{mea} are the estimated and measured average monthly global solar radiation respectively, and n_p is the number of possible outcome.

The coefficient of determination (R^2), is also another statistical parameter used as evaluation criterion. The R^2 value ranges between zero to one, but should be reasonably close to one for higher accuracy of prediction of a model.

$$R^2 = 1 - \frac{\sum\ (H_{mea} - H_{est})^2}{\sum\ (H_{mea} - \bar{H}_{mea})^2} \quad (14)$$

$\bar{H}_{mea}$ is the mean of measured average monthly global solar radiation.

Validation of comparative assessment of the models is confirmed for each month by the estimation of the relative percentage error(e) between the measured and predicted average monthly global solar radiation on a horizontal surface. The relative percentage error for each month is estimated from

$$e = \left(\frac{H_{est} - H_{mea}}{H_{mea}}\right) x\ 100 \quad (15)$$

4.0 Results and Discussion

Table 1, presents the measured average monthly global solar radiation and sunshine hours for Owerri. At the study location, the months of the dry season (October, November, December, January, February, and March) and rainy season (April, May, June, July, August, and September) contribute 52.10% and 47.90% of the measured average monthly global solar radiation, respectively. The K_T values range between 0.405 – 0.459 and 0.351 - 0.421, for the dry and rainy season periods, respectively. The highest and lowest value of the average monthly K_T values occurred in the months of December (0.421) and August (0.351), respectively. The relative sunshine duration varies from 0.202 and 0.484 for the months of the rain and dry season, respectively. August recorded the worst relative sunshine duration value as seen in Fig 1. This is expected as August is known to be a month of high level of rainfall, hence, most days in this month are usually characterize with heavily overcast periods. Thus, a low level of global solar radiation is expected to be harvested in August.

Table 1 meteorological data for Owerri

	$\bar{H}(MJm^{-2}day^{-1})$	$\bar{N}$
JAN	15.40	11.60
FEB	16.16	11.83
MAR	15.62	11.97
APR	15.82	12.12
MAY	15.27	12.22
JUN	14.56	12.31
JUL	13.02	12.29
AUG	13.10	12.03
SEPT	13.10	12.18
OCT	14.67	11.88
NOV	15.20	11.75
DEC	15.26	11.69

Table 2 summary of statistical results

model	RMSE	MBE	MPE (%)	R^2
Glower and McCulloch Model	2.813	2.729	18.38	0.3351
Page Model	0.5887	0.0737	0.3448	0.9415
Rietveld Model	1.002	0.1954	0.9514	0.8306
Fagbenle Model	0.7661	0.6371	4.3262	0.9010
Turton Model	4.3934	4.3667	29.72	-2.2568

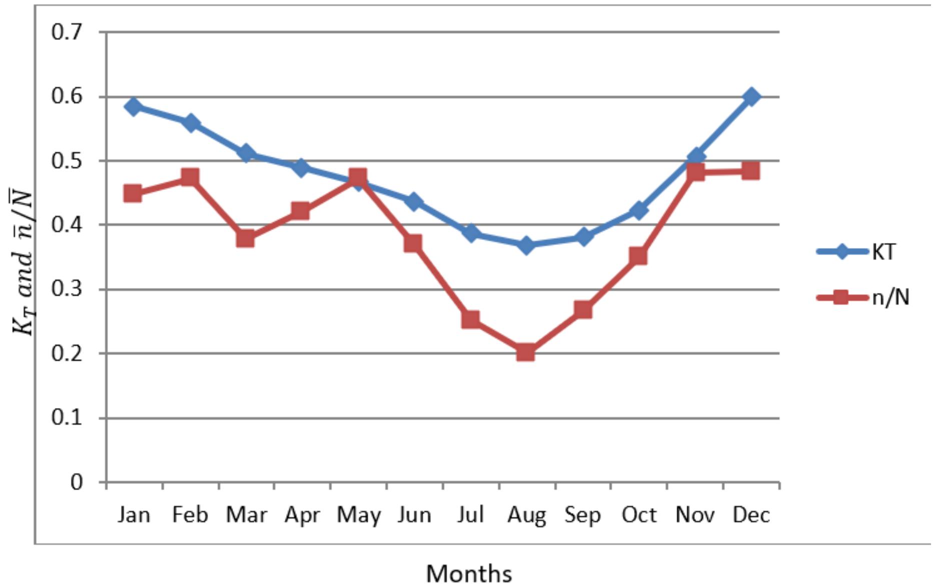

Figure 1 monthly variation of K_T and $\bar{n}/\bar{N}$

From Table 2, it is observed that the RMSE values for all the models indicate that there is an error in the estimated values of global solar radiation. Chen et al [26] reported that RMSE value close to one is efficient. Thus, from Table 2, that of Rietveld model (1.002 MJm^{-2} day^{-1}) is closer to one followed by those of Fagbenle model (0.7661 MJm^{-2} day^{-1}) and Page model (0.5887 MJm^{-2} day^{-1}).

The MBE value of 0.0737 MJm^{-2} day^{-1} is obtained for Page model which is close to zero when compared to the values obtained for the Rietveld (0.1954 MJm^{-2} day^{-1}) and Fagbenle (0.6371 MJm^{-2} day^{-1}) models.

Ahmad et al. [27] suggested that MPE value less than 5 % is viable. Three of the models under study exhibited this characteristic. These include; Page model (0.3448 %), Rietveld model (0.9514 %) and Fagbenle model (4.3262 %). It is observed that Page model recorded the lowest MPE value. Thus, this indicates that the MPE value of Page model is more efficient than the other models.

The value of R^2 should be between the range of zero and one. This is the case for all the models expert that of Turton (-2.2568). However, for higher accuracy the value of R^2 should be close to one. It is observed that Page model (0.9415) is closer to one compare to the other models.

A comparison of the average monthly global solar radiation values of the measured and those of the models are shown in Fig 2. While, the percentage error deviation is presented in Fig 3. It is observed from Fig 2, that the values of average monthly global solar radiation for the measured data and those estimated by Page, Fagbenle and Rietveld models fall within approximately similar range of solar radiation depending on the month of the year as compare to the models of Glower and McCulloh and Turton that estimate higher values of average monthly global solar radiation. The percentage error deviation reached 27.39 % for the Glower and McCulloch models, 8.89 % for Fagbenle model, 12.73 % for Rietveld model, 9.69% for Page model and 38.42 % for Turton model as shown in Fig 3. Still on Fig 3, the months of the dry season are seen to follow similar curve patterns for Page, Fagbenle and Rietveld models. Though, with slight deviation in the monthly percentage error values. While, in the months of dry season, the curve patterns of these three models are seen to deviate widely from one another. But those of Page and Fagbenle models are seen to fall within the ± 10 error value range. The percentage error range of Fagbenle is seen to fall on the positive side and less, while, Page model has negative value and more. Thus, Fagbenle and Page models that estimated percentage error within the range of ± 10 % is preferable.

The statistical results evaluated from the estimated average monthly global solar radiation of the five models and the measured average monthly global solar radiation indicate that Fagbenle model followed by Page and Rietveld models are more appropriate for estimation of average monthly global solar radiation for Owerri. Thus, these models can also be used for other localities with similar meteorological conditions for the prediction of monthly global solar radiation.

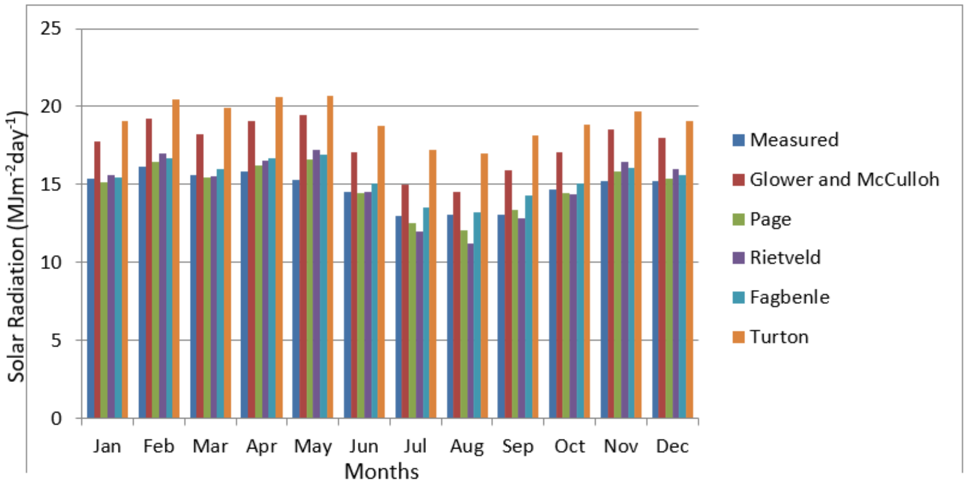

Figure 2 comparison of measured and model estimated global solar radiation

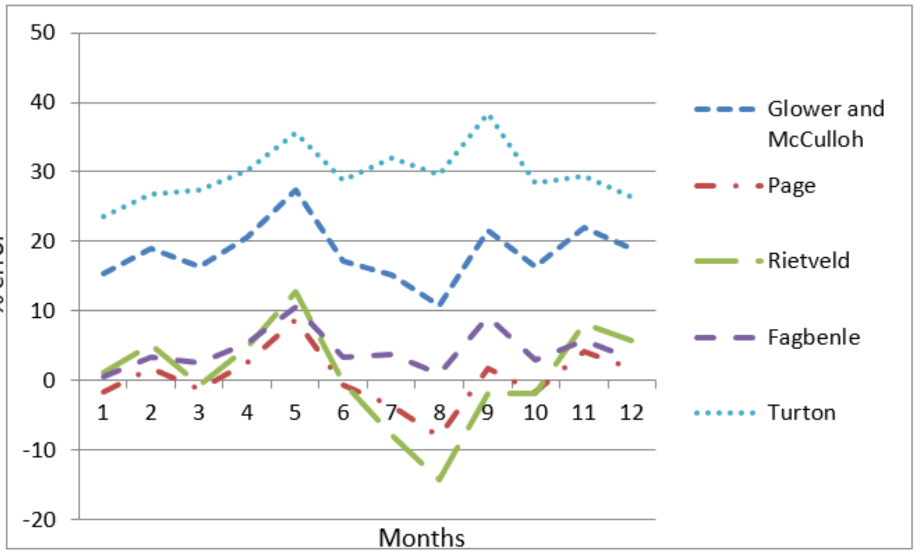

Figure 3 comparisons of monthly percentage error

5.0 Conclusion:

This study has established that in Owerri, August is identified as the worst month of the harvest of global solar radiation. More also, among the Angstrom sunshine-base models examined, Fagbenle and Page models outperformed the other models on consideration of the statistical evaluation carried out, followed by that of Rietveld models. Hence, for proper evaluation and installation of solar equipment in Owerri and locations with similar meteorological conditions Fagbenle, Page and Rietveld models may be used to approximately evaluate correctly the values of monthly global solar radiation incident on a horizontal surface.

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