https://dx.doi.org/10.4314/dujopas.v10i1c.7
ISSN (Print): 2476-8316
ISSN (Online): 2635-3490
Dutse Journal of Pure and Applied Sciences (DUJOPAS), *Vol. 10 No. 1c March 2024*

New Models for Estimation of Diffuse Solar Radiation for Warri, Nigeria

Akpootu, D. O. [1] and Salifu, S. I. [2*]
[1]Department of Physics,
Usmanu Danfodiyo University,
Sokoto, Nigeria

[2]Department of Physics,
Kogi State College of Education Technical,
Kabba, Nigeria

Email: imaben22@gmail.com

Abstract

This study utilized a 22-year dataset (2001-2022) comprising monthly average daily global solar radiation, diffuse solar radiation, relative humidity, atmospheric pressure, wind speed, and mean temperature for Warri (Latitude 5.52 °N, Longitude 5.73 °E and 6.10 m above sea level). Nineteen models, categorized into modified Page, Liu, and Jordan models; clearness index and one variable models; two variable models; three variable models; and four variable models, were developed and statistically tested using the following validation indices of Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), t-test, and coefficient of determination (R^2). Among the models, the linear page model from the modified Page, Liu, and Jordan category, the model that relates the diffuse solar radiation with clearness index and mean temperature for clearness index and one variable models, the model that relates wind speed and atmospheric pressure for two variable models, and the model that relates wind speed, atmospheric pressure and relative humidity for three variable models were found more appropriate. Upon ranking the best-performing models from each category, the model that relates that diffuse solar radiation with clearness index and mean temperature performed best as the most suitable model for estimating diffuse solar radiation in Warri.

Keywords: Diffuse solar radiation, NASA, Models, Validation Indices, Warri

INTRODUCTION

The solar energy incident on earth's surface is influenced by multiple factors, encompassing astronomical elements such as atmospheric transmittance and extraterrestrial radiation, as well as physical factors like latitude and the reciprocal relative distance between the earth and the sun. Meteorological variables, including actual sunshine duration, sunset hour angle, relative humidity, ambient temperature, and cloudiness at specific locations, are also pivotal in this context (Duzen and Aydin, 2012; Adaramola, 2012; Khatib *et al*., 2012; Wang *et al*., 2016; Qui *et al*., 2022). The term renewable energy refers to sources naturally replenished over time with minimal or no negative environmental impact. Examples include biomass, geothermal, hydropower, solar energy, and wind energy (Myers, 2013). Solar energy, distinguished by its significantly reduced environmental impact compared to conventional sources like fossil fuels, is anticipated to play a crucial role in mitigating carbon emissions and creating

**Author for Correspondence*

employment opportunities, particularly in developing nations (Akpootu *et al.*, 2015; Guermoui *et al.*, 2020).

The accurate estimation of diffuse solar radiation presents formidable challenges in solar energy research due to constrained ground-based measurements. The high costs of devices like pyranometers and solarimeters impede data collection in developing countries like Nigeria, resulting in a dearth of comprehensive and long-term data. This scarcity hampers effective model development and validation, posing challenges in assessing accuracy and generalizability, especially for region-specific models tailored to diverse environmental conditions. The diversity in existing models, with variations in complexity, input data requirements, and accuracy, further complicates the situation. Architects and engineers utilize solar radiation data to optimize natural light usage, reducing artificial lighting needs and overall energy consumption. Additionally, applying diffuse radiation in passive solar design aids in heating and cooling buildings, enhancing energy efficiency and reducing reliance on traditional energy sources (Iqbal, 1983; Myers, 2013; Goswami, 2015).

After the pioneer works of Page (1961), Liu and Jordan (1960), many researchers have made significant contributions to the estimation of diffuse solar radiation. Gopinathan and Soler (1995) developed models covering a wide latitude range, emphasizing the importance of incorporating clearness-index (K_T) and sunshine fraction (S), along with declinations and latitude, for accurate predictions. Udo (2000) categorized sky conditions in Ilorin based on clearness index and relative sunshine over a two-year period, revealing distinct patterns. Mubiru and Banda (2006) focused on Kampala, finding that models linking diffuse transmittance with relative sunshine duration were reliable for predicting diffuse solar radiation. Sanusi and Abisoye (2013) explored methods in Lagos, introducing new models tailored for the region. The second-order quadratic model showed superior accuracy. Akpootu and Mustapha (2015) conducted a comparative study in Yola over 31 years, demonstrating the reliability of established models for predicting diffuse solar radiation. In another study, Akpootu *et al.*, (2015) developed several regression models to estimate diffuse solar radiation in Yola, Nigeria, using 31 years of local climate data, including solar radiation, sunshine duration, and other meteorological variables. Their research improved the Page model by adding one meteorological factor, enhancing solar radiation estimates in Yola. The models' accuracy was evaluated using statistical tests like MBE, RMSE, MPE, t-test, and R^2, leading to the recommendation of specific models based on these statistical indicators.

The study aims to achieve these specific objectives: (i) to identify the most suitable models for estimating diffuse solar radiation in Warri, utilizing modified versions of the Page, Liu, and Jordan models. (ii) to develop correlation models incorporating two to four variables for the estimation of diffuse solar radiation. (iii) to rank these models to ascertain the most appropriate one for accurate estimation and (iv) lastly, to analyze the correlations between the estimated or predicted values and the measured diffuse solar radiation values, providing a comprehensive evaluation of the model performance.

METHODOLOGY

Data collection

For this study, twenty-two (22) years (2001-2022) monthly average climatic data for Warri (Latitude 5.52 ^{o}N, Longitude 5.73 ^{o}E and 6.10 m above sea level) which is located in the coastal region of Nigeria, was acquired. The data include measurements of all-sky surface shortwave diffuse irradiance, global solar radiation, wind speed, mean temperatures, surface pressure, and relative humidity. The data was obtained from the National Aeronautics and Space Administration (NASA) website.

The mean daily extraterrestrial radiation on a horizontal surface, denoted by H_O and measured in $MJm^{-2}day^{-1}$, can be estimated for each day of a month by averaging the daily values over that month (Iqbal, 1983; Zekai, 2008; Saidur *et al.*, 2009). This calculation is based on the equations presented by Iqbal (1983) and Zekai (2008) as reported by Akpootu and Momoh (2014); Akpootu and Abdullahi (2022)

$$H_o = \left(\frac{24}{\pi}\right) I_{sc}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right]\left[\cos\varphi\cos\delta\sin\omega_s + \left(\frac{2\pi\omega_s}{360}\right)\sin\varphi\sin\delta\right] \tag{1}$$

where $I_{SC} = 1367 Wm^{-2}$

The parameters I_{sc}, φ, δ, and ω_s, representing the solar constant, site latitude, solar declination, and mean sunrise hour angle, respectively, are utilized in the equation to determine H_O. Additionally, n, the number of days in a year from January 1st to December 31st, is incorporated into the calculation. The solar declination and mean sunrise hour angle are determined using the methods presented by Iqbal (1983) and Zekai (2008) as reported by Akpootu *et al.* (2022) are given by:

$$\delta = 23.45\sin\left\{360\left(\frac{284+n}{365}\right)\right\} \tag{2}$$

$$\omega_s = \cos^{-1}(-\tan\varphi\tan\delta) \tag{3}$$

The clearness index, K_T, provides valuable information about the availability of solar radiation at a specific location. K_T value of one (1) indicates that the sky is completely clear and that the maximum amount of solar radiation is reaching the Earth's surface. K_T value of zero (0) indicates that the sky is completely overcast and that no solar radiation is reaching the Earth's surface. K_T values typically range between 0.2 and 0.8, with higher values indicating clearer skies and more available solar radiation (Iqbal, 1983). Mathematically, the clearness index as reported by Akpootu *et al.*, (2023) is given by:

$$K_T = \frac{H_m}{H_o} \tag{4}$$

The total incoming solar radiation, denoted by H_m, is the measured global solar radiation in $MJm^{-2}day^{-1}$

2.2 Developed Diffuse Solar Radiation Models

The proposed models of diffuse solar radiation based on the modified Page, Liu and Jordan models are:

$$\frac{H_d}{H_m} = a + bK_T \tag{5}$$

$$\frac{H_d}{H_m} = a + bK_T + cK_T^{\,2} \tag{6}$$

$$\frac{H_d}{H_m} = a + bK_T + cK_T^{\ 2} + dK_T^{\ 3} \tag{7}$$

$$\frac{H_d}{H_m} = a + bK_T + cK_T^{\ 2} + dK_T^{\ 3} + eK_T^{\ 4} \tag{8}$$

To ensure that no relevant parameters are omitted, multiple linear regression was employed, using the four meteorological parameters (WS ,T_{mean}, RH ,PS) as independent variables and $\frac{H_d}{H_m}$ as the dependent variable. These meteorological parameters represent, respectively, monthly average daily wind speed (ms^{-1}), monthly average mean temperature (^{O}C), monthly average daily relative humidity ($\%$) and monthly average daily atmospheric pressure (hPa).

The other proposed diffuse solar radiation models, developed in this study, involves correlations of the linear Page model with meteorological parameters as follows:

$$\frac{H_d}{H_m} = a + b\frac{H}{H_o} + cWS \tag{9}$$

$$\frac{H_d}{H_m} = a + b\frac{H}{H_o} + cRH \tag{10}$$

$$\frac{H_d}{H_m} = a + b\frac{H}{H_o} + cPS \tag{11}$$

$$\frac{H_d}{H_m} = a + b\frac{H}{H_o} + cT_{mean} \tag{12}$$

The proposed two variables correlation models are:

$$H_d = a + bWS + cRH \tag{13}$$

$$H_d = a + bWS + cT_{mean} \tag{14}$$

$$H_d = a + bWS + cPS \tag{15}$$

$$H_d = a + bRH + cT_{mean} \tag{16}$$

$$H_d = a + bRH + cPS \tag{17}$$

$$H_d = a + bT_{mean} + cPS \tag{18}$$

The proposed three variables correlation models are:

$$H_d = a + bWS + cRH + dT_{mean} \tag{19}$$

$$H_d = a + bWS + cT_{mean} + dPS \tag{20}$$

$$H_d = a + bWS + cPS + dRH \tag{21}$$

$$H_d = a + bRH + cT_{mean} + dPS \tag{22}$$

The proposed four variables correlations model is:

$$H_d = a + bWS + cRH + dT_{mean} + ePS \tag{23}$$

From equations (5) to (23), the algebraic constants a, b, c, d, and e are known as empirical constants or coefficients.

The Minitab software (version 21.2) package was employed to assess the model parameters used in obtaining the empirical constants.

Accuracy of the Models

The effectiveness of each model was statistically tested by employing the following indices, Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), and t-test. The equations for calculating MBE, RMSE, and MPE, based on the method proposed by El-Sebaii and Trabea (2005) as proposed by Akpootu *et al*. (2015) are presented as follows:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(H_{d_{i,cal}} - H_{d_{i,meas}}\right) \tag{24}$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(H_{d_{i,cal}} - H_{d_{i,meas}}\right)^2\right]^{\frac{1}{2}} \tag{25}$$

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{H_{d_{i,meas}} - H_{d_{i,cal}}}{H_{d_{i,meas}}}\right) \text{x } 100 \tag{26}$$

As described by Bevington (1969), the t-test, being one of the statistical methods employed to evaluate mean values, utilizes a random variable denoted as t, possessing $n-1$ degrees of freedom. Also, according to (Akpootu *et al*., 2019c,d; Akpootu *et al*., 2023) t –test is a non-dimensional parameter.

It can be expressed as follows:

$$t = \left[\frac{(n-1)(MBE)^2}{(RMSE)^2 - (MBE)^2}\right]^{\frac{1}{2}} \tag{27}$$

As derived from equations (24), (25), and (26), the variables $H_{d_{i,meas}}$ and $H_{d_{i,cal}}$ represents the i^{th} measured and i^{th} calculated values of daily diffuse solar radiation, respectively, along with the total number of observations denoted by n. Lower values of MBE, RMSE, MPE, and t-test indicate superior model performance. These statistical measures assess the accuracy of a model's predictions compared to actual observed values. Positive values of MPE and MBE quantify the average degree of overestimation in the model's predictions, while negative values indicate underestimation (Akpootu *et al*., 2023). According to Merges *et al*., (2006); Gana and Akpootu (2013a; b); Akpootu and Gana, (2014); Akpootu and Sulu, (2015); Olomiyesan *et al*., (2021), for a model to perform better, a low value for MPE is desirable and the percentage error between –10 % and +10 % is considered acceptable. Also, Halouani *et al*., (1993); Almorox *et al*., (2005) and Chen *et al*., (2004) did recommend a zero value for MBE as ideal and a low value for RMSE as desirable.

To achieve a more accurate and reliable data modeling outcome, the coefficient of determination (R^2) should strive to approach a value of 1, ideally reaching 100% (Akpootu and Iliyasu 2015a,b; Akpootu *et al.*, 2019a,b). This indicates a strong correlation between the predicted and observed values, suggesting a robust and well-fitting model.

RESULTS AND DISCUSSION

The results of the modified Page, Liu and Jordan models; clearness index and one variable correlation models; two variables correlation model; three variables correlation models and four variables correlation model based on equations (5) to (23) are:

$$\frac{H_d}{H_m} = 0.9276 - 0.698K_T \quad (28a)$$

$$\frac{H_d}{H_m} = 0.449 + 1.58K_T - 2.66cK_T^{\ 2} \quad (28b)$$

$$\frac{H_d}{H_m} = 5.27 - 32.70K_T + 77.60K_T^{\ 2} - 62.0K_T^{\ 3} \quad (28c)$$

$$\frac{H_d}{H_m} = 6.5 - 45K_T + 121K_T^{\ 2} - 130dK_T^{\ 3} + 40K_T^{\ 4} \quad (28d)$$

$$\frac{H_d}{H_m} = 0.869 - 0.649\frac{H}{H_o} + 0.096WS \quad (28e)$$

$$\frac{H_d}{H_m} = 1.128 - 0.813\frac{H}{H_o} - 0.00272RH \quad (28f)$$

$$\frac{H_d}{H_m} = 17.80 - 0.995\frac{H}{H_o} - 0.01658PS \quad (28g)$$

$$\frac{H_d}{H_m} = 0.594 - 0.790\frac{H}{H_o} + 0.01442T_{mean} \quad (28h)$$

$$H_d = 20.64 - 8.42WS - 0.0883RH \quad (28i)$$

$$H_d = -16.72 + 3.34WS + 0.968T_{mean} \quad (28j)$$

$$H_d = 616.2 + 3.71WS - 0.6021PS \quad (28k)$$

$$H_d = -4.89 - 0.0701RH + 0.800T_{mean} \quad (28l)$$

$$H_d = 538.9 + 0.0095RH - 0.5249PS \quad (28m)$$

$$H_d = 484 + 0.084T_{mean} - 0.472PS \quad (28n)$$

$$H_d = -8.42 + 2.08WS - 0.0668RH + 0.894T_{mean} \quad (28o)$$

$$H_d = 510 + 4.64WS + 0.245T_{mean} - 0.503PS \quad (28p)$$

$$H_d = 736.60 + 6.42WS - 0.7268PS + 0.0506RH \quad (28q)$$

$$H_d = 509 + 0.0053RH + 0.047T_{mean} - 0.497PS \quad (28r)$$

$$H_d = 816 + 6.61WS + 0.0624RH - 0.118T_{mean} - 0.804PS \quad (28s)$$

3.1 Modified Page, Liu and Jordan Models

Below are the statistical analysis summary of the models based on the modified Page, Liu and Jordan models

Table 1: Modified Page, Liu and Jordan Models Statistical Error indicators

Models	R^2	MBE	RMSE	MPE	t
Eqn 28a	82.94%	-0.0029	0.2979	-0.1133	0.0323
Eqn 28b	86.16%	0.0056	0.2645	-0.1477	0.0706
Eqn 28c	88.24%	-0.1023	0.2694	0.9885	1.3611
Eqn 28d	88.25%	-1.2121	1.2450	12.5597	14.1373

Table 1 presents a condensed overview of the statistical validation test conducted on the modified Page, Liu and Jordan models for Warri. Among the models, the modified equation 28d, a polynomial of degree 4, exhibits the highest R^2 value as 88.25 %. Notably, the linear equation (equation 28a) had the lowest for MBE, MPE, and t-test values with underestimation of 0.0029 $MJm^{-2}day^{-1}$, 0.1133 % in its estimated values and 0.0323 respectively. The quadratic regression model (equation 28b), has the lowest RMSE value of 0.2645 $MJm^{-2}day^{-1}$. The results equally shows that MPE values for all the developed models excluding equation 28d are within the acceptable range of $\pm$ 10 %. The t-test values for equation 28a, equation 28b and equation 28c models are significant at 95% and 99% while the model equation 28d isn't.

Table 2: Ranks obtained from the estimated modified Page, Liu and Jordan Models for Warri

Models	R^2	MBE	RMSE	MPE	t	Rank
Eqn 28a	4	1	3	1	1	**10**
Eqn 28b	3	2	1	2	2	**10**
Eqn 28c	2	3	2	3	3	13
Eqn 28d	1	4	4	4	4	17

Table 2 above provides a summary of the ranks derived from the estimated modified Page, Liu and Jordan models for Warri. It is evident from the table that the ranks achieved by each model range from 10 to 17. The comprehensive findings indicate that both the quadratic regression model, as defined in equation 28b, and the linear regression model (equation 28a) proves to be more accurate when compared to the other four models.

Further comparison of both model equations 28a and 28b was carried out

Table 3: Statistical error indicators for equation 28a and equation 28b

Models	R^2	MBE	RMSE	MPE	t
Eqn 28a	82.94%	-0.0029	0.2979	-0.1133	0.0323

Eqn 28b	86.16%	0.0056	0.2645	-0.1477	0.0706

Table 4: Ranks Obtained from table 3

Models	R^2	MBE	RMSE	MPE	t	Rank
Eqn 28a	2	1	2	1	1	**7**
Eqn 28b	1	2	1	2	2	8

Overall findings based on table 3 and 4 shows that the linear model (equation 28a) is the most suitable model for estimating diffuse solar radiation in Warri based on the modified Page, Liu and Jordan models.

Clearness Index and One Variable Correlation Models

Table 5: Clearness index and one variable models statistical error indicators

Models	R^2	MBE	RMSE	MPE	t
Eqn 28e	83.55%	-0.0065	0.2919	-0.0820	0.0735
Eqn 28f	85.30%	0.0021	0.2761	-0.1689	0.0248
Eqn 28g	92.34%	0.0080	0.2015	-0.1117	0.1320
Eqn 28h	87.38%	-0.0068	0.2583	-0.0070	0.0871

Table 5 provides a summarized overview of the statistical validation tests conducted on the clearness index and a single variable model in this study. Among these models, modified equation 28g stands out with the highest R^2 value at 92.34 % and the lowest RSME value of 0.2015 $MJm^{-2}day^{-1}$. Notably, equation 28f exhibits the lowest values for both MBE and t-test, recording overestimation of 0.0021 $MJm^{-2}day^{-1}$ in its estimated value and 0.0248 respectively. Regarding MPE, equation 28h achieves the lowest value with underestimation of 0.0070 % in its estimated value. Furthermore, the results indicate that the MPE values for all developed models fall within the acceptable range of ±10%. Additionally, the t-test values for all models are statistically significant at both 95% and 99%.

Table 6: Ranks obtained from the estimated clearness index and one variable correlation models for Warri

Models	R^2	MBE	RMSE	MPE	t	Rank
Eqn 28e	4	2	4	2	2	14
Eqn 28f	3	1	3	4	1	12
Eqn 28g	1	4	1	3	4	13
Eqn 28h	2	3	2	1	3	**11**

Table 6 above presents a concise summary of the rankings obtained from the estimated clearness index and one variable models for Warri. The table clearly shows that the ranks attained by each model fall within the range of 11 to 14. The overall findings indicated that, in estimating diffuse solar radiation in Warri, model that relates the diffuse solar radiation with clearness index and mean temperature (equation 28h) demonstrates greater performance and accuracy compared to the other three models.

Two Variables Correlation Models

Table 7: Two variables correlation models statistical error indicators

Models	R^2	MBE	RMSE	MPE	t
Eqn 28i	43.90%	0.0018	0.5371	-0.3215	0.0108
Eqn 28j	73.29%	0.0035	0.3706	-0.1928	0.0316
Eqn 28k	91.20%	-0.0180	0.2135	0.1407	0.2809
Eqn 28l	82.59%	0.0047	0.2993	-0.1468	0.0521
Eqn 28m	88.29%	0.0560	0.2516	-0.6488	0.7572
Eqn 28n	88.29%	-0.0889	0.2609	0.8710	1.2012

Table 7, provides a summarized overview of the statistical validation tests conducted on the two variable models in this study. Among these models, equation 28k stands out with the highest R^2, the lowest MPE and RMSE values of 91.20 %, with overestimation of 0.1407 % in its estimated value and 0.2135 $MJm^{-2}day^{-1}$ respectively. Notably, equation 28i exhibits the lowest for MBE and t-test values with an overestimation of 0.0018 $MJm^{-2}day^{-1}$ in its estimated value and 0.0108 respectively. Furthermore, the results indicate that the MPE values for all developed models fall within the acceptable range of ±10%. Additionally, the t-test values for all models are statistically significant at both 95% and 99%.

Table 8: Ranks obtained from the estimated two variables models for Warri

Models	R^2	MBE	RMSE	MPE	t	Rank
Eqn 28i	6	1	6	4	1	18
Eqn 28j	5	2	5	3	2	17
Eqn 28k	1	4	1	1	4	**11**
Eqn 28l	4	3	4	2	3	16
Eqn 28m	2	5	2	5	5	19
Eqn 28n	2	6	3	6	6	23

Table 8 above provides a summary of the ranks derived from the estimated two variables models for Warri. It is evident from the table that the ranks achieved by each model range from 11 to 23. The comprehensive findings indicate that the model that relates diffuse solar radiation with the wind speed and atmospheric pressure (equation 28k), proves to be more accurate in estimating diffuse solar radiation in Warri when compared to the other five models in terms of the two variable correlation models above.

Three Variables Correlation Models

Table 8: Three variable models statistical error indicators for Warri

Models	R^2	MBE	RMSE	MPE	t
Eqn 28o	83.41%	-0.0018	0.2920	-0.0772	0.0203
Eqn 28p	92.48%	0.5547	0.5885	-5.8650	9.3558
Eqn 28q	94.36%	-0.0341	0.1737	0.3241	0.6641
Eqn 28r	88.31%	-0.8242	0.8599	8.5886	11.1519

Table 8 presents a condensed overview of the statistical validation test conducted on the three variables correlation models for this study. Among the models, the equation 28q, exhibits the highest R^2 and lowest RSME with values 94.36 % and 0.1737 $MJm^{-2}day^{-1}$ respectively. The model equation equation 28o had the lowest MBE, MPE, and t-test values with underestimation of 0.0018 $MJm^{-2}day^{-1}$, 0.0772 % in its estimated value and 0.0203 respectively. The results equally show that MPE values for all the developed models are within the acceptable range of $\pm$10 %. The t-test values for equation 28o and equation 28q models are significant at 95% and 99% while the other two models aren't.

Table 9: Ranks obtained from the estimated three variables correlation models for Warri

Models	R^2	MBE	RMSE	MPE	t	Rank
Eqn 28o	4	1	2	1	1	9
Eqn 28p	2	3	3	3	3	14
Eqn 28q	1	2	1	2	2	**8**
Eqn 28r	3	4	4	4	4	19

Table 9 above provides a summary of the ranks derived from the estimated three variable correlation models for Warri. It is evident from the table that the ranks achieved by each model range from 8 to 19. The comprehensive findings indicate that the model that relates diffuse solar radiation with wind speed, atmospheric pressure and relative humidity (equation 28q), proves to be more accurate in estimating diffuse solar radiation in Warri when compared to the other three models.

Four Variables Correlation Model

Table 10: Four variable model statistical error indicators for Warri

Model	R^2	MBE	RMSE	MPE	t
Eqn 4.1s	94.48%	-0.5321	0.5581	5.5516	10.4741

Table 10 above is the summary of the statistical analysis for the four variable correlation model for Warri, indicating that the model has underestimation of 0.5321 $MJm^{-2}day^{-1}$ and overestimation of 5.5516 % in its estimated values respectively. The R^2 value is 94.48 %. The t-test value is not significant at 95% and 99%.

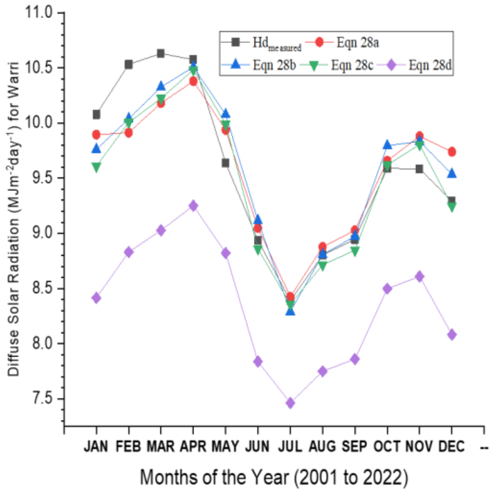

Figure 1: Comparison between the measured diffused solar radiation and estimated modified Page, Liu and Jordan models for Warri.

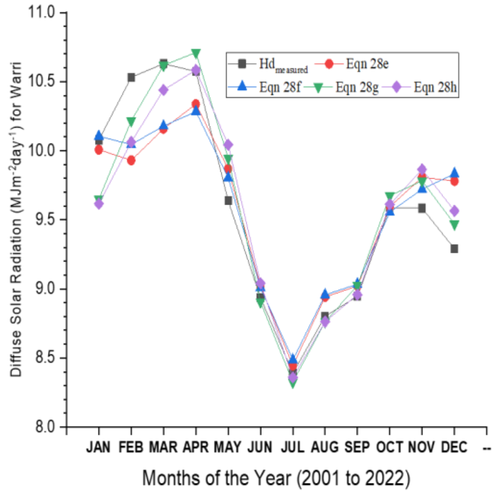

Figure 2: Comparison between the measured diffused solar radiation and estimated clearness index and a single variable models for Warri.

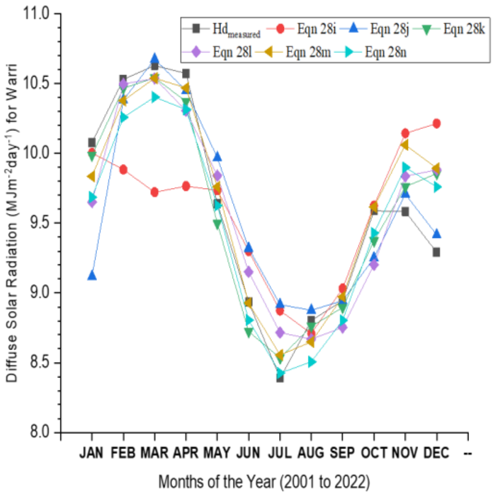

Figure 3: Comparison between the measured diffused solar radiation and estimated two variables models for Warri.

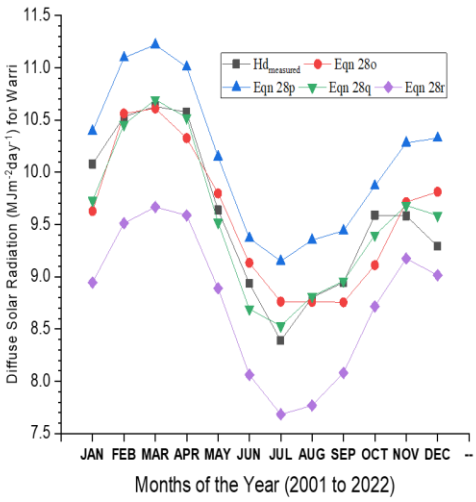

Figure 4: Comparison between the measured diffused solar radiation and estimated three variables models for Warri.

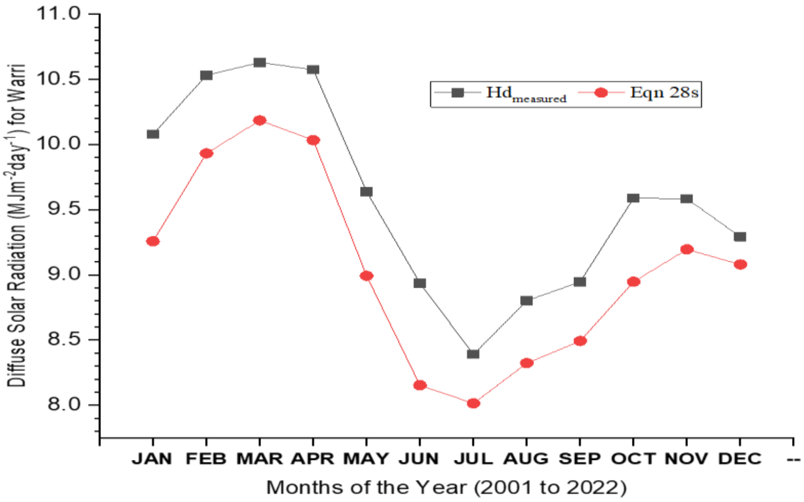

Figure 5: Comparison between the measured diffused solar radiation and estimated four variables models for Warri.

Figure 1 shows the comparison between the measured diffuse solar radiation and estimated models based on the modified Page, Liu and Jordan models for Warri. It appears evidently from the figure that the developed fourth degree polynomial model (equation 28d) underestimated the measured diffuse solar radiation and other developed models from the month of January to December. The linear model (equation 28a) followed similar pattern of variation with the measured diffuse solar radiation and was reported to be most suitable model for estimating diffuse solar radiation in Warri based on the modified Page, Liu and Jordan models as compared to other estimated models in this category.

Figure 2 shows the comparison between the measured diffuse solar radiation and estimated models based on the clearness index and a single variable models for Warri. It appears evidently from the figure that the developed model equation 28g overestimated the measured diffuse solar radiation and other developed models in the month of April. The model equation 28h followed similar pattern of variation with the measured diffuse solar radiation and was reported to be the most suitable model for estimating diffuse solar radiation in Warri based on the clearness index and a single variable models as compared to other estimated models in this category.

Figure 3 shows the comparison between the measured diffuse solar radiation and estimated models based on the two variables models for Warri. It appears evidently from the figure that the developed model equation 28i underestimated the measured diffuse solar radiation and other developed models from the month February to April. The model equation 28k followed similar pattern of variation with the measured diffuse solar radiation and was reported to be the most suitable model for estimating diffuse solar radiation in Warri based on the two variable models as compared to other estimated models in this category.

Figure 4 shows the comparison between the measured diffuse solar radiation and estimated models based on the three variables models for Warri. It appears evidently from the figure that the developed model equation 28r underestimated the measured diffuse solar radiation and other developed models from the month January to December. Also, the developed model equation 28p overestimated the measured diffuse solar radiation and other developed models from the month January to December. The model equation 28q followed similar pattern of variation with the measured diffuse solar radiation and was reported to be the most suitable model for estimating diffuse solar radiation in Warri based on the three variable models as compared to other estimated models.

Figure 5 shows the comparison between the measured diffuse solar radiation and estimated models based on the four variables models for Warri. It appears evidently from the figure that the developed model equation 28s underestimated the measured diffuse solar radiation from the month January to December.

Comparison of all Categories of Models

Table 11: Statistical summary of better performed models across each category for Warri

Models	R^2	MBE	RMSE	MPE	t
Eqn 28a	82.94%	-0.0029	0.2979	-0.1133	0.0323
Eqn 28h	87.38%	-0.0068	0.2583	-0.0070	0.0871
Eqn 28k	91.20%	-0.0180	0.2135	0.1407	0.2809
Eqn 28q	94.36%	-0.0341	0.1737	0.3241	0.6641
Eqn 28s	94.48%	-0.5321	0.5581	5.5516	10.4741

Table 12: Ranks obtained for the performed models across each category for Warri

Models	R^2	MBE	RMSE	MPE	t	Rank
Eqn 28a	5	1	4	2	1	13
Eqn 28h	4	2	3	1	2	**12**
Eqn 28k	3	3	2	3	3	14
Eqn 28q	2	4	1	4	4	15
Eqn 28s	1	5	5	5	5	21

From table 11 and 12, it was observed that the model, equation 28h of the clearness index and one variable model category that relates the diffuse solar radiation with the clearness index and mean temperature was found to perform best in estimating diffuse solar radiation for Warri when compared to all outstanding models from the different categories.

CONCLUSION

In this study the measured monthly average daily global solar radiation, diffuse solar radiation, relative humidity, atmospheric pressure, wind speed and mean temperature spanning a period of twenty-two years (2001 to 2022) dataset were utilized to develop new models for the estimation of diffuse solar radiation. A total of 19 models of five categories based on modified Page, Liu and Jordan models; clearness index and one variable models; two variable models; three variable models and four variable model were developed and tested using five validation indices of MBE, RMSE, MPE, t-test and R^2. The results obtained based on the models developed, in modified Page, Liu and Jordan models category, equations 28a was found to be appropriate; equation 28h was found appropriate for the clearness index and one variable models category; equation 28k was found appropriate for the two variable models category; equation 28q was found appropriate for the three variable category. When all the best performed developed models from each categories were ranked, it was found that the model that relates the diffuse solar radiation with clearness index and the mean temperature (equation 28h) performed most appropriate for estimation of diffuse solar radiation for Warri, found in the coastal region of Nigeria.

ACKNOWLEDGEMENTS
The authors wish to acknowledge the management and staff of National Aeronautics and space Administration (NASA) for making all the data used in this study available online. The suggestions by the reviewers are well appreciated.

REFERENCES

Adaramola, M. S. (2012). Estimating global solar radiation using common meteorological data in Akure, Nigeria. *Renewable Energy*, *47*, 38–44.

Akpootu, D. O., & Abdullahi, Z. (2022). Development of sunshine based models for estimating global solar radiation over Kano and Ikeja, Nigeria. *FUDMA Journal of Sciences, 6(3*), 290-300. https://doi.org/10.33003/fjs-2022-0603-1001

Akpootu, D. O., & Gana, N. N. (2014). Comparative study of global solar radiation between Nguru and Abuja. Paper presented at the 24th Annual Congress and Colloquium of the Nigerian Association of Mathematical Physics, University of Benin, Benin City, Nigeria.

Akpootu, D. O., & Iliyasu, M. I. (2015a). A comparative study of some meteorological parameters for predicting global solar radiation in Kano, Nigeria based on three variable correlations. *Advances in Physics Theories and Applications*, *49*, 1–9.

Akpootu, D. O., & Iliyasu, M. I. (2015b). The impact of some meteorological variables on the estimation of global solar radiation in Kano, North Western, Nigeria. *Journal of Natural Sciences Research, 5(22*), 1–13.

Akpootu, D. O., & Momoh, M. (2014). Empirical model for estimating global solar radiation in Makurdi, Benue State, North Central Nigeria. Paper presented at the 36th Annual Nigerian Institute of Physics, National Conference, University of Uyo, Nigeria.

Akpootu, D. O., & Mustapha, W. (2015). Estimation of diffuse solar radiation for Yola, Adamawa State, North-Eastern, Nigeria. *International Research Journal of Engineering and Technology, 2(8)*, 77-82.

Akpootu, D. O., & Sulu, H. T. (2015). A comparative study of various sunshine-based models for estimating global solar radiation in Zaria, North-Western, Nigeria. *International Journal of Technology Enhancements and Emerging Engineering Research, 3(12*), 1–5.

Akpootu, D. O., Alaiyemola, S. R., Abdulsalam, M. K., Bello, G., Umar, M., Aruna, S., Isah, A. K., Aminu, Z., Abdullahi, Z., & Badmus, T. O. (2023). Sunshine and temperature based models for estimating global solar radiation in Maiduguri, Nigeria. *Saudi Journal of Engineering and Technology, 8(5*), 82-90. https://doi.org/10.36348/sjet.2023.v08i05.001

Akpootu, D. O., Iliyasu, M. I., Mustapha, W & Aruna, S. (2015). Developing empirical models for predicting diffuse solar radiation over Yola, Adamawa State, North-Eastern, Nigeria. *International Research Journal of Engineering and Technology 2(8*): 113-121

Akpootu, D. O., Iliyasu, M. I., Olomiyesan, B. M., Fagbemi, S. A., Sharafa, S. B., Idris, M., Abdullahi, Z., & Meseke, N. O. (2022). Multivariate models for estimating global solar radiation in Jos, Nigeria. *Matrix Science Mathematic, 6(1*), 05-12. http://doi.org/10.26480/mkmk.01.2022.05.12

Akpootu, D. O., Tijjani, B. I., & Gana, U. M. (2019a). Empirical models for predicting global solar radiation using meteorological parameters for Sokoto, *Nigeria. International Journal of Physical Research, 7(2*), 48–60. https://doi.org/10.14419/ijpr.v7i2.29160

Akpootu, D. O., Tijjani, B. I., & Gana, U. M. (2019b). Sunshine and temperature-dependent models for estimating global solar radiation across the Guinea savannah climatic zone of Nigeria. *American Journal of Physics and Applications, 7(5*), 125-135. https://doi.org/10.11648/j.ajpa.20190705.15

Akpootu, D. O., Tijjani, B. I., & Gana, U. M. (2019c). New temperature-dependent models for estimating global solar radiation across the midland climatic zone of Nigeria. *International Journal of Physical Research, 7(2)*, 70–80. https://doi.org/10.14419/ijpr.v7i2.29214

Akpootu, D. O., Tijjani, B. I., & Gana, U. M. (2019d). New temperature-dependent models for estimating global solar radiation across the coastal climatic zone of Nigeria. *International Journal of Advances in Scientific Research and Engineering (IJASRE), 5(9*), 126–141. https://doi.org/10.31695/IJASRE.2019.33523

Almorox, J., Benito, M., & Hontoria, C. (2005). Estimation of monthly Ångström-Prescott equation coefficients from measured daily data in Toledo, Spain. *Renewable Energy, 30,* 931-936.

Liu B. H., & Jordan R. C.. (1960). The interrelationship and characteristics distribution of direct, diffuse and total solar radiation from meteorological data. *Solar Energy, 4*, 1–9.

Bevington P. R. (1969) *Data Reduction and Error Analysis for the Physical Sciences*, first Edition McGraw Hill Book Co., New York.

Chen, R., Ersi, K., Yang, J., Lu, S., & Zhao, W. (2004). Validation of five global radiation models with measured daily data in China. *Energy Conversion and Management, 45*, 1759-1769.

Duzen, H., & Aydin, H. (2012). Sunshine-based estimation of global solar radiation on a horizontal surface at Lake Van region (Turkey). Energy Conversion and Management, 58, 35–46. https://doi.org/10.1016/S0306-2619(01)00012-5

El-Sebaii, A., & Trabea, A. (2005). Estimation of global solar radiation on horizontal surfaces over Egypt. *Egypt. J. Solids*, *28(1)*, 163–175.

Gana, N. N., & Akpootu, D. O. (2013a). Ångström type empirical correlation for estimating global solar radiation in North-Eastern Nigeria. *The International Journal of Engineering and Science, 2(11)*, 58-78.

Gana, N. N., & Akpootu, D. O. (2013b). Estimation of global solar radiation using four sunshine-based models in Kebbi, North-Western, Nigeria. *Pelagia Research Library, 4(5),* 409-421.

Gopinathan, K. K., & Alfonso Soler. (1995). Diffuse radiation models and monthly-average, daily, diffuse data for a wide latitude range. *Energy, 20(7)*, 657–667.

Goswami D. Yogi, (2015). *Principles of Solar Engineering*. CRC Press

Guermoui, M., Melgani, F., Gairaa, K., & Mekhalfi, M. L. (2020). A comprehensive review of hybrid models for solar radiation forecasting. *Journal of Cleaner Production, 258*, 120357.

Halouani, N., Nguyen, C. T., & Vo-Ngoc, D. (1993). Calculation of monthly average solar radiation on horizontal surfaces using daily hours of bright sunshine. *Solar Energy, 50*, 247-248.

Iqbal, M. (1983). *An Introduction to Solar Radiation*. Academic Press.

Page J. K. (1961). The estimation of monthly mean values of daily total short-wave radiation on vertical and inclined surfaces from sunshine records for latitudes 40°N – 40°S. Proceedings of the UN Conference on *New Sources of Energy*, 4, 378-390.

Khatib, T., Mohamed, A., & Sopian, K. (2012). A review of solar energy modeling techniques. *Renewable and Sustainable Energy Reviews, 16(5*), 2864-2869.

Merges, H. O., Ertekin, C., & Sonmete, M. H. (2006). Evaluation of global solar radiation models for Konya, Turkey. *Energy Conversion and Management, 47*, 3149-3173.

Mubiru, J., & Banda, E. J. K. B. (2006). Performance of empirical correlations for predicting monthly mean daily diffuse solar radiation values at Kampala, Uganda. *Theoretical and Applied Climatology, 88(1-2),* 127–131. https://doi.org/10.1007/s00704-006-0249-1

Myers, R. D. (2013). *Solar Radiation: Practical Modeling for Renewable Energy*. CRC Press.

Olomiyesan, B. M., Akpootu, D. O., Oyedum, D. O., Olubusade, J. E., & Adebunmi, S. O. (2021). Evaluation of global solar radiation models performance using global performance indicator (GPI): A case study of Ado Ekiti, South West, Nigeria. Paper presented at the 43rd Annual Nigerian Institute of Physics, National Conference, Nnamdi Azikiwe University, Awka, Anambra State, May 26-29.

Qiu, R., Li, L., Wu, L., Agathokleous, E., Liu, C., Zhang, B., et al. (2022). Modeling daily global solar radiation using only temperature data: Past, development, and future. *Renewable and Sustainable Energy Reviews, 163,* 112511.

Saidur, R., Masjuki, H. H., & Hassanuzzaman, M. (2009). Performance of an improved solar car ventilator. *International Journal of Mechanical and Materials Engineering, 4(1),* 24–34.

Sanusi, Y. K., & Abisoye, S. G. (2013). Estimation of diffuse solar radiation in Lagos, Nigeria. In Proceedings of the 2nd International Conference on Chemical, Environmental and Biological Sciences (ICCEBS), Dubai, UAE, March 17-18, 2013 (pp. 6-9).

Udo, S. O. (2000). Sky conditions at Ilorin as characterized by clearness index and relative sunshine. *Solar Energy, 69(1)*, 45–53.

Wang, L., Kisi, O., Zounemat-Kermani, M., Salazar, G. A., Zhu, Z., & Gong, W. (2016). Solar radiation prediction using different techniques: Model evaluation and comparison. *Renewable and Sustainable Energy Reviews, 61*, 384–397.

Zekai, S. (2008). *Solar Energy Fundamentals and Modeling Techniques: Atmosphere, Environment, Climate change, and Renewable Energy* (1st ed.). Springer, London.