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Optimization model for determining global solar radiation in the northeastern states of Nigeria using both meteorological and satellite imagery data

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ABSTRACT

This study presents an optimization model for determining global solar radiation in the northeastern region of Nigeria using a combination of meteorological data and satellite imagery. Ten recent models were chosen from the literature review and optimized to select the one that best fits the study region. Two models were developed to provide accurate solar radiation predictions, which can be used to improve the planning and implementation of a solar energy project in the region. The model integrates the Angstrom-Prescott model with various climate parameters such as Temperature (ΔT), relative humidity (RH), location latitude (Φ), solar declination angle (δ), and the number of days in a year (n) with satellite image data to determine the global solar radiation. The finding of optimization models shows that the model10 performed very well with minimum error as Mean Base Error (0.028), Mean Percentage Error (-0.001), Root Mean Square Error (0.098), and coefficient of determination R2 (0.994), which suggested as the optimized model for determining of global solar radiation in northeastern Nigeria. The two models were developed, that is, proposed Model1 and proposed Model2. Proposed Model1 slightly overestimated the global solar radiation with Mean Base Error (-0.863), Mean Percentage Error (-0.039), Root Mean Square Error (2.990), and coefficient of determination R2 (0.745), while proposed Model2 performed better with Mean Base Error (-0.005), Mean Percentage Error (0.0003), Root Mean Square Error (0.02) with the coefficient of determination R2 (0.985). The proposed models were validated using the suggested optimized model10 and satellite data model, which show that the proposed model can accurately determine global solar radiation in the northeastern region of Nigeria. This study's findings will benefit the region's solar energy project developers, researchers, and policymakers.

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1. Introduction

The northeastern region of Nigeria is known for its abundant sunshine, making it an ideal point for solar energy generation. However, the area also faces challenges such as frequent cloud cover and dust haze, which can reduce the efficiency of solar panels. Optimizing the solar radiation models is vital to maximizing the potential of solar energy in the region.

Solar radiance is the amount of solar energy that reaches a unit area on the Earth's surface. The rate of solar radiation that reaches the Earth's surface is influenced by several factors, including the sun's angle, the distance between the sun and the Earth, and atmospheric conditions. In northeastern Nigeria, the average solar radiation is about 4.5 kWh/m2/day, with a peak of 5.5 kWh/m2/day during the dry season [1].

To optimize the model for determining global solar radiation in the northeastern region of Nigeria, it is essential to consider these factors and develop a model that considers the weather conditions, panel orientation, and panel efficiency. This model can be applied to design and install solar energy systems that maximize the potential of solar energy in the region; by doing so, we can use the power of the sun to provide clean and lasting significance for the area.

To get accurate and precise global solar radiation for solar energy system design, combine meteorological and satellite image measurements at the site of interest. Meteorological data measurements are point measurements that are temporally integrated. Although ground estimation data are said to be precise and reliable, the extensive implication involved has made such data unavailable in many places. This has led to the search for another means of getting solar radiation data for research and development of solar energy systems, which led to the introduction of satellite image-derived data sources. Satellite image data measurements give easy access to long-term and verifiable means of deriving regular solar radiation data for any desired location worldwide. Satellite-derived data is better for a selected site than meteorological measurements data from over 25km away.

Chabane et al. [1] carried out a theoretical study of global solar radiation on the horizontal area for the determination of direct and diffuse solar radiation. Ghazouani et al. [2] Performed an evaluation of temperature-based global solar radiation models. Akpootu et al [3] carried out research on multivariate models for predicting global solar radiation in Jos, Nigeria. Soulouknga et al. [4] determined the empirical models for the evaluation of global solar irradiation for the area of Abeche in the province of Ouaddaï, in Chad. Muhammad & Ali [5] studied the geospatial merging of ground measurements with satellite data to exploit solar energy potentials in Kano, Nigeria. Zhang et al. [6] Estimated daily ground-received global solar radiation using air pollutant data. Tanu et al. [7]. Evaluated global solar radiation, cloudiness index, and sky view factor as potential indicators of Ghana. Onyeka et al. [8]. Estimated global solar radiation using empirical models. Chabane et al. [9]. Study a new approach to estimate the distribution of solar radiation using the Linke turbidity factor and tilt angle. Karaman et al. [10] Estimation of solar radiation using modern methods. Mirzabe et al. [11] Assessed and categorized the empirical models for calculating monthly, daily, and hourly diffuse solar radiation: Rehman et al. [12] Estimated daily solar radiation from clearness index, sunshine duration, and meteorological parameters for different climatic conditions. Bamigbola & Atolagbe [13] developed empirical models for determining global solar irradiation on the African continent based on factors of location and season. Almorox et al. [14] study the effect of total solar irradiances on the performance of empirical models for estimating global solar radiation. Aweda. et al. [15]. Modeled the net irradiative measurement of meteorological parameters using merra-2 data in a sub-Sahara African town. Aweda et al. [16]. Validated the Earth's Irradiance over Some Selected Towns in Nigeria. Chang & Zhang. [17] Developed solar radiation model considering the hourly sunshine duration for all-sky conditions. Chabane [18]. Estimated solar irradiation on the horizontal axis using turbidity and factor air quality index in Assekrem. Li et al. [19] Empirical Estimated daily global solar irradiation with contrasting seasons of rain and drought characterize tropical China. Hai et al. [20] Estimated global solar radiation and climatic variability analysis using an extreme learning machine-based predictive model. Feng et al. [21] developed and calibrated an empirical models for estimated daily global solar radiation in China. Chabane et al. [22] Predicted global solar radiation on the inclined area. Husain [23] Estimated global solar radiation from temperature extremes. Nathaniel et al. [24] estimated global solar radiation and clearness index on the coast of the Gulf of Guinea, Nigeria. Zhu et al. [25] estimated solar radiation using sunshine duration and hourly total cloud amount data from a geostationary meteorological satellite. Fan et al. [26] evaluated and Developed temperature-based empirical models for estimating daily global smart grid and renewable energy solar radiation in humid regions. Yusuf [27] Characterized sky conditions using the clearness index and relative sunshine duration for Iseyin, Nigeria. Hassan el-al. [28] Performed assessment of different day-of-the-year-based models for estimating global solar radiation. Alkasim et-al. [27] used an empirical model to estimate global and diffuse solar radiation over Yola, northeastern Nigeria, based on air temperature.

This study was therefore used to create a new optimized regression model for northeastern Nigeria, which cover differences due to the changes in geographical location and is done by including the location latitude, inclination angle, Change in temperature, and relative humidity as an additional variable, These variables are better instantaneous climatic indicators of the amount of global solar radiation that could be captured for that location on a particular day. To capture the seasonal changes of the region by adding to the optimized model the cosine of the day number of the year. The optimized model, therefore, combines the location latitude, average daily relative humidity, daily ratio of sunshine duration, daily maximum temperature, and cosine of day number. Two equations were developed, and their coefficients were deduced. As calculated from the correlations, the predicted global solar radiation values were also compared with measured values and values cited in the literature.

This study was used to create a new regression model for the optimization of global solar radiation in the northeastern region of Nigeria that: Covers lapses due to the different geographical locations and is sensitive to climatic and weather changes and seasonal fluctuations. These can be achieved by introducing region latitude, maximum daily temperature, mean daily relative humidity, and cosine of the day number of the year as additional variables. Ten recent models were selected from many cited in the literature review to optimize the models for northeastern Nigeria.

This paper is based on three objectives: Optimize the model for determining global solar irradiance in northeastern Nigeria based on the readily measured meteorological variables to calculate the monthly average global solar irradiance over northeast Nigeria, to validate the optimized model with satellite image-measured data. Furthermore, find the most suitable models using some statistical tests to estimate monthly averaged global solar irradiance over the northeastern zone.

2. Method

2.1. Data Collection

The ten years (2010-2020) meteorological data consisting of monthly mean sunshine hour duration, temperatures, and global solar radiation utilized for this study were received from two (2) data sources: the Nigerian Meteorological (NIMET) Agency and the archives of the National Aeronautics Space Agency (NASA).

2.2. Optimizing Models for Determining Global Solar Radiation in North Eastern Region.

The mean monthly values of weather parameters such, Global irradiance G, Extraterrestrial radiation (Go), relative sunshine ratio (S/So), mean relative humidity (RH), air temperature ratio (T_{Min}/T_{Max}), air temperature range $(T_{Max} - T_{Min})$,Solar declination angle (δ), Station latitude (Φ) were used in validating the optimizing model equations for the determination of global solar irradiance of the study region.

Angstrom–Prescott model1 (M1) is the model that relates the global solar radiation to the relative sunshine hours:

$$\frac{\bar{G}}{G_0} = a + b\,\frac{\bar{s}}{S_0} \tag{1}$$

$$\acute{G}_0 = \frac{24}{\pi} I_0 \left(1 + 0.033 \cos\frac{360n}{365}\right) \tag{2}$$

$$S_0 = \frac{2}{15}\cos^{-1}(-\tan\delta\tan\varphi) \tag{3}$$

$$\delta = 23.45 \sin\left(360\,\frac{284n}{365}\right) \tag{4}$$

$$\omega_s = 12 + \left[\frac{\cos^{-1}(-\tan\delta\tan\emptyset)}{15}\right] \tag{5}$$

Later, many more researchers modified the Angstrom-Prescott models to suit their region or location of studies. Based on the past review of this study, some models were selected to optimize and validate the proposed models. The regression analysis has been carried out between the mean monthly global solar irradiance and the rest parameters to obtain the regression constants a, b, c, e, f, g, and h.

M2. Garba et al. [29] modified the Angstrom-Prescott model into a temperature-based model to estimate monthly mean global solar radiation.

$$\frac{\bar{G}}{G_o} = a + b\left(\frac{\bar{T}_{max} - \bar{T}_{min}}{\bar{T}_{max}}\right) \tag{6}$$

M3. Ajenikoko & Salami [30] developed temperature-based linear regression models; the model is used to estimate global solar radiation at different locations.

$$\frac{\bar{G}}{G_o} = a + b\frac{\bar{T}_{min}}{\bar{T}_{max}} + c\bar{T}_{max} \tag{7}$$

M4. Aras et al. [31] have suggested polynomial correlation equations using sunshine and extraterrestrials solar radiation weather parameters.

$$\frac{\bar{G}}{G_o} = a + b\frac{\bar{S}}{S_o} + c\left(\frac{\bar{S}}{S_o}\right)^2 - d\left(\frac{\bar{S}}{S_o}\right)^3 \tag{8}$$

Model 5&6. Boluwaji et at. [32] developed two multi-linear two-parameter regression models for estimating global solar radiation in selected sites with three regression constants.

$$\frac{\bar{G}}{G_o} = a + b\frac{\Delta T}{S_o} \tag{9}$$

$$\frac{\bar{G}}{G_o} = a + b\frac{\bar{S}}{S_o} + c\frac{\Delta T}{S_o} \tag{10}$$

M7&M8. Adekunle & Emmanuel [33] developed two models for estimating global horizontal solar radiation with three parameters: sunshine ratio, declination angle, and air temperature.

$$G = a + b\sin\delta + c\left(\frac{S}{S_o}\right) + dRH + e\bar{T}_{max} \tag{11}$$

$$G = a + b\left(\frac{S}{S_o}\right) + c\cos\delta + d\bar{T}_{max} \tag{12}$$

M9&M10 Augustine & Nnabuchi [7] developed two models to determine solar radiation using the cloudless index, air temperature, and relative humidity.

$$\frac{G}{G_o} = a + b\frac{S}{S_o} + c\frac{c}{\bar{C}} + d\frac{RH}{100} \tag{13}$$

$$\frac{G}{G_o} = a + b\frac{S}{S_o} + c\frac{c}{\bar{C}} + d\frac{R}{100} + eT_{max} \tag{14}$$

2.3. Propose Model (MP) for Determination of Solar Radiation in North Eastern State of Nigeria

This research focused on optimizing the model for determining global solar radiation in the northeastern region of Nigeria. Ten years of monthly data for meteorological and satellite image stations spread across the region were obtained for the study. This method was chosen because of its better optimization. By carrying out independent correlations between the criterion variable and some predictor models mentioned in the literature reviews when multiple independent variables are involved in an optimized model, the equations of the optimized model proposed for the determination of global solar radiation in the northeastern region of Nigeria are of the form indicated in the Equation. (15– 16):

Proposed Model: A multi-linear two-parameter regression model was developed to estimate global solar radiation in the northeastern region of Nigeria. Some critical study areas' weather parameters, such as latitude, declination angle, relative humidity, day's number, and temperature, were incorporated into the Angstrom-Prescott model to form a new model with 5-6 regression constants. The proposed model is of the form:

MP1. (Proposed Model)

$$\frac{\bar{G}}{G_o} = a + b\frac{\bar{S}}{S_o} + c\frac{T_{min}}{T_{max}} + \text{d}\cos\emptyset + e\cos n \quad (15)$$

MP2. (Proposed Model)

$$\frac{\bar{G}}{G_o} = a + b\frac{\bar{S}}{S_o} + c\frac{\Delta T}{RH} + d\cos\emptyset + \text{d}\cos\delta \quad (16)$$

Where

Latitude of the site= (∅), solar declination = (δ), and the number of days number of the year starting from the first of January = (*n*).

2.4. Determination of regression constant

Given the data points of the form (x_i y_i) for i = 1, 2, 3… set of points and that y_i depends linearly on x_i, then, for an accurate value of the set points, there is a need to obtain the slope (m) and G – intercept (m_o), defined by:

$$y_i = m_o + mx_i \quad (17)$$

If x_i are j independent variables (x_{1i}, x_{2i}… x_{ji}), then equation (17) becomes.

$$y_i = m_o + m_1x_{1i} + m_2x_{2i} \pm \cdots \ldots + m_jx_{ji} \quad (18)$$

The coefficients of determination are defined by.

$$R^2 = \sum_{i=1}^{i}\left(m_o + m_1x_{1i} + \cdots \ldots + m_jx_{ji} - y_i\right) \quad (19)$$

If the dependent variable of Equation (19) is $H = \frac{\bar{G}}{G_o}$ and the independent variable is the monthly average daily sunshine ratio $SR = \frac{\bar{S}}{S_o}$, and the monthly average daily maximum air temperature, $\overline{T_{max}}$ then equation (18) becomes

$$H_i = m_o + m_1SR_i + m_2\overline{T_{max}} \quad (20)$$

The subscripts i = 1, 2, ---12 refer to the monthly average daily dataset for a typical year. In matrix form, Equation (20) becomes

$$\begin{bmatrix} H_1 \\ \vdots \\ H_i \end{bmatrix} = \begin{bmatrix} 1 & SR_1 & \bar{T}_{max1} \\ \vdots & \vdots & \vdots \\ 1 & SR_i & \bar{T}_{maxi} \end{bmatrix} \begin{bmatrix} m_0 \\ \vdots \\ m_i \end{bmatrix} \quad (21)$$

Where

$$A = \begin{bmatrix} 1 & SR_1 & \bar{T}_{max1} \\ \vdots & \vdots & \vdots \\ 1 & SR_i & \bar{T}_{maxi} \end{bmatrix} \qquad H = \begin{bmatrix} H_1 \\ \vdots \\ H_i \end{bmatrix} \qquad M = \begin{bmatrix} m_0 \\ \vdots \\ m_i \end{bmatrix}$$

To solve for A, there is the need to transform A into a square matrix (where I ≠ j ≠ 1).

$$A^T xH = A^T xAxM \quad (22)$$

Where

A^T Is the transpose of A. If $(A^TA)^{-1}$ exits, then

$$M = (A^TA)^{-1}A^TH \quad (23)$$

The solution of Equation (23) is a matrix of regression constants, $M = [m_0, m_1, m_2 \ldots\ldots m_i]$, which is a, b, c, d, e…… and it depends on the location of the study [34].

2.5. Satellite Data Model (SDM) for Determining Global Solar Radiation

A satellite image comprises a two-dimensional array of individual picture elements called pixels fixed in columns and rows. Every pixel represents an area on the Earth's surface**.** The number of bits determines the radiometric resolution of the satellite image. An 8-bit Digital Number (DN) ranges from 0 to 255 (i.e., 2^8 - 1), while an 11-bit DN ranges from 0 to 2047. To determine global solar radiation, you have to Conversion of the DN to Spectral Radiance (Lλ).

$$L_\lambda = \frac{L_{max} - L_{min}}{255}\; x\; DN + L_{min} \tag{24}$$

Given that L_{MIN} = 1.238; L_{MAX} = 15.600**.** [5]**,** [35]

2.6. Statistical Analysis of the Optimized Models

Statistical analyses have been used to assess the optimized model equations' performance. The Root Mean Square Error (RMSE), Mean Percentage Error (MPE), Mean Bias Error (MBE) and were adopted to test the accuracy of the determined values [36]. The satellite-image and persistent meteorological data of global solar radiation values were validated using percentage error. The equations are as follows:

$$MBE = \frac{\{\Sigma(G_{iest} - G_{ical})\}}{n} \tag{25}$$

$$MPE = \left\{\frac{\Sigma \left(\frac{(G_{ical} - G_{iest})}{G_{ical}}\right) x100}{n}\right\} \tag{26}$$

$$RMSE = \left\{\frac{\Sigma(G_{iest} - G_{ical})^2}{n}\right\}^{1/2} \tag{27}$$

$$R = \frac{[\Sigma(G_{iest} - \bar{G}_{iest})(G_{ical} - \bar{G}_{ical})]}{\sqrt{\Sigma(G_{iest} - \bar{G}_{iest})^2 \,\Sigma(G_{ical} - \bar{G}_{ical})^2}} \tag{28}$$

3. Results and Discussion

3.1. Determination of Regression Constant to Modified the Equations

$$\text{M1}\ \frac{\bar{G}}{G_o} = 0.346 + 0.423\frac{\bar{S}}{S_o} \tag{29}$$

$$\text{M2}\ \frac{\bar{G}}{G_o} = 1.314 - 1.145\left(\frac{T_{max} - T_{min}}{T_{max}}\right) \tag{30}$$

$$\text{M3}\ \frac{\bar{G}}{G_o} = 0.352 + 1.490\frac{\bar{T}_{min}}{\bar{T}_{max}} - 0.01\bar{T}_{max} \tag{31}$$

$$\text{M4}\ \frac{\bar{G}}{G_o} = -0.216 + 0.828\frac{\bar{S}}{S_o} + 0.632\left(\frac{\bar{S}}{S_o}\right)^2 - 0.045\left(\frac{\bar{S}}{S_o}\right)^3 \tag{32}$$

$$\text{M5}\ \frac{\bar{G}}{G_o} = 0.334 + 0.212\frac{\Delta T}{S_o} \tag{33}$$

$$\text{M6}\ \frac{\bar{G}}{G_o} = 0.181 + 0.315\frac{\bar{S}}{S_o} + 0.128\frac{\Delta T}{S_o} \tag{34}$$

$$\text{M7}\ G = 2.482 + 0.452\cos\delta - 18.22\left(\frac{S}{S_o}\right) + 0.062RH + 0.026\bar{T}_{max} \tag{35}$$

$$\text{M8}\ G = -6.096 + 21.50\left(\frac{S}{S_o}\right) + 10.57\cos\delta - 0.058\bar{T}_{max} \tag{36}$$

$$\text{M9}\ \frac{G}{G_O} = 0.022 + 0.334\frac{s}{s_O} + 0.862\frac{c}{\bar{C}} + 0.014\frac{RH}{100} \quad (37)$$

$$\text{M10}\ \frac{G}{G_O} = -0.062 + 0.12\frac{s}{s_O} + 0.06\frac{c}{\bar{C}} + 2.11\frac{RH}{100} + 0.042T_{max} \quad (38)$$

$$\frac{\bar{G}}{G_O} = -0.160 + 0.337\frac{\bar{S}}{S_O} + 0.691\frac{\Delta T}{RH} + 0.038\cos\emptyset + 0.573\cos n \quad (39)$$

$$\frac{\bar{G}}{G_O} = -0.156 + 0.804\frac{\bar{S}}{S_O} + 0.193\frac{T_{min}}{T_{max}} - 0.476\cos\emptyset + 0.829\cos\delta \quad (40)$$

3.2. Optimization of Models for Determination of solar radiation in Northeastern Nigeria

Table 1. The global solar radiation determined by ten models chosen for optimization of northeastern Nigeria

Month	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
January	196.79	196.58	189.62	192.37	196.02	223.19	197.79	192.25	196.27	194.96
February	188.55	187.25	191.20	192.09	189.78	199.14	195.37	192.70	192.03	192.70
March	228.36	226.00	220.20	206.82	219.67	210.44	220.57	213.23	214.68	216.51
April	215.23	214.21	201.30	208.98	225.19	213.07	208.05	184.37	188.34	188.05
May	211.83	198.19	206.79	202.26	215.13	208.37	194.04	198.97	193.43	194.21
June	183.99	180.82	179.83	194.20	194.76	185.74	184.42	170.82	176.60	172.22
July	183.00	175.37	183.97	178.92	180.43	180.48	164.12	180.01	161.62	164.53
August	163.72	161.85	152.09	171.80	174.27	164.68	161.36	142.51	151.63	147.69
September	179.23	188.26	178.63	179.90	180.81	185.10	173.16	174.38	174.86	168.00
October	198.27	194.37	199.60	193.61	201.82	204.75	191.90	195.79	194.23	195.27
November	196.26	188.54	190.98	189.92	192.99	190.33	190.45	193.27	192.11	193.05
December	191.78	190.56	187.34	188.14	186.21	184.24	193.50	191.49	193.57	192.59

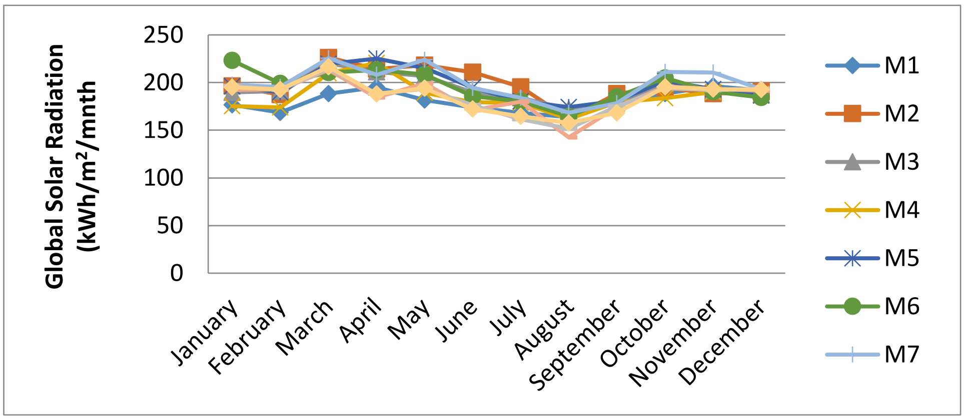

Fig. 1. Comparison of global solar radiation determined using all models of the optimization

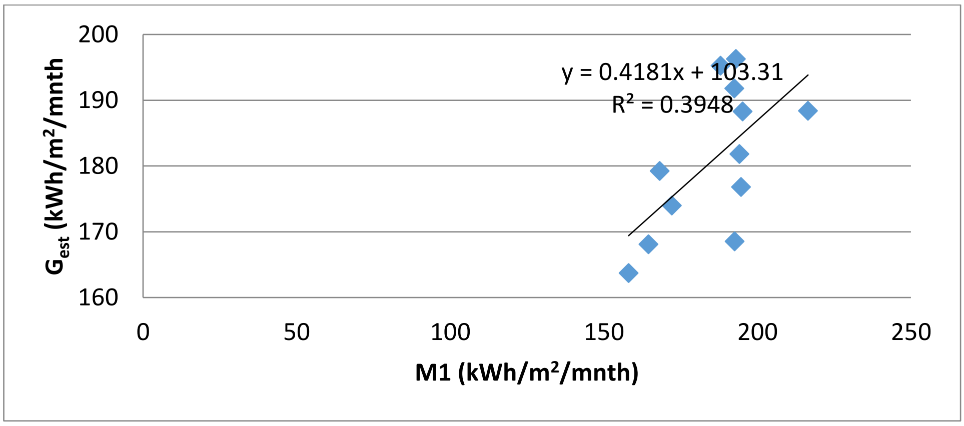

Fig. 2. Show the graph of solar radiation G_{est} against solar radiation determined by M1

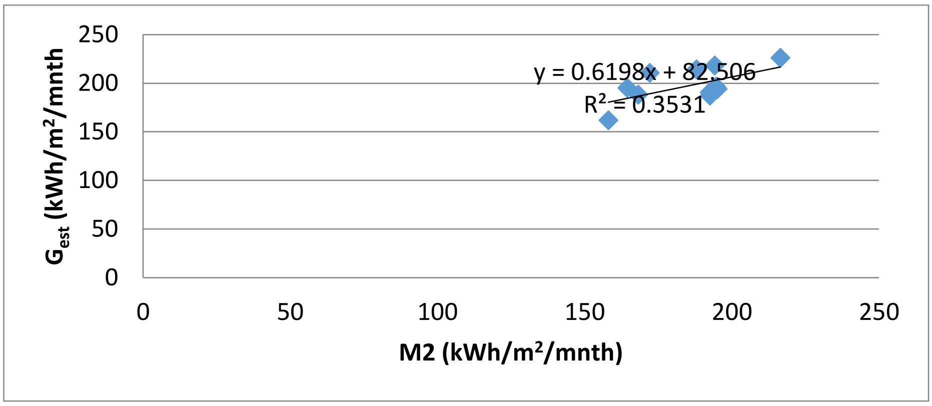

Fig. 3. Show the graph of solar radiation G_{est} against solar radiation determined by M2

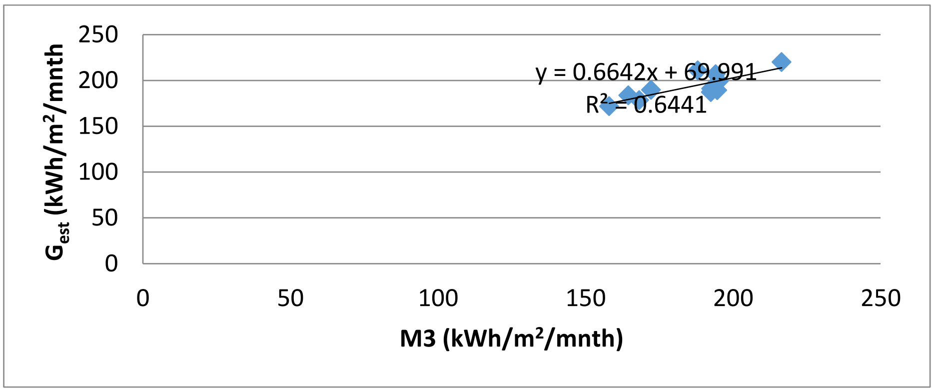

Fig. 4. Show the graph of solar radiation G_{est} against solar radiation determined by M3

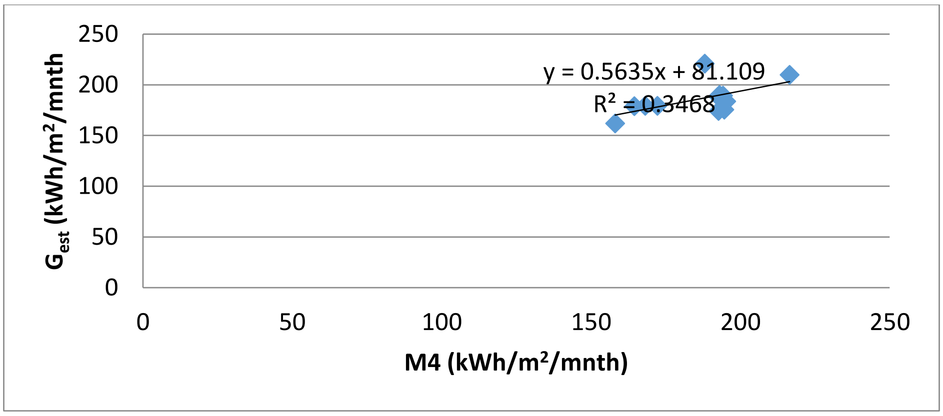

Fig. 5. Show the graph of solar radiation G_{est} against solar radiation determined by M4

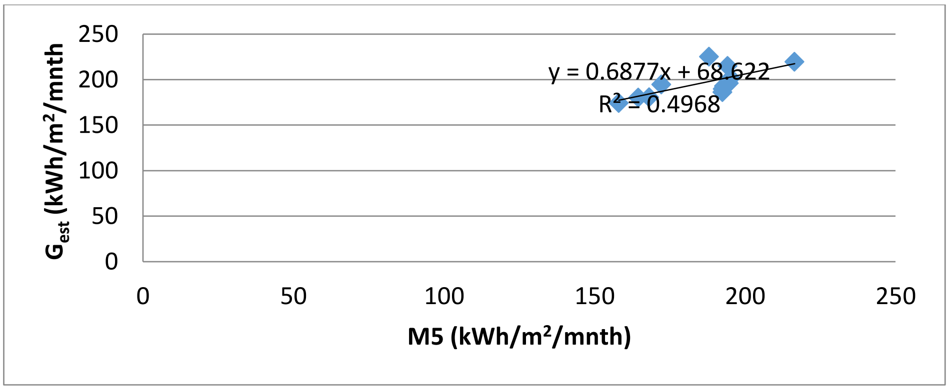

Fig. 6. Show the graph of solar radiation G_{est} against solar radiation determined by M5

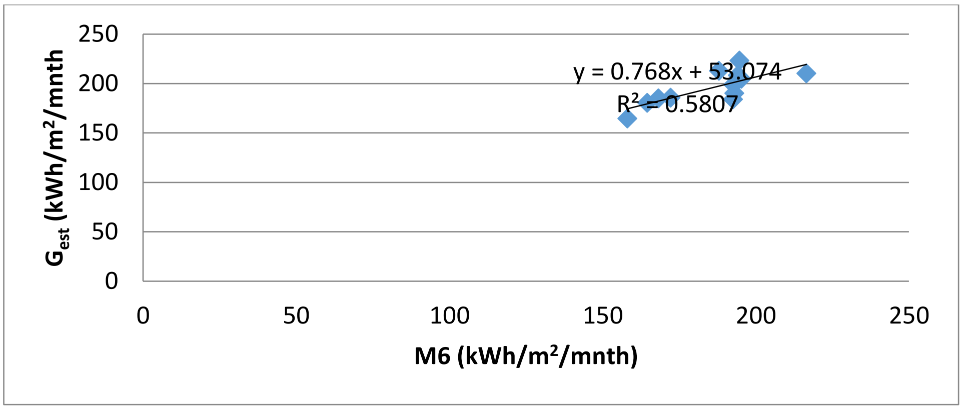

Fig. 7. Show the graph of solar radiation G_{est} against solar radiation determined by M6

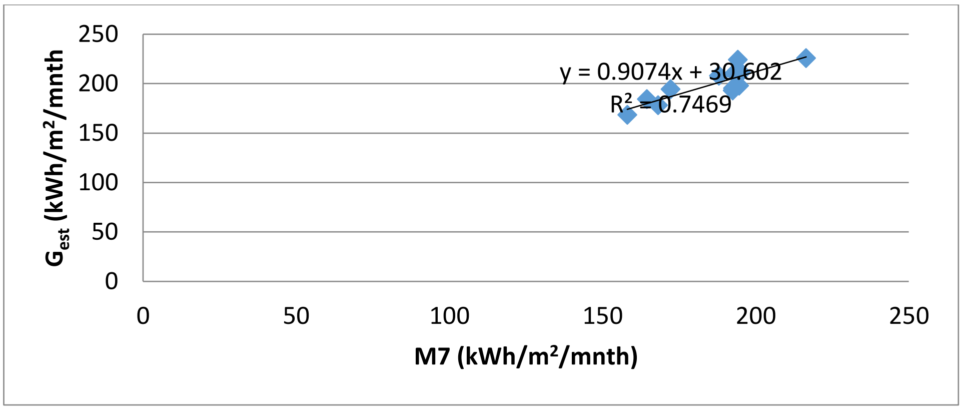

Fig. 8. Show the graph of solar radiation G_{est} against solar radiation determined by M7

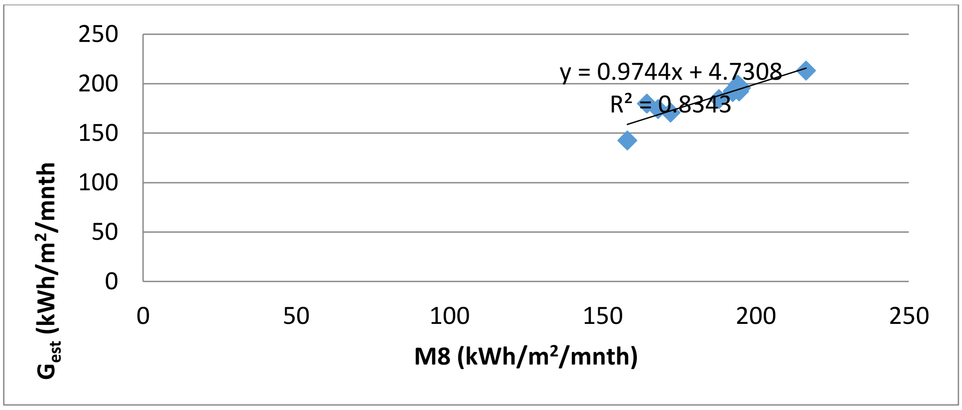

Fig. 9. Show the graph of solar radiation G_{est} against solar radiation determined by M8

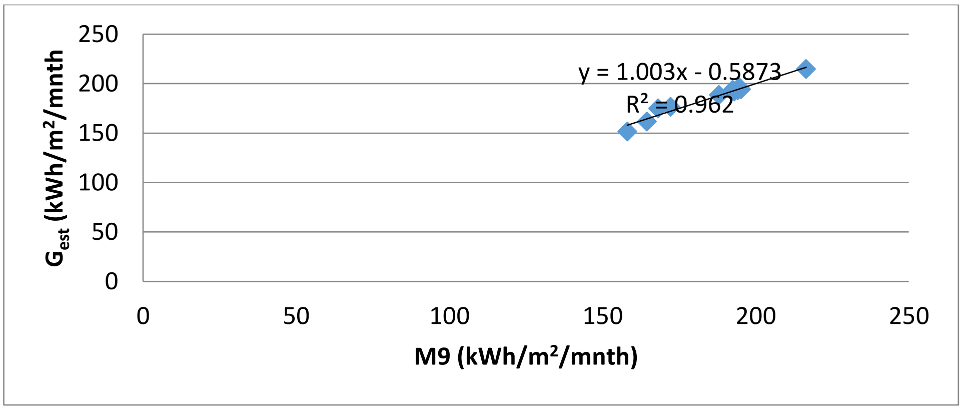

Fig. 10. Show the graph of solar radiation G_{est} against solar radiation determined by M9

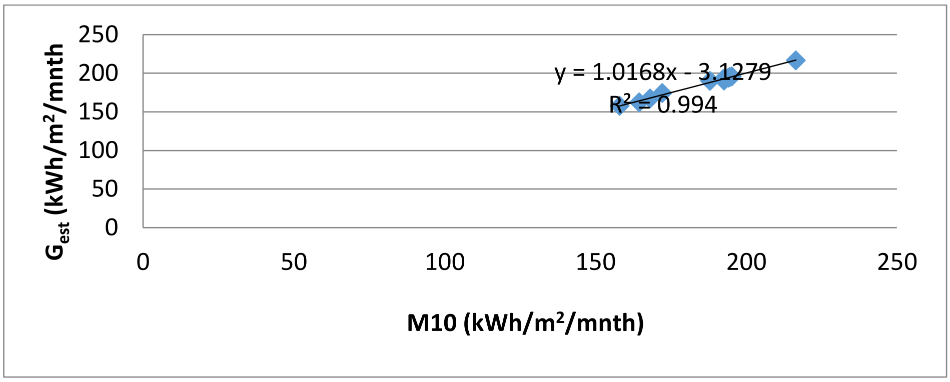

Fig. 11. Show the graph of solar radiation G_{est} against solar radiation determined by M10

Table 2. The summaries of error indices of the studied models of determined solar radiation (kWh/m^2/month)

Models	MBE	MPE	RMSE	R	R^2
M1	4.848	-0.223	16.80	0.628	0.394
M2	-11.83	0.499	40.97	0.593	0.352
M3	-7.565	0.326	26.21	0.802	0.644
M4	0.041	-0.002	0.124	0.588	0.346
M5	-10.57	0.448	36.60	0.704	0.496
M6	-9.936	0.423	34.42	0.762	0.580
M7	-13.37	0.559	46.29	0.864	0.746
M8	0.042	-0.002	0.147	0.913	0.834
M9	0.056	-0.003	0.194	0.981	0.962
M10	0.028	0.001	0.098	0.997	0.994

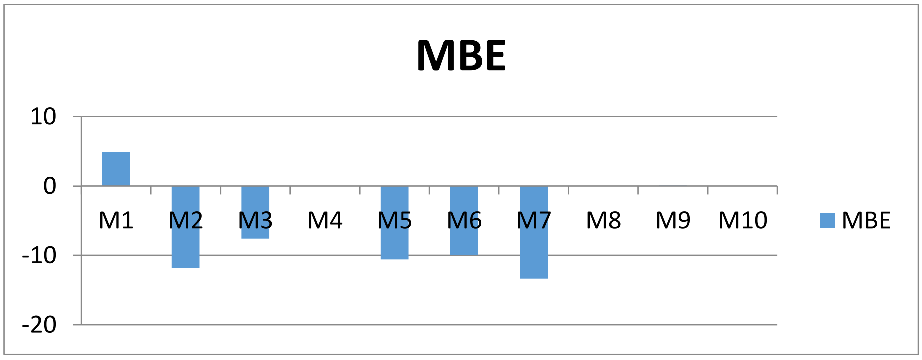

Fig. 12. Show the graph of MBE solar radiation (kWh/m^2/month) determined by all models

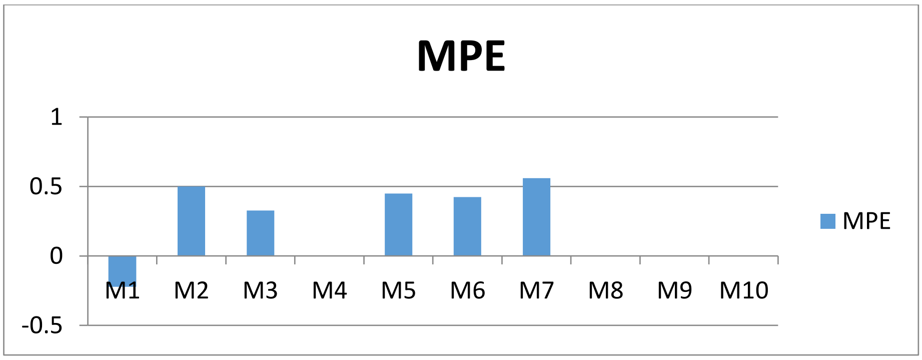

Fig. 13. Show the graph of MPE solar radiation (kWh/m^2/month) determined by all models

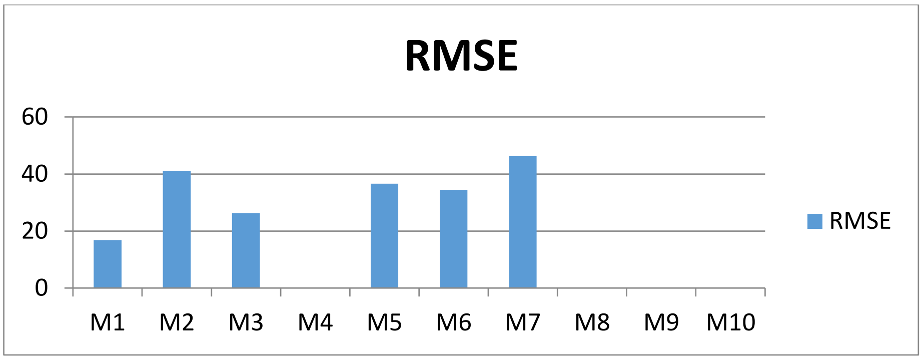

Fig. 14. Show the graph of RMSE solar radiation (kWh/m^2/month) determined by all models

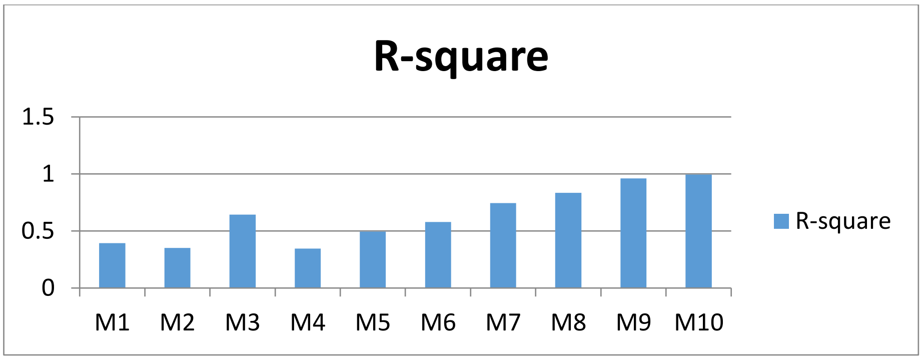

Fig. 15. Show the graph of RMSE solar radiation (kWh/m^2/month) determined by all models

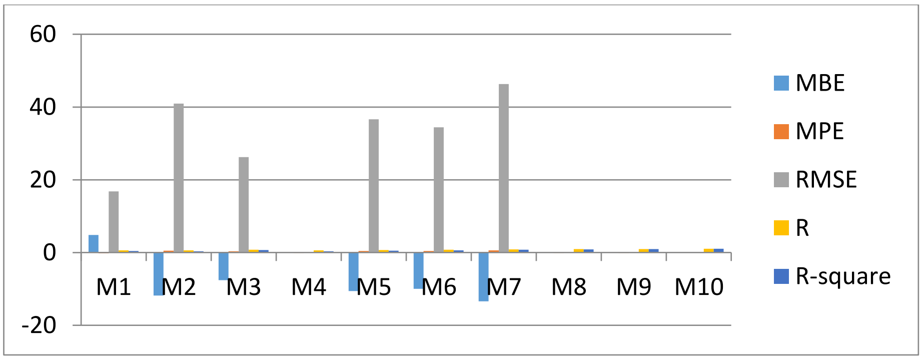

Fig. 16. Show the graph of MBE, MPE, RMSE, R, and R-square solar radiation (kWh/m^2/month) determined by all models

3.3. Validation of proposed model with optimized model and estimated Satellite image solar radiation for northeastern Nigeria.

Table 3. Show solar radiation (kWh/m^2/mnth) determined by SDM, PM1, PM2 and M10

	SDM	PM1	PM2	M10
January	196.79	192.94	196.06	194.96
February	194.55	182.38	178.61	192.67
March	218.36	198.21	216.98	216.51
April	185.23	186.43	198.12	188.05
May	193.83	194.63	212.2	194.21
June	173.99	162.91	182.99	172.22
July	163.86	175.3	183.38	164.53
August	163.72	145.47	162.2	157.69
September	169.23	169.38	179.12	168.21
October	198.27	191.15	201.59	195.27
November	192.26	182.67	196.77	193.05
December	191.78	183.27	192.2	192.59

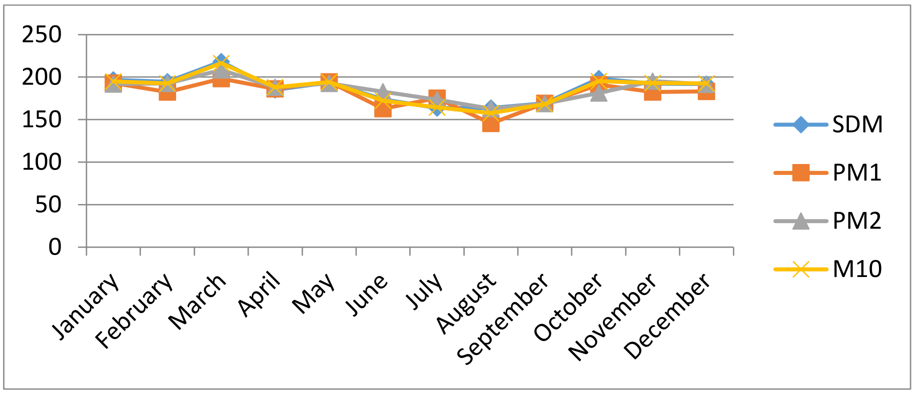

Fig. 17. Comparison of the estimated value of global solar radiation (kWh/m²/month) from two proposed models calculated solar radiation

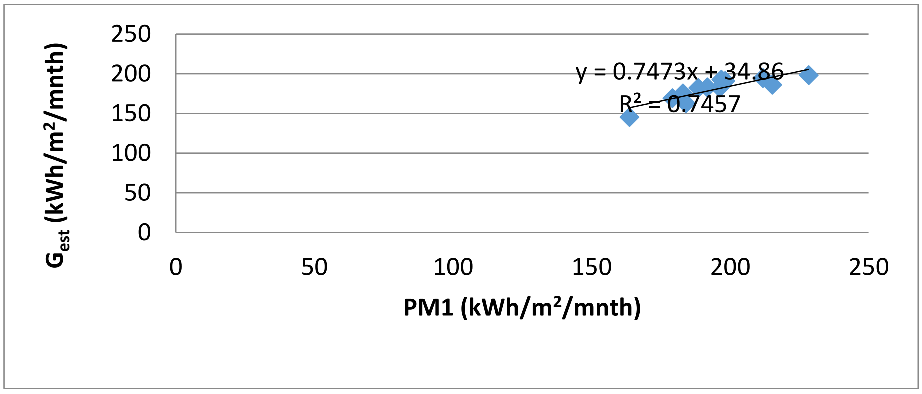

Fig. 18. Show the graph of solar radiation G_{est} against solar radiation determined by MP1

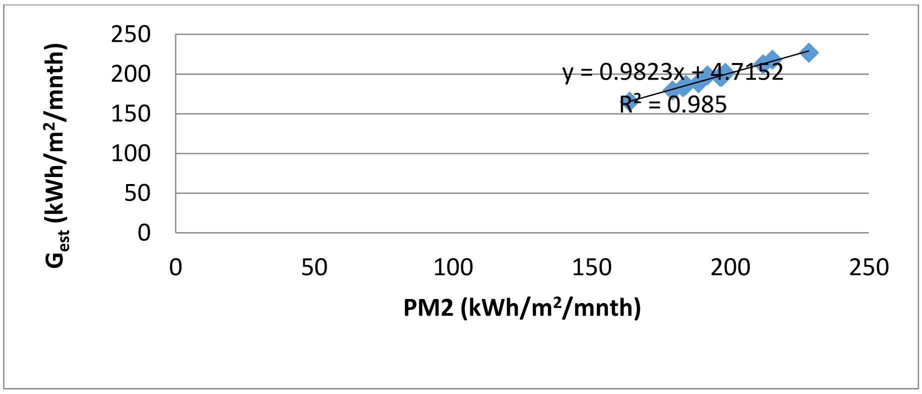

Fig. 19. Show the graph of solar radiation G_{est} against solar radiation determined by MP2

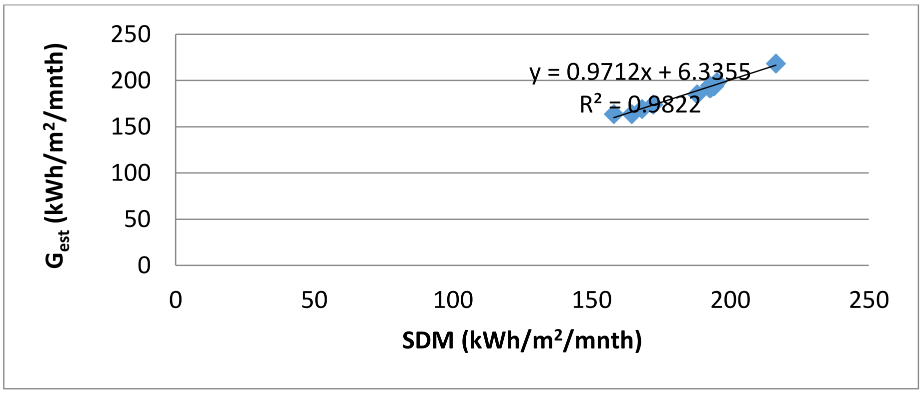

Fig. 20. Show the graph of solar radiation G_{est} against solar radiation determined by SDM

Table 4. the summaries of error indices of SDM, M10, PM1 and PM2 of determined solar radiation (kWh/m^2/month)

Models	MBE	MPE	RMSE	R	R-Square
M10	0.0280	0.0010	0.0980	0.9970	0.9940
SDM	-0.9640	0.0430	3.3400	0.9910	0.9820
PM1	0.8630	-0.0386	5.0680	0.8631	0.7450
PM2	0.0050	-0.0003	0.0200	0.9925	0.9850

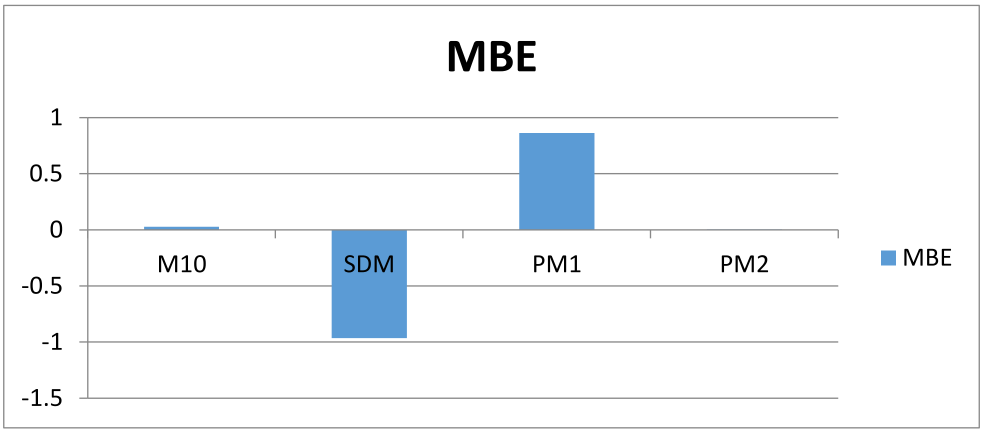

Fig. 21. Show the graph of MBE solar radiation (kWh/m^2/mnth) determined by M10, SDM, PM1and PM2

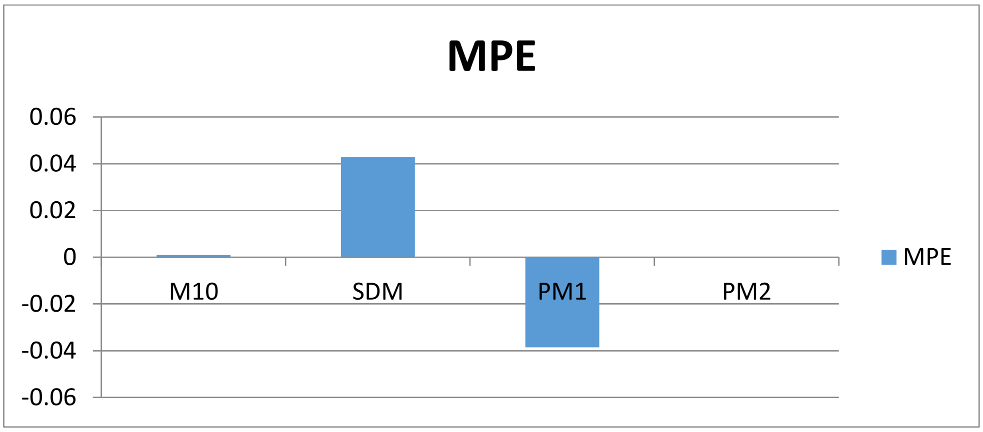

Fig. 22. Show the graph of MPE solar radiation (kWh/m^2/mnth) determined by M10, SDM, PM1and PM2

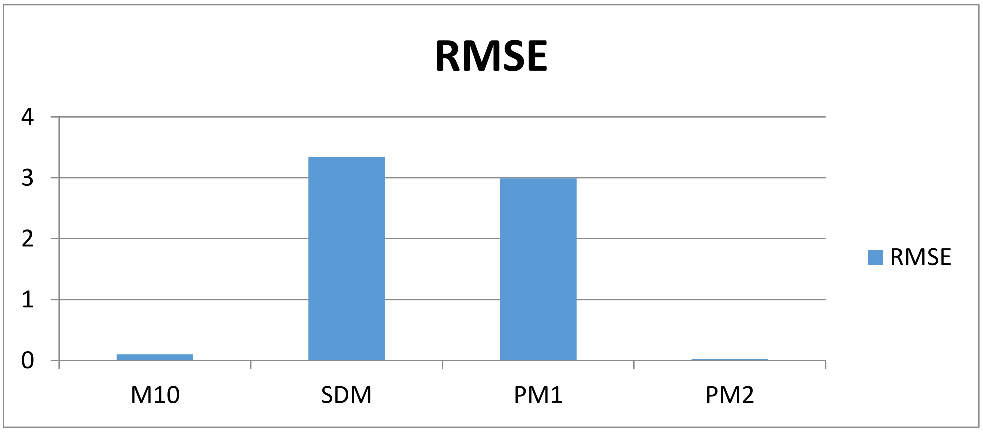

Fig. 23. Show the graph of RMSE solar radiation (kWh/m^2/mnth) determined by M10, SDM, PM1and PM2

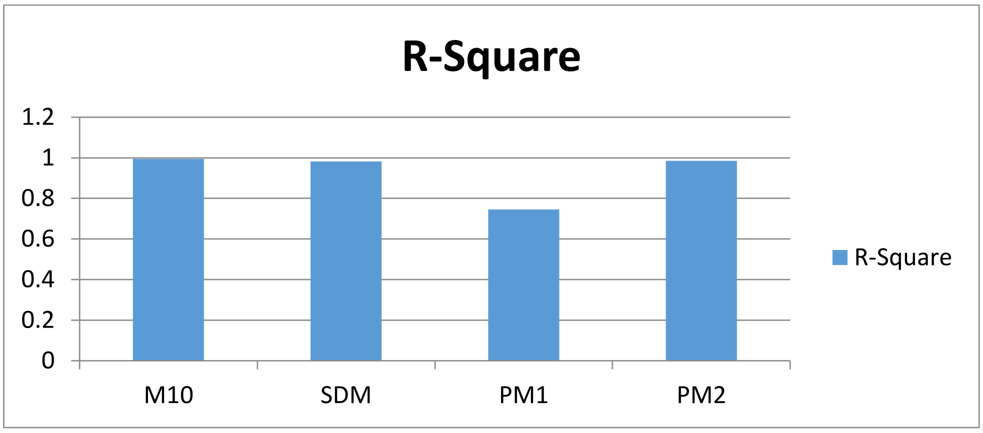

Fig. 24. Show the graph of R-square solar radiation (kWh/m^2/mnth) determined by M10, SDM, PM1and PM2

3.4. Discussion

The constants of regression a, b, c, d, and e for model equations (6-14) and the proposed models 15 and 16 were obtained using equations 20-23. Linear regression analysis was conducted between the monthly estimated clearness index and other meteorological parameters using ten years of data (2010-2020). The regression constants' result was slotted into equations (6-16). The modified equations and the proposed model equations, respectively obtained, are presented in Equation (30-41).

The global solar radiation for the Northeastern region was calculated using the modified equations of the ten models as presented in Equations (30–39). Long-term average (10 years) sunshine duration, relative humidity, and air temperature data were obtained from NIMET as input parameters for the models. The input parameters used in this explanation and the results obtained are shown in Table 1 and Fig. 1. In contrast, Fig. 2 – Fig. 11 shows the determined result of the error values of the studied models for northeastern Nigeria, summarized in Table 2. A low RMSE is desirable. A positive value of MBE and MPE indicates overestimation and a negative value shows underestimation in the calculated values, respectively [6]. It is the view from Table 2 that the error indices of the studied models. It could be due to the fluctuations in the atmospheric parameters, which influence the solar radiation on the performance of the models.

The MBE values for the models show that the model1 with an MBE value of 4.848 is an overestimation, and models2 (-11.83), model3 (-7.565), model5 (-10.57), model6 (-9.936), and model7 (-13.37) all gives underestimation of the estimated global solar radiation, respectively. However, it can be noted that models 4, 8, 9, and 10 with MBE Values of 0.041, 0.042, 0.056, and 0.028 collectively, as shown in Fig. 15. [10], [12], [15].

For MPE in Fig.16, model1(-0.223) and model 2, 3, 5, 6, and 7 with MPE values as 0.499, 0.326, 0.448, 0.432, and 0.559, respectively, give the overestimate and underestimate in the determination of eastern of global solar radiation of northeastern Nigeria. In contrast, models 4, 8, 9, and 10 have the most negligible value of MPE as -0.002, -0.002, 0.003, and 0.001, respectively [15], [34].

Fig. 17 gives the RMSE of the ten models chosen for this study, while models 1, 2, 3, 5, 6, and 7 gave high values of RMSE as 16.80, 40.97, 26.21, 36.60, 34.42, and 46.29, respectively, while model 4, 8, 9 and 10 give low values of RMSE as 0.124, 0.417, 0.194 and 0.098 [25].

The coefficient of determination R^2 measures how relevant forecast values predict trends in measured values [37]. For better modeling, R^2 should approach unity as closely as possible. As shown in the figure, model 8, 9, and 10 has a good coefficient of determination approaching unity (1) with given values as 0.834, 0.962, and 0.994 [16].

Table 2 indicates Fig. 15, Fig. 16, Fig. 17, Fig. 18, and Fig. 19. M1, M2, M3, M5, M6, and M7 indicate poor performance of the model on a long-term basis, while M4, M8, M9, and M10 indicate good performance models on a long-term basis. The statistical error indices in Table 2 and Fig. 18 also show that M9 and M10 have higher coefficient of correlation (R) and coefficient determination

(R^2) values. The coefficient of determination, with R^2 values of 0.994 and 0.962 obtained for M9 and M10, indicates that this model performed very well [7]. This makes the monthly mean global solar radiation estimated from M9 and M10 more accurate. Based on the statistical error indicators, it can be concluded that M9 and M10 performed better than M1 (Angstrom-Prescott model) in the northeastern region. On the whole, M10 gives the best error estimates in terms of MBE (0.028), MPE (-0.001), RMSE (0.098), and the highest values of R^2 (0.994) [31]. This implies that M10 performs best among the ten studied models. Hence, the M10 [7] is recommended as the optimal model for estimating the monthly mean global solar radiation on the horizontal surface in Northeastern Nigeria and another area with similar meteorological parameters.

The global solar radiations obtained from the optimized model (M10) were used to validate with determined values from the proposed models and satellite-derived data. The proposed models PM1 and PM2, as stated in equations (15 and 16), as modified in equations (40 & 41), and for satellite imagery data model Equation (25), were used to determine the global solar radiation of northeastern Nigeria. Table 3 and Table 4 and Fig. 20 – Fig. 24 present the summary of global solar radiation and its comparison in terms of their error indices.

From Table 4 and Fig. 21 – Fig. 24, it can be observed that the satellite-derived global solar radiation data is slightly underestimated due to the cloud and other factors with MBE (-0.964), MPE (0.043) and RMSE (3.340) and the SDM performed better which has a coefficient of determination R^2 (0.982) [35] exceeds some meteorological measurements in all the months of the year. This indicates that the variation between the meteorological model and satellite data model is minimal. For the proposed models PM1 and PM2, PM1 slightly overestimated with MBE (0.863), MPE (-0.039), and RMSE (2.990) while its coefficient of determination R^2 (0.745), while PM2 performed better than all the study models with MBE (0.005), MPE (-0.0003) and RMSE (0.02), it has a perfect coefficient of determination R^2 (0.985) [30], [36], [35] which is almost equal to that of optimized model M10 of Northeastern Nigeria.

However, the inclusion of Change in temperature(ΔT), location latitude(Φ), relative humidity (RH), solar declination angle (δ), and the of days in a year (n) to Angstrom-Prescott model (M1) in the proposed model (Equation (14)) must have a significant impact on the correct of the sunshine-based model. This is in agreement with [37], where the inclusion of weather parameters as input parameters improves the performance of global solar radiation in locations with a high-temperature difference

4. Conclusion

The optimization model for determining global solar radiation in northeastern Nigeria was carried out in this study; from the ten recently developed models chosen, Augustine & Nnabuchi's 2010 model (equation 14) was the best recommended as the optimal model for estimating the monthly mean global solar radiation in Northeastern Nigeria and other places with similar meteorological parameters.

This study also developed a new regression model for northeastern Nigeria that is dependent and able to capture the differences due to changes in geographical locations by the inclusion of the changing temperature, relative humidity, solar declination angle, location latitude, and day's number of the year makes the model much more sensitive to climatic and weather changes. The developed models were validated with the optimized model and satellite data model. Based on those mentioned above, the model fit that best approximates the global solar radiation over northeastern Nigeria is given as Equation. (16). Since the developed model is latitude based, it may be employed for estimating monthly global solar radiation of other locations outside northeastern Nigeria with similar climatic conditions, especially those within the same latitude range. This study's findings will benefit the region's solar energy project developers, researchers, and policymakers.

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Declarations

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