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Model Development for Solar Radiation Potential in AWKA Metropolis

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***Abstract*— In this research, a non-linear model correlating insolation in terms of meteorological and astronomical parameters for estimation of solar energy potential in Awka has been developed. Temperature data was collected from Nigeria Meteorological Agency (NIMET). Awka data for extraterrestrial solar radiation was calculated using analytical integration, and the results were presented in tabular and graphical forms for direct use in future solar energy research on Awka. Hargreaves regression solar radiation model for Awka was developed. Based on the results of this work, quantifiable measures were recommended for solar energy integration in Awka. The developed model was compared with an existing model generalized for Nigeria and improvements in accuracy of prediction were recorded. The R^2 value of the proposed model is closer to unity at 0.9483 than that of the known model at 0.7868; indicating higher accuracy of the presented model. The model was validated using Analysis of Variance (ANOVA) and percentage deviation. The developed model had a higher prediction percentage at 92.68 percent against that of the generalized model at 79.83 percent. Correlation of the proposed model was done by comparison with the existing model and measured data. A linear relationship exists between the developed model and the existing model with the equation of line given as $h^{(d)}_{Hg,km}$= 0.893$h^{(d)}_{Hg,pm}$- 2E-13. The developed model can be directly applied to resource (solar energy) evaluation and quantification for solar energy technology in Awka, which is the first step in solar energy integration in modern energy mix.**

***Index Terms*— Extraterrestrial, Irradiance, Regression Model, Solar Energy, Solar potential, Transmittance.**

I. INTRODUCTION

Solar radiation is a clean and abundant source of energy. It is the mechanism by which solar energy reaches Earth [1]. With fast technological improvement, decreasing costs, increasing public acceptance, and the introductory details on definition of the sun, the solar radiation and travel of solar radiation through space and matter as seen in the works of [2]-[4], then one is sure that solar energy will surely play a relevant share of future energy systems. These make solar energy an appealing field of investment and research.

It is obvious that the best and most reliable solar radiation information is that obtained from daily experimental measurements of the global and diffuse components of the solar insolation of a specific location. Unfortunately, there are few meteorological stations conducting such measurements in developing countries such as Nigeria, this is due to the fact that the measuring equipment is expensive to afford, or lack of trained personnel to handle the measurement, also the equipments need to be recalibrated from time to time to maintain accuracy; this is due to the sensitivity of the solar radiation measuring devices [5]. For this reason, precise measurement of solar radiation would necessitate frequent calibration and maintenance.

Therefore, it is rather important to develop models to estimate the solar radiation using the available weather parameters [6]. The model developed will be useful for resource evaluation and quantification as regards to solar energy. A reasonably accurate knowledge of the solar radiation data at a particular geographical location is significant for solar energy related system design, such as design of solar thermal power plants. Hence Solar radiation is an important input parameter for the design, performance prediction and monitoring of solar energy devices; especially in sizing solar power systems.

II. MATERIALS AND METHOD

The study area Awka has a temperature which ranges from 27 to 30 degrees between June and September, it increases to 32 degrees between January and April with the last few months of the dry season characterized by extreme heat. The town has an average height of 93m.

Data Collection

Daily air temperature data was collected for Six months (November to April 2010) from the Nigerian Meteorological Agency (NIMET), at Amawbia. The daily maximum and minimum air temperature was measured using maximum thermometer and minimum thermometer respectively. Solarimeter (Day star meter, DS 05A) was used for measuring the incident solar radiation in W/m^2. Measurements of the incident solar radiation were done at intervals of one hour between 0600 hours and 1800 hours each day.

A regression model for monthly averages of solar radiation was developed. Accuracy of the regression model was judged in terms of goodness of fit that was established through various error indices.

Regression Modeling of Solar Energy of Awka

The first approach to developing a regression model was to first develop a theoretical model for the extraterrestrial solar radiation of Awka.

Extraterrestrial solar radiation model was developed using analytical integration.

The general Hargreaves model presented by [7] goes as follows;

$$\frac{h^{(d)}_{H,g}}{h^{(d)}_{0H}} = a(T_{max} - T_{min})^{0.5} \qquad (1)$$

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Where T_{max} and T_{min} are respectively the maximum and minimum temperatures, a is the regression coefficient, $h_{H,g}^{(d)}$ is the measured (experimental) solar irradiation, $h_{0H}^{(d)}$ is the extraterrestrial solar irradiation. The regression coefficient a is a parameter characterizing the solar energy of a location. The case of single-data point (single experimental measurement or run) is easily handled by solving (1) to give a as

$$a = \frac{h_{H,g}^{(d)}}{h_{0H}^{(d)}}(T_{max} - T_{min})^{-0.5} \quad (2)$$

The regression modeling of solar energy of a location is actually much more rigorous being that very numerous experimental data spanning months are normally involved for any arising model to be reliably accurate in application. The Multiple-data point case is considered as a vector/matrix problem of form

$$\boldsymbol{Y} = \boldsymbol{aX} \quad (3)$$

With solution

$$a = \{X^T X\}^{-1} X^T Y \quad (4)$$

Where $\boldsymbol{X} = \{x_1\ x_2\ x_3\ \ldots\ldots\ x_k\}^T$ and $\boldsymbol{Y} = \{y_1\ y_2\ y_3\ \ldots\ldots\ y_k\}^T$. The elements $x_1 = (T_{max} - T_{min})^{0.5})_1$ and $y_1 = \left.\frac{h_{H,g}^{(d)}}{h_{0H}^{(d)}}\right)_1$ are the experimental data values of the independent and dependent variables of the model : **Y = aX + e$_i$** where e_i is the error term/unexplained variable.

Model Validation

The accuracy of the model developed was ascertained using statistical indices such as R- square value, P-Value, F-Statistics, Percentage deviation $\mathbb{Q}$ and average percentage deviation $\bar{\mathbb{Q}}$.

The Model is of the form: **Y = aX + e$_i$**

Where **Y** = $\frac{h_{H,g}^{(d)}}{h_{0H}^{(d)}}$ and X= $(T_{max} - T_{min})^{0.5})$ and **e$_i$** is the error term.

The R^2 is computed with the equation

$$R^2 = 1 - \frac{\sum_{i=1}^{k}(Y_e - Y_m)^2}{\sum_{i=1}^{k}(Y_e - \bar{Y})^2} \quad (5)$$

The model is said to be significant if the p-value of the model using ANOVA is less than 0.05, otherwise, the model is insignificant. Also, the parameter in the model is significant if the p-value of test of significant of parameter (t-test) is less than 0.05 otherwise, the parameter is insignificant.

Percentage Deviation

The percentage deviation is given by [8] as

$$\mathbb{Q}_i = \frac{Y_{pm} - Y_{md}}{Y_{md}} X\,100 \quad (6)$$

For global solar radiation, the deviation is given thus;

$$\mathbb{Q}_i = \frac{H_{g,pm} - H_{g,md}}{H_{g,md}} X\,100 \quad (7)$$

Where $\mathbb{Q}_i$ is percentage deviation for single data point, Y_{pm} and $H_{g,pm}$ are predicted clearness index and global solar radiation respectively. They are generated by the simple regression.

Y_{md} and $H_{g,md}$ are clearness index and global solar radiation respectively gotten from measured data.

$H_{g,pm}$ and $H_{g,md}$ are and global solar radiation respectively. Similarly, the average percentage deviation for all sample data is stated as follows:

$$\bar{\mathbb{Q}} = \frac{(\sum_{i=1}^{n} \mathbb{Q}_i X100)}{n} \quad (8)$$

Percentage Prediction is given as 100 - $\bar{\mathbb{Q}}$ (9)

Where n is the total number of data points

III. Results and Discussion

Extraterrestrial Solar Radiation Model Result

The first step involved in this model development is the theoretical estimation of extraterrestrial solar radiation.

Reference [9] gave a simple periodic equation for direct normal extraterrestrial solar irradiance designated $q_{0N}(n)$ as

$$q_{0N}(n) = q_b(0)\left[1 + 0.033\cos\left(\frac{360}{365}n\right)\right] \quad (10)$$

Where $q_b(0)$ is solar constant; a popular value for solar constant which was adopted for analysis in this work is the 1367Wm^{-2} which is the value recommended by World Meteorological Organization (WMO), n is the day number of the year and N indicates normal to a surface.

The case where extraterrestrial solar irradiance is not on a normal surface but on a horizontal surface it becomes designated as $q_{0H}(n)$ and is given as

$$q_{0H}(n,t) = q_b(0)\left[1 + 0.033\cos\left(\frac{360}{365}n\right)\right]\cos\theta_z \quad (11)$$

Where θ_z is called the zenith angle. The mathematical description of θ_z is

$$\cos\theta_z = \cos l \cos\delta(n)\cos\omega(t) + \sin l \sin\delta \quad (12)$$

substituting (12) into (11) gives the extraterrestrial solar irradiance as

$$q_{0H}(n,t) = q_b(0)\left[1 + 0.033\cos\left(\frac{360}{365}n\right)\right](\cos l\cos[\delta(n)]\cos\omega(t) + \sin l\sin[\delta(n)]) \quad (13)$$

Where l is the latitude angle of the location and the symbol $\delta(n)$ represents the declination of the location. The $\delta(n)$ is a function of day number of a year. The approximate equation for solar declination $\delta(n)$ by [10] is

$$\delta(n) = 23.45\sin\left[\frac{360}{365}(284 + n)\right] \quad (14)$$

The extraterrestrial solar irradiation over a time interval $[t_1, t_2]$ is given as

$$h_{0H}(n) = \int_{t_1}^{t_2} q_{0H}(n,t)\,dt \quad (15)$$

For daily extraterrestrial solar irradiation which is very essential in solar energy applications, (14) becomes

$$h_{0H}^{(d)}(n) = 2\int_0^{\omega_s/\dot{\omega}} q_{0H}(n,t)\,dt \quad (16)$$

Where ω_s is the sunset hour angle, $\dot{\omega}$ is angular velocity of earth's rotation about its axis. Equation (16) is formulated with the idea that integral from solar noon to sunset is doubled to include the pre-noon interval.

Reference [11] presented the expression for sunset hour angle ω_s as shown in (17)

$$\omega_s = \cos^{-1}\{-\tan l \tan[\delta(n)]\} \quad (17)$$

Implementing the integral in (15) leads to daily solar irradiation on a horizontal surface as

$$h_{0H}^{(d)}(n) = q_b(0)\,\frac{86400}{\pi}\left[1 + 0.033\cos\left(\frac{360}{365}n\right)\right]\left(\cos l \cos[\delta(n)]\sin\omega_s + \frac{\pi}{180}\omega_s \sin l \sin[\delta(n)]\right) \quad (18)$$

Where ω_s is in degrees. If expressions for $\delta(n)$ and ω_s are inserted in (17) then $h_{0H}(n)$ becomes solely a function of day of the year n

$$h_{0H}^{(d)}(n) = q_b(0)\,\frac{86400}{\pi}\left[1 + 0.033\cos\left(\frac{360}{365}n\right)\right]\left(\cos l \cos\left[23.45\sin\left[\frac{360}{365}(284+n)\right]\right]\sin\left(\cos^{-1}\left\{-\tan l \tan\left[23.45\sin\left[\frac{360}{365}(284+n)\right]\right]\right\}\right) + \frac{\pi}{180}\cos^{-1}\left\{-\tan l \tan\left[23.45\sin\left[\frac{360}{365}(284+n)\right]\right]\right\}\sin l \sin\delta(n)\right) \quad (19)$$

The average value of daily extraterrestrial solar irradiation for a month designated in this work as $h_{0H}^{(m)}(n)$ is very popular among the existing Angstrom-Prescott type models and is given for the jth month of the year by

$$h_{0H}^{(m)}(j) = \frac{1}{n_e^{(j)} - n_s^{(j)}}\sum_{n=n_s^{(j)}}^{n=n_e^{(j)}} h_{0H}^{(d)}(n) \quad (20)$$

Where $n_s^{(j)}$ and $n_e^{(j)}$ are the number of the start and end days of the jth month.

The latitude and longitude of Awka are 6.2069° N and 7.0678° E respectively [12]. Inserting $l = 6.2069°$ and $q_b(0) = 1367\,\mathrm{Wm^{-2}}$ in (19) gives the specific model for daily extraterrestrial solar irradiation on a horizontal surface located at Awka as

$$h_{0H,Awka}^{(d)}(n) = 1367\,\frac{86400}{\pi}\left[1 + 0.033\cos\left(\frac{360}{365}n\right)\right]\left(\cos\left[6.2069\frac{\pi}{180}\right]\cos\left[23.45\sin\left[\frac{360}{365}(284+n)\right]\right]\sin\left(\cos^{-1}\left\{-\tan\left[6.2069\frac{\pi}{180}\right]\tan\left[23.45\sin\left[\frac{360}{365}(284+n)\right]\right]\right\}\right) + \frac{\pi}{180}\cos^{-1}\left\{-\tan\left[6.2069\frac{\pi}{180}\right]\tan\left[23.45\sin\left[\frac{360}{365}(284+n)\right]\right]\right\}\sin\left[6.2069\frac{\pi}{180}\right]\sin\delta(n)\right) \quad (21)$$

It will be cumbersome to use the above model to compute daily extraterrestrial solar irradiation on a horizontal surface located at Awka for every day on interest so it is more practical to generate the graphical forms for all the months as shown in Fig. 1. The yearly variation of daily extraterrestrial solar irradiation for Awka was also computed and presented in graphical form as seen in Fig. 2. The monthly average of daily extraterrestrial solar radiation is computed for all the months using (20) and the results summarized in Fig. 3.

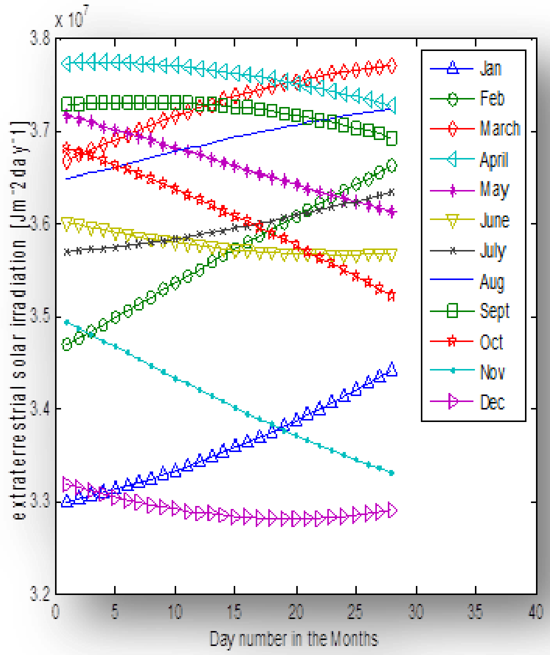

Fig. 1 Combined Plot for Extraterrestrial solar radiation of Awka for the month of January to December

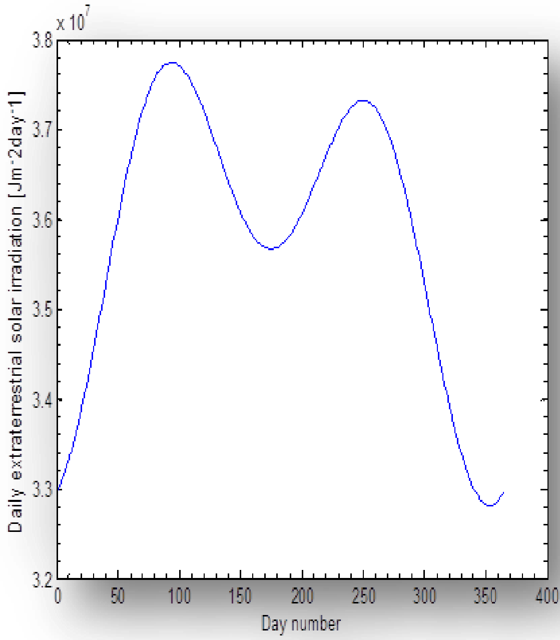

Fig. 2 The yearly variation of daily extraterrestrial solar irradiation for Awka

The daily extraterrestrial solar irradiation is calculated from (21) and combined in a series to generate the yearly variation as given in Fig. 2. As expected, daily extraterrestrial solar irradiation for Awka has its smallest values when declination has its lowest values in the January and December.

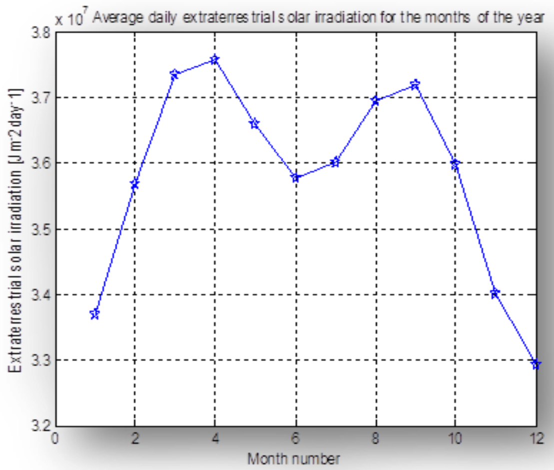

Fig. 3 The monthly average daily extraterrestrial solar irradiation of Awka.

The monthly average daily extraterrestrial solar irradiation of Awka for the months of the year is plotted using (20) to give Fig. 3

Okonkwo and Nwokoye, (2012) have presented 181-point experimental solar radiation data in their work which lacked a comprehensive modeling of solar radiation of Awka; a gap which this work among other things seek to plug. The experimental data is represented as $\boldsymbol{X} = \{(T_{max} - T_{min})^{0.5})_1 \ (T_{max} - T_{min})^{0.5})_2 \ \dots \ \dots\dots \ \dots \ (T_{max} - T_{min})^{0.5})_{181}\}^T$ and $\boldsymbol{Y} = \left\{ \left(\frac{h_{H,g}^{(d)}}{h_{0H}^{(d)}}\right)_1 \ \left(\frac{h_{H,g}^{(d)}}{h_{0H}^{(d)}}\right)_2 \ \dots \ \dots\dots \ \dots \ \left(\frac{h_{H,g}^{(d)}}{h_{0H}^{(d)}}\right)_{181} \right\}^T$. The measured values of the vector $\boldsymbol{X}$ are contained in table 2, while the measured values of solar radiation $\boldsymbol{Y}$ are contained in table 3. The month and day associated with each parameter are indicated in the table.

The declination $\delta(n)$ is calculated using equation (14) followed by calculation of sunset hour angle ω_s using equation (17) then $h_{0H}^{(d)}$ is calculated using equation (18). Alternatively the extraterrestrial solar irradiation $h_{0H}^{(d)}$ is calculated straight-forwardly using equation (21).

Because there are approximately twelve hours clear day in Awka, the daily average solar irradiance (W/m^2) values are converted to irradiation values by multiplying each value with 43200. The numerical elements of the vectors $\boldsymbol{X}$ and $\boldsymbol{Y}$ are as computed from experimental data table 4. Equation (4) is then solved using MATLAB code to give

$$a = 0.1429 \qquad (22)$$

The developed Hargreaves solar energy model for Awka using the available data becomes

$$\frac{h_{H,g}^{(d)}}{h_{0H}^{(d)}} = 0.1429(T_{max} - T_{min})^{0.5} \qquad (23)$$

The arising model is somewhat close to the Hargreaves model developed for Nigeria in the work of [14] which is given as follows;

$$\frac{h_{H,g}^{(d)}}{h_{0H}^{(d)}} = 0.16(T_{max} - T_{min})^{0.5} \qquad (24)$$

IV. Overall Model Performance Assessment

The model is of the form Y = 0.1429*X. The coefficient can be interpreted as a unit increase in X is leading to 0.1429 unit increase in the dependent variable Y. The R-Square Value for the developed model is 0.9483

Using Analysis of Variance (ANOVA), the values in Table 1 were obtained.

Table 1 Analysis of Variance Table

Source of Variation	Degree of Freedom (DF)	Sum of Squares SS	Mean Squares	F-Statistics (F^*)	P- Value
Regression	1	(SSR) = 44.23103	(MSR) = 44.23103	F^* = 3307.581	P-value = 2.4E-117
Residual Error	n-2	(SSE) = 2.407072	(MSE) = 0.013373		
Total	n-1	(SST) = 46.63811			

Interpretation: The F-Statistic is used to determine adequacy of the model. The p-value of the model is less than 0.05 which implies the model is significant. The F- Value is 3307.581. This implies that there is 1% chance that an F-value this large will occur due to noise.

Test of Significance of the model:

T-Statistic	P-value
57.51167	8.6E-118

Interpretation: The t-Statistic is 57.51 with p-value less than 0.05. This implies the parameter (coefficient) in the model is significant and there is a good relationship between the model parameters. The P-value of 8.6E118 implies that the difference in the average score is not significant.

Interpretation of R- Square Value: R-Square value is the coefficient of determination which shows percentage of fluctuation in the dependent variable that can be explained by the independent variable. Equation (5) gives the R^2 value of the proposed model as 0.948. In the model, temperature is responsible for 94.8% of the fluctuation in ratio of global solar radiation to extra terrestrial solar radiation of Awka.

comparing the R^2 value of the presented model with that of the known model of [14] which is 0.7868; since R^2 value closer to unity indicates better model, the presented model of this work is more accurate in application to Awka than the known model of [14] which was proposed for Nigeria as a whole. The reason for this higher accuracy originates from the fact that meteorological data and thus solar energy is a function of geographic location. It is then less accurate to generalize solar radiation model for a wider region than to particularize a solar model for a smaller location.

The Average percentage deviation $\bar{\Phi}$ is gotten from (8). For the developed model, the deviation is 7.32% while that of the existing model is 20.17%. This makes the average percentage prediction of the developed model to be 92.68% while that of the existing model is 79.83% from (9).

The result for the average percentage deviation and prediction shows that the developed model which is location specific will predict more accurately than the generalized model developed by [14].

The two models are compared graphically in Fig. 4 on a plot of clearness index versus the day number of the year. Fig. 4 shows that the clearness index of the developed model Y_{pm} agrees more with that of the measured data than the clearness index of the existing model Y_{km} (which is a generalized model). The agreement is quantified by the percentage prediction and deviation values; which makes it useful in estimating global solar radiation where there is scarce or no data. This agreement may be considered as an indication of the applicability of the developed model for Awka.

It is expected that the presented model which is developed specifically for Awka using the experimental data of Awka should be more reliable than the known model in the work done by [14] held to predict solar radiation for the whole Nigeria.

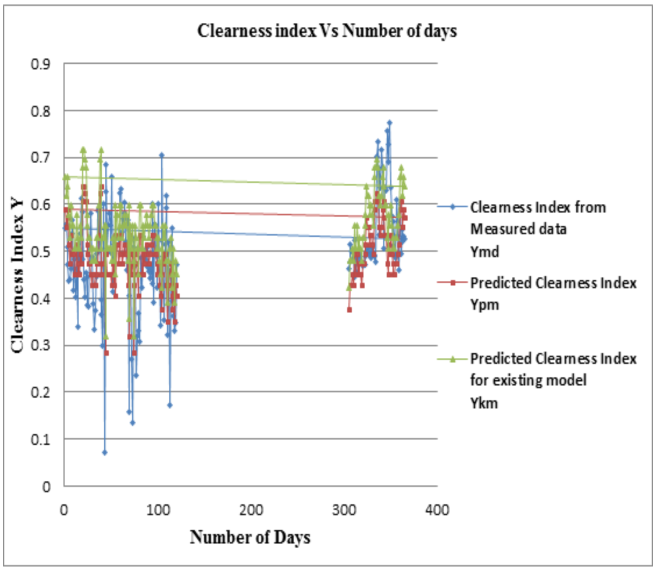

Fig. 4 A comparative plot of Clearness index (Y) Versus the day number of the year (n) for the proposed solar energy model for Awka Y_{pm} , the measured data Y_{md} and the existing solar energy model for Nigeria Y_{km},

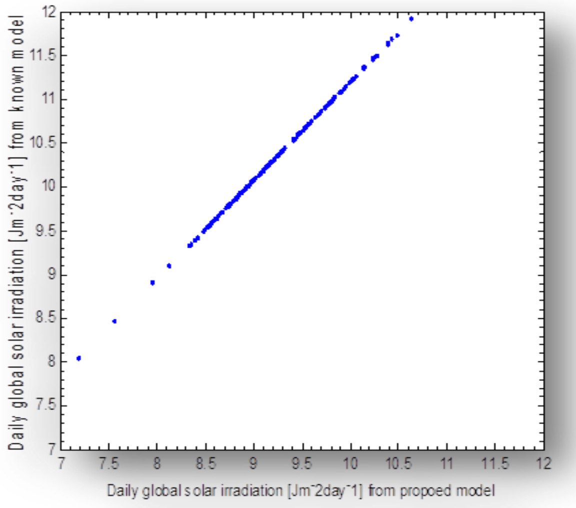

Fig. 5 Plot of $h_{H,g}^{(d)}$ of the known model versus the developed model

From Fig. 5, a linear relationship exists between daily global solar radiation of the existing model and the proposed model, with $R^2_{(r)}$ value of 1 and the equation of line given as $h_{Hg,km}^{(d)}$ = $0.893h_{Hg,pm}^{(d)}$ - 2E-13.

Though there is a linear relationship between the two models, the proposed model is more accurate because has R^2 value of 0.9483, percentage deviation of 7.32% and average percentage prediction of 92.68% than the existing model which has R^2 value of 0.7868, deviation of 20.17% and average percentage prediction of 79.83%. Hence the proposed model which is location specific will predict global solar radiation more accurately than the existing generalized model.

Table 2: The maximum and minimum temperature values for November to April 2010

	Nov		Dec		Jan		Feb		Mar		Apr	
DAY	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin	Tmax	Tmin
1	32	25	36	17	36	19	35	26	38	24	38	27
2	32	23	36	18	36	21	35	26	38	24	37	25
3	34	25	35	20	37	21	37	27	38	27	37	24
4	33	24	35	20	35	18	37	26	38	26	38	24
5	33	23	35	21	35	22	37	26	38	25	37	23
6	34	25	35	20	34	23	37	23	37	25	37	23
7	34	22	36	19	35	21	36	17	37	25	34	22
8	32	22	35	17	35	23	37	17	38	25	36	24
9	32	22	35	19	36	24	35	25	36	27	36	25
10	35	23	35	21	36	24	36	25	37	23	33	23
11	34	24	35	21	35	25	35	24	31	26	35	24
12	34	23	35	24	36	26	37	25	36	24	35	26
13	34	24	35	25	37	24	31	27	36	26	35	27

14	34	24	36	23	36	26	33	21	36	24	36	26
15	33	24	36	24	35	24	34	24	35	26	34	27
16	33	22	37	23	35	25	35	25	27	23	36	24
17	33	22	37	25	35	23	36	26	34	22	34	23
18	32	20	37	26	34	23	37	27	36	25	35	23
19	33	20	36	26	34	16	37	27	35	25	36	27
20	34	18	36	26	35	15	36	27	34	26	33	24
21	34	19	36	25	36	16	37	26	35	25	32	26
22	34	19	36	25	35	16	36	27	37	23	34	25
23	33	20	36	24	37	19	37	23	37	23	35	25
24	34	20	36	24	35	22	36	28	37	27	34	23
25	35	21	37	24	36	24	37	24	37	27	33	25
26	34	21	35	18	36	25	37	24	37	25	33	26
27	32	20	36	18	37	26	37	26	38	27	34	24
28	34	17	35	20	36	26	37	25	37	25	29	23
29	35	17	36	21	35	26			38	25	32	23
30	35	17	36	19	36	26			38	26	32	24
31			35		36	26			39	27		

Table 3: Daily average solar irradiance (W/m^2) for November to April 2010.

Adapted from Okonkwo and Nwokoye, (2012)

DAY	MONTH					
	Nov	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**
1	375.23	539.23	419	267.77	530.46	398.62
2	385.24	562.38	427.38	301.85	537.54	387.77
3	414.68	409	389.54	398.38	461.38	404.77
4	401.38	518.38	362.23	359.77	485.54	377.77
5	404.21	486.38	334.62	475.38	497.31	524.54
6	390.11	546.62	337.54	405.77	516.77	342.52
7	356.26	518.31	356.31	482.31	445.77	488.46
8	416.56	385.46	413.08	296.54	394.31	436.92
9	363.65	451.54	436.77	323.23	487	428.08
10	386.34	483.92	322	243.85	135.54	368.08
11	392.22	479.31	372.92	492.62	349.31	524.92
12	389.96	575.31	311.54	59.69	425.77	395.92
13	395.35	525.23	358.62	515.46	234	298.69
14	378.89	554.46	263.54	564	116.15	457.23
15	376.19	588.69	399.46	418.46	455.77	613.46
16	368.86	482.62	354.08	459.31	442.08	424.54
17	371.2	437.85	419.85	482.23	407.08	308.23
18	369.97	389.15	478.31	461.85	204.54	446.69
19	382.31	428.69	379.08	416	277.92	515.15
20	387.44	403.69	458.31	549.92	287	537.69
21	393.64	369.31	345.15	346.69	319.23	280.31
22	388.87	462.38	316.85	430.85	267.15	450.46
23	384.49	428.31	358.77	447.62	424	150.46

24	380.77	403.69	351.46	442.92	369.46	397.54
25	375.82	348.92	304.08	445.27	465	474.77
26	391.21	457.92	303.85	446.44	410.31	340.33
27	385.01	375.85	400.85	444.68	432.15	313.33
28	379.64	416.88	463.11	445.56	421.23	285.36
29	376.87	396.37	384.16		443.12	300
30	366.58	406.63	390.36		406.06	405.23
31		401.5	310.56		415.03	

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