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An Evaluation of the Global Solar Energy Resource for Offa, Kwara State, Nigeria

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Abstract
Man's need for energy is growing as a result of his propensity for needing energy for comfort. Still making up a larger portion of the world's energy supply are fossil fuels and hydropower. However, there is a need to investigate unconventional sources of energy because fossil fuel deposits are quickly running out and their prices are generally rising. In addition, there are several problems and worries about the effects fossil fuels have on the environment and human health, such as acid rain, water pollution, and land degradation brought on by mining and oil and gas drilling. Due to its benefits and purposeful governmental strategy, renewable energy has recently gained a lot of attention in light of the aforementioned reasons. This work focussed on solar resource evaluation of Offa, a town located in Kwara State, North Central, Nigeria, with coordinates: longitudes 8^0 30' 05'' N and latitude 8^0 15' 55'' E. Five selected models were evaluated with measured data. The daily incident solar radiation fluctuates around 180 W/m^2

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I. Introduction

The energy need of the modern man is on the increase, this is due to man's penchant for energy, which is needed for his comfort. As shown in Figure 1, various energy sources have been used, such as coal, oil, gas, electricity, heat biomass, hydropower and other waste. It also included other renewable energy or non-conventional sources such as bioenergy, geothermal, hydropower, ocean energy, wind and direct solar energy. Since the industrial revolution centuries ago, man has explored and exploited fossil fuels – coal, oil and gas to meet their energy demand. The total energy consumption worldwide in million tons of oil equivalent was 8,267 in 2002 and is projected to increase to 11, 176 in 2025 (Solangi, et al. 2011). Fossil fuel and hydropower still account for a higher percentage of the global energy supply. However, with fossil fuel deposits rapidly depleting and their price generally on the increase, there is a need to explore non-conventional sources of energy (Abdu Samad & Ganesh 2015, Kalyani& Pandey, 2014, Demİrbaş, 2005). Moreover, there are multiple issues and concerns about the fossil fuel impact on the environment and well-being of man such as (Solangi, et al. 2011):

~ Land degradation due to mining and oil and gas exploration
~ Acid rain and water pollution
~ Air pollution, due to the greenhouse (GHG)

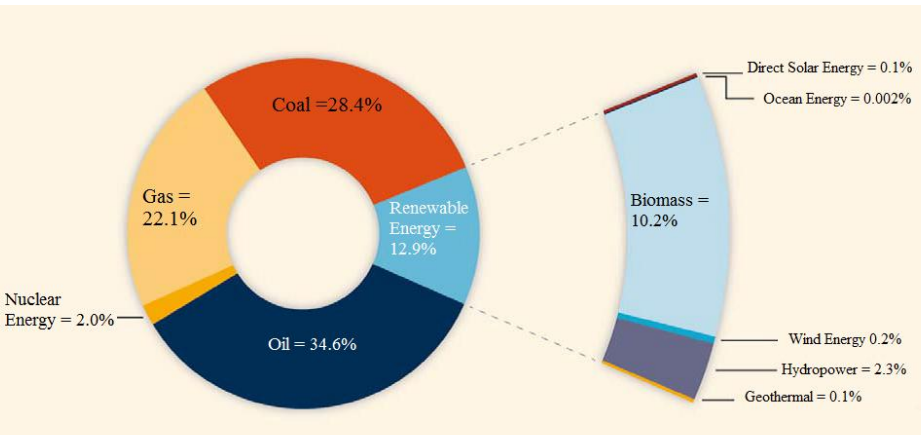

Figure 1: Energy sources (IPCC 2011)

It is reported that electricity generation contributes to 40% of the emission of GHG, such as CO2, NOx, SO2, and so on (Saber& Venayagamoorthy,2010). According to (Solangi, et al. 2011) CO2 have increased by 39% above the pre-industrial revolution level. The projected CO2 emission by years is summarized as follows:

	Year	World	Africa
~	2015	33,284	1283
~	2020	36, 023	1415
~	2025	38, 790	1524

On the hand, (IPCC 2011) pointed out efforts that have been directed towards minimizing GHG while satisfying energy demand, namely:

~ Energy conservative and efficient methods
~ Fossil fuel switching
~ Use of renewable energy
~ Development of nuclear energy
~ Carbon capture and storage techniques

In addition, the rapid deployment of nuclear power plants is limited by fear of nuclear proliferation, disposition of spent fuel, issues related to peace and stability and the fear of accidents limiting the aggressive deployment of nuclear energy sources (Chu & Majumdar 2012).

Owing to the foregoing, renewable energy has attracted a lot of attention recently due to its advantages and the following factors (IPCC 2011):

~ Deliberate governmental policy
~ Instability in the prices of fossil fuel
~ Continuous increase in energy demand
~ Decrease in the cost of renewable energy technology

Among the renewable energy sources that can substitute for fossil fuel is hydropower, which on the other hand has the following associated negative impacts (Solangi, et al. 2011):

~ Affects the balance of the aquatic ecosystem
~ Occasional flooding
~ Competition with other water users

The merits of solar energy motivating its consideration in this research are highlighted as follows (Solangi, et al. 2011):

~ It allows for degraded land reclamation
~ Contributes to the reduction of transmission line
~ Does not contribute to GHG or other air pollutants
~ It increases regional/national energy independence
~ Does not compete for or pollute water
~ Contributes to quicker rural electrification
~ It helps to diversify the energy mix of the country

Nigeria is blessed with huge solar resource potential as may be deduced from Figure 2. The development of the solar resource model can enhance the extraction of solar energy towards growth and environmental sustainability.

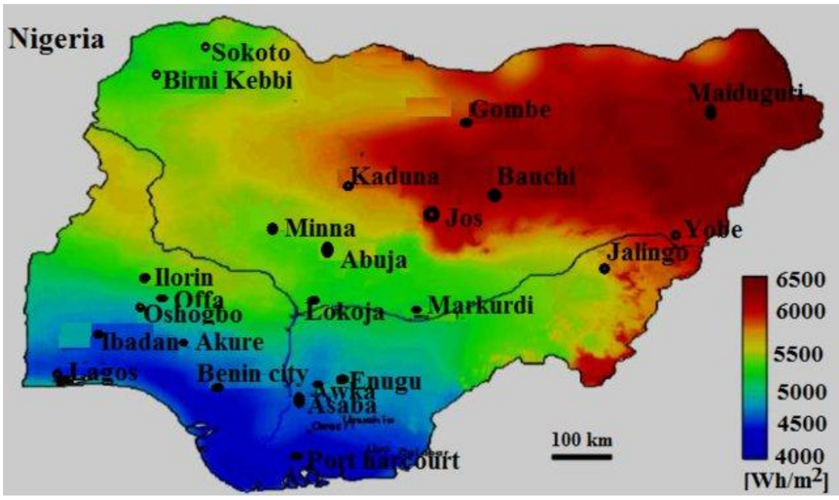

Figure 2: Solar Radiation for Nigeria. Source: Kehinde,Ehiagwina, Afolabi and Olaoye (2016)

In designing solar power systems, one of the most essential parameters of interest is the long-term average daily global irradiation. There are numerous models used in evaluating global solar irradiation, but many are region-specific. Moreover, the models that are applicable in general cases can only give approximate results. In addition, no model thus far has been developed to evaluate global solar resources in Offa. Therefore, this study attempts to develop a global solar resource model and solar power system for Offa, Kwara State, Nigeria.

According to (Martı´n, et al. 2010) the investment possibility in solar energy is huge, this is due to the Kyoto protocol aimed at reducing carbon emission and progressive series of regulations regarding green energy established in several countries.

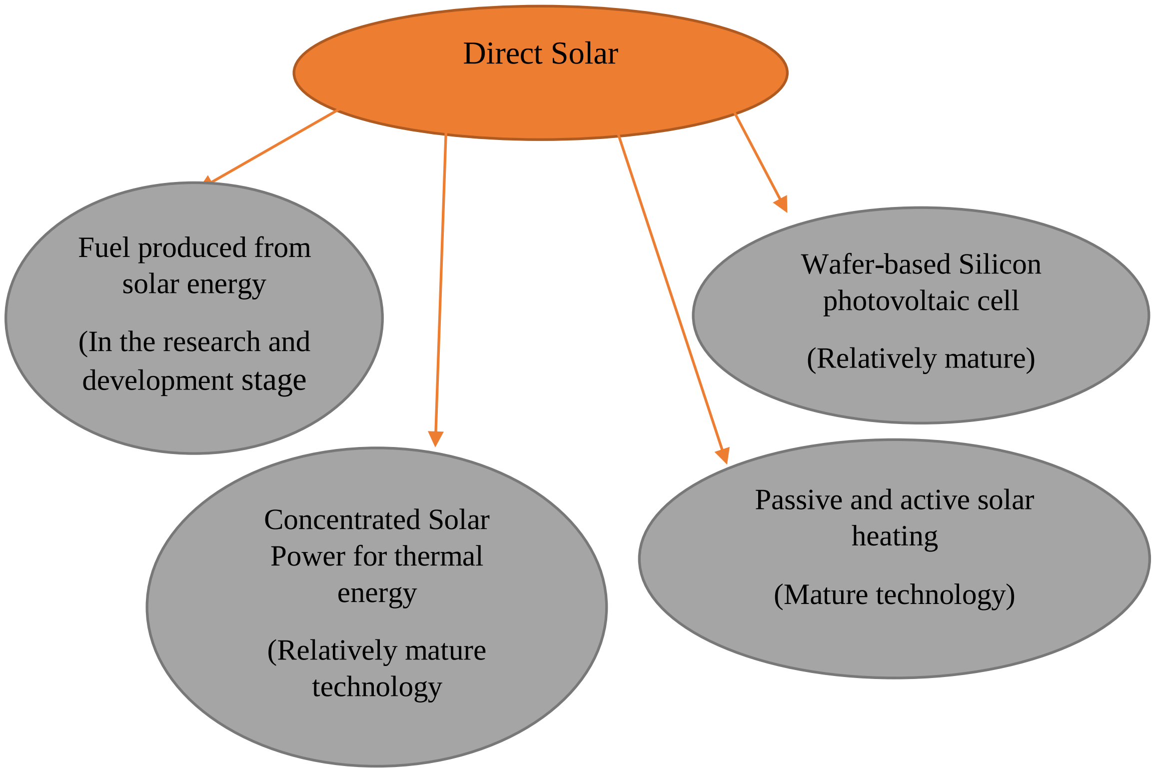

Figure3: Approaches for harnessing direct solar energy

Going by the submissions of (Solangi, et al. 2011), in 2005, global solar markets got to US$ 11.8 billion, up 55% from 2004. The demand for silicon for solar cells is expected to increase from 41,000 tons in 2006 to 400,000 tons in 2015. There are four approaches for harnessing direct solar energy (IPCC 2011), which are shown in Figure 3.

In terms of electrical power generation, transmission and distribution, Nigeria is still struggling to make power available. The reasons for this include; inadequate generating capabilities of its power, no proper maintenance, irregular supply of gas to power thermal plants due to frequent pipeline vandalization and variability of water levels in hydropower plants. Another reason is that the energy mix is not robust-dependence on basically two sources of electrical power, namely; hydropower and thermal power plant. Moreover, the transmission and distribution capabilities of the National grid are inadequate, favouring modular grid systems.

Problems associated with the use of fossil fuels and hydropower have been highlighted earlier in this section. Sources of renewable energy in Nigeria include direct solar, hydropower, wind energy and bioenergy.

Owing to its advantages, solar power systems have drawn a lot of research interest in evaluating global solar resources. An overview of some of the research contributions is presented next.

The Angstrom-Prescott linear regression model is one of the most popular models used in evaluating global solar resources. It involves using observation data of global radiation and sunshine hours from observation to determine all necessary parameters by which the monthly average solar radiation data. Examples of its use are reported in (Gao et al. 2014, and Ji, et al. 2011). However, (Karim, et al. 2011), owing to the variability of solar data with time, proposed wavelet transform and curve fitting methods for solar radiation compression and prediction-based modelling in analyzing the transient nature of solar radiation. In other to improve accuracy in solar resource evaluation, researchers have applied a set of artificial neural network (ANN) models (Assi et al., 2013).

Examples are reported in (Deng et al., 2010, Assi, Shamisi & Hejase, 2012, Assas et al., 2014, Khan, Huque & Mohammad, 2014). It was shown (Assas et al., 2014) that relative humidity is the most important feature influencing the prediction performance of global solar resources. However, the need to carry out measurement of solar resources and to develop a solar resource model for a given region was pointed out by (Jakhrani, et al. 2010), while evaluating the various models for the estimation of monthly average global solar radiation from bright sunshine hours and other meteorological parameters at four locations in Malaysia. The approach involved the investigation of six different solar radiation models, such as Angstrom, et al. subsequently compared the computed values with values obtained from solar measurement.

The Iranna-Bapat's model is yet another solar resource model which takes ambient temperature, humidity, wind speed and moisture in a given location (Korachagaon & Bapat, 2012). A total of 78 models were identified from a chronological review of existing global solar resource models by (Besharat, Dehghan & Faghih, 2013), who consequently grouped them into four categories as follows:

~ Sunshine-based models – 35

~ Cloud-based models – 6

~ Temperature-based models – 16

Other meteorological parameters-based models – 21

The approach is to comprehensively review existing literature on existing global solar resource models and identify reliable models. These models would then be subsequently used to evaluate the solar irradiation for Offa.

The next step is to use available equipment such as a thermometerto measure solar-related datafor six in Offa. The measured data (solar irradiance, temperature, wind speed and direction and humidity) would subsequently be used to develop a model for predicting the global solar resource. An energy audit for Offa would be carried out, and the result used in designing a solar system for Offa.

The hygrometer will be utilised in the measurement of the amount of humidity in the atmosphere. The hygrometer is shown in Figure 6.

Figure 6: Commercially available hygrometer

In the collection of solar radiation data, the procedure outlined in Cavaco, Canhoto and Pereira (2021) will be followed.

Added value and accuracy chain for solar radiation model output is shown in Figure 5.

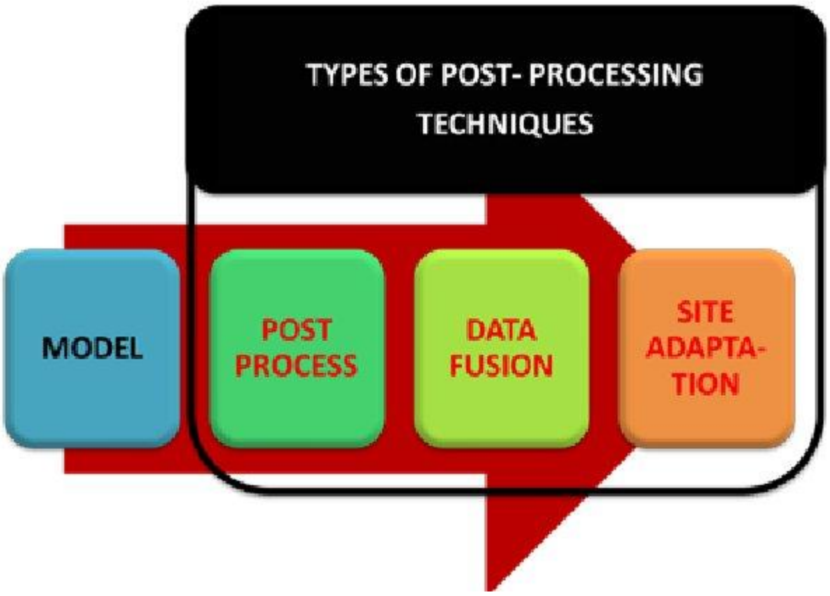

Figure 5: Added value and accuracy chain for solar radiation model output

Additionally, a variety of models exist that link several climatic characteristics to assess a location's global sun irradiance (H). Some of these evaluate H based on the correlation of variables such as sunshine duration, maximum air temperature, altitude and location of the place to water surfaces, the solar declination angle, mean daily vapour pressure, and extraterrestrial radiation, as well as variables such as maximum and minimum temperatures, cloud cover, extraterrestrial radiation, relative humidity, latitude, elevation, soil temperature, precipitation, evaporation, and the number of rainy days. The Angstrom-Prescott model, which connects the amount of solar energy received worldwide to the number of hours of sunlight, is given by Eq. (1):

$$K_T = \frac{H}{H_o} = a + b\frac{\bar{n}}{N} \quad (1)$$

Where K_T = clearness index, H_o = extraterrestrial solar radiation, $\bar{n}$ = the monthly average sunshine hours, N = monthly average sunshine duration or day length, and a and b are correlation coefficients (or constants). The ratio $\frac{\bar{n}}{N}$ is called relative sunshine.

The main criticism of Eq. (1) or its variants has been that it depends on the locality. On the other hand, it is noted by some that Eq. (1) type models provide greater accuracy than others and are practical to implement.

There is literature that describes global solar radiation models of the Angstrom-Prescott and other model types for the situation of Nigeria. The Fagbenle model is one of the Angstrom-Prescott type models. He created quadratic models to calculate the worldwide sun radiation for three places in Nigeria: Benin City, Samaru, and Ibadan. For Onne, Nigeria, Akpabio and Etuk created a liner Angstrom- Prescott type model (Akpabi & Etuk, 2003; Fagbenle, 1993).

Using location-dependent equations for each of the cities, Augustine et al.also developed several regression models for four cities in Southern Nigeria, with the predictor variables being the clearness index, relative sunlight, maximum temperature, cloudiness index, and relative humidity. Additionally, Olayinka used regression analysis to estimate diffuse and global solar radiation for four Nigerian cities using the same predictor variables.But the models were additionally site-specific. A location-dependent Angstrom-Prescott type model was also developed by Yohanna et al. for Makurdi, Nigeria (Augustine et al. 2010; Olayinka, 2011; Yohanna et al. 2011).

The location latitude, average daily relative humidity, the daily ratio of sunshine length, daily maximum temperature, and cosine of day number are all combined in this study. The coefficients of five equations were created and determined. Additionally, the anticipated values of global solar radiation derived from the five correlations were compared to actual observed values and published data.

Based on the foregoing, the goal of this study was to create a new multivariate regression model by using 24 years of daily data from additional stations dispersed throughout Nigeria's geopolitical zones.

When there is a link between a dependent variable and two or more independent variables, multivariate regression analysis is performed. This approach was chosen because of its enhanced predictability, which was made feasible by the employment of numerous predictors.It is noteworthy that models that simulate real-world phenomena typically incorporate several independent variables. By conducting independent correlations between the criteria variable and each predictor beforehand, it is also helpful in optimizing combinations of predictors. More complex research hypotheses may be examined than with simple correlations when numerous independent variables are included in a model. This is because the independent variables may be either numerical or categorical. Polynomial terms and hypothetical interactions between the variables can both be used in the analysis.

The equations developed by Ajayi et al. (2014) are of the form indicated in Equations (2-6)

Model 1

$$H = a\cos\emptyset + b\cos n + cT_{max} + d\left(\frac{\bar{n}}{N}\right) + e\left(\frac{T_{max}}{R.H}\right) + f\left(\frac{T_{max}}{R.H}\right)^2 + g\cos\emptyset.\cos n + h \quad (2)$$

Model 2

$$H = a\cos\emptyset + b\cos n + cT_{max} + d\left(\frac{\bar{n}}{N}\right) + e\left(\frac{T_{max}}{R.H}\right) + f\left(\frac{T_{max}}{R.H}\right)^4 + g\cos\emptyset.\cos n + h\frac{T_{max}}{\cos\emptyset} + i \quad (3)$$

Model 3

$$H = a\cos\emptyset + b\cos n + cT_{max} + d\left(\frac{\bar{n}}{N}\right) + e\left(\frac{\bar{n}}{N}\right)^3 + f\left(\frac{T_{max}}{R.H}\right) + g\left(\frac{T_{max}}{R.H}\right)^2 + h\left(\frac{T_{max}}{R.H}\right)^3 + i\cos\emptyset.\cos n + jT_{max}\cos\emptyset + k\cos 2n + l \quad (4)$$

Model 4

$$H = a\cos\emptyset + b\cos n + cT_{max} + d\left(\frac{\bar{n}}{N}\right) + e\left(\frac{\bar{n}}{N}\right)^3 + f\left(\frac{T_{max}}{R.H}\right) + g\left(\frac{T_{max}}{R.H}\right)^2 + h\left(\frac{T_{max}}{R.H}\right)^3 + i\left(\frac{T_{max}}{R.H}\right)^4 + j\cos\emptyset.\cos n + kT_{max}\cos\emptyset + l\cos 2n + m \quad (5)$$

Model 5

$$H = a\cos\emptyset + b\cos n + cT_{max} + d\left(\frac{\bar{n}}{N}\right) + e\left(\frac{T_{max}}{R.H}\right) + f(R.H) + g\cos\emptyset.\cos n + h\left(\frac{T_{max}}{\cos\emptyset}\right) + i\left(\frac{T_{max}}{\cos\emptyset}\right)^2 + jnN2 + k\cos 2n + l \quad (6)$$

Where $\emptyset$ = location latitude (^{o}), $\bar{n}$ = the daily sunshine hours, *N*= maximum sunshine duration or day length, T_{max}= maximum daily temperature (^{o}C), n = day number in the year, *R.H* = daily relative humidity and *a, b, c, d, e, f, g, h, i, j, k, l, m* are correlation coefficients (or constants). The ratio $\frac{\bar{n}}{N}$ is called the relative sunshine and *H* is the daily global solar irradiance value (W/m^2).

Using a Gunn-Bellani radiometer, the instantaneous sun radiation over the globe was measured. By measuring the volume of liquid that is distilled by the radiation, the device offers a time-integrated measurement of the radiation incident on a black body. Since not all NIMET stations accurately measure global solar radiation, the data used in this study came from stations with reliable databases.

As a result, the data on worldwide solar radiation measured in millimetres using the Gunn-Bellani method was transformed into a useable form (using a conversion factor of 1.1364 to (Mj/m2 day) and then converted again into (W/m2) using a conversion ratio of 11.5741.The NIMET data was gathered for quality assurance purposes as well as for assessing the correctness of the model created for this study. This was done by comparing the calculated daily global solar radiation (H_{cal}) with that obtained from the NIMET gun-Bellani apparatus (H_m).

Estimation of Extraterrestrial Solar Radiation

Equation (7) was used to estimate the extraterrestrial radiation:

$$H_o = \frac{24}{\pi} l_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right)\left(\cos\emptyset\cos\delta\sin\omega_s + \frac{2\pi\omega_s}{360} \times \sin\emptyset\sin\delta\right) \quad (7)$$

Where l_{sc}= solar constant = 1367 W/m^2, n = day number in the year, $\emptyset$ = location latitude (LAT), δ= declination angle (degrees) and ω_s = sunset hour angle (degrees).

$$\delta = 23.45 \sin\left(\frac{260(n+284)}{365}\right) \quad (8)$$

$$\omega_s = \cos^{-1}(-\tan(\delta)\tan(\emptyset)) \quad (9)$$

$$N = \frac{2}{15}\omega_s \quad (10)$$

Model Performance estimation

The Nash-Sutcliffe Coefficient of Efficiency (COE) (Equation 11), Mean Absolute Bias Error (MABE) (Equation 12), Mean Bias Error (MBE) (Equation 13), Mean Absolute Percentage Error (MAPE) (Equation 14) and Root Mean Square Error (RMSE)(Equation 15) were used to forecast the accuracy of the model and then choose the best-performing model.

$$\text{COE} = 1 - \frac{\sum_{i=1}^{k}(H_{cal} - H_m)^2}{\sum_{i=1}^{k}(H_{cal} - \overline{H}_m)^2} \quad (11)$$

$$\text{MABE} = \left(\sum_{i=1}^{k}|H_m - H_{cal}|\right)/k \quad (12)$$

$$\text{MBE} = \left(\sum_{i=1}^{k}(H_m - H_{cal})\right)/k \quad (13)$$

$$\text{MAPE} = \frac{\left\{\sum_{i=1}^{k}\left|\left(\frac{H_m - H_{cal}}{H_m}\right)\right| \times 100\right\}}{k} \quad (14)$$

$$\text{RMSE} = \sqrt{(\sum_{i=1}^{k}(H_m - H_{cal})^2)/k} \qquad (15)$$

This work would be limited to solar resource evaluation of Offa, a town located in Kwara State, North Central, Nigeria, with coordinates: longitudes 8^0 30' 05'' N and latitude 8^0 15' 55'' E. It is also limited to designing solar power systems

II. Results and Discussion

The constants of Equations (2-6)were determined using the leastsquare statistics. The corresponding results are presented in Table 1.

Table 1: Results of the determined coefficients for the five models under investigation

Coefficients	Model 1	Model 2	Model 3	Model 4	Model 5
a	0.520	—1.152	—3.081	—1.172	—3.689
b	19.229	18.097	27.875	28.161	29.309
c	5.513	5.684	6.222	7.011	7.665
d	125.761	123.143	51.454	110.162	57.524
e	—21.682	—9.077	92.903	30.619	7.962
f	5.632	0.198	0.061	—184.105	0.642
g	—2.693	—2.5541	—6.436	154.082	—3.683
h	—33.151	—3.421	1.888	—52.038	—8.855
i	0	—14.276	—3.737	6.048	0.499
j	0	0	—6.259	—3.288	91.308
k	0	0	—3.833	—5.083	—2.986
l	0	0	15.859	—0.035	—61.702
m	0	0	0	13.852	0

It was important to assess the degree of performance of the models to choose the Eqs (3)–(7) model that best matches the data set for the case study site. To assess this, Eqs. (12)- (17) and presented in Table 2.
The minimum values are shown in **green** font and the maximum values are shown in **red** font.

Table 2: Results of error and performance analyses of the different models

Error Measures	Model 1	Model 2	Model 3	Model 4	Model 5
COE	0.656	0.665	0.668	0.340	0.596
MABE	0.085	0.085	**0.083**	**0.139**	0.099
MBE	**0.012**	**0.012**	**0.012**	**0.012**	**0.064**
MAPE x100%	**0.014**	**0.014**	**0.014**	**0.032**	0.019
RMSE	**0.118**	**0.118**	**0.118**	**0.180**	0.139

Models 1-3 showed superior performance as may be seen from MBE, MAPE and RMSE.
The results of the use of these model in the forecast of the incident solar radiation (W/m^2) is shown in Figure 6.

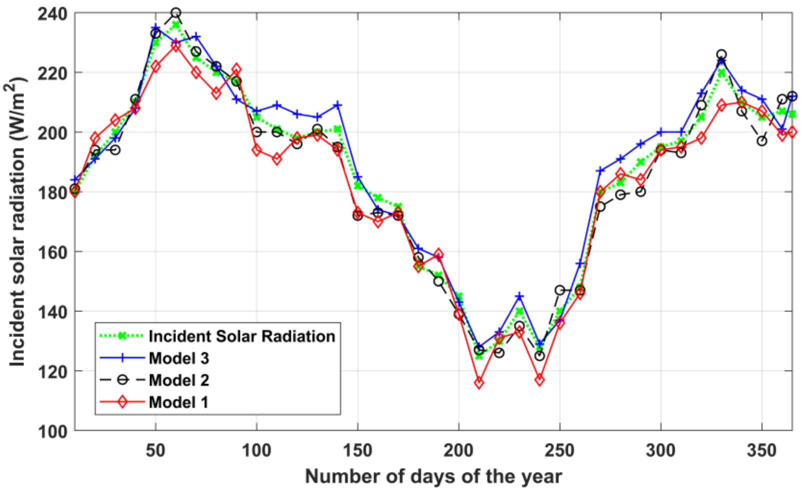

Figure 6: Comparison of estimated and actual incident solar radiation

III. Conclusions

In this research, we identified five models from Ajayi et al. (2014) and evaluated them for the incident solar radiation of Offa. The results were discussed earlier. The daily incident solar radiation fluctuates around 180 W/m^2. This study will assist in the development of a robust solar-powered system.

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