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Research paper

Performance evaluation of existing sunshine-based computing models for estimating global solar radiation at Lagos, Nigeria

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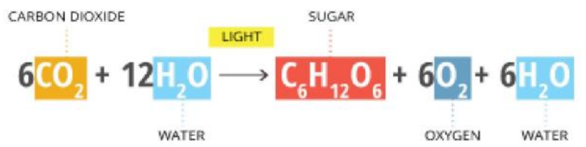
Abstract

Several empirical models have been fitted in literature for estimating global solar radiation across the globe in order to produce global solar radiation data and also as a baseline for further scientific and environmental research without the substantial cost of instrumental network that would otherwise be needed. However, peers and researchers have reported that the most commonly employed parameter for predicting global solar radiation is sunshine duration as a result of its availability and simplicity in course of measurement globally. In this research, the author considered the performance of 63 sunshine-based models for the prediction of global solar radiation at Lagos, Nigeria. Numerous models are found unreliable for use in this location, and others vary in performance. On the whole, the best model was identified due to its values of statistical indicators.

Keywords: *Global Solar Radiation; Sunshine Based Models; Statistical Indicators; Tropical Rainforest Zone; Lagos.*

1. Introduction

Solar energy has evolved to become a topical issue globally because of its enormous significance in many industries and application areas such as exciting electrons in a photovoltaic cell, solar heating, solar thermal energy, solar architecture, molten salt power plants and supplying energy to natural processes like photosynthesis as shown in equation 1.



(1)

Solar energy is well known as the source of life on earth. It supplies heat to the atmosphere and lands, generates its winds, drives the water cycle, warms the oceans, grows the plants, feeds the animals, and even generates fossil fuels.

Increase in population and growing demand in urban and rural areas with the corresponding development in science and technology, changes in rural scenario and agricultural practices has necessitated the high demand of alternative (renewable) energy for both developing and developed nations across the globe.

The abundance of solar energy availability qualifies it as a highly appealing source of electricity irrespective of the efforts of researches, scientists, government as well as non-governmental agencies (NGOs) so far to exploiting this unique energy via numerous technologies, solar energy potential is fundamentally in exploited yet. The quantity of energy emitted by sun is so enormous that in case of converting only 0.1% of the solar energy reaching the earth surface to electricity with the efficiency of 10%, the output power would be 17,300GW, which is 7 times higher than the global average momentary electricity consumption in 2012 [1-3].

Solar energy is primarily derived from solar radiation reaching the surface of the earth. It is an electromagnetic radiation of varying wavelengths ranging from 10^{8} μm (μ rays) to 10^{8} μm (radio wave) [4]. It serve as a baseline for estimating and understanding solar radiation parameters such as diffuse solar radiation, direct solar radiation, ground reflected, reference evapotranspiration, crop evaporation and actual evaporation.

A good working knowledge of solar radiation is needed for many application such as exciting electrons in an photovoltaic cell and supplying energy to natural processes like photosynthesis, thermal system and photovoltaic [5]; meteorology, climatology, radiation and energy budgets, water treatment processes, heating and natural lighting, agriculture and forestry, and use in renewable energy; air conditioning engineers and energy-conscious designers of building [6-7].

Solar radiation varies from one climate and geographical site to another. It is function of meteorological parameters such as evaporation, effects of cloudiness, relative humidity, precipitation, temperature, sunshine duration, extraterrestrial solar radiation, and reflection of the environs; geographical parameters such as latitude, longitude and elevation of the site; geometrical factors such as azimuth angle, sun azimuth angle; astronomical parameters like solar constant, earth-sun distance, solar declination and hour angle; physical parameters such as scattering air molecules, water vapour content, scattering of dust and other atmospheric constituents like O_2, N_2, CO_2, and O [4], [8].

Global solar radiation has been measured and quantify in numerous locations in Nigeria and across the globe using a variety of measurement instrument and techniques. These assessments have involved direct measurement with meteorological measuring instrument such as Eppley pyranometer and satellite remote-sensing instrument such as Moderate-Resolutoin Imaging Spectroradiometer (MODIS) products, and meteosat-images etc.

As a result of cost implication, maintenance, expertise involved in ground measurement and satellite-derived data especially in rural and developing locations in Nigeria and the world at large, numerous estimation models employing empirical, artificial neutral network, adaptive neural fuzzy inference system approach, autoregressive Moving Average, support vector machine, genetic programming etc. had been proposed by solar energy researchers that can produce global solar radiation data without the substantial cost of the instrumental network that would otherwise be needed [9-12].

Angstrom [13] developed the first empirical model for estimating average daily global solar radiation to average clear-sky daily global radiation at a particular location with the sunshine duration fraction. In order to correct the anomalies in the definition of a clear sky, other researchers Prescott [14] have put the correlation in a more convenient form by substituting the clear-sky radiation with average daily extraterrestrial radiation on horizontal surface.

Since last decades, several solar energy researchers have employed Angstrom-Prescott model globally as a baseline further developing empirical models for estimating global solar radiation using the same parameter, other meteorological parameters, geographical parameters, geometrical parameters and astronomical parameters that will best fit the local climate of their interest.

Therefore, the main purpose of this research is to determine the performance and reliability of sixty three sunshine-based computing models for estimating global solar radiation at Lagos, Nigeria. Thus this research will determine greatly numerous functional forms of sunshine –based models employed for estimating global solar radiation.

2. Study area

Lagos is located in Nigeria between latitude 3.33 ^{0}N and longitude 6.58 ^{0}E with an altitude of 73m above the sea level as shown in Fig. 1. Lagos has a tropical wet and dry climate with two distinct rainy seasons; the more intense season occurs between April and July, with a milder one from October to November. At the climax of the rainy season, the weather in Lagos is wet about half the time. Lagos experiences a dry season (when it rains less than two days per month) during August and September, as well as between December and March, accompanied by Harmattan winds from the Sahara Desert, which are at their strongest from December to early February. The temperature range in Lagos is fairly small, generally staying between a high of 33°C and low of 21°C. The hottest month is March, when average daytime temperatures reach 29°C, while July is the coldest month with an average temperature of 25°C.

Fig. 1: Map of Nigeria Showing Study Area.

3. Materials and methods

3.1. Data acquisition

The long term monthly mean daily global solar radiation and sunshine duration for the period of 43 years (1970-2012) were obtained from the Nigerian Meteorological Agency (NIMET), Oshodi, Lagos. The global solar radiation data were captured using Gun-Bellani distillate (measured in milliliters) and were converted into MJm^{-2}day^{-1} using a conversion factor of 1.216 H_{GB} (where H_{GB} is the Gun-Bellani reading) proposed by Ododo [15].

The Gun-Bellani distillate solar radiation integrator provides a time integrated reading of radiation falling on a black body by measuring the volume of the liquid distilled in a receiving graduated tube. It is normally calibrated against standard solar radiation recorder such as pyranometer, pyrheliometer to obtain accurate result associated with the respective actinometer. In developing countries like Nigeria, the Gun-Bellani distillate solar radiation integrator low cost, simple observation procedure and absence of any replaceable mechanical and electronic part favours it application for weather data assessment across a number of experimental stations.

The daily sunshine hours was measured employing the Campbell Stokes sunshine recorder which comprises a glass sphere mounted concentrically in a section of a spherical bowl. The length of the burn trace left on the card represents the sunshine duration in hour. To generate accurate readings, both the spherical part and the sphere should be designed so that the sphere can be accurately centered on it.

3.2. Evaluation techniques

The authors review the ISI Web of Science, Scopus, SciELO, and Google Scholar databases in order to obtain the models and its basic parameters for estimating global solar radiation. The following information was obtained from the published works: city, year of publication, functional forms, estimation models, performance of the models such as root mean square error, mean bias error, mean percentage error, coefficient of correlation, coefficient of determination etc. The accuracy of a model determines to a great extent its value for application. The three statistical indicators via mean bias error (MBE), mean percentage error (MPE) and root mean square error (RMSE) are often applied by solar energy researchers for evaluating the performance of a predictive model. MBE provides information on the long-term performance of model studied. RMSE provides information on the short-term performance of the model as it allows a term-by-term comparison of the actual deviation between the measured and estimated values. Generally, small values of MBE and RMSE are desirable [16-17]. MPE is an overall measure of estimation bias. It provides information regarding underestimation or overestimation of estimated data. A positive MPE value gives the average amount of overestimation in the predicted values and vice versa. Akpabio and Etuk [18] recommended low values of MPE for optimal performance of solar system. Thus, the models considered and selected in this paper are models with small values (close to zero) of MBE, MPE and RMSE as recommended by [16-18]. These relations are given as:

$$MBE = \left[\sum_{i=1}^{N} \frac{(Mi - Ei)}{N} \right] \quad (2)$$

$$MPE = \left[\sum_{i=1}^{N} \left(\frac{(Mi - Ei)^2}{Mi} \right) \times 100 \right] / N \quad (3)$$

$$RMSE = \left[\sum_{i=1}^{N} \frac{(Mi - Ei)^2}{N} \right]^{1/2} \quad (4)$$

Relative percentage error (e) was used to compare between the measured and estimated values for an individual month given as:

$$e = \frac{H_{Mi} - H_{Ei}}{H_{Mi}} \times 100 \quad (5)$$

Where N is the total number of observation, Mi is the i^{th} measured H values, Ei is the i^{th} estimated H values and other symbols retain their usual meaning.

3.3. Fundamental requirements

The basic parameters of sunshine duration fraction, daily extraterrestrial radiation on the horizontal surface (H_o) is significant for the estimation of global solar radiation. Sunshine duration fraction is the ratio of actual sunshine duration to maximum possible sunshine duration expressed mathematically as:

$$S_o = \frac{2}{15}\cos^{-1}[\tan\delta\tan\varphi] \tag{6}$$

$$\delta = 23.45\sin\left[\frac{360(n+284)}{365}\right] \tag{7}$$

Where φ is the latitude, δ is the solar declination given by Yaniktepe and Genc [5] and n the number of days of the year starting from first January. The daily extraterrestrial solar radiation is the solar radiation intercepted by horizontal surface during a day without the atmosphere expressed theoretically as given by Yaniktepe and Genc [[5]:

$$H_o = \frac{24}{\pi} I_{SC} \begin{pmatrix} 1 \\ +0.033\cos\frac{360n}{365} \end{pmatrix} \times \begin{pmatrix} \cos\varphi\cos\delta\sin\omega_S \\ +\frac{2\pi\omega_S}{360}\sin\varphi\sin\delta \end{pmatrix} \tag{8}$$

Where the mean sunrise hour angle (ω_s) can be evaluated as:

$$\omega_S = \cos^{-1}[\tan\delta\tan\varphi] \tag{9}$$

I_{SC} is the solar constant and other symbols retain their usual meaning

3.4. Empirical models

In global solar radiation estimation, an empirical model relates global solar radiation with other easily measurable variables such as sunshine duration etc by employing concise mathematical functions. As a result of its simplicity and high operability, the empirical models are much more convenient for engineering applications. Numerous sunshine-based models have been reported in literature for estimating global solar radiation on the horizontal surface (H) either on daily mean basis (DB) or monthly mean basis (MB) across the globe. In this paper, different functional forms of sunshine models were selected owing to the findings from peers and reviews that sunshine-based models reported the highest influence on models performance accuracy for estimating global solar radiation across the globe compared to other meteorological and atmospheric parameters employed. This radiometric model pioneered by Angstrom [13] and modified by Prescott [14] and other researchers have been applied by countless number of solar radiation researchers for estimating the monthly mean daily global solar radiation on the horizontal surface for several stations within Nigeria and across the globe by determining the empirical constants (a, b) of equation (10) employing meteorological parameters of the site of interest. This relation is given as follows:

$$\frac{H}{H_o} = a + b\left(\frac{S}{S_o}\right) \tag{10}$$

Where a and b are the empirical constants, S is the measure of sunshine duration and S_o is the daily maximum possible sunshine duration.

Apart from Angstrom-Prescott type model, those fitted by Rietveld [19] seems to be universally applicable. However, Akpabio et al. [20] and Falayi and Rabiu [21] employed empirical model for estimating monthly mean daily global solar radiation on the horizontal surface with fraction of sunshine duration for several locations in Nigeria; the result showed better performance and high accuracy in the fitted sites as compared to reported models in literature that seems to be universally applicable. As a result, the author employed greater number of estimation models proposed for Nigerian environment since global solar radiation depends grossly on the climate and geographical location of the site. Numerous sunshine-based models employing Angstrom-Prescott type model and other modified (exponential form, logarithm form, second order, third order and power form) models applied for estimating global solar radiation in literature as presented in Table 1.

3.4.1. Group 1 (linear models)

Empirical models from this group are parameterized as the first-order polynomial function of the relative sunshine-based model proposed by Angstrom [13] and Prescott [14] as shown in equation 10. Thus, the empirical coefficients a and b differ depending on the result reported for the first-order regression analysis.

3.4.2. Group 2 (second-order models)

The empirical models from this group employed second order Angstrom-Prescott type model for estimating global solar radiation. The empirical model has the form:

$$\frac{H}{H_o} = a + b\left(\frac{S}{S_o}\right) + c\left(\frac{S}{S_o}\right)^2 \tag{11}$$

3.4.3. Group 3 (third-order models)

In this group, the monthly mean of the daily global solar radiation employed third-order Angstrom-Prescott type model for estimating global solar radiation in the form:

$$\frac{H}{H_o} = a + b\left(\frac{S}{S_o}\right) + c\left(\frac{S}{S_o}\right)^2 + d\left(\frac{S}{S_o}\right)^3 \tag{12}$$

3.4.4. Group 4 (other models)

In this category, models that differ from group 1-3 are classified under this group. This includes exponential, non-linear, logarithm, power models etc as shown in Table 1.

Table 1: Sunshine-Based Models for Estimating Monthly Mean Daily Global Solar Radiation

Reference	Group Number	Model	City	Empirical Models
Maduekwu and Chendo [22]	1	1	Lagos	$H/H_o = 0.36 + 0.34(S/S_o)$
Kholagi et al. [23]	1	2	Yemen	$H/H_o = 0.262 + 0.454(S/S_o)$
Friend [24]	1	3	World	$H/H_o = 0.25 + 0.5(S/S_o)$
Rietveld [19]	1	4	42 Nations	$H/H_o = 0.18 + 0.62(S/S_o)$
Turton [25]	1	5	Humid Tropics	$H/H_o = 0.30 + 0.40(S/S_o)$
Ezekwu and Ezeifo [26]	1	6	Nsukka	$H/H_o = 0.276 + 0.648(S/S_o)$
Ezeillo [27]	1	7	Nsukka	$H/H_o = 0.21 + 0.49(S/S_o)$
Arinze and Obi [28]	1	8	Nigeria	$H/H_o = 0.20 + 0.74(S/S_o)$
Sambo [29]	1	9	Kano	$H/H_o = 0.413 + 0.241(S/S_o)$
Folayan and Ogunbiyi [30]	1	10	Zaira	$H/H_o = 0.16 + 0.53(S/S_o)$
Sambo [31]	1	11	Iseyin	$H/H_o = 0.208 + 0.748(S/S_o)$
Fagbenle [32]	1	12	Nigeria	$H/H_o = 0.28 + 0.30(S/S_o)$
Kuye and Jagtap [33]	1	13	P.Harcourt	$H/H_o = 0.210 + 0.306(S/S_o)$
Akinbode [34]	1	14	Minna	$H/H_o = 0.2466 + 0.4276(S/S_o)$
Fagbenle [35]	1	15	Ibadan	$H/H_o = 0.308 + 0.358(S/S_o)$
Burari and Sambo [36]	1	16	Bauchi	$H/H_o = 0.24 + 0.46(S/S_o)$
Akpabio and Etuk [18]	1	17	Onne	$H/H_o = 0.23 + 0.38(S/S_o)$
Falayi et al. [37]	1	18	Iseyin	$H/H_o = 0.2076 + 0.7475(S/S_o)$
Tijjiani [38]	1	19	Kastina	$H/H_o = 0.320 + 0.308(S/S_o)$
Yohanna and Itodo [39]	1	20	Makurdi	$H/H_o = 0.170 + 0.680(S/S_o)$
Ituen et al. [17]	1	21	Uyo	$H/H_o = 0.239 + 0.585(S/S_o)$
Adaramola [40]	1	22	Akure	$H/H_o = 0.249 + 0.566(S/S_o)$
Yakubu and Medugu [41]	1	23	Abuja	$H/H_o = 0.30 + 0.53(S/S_o)$
Musa et al. [42]	1	24	Maiduguri	$H/H_o = 0.287 + 0.547(S/S_o)$
Kolebaje and Mustapha [43]	1	25	P.Harcourt	$H/H_o = 0.239 + 0.717(S/S_o)$
Ohunakin et al. [44]	1	26	Osogbo	$H/H_o = 0.1943 + 0.3986(S/S_o)$
Solomon [45]	1	27	Nsukka	$H/H_o = 0.1150 + 0.5666(S/S_o)$
Gana and Akpootu [46]	1	28	Kebbi	$H/H_o = 0.351 + 0.420(S/S_o)$
Medugu et al. [47]	1	39	Mubi	$H/H_o = 0.35 + 0.41(S/S_o)$
Isikwue et al. [48]	1	30	Makurdi	$H/H_o = 0.461 + 0.605(S/S_o)$
Okonkwo and Nwokoye [49]	1	31	Minna	$H/H_o = 0.244 + 0.415(S/S_o)$
Ogolo [50]	1	32	Nigeria	$H/H_o = 0.281 + 0.414(S/S_o)$
Nwokoye and Okonkwo [51]	1	33	Bida	$H/H_o = 0.11 + 0.79(S/S_o)$
Kaltiya et al. [52]	1	34	Makurdi	$H/H_o = 0.24 + 0.57(S/S_o)$
Sheriff et al. [53]	1	35	Maiduguri	$H/H_o = 0.288 + 0.547(S/S_o)$
Ike et al. [54]	1	36	Akure	$H/H_o = 0.1915 + 0.4422(S/S_o)$
Gana et al. [55]	1	37	Sokoto	$H/H_o = 0.35 + 0.41(S/S_o)$
Sani et al. [56]	1	38	Kano	$H/H_o = 0.45 + 0.051(S/S_o)$
Adesina et al. [57]	1	39	Nasarawa	$H/H_o = 0.01 + 0.75(S/S_o)$
Olatona and Adeleke [58]	1	40	Ibadan	$H/H_o = 0.24 + 0.35(S/S_o)$
Okonkwo et al. [59]	1	41	Bida	$H/H_o = 0.11 + 0.79(S/S_o)$

Table 1 (continued**):** Sunshine-Based Models for Estimating Monthly Mean Daily Global Solar Radiation

Reference	Group Number	Model	City	Empirical Models

Innocent et al. [60]	1	42	Gusua	$H/H_o = 0.2950 + 0.5317(S/S_o)$
Boluwaji and Onyedi [61]	1	43	Sokoto	$H/H_o = 0.250 + 0.522(S/S_o)$
Okundamiya et al. [62]	1	44	Sokoto	$H/H_o = 0.4785 + 0.2465(S/S_o)$
Ayodele and Ogunjuyigbo [63]	1	45	Ibadan	$H/H_o = 0.27 + 0.24(S/S_o)$
Fagbenle [35]	2	46	Nigeria	$H/H_o = 0.375 + 0.128(S/S_o) + 0.660(S/S_o)^2$
Udo [64]	2	47	Ilorin	$H/H_o = 0.053 + 1.280(S/S_o) + 0.830(S/S_o)^2$
Akpabio et al. [20]	2	48	Onne	$H/H_o = 0.147 + 1.250(S/S_o) - 1.416(S/S_o)^2$
Ohunakin [44]	2	49	Osogbo	$H/H_o = 0.0836 + 1.0054(S/S_o) - 0.7646(S/S_o)^2$
Ayodele and Ogunjuyigbe [63]	2	50	Ibadan	$H/H_o = 0.26 + 0.34(S/S_o) - 0.11(S/S_o)^2$
Maduekwu and Chendo [22]	2	51	Lagos	$H/H_o = 0.18 + 1.16(S/S_o) - 0.91(S/S_o)^2$
Lewis [65]	3	52	Tennessee	$H/H_o = 0.81 - 3.34(S/S_o) + 7.38(S/S_o)^2 - 4.51(S/S_o)^3$
Trahran and Sari [66]	3	53	Turkey	$H/H_o = 0.1520 + 1.1334(S/S_o) - 1.1126(S/S_o)^2 + 0.4516(S/S_o)^3$
Burari et al. [67]	3	54	Maiduguri	$H/H_o = 0.171 + 0.026(S/S_o) + 2.01(S/S_o)^2 - 1.64(S/S_o)^3$
Ayodele and Ogunjuyigbo [63]	3	55	Ibadan	$H/H_o = 0.25 + 0.38(S/S_o) - 0.21(S/S_o)^2 + 0.074(S/S_o)^3$
Okundamiya et al. [62]	4	56	Abuja	$H/H_o = 0.7349(1/S)$
Gana and Akpootu [55]	5	57	Kebbi	$H/H_o = 0.747(1/S/S_o)$
Gana and Akpootu [56]	6	58	Kebbi	$H/H_o = 0.392(S/S_o)^{0.714}$
Ayodele and Ogunjuyigbo [63]	7	59	Ibadan	$H/H_o = 0.14e^{0.15(S/S_o)}$
Ayodele and Ogunjuyigbo [63]	8	60	Ibadan	$H/H_o = 0.46 + 0.17\log(S/S_o)$
Togrul and Togrul [68]	9	61	Turkey	$H/H_o = 0.46 + 0.17In(S/S_o)$
Ulgen and Hepbasli [69]	10	62	Turkey	$H/H_o = -0.0271 + 0.3096\exp(S/S_o)$
Glover and McCulloch [70]	11	63	World	$H/H_o = 0.29\cos(\varphi) + 0.52(S/S_o)$

4. Results and discussion

4.1 Variation of Atmospheric Parameters

The observed values of sunshine duration (S), global solar radiation on a horizontal surface (H), calculated values of monthly mean extraterrestrial solar radiation (H_o), monthly mean daylight hour (S_o), clearness index (H/H_o) and sunshine fraction (S/S_o) are presented in Table 2. Seasonal and monthly variations are observed in both the observed global solar radiation and sunshine duration. Lower values of these parameters are generally observed in the rainy season (April to October) when compared to the dry season (November to March). The maximum values of the monthly mean daily sunshine duration and the monthly mean daily global solar radiation on a horizontal surface in this site are 6.15 hours and 16.40 $MJm^{-2}day^{-1}$ in the months of December and April respectively; while the minimum values occur in August as 3.24 hours and 9.56 $MJm^{-2}day^{-1}$ with a corresponding overall mean values of 4.98 hours and 12.97 $MJm^{-2}day^{-1}$ for the monthly mean daily sunshine hours and global solar radiation on a horizontal surface respectively. These months of occurrence coincides with the dry and rainy seasons respectively at the site. High values of sunshine duration and global solar radiation obtained during the dry season can be attributed to the presence of low smog, relative humidity, cloud cover, low absorption of diffuse solar radiation and near infrared radiation in the solar spectrum, prolonged dry season with associated latitude and prevailing cloudiness and associated atmospheric moisture with the movement of the Hadley cell circulation system along the equatorial line during this period over Lagos and its environs thereby enhancing global solar radiation and clearness index received in the site; while the low values of sunshine duration and global solar radiation obtained during the rainy season could be due to relatively higher cloud cover, relative humidity, prolonged rainy season and more absorption of diffuse and near infrared radiation in the solar spectrum thereby producing low magnitude of global solar radiation received in the site. These trends are similar to the report of several solar energy researchers in the region-tropical rainforest zone in Nigeria [22], [35], [37], [40], [44], [62-63].

4.2. Classification

4.2.1. Clearness index

The monthly mean clearness index designates the percentage depletion by the sky of the incoming global solar radiation and therefore indicates both the level of availability of solar radiation and changes in the atmospheric condition in a given locality. The prevailing clearness index varied between the range of 0.26 – 0.44 between the months of April to October in the rainy season and 0.40 - 0.42 between the months of November to March in the dry Season with an annual value of 0.36 as shown in Table 2. These values are comparable to the report in the same region in Nigeria [17-18], [22], [33], [35], [37], [44]. Using the weather classification proposed by Iqbal [71] which are: (1) heavily overcast weather (kt ≤ 0.4); (2) partly overcast weather (0.6 ≤ kt ≤ 0.4); and (3) clear weather (kt ≥ 7). Judging from the overall mean value, the prevailing weather conditions of Lagos falls within the heavily overcast weather except during the months of November to April when weather condition can be considered as partly overcast weather. These indicate that the remarkable features of Lagos are dominance of heavily overcast weather. It was observed that global solar radiation increases temporarily with increase in the clearness index and then increases rapidly as the heavily overcast weather become clearer. This reveals that global solar radiation is optimally controlled by clearness index at Lagos, Nigeria.

4.2.2. Sunshine fraction

The monthly sunshine fraction is the ratio of actual sunshine duration to maximum possible sunshine duration which varies from one month to another because of the movement of the earth as shown in Table 2. Based on the sunshine fraction registered by World Meteorological Organization [72] which are: (1) cloudy sky ($0 \leq S/S_o < 0.3$), (2) scattered clouds sky ($0.3 \leq S/S_o < 0.7$), and (30 cloudy sky ($0.7 \leq S/S_o 1.0$), the prevailing sunshine condition in Lagos is mainly scattered clouds sky except during June to September when it can be considered as cloudy sky condition. These reports are comparable to values registered in literature in the same tropical rain forest region of Nigeria [17-18], [22], [33], [35], [37], [44].

Table 2: Meteorological Data and Sunshine Values for Lagos

Month	H	H_o	H/H_o	S	S_o	S/S_o
January	13.41	35.70	0.40	4.89	11.64	0.42
February	14.99	35.78	0.42	5.76	12.00	0.48
March	15.28	37.44	0.41	5.35	11.89	0.45
April	16.40	37.44	0.44	6.00	12.24	0.49
May	13.75	36.36	0.38	5.66	12.30	0.46
June	11.55	35.89	0.32	4.05	12.66	0.32
July	10.20	36.00	0.28	3.46	12.36	0.28
August	9.56	36.72	0.26	3.24	12.46	0.26
September	11.14	37.08	0.30	3.60	12.00	0.30
October	12.64	36.00	0.35	5.42	11.78	0.46
November	13.67	34.06	0.40	6.12	11.77	0.52
December	13.01	32.80	0.40	6.15	11.60	0.53
Average	12.97	35.77	0.36	4.98	12.06	0.41

H: measured global solar radiation ($MJm^{-2}day^{-1}$), H_o: extraterrestrial solar radiation ($MJm^{-2}day^{-1}$), H/H_o: clearness index, S: sunshine duration (hrs), S_o: maximum possible sunshine duration (hrs), S/S_o: sunshine fraction

4.3. Performance evaluation

Table 4 outlines the relative percentage error for each model for each month during the year. Each model's performance varies from one month to another. This could be attributed to different climate and geographical information of the developed models. As a result of this climate and geographical parameter influence on global solar radiation, few models performed well in some months and reported higher values in other months.

The following models recorded relative percentage errors between -15 to 15 %: in group 1, model 10 with corresponding average value of relative percentage errors -5.14 %, model 26 with an average relative percentage errors 0.00 %, model 27 with respective average relative percentage errors 3.45 %; In group 2, model 49 having average relative percentage errors -1.39%.

Within the relative percentage errors range of -20 to -15 and 15 to 20 %, only two (2) models from group 1 falls within the limit. These models include models 13 with average relative percentage errors 6.02 % and model 36 having an average relative percentage errors -4.13 %.

There are two (2) models with relative percentage errors ranging from -25 to -20 and 20 to 25 from group 1 and group 9. These models include model 39 with a corresponding relative percentage error 12.43 % and model 61 with an average relative percentage error 15.54 %.

In Table 4, it was observed that relative percentage error ranging from -30 to -25 and 25 to 30 % were reported from group 1 and group 3. The models are as follows: model 7 with a corresponding average relative percentage error -14. 76% ; model 17 with an average relative percentage errors -7.99 %; model 40 having an average relative percentage errors -7.43 %; model 45 with an average relative percentage errors -3.49 %; model 54 with an average relative percentage errors -12.67 % and -5.18 % reported for corresponding value of relative percentage errors for model 55.

However, models having relative percentage errors above -30 to -25 % and 25 to 30 % were excluded due to their high errors exhibited for different months of the year. The models includes models 1-6, 8-9, 11-12, 14-16, 18-25, 28-35, 37-38, 41-44, and 46 from group 1; 47-48, and 50-51 from group 2; 52 and 53 in group 3; model 56 from group 4; model 57 in group 5; model 58 from group 6; model 59 from group 7; model 60 from group 8; model 62 from group 10; model 63 from group 11. On the whole, 49 models were excluded while 14 models falls with the relative percentage error range of -30 to -15 % and 15 to 30 %. Fig. 2 shows the monthly performance for these 14 models which recorded relative percentage errors between -30 and -15 %.

In order to ascertain the annual performance of the models in different groups, regression analysis, MBEs, MPEs and RMSEs were employed as shown in Table 3. A close look at the 14 models (model 7, model 10, model 13, model 17, model 26, model 27, model 36, model 39, model 40, model 45, model 49, model 54, model 55 and 61) selected using relative percentage errors analysis in Table 4, the readers will observed that MBE ranged from -0.15 to 0.17 $MJm^{-2}day^{-1}$, MPE from -1.15 to 1.33 % and RMSE from 0.02 to 0.60 $MJm^{-2}day^{-1}$. It could also be observed that model 49, group 2, yielded the lowest value of these statistical indicators via 0.00 $MJm^{-2}day^{-1}$for MBE, -0.03 % for MPE, 0.02 $MJm^{-2}day^{-1}$ for RMSE, and coefficient of correlation 0.936 and the relationship with the measured data was presented in Fig. 3; followed by model 26 in group 1. Applying the recommendation of solar energy researchers for models used in estimating global solar radiation that small values of MBE, MPE and RMSE are required for optimal performance of a solar system [11-12], [16], [18] model 49 exhibited the best performance both among the entire models and among the models in group 2 (second-order polynomial of Angstrom-Prescott type model) fitted in Osogbo, Nigeria in the same tropical rainforest zone as Lagos. It is worthwhile to state emphatically that several solar energy researchers in Nigeria reported that the second-order polynomial of Angstrom-Prescott type model perform better than original first order model and third order models [20], [22], [35], [44], [63], [64]. This result also validates the background of this paper methodology by applying numerous models developed from Nigeria as global solar radiation solely depends on the local climate and geographical information in a give location. The result agrees favourably with report of several investigators across the globe that since most existing models are empirical in nature, they are likely to be specific to the atmospheric conditions under which they were developed, and thus may either over or underestimate measured data at other sites [73-76].

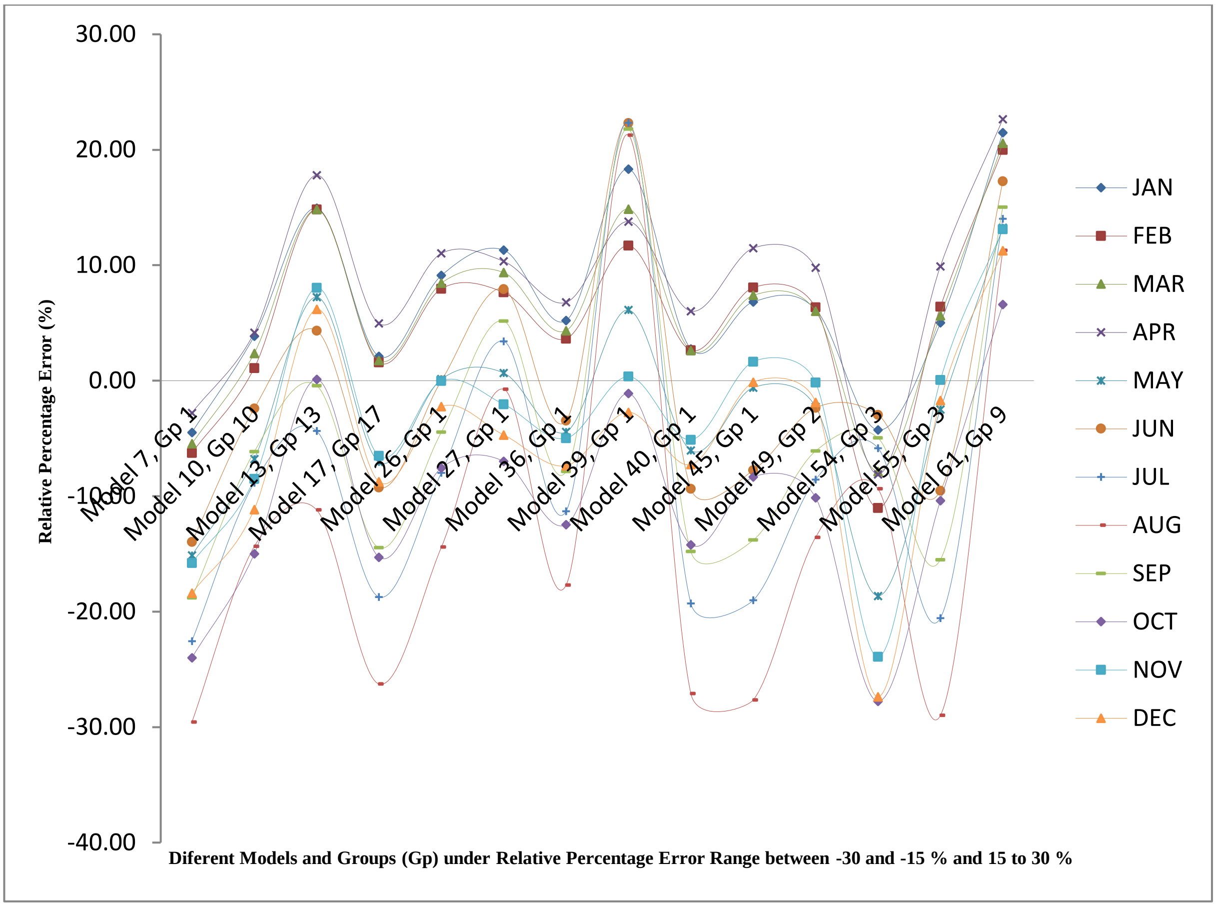


Fig. 2: Monthly Performance of Models with Relative Percentage Error (%) With -30 and -15 % and 15 to 30 %.

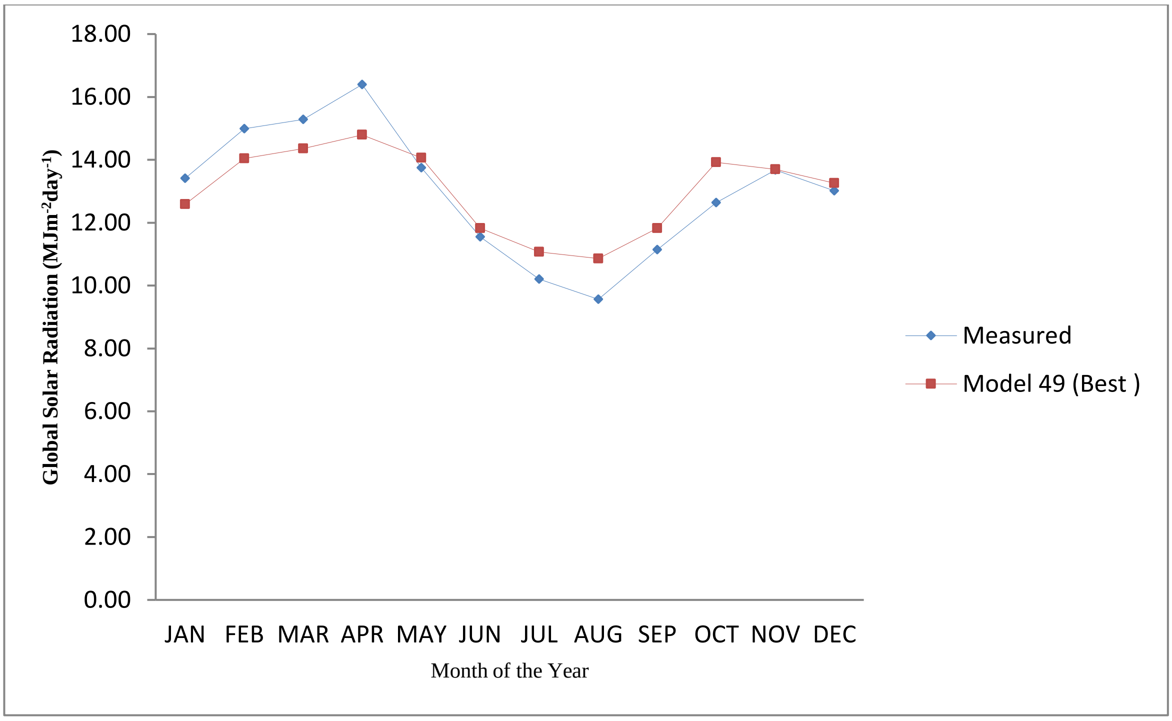


Fig. 3: Comparison Between Measured and Model 49 (Best Model) for Estimating Global Solar Radiation at Lagos, Nigeria.

Table 3: Model Number, Group, Mean and Statistical Indicators for Measured and existing sunshine-based models at Lagos, Nigeria

Model	Group	Mean	MBE	MPE	RMSE	a	b	R
1	1	17.90	-0.41	-3.17	1.42	11.530	0.490	0.899
2	1	16.07	-0.26	-1.99	0.90	7.655	0.649	0.922
3	1	16.32	-0.28	-2.15	0.97	7.055	0.715	0.922
4	1	15.59	-0.22	-1.69	0.76	4.152	0.882	0.915
5	1	16.64	-0.31	-2.36	1.06	9.178	0.575	0.919
6	1	16.96	-0.33	-2.57	1.15	8.045	0.687	0.923
7	1	14.75	-0.15	-1.15	0.51	5.676	0.699	0.920
8	1	18.08	-0.43	-3.29	1.48	4.424	1.053	0.914
9	1	18.33	-0.45	-3.45	1.55	13.764	0.352	0.817
10	1	13.55	-0.05	-0.35	0.17	3.767	0.754	0.915
11	1	18.48	-0.46	-3.54	1.59	4.679	1.065	0.914
12	1	14.14	-0.12	-0.95	0.42	8.832	0.433	0.909
13	1	12.03	0.08	0.60	0.27	6.325	0.440	0.921
14	1	15.13	-0.18	-1.39	0.62	7.194	0.612	0.922
15	1	16.30	-0.28	-2.14	0.96	9.626	0.515	0.914
16	1	15.38	-0.20	-1.55	0.70	6.848	0.658	0.922
17	1	13.84	-0.07	-0.56	0.25	6.780	0.544	0.922
18	1	18.46	-0.46	-3.53	1.59	4.659	1.064	0.915
19	1	17.73	-0.40	-3.06	1.37	2.877	1.145	0.909
20	1	10.21	0.23	1.77	0.80	-2.288	0.964	0.894
21	1	17.19	-0.35	-2.71	1.22	6.363	0.835	0.920
22	1	17.26	-0.36	-2.76	1.24	6.785	0.808	0.921
23	1	18.56	-0.47	-3.59	1.61	8.715	0.759	0.922
24	1	18.34	-0.45	-3.45	1.55	8.203	0.782	0.922
25	1	19.13	-0.51	-3.96	1.78	5.883	1.022	0.917
26	1	12.83	0.01	0.09	0.04	5.443	0.570	0.922
27	1	12.48	0.04	0.31	0.14	2.030	0.806	0.910
28	1	18.76	-0.48	-3.72	1.67	10.919	0.604	0.915
29	1	18.57	-0.47	-3.60	1.62	10.922	0.590	0.914
30	1	25.42	-1.04	-8.00	3.59	14.136	0.870	0.919
31	1	14.85	-0.16	-1.21	0.54	7.143	0.595	0.922
32	1	10.05	0.24	1.88	0.84	9.962	0.007	0.035
33	1	15.60	-0.22	-1.69	0.76	1.055	1.121	0.905
34	1	17.00	-0.34	-2.59	1.16	6.449	0.814	0.920
35	1	18.38	-0.48	-3.48	1.56	8.229	0.783	0.922
36	1	13.38	-0.03	-0.26	0.12	5.188	0.632	0.920
37	1	18.57	-0.47	-3.60	1.62	10.922	0.590	0.914
38	1	16.85	-0.32	-2.49	1.12	15.746	0.085	0.269
39	1	11.43	0.13	0.99	0.44	-2.339	1.062	0.893
40	1	13.75	-0.07	-0.50	0.23	7.234	0.503	0.921
41	1	15.60	-0.22	-1.69	0.76	1.055	1.121	0.905
42	1	18.40	-0.45	-3.49	1.57	8532	0.761	0.923
43	1	16.65	-0.31	-2.37	1.06	6.973	0.746	0.922
44	1	16.92	-0.33	-2.54	1.14	5.551	0.877	0.918
45	1	13.20	-0.02	-0.15	0.07	8.707	0.347	0.894
46	2	19.53	-0.55	-4.22	1.89	7.880	0.898	0.906
47	2	26.10	-1.09	-8.44	3.79	-8.930	2.702	0.881
48	2	14.65	-0.14	-1.08	0.49	11.306	0.258	0.691
49	2	13.02	0.00	-0.03	0.02	5.148	0.607	0.936
50	2	13.62	-0.05	-0.42	0.19	8.812	0.370	0.900
51	2	17.74	-0.40	-3.07	1.38	9.012	0.673	0.932
52	3	13.91	-0.08	-0.61	0.27	8.963	0.381	0.782
53	3	16.35	-0.28	-2.17	0.98	7.271	0.700	0.932
54	3	14.64	-0.14	-1.07	0.48	-0.525	1.169	0.899
55	3	13.42	-0.04	-0.29	0.13	8.671	0.366	0.900
56	4	5.59	0.61	4.74	2.13	13.353	-0.599	0.818
57	5	68.76	-4.65	-35.85	16.11	170.275	-7.829	0.811
58	6	9.69	0.27	2.11	0.95	0.750	0.689	0.910
59	7	5.33	0.64	4.91	2.20	4.878	0.035	0.348
60	8	14.04	-0.09	-0.69	0.31	10.266	0.291	0.837
61	9	10.90	0.17	1.33	0.60	2.421	0.654	0.926
62	10	15.83	-0.24	-1.84	0.83	7.422	0.649	0.917
63	11	17.59	-0.39	-2.97	1.33	7.956	0.743	0.922

MBE: mean bias error ($MJm^{-2}day^{-1}$), RMSE: root mean square error ($MJm^{-2}day^{-1}$), MPE: mean percentage error (%), a and b are the regression constants between measured and the estimated values, R is the correlation coefficient between measured and estimated values

Table 4: Relative Percentage Error for Each Model for Each Month and Average during the Year in Lagos, Nigeria

Model	Group	Relative Percentage Error (%)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
1	1	-26.34	-24.87	-25.67	20.26	-36.55	-45.65	-60.66	-72.19	-53.74	-47.06	-33.72	-36.18	-40.24
2	1	-13.74	-14.54	-14.23	-10.63	-24.51	-26.53	-37.34	-45.94	-32.51	-34.09	-24.07	-26.71	-25.40
3	1	-15.58	-16.94	-16.36	-13.04	-26.93	-27.38	-37.65	-45.93	-33.11	-36.70	-27.04	-29.83	-27.21
4	1	-10.66	-13.98	-12.44	-10.48	-23.02	-17.56	-24.80	-31.03	-21.79	-32.48	-25.15	-28.22	-20.97
5	1	-17.59	-17.42	-17.59	-13.27	-27.99	-32.97	-45.41	-55.14	-39.76	-37.84	-26.54	-29.07	-30.05
6	1	-20.01	-20.86	-20.53	-16.74	-31.37	-33.47	-44.85	-53.92	-39.76	-41.48	-30.93	-33.71	-32.30
7	1	-4.48	-6.25	-5.46	-2.79	-15.14	-13.96	-22.54	-29.57	-18.80	-24.00	-15.78	-18.41	-14.76
8	1	-28.35	-32.50	-30.57	-28.48	-42.90	-35.71	-43.72	-50.69	-40.43	-53.90	-45.68	-49.29	-40.18
9	1	-29.21	-26.18	-27.74	-21.28	-38.53	-52.27	-69.58	-82.66	-61.49	-49.19	-34.10	-36.31	-44.05
10	1	3.87	1.10	2.38	4.16	-6.78	-2.40	-8.85	-14.36	-6.15	-15.00	-8.51	-11.15	-5.14
11	1	-31.20	-35.33	-33.42	-31.20	-45.99	-38.99	-47.33	-54.56	-43.89	-57.23	-48.71	-52.38	-43.35
12	1	-2.01	-1.19	-1.67	2.49	-10.53	-16.82	-28.47	-37.48	-23.12	-19.04	-8.61	-10.67	-13.09
13	1	14.94	14.83	14.82	17.80	7.25	4.33	-4.36	-11.20	-0.43	0.11	8.05	6.18	6.03
14	1	-7.09	-7.84	-7.55	-4.16	-17.22	-19.13	-29.29	-37.39	-24.75	-26.25	-16.82	-19.30	-18.07
15	1	-15.17	-14.52	-14.92	-10.39	-24.99	-31.28	-44.08	-54.02	-38.23	-34.61	-23.10	-25.48	-27.57
16	1	-8.85	-9.97	-9.51	-6.28	-19.42	-20.30	-30.16	-38.09	-25.79	-28.61	-19.37	-21.96	-19.86
17	1	2.11	1.58	1.76	4.96	-7.04	-9.24	-18.73	-26.27	-14.47	-15.28	-6.52	-8.72	-7.99
18	1	-31.05	-35.18	-33.26	-31.05	-45.82	-38.81	-47.14	-54.36	-43.70	-57.05	-48.54	-52.21	-43.18
19	1	-26.02	-31.23	-28.78	-27.41	-41.15	-30.77	-37.18	-43.07	-34.70	-52.01	-45.01	-48.78	-37.18
20	1	26.97	20.97	23.92	22.87	16.05	30.92	31.13	30.33	30.59	9.57	10.67	7.84	21.82
21	1	-21.79	-24.06	-23.04	-20.04	-34.36	-32.41	-42.16	-50.19	-37.93	-44.70	-35.31	-38.41	-33.70
22	1	-22.30	-24.27	-23.40	-20.20	-34.69	-33.63	-43.82	-52.13	-39.36	-45.06	-35.34	-38.39	-34.38
23	1	-31.31	-32.31	-31.92	-27.81	-43.80	-45.90	-58.26	-68.12	-52.74	-54.87	-43.38	-46.44	-44.74
24	1	-29.84	-31.16	-30.61	-26.75	-42.43	-43.55	-55.35	-64.83	-50.11	-53.39	-42.35	-45.44	-42.98
25	1	-35.72	-39.18	-37.59	-34.81	-50.42	-45.54	-55.21	-63.37	-51.11	-61.99	-52.41	-56.05	-48.62
26	1	9.11	7.97	8.46	11.03	0.13	0.01	-7.97	-14.41	-4.45	-7.55	-0.03	-2.24	0.00
27	1	11.31	7.65	9.37	10.34	0.67	7.94	3.42	-0.73	5.17	-6.98	-2.04	-4.69	3.45
28	1	-32.52	-31.88	-32.29	-27.15	-43.91	-50.81	-65.39	-76.73	-58.73	-54.98	-41.84	-44.60	-46.73
29	1	-31.21	-30.50	-30.94	-25.80	-42.43	-49.50	-64.05	-75.34	-57.40	-53.39	-40.30	-43.01	-45.32
30	1	-79.68	-79.33	-79.63	-72.97	-95.50	-103.37	-122.49	-137.44	-113.80	-110.54	-93.21	-97.05	-98.75
31	1	-5.21	-5.77	-5.52	-2.16	-15.00	-17.07	-27.13	-35.14	-22.62	-23.85	-14.54	-16.96	-15.91
32	1	29.39	32.94	31.16	35.83	25.69	12.70	0.82	-7.91	6.49	19.97	30.00	29.16	20.52
33	1	-11.01	-16.75	-14.04	-13.52	-25.18	-12.72	-16.89	-21.12	-15.47	-34.82	-29.73	-33.28	-20.38
34	1	-20.46	-22.58	-21.63	-18.59	-32.80	-31.23	-41.04	-49.08	-36.77	-43.02	-33.62	-36.66	-32.29
35	1	-30.09	-31.40	-30.86	-26.98	-42.70	-43.86	-55.70	-65.21	-50.44	-53.68	-42.60	-45.69	-43.27
36	1	5.22	3.64	4.34	6.79	-4.43	-3.46	-11.29	-17.69	-7.87	-12.47	-4.98	-7.36	-4.13
37	1	-31.21	-30.50	-30.94	-25.80	-42.43	-49.50	-64.05	-75.34	-57.40	-53.39	-40.30	-43.01	-45.32
38	1	-18.45	-13.24	-15.86	-8.47	-25.20	-44.88	-63.86	-77.90	-54.84	-34.84	-18.70	-20.26	-33.04
39	1	18.34	11.70	14.87	13.79	6.13	22.33	22.35	21.28	21.80	-1.10	0.36	-2.73	12.43
40	1	2.76	2.63	2.62	6.03	-6.04	-9.36	-19.29	-27.11	-14.80	-14.20	-5.12	-7.27	-7.43
41	1	-11.01	-16.75	-14.04	-13.52	-25.18	-12.72	-16.89	-21.12	-15.47	-34.82	-29.73	-33.28	-20.38
42	1	-30.24	-31.31	-30.88	-26.86	-42.69	-44.51	-56.66	-66.37	-51.25	-53.67	-42.36	-45.41	-43.52
43	1	-17.90	-19.46	-18.79	-15.50	-29.61	-29.57	-39.82	-48.12	-35.30	-39.58	-29.89	-32.77	-29.69
44	1	-19.98	-22.76	-21.49	-18.86	-32.77	-29.27	-38.18	-45.63	-34.37	-42.99	-34.25	-37.41	-31.50
45	1	6.83	8.07	7.40	11.49	-0.59	-7.74	-19.01	-27.65	-13.81	-8.33	1.65	-0.13	-3.49
46	2	-36.99	-40.45	-38.72	-36.15	-51.66	-50.23	-63.26	-73.92	-57.33	-63.34	-54.45	-58.37	-52.07
47	2	-85.19	-104.92	-95.27	-100.84	-116.16	-70.13	-68.17	-69.70	-70.28	-132.79	-134.91	-143.16	-99.29
48	2	-6.09	-0.42	-3.57	4.20	-11.69	-24.89	-36.23	-44.50	-31.30	-20.29	-3.16	-3.80	-15.14
49	2	6.18	6.34	6.03	9.78	-2.26	-2.35	-8.55	-13.56	-6.09	-10.13	-0.15	-1.87	-1.39
50	2	3.67	5.05	4.28	8.61	-3.96	-11.08	-22.32	-30.94	-17.17	-11.96	-1.40	-3.18	-6.70
51	2	-27.31	-25.81	-26.83	-21.01	-37.78	-42.30	-52.98	-61.32	-48.45	-48.39	-33.80	-35.92	-38.49
52	3	5.80	2.54	4.34	5.29	-4.78	-8.47	-25.08	-38.72	-16.61	-12.84	-8.26	-11.28	-9.01
53	3	-16.90	-16.86	-17.07	-12.67	-27.43	-29.11	-38.37	-45.70	-34.46	-37.24	-25.55	-27.91	-27.44
54	3	-4.27	-11.03	-7.86	-8.11	-18.64	-2.96	-5.83	-9.37	-4.96	-27.77	-23.91	-27.37	-12.67
55	3	5.01	6.40	5.63	9.91	-2.49	-9.52	-20.55	-28.99	-15.50	-10.37	0.05	-1.70	-5.18
56	4	62.24	69.55	66.35	72.03	65.67	43.62	25.04	12.90	32.07	61.39	70.09	69.88	54.23
57	5	-346.90	-271.42	-306.65	-248.14	-329.42	-625.25	-841.60	-1003.32	-728.58	-362.47	-257.85	-255.31	-464.74
58	6	30.70	27.59	29.02	29.69	22.17	29.43	27.12	24.79	27.82	16.18	19.98	17.91	25.20
59	7	62.54	64.09	63.31	65.59	60.33	54.37	48.47	44.10	51.27	57.28	62.30	61.79	57.95
60	8	0.51	3.15	1.75	6.98	-6.48	-16.78	-29.18	-38.46	-23.49	-14.68	-2.56	-4.15	-10.28
61	9	21.47	19.99	20.56	22.65	13.27	17.27	14.02	11.29	15.04	6.59	13.10	11.24	15.54
62	10	-11.59	-12.94	-12.31	-9.22	-22.52	-24.04	-35.01	-43.79	-30.05	-31.95	-22.97	-25.77	-23.51
63	11	-24.49	-25.69	-25.20	-21.46	-36.52	-37.78	-49.18	-58.32	-44.11	-47.03	36.38	-39.32	-37.12

5. Conclusion

The performance of 63 sunshine-based models of different functional forms was evaluated for predicting the monthly global solar radiation on the horizontal surface for Lagos, Nigeria. The authors observed that 49 models performed poorly with respect to both monthly and annual data after applying relative percentage error analysis while 14 models exhibited better performances. The 14 models were subjected to further statistical analysis by employing regression analysis, MBE, MPE and RMSE. At the end of the analysis model 49 yielded the lowest MBE, MPE, RMSE and highest coefficient of correlation values which is recommended by solar energy researchers for obtaining optimal solar system.

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