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Estimation of Mean Monthly Global Solar Radiation in Barkin Ladi and its Environs using Maximum and Minimum Temperature Data

By

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Abstract: *This paper described how an empirical model originally formulated by Hargreaves – Samani to compute the monthly global solar radiation has been modified to make it fit Barkin Ladi's environs. The study was undertaken to estimate the global solar radiation in Barkin Ladi, Plateau State, Nigeria; Latitude 9.5oN and Longitude 8.9oE. The solar radiation and maximum and minimum temperatures for a period of 10 years (2011-2020) were obtained from Yakubu Gowon Airport Meteorological Unit, Heipang. The corresponding monthly value of extraterrestrial solar radiation (Ho) was calculated for each data. Three models based on the meteorological variables were generated and validated using daily data in 2011-2020. The performance of each of the models was evaluated based on the coefficient of determination (r2), mean bias error, (MBE), Root mean square error (RMSE) and mean percentage error (MPE). The Hargreaves -Samani model with linear regression has the highest r2-value of 0.76 and lowest MBE, RMSE and MPE values of 2.81 w/m2, 1.46 w/m2 and -6.42% respectively. The analysis showed that the best performance for the present data set was found at the Hargreaves-Samani model with linear regression followed by H-S model with power regression and the original H-S model. The H-S model is simple and recommended for estimating the daily global solar radiation when only temperature data are available. Based on the overall results, it was concluded that the meteorological-based method provides reasonably accurate estimates of global solar radiation for the environs where coefficients of the model were developed.*

Keywords: *Estimation, Global Solar Radiation, Extraterrestrial radiation, temperature, Barkin Ladi, Nigeria***.**

INTRODUCTION

Solar radiation, which is the radiant heat energy emitted by or from the sun, is propagated through space at the speed of light. According to UOSRML (2005), solar radiation reaching the earth's surface either being transmitted directly through the atmosphere (direct or beam radiation) or being scattered or reflected to the surface (diffuse sky radiation). The intensity of solar radiation striking a horizontal surface is measured by a pyranometer or solarimeter/sunmeter. Pyranometer measures global or total radiation: the sum of direct solar and diffuse sky radiation.

Solar radiation varies with season, time of the day and year, cloud cover, albedo, dust and aerosol content of the atmosphere (Stine and Harrigan, 1985, Iloeje 1997, UOSRML 2005, Yohanna, 2011). One of the parameters used in accounting for these effects in a given day or month is the number of hours of sunshine. Values above seven (7) hours per day may be considered high. These taken together with the solar radiation intensities indicate that the Northern Region of Nigeria has a high solar energy resource endowment, particularly in areas removed from the coastal tropical rainforest zone (Yohanna, 2015b).

Global or total solar radiation consists of direct and diffuse components. The direct component has suffered no change in direction from the sun while the diffuse is made up of scattered or reflected radiation (Habou et al., 2005, Dandakoubu et al, 2006). Solar energy devices such as solar dryers can only be properly harnessed with accurate values of solar radiation in that location since solar radiation varies from one location to the other all year round (Yohanna et al., 2011).

When measured solar radiation data are not available, the daily solar energy falling upon a horizontal plane located at the earth's surface can be estimated. Page (1986) suggested that an Angstrom-type correlation may be used for estimation purposes. The Angstrom-Page linear correlation is a widely accepted empirical formula for estimating global radiation for locations. It relates the average monthly, daily global radiation to the number of hours of bright sunshine and possible hours of sunshine in a location as shown in the equation 1 and 2.

$H/H_O = a + b\,(^{NS}/_{N})$ ……………………………………… (1)

$H = H_O\,[a + b\,(^{NS}/_{N})]$ …………………………………….. (2)

Where H/H_O – clearness index

H – monthly average daily global solar radiation on a horizontal surface, w/m^2

H_O – monthly average daily extraterrestrial radiation, w/m^2

Ps – monthly average daily number of hours of bright sunshine, hr

N – monthly average daily number of hours of possible sunshine, hr

$^{NS}/_{N}$ – relative sunshine duration.

a & b – regression constants or coefficients.

Different models use different approaches for estimating the constants 'a' and 'b' (Sanusi and Abisoye, 2011). Hargreaves and Samani (1982) proposed solar radiation estimation using the differences between maximum and minimum ambient temperatures and extraterrestrial radiation. They correlated solar radiation with maximum and minimum temperature and extraterrestrial radiation. Some studies also added measured precipitation to the temperature based on hourly solar radiation prediction and the methods are claimed to perform well (Donatalli and Campbell, 1998). The original equation is as in equation 3.

$H = H_O\,K_r\,(Tmax – Tmin)^{1/2}$……………….. …………….3

Where Tmax and Tmin are the mean daily maximum and minimum air temperatures (^OC) respectively and Kr in the regional coefficient = 0.16 for interior regions and 0.19 for coastal regions. In this study, Kr = 0.16 was adopted from the original H-S model.

Many researchers developed empirical models to determine solar radiation for different locations such as Bamiro (1983) for Ibadan, Akpabio et al (2004) for Onne, Nigeria, Yohanna et al (2011) for Makurdi, Nigeria, Yohanna et al (2005b) for Lafia, Yohanna et al 2015 for Barkin Ladi, Nigeria etc. However, accurate modeling depends on the quality and quantity of the measured data used and it is a better tool for estimating the global solar radiation of a location where measurements are not available.

The objective of this work is to develop models for estimating the daily global solar radiation in Barkin Ladi based on daily maximum and minimum temperature data obtained from the meteorological unit of Yakubu Gowon Airport, Heipang, Barkin Ladi, L.G.A. The models were validated to use the suitable one that can be used to relate global solar radiation and temperature for the study area and other locations having similar solar characteristics. This is important for the design and development of solar energy conversion systems/devices and the application of solar energy technology.

MATERIALS AND METHODS

Description of the Study Area

The study was carried out at Barkin Ladi LGA of Plateau State. It lies between latitude 9.5^{o}N of the equator and longitude 8.9^{O}E of Greenwich Meridian with an altitude of 1515m above mean sea level (MSL). It has an estimated population of 175,267 inhabitants. The Local Government Area is bounded in the North by Jos East LGA, in the East by Mangu LGA, in the West by Riyom LGA and in the South by Bokkos LGA. It has a land area of 1,032 km^2 . The Local Government Area is blessed with mineral resources (Tin) and agricultural resources coupled with a resourceful industrious and hospitable people (Wikipedia, 2015). The climate of the area is tropical with two distinct seasons: The rainy and the dry seasons. The temperature throughout the year ranges from 16.^{O}C to 28.^{O}C while humidity is relatively moderate from 42% to 48%. The annual rainfall varies from 1520mm-2050mm. The Local Government is an agrarian area; hence agriculture has always played a leading role in the lives of the people.

Data Collection

The thermal analysis of solar energy requires the knowledge of direct and diffuse components of solar radiation in order to estimate the total solar radiation quantity in a locality. The data for estimating the solar radiation in Barkin Ladi were obtained from Yakubu Gowon Airport Meteorological Unit, Heipang. The data obtained covered a period of five (5) years (2010-2014). The monthly average data of solar radiation parameters processed are presented in table 1.

Extraterrestrial Solar Radiation

Extraterrestrial solar radiation (Ho) is the sun's energy expected if the atmosphere were perfectly transparent. It is the maximum amount of solar radiation available to the earth and in attenuated as it passes through the top of the atmosphere and then atmosphere to the ground surface as global solar radiation (H). The attenuation is caused by cloud, air molecules, aerosols, water vapour and ozone. The extraterrestrial solar radiation is calculated using latitude and day of the year by the following equations.

$$H_o = \frac{24}{\pi} G_{Sc} \left[1+0.033 \cos \left(\frac{360 n_y}{365}\right)\right] \left[\cos \varphi \cos \delta \sin \omega_s + \frac{\pi}{180} \omega_s \sin \varphi \sin \delta\right] \quad \ldots 4$$

Where Gsc – solar constant = 1367 w/m^2 = 4921 kJ/m^{2}hr $^{-1}$ to be used in equation 4 (Stine and Harrigan 1985, Page 1986, Nwokoye, 2006, Montero et al., 2009, Yohanna et al., 2011, 2015 a & b)

ny – mean day of each of the year or Julian day number (Lunde, 1980)

φ - Latitude of the location

d – solar declination angle = $23.45 \sin \left[360 \frac{(264 + n_y)}{365}\right]$ …………………………………..5 (Anderson, 1983)

ωs – sunset hour angle in degress = $\cos^{-1} (-\tan \varphi \tan \delta)$ …….6

Hargreaves and Samani model

Air temperature-based estimation models use maximum and minimum air temperature to estimate atmospheric transmissivity. These models assume that maximum temperature will remain with reduced transmissivity, whilst minimum temperature will increase with maximum temperature due to higher short wave radiation, air minimum temperature with decrease due to higher transmissivity.

Hargreaves and Samani were the first to suggest that global radiation could be evaluated from the difference between daily maximum and minimum temperatures. The equation introduced by Hargreaves and Samani (1982) to estimate global solar radiation is:

$H = H_o K_r (T_{max} – T_{min})^{1/2}$ ……… 7

$= H_o K_r (T_d)^{1/2}$ …………..8

Where H, Ho, Tmax and Tmin are as defined earlier.

Kr = regional empirical coefficient = ($^{ns}/_N$)

Td = difference between maximum and minimum temperatures.

Normal value of 0.16 for interior regions was adopted for original H-S model and was used by the researchers in the evaluation.

Hargreaves model with Linear Regression.

Linear regression could be applied to improve Hargreaves model, instead of using the nominal Kr value of 0.16 for interior regions. That is:

$H/H_o = a + b \sqrt{T_d}^{\,b}$ ……………………………..…..…. 8

$H = H_o [a + b \sqrt{T_d}]$ ……………………………….…… 9

Where ‘a’ and ‘b’ are the empirical coefficients for Hargreaves model with linear regression.

Hargreaves model with power regression.

Here, a power regression is applied to the Hargreaves model to improve the model performance, Hence,

$\frac{H}{} = a \sqrt{T_d}^{\,b}$ ……………………………………….... 10

$H = H_o [a \sqrt{T_d}^{\,b}]$ ……………………………………… 11

Where ‘a’ and ‘b’ are the empirical coefficients for Hargreaves model with power regression.

Model statistical evaluation

The goodness of the estimation of global solar radiation was based on a set of statistical parameters (R^2, RMSE, MBE, MPE) investigated. The performance of the models was evaluated by comparing daily solar radiation with the measured daily solar radiation data as stated by Yarukuglu and Celik (2006). In this study, the accuracy of the estimated values was tested by calculating the R^2, MBE, RMSE and MPE.

The R^2 is a measure of the degree of linear correlation between these variables (one independent variable and the other dependent variable). A model is more efficient when R^2 is closer to 1. The RMSE is a measure of the variable of predicted values around the measured values. It provides information in the short-term performance of the correlations by allowing a term-by-term comparison of the deviation between the calculated and measured values. The MBE is an indication of the average deviation of the predicted values from the measured values. The value of MBE represents the systematic error or bias, a positive value of MBE shows an overestimation while a negative value shows underestimation by the model. The MBE is an overall measure of forecast bias, computed from the actual differences between a series of forecasts and actual data points observed. Each difference is expressed as a percentage of each observed data point, then summed up and averaged.

The smaller the value of MBE and MPE, the better the model performs. The MBE and MPE offer information regarding over-estimation or under-estimation of estimated data. Low values of these mean errors are desirable, though it should be noted that over-estimation of an individual data element will cancel underestimation in a separate observation.

These tests are defined by the expressions as thus:

$$R^2 = 1 - \left[\frac{\Sigma(H_m - H_c)^2}{\Sigma(H_m - H_{av\text{-}m})^2}\right] \quad \ldots\ldots 12$$

$$MBE = \frac{1}{N_{obs}} \Sigma H_m - H_c \quad w/m^2 \quad \ldots\ldots 13$$

$$RMSE = \left[\frac{1}{N_{obs}} \Sigma(H_m - H_c)^2\right]^{1/2} \quad w/m^2 \quad \ldots\ldots 14$$

$$MPE = \frac{100}{N_{obs}} \Sigma \frac{H_m - H_c}{H_m} \text{ (percentage)} \quad \ldots\ldots 15$$

Where, H_m is the measured solar radiation, Hc is the calculated solar radiation, $H_{av.m}$ is the average or mean measured radiation and Nobs is the number of data pairs.

RESULTS AND DISCUSSIONS

The empirical models for estimating solar radiation are a suitable tool. These models have the advantage of using meteorological data that are commonly available. The calculated values of the monthly extraterrestrial solar radiation (Ho) in a horizontal surface at latitude 9.5°N and longitude 8.9°E outside the earth's atmosphere at Barkin Ladi, Nigeria is as shown in Table 2. The highest extraterrestrial solar radiation value of 481.31w/m² was obtained on the 212th day in the month of July while the lowest value of 363.12 w/m² was obtained on the 365th day in the month of December (Table 2 and Fig.1).

Figure 2 shows that in the overall average years 2010-2014, there were two maxima periods (major and minor). The major maxima occurred between January-February during the dry season and the minor between November and December. In the rainy season, maxima occurred from the months of March – October. Figure 2 also indicates the highest value of global solar radiation at Barkin Ladi occurring during the dry season while the minimum global solar radiation occurs during the rainy season, as a result of the rain cloud cover, albedo, dust and aerosol content of the atmosphere as stated by UOSRML (2005) and Yohanna (2010, 2011, 2015).

The month of February with the highest solar radiation of 337.2w/m² contributed 10.1% and the lowest month August with 23.4 w/m² contributed 6.9% of the annual total solar radiation. The result also shows that the global solar radiation value of Barkin Ladi is between 195 and 364 w/m².

Three empirical models were developed based on the solar radiation parameters collected with monthly temperature range data as follows: Hargreaves and Samani model,

$H = Ho[0.16\sqrt{Td}]$ with $R^2 = 0.52$ ……………………….16

Hargreaves and Samani with linear regression, $H=Ho[-0.11+0.83\sqrt{Td}]$ with $R^2=0.76$ ……..,,,,,,,,,,,,,,,,,…..,,,,,,..17

Hargreaves and Samani with power regression, $H=Ho[0.06\sqrt{Td}^{1.73}]$ with $R^2=0.67$ ……………………………..18

Hargreaves and Samani with linear regression has the best coefficient of determination, $R^2=0.76$ followed by Hargreaves and Samani model with power regression, $R^2=0.67$ and Hargreaves and Samani model with the lowest coefficient of determination, $R^2=0.52$.

From the coefficient of determination obtained from equations 16-18, equation 17 gives the best fit to the global solar radiation data, while equation 16 does not fit the measured data very well because of its over-estimation. Figures 3,4 and 5 compared the predicted global solar radiation given by equations 15,16 and 17 and the monthly average daily global solar radiation measured for the five (5) years.

The model performance of the three empirical models was compared based on R^2, MBE, RMSE and MPE as shown in Table 2. Based on R^2, Hargreaves model with linear regression produces the best overall results with the best coefficient of correlation, r=0.87 and determination $R^2=0.76$ while the H-S model produced the worst with larger value of RMSE (4.17w/m²). It was observed that the lower the RMSE, the accurate the equation used. For MBE and MPE, the result shows that the H-S model with linear regression offers best correlation while the H-S model gives the worst correlation.

The estimation of global solar radiation using H-S model gave worst results in all the criteria of R^2, MBE, RMSE and MPE while the application of H-S model with linear regression gave the best results or correlation by all the criteria applied in this study. Such a model could be used to fill in missing data when solar radiation data are not available but temperature data are available.

Table 1: Monthly average solar radiation (w/m2) data for Barkin Ladi, Nigeria

Months	Year 2010	2011	2012	2013	2014	Monthly average daily global solar radiation (Hm) (w/m^2)
Jan	306	292	288	306	331	304.6
Feb	339	364	303	331	349	337.2
Mar	314	316	324	338	350	265.4
Apr	295	276	270	280	289	282.0
May	247	245	273	284	295	268.8
Jun	233	233	193	278	291	245.6
Jul	195	220	206	284	284	237.8
Aug	226	192	244	237	258	231.4
Sep	251	247	255	275	277	261.0
Oct	303	273	270	262	309	283.4
Nov	297	305	319	324	327	314.4
Dec	295	305	300	338	341	315.8

Source: From Yakubu Gowon Airport Meteorological Unit, Heipang-Barkin, Nigeria.

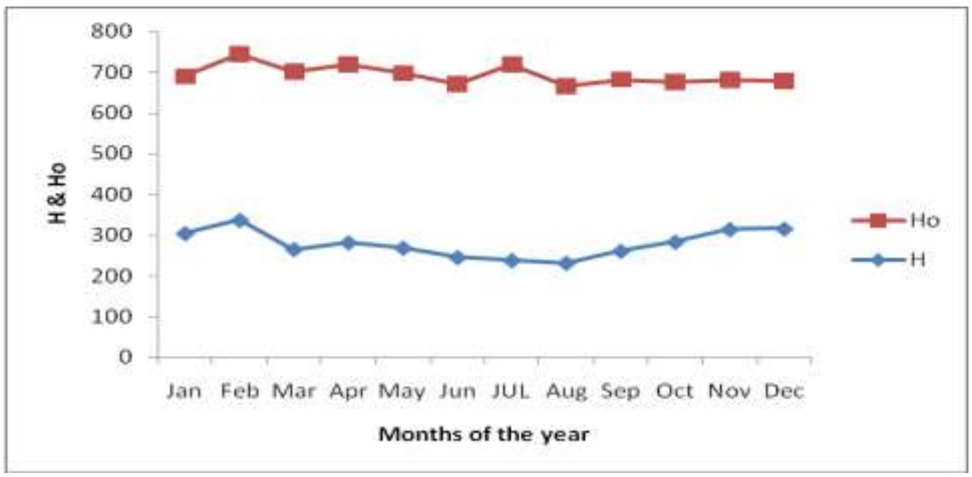

Fig. 1: Monthly average daily global radiation versus months of the year.

Table 2: Calculated solar radiation parameters and day number (ny) of the year.

Months	Ho(w/m^2)	Td=Tmax-Tmin	ny	Hcol H-S model	Hcal H-S model with linear regression	Hcal H-S model with power regression.
Jan	385.45	18.3	31	263.82	339.19	340.82
Feb	408.10	16.5	59	265.23	351.01	352.12
Mar	435.75	16.2	90	280.62	407.77	407.25
Apr	437.17	11.4	120	236.17	287.04	288.76
May	428.68	10.0	151	216.90	247.00	247.61
Jun	425.43	9.6	181	210.90	280.26	280.28
Jul	481.31	7.6	212	212.30	288.37	288.54
Aug	433.53	12.0	243	240.29	248.80	248.43
Sep	420.53	8.0	273	190.31	294.98	294.85
Oct	392.22	11.5	304	212.81	260.82	260.39
Nov	366.81	11.0	334	194.65	339.40	338.81
Dec	363.12	11.5	365	197.02	352.12	351.13

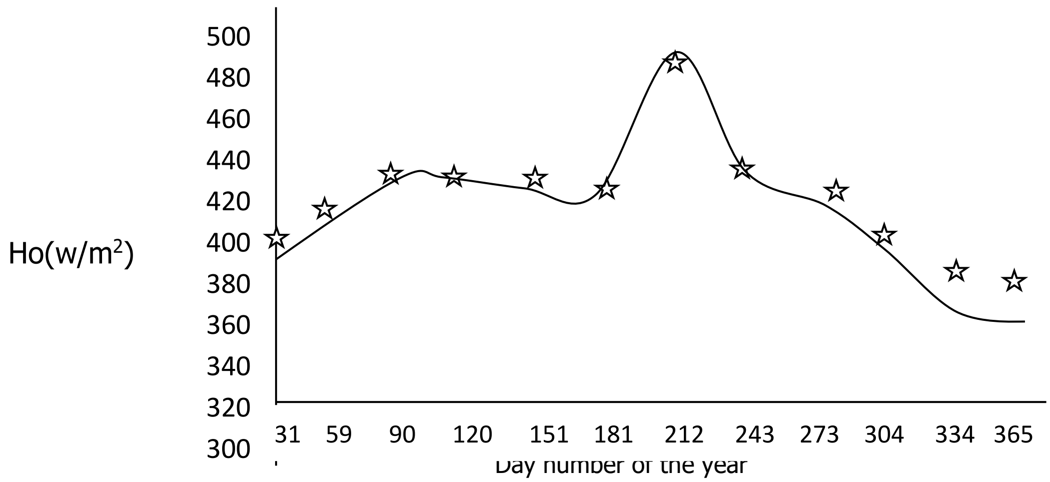

Fig. 2: Extraterrestrial radiation at Barkin Ladi versus day number of the year.

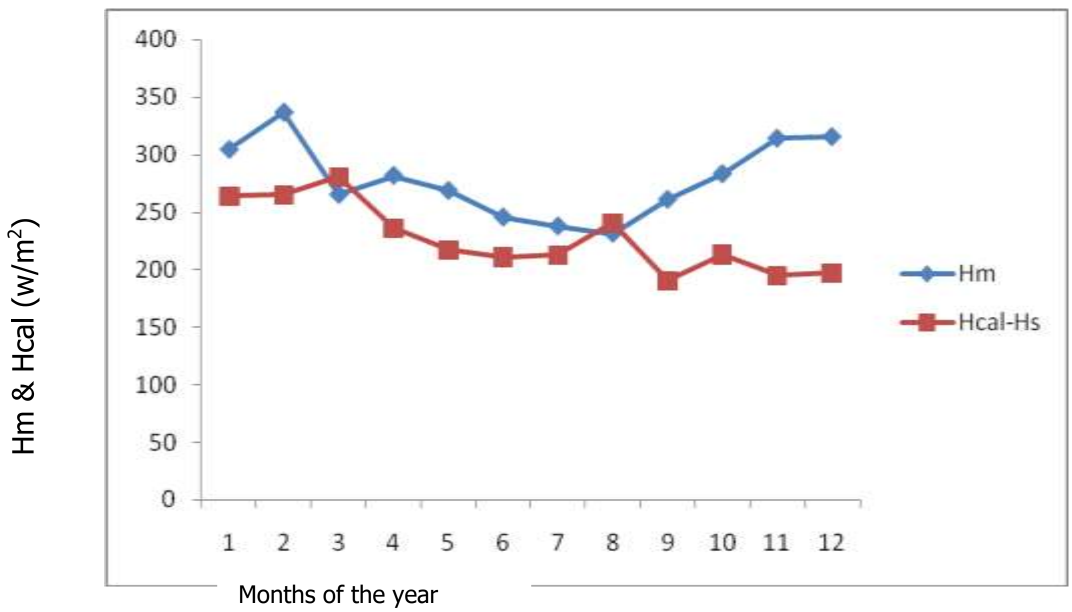

Fig. 3: Comparison of the measured and estimated solar radiation values of H-S model.

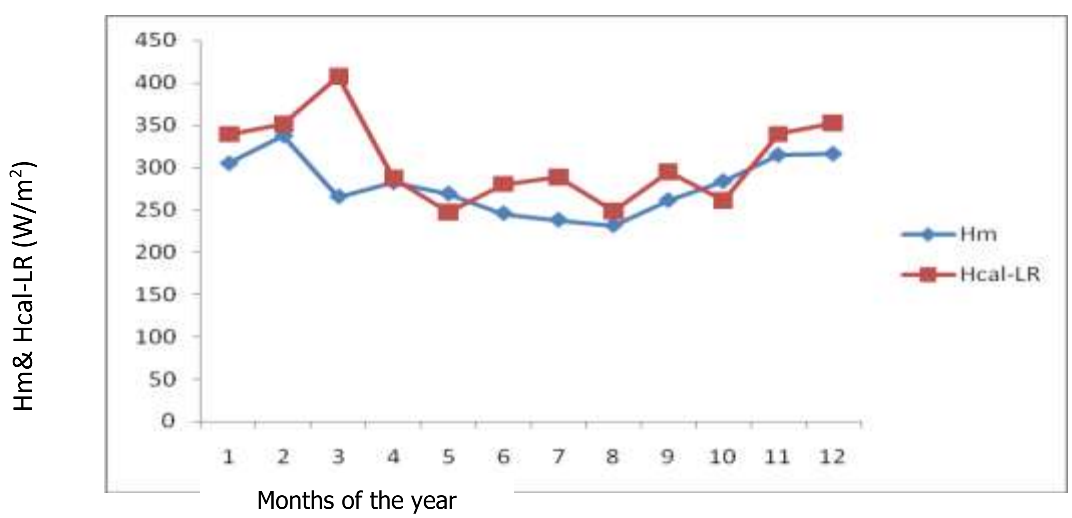

Fig. 4: Comparison of the measured and estimated values of H-S model with linear regression.

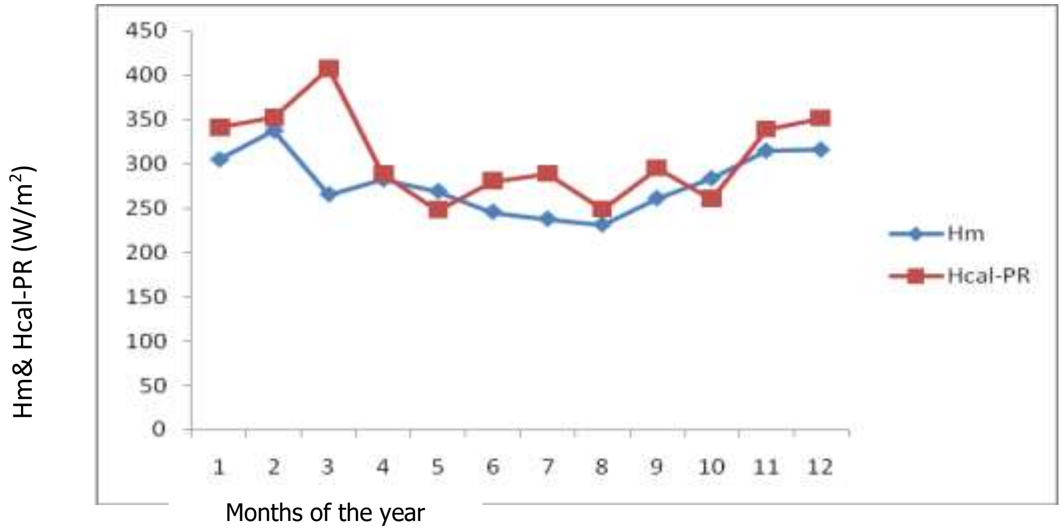

Fig. 5: Comparison of the measured and estimated values of H-S model with power regression.

Table 3: The comparison of error values for the estimated average global solar radiation from the different models.

Models	Coefficient of determination / correlation	MBE (w/m^2)	RMSE (w/m^2)	MPE (%)
Original H-S	0.52 / 0.72	8.02	4.17	-33.22
H-S with linear regression	0.76 / 0.87	2.81	1.46	-6.42
H-S with power regression	0.67 / 0.81	2.87	1.49	-6.70

CONCLUSION

It is concluded that from the monthly average solar radiation measurements, three empirical equations have been developed for use in estimating global solar radiation at Barkin Ladi, Plateau State of Nigeria. The first equation was originally developed by Hargreaves-Samani while the other two were modified by the Researchers to make it fit Heipang in Barkin Ladi LGA Meteorological Unit of the Yakubu Gowon Airport measurement; since the models require only the maximum and minimum temperatures. The performance of the models was evaluated and analysed using statistical indicators of R^2, MBE, RMSE and MPE. It was observed that the Hargreaves-Samani model with linear regression had the highest values of coefficient of correlation (r) and determination (R^2) and the lowest values of MBE, RMSE and MPE. Therefore, the model could be employed in estimating the global solar radiation of Barkin Ladi, Nigeria as well as any location that has the same geographical location or characteristics as Barkin Ladi, Nigeria.

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