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Empirical Models for the Estimation of Global Solar Radiation in Yola, Nigeria.

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Abstract

In this research paper, monthly average global solar radiation measured on a horizontal surface (S), average daily temperature (T), average daily relative humidity (RH) and average daily wind speed (WS) for the interval of three years (2010 – 2012) measured using various instruments for Yola of recorded data collected from the Center for Atmospheric Research (CAR), Anyigba are presented and analyzed. Various empirical models were developed; from the models developed, the model that contains the three variables gave the highest coefficient of determination of 76.5% which is S = -141.885 + 0.1802RH + 22.297T – 167.5WS.The suites of the empirical models were investigated that can be used to estimate the global solar radiation from the meteorological parameters obtained from Yola. Statistical package software SPSS version 16 was used for the regression analysis.

Keywords: Solar radiation, relative humidity, Temperature, Wind speed.

1.0 Introduction

The area of the study, Yola is the capital city and administrative center of Adamawa State, Nigeria. Situated along latitude $9^0$12’N and longitude$12^0$29’E on the Benue River is geographically favorably located to tap unlimited solar energy, the most dependable renewable energy source. The climate of this zone is characterized by two distinct and well-defined seasons, namely wet (or rainy) and dry seasons (also known as Harmattan). These seasons correspond to northern hemisphere summer and winter respectively. The annual onset and cessation of the dry and wet sessions follow the quasi-periodic north-south to-and fro movement of the inter-tropical convergence zone (ITCZ). The ITCZ demarcates the dry dust north-east trade wind from the moisture south-west trade wind. The dry season in the Sahel zone of Nigeria sets in about October each year and persists till next year. This is the period when the ITCZ is displaced to the south and the prevailing north-east trade wind transports large quantities of dust and smoke from biomass burning into the atmosphere over the entire region [1].

The design of a solar energy conversion system requires precise knowledge regarding the availability of global solar radiation and its components at the location of interest. Since the solar radiation reaching the earth’s surface depends upon climatic conditions of the place, a study of solar radiation under local climatic conditions is essential. An accurate knowledge of solar radiation distribution at a particular geographical location is of vital importance for the development of many solar energy devices and for estimates of their performances.

While it is appreciated that a number of commonly measurable atmospheric and meteorological parameters such as turbidity, relative humidity, degree of cloudiness, temperature and sunshine duration taken severally or jointly, affect the magnitude of the global irradiation incident on a given location, the preponderance of data now clearly, perhaps incontestably, point to the fact that the greatest influence is exerted by sunshine hours [2].

The first empirical correlation using the idea of employing sunshine hours for the estimation global solar radiation was proposed by Angstrom [3]. The Angstrom correlation was modified by Prescott [4], and Page [5]. Many researchers have employed hours of bright sunshine to estimate solar radiation [6-8].

A maximum-likelihood quadratic fit was later employed in [9] to estimate monthly global solar radiation. This quadratic fit method has been utilized by a number of authors like Akinoglu and Ecevit [10] and Fagbenle [11] to estimate global solar radiation. The maximum-likelihood quadratic fit method according to Fagbenle appears to widen the range of applicability of the one-parameter correlation to cover climatologically different zones of the same geographical region. All these empirical models have been shown severally to work reasonably well on a daily or longer-term basis.

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A lot of researchers have developed a correlation involving global solar radiation and sunshine hours for different locations in Nigeria. For example Fagbenle [11] developed a linear and quadratic equation for Benin, Ibadan and Samaru. Sambo [12] also developed a linear relation for Northern Nigeria. Okogbue and Adedokun [13] developed the linear relation for Ondo while Augustine and Nnabuchi [14] developed a quadratic relation for Calabar, Port Harcourt and Enugu. Udo [2] developed a model for Ilorin while Akpabio et al [15, 16] developed models for Onne. It is observed that the regression coefficients are not universal but depends on climatic conditions and the nature of pollutants of the environments.

2.0 Materials and Methods

Daily data used in this research work were obtained from Centre for Atmospheric Research (CAR), sited at Kogi State University Campus, Anyigba, Nigeria. The station has in its data base, for the meteorological parameters of solar radiation, relative humidity, temperature and wind speed, daily data spanning for three years (2010, 2011 and2012). The data which was recorded at five minutes intervals was averaged monthly for sunshine hours between 07.00 and 18.00 hours local time, using Microsoft Excel spread sheet.

The centre is under the supervision of National Space Research and Development Agency (NASRDA). The data were collected from a network of automatic weather stations across Nigeria, under a project with an acronym TRODAN which means Tropospheric Data Acquisition Network, initiated to provide data to the atmospheric and earth science communities in Nigeria as well as world at large.

Table1: Average Whether Data for The Three Years (2010 – 2012)

Months	**Solar Radiation (W/m^2)**	**Relative Humidity (%)**	**Temperature (^0C)**	**Wind Speed (m/s)**
January	391.2218	15.0494	30.5438	0.9222
February	398.1696	18.2388	33.4187	1.0347
March	453.18	10.0711	35.6040	1.0954
April	468.2693	35.9493	37.6452	1.5481
May	394.3752	52.1325	34.5526	1.3452
June	351.1577	62.8889	31.1713	1.2960
July	315.6666	71.8646	29.6610	1.1621
August	322.3049	72.0824	28.7524	1.0341
September	385.6373	67.5169	29.6316	0.9012
October	428.2899	58.4905	30.3251	0.9595
November	435.2211	15.8162	32.5450	1.0696
December	413.7788	15.7150	31.3445	0.8745

The value sunshine hours = n/N is the ratio of actual number of hours of sunshine received at a site to the length of the day. $H_{m,}$ represents the average measured daily global radiation. The extraterrestrial solar radiation (H_0) was calculated using the formula given by Klien [17] as

$$H_0 = \frac{24}{\pi} I_0 \left(1 + \frac{0.33cos360n}{365}\right)\left(cos\varphi cos\delta sinw_s + \frac{2\pi w_s}{360} sin\varphi sin\delta\right) \quad (1)$$

The value of $1367 W/m^2$ has been recommended for solar constant, I_0. The sunset angle w_s and the solar declination δ are defined by the following relations

$$w_s = cos^{-1}[cos(-tan\varphi tan\delta)] \quad (2)$$

and

$$\delta = 23.45 sin\left(360 \frac{284+d}{365}\right) \quad (3)$$

Where d is the day of the year. Usually, the 15^{th} of each month is the day of the month on which the solar declination is calculated.

The day length of N is the number of hours sunshine or darkness within the 24 hours in a given day and is given as:

$$N = \frac{2}{15} cos^{-1}(-tan\varphi tan\delta) = \frac{2}{15} w_s \quad (4)$$

Clearness index K_T ($=H_M/H_0$) gives the percentage deflection by the sky of the incoming global radiation and therefore indicates both the level of availability of solar radiation and changes in atmospheric conditions in a given locality.

The proposed regression models are:

Linear: this is of the form

$$y = a + bx_i, for\ i = 1\ to\ 3. \quad (5)$$

Quadratic: it is of the form

$$y = a + bx_i + cx_i^2, for\ i = 1\ to\ 3. \quad (6)$$

Cubic: it is of the form

$$y = a + bx_i + cx_i^2 + dx_i^3, for\ i = 1\ to\ 3. \quad (7)$$

Two Variables Regression:

$$y = a + bx_i + cx_j, for\ i,j = 1\ to\ 3\ and\ i \neq j. \quad (8)$$

Three Variables Regression:

$$y = a + bx_i + cx_j + dx_k, for\ i,j,k = 1\ to\ 3\ and\ i \neq j \neq k \quad (9)$$

Logarithmic Regression Model

$$y = a + b\ln(x) \quad (10)$$

Power Regression Model

$$y = ax^b \quad (11)$$

Exponential Regression Model

$$y = ae^{bx} \quad (12)$$

Where a and b are constants which will be determined. y is the same as solar radiation (S) and it is the dependent variable. x is the independent variable which can be replaced by any of the meteorological parameters such as average temperature, wind speed and relative humidity.

3.0 Results And Discussions

The transmissivity of the atmosphere for global solar radiation under perfectly clear sky conditions is obtained when all the independent variables are set to 1 and the transmissivity of an overcast atmosphere is obtained when all the independent variable are set to 0. R^2 is the coefficients of determination indicating the goodness of fit of the regressor. $R^2 = 1$ if fit is perfect and zero when regressor has no explanatory power whatever.

Linear Models:

S= 449.6063 – 1.28678 RH	$R^2 = 0.454$	(13)
S = -24.0+13.098T	$R^2 = 0.548$	(14)
S = 358.027+34.807WS	$R^2 = 0.022$	(15)

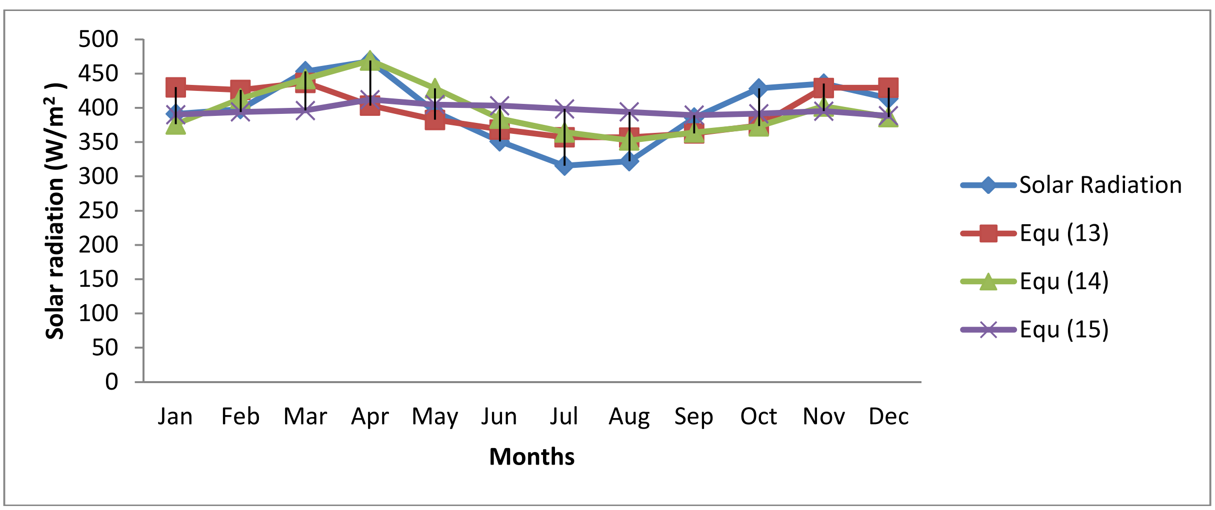

Figure 1: Comparison between the measured and calculated values of monthly averaged solar radiation using linear model.

From fig. 1, comparing these models, equations (14) is better, though the model overestimated the monthly averaged daily global solar radiation from the month of May to August while it underestimates from September to December. Additionally it gives the highest coefficient of determination of 54.8%.

Quadratic Model:

$S = 369.542+4.642RH– 0.072RH^2$	$R^2 = 0.672$	(16)
$S = -911.754+67.212T–0.819T^2$	$R^2 = 0.562$	(17)
$S = 1466–1859WS+778.7WS^2$	$R^2 = 0.304$	(18)

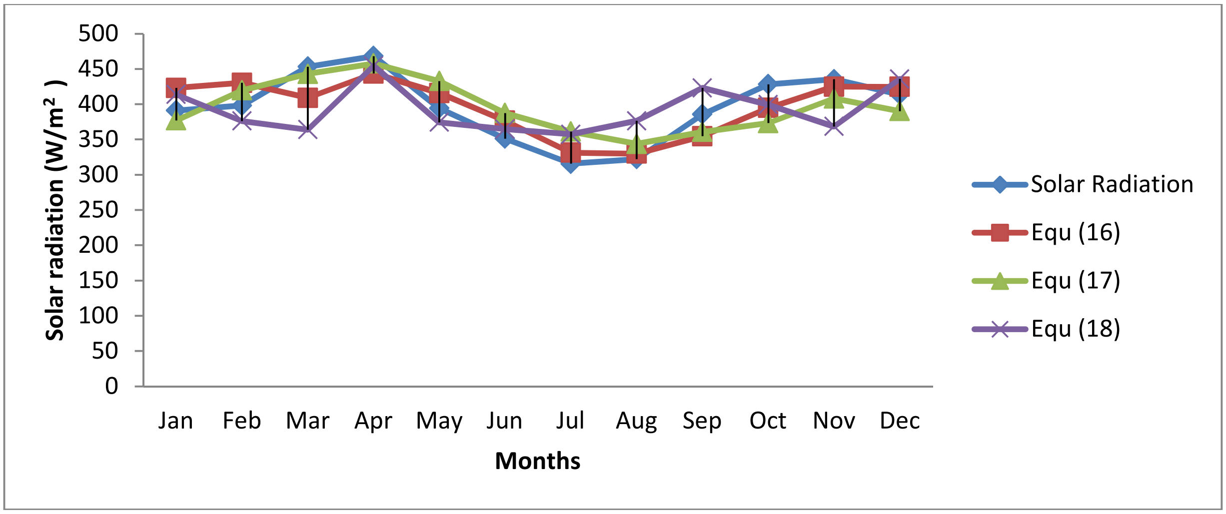

Figure 2: Comparison between the measured and calculated values of monthly averaged solar radiation using Quadratic model.

Comparing these models, we can see that equation (18) is the best more especially from January to April though it over estimate from May to August and under estimates from September to December.

Cubic Model:

$S = 459.297–4.805RH+0.182 RH^2–0.002RH^3 \quad R^2 = 0.672$ (19)

$S = -911.754+67.212T–0.819T^2 \quad R^2 = 0.562$ (20)

$S = 627.571–544.411WS^2+306.58WS^3 \quad R^2 = 0.256$ (21)

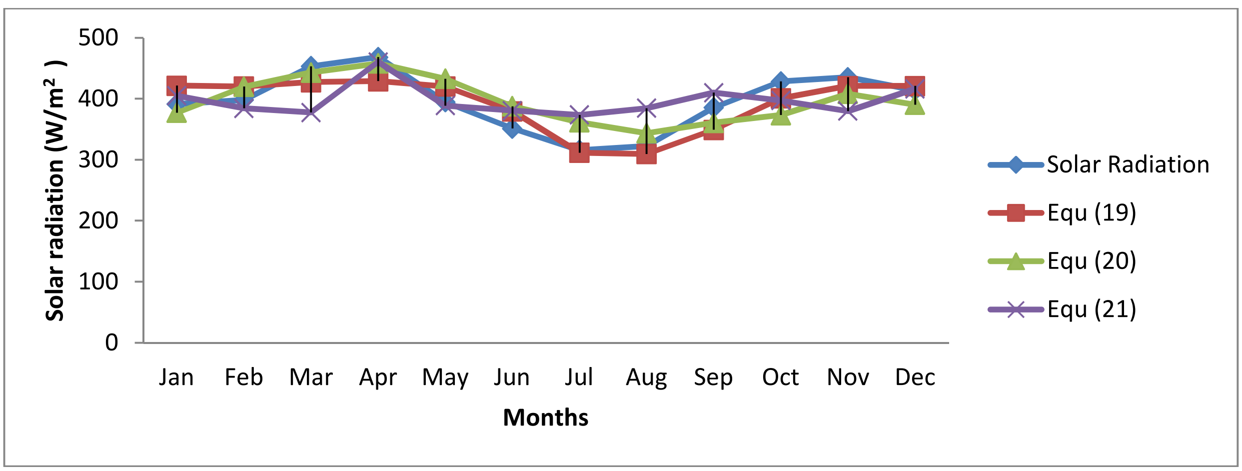

Figure 3: Comparison between the measured and calculated values of monthly averaged solar radiation using Cubic model.

Equation (19) gives a higher estimate and in addition it gives the highest coefficient of determination of 67.2%. This model is the same as that of equation (16) because the coefficient of T^3 is zero.

Two Variables Model:

$S = 123.9059 – 0.7615RH + 9.4704T \quad R^2 = 0.665$ (22)

$S = 382.7925 – 1.3745RH + 63.8299WS \quad R^2 = 0.525$ (23)

$S = - 96.6998 + 20.412T – 146.933WS \quad R^2 = 0.763$ (24)

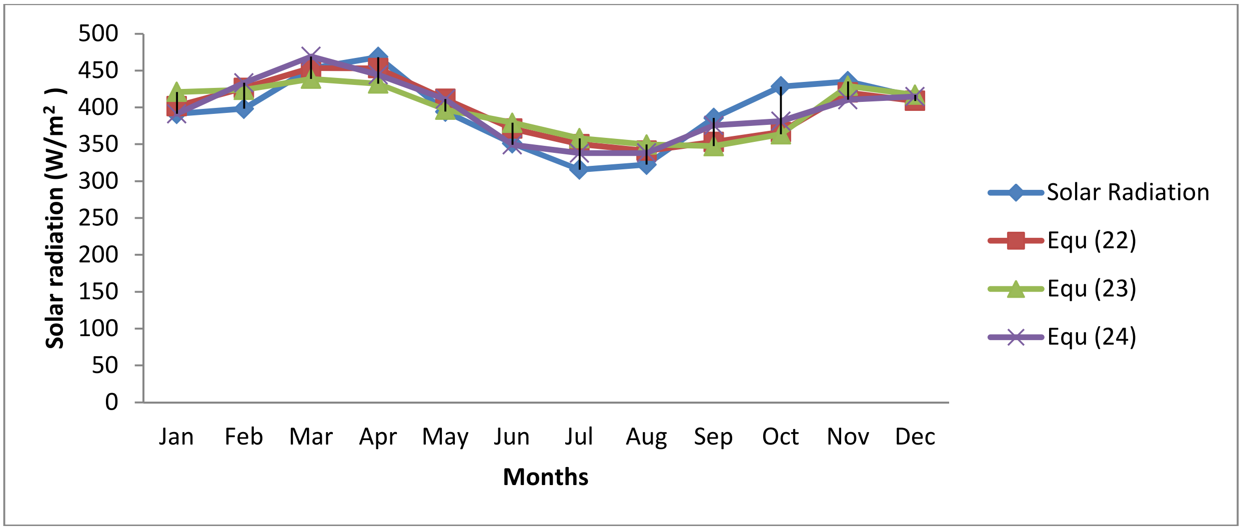

Figure 4: Comparison between the measured and calculated values of monthly averaged solar radiation using two variables model.

From Figure 4:Comparing these models that contain two variables, it is clear that equation (24) gives the best estimate of the monthly averaged daily global solar radiation. The coefficient of determination indicates that equation (24) gives 76.3% of the monthly averaged daily global solar radiation in the location.

Three Variables Model:

$S = -141.885 + 0.1802RH + 22.297T - 167.5WS \qquad R^2 = 0.765 \qquad (25)$

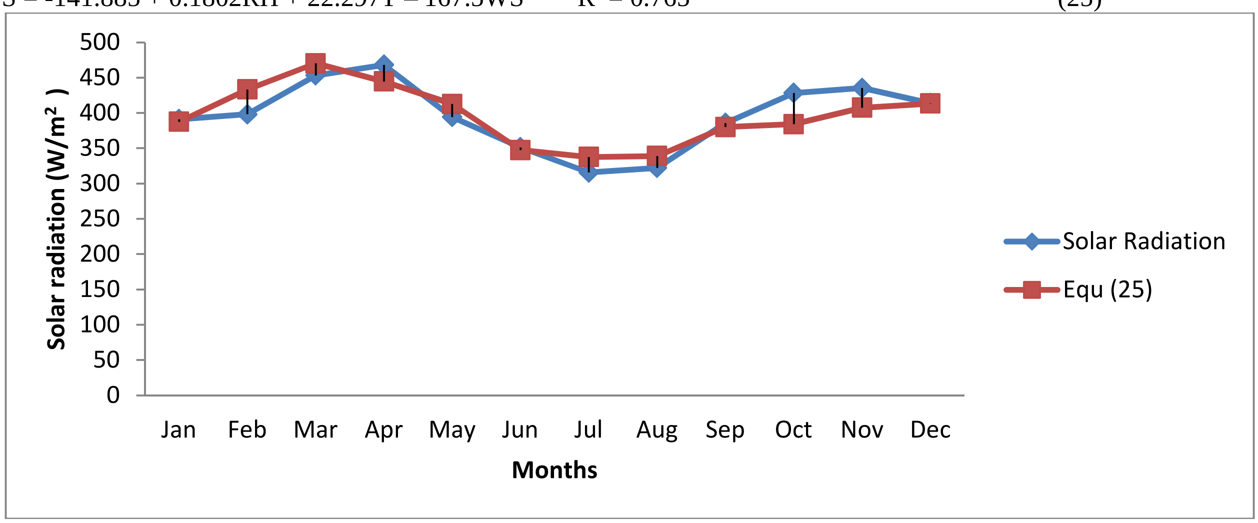

Figure 5: Comparison between the measured and calculated values of monthly averaged solar radiation using three variables model.

From Figure 5: This model over estimates the monthly averaged daily global solar radiation from February to March and July to August but under estimates from October to November while it estimates well in the month of January, June, September and December. The coefficient of determination implies that equation (25) gives 76.5% of the monthly averaged daily global solar radiation in the area of the study.

Logarithmic Model:

$S = 532.69 - 38.974\ln(RH) \qquad R^2 = 0.368 \qquad (26)$

$S = -1105 + 433.18\ln(T) \qquad R^2 = 0.555 \qquad (27)$

$S = 393.898 + 30.234\ln(WS) \qquad R^2 = 0.012 \qquad (28)$

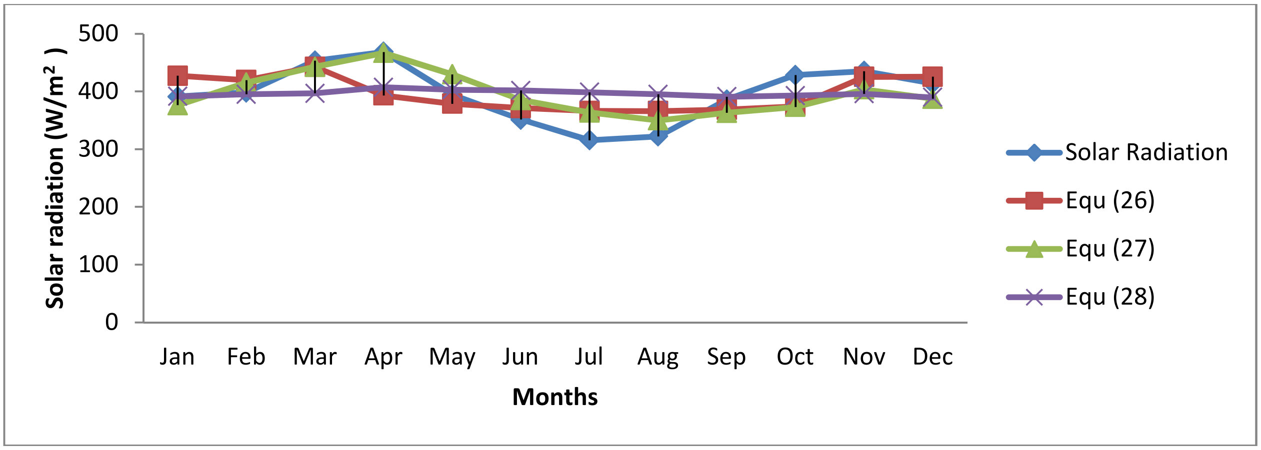

Figure 6: Comparison between the measured and calculated values of monthly averaged solar radiation using Logarithmic model.

Equation (27) is better than equations (26) and (28), the model estimates well the monthly averaged global solar radiation from the month of February to April while over estimates the solar radiation from May to August and under estimates in the month of January and September to December.

Exponential Model:

$S = 452.988\, e^{-0.003(RH)}$ $R^2 = 0.468$ (29)

$S = 135.063e^{0.033(T)}$ $R^2 = 0.525$ (30)

$S = 570.0e^{-0.36(WS)}$ $R^2 = 0.212$ (31)

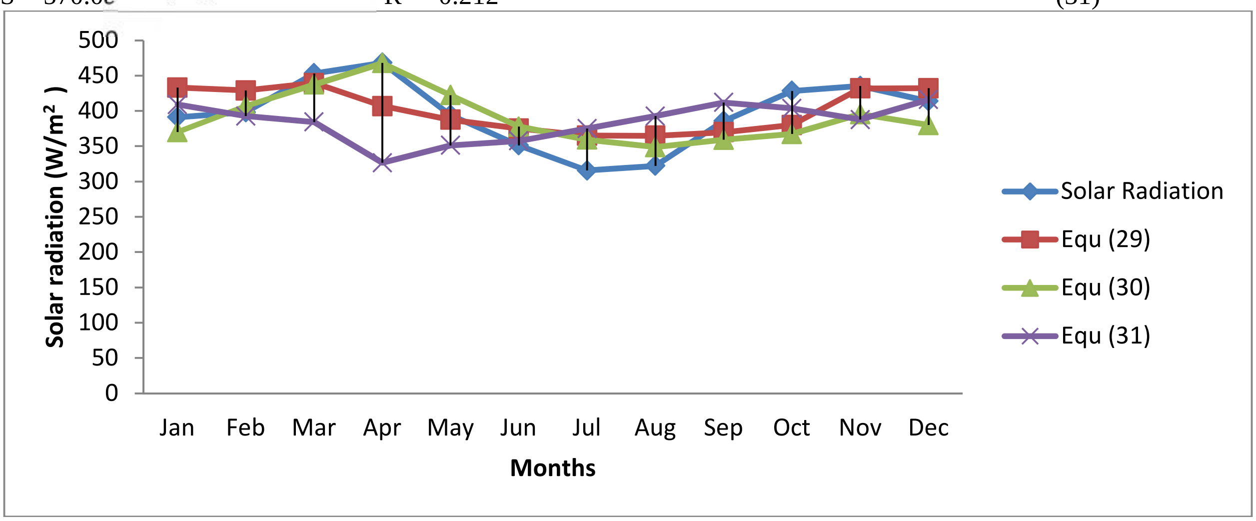

Figure 7: Comparison between the measured and calculated values of monthly averaged solar radiation using Exponential model.

From the figure above out of the three models developed equation (30) gives a better estimates of the average global solar radiation, despite that the model over estimates from the month of May to August while it under estimates the month of January and from September to December and it estimates fairly well in the months of February and April.

Power Model

$S = 563.736\, (RH)^{-0.103}$ $R^2 = 0.378$ (32)

$S = 8.556(T)^{1.105}$ $R^2 = 0.533$ (33)

$S = 396.3\, (WS)^{-0.40}$ $R^2 = 0.227$ (34)

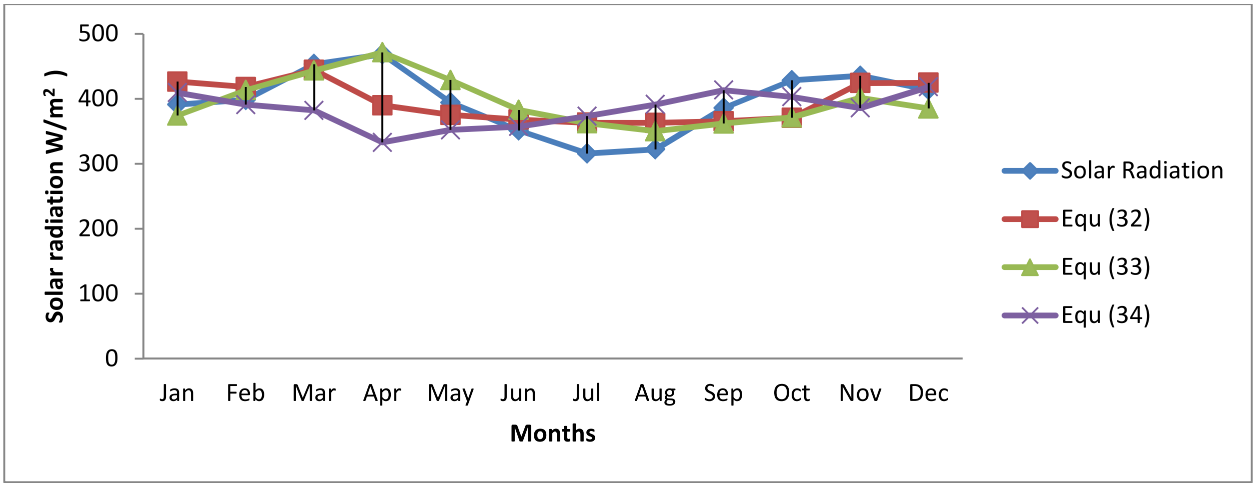

Figure 8: Comparison between the measured and calculated values of monthly averaged solar radiation using Power model.

In these models, equation (33) gives higher estimates than equations (32) and (34).This model estimates the solar radiation fairly well in the months of February, March and April, while underestimates in January and September to December and it over estimates from the month of May to August. Additionally the model gives the highest coefficient of determination of 53.3%.

4.0 Summary

In view of the worldwide concern about the economic importance of global solar radiation as an alternative renewable energy, the monthly global solar radiation using relative humidity, temperature and wind speed have been employed in this study to develop correlation equations.

Three variables have been developed with different types of equations obtained. These equations could be employed in the determination of global solar radiation of location with similar latitude and other geographical information as in Yola.

The global solar radiation intensity values produced by this approach can be used in the design and prediction of performance of solar applications system which is gaining attention in Nigeria.

5.0 Conclusion

From all the empirical models developed for the estimation of average monthly global solar radiation for Yola Adamawa State Nigeria, the model that contained all the three meteorological parameters of average daily temperature (T), average daily relative humidity (RH) and average daily wind speed (WS) (S = -141.885 + 0.1802RH + 22.29T – 167.5WS) is found to be better than all the other models developed and it gave the highest coefficient of determination of 76.5%.

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