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Research Paper

Development of a Simulation Equation For Estimating the Total Solar Radiation for Barkin Ladi, Plateau State of Nigeria

By

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Engineering Paper

Abstract: *An empirical equation for estimating the total solar radiation for Barkin Ladi location (Lat. 9.5°N and long. 8.9°E) was developed using the Angstrom-page linear equation. The equation was developed from measured solar radiation and sunshine hours for January to December, 2013. Solar radiation (W/m^2), wind speed (m/s), maximum and minimum temperature (°C), hours of sunshine (hr) and relative humidity (%) were collected from Yakubu Gowon Airport meteorological unit, Heipang in Barkin Ladi LGA. The highest solar radiation of 350 W/m^2 and the corresponding highest sunshine hours of 10.81 hrs occurred in measured solar radiation was 297.08 W/m^2. The average relative humidity of 46% was determined from the average ambient temperature of 28.16°C and the average minimum temperature of 16.19°C. The average wind speed was 28.33 m/s. The constants 'a' and 'b' of the Angstrom-Page equation were determined by plotting the clearness index (H/Ho) on the Y-axis and the fractional possible sunshine hours (ns/N) on the x – axis to obtain the line of best fit. The slope of this line is the value of the constant 'b' whilst the intercept of this line on the y–axis is the value of the constant 'a' with the coefficient of correlation of 0.54 and a coefficient of determination of 0.292. The developed empirical equation can therefore be used to determine the solar radiation at Barkin Ladi location, Nigeria. This fitted model can be further improved with database from continuous hourly measurements including other relevant meteorological parameters for not less than five (5) years.*

Keywords: *Development, Simulation equation, Solar radiation, Barkin Ladi, Nigeria.*

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1.0 INTRODUCTION

Solar radiation is the radiant heat energy emitted by or from the sun, which is propagated through space at the speed of light. Solar radiation varies with season, time of the day and year, cloud cover, albedo, dust and aerosol content of the atmosphere (Iloeje, 1997, Yohanna, 2010). Global or total solar radiation consists of direct and diffuse components. The direct component has suffered no charge in durations from the sun while the diffuse is made up of shattered and reflected radiation (Habou et al., 2005, Dandakouba et al., 2006, Yohanna et al., 2011& 2023).

Solar radiation at the earth's surface is essential for the development and utilization of solar energy. It is needed for designing collectors for solar heaters and other photovoltaic equipment that depend on solar energy. Incoming solar radiation has a significant role in hydrological and crop growth modelling. It is a key input for estimating potential evapo-transpiration, which plays a major role in the design of water supply storage reservoirs and irrigation systems (Sanusi and Abisoye, 2011). In spite of the importance of global solar radiation data, its measurements are not frequently available in developing countries like Nigeria. Akpabio et al., (2004) observed that meteorological stations measuring solar radiation data in developing countries are few. This situation can be solved by using empirical models, which estimate global solar radiation based on the relationships with frequently measured climatic variables. Many studies have been calculated to estimate incoming solar radiation in Nigeria (Bamiro, 1983, Akpabio et al., 2004, Yohanna et al., 2011). Angstrom (1924) was the first scientist known to suggest a simple linear relationship to estimate global solar radiation.

Solar energy applications require complete knowledge and detailed analysis of the potential of the site, so a database at ground level is an important feature of solar energy systems (Gairaa and Bakelli, 2013). Measurements of global solar radiation reaching the surface of the earth and its two components- direct and diffuse are essential in most research fields of solar energy. The daily values as well as the monthly ones are needed to evaluate the performance of existing solar devices and estimate the efficiency of future installations (Gairaa and Benkaciali, 2011; Desouza et al., 2009). When the site under consideration is equipped with a radio metric station operating regularly for several years, it will be easier to exploit solar energy resources. However, in most cases, there are no local measurements or ground measured solar radiation is scarcely available for a given site where a solar system is planned so we resort to approximate methods to predict the characteristics of solar radiation (Gairaa and Bakelli, 2013) or the use of satellite data, in conjunction with quality solar ground data sets and other meteorological data as well has become an effective way of developing site-time-specific resource assessment over large area (Zarzalejo, 2006, Polo et al., 2006 and Yohanna et al.,2023).

Knowledge of the local global solar radiation is required by most models that estimate crop growth and is essential for many applications including evapotranspiration estimates, architectural design and for planning any solar energy systems at a given location (Zarzalejo et al., 2009). Design of a solar energy system requires precise knowledge regarding the availability of global solar radiation at the location of interest. Since the global solar radiation reaching the earth's surface depends upon the local meteorological conditions, a study of solar radiation under local climatic conditions is essential (Ahmed and Ulfat, 2005). For locations where measured values are not available, solar irradiance can be estimated using empirical models (Almorox, 2011, Yohanna et al., 2011 &2023).

The scantiness of hourly data in Nigeria and so many countries in Africa makes it necessary to resort to empirical models to evaluate hourly inputs of diffuse and beam radiation for the design and optimization of solar devices (Maduekwe et al., 1999). Solar energy is an abundant, clear, pollution-free and never-ending source of energy (Jiya and Alfa, 1999; Yohanna, 2010). The growing population, fast-depleting reserves of fossil fuels (petrol, diesel, kerosene) and the location of Nigeria in the globe have led researchers in the field of energy resources and development to pursue the development and use of solar energy devices.

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 (Yohanna et al., 2011). The Angstrom-Page equation is a widely accepted numerical method for determining the monthly daily global solar radiation in a location. The regression coefficients 'a' and 'b' are specific to every location and the accurate determination of the coefficients will result in the accurate determination of global or total solar radiation of that location. The coefficient 'a' refers to the fraction of extraterrestrial radiation that is diffused (scattered), which is called diffuse radiation and the coefficient 'b' refers to the fraction of the extraterrestrial radiation that is direct (beam), which is called beam radiation. The Angstrom-page equation can be used to determine total radiation on a horizontal surface if the ns, Ho and N are known as shown in equations 1 and 2.

$$H/_{Ho} = a + b\ (^{ns}/_{N}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$H = Ho\ \ [a + b\ (^{ns}/_{N})] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where. H = monthly average daily global radiation on a horizontal surface, W/m^2

Ho = monthly average daily extraterrestrial radiation W/ m^2,

ns = monthly average daily number of hours of bright sunshine, hr.

H= monthly average daily number of possible sunshine, hr.

'a' and 'b' – Regression constants or coefficients.

The objective of the project is to develop a simulation model or equation for estimating the average daily global solar radiation for Barkin Ladi location and its environs using the Angstrom – Page equation.

2.0 MATERIALS AND METHODS

2.1 Description of the Study Area

The study was carried out at Barkin Ladi L.G.A. of Plateau State. It lies between latitude 9.5^{0}N and longitude 8.9^{o}E with an average altitude of 1515 metres above mean sea level (Wikipedia, 2015). It has an estimated population of 175, 267 inhabitants. The local government area is bounded in the North by Jos South and Jos East LGAs, in the East by Mangu LGA, in the west by Riyom LGA and in the south by Bokkos, LGA.

(Fig,1). Barkin Ladi has a land area of 1,032 km^2. The local government 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 high from 42 to 45%. The mean annual total rainfall varies from 1520mm to 2050mm. The local government area enjoys luxuriant vegetation and is an agrarian area; hence agriculture has always played a leading role in the lives of the people. The geographical location of the area makes it a veritable agricultural zone for the cultivation of diverse crops. The predominantly crops grown include: maize (Zea mays), groundnut (Arachis hypogaea), guinea corn (sorghum bicolor or sorghum saccharatum), millet, (penniseturn typhoides), irish potatoes (Solanum tuberosum), sweet potatoes(Ipomoea batatas), Tomatoes(Solnum iycopersicum), onions (Allum cepa), Peanuts (Arachis hypogaea) cabbage (Brassica oleracea), Acha/hungry rice(Digitaria exilis), Okro/Okra(Abelmoschus escutentus),Vegetable leaves (Amaranthus), cowpea/ beans (Vigna unguiculata), Pepper (Capsicum annuum), millet (Setaria italic), Carrot(Daucus carota), Soybean (Glycine max), Spinach (Spinacia oleracea),Amaranth (Amaranthus cruentus),Water leaf(Talinum triangulare), Bitter leaf (Vernonia amygolalina) etc.

Figure 1: Map of Plateau State of Nigeria showing the seventeen (17) local government areas.
NB. The shaded LGA is the area of study.

3.2 Data Collection and Measurements/ Instrumentations

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 the development of an empirical model for estimating the solar radiation in Barkin Ladi were obtained from Yakubu Gowon Air port meteorological unit located at Heipang, Barkin Ladi LGA.

The data collected included mean monthly values of the following:

(i) The solar radiation measured from a Gun-Bellani instrument graduated in millilitres (ml) and converted to Watts per square metre (W/m^2) using the formula 1ml = 1.357 $\pm$ 0.176 mJ/day m^2 = 15.70 6 W/m^2 (Okonkwo and Akubuo, 2001; Yohanna et al., 2015).

(ii) Maximum and minimum temperatures measured from a temperature thermometer in degree Celsius or centigrade (^{o}C).

(iii) Relative humidity obtained using the maximum and minimum temperature from humidity slide rule UK BA in percentage (%).

(iv) Wind speed measured from a digital cup anemometer graduated in knots, km/hr, m/s, miles/hr and miles/sec. The scale used was in m/sec.
(v) Station surface pressure = 12.90HPa above mean sea level measured from Aneroid barometer graduated in millibars or pascals.
(vi) Hours of bright sunshine (i.e. sun shine duration) taken from Casella card paper graduated in hours or sunshine Trinidal recorder in hours.
Sun shine is the sum of all the time periods during the day when the direct solar radiation measured equals or exceeds 120W/m^2 (Coulson, 1975). This implied that at any point in time that the solar radiation is less than 120 W/m^2, it was an hour of cloudiness and when it was equal or greater than 120 W/m^2, it was taken as a bright sun shine hour.

2.3 **Determination of Angstrom-Regression Coefficients**

The Angstrom regression constants 'a' and 'b' of the Angstrom-Page linear equation were determined by plotting clearness index (H/Ho) on the y-axis and fractional possible sunshine hour (ns/N) on the x-axis to obtain line of best fit. The intercept of this line in the y-axis is the constant 'a' while the slope of this line is the constant 'b'.

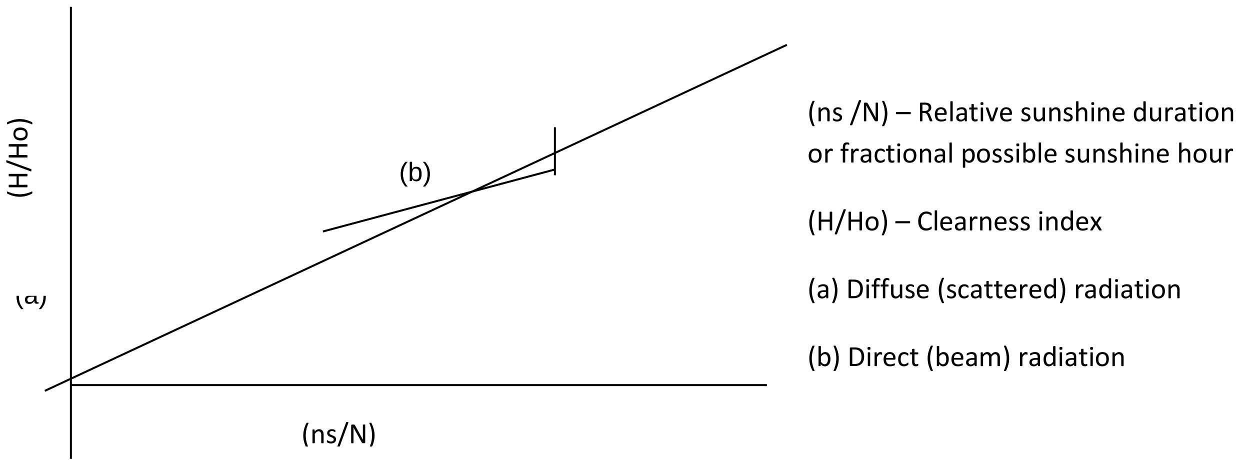

Figure 2: Plot of (H/Ho) vs (ns/N) showing how to determine regression coefficients 'a' and 'b'

2.4 Determination of Extra Terrestrial Radiation (Ho), Hour Angle (ω), Declination Angle (б) and Average Monthly Number of Hours of Possible Sun Shine (N).

The extra-terrestrial radiation, Ho, is the sun energy or radiation expected if the atmosphere were perfectly transparent or it is the solar radiation incident outside the earth's atmosphere. The above parameters were respectively obtained from the following equations.

Ho = $24/_{\pi}$ 1sc [1 + 0.033 cos ($\frac{360}{365}$ ny)] [cos φ cos δ sin ω + π/180 ω sin φ sin δ] kJ/m^2 day……………...……….3

Cos ω = - tan φ tan δ…………………………….……….4

δ = 23.45 sin [360/365 (284 + ny)] ……………………….5

N=2ω/15 ……………………………………………………6

3.0 RESULTS AND DISCUSSION

3.1 Results Presentation

Table 2 is the summary of measured monthly average solar radiation parameters. Table 3 is the summary of calculated solar radiation parameters for Barkin Ladi location. Table 4 is the summary of monthly means of H/Ho and ns/N for Barkin Ladi location. Table 5 is the average determined Angstrom- Page equation and correlation coefficient. Figure 3 is a plot of the Angstrom-Page linear equation for Bakin Ladi location based on monthly means. Figure 4 is a plot of measured and calculated total solar radiation against months of the year for Barkin Ladi location.

Table 2: Summary of measured monthly average daily Total Solar Radiation parameters

Month /year	Measured solar radiation H(W/m²)	Wind speed V (m/s)	Air Temperature		Relative Humidity R.H (%)	Sunshine duration ns (hr)
			T_{max} (^{0}c)	T_{min} (^{0}c)		
Jan 2013	331	26	28.3	10.0	20	9.17
Feb	349	20	31.2	14.7	27	8.18
Mar	350	29	31.7	15.5	26	10.18
Apr	289	34	29.9	18.5	37	5.43
May	248	32	27.7	17.7	58	5.70
Jun	278	39	26.2	16.6	65	6.19
Jul	284	28	24.0	16.4	75	3.38
Aug	237	27	28.8	16.8	73	4.00
Sep	275	20	24.9	16.9	62	4.50
Oct	262	23	28.5	17.0	53	3.75
Nov	324	28	28.2	17.2	35	4.13
Dec 2013	338	34	28.5	17.0	21	5.95
TOTAL	3565	340	337.9	194.3	552	72.39
AVERAGE	297.08	28.33	28.16	16.19	46	6.03

Table 3: Summary of calculated monthly average daily total solar radiation parameters

Month /year	Measured solar radiation H(W/m²)	Calculated extraterrestrial radiation Ho (W/m²)	Sunshine duration ns (hr)	Hrs. of possible sunshine N (hr)	Clearness index (H/Ho)	Fractional possible sunshine hr (ns/N)
Jan 2013	331	385.45	9.17	11.59	0.86	0.79
Feb	349	408.10	8.18	11.81	0.86	0.69
Mar	350	435.75	10.81	12.08	0.80	0.89
Apr	289	437.17	5.43	12.33	0.66	0.44
May	248	428.68	5.70	12.51	0.58	0.46
Jun	278	425.43	6.19	12.55	0.65	0.49
Jul	284	481.31	3.38	12.42	0.66	0.27
Aug	237	433.53	4.00	12.18	0.55	0.33
Sep	275	420.53	4.50	11.92	0.65	0.38
Oct	262	392.22	3.75	11.66	0.67	0.32
Nov	324	366.81	4.13	11.48	0.88	0.36
Dec 2013	338	363.12	5.95	11.46	0.93	0.52
TOTAL	3565	4928.10	72.39	143.99	8.75	5.94
AVERAGE	297.08	410.68	6.03	12.00	0.73	0.50

Table 4: Summary of monthly means of measured, H/Ho and $^{ns}/_{N}$ for Barkin Ladi location

Month/year	H/Ho	$^{ns}/_{N}$
Jan 2013	0.86	0.79
Feb	0.86	0.69
Mar	0.80	0.89
Apr	0.66	0.44
May	0.58	0.46
Jun	0.65	0.49
Jul	0.66	0.27
Aug	0.55	0.33
Sep	0.65	0.38
Oct	0.67	0.32
Nov	0.88	0.36
Dec	**0.93**	**0.52**
Total	**8.75**	**5.94**
Average	**0.73**	**0.50**

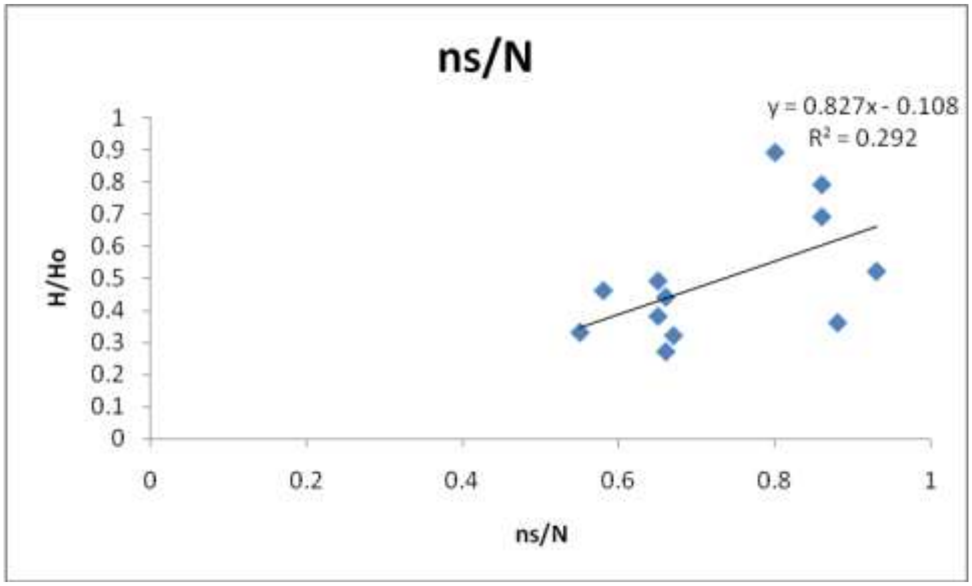

Figure. 3. Plot of Angstrom-Page equation for Barkin Ladi Location based on monthly means.

Table 5: Summary of the determined Angstrom- Page equation and correlation coefficient for the study area.

Month/ year	H/Ho	ns/N	Regression constants 'a'	'b'	Equation	Coef of det R^2	Coef of corr. r
Jan 2013	0.86	0.79	-	-	-	-	-
Feb	0.86	0.69	-	-	-	-	-
Mar	0.80	0.89	-	-	-	-	-
Apr	0.66	0.44	-	-	-	-	-
May	0.58	0.46	-	-	-	-	-
Jun	0.65	0.49	-	-	-	-	-
Jul	0.66	0.27	-	-	-	-	-
Aug	0.55	0.33	-	-	-	-	-
Sep	0.65	0.38	-	-	-	-	-
Oct	0.67	0.32	-	-	-	-	-
Nov	0.88	0.36	-	-	-	-	-
Dec	0.93	0.52	-	-	-	-	-
Total	8.75	5.94	-	-	-	-	-
Average	0.73	0.50	-0.11	0.83	H=Ho[-0.11+0.83(ns/N)]	0.292	0.54

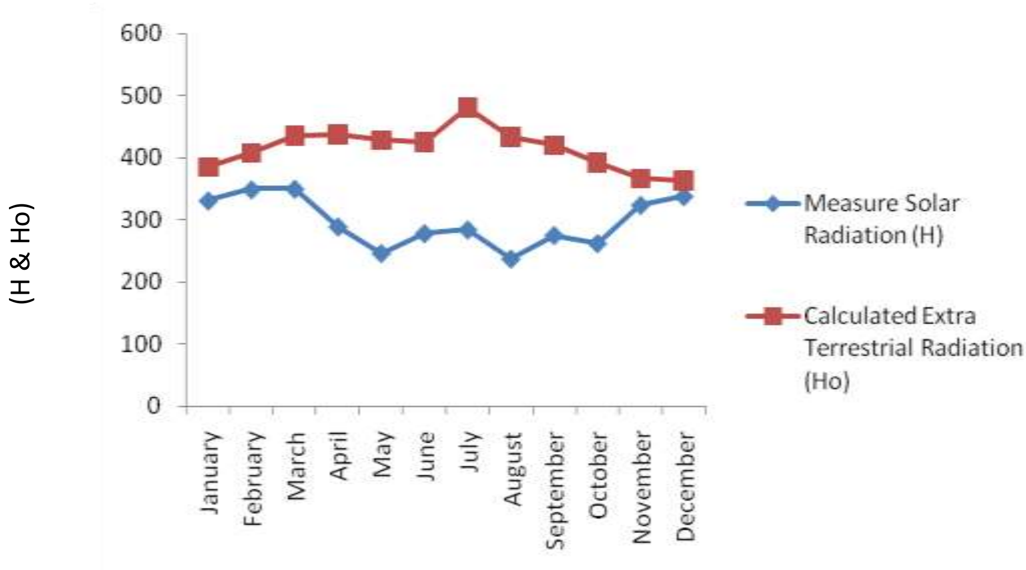

Figure 4: Plots of Measured and Calculated Total Solar Radiation vs months of the year for Barkin Ladi location Months of the Year

3.2 Discussion of Results

Table 2 is the summary of the measured monthly average solar radiation parameters. The average solar radiation, wind speed, maximum and minimum temperatures, element relative humidity and bright sunshine duration were 297.08W/m^2, 28.33m/s, 28.16^{0}c and 16.19^{0}c, 46% and 6.03hrs respectively. It can be seen that the highest measured solar radiation (350W/m^2) and the highest ambient temperature (31.7^{0}c) were recorded in March 2013. This implies that solar radiation increases as temperature increases (Sanusi and Abisoye, 2011). This is expected because the amount of solar radiation on a flat surface depends on the weather, latitude of the location and surface orientation (Yohanna, 2010) and Barkin Ladi's location (lat 9.5^{0}N) is within the equatorial belt. However, the solar radiation (237W/m^2) measured in August, 2013 may have been due to dusty cloud cover and interruption by passing cloud at that period because solar energy is available only when the sun shines (Yohanna, 2010, Yohanna et al., 2011). Also under heavy cloud condition no direct radiation reaches the horizontal surface (Stine and Harrigan, 1985). The hours of bright sunshine are the hours during which the sun's disk is visible and this depends on the length of the solar day (Anderson, 1983). The mean sun shine hours (ns) recorded was 6.03 hrs. Table 2 also shows the monthly distribution of sunshine hours (10.81 hrs) corresponding to the highest measured solar radiation of 350 W/m^2 in March, 2013. This agreed with the work of Zarzalejo (2006) and Zarzalejo et al., 2009), which states that the solar radiation increases with duration of sun shine. Generally, Barkin Ladi location has a very low humidity level as measured in this study with an average relative humidity of 46%. The average wind speed for the period of the study was 28.33m/s (Table 2). This wind speed can support any meaningful wind project in the location since the average speed of the wind is more than 10m/s (Yohanna, 2010).

Table 3 showed the calculated average extra-terrestrial solar radiation (Ho), hours of possible sunshine (N), clearness index (H/H0) and fractional sunshine duration (ns/N) to be 410.68W/m^2, 12.00hrs, 0.73 and 0.50 respectively. Table 4 is the summary of the calculated average clearness index and fractional sunshine hours while Fig 3 is a plot of Angstrom-Page equation for Barkin Ladi location based on monthly means.

Table 5 is the summary of the average determined the Angstrom-Page equation and a correlating coefficient for the study period. The determined Angstrom-Page linear equation for predicting the monthly average daily total solar radiation for Barkin Ladi is H = Ho [-0.11 + 0.83 (ns/$_N$)]. The constant 'a' which is the fraction of the extraterrestrial total radiation component of the location that is diffuse is -0.11. This value is within the accepted range (Stine and Harrigan, 1985). The constant 'b' which is the fraction of the extraterrestrial total radiation component of the location that is direct is 0.83. This is also within the acceptable range as it is highest during clear day conditions but lowest during cloudy conditions. The coefficient of correlation of 0.54 for the prediction equation showed that 54% of the variation in the measured solar parameters was explained by the developed model leaving 46% to be explained by other factors (Yohanna, 2010), such as light intensity, temperature variations, humility etc, which may change with time and location. Fig.4 is a plot of measured and calculated solar radiation against months of the year for the Barkin Ladi location.

4.0 CONCLUSION AND RECOMMENDATIONS.

4.1 CONCLUSION

There is scantiness of hourly data in Nigeria so it is necessary to resort to empirical models to evaluate hourly inputs of diffuse and direct radiation for the design and optimization of solar devices. However, there are no local measurements in most cases, such as Barkin Ladi, so there is the need to resort to approximate methods to predict the solar radiation of a locality.

An empirical model for estimating the solar radiation in Barkin Ladi, (lat. 9.5°N and long 8.9°E) has been developed from measured data collected from Yakubu Gowon Air Port, Heipang, Barkin Ladi LGA using the Angstrom-Page linear equation type. The constants 'a' and 'b' are -0.11 and 0.83 respectively. The average monthly daily total solar radiation can be estimated from the equation H=Ho [-0.11 + 0.83 (ns/N)]. The correlation coefficient of 0.54 for this equation shows that the equation can be used to estimate total solar radiation for Barkin Ladi's location. The highest solar radiation of 350 W/m^2 occurred in the month of March 2013 while the lowest radiation of 237 W/m^2 occurs in August 2013. The measured average radiation and sunshine duration were 247.08W/m^2 and 6.03 hrs respectively. The ambient temperature increased with increasing insolation and increasing sunshine hours. The average ambient temperature, relative humidity and wind speed for Barkin Ladi were 28.16°C, 46% and 28.33 m/s respectively.

4.2 RECOMMENDATIONS

It is recommended that:

i. The developed empirical model should be used to estimate the total solar radiation for now since no model has been developed for this location.

ii. The polytechnic should establish a meteorological unit far from obstructions that will block the sun's rays so that it will be permanently or otherwise logged into a computer that can read and record the solar radiation hourly as well as other parameters such as maximum and minimum temperatures, wind speed, relative humidity, thereby reducing the rigours of the work or hardship in taking the hourly readings. This will help researchers in the field of solar energy in collecting solar radiation data or parameters for the determination of an empirical formula/equation for a location; which can be used for the next 5 – 10 years; since every year has different climatologically effects and depletion of the ozone layer also affects solar radiation falling on the earth horizontal surface.

iii. Further study should be undertaken to obtain direct hourly daily measured or observed solar radiation parameters for at least five (5) years and the average taken to enable the development of a more accurate or established prediction empirical model for Barkin Ladi location as the readings obtained from the airport were not taken consistently and were mean monthly values and were not obtained hourly.

iv. The very high average wind speed for the location (28.33m/s) does recommend the use of wind machines since this speed can support a meaningful wind project in the location.

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