International Journal of Information Processing and Communication (IJIPC) Vol. 9 No. 1&2 [May, 2020], pp. 184-198

Special Issue on Computing and Communication Technologies
Online: ISSN 2645-2960; Print ISSN: 2141-3959

Statistical Analyses of Solar Energy Potential and Energy Yield in Kano, Nigeria

Ibrahim S. Madugu[1], Fatima Abdulkadir[2], Muhammad S. Gaya[1], Bala Abdullahi[3], A. Abdulkarim[4], O. Ibrahim[5], Mubarak A. Afolayan[5], Olalekan Ogunbiyi[6], Yinusa A. Adediran[5], B. J. Olufeagba[5], Oludare Y. Ogundepo[7]

[1]Department of Electrical Engineering, Kano University of Science and Technology, Wudil, Nigeria
[2]Department of Chemistry Education, Kano University of Science and Technology, Wudil, Nigeria
[3]Department of Mechanical Engineering, Kano University of Science and Technology, Wudil, Nigeria
[4]Department of Electrical Engineering, Ahmadu Bello University, Zaria, Nigeria
[5]Department of Electrical and Electronics Engineering, University of Ilorin, Nigeria
[6]Department of Electrical and Computer Engineering, Kwara State University, Malete, Nigeria
[7]Department of Electrical and Electr. Engineering, Fed. Univ. of Petroleum and Resources, Effurun, Delta State, Nigeria

[*]Corresponding author: maduguemir@gmail.com, maduguemir@kustwudil.edu.ng Tel: +2348035895320

Abstract

This study presents the statistical analysis and energy yield for the solar energy potential at Kano, Kano State, Nigeria. The City is situated geographically at 12.05°N; 08.2°E; altitude of 472.5 m; and 1.1705 kg/m3 air density. The output of the analysis could be used for realistic sizing and implementation of renewable energy systems in the region. The daily mean solar radiation data for 46 years used is collected from the Nigeria Meteorological Agency. Statistical analyses of the data were achieved with the help of probability density functions in order to extract monthly energy potential of the area. The results show that the month of March recorded the highest solar energy at 291.75 W/m2 and August with the least at 227.05 W/m2. These results signify that the potential of solar energy in Kano is economically viable for solar electricity generation.

Keywords: Solar energy, irradiation, Renewable Energy and energy yield.

1. INTRODUCTION

Power systems require flexibility to balance demand and supply. This flexibility is increased when integrating variable renewable energy sources such as solar and wind. Improvement in design and operation of electricity infrastructure, grid optimization can give the desired flexibility. Renewable energy has shown a tremendous penetration in many areas such as transportation, heating and cooling. In the same way, in 2017, renewable sources provide about 19% of the world energy requirements and the trend is expected to grow (Environment, 2017). Global energy demand growth is at about 1.8% yearly since from 2011 to date and is predicted to triple by the year 2050 (International Energy Agency-IEA). The growth is more eminent in developing countries (Nigeria inclusive). This makes the penetration of renewable energy to be pertinent in reducing global warming. Presently renewable energy resources account for 20% of the total world energy demand and are predicted to increase to around 45% by 2035 due to the effort of the World Bank and IEA.

The global solar PV installations continue to rise, thus surpassing all other solar energy installations. In 2017 there was an addition of about 97 GW of global solar PV installation to achieve a total of 400 GW. In Figure 1 the outlook of the world solar energy shows that by 2017 China has already overtaken all other nations. India recorded a remarkable success in the last 10 years and is now among the leading solar PV nations in the world. These successes were as a result of numerous governments policies including subsidy and loan schemes, feed-in-tariff, renewable energy certificates, tax holidays and rebates and direct support among others.

Energy demand in the world and in Nigeria had experienced a tremendous increase as human activities are relying on electronics and electrical devices (Computer, handset, electric car, washing machine etc.). This energy demand is projected to triple by the year 2050 thereby compounding on the already greenhouse effect. According to the Kyoto agreement, there is a need to reduce greenhouse gas emission by 50% by 2050. Recently, According to the World Energy Council (WEC) estimates; about 1.5 billion people are known to have no access to electricity and about three billion are forced to use fuels for their day to day activities (Ullah, 2013; Shaaban &

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Online: ISSN 2645-2960; Print ISSN: 2141-3959

Petinrin, 2014). Greater percentages of these people are from Sub-Saharan Africa, India and South Asia (Zhang, Barakat, & Yassin, 2012). Therefore there is a need for more commitment to reducing the number of people without continuous access to electricity across the globe. WEC estimated that, if all the stakeholders are not committed there could still be about 880 million people without electricity by 2030 and 530 million by 2050 (Abdulkarim, Abdelkader & Morrow, 2015).

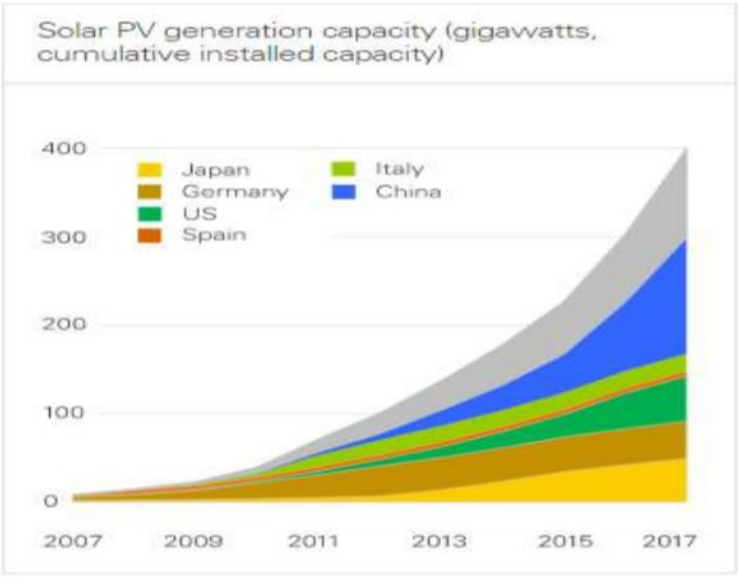


Figure 1. Estimated Renewable Energy Share of Total Final Energy Consumption, 2015 (Kilisek, 2015)

According to the report for the World Bank and IEA, there is a need to double the install energy capacity in order to meet the demand from the developing countries in the next 40 years. Regarding these issues, it can be seen that isolated communities/loads are still searching for a robust and cost-effective alternative source of power generation (Abdulkarim, Nasir, Olayede, Olawoyin, Akorede, Madugu, Abdelkader, Morrow, Adediran, 2018).

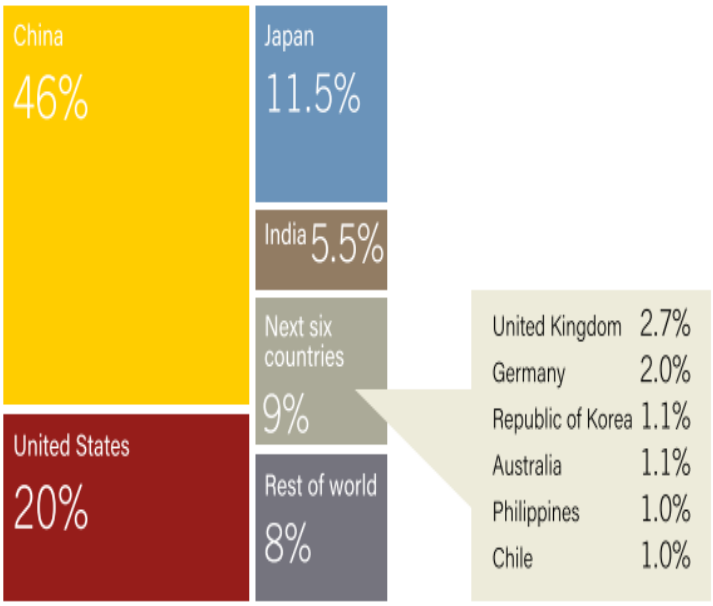


Figure 2: Solar PV Global Capacity Additions, Shares of Top 10 Countries and Rest of World, 2016

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Online: ISSN 2645-2960; Print ISSN: 2141-3959

In terms of capacity, renewable power experienced the highest amount in a year in 2016 with an estimated of about 161 GW. In the same year, renewable energy experienced about 9% increase compared to the previous year and to about 2,017 GW at the end of the same year. Solar PV saw record additions and, for the first time, accounted for more additional power compared to any other renewable energy generating technology. This account for an additional 75 GW dc of solar PV capacity worldwide. This is equivalent to the installation of more than 31,000 solar panels every hour globally. Figure 2 shows the solar PV global capacity of 2016. More solar PV capacity was installed in 2016 (up 48% over 2015) than the cumulative world capacity five years earlier. By the same year-end, global solar PV capacity totalled at about 303 GW (Environment, 2017).

A successful design of any solar based-project requires accurate information on the availability of solar irradiation and its potential for any specific region (Galip, Arif & Asir, 2003). This can be achieved in the past via empirical formulas using several weather parameters of the area or other area of similar climate (Fritz & Mcdonald, 1949). This study computed the monthly solar energy potential of Kano, Nigeria from the 46-years daily solar radiation data using a statistical approach. The data is further analysed on ten years basis to establish seasonal effects.

2. Related Works

It is evident that electricity is one of the indexes used for classifications of countries. That is developed, underdeveloped and developing nations. Therefore, for any nation to join the league of developed nations; electricity available must be very high, adequate and reliable for the transformation of the people standard of living. These could boost industrial, economic and technological advancement of the overall society in general (Fanchi, 2005).

Statistical approach to the development of solar energy potential prediction model is considered as a better option to the use of the empirical method from the economic and minimal forecast error perspectives. The empirical method can also be time-consuming especially in such situation where some data are missing and/or possessing very few data (Abdulkarim et al., 2015). Numerous works considered statistical probability distributions functions (PDFs) such as Weibull, normal, lognormal and gamma. In (Yarhands, Kwasi, & Appiah, 2013) various PDFs were used to find the distribution that best fits the hourly solar irradiation data of Kumasi, Ghana. Abdulkarim et al. (2015), Mohammed, Mustafa, Bashir and Mokhtara (2013) and Kamran et al. (2012) used a statistical approach to fit distributed energy data. The use of probability analysis for solar energy system planning was employed in Ciprian, Romeo and Calin (2018) and statistical behaviour of clearness index was modelled using probability distribution function models in Bendt, Collares-Pereira and Rabl (1981), Hollands and Huget (1983) and Hassan (2014).

2.1 SOLAR RADIATION

The use of solar, geothermal and biomass for power generation had become prominent due to their availability (EEhsanul, Pawan, Sandeep, Adedeji & Ki-Hyun, 2018). Though such availability varies from one region to the other. The Sun is the source of this wealth of inexhaustible energy for the Earth planet that can be harvested as solar energy for the production of electricity. This can be achieved via the use of various technologies such as the solar photovoltaic, mirrors and so on.

The earth is one of the nine planets that revolve around the sun. The earth diameter is about $12.7X10^3$ km and its distance to the sun is $1.5X10^8$ km. However, this distance varies throughout the year (365.25 days). It is closest to the sun around January 1st and receives more radiation, while it is farthest around 1st July by 3.3% of the average distance and receives 7% less radiation (Hamidi, 2019).

There are three components of the solar radiation that strikes the earth. These are the direct (solar flux that directly hits the earth without the interference of the atmosphere); the diffused (solar flux scattered by the atmosphere) and the reflected (received when the rays are reflected by ground, wall, plant and other near surfaces). The total solar radiation that strikes the earth surface is the summation of the three components given in (DOCPLAYER, 2019) as:

$$J_T = J_R + J_d + J_D \quad (1)$$

where J_R, J_d and J_D are the reflected, diffused and direct solar radiations defined in (DOCPLAYER, 2019) by:

$$J_R = \frac{\rho_g I_H (1-cos\theta)}{2} \quad (2)$$

$$\frac{I_d}{I_{dH}} = \frac{1+cos\theta}{2} \quad (3)$$

$$I_D = I_{DN} cos\theta \quad (4)$$

where ρ_g is the solar reflectance of the surrounding in °C, I_H is the total solar flux that strikes the horizontal ground in MJ/m^2, I_{dH} is the diffuse radiation for a horizontal surface in MJ/m^2/day, I_{DN} is the direct normal flux energy per area-time and θ angle of incidence in radians.

Recent estimate of the solar constant stands at 1366.1 W/m^2. The solar radiation reaching the surface of the earth is only about 55% of solar rays at the top of the atmosphere and only 51% is absorbed, while 4% is reflected (Council, 2015). The remaining 45% (that did not reach the earth surface) is classified as having 26% reflected by clouds (20%) and by the atmosphere (6%), while 19% is absorbed (3% by clouds and 16% by the atmosphere). This made solar energy to be a variable renewable energy resource on both temporal and spatial measures (Ozoegwu, Mgbemene & Ozor, 2017).

The total average solar irradiance values in the actual application are location-specific. It depends on geography, meteorological parameters, latitude, time, and seasons. Therefore, there is a need to use either the available empirical values of a location. While for those locations lacking available data then various models can be used that include: using acceptable empirical models of similar weather, direct measuring of the solar radiation (this could not be reliable as the data might be too short for a reliable analysis), use data from archives stored in websites (for example NASA) that might be recorded using satellite (Chineke, 2008).

Nigeria has huge solar energy potentials ranging between 1,800 kWh/m2 to the Southern region and more than 2,300 kWh/m2 to the Northern region as shown in Figure 3 (Anoliefo, 2016). The abundance of solar energy in Nigeria is huge; the radiated sun's energy is nearly 3.8 × 10 kW which is 1.082 million tonnes of oil equivalent (mtoe). This solar potential is more than 4000 times and 13000 times of Nigeria's daily production of crude oil and natural gas respectively. The total country energy demand could be met if just 0.1% of its solar energy could be harvested at 1% efficiency (Shaaban & Petinrin, 2014).

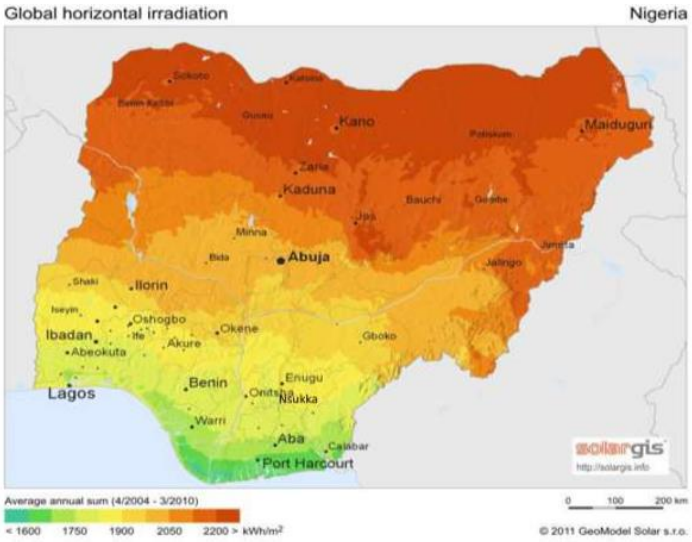


Figure 3. Map of Nigeria Solar Energy Potential (Anoliefo, 2016)

The Nigeria Energy Commission in 2012 developed a draft master plan for the development of renewable energy potential in Nigeria to compete in the global outlook (Anoliefo, 2016). This encouraged some solar energy projects across the country while solar street lights started springing up in various cities, rooftop solar distributed energy, and so on (Anoliefo, 2016).

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Online: ISSN 2645-2960; Print ISSN: 2141-3959

3. METHODOLOGY

3.1 Solar Radiation Measurement

There are two classes of measuring solar radiation. These are the direct normal beam solar radiation measured with pyrheliometer (shown in Figure 4) and the total radiation within its semi-circular area measured with pyranometer (shown in Figure 5) (DOCPLAYER, 2019).

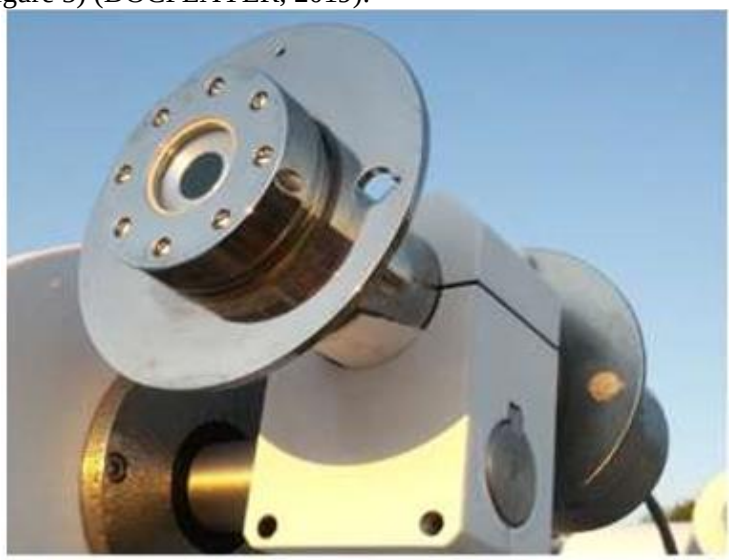


Figure 4. An Eppley Pyrheliometer with a Tracking Mount (Eplab(a), 2019)

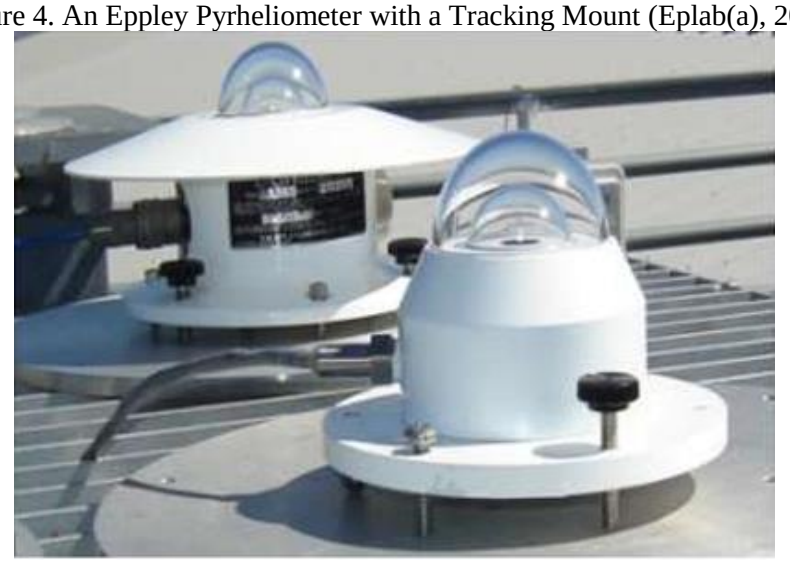


Figure 5. Global Precision pyranometer (Eplab, 2019)

3.2 Probability Distribution Function

3.2.1 Normal Distributions

A normal distribution has many applications in Engineering, Science and Statistics, therefore; it has been categories as one of the most widely applicable probability distribution. Due to its nature, that it could be approximated in may form, it has become a reference probability distribution function for statistical analysis (Tsagris, 2014).

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When a very large number of continuous variables (like solar radiation) are made and the range is divided into a very large number of 'narrow' classes, the resulting frequency curve in many cases approximate closely to a standard curve (normal curve) known as the standard normal curve, which has a characteristic like a bell-shaped formation. The normal curve is symmetrical about its centre line that coincides with the mean of the observations. There is a close connection between the standard deviation (SD) from the mean of a set of values and the normal curve (Abdulkarim, et al., 2015).
The mean is defined as;

$$\bar{x} = \frac{\sum xf}{n} \tag{5}$$

Also, the mode of the distribution is the value that occurs most often and is defined by;

$$mode = L + \left(\frac{l}{l+u}\right)c \tag{6}$$

where l is the minimum value of the group, u is the maximum and c is the difference between the group.
The median is the value of the middle term when all values are put in ascending or descending order, with an even number of terms. The median is the average of the two middle terms. The standard deviation is given as;

$$\sigma = \sqrt{\frac{\sum x^2 f}{n} - (\bar{x})^2} \tag{7}$$

where, n is the number of observations.
With coded mean, $\bar{x}_c$ the coded standard deviation becomes,

$$\sigma_c = \sqrt{\frac{\sum x^2 f}{n} - (\bar{x}_c)^2} \tag{8}$$

The standardized normal curve is obtained from the normal curve by the following:

$$z = \frac{x-\mu}{\sigma} \tag{9}$$

where, z is the standardized normal variable, x is the sample and μ is the mean. With zero mean the equation of the standardized normal curve is given by;

$$\gamma = \emptyset(z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} \tag{10}$$

$\emptyset(z)$ is the probability density function.

3.3 Generating Solar Radiation Group

Sturge's rule is used to get the solar radiation data interval/classes. This is defined in (Encyclopedia, 2019) as:

$$k = 1 + 3.3 \log y_t \tag{11}$$

where k is the number of intervals and y_t is the solar radiation data.
The data step or data width is computed as:

$$y_w = \frac{(y_{max} - y_{min})}{k} \tag{12}$$

where y_w is the data step/width, y_{max} is the highest value of the data and y_{min} is the minimum value of the data.
The data range, $R_{n,}$ was found using the following:

$$R_n = \begin{cases} y_{min} & n = 1 \\ R_{n-1} + y_w & 2 \geq n \leq k \\ y_{max} & n > k \end{cases} \tag{13}$$

3.4 Solar Radiation Data Histogram and Cumulative Distribution Function

A data group table is used to compute the frequency distribution table consisting of the frequency and cumulative frequency columns for the histogram and cumulative distribution function respectively (Yarhands et al., 2013). The formula, for the computations, is given in equations (14) and (15). Thus,

$$F_h = frequency(y_t, R_T) \tag{14}$$

$$CDF_i = \frac{CF_i}{N} \tag{15}$$

where F_h is the frequency (number of data points in a range), R_T is the aggregate of the range (from the minimum to the maximum data in the range), CDF_i is the i[th] cumulative distribution function, *CF* is the normal cumulative frequency and *N* is the data set.
The normal cumulative frequency is defined as:

$$CF_i = F_{h_i} + CF_{i-1}, \quad i=1,2,3,\ldots,k \tag{16}$$

3.5 Goodness of Fit

The measured and calculated solar radiation are compared to determine the degree of fitness of the data to the probability distribution function, using the square of errors, R^2 given as:

$$R^2 = \sum_{i=1}^{N}(f(y_t)_i - f'(y_t)_i) \tag{17}$$

where $f(y_t)$ is the calculated normal probability distribution function and $f'(y_t)$ is the theoretical normal probability distribution function.

3.6 Solar Irradiance

The solar energy (irradiance) Y_b in W/m^2 is calculated from solar radiation using equation (18) defined in (Robishaw, 2019) as:

$$Y_\mathrm{b} = Y_\mathrm{t} \times 11.6 \tag{18}$$

where Y_t is solar radiation in MJ/m^2/day.
The conversion from daily solar radiation (MJ/m^2/day) to solar irradiance (W/m^2) used the general formula defined as (Niwa, 2019):

$$Y_b = \frac{Y_t \times 1000000}{t_d} \tag{19}$$

where t_d is number of period in seconds given as 86400 seconds (24*60*60).

3.7 Solar Energy Yield

To successfully compute the solar energy yield a solar panel must be deployed. The simplest steps for computing the expected power yield of a particular area are:

i. Conversion of the daily average of energy yield into Peak Sunshine hours (PSH)
ii. Calculate the Operating Cell temperature. This is given by equation (20).
iii. Derate the Panel output power; by the manufacturer's tolerance, temperature rise above rated temperature and percentage (usually 5%) due to dust and dirt.

Calculate Expected energy yield.

$$T_{cell} = T_{air} + \frac{NOCT-25}{800} \times G \tag{20}$$

where;
T_{air} is the expected air temperature, NOCT: is the Nominal operating cell temperature and G is the solar irradiance.

4. Results and Discussion

The average of the daily solar irradiance of the study area is presented in Figure 6. It can be observed that the minimum solar energy occurred around August and January while the peak values occur in March and November. Also, the 1[st] peak occurs around the end of the 1[st] quarter and the beginning of the 2[nd] quarter. While the 2[nd] peak occurs at the end of the 3[rd] quarter and the beginning of the 4[th] quarter. Also, in the 3[rd] quarter, the lowest solar radiation is usually recorded due to cloud cover. The maximum solar energy is recorded as 300.5 W/m^2 around March and the minimum is 213 W/m^2 recorded around July.

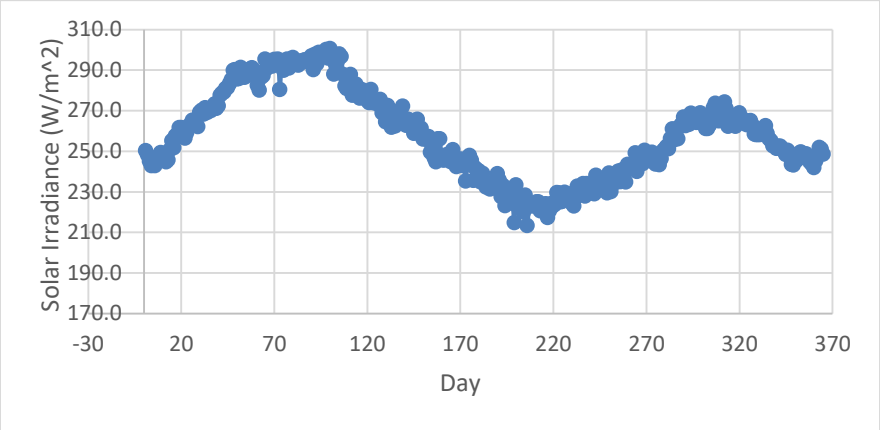


Figure 6. Mean Daily Solar Irradiance of Kano-Nigeria (1971-2016)

In Figure 7 the monthly average solar irradiance is presented. It can be seen that the month of March has the highest value at 291.75 W/m^2 and the lowest value is found to be the month of August with 227.05 W/m^2.

The normal distribution histogram, cumulative frequency ratio and goodness of fit of 10 years (1971-1980) quarterly statistical analyses of the solar energy are presented between Figure 8 and 19. It can be seen from the 1st quarter that the energy is normally distributed. The minimum, mean and maximum values are 184.44, 275.07, and 360.76 W/m^2 respectively. The correlation between the calculated energy and the theoretical is 99.96%.

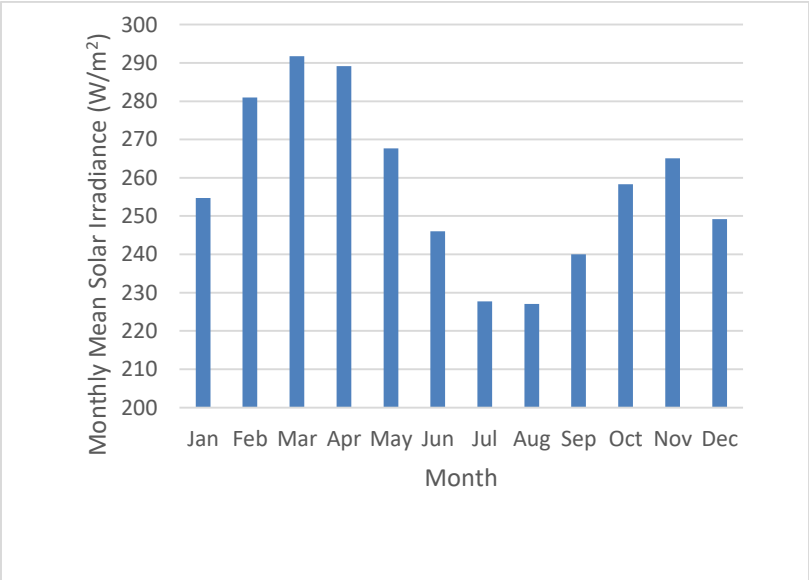


Figure 7. Mean Monthly Solar Irradiance

The second quarter has a minimum, mean and maximum irradiance of 151.96, 278.42 and 352.64 W/m^2 respectively. While about 99.1% of the calculated values fit the theoretical normal distribution.

The values in the third quarter is lower than that of second quarter at 107.88 W/m^2 (minimum), 239.01 W/m^2 (average) and 295.80 W/m^2 (maximum). The goodness of fit for the normal distributions is 99.54%.

The 4th quarter has 920 data points, a mean of 253.34 W/m^2. The range is between 120.64 and 321.32 W/m^2 with higher values more available than lower values at 71%. It can be deduced that this quarter has a slightly lower percentage of highest values above the mean value after the 2nd quarter.

Table 1 shows the maximum, minimum and average values of the four quarters for each 10 years and the last 5 years.

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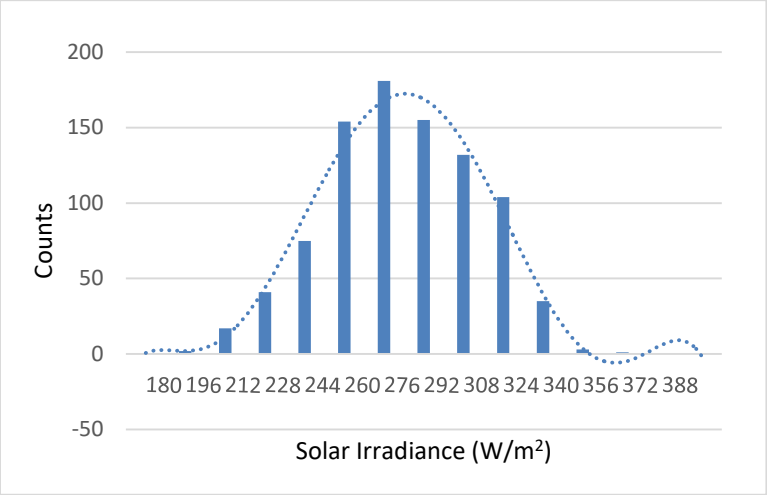


Figure 8: Histogram of the Frequency, 1st Quarter (1971-1980)

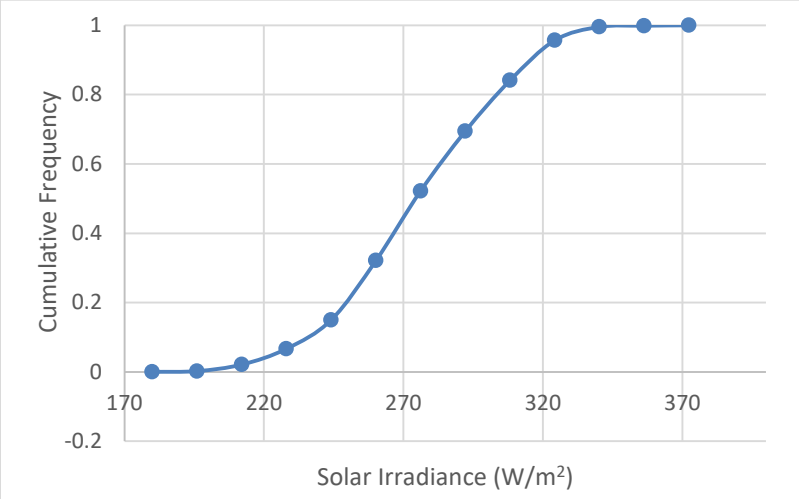


Figure 9: 1st Quarter Cumulative Frequency Ratio

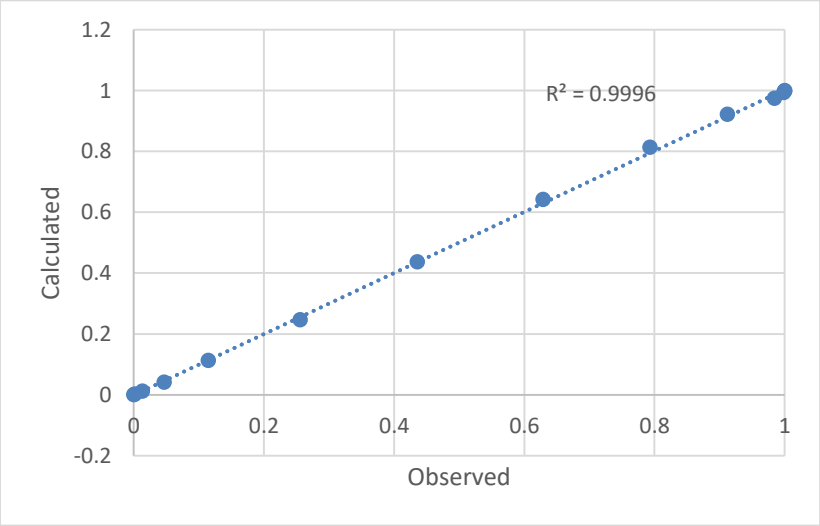


Figure 10: 1st Quarter Analysis between Calculated and Observed Cumulative Frequency Distributions

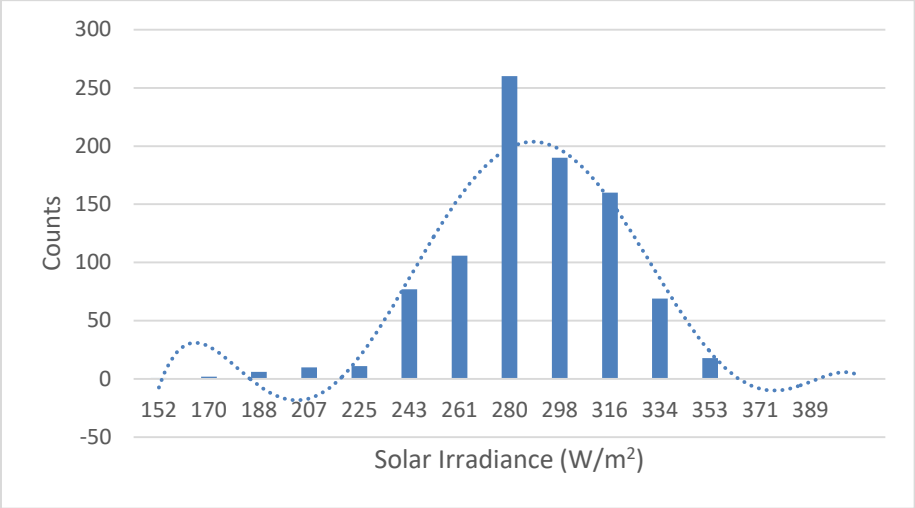


Figure 11: Histogram of the Frequency, 2nd Quarter (1971-1980)

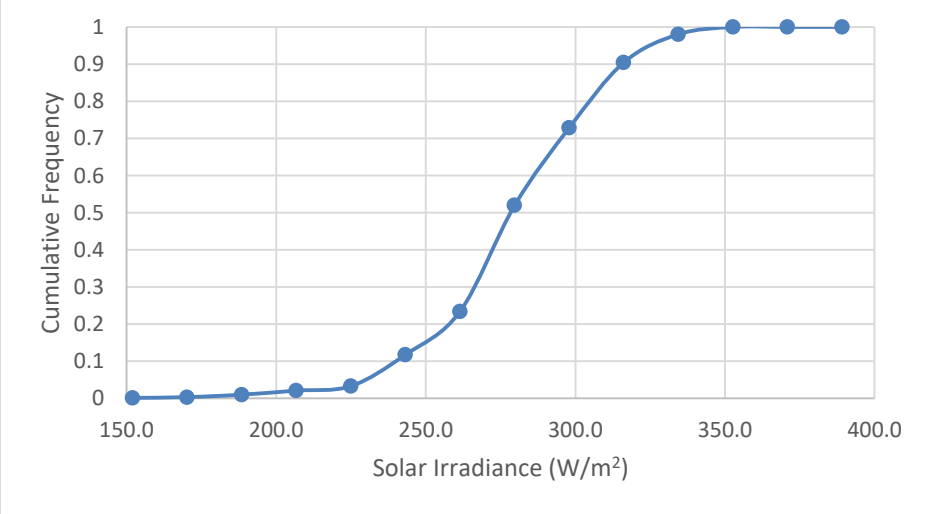


Figure 12: 2nd Quarter Cumulative Frequency Ratio

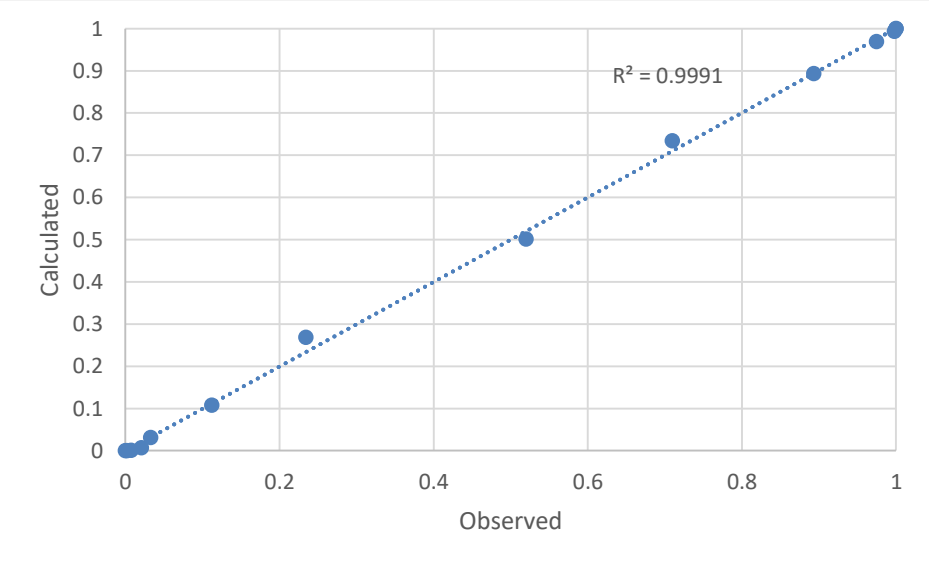


Figure 13: 2nd Quarter Analysis between Calculated and Observed Cumulative Frequency Distributions

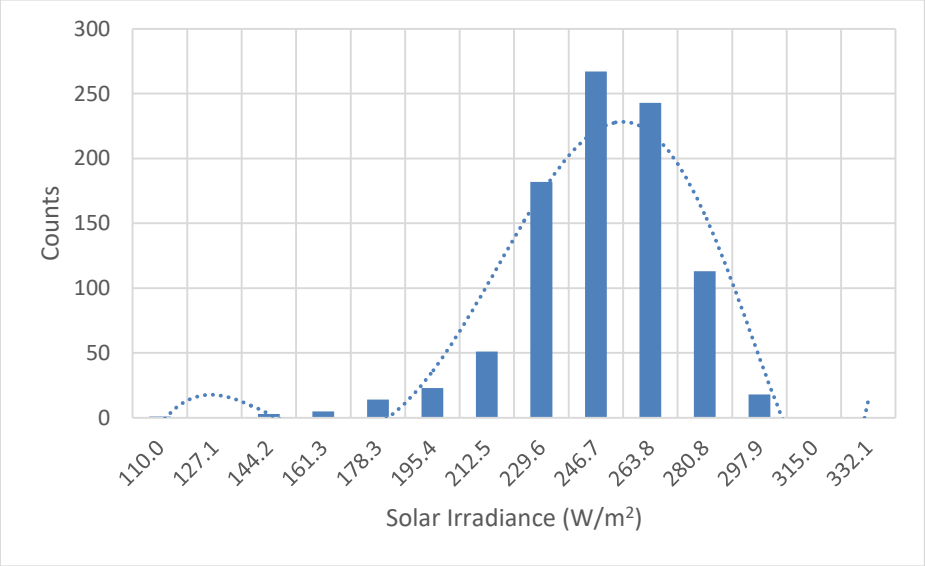


Figure 14: Histogram of the Frequency, 3rd Quarter (1971-1980)

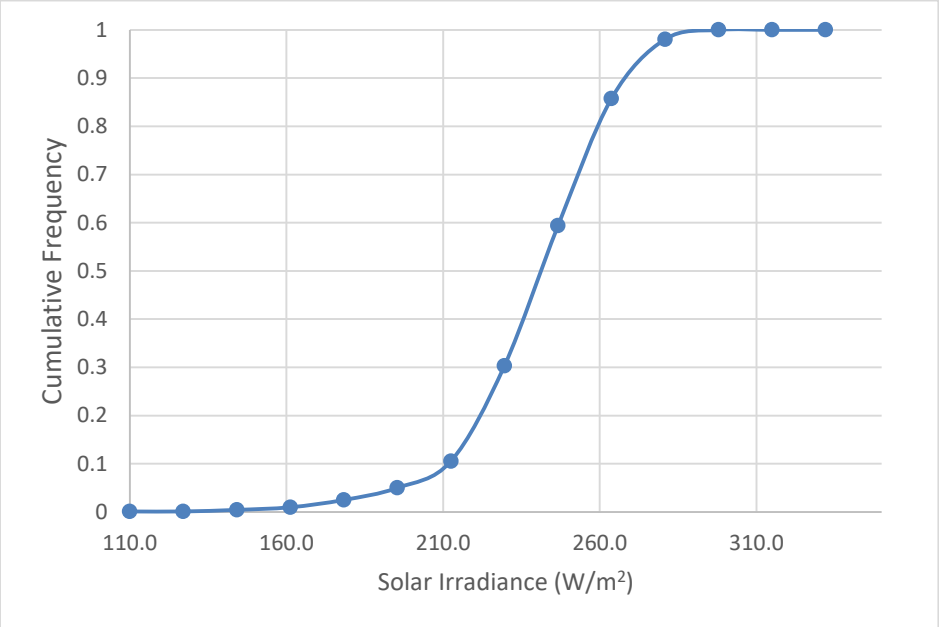


Figure 15: 3rd Quarter Cumulative Frequency Ratio.

The histogram of the calculated solar irradiance of the 46 years solar radiation is shown in Figure 20. It can be observed that about 60% of the data is above the median value of 256.36W/m^2. The frequency graph shows that the solar energy is normally distributed and the value 255.1W/m^2 has the highest number of occurrence at 3,905. Figure 21 shows that 99.96% of the empirical solar irradiance data of Kano, Nigeria fits the normal distribution. The harvested energy yield is presented in Figure 22, and considering a solar panel with the following datasheet: Rated Max Power (Pmax) of 190W, Power Tolerance of +/- 3%, Temperature coefficient of power at -0.45% °C, Normal Operating Temperature Condition (NOCT) of 45, Standard test Conditions (STC) with Air Mass=1.5, 1000W/m^2, Cell Temperature of 25 °C. It can be seen that March has the highest harvested energy at 32.92 kWh and August with the lowest at 25.62 kWh. This indicated that Kano, Nigeria has abundant solar energy that can be harvested throughout the year for electricity generation.

Special Issue on Computing and Communication Technologies
Online: ISSN 2645-2960; Print ISSN: 2141-3959

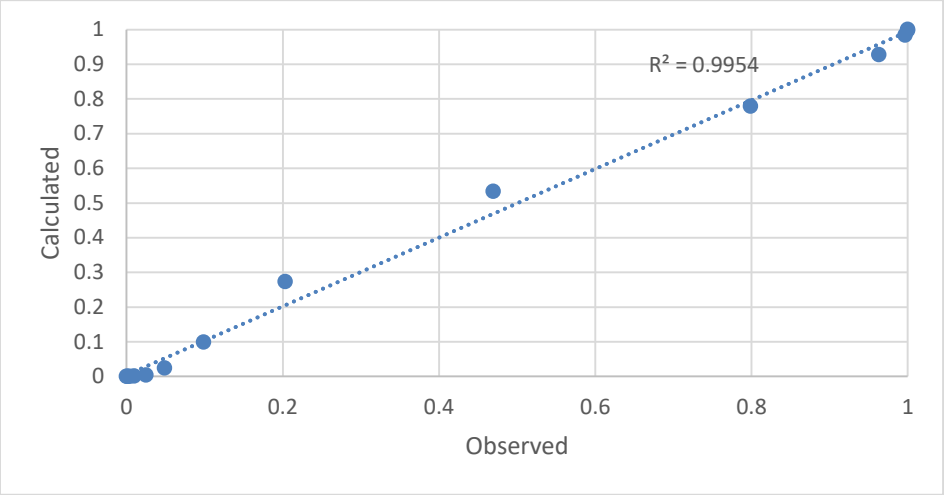


Figure 16: 3rd Quarter Analysis between Calculated and Observed Cumulative Frequency Distributions.

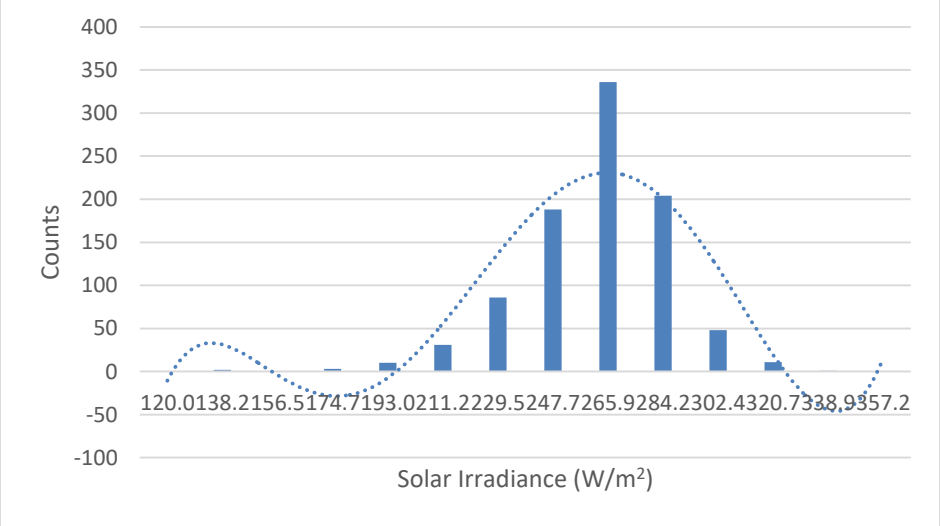


Figure 17: Histogram of the Frequency, 4th Quarter (1971-1980)

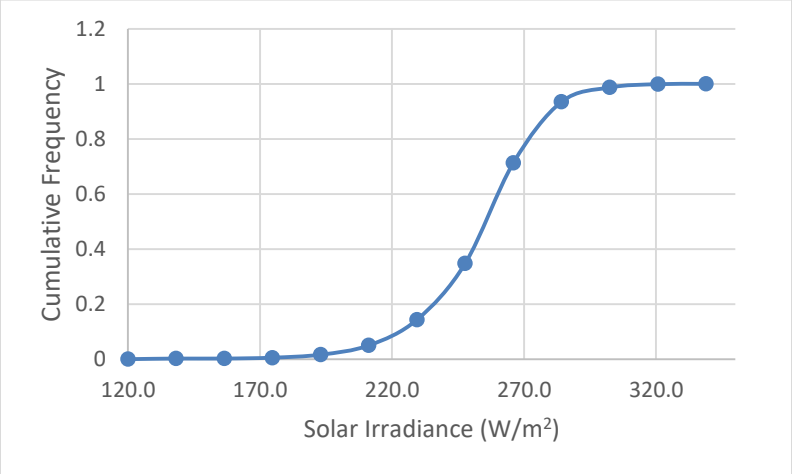


Figure 18: 4th Quarter Cumulative Frequency Ratio.

International Journal of Information Processing and Communication (IJIPC) Vol. 9 No. 1&2 [May, 2020], pp. 184-198
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Online: ISSN 2645-2960; Print ISSN: 2141-3959

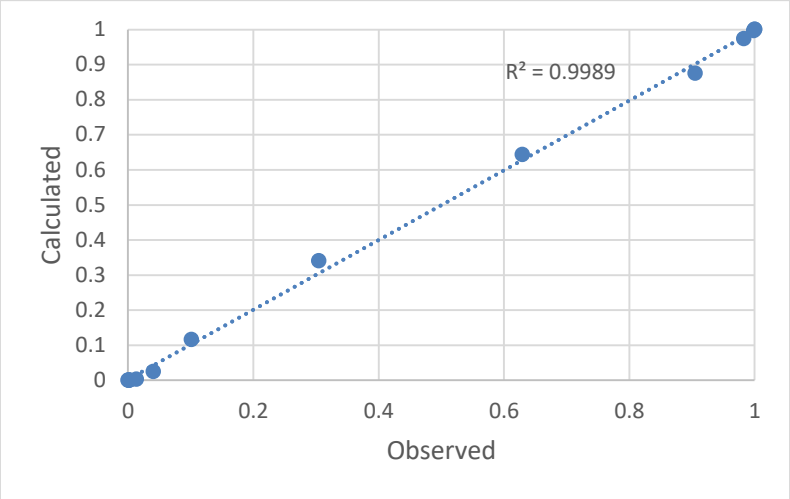


Figure 19: 4th Quarter Analysis between Calculated and Observed Cumulative Frequency Distributions.

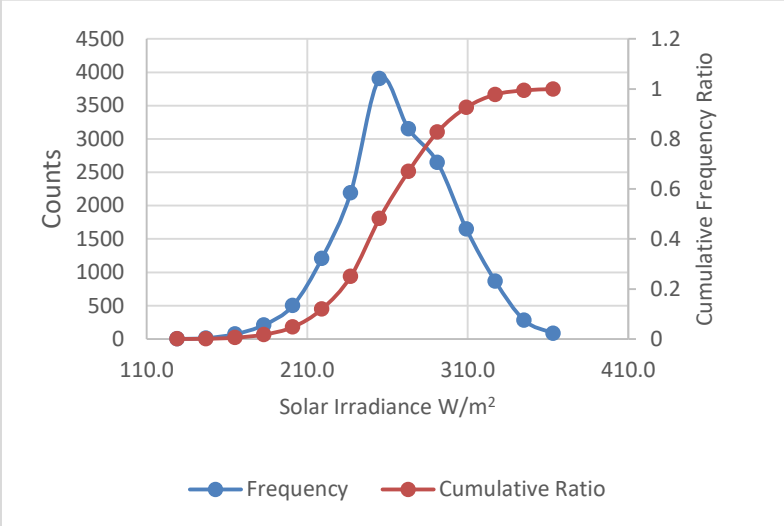


Figure 20: Frequency Histogram and Cumulative Frequency Ratio of Solar Irradiance (1971-2016)

Table 1: Quarterly Analyses

Period	Quarter	Maximum (W/m^2)	Minimum (W/m^2)	Average (W/m^2)
1971-1980	First	360.76	184.44	274.92
1971-1980	Second	352.64	151.96	278.40
1971-1980	Third	295.80	107.88	238.96
1971-1980	Fourth	321.32	120.64	252.88
1981-1990	First	345.68	131.08	262.16
1981-1990	Second	358.44	109.04	273.76
1981-1990	Third	341.04	107.88	242.44
1981-1990	Fourth	312.04	135.72	247.08
1991-2000	First	359.60	128.76	267.96
1991-2000	Second	351.48	151.96	270.28
1991-2000	Third	305.08	76.56	233.16
1991-2000	Fourth	324.80	120.64	248.24
2001-2010	First	368.88	150.80	280.72
2001-2010	Second	352.64	132.24	262.16
2001-2010	Third	302.76	112.52	223.88
2001-2010	Fourth	328.28	52.20	259.84

2011-2016	First	400.20	199.52	301.60
2011-2016	Second	390.92	129.92	248.24
2011-2016	Third	283.04	87.00	212.28
2011-2016	Fourth	364.24	191.4	294.64

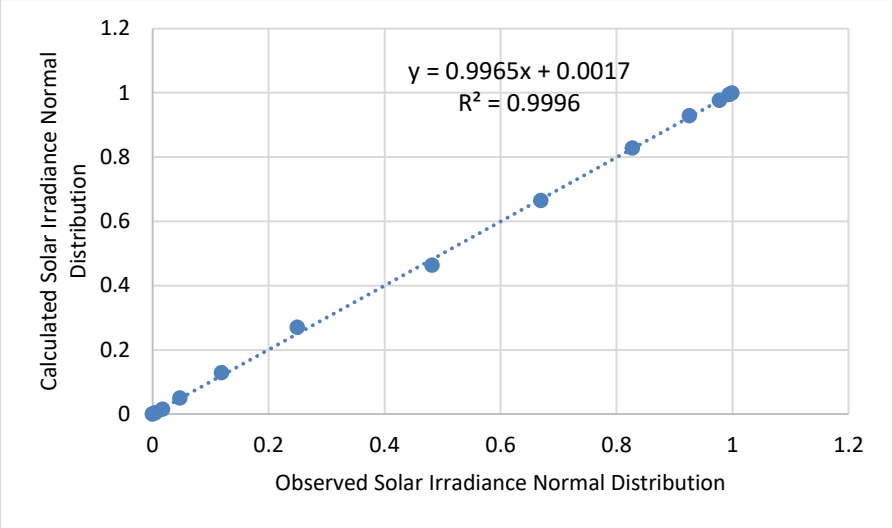


Figure 21: Goodness of Fit Plot of Solar Irradiance (1971-2016)

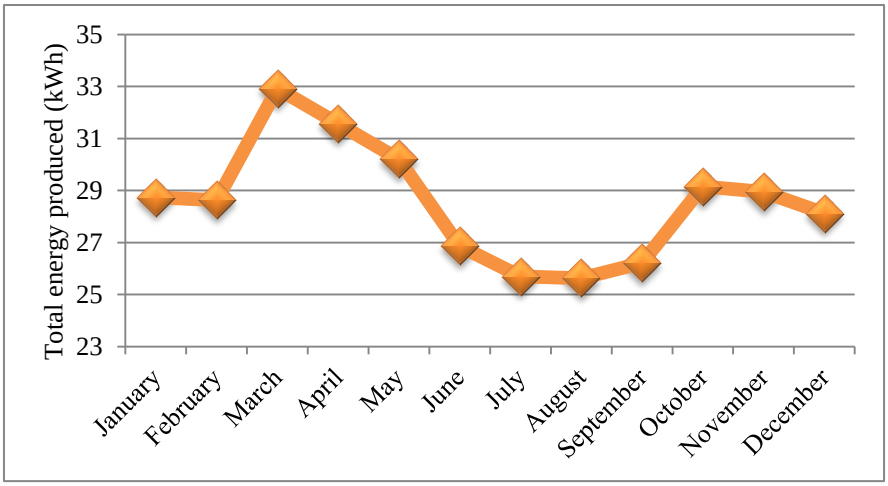


Figure 22: Monthly total produced solar energy

5. Conclusion

Forty-six years of solar radiation data were obtained from the Nigerian Metrological Agency (NiMet). The solar energy potential of Kano state is computed using the statistical method and the energy yield is found for each month by using a solar PV panel having a rated power of 190W. From the analyses, it is shown that the maximum monthly mean solar irradiance is recorded in March at 291.75 W/m^2 and August has the minimum solar energy at 227.05 W/m^2. The total energy produced using the monthly mean solar radiation is calculated with March having 32.92kWh as the highest and August having the lowest at 25.62kWh.

It is therefore pertinent to note that investment in solar energy generation in Kano could yield a return of investment (ROI). Moreover, with government interventions in providing subsidy and creating awareness will enhance the utilization of this efficient renewable energy source. This will, however, improve the safety of the environment by reducing the GHGs that pose a serious threat to the Kano metropolis.

Special Issue on Computing and Communication Technologies
Online: ISSN 2645-2960; Print ISSN: 2141-3959

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