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Statistical and economic analysis of solar radiation and climatic data for the development of solar PV system in Nigeria

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Abstract

The growth in energy demand and global concern about the environment has resulted in the drive towards alternative energy sources and consequently this research concerning solar energy harvesting of radiation received at the earth's surface. Analysis of solar radiation data is an important tool in the accurate designing/sizing of solar Photovoltaic (PV) systems and conducting performance analysis of the system. This paper presents the statistical and economic analysis of solar radiation and climatic data for the development of Solar PV systems in Nigeria. The data for three locations, one from each of the radiation regions in Nigeria were analysed using Minitab 17. The analysis shows that Maiduguri is more viable for solar energy conversion system than the two other locations, and for the same energy demand of 1.1MWh, the peak watt (Wp) of solar PV array required are 619419.27 Wp, 821142.52 Wp and 1219489.32 Wp for Maiduguri, Minna and Port Harcourt respectively. This leads to a difference of $460,984.72 in the total project cost between Maiduguri and Minna for the same energy demand.

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Keywords: Analysis; Energy; Environment; Data; Nigeria; PV system

1. Introduction

Energy is the major key to the economic and social growth of any country, and its importance is increasing with technological and industrial developments in the world. The most widely used resource for electrical energy generation are the fossil fuels but studies have shown that these resources have many negative impacts such as global warming and pollution on environment [1]. The development of solar energy sources has in the recent times taken the centre stage all over the world [2]. This may be attributed to the fact that solar energy is a clean energy source with no negative environment impact [3]. Solar energy can be converted to any form of energy using processes which involves a number of stages [4,5]. The availability of solar energy is an important requirements in the

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Nomenclature

a	Angstrom constant
b	Angstrom constant
H	Monthly average daily global radiation on a horizontal surface (MJ/m^2 day)
H_o	Monthly average daily extra-terrestrial radiation on a horizontal surface (MJ/m^2 day)
I_{sc}	Solar constant (= 1367 W/m^2)
n	The number of days of the year starting from the first of January
S	Monthly average daily number of observed sunshine hours
S_{max}	Monthly mean value of day length at a location
ω_s	The mean sunrise hour angle for the given month
ϕ	The latitude of the site
δ	The solar declination

design and development of its conversion systems [3]. Its applications such as concentrated solar power (CSP) systems, photovoltaic system sizing, and solar drying systems require the knowledge of the availability of global solar irradiance. The intensity of solar radiation per day is usually one of the variables collected by meteorological stations in tropical Africa, Nigeria especially. The magnitude and variability of solar radiation data may have a significant impact on the viability analysis of a solar energy project, its detailed design as well as its economic viability [6,7]. A common approach to quantify and evaluate the solar resource in a given region is the analysis of daily, monthly and annual values of Global Horizontal Irradiation (GHI) [6]. Nigeria was chosen because it has high availability of solar irradiance which favours the development of solar energy conversion system. Fig. 1 shows Nigeria's solar radiation map. The areas under study are indicated on the map by Zone I for Maiduguri, Zone II for Minna and Zone III for Port Harcourt. The thick circle close to Maiduguri indicates the location of study which is in the North-Eastern Nigeria. The utilization of solar energy to economically meet the world's increase energy demand depends on two factors: available solar energy resource and appropriate technology to harness it. Electricity generation from photovoltaic panel is directly affected by solar radiation, this also makes global solar radiation data in a particular region essential for solar energy applications [1,8]. This important data must be available, reliable and accurate for planning, projection and continuity of the system [1,8].

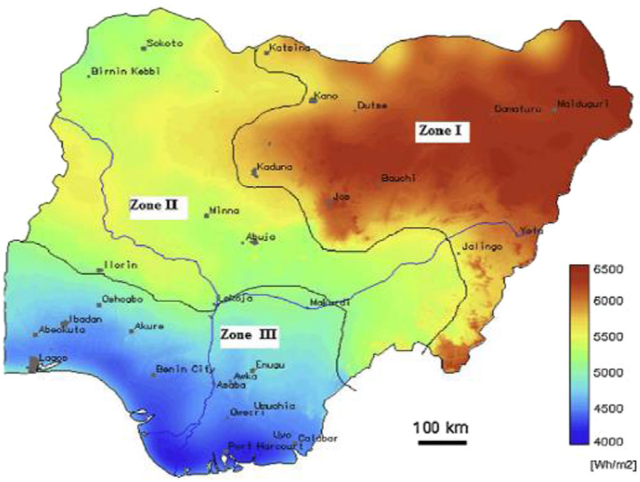

Fig. 1. Nigeria's solar radiation zones [9].

Nigeria has three radiation zones as indicated in Fig. 1. In this study, radiation and climatic data were analysed for three locations which have been carefully selected to comprise one location each from the three radiation zones. This analysis will guide the development of solar PV systems in Nigeria

2. Data and methodology

2.1. Study area

The study areas are Maiduguri in the Northeast, Minna in North-central and Port Harcourt in the South-south of Nigeria. These locations were carefully chosen to represent the three radiation zones in Nigeria. Table 1 presents the geographical location of the cities selected in Nigeria.

Table 1. Details of study area.

Location	Latitude [deg.]	Longitude [deg.]	Altitude [m]	Average annual sunshine hours
Maiduguri	11.8°N	13.2°E	320	2877.5
Minna	9.6°N	6.5°E	299	2435.4
Port Harcourt	4.8°N	7.0E	468	1474.2

Data

The data used in this study are daily average insolation, monthly ambient temperature, relative humidity, and monthly sunshine hours for 11 years (2006–2016) and were collected from the Nigeria Meteorological Agency, Abuja.

2.2. Data analysis

The data were analysed using Minitab 17 and considering some statistical and economic indicators. The frequency distribution was explored with correlation of the solar data by making the solar irradiance a dependent variable and individually making temperature, relative humidity and sunshine hours independent variables. The statistical indicators are R^2 which is the Coefficient of Determination, R (Coefficient of Correlation), Root Mean Square Error (RMSE), Mean Bias Error (MBE) and Mean Absolute Bias Error (MABE). Economic analysis was carried out using an assumed energy demand of 1.1 MWh/day. Existing models were used in the calculation of solar radiation. There are several empirical models which have been developed to predict solar radiation. The most widely used model is the modified Angstrom-type regression equation as presented in Eq. (1).

$$H = H_o\left(a + b\frac{S}{S_{max}}\right) \tag{1}$$

H is the monthly average daily global solar radiation falling on a horizontal surface at a particular location, H_o the monthly average daily extra-terrestrial radiation, S the monthly average daily number of observed sunshine hours, S_{max} the monthly mean value of day length at a particular location and "a", "b" the climatologically determined regression constants to be determined as follows [10]:

$$a = -0.110 + 0.235Cos\emptyset\left(\frac{S}{S_{max}}\right) \tag{2}$$

$$b = 1.449 - 0.553Cos\emptyset - 0.694\left(\frac{S}{S_{max}}\right) \tag{3}$$

The monthly average daily extra-terrestrial radiation, H_o is given by Eq. (4)

$$H_o = \frac{24}{\pi}I_{sc}\left[1 + 0.033cos\left(\frac{360n}{365}\right)\right]\left[cos\emptyset cos\delta sin\omega_s + sin\emptyset sin\delta\left(\frac{2\pi\omega_s}{360}\right)\right] \tag{4}$$

The sunset hour angle, ω_s is given as

$$\omega_s = cos^{-1}\left[-tan\delta tan\emptyset\right] \tag{5}$$

The solar declination, δ can obtained from the following expression:

$$\delta = 23.45\, sin\left(\frac{360\,(n+284)}{365}\right) \tag{6}$$

The accuracy of the calculated global radiation is examined using RMSE, MBE and MABE which are given by Eqs. (7) to (9) [1].

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(c_i - m_i)^2} \tag{7}$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(c_i - m_i) \tag{8}$$

$$MABE = \frac{1}{n}\sum_{i=1}^{n}(|c_i - m_i|) \tag{9}$$

where c_i is the ith calculated global radiation data, m_i is the ith measured global radiation data and n is the number of data. The sunshine hours and the day length S_{max} was used to establish the percentage daily sunshine.

2.3. Economic implication of differences in average solar irradiance

The economic implication of differences in average solar irradiance from one location to another was studied by assuming an energy demand of 1.1 MWh per day designing a complete solar PV system for power supply in each of the locations. The panel generation factor (PGF) and peak watt are can be obtained from Eqs. (10) and (11).

$$PGF = \frac{Average\ solar\ irradiance \times sun\ shine\ hours}{Standard\ Test\ Condition\ Irradiance} \tag{10}$$

$$W_p = \frac{1.3 \times Energy\ demand}{PGF} \tag{11}$$

3. Results and discussion

The group frequency distribution (GFD) histogram of the solar irradiance for the three cities are presented in Figs. 2 to 4. The data for the global daily solar irradiance for the three locations were correlated using relative humidity and ambient temperature as independent variable. Figs. 2 to 4 shows that solar irradiance of more than 200 W/m^2 occurs about 80.1% and 61.1% in Minna and Port Harcourt respectively. A solar irradiance of more than 210 W/m^2 occurs about 84.3% in Maiduguri. The daily average solar irradiance was found to be 266 W/m^2, 237 W/m^2, 208 W/m^2 for Maiduguri, Minna and Port Harcourt respectively. The highest frequency occurs at solar irradiance of 311–330 W/m^2, 261–280 W/m^2 and 221–240 W/m^2 for Maiduguri, Minna and Port Harcourt respectively.

Table 2 shows some statistical indicator, sunshine hours and day length. The percentage sunshine per day is highest in the month of November with 68.6% and the least occurred in the month of August with 32.9%. This result shows that there exist *s* more cloudy sky in the month of August than any other month in the year.

Figs. 5 to 10 shows the correlation between Solar Irradiance and ambient temperature and relative humidity.

The Pearson's correlation coefficient describing the relationship between solar irradiance as the dependent variable and temperature and relative humidity as independent variables are 0.252 and −0.906; 0.880 and −0.928; 0.949 and −0.909 for Maiduguri, Minna and Port Harcourt respectively. The relationship between solar irradiance and ambient temperature in the three location shows a positive linear relationship with the result for Maiduguri coming out weak. The relationship between solar irradiance and relative humidity in the three location shows a negative linear relationship with the result for the three locations showing strong compliance with the linearity between the two parameters.

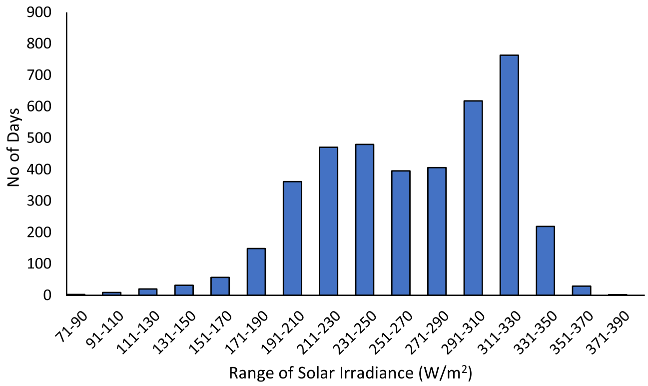

Fig. 2. Grouped frequency distribution histogram of solar irradiance for Maiduguri (2006–2016).

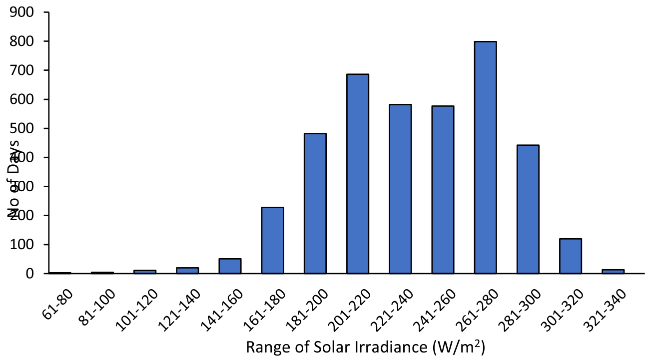

Fig. 3. Grouped frequency distribution histogram of solar irradiance in Minna (2006–2016).

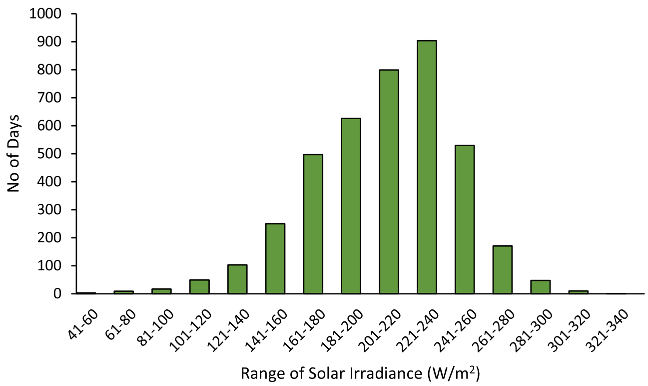

Fig. 4. Grouped frequency distribution histogram of solar irradiance for Port Harcourt (2006–2016).

3.1. Economic implications

To study the economic implications of the differences in the average solar irradiance of the cities, an energy demand of 1.1 MWh per day was assumed. The PGF, Wp and sizing of other components were calculated (Table 3). Eq. (12) shows the total project cost (TPC).

$$TPC = PV + Inverter + Charge\ Controller + Battery + Cable + Land/permitting + Construction/Installation\ costs \tag{12}$$

Table 2. Some statistical indicators.

Month	S	S_{max}	S/S_{max}	RMSE	MBE	MABE
JAN	6.9	11.6	0.595	15.3	−13.3	14.1
FEB	7.6	11.8	0.643	9.9	−7.4	7.9
MAR	6.7	12.1	0.558	17.0	14.5	14.7
APR	7.6	12.3	0.616	19.4	17.1	17.9
MAY	7.5	12.6	0.596	18.4	16.2	15.8
JUN	6.6	12.7	0.525	18.7	16.1	15.9
JUL	4.7	12.6	0.375	9.4	3.2	7.4
AUG	4.1	12.4	0.329	13.6	8.3	10.2
SEP	5.5	12.2	0.456	11.4	−3.3	8.3
OCT	7.5	11.9	0.628	18.8	−10.6	13.3
NOV	8.0	11.7	0.686	21.9	−14.9	18.0
DEC	7.4	11.6	0.641	11.2	1.0	8.5

Table 3. Peak watt and project cost.

Location	11-year daily average solar irradiance (W/m^2)	11-year daily average sunshine hour	Peak watt of solar array required	Total project cost ($)
Maiduguri	266	7.89	619 419.27	3,223,971.60
Minna	237	6.68	821 142.52	3,6849,56.32
Port Harcourt	218	4.89	1 219 489.32	4,595,270.99

There is about 24.6% increase in peak watt and about $460,984.72 increase in total project cost.

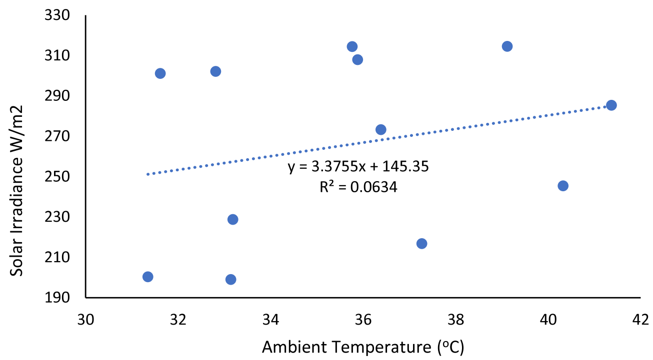

Fig. 5. Fitted regression line of ambient temperature and solar irradiance for Maiduguri (2006–2016).

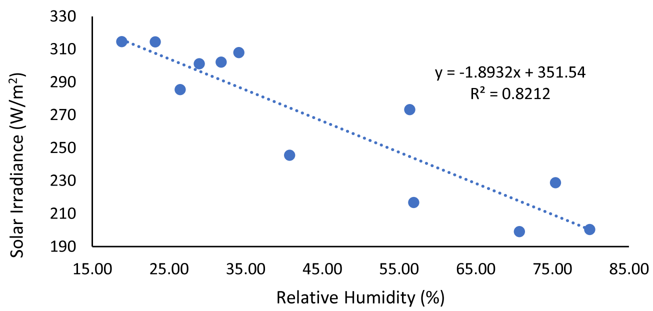

Fig. 6. Fitted regression line of relative humidity and solar irradiance for Maiduguri (2006–2016).

4. Conclusion

In the light of the preceding results, the following conclusions were drawn:

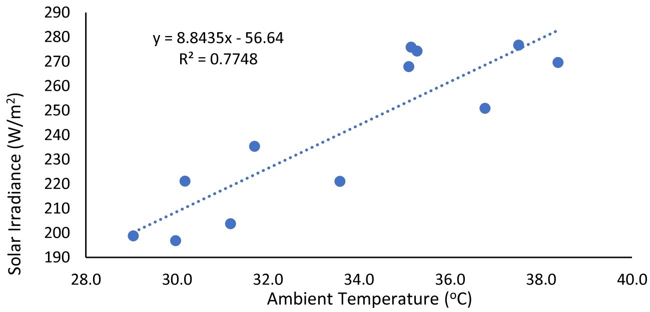

Fig. 7. Fitted regression line of ambient temperature and solar irradiance for Minna (2006–2016).

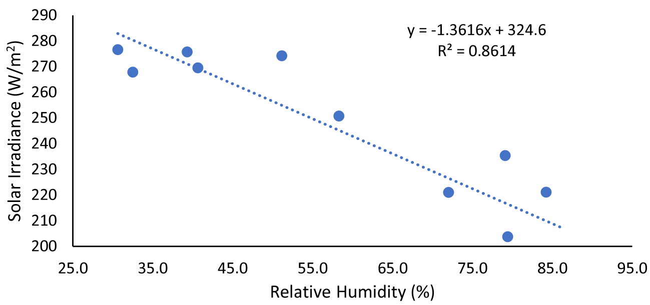

Fig. 8. Fitted regression line of relative humidity and solar irradiance for Minna (2006–2016).

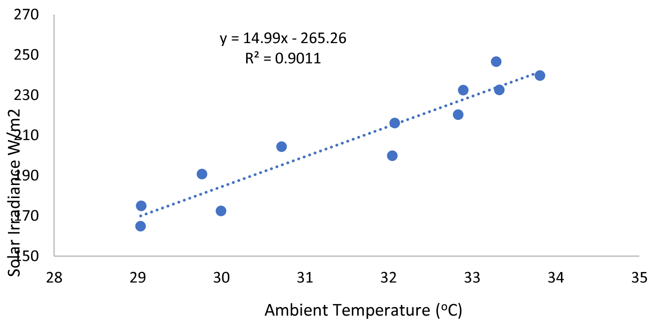

Fig. 9. Fitted regression line of ambient temperature and solar irradiance for Port Harcourt (2006–2016).

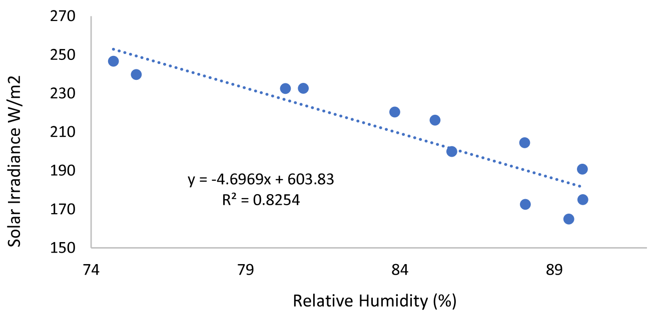

Fig. 10. Fitted regression line of relative humidity and solar irradiance for Port Harcourt (2006–2016).

1. Maiduguri has the highest average daily solar irradiance and Port Harcourt with lowest, therefore Maiduguri is more viable for solar energy system development,

2. 84.3%, 80.1% and 61.1% of the period under study has a solar irradiance of above 200 W/m^2 for Maiduguri, Minna and Port Harcourt respectively.
3. The Project Cost of solar PV system increase with reduction in average solar irradiance and sunshine hours.
4. There is a significant positive linear relationship between solar irradiance and ambient temperature for the three locations because the correlation coefficients are significantly different from zero.
5. Also, there is a significant negative linear relationship between solar irradiance and relative humidity for the three locations because the correlation coefficients are significantly different from zero although negative.

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