Spatial Regression Models For Characterizing The Distribution Of Peak Sun Hours, PV Daily Energy Yield And Storage Battery Capacity For Standalone Photovoltaic (PV) Installations Across Nigeria

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Abstract— **In this paper, spatial regression models for characterizing the distribution of peak sun hours, PV daily energy yield and storage battery capacity for standalone photovoltaic (PV) installations across Nigeria is presented. The prime study data is the Peak Sun Hour (PSH) data obtained from NASA meteorological data for the States in Nigeria. Practically, the PSH is obtained for a one location in each of the 36 States and the Federal Capital Territory (Abuja). Then analytical expressions were presented for computing the PV daily energy yield as a function of the PSH. Also, analytical expressions were presented for the computation of the storage battery capacity required for a given number of days of autonomy. Spatial multiple regression models were developed for estimating the PSH, the daily energy yield and the battery capacity as function of the geo-coordinates (latitude and longitude). Sample numerical example used the data for Bayelsa State as the reference design data. Particularly, Bayelsa has the lowest PSH of 4.13 hours and hence the lowest daily PV energy yield of 3304 Wh for the case study PV array with rated peak power of 1000 W and system efficiency of 80 %. On the other hand, Sokoto State has PSH of 6.24 hours and hence the highest daily PV energy yield of 4992 Wh which is about 51 % above the energy yield in Bayelsa. The higher daily energy yield in Sokoto amounts to low battery storage capacity required to meet the days of autonomy. Essentially, the models presented in this paper will enable PV system designers and installers to select appropriate PV array size and battery capacity that will satisfy the daily energy demand for the given location with the minimal cost. Equally, if an off the shelve standalone PV power supply system is acquired, the models will enable the installer to select the minimum number of batteries that will satisfy the required days of autonomy. This will cut down both initial investment cost and the battery replacement cost which is a major cost factor for PV system.**

Keywords— Photovoltaic, Renewable energy, Spatial regression model, peak sun hour, energy yield, battery capacity, days of autonomy.

I. INTRODUCTION

Your Over the years, there has been tremendous growth in the adoption of solar photovoltaic (PV) power systems across the globe [1,2,3,4]. This has been due to several factors. One, advances in various technologies are driving down the cost of acquisition and maintenance of PV power systems [5,6]. Also, there is growing global demand for the adoption of renewable energy instead of the prevailing fossil fuel energy sources that are adding to the global warming problem [7,8]. Also, in many developing countries like Nigeria, energy supply crisis is a major concern; a large portion of the population does not have access to power supply from the national grid [9,10,11,12]. Also, in most cases, the available power from the national grid is epileptic and in some case of poor quality. As such, most of the citizens and business operators opt for alternative power supply such as diesel generator or any of the renewable energy options [13,14,15].

Although the adoption of solar PV power system is on the increase, the high initial investment cost and the battery replacement cost are the key factors that are slowing down the rate of adoption of PV power system [16,17,18]. As such, designers and experts in solar power systems are looking for ways to address the various cost factors associated with PV power system. In this paper, a spatial regression model is developed which will assist PV system installers to select the minimal number of PV panels and battery that will satisfy the daily energy demand based on the specific climatic condition of the installation site. The study is based on the Peak Sun Hour (PSH) data of locations in each of the States in Nigeria [19,20,21,22]. The geo-coordinates of the locations are used along with the PSH to develop spatial regression models [23] that will determine the PV array energy yield and the battery capacity that will be required to satisfy the energy demand with the required days of autonomy for any given location within Nigeria. Sample numerical example is used to demonstrate the applicability of the models.

Particularly, the annual average PSH data were obtained from NASA meteorological portal for locations in each of the 36 States in Nigeria and Abuja. Then, Bayelsa State which has the lowest PSH value is used as the reference site and PV system with a 1000 Watt rated PV array, 12 V line voltage and 80 % system efficiency and with 3 days storage autonomy was considered. The model was then applied such that when the latitude and longitude for any location within Nigeria is provided, the models can provide the expected PSH , the energy yield for the PV array and the battery capacity required to satisfy the energy supply for the 3 days of autonomy for the PV power supply installed at that location. The results show that the locations with higher PSH values than the reference value require smaller battery capacity to satisfy the days of storage autonomy. In all, the idea presented in this paper will enable PV power system users to avoid over excess spending on the battery and PV array since they can use the models to determine the minimum battery capacity and PV array that can satisfy their energy demand even when the PV power system is an off the shelf product.

II. METHODOLOGY

A. *THE CASE STUDY AREA AND STUDY DATA*

In this study, analytical models that show how annual average meteorological data, along with the photovoltaic (PV) energy yield for various locations across Nigeria are studied. The annual meteorological data and the geo-coordinates of the locations across Nigeria are presented in Table 1. Specifically, the geo-coordinates of one location in each State in Nigeria are obtained using Google Maps. The geo-coordinates are then used in NASA portal [24,25] to download the annual average peak sun hour (PSH) as shown in Table 1. The spatial distribution of the locations (latitude and longitude) is plotted in Figure 1. The spatial models presented in this paper are targeted for locations within Nigeria and based on the Nigerian map showing location of latitudes and longitudes as presented by Evelyn and Allu [26] and also as obtained using Google Maps. Consequently, the edge coordinates of a rectangular area around Nigeria as used in the study are 4.293703, 2.662806 and 13.893423, 14.659876, as shown in Figure 1. Essentially, the spatial models developed in this study are applicable for geo-coordinated within the geo-fenced region marked by the blue rectangle in Figure 1.

Table 1 The annual average meteorological data for the 36 States and Abuja in Nigeria

S/N	State	Latitude	Longitude	Solar Radiation (kW-hr/m^2/day)
1	Abia	5.124362	7.369992	4.71
2	Adamawa	9.215883	12.483067	5.7
3	Akwa Ibom	5.036234	7.91184	4.71
4	Anambra	6.167619	6.773843	4.81
5	Bauchi	10.291452	9.847115	5.77
6	Bayelsa	4.914382	6.25461	4.13
7	Benue	7.73513	8.539126	5.19
8	Borno	11.850952	13.142112	5.9
9	Cross River	4.992057	8.327812	4.28
10	Delta	5.589503	5.808841	4.53
11	Ebonyi	6.33409	8.107843	5.05
12	Enugu	6.453197	7.541863	4.92
13	Edo	6.374894	5.587327	4.66
14	Ekiti	7.607103	5.252601	4.94
15	Gombe	10.286053	11.174129	5.77
16	Imo	5.491316	7.0106	4.71
17	Jigawa	12.570862	8.937273	6.04
18	Kaduna	10.519388	7.39628	5.64
19	Kano	12.035116	8.521868	6.04
20	Katsina	12.984339	7.627888	5.94
21	Kebbi	12.453605	4.193382	5.98
22	Kogi	7.807129	6.731396	5.1
23	Kwara	8.491979	4.553016	5.16
24	Lagos	6.558871	3.348704	4.74
25	Nasarawa	8.348792	7.69017	5.36
26	Niger	9.592227	6.515928	5.49
27	Ogun	7.148177	3.36977	4.91
28	Ondo	7.106686	4.837432	4.89
29	Osun	7.763949	4.521798	4.89
30	Oyo	7.356947	3.945112	4.91
31	Plateau	9.934549	8.897799	5.47
32	Rivers	4.832462	7.015553	4.21
33	Sokoto	13.03403	5.231762	6.24
34	Taraba	8.894728	11.381261	5.57
35	Yobe	11.725131	11.622642	5.96
36	Zamfara	12.177145	6.665446	6.01
37	Abuja (FCT)	9.072591	7.39505	5.45

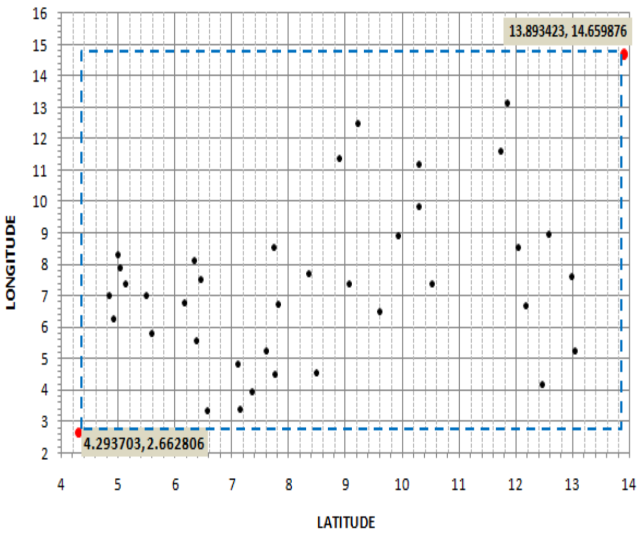

Figure 1: The spatial distribution of the locations (latitude and longitude) along with the edge coordinates of a rectangular area around Nigeria as used in the study

B. *THE DAILY ENERGY YIELD OF THE PV ARRAY AND THE REQUIRED BATTERY CAPACITY*

The daily energy output ($\mathbf{E_{dop}}$) of a solar PV array with rated peak power ($\mathbf{P_{pvpk}}$) operating with system efficiency (η_{sys}) and a climatic condition with Peak Sun Hour (PSH) given by [19, 27,28,29];

$$\mathbf{E_{dop}} = (\mathbf{P_{pvpk}})(\eta_{sys})(\mathbf{PSH}) \quad (1)$$

Where daily energy output ($\mathbf{E_{dop}}$) is in Wh/day, rated peak power ($\mathbf{P_{pvpk}}$) is in W, Peak Sun Hour (PSH) is in hours and system efficiency (η_{sys}) is in percentage of fraction where $\mathbf{0} < \eta_{sys} \leq \mathbf{1}$. In reality, the system efficiency (η_{sys}) is affected by many factors such as the choice of system components (cable, inverter, battery etc) and environmental factors such as the ambient temperature and dust. However, in this study, to simplify the model, a uniform system efficiency (η_{sys}) is used for all the different locations considered in the study. Also, the system efficiency as used in the models can also be referred to as the performance ratio.

In this study, a PV array with rated peak power ($\mathbf{P_{pvpk}}$) of 1000W and operating with system efficiency (η_{sys}) of 80 % is used. Hence, the daily energy yield of the PV array in Wh is given as;

$$\mathbf{E_{dop}} = (\mathbf{1000W})\left(\frac{\mathbf{80}}{\mathbf{100}}\right)(\mathbf{PSH}) = \mathbf{800}(\mathbf{PSH}) \quad (2)$$

Assume the daily load demand $\mathbf{E_{dLD}}$ is just satisfied for a reference Peak Sun Hour ($\mathbf{PSH_{RF}}$) such that;

$$\boldsymbol{E_{dLD}} = (\boldsymbol{P_{pvpk}})(\eta_{sys})(\mathbf{PSH_{RF}}) = \mathbf{800}(\mathbf{PSH_{RF}}) \quad (3)$$

For the given case study,

$$\boldsymbol{E_{dLD}} = (\boldsymbol{P_{pvpk}})(\eta_{sys})(\mathbf{PSH_{RF}}) = \mathbf{800}(\mathbf{PSH_{RF}}) \quad (4)$$

Importantly, the actual daily energy yield is $\boldsymbol{E_{dop}}$ and the required daily energy demand is $\boldsymbol{E_{dLD}}$. Then, the normalized energy deficit or excess energy ($\boldsymbol{E_{ND/E}}$) produced per day is given as;

$$\boldsymbol{E_{ND/E}} = \left(\frac{\boldsymbol{E_{dop}} - \boldsymbol{E_{dLD}}}{\boldsymbol{E_{dLD}}}\right)\mathbf{100}\ \% \quad (5)$$

If $\boldsymbol{E_{ND/E}}$ is positive it means excess energy is produced more than the required energy for the climatic condition with the given Peak Sun Hour (PSH). However, if $\boldsymbol{E_{ND/E}}$ is negative it means less energy is produced as compared to the required daily energy demand for the climatic condition with the given Peak Sun Hour (PSH).

The required battery capacity ($\mathbf{C_{bat}}$)in Ampere hour (Ah) for the system with number of autonomy days (day with minimum solar irradiation) denoted as $\mathbf{N_a}$, rated voltage of the system ($\boldsymbol{V_{sys}}$) in Volts and the maximum allowable level of discharge (DOD) is given as [19,30];

$$\boldsymbol{C_{bat}} = \frac{\boldsymbol{N_a}(\boldsymbol{E_{dLD}})}{(\mathbf{DoD})\boldsymbol{V_{sys}}} \quad (6)$$

For the case study, three days ($\mathbf{N_a} = \mathbf{3}$) autonomy is used , system line voltage ($\mathbf{V_{sys}} = \mathbf{12}$) and maximum allowable level of discharge (DOD =60 %), hence;

$$\boldsymbol{C_{bat}} = \frac{3(\boldsymbol{E_{dLD}})}{(\mathbf{0.6})\mathbf{12}} = 0.416667(\boldsymbol{E_{dLD}}) = 333.333\ (\mathbf{PSH_{RF}}) \quad (7)$$

The operating or actual battery capacity ($\boldsymbol{C_{batAct}}$) for any given Peak Sun Hour (PSH) is given as

$$\boldsymbol{C_{batAct}} = \frac{\boldsymbol{N_a}(\boldsymbol{E_{dLD}}) - \boldsymbol{N_a}(\boldsymbol{E_{dop}} - \boldsymbol{E_{dLD}})}{(\mathbf{DoD})\boldsymbol{V_{sys}}} = \frac{\boldsymbol{N_a}(2(\boldsymbol{E_{dLD}}) - \boldsymbol{E_{dop}})}{(\mathrm{DoD})V_{sys}} = \frac{N_a\left((\mathrm{P_{pvpk}})(\eta_{sys})(2(\mathrm{PSH_{RF}}) - \mathrm{PSH})\right)}{(\mathrm{DoD})V_{sys}} \quad (8)$$

$$C_{batAct} = \frac{3\left((1000\ \mathrm{W})(0.8)(2(\mathrm{PSH_{RF}}) - \mathrm{PSH})\right)}{(0.6)12} = 333.3333\left((2(\mathrm{PSH_{RF}}) - \mathrm{PSH}\right)\right) \quad (9)$$

Also, the normalized battery capacity deficit or excess battery capacity ($C_{batND/E}$) is given as;

$$C_{batND/E} = \left(\frac{C_{batAct} - C_{bat}}{C_{bat}}\right) 100\ \% \quad (10)$$

If $C_{batND/E}$ is positive it means additional battery capacity is required to satisfy the storage requirement of the system for the climatic condition with the given Peak Sun Hour (PSH). However, if $E_{ND/E}$ is negative it means less battery capacity is required to satisfy the storage requirement of the system for the climatic condition with the given Peak Sun Hour (PSH).

III. SIMULATIONS RESULTS, MODEL DEVELOPMENT AND DISCUSSIONS

First, based on the study data in Table 1 and given that the PV energy yield and the battery capacity are expressed as function of the PSH, then a multiple linear regression models is developed for estimating the PSH across Nigeria based on the latitude and longitude of the location. Next, based on the study data in Table 1 and the analytical expressions in Equations 1 to 15, the following parameters are computer;

i. The actual daily energy yield is E_{dop}
ii. The required daily energy demand is E_{dLD}
iii. The normalized energy deficit or excess energy ($E_{ND/E}$) produced per day
iv. The required battery capacity ($\mathrm{C_{bat}}$)
v. The actual battery capacity (C_{batAct}) for any given Peak Sun Hour (PSH)
vi. The normalized battery capacity deficit or excess battery capacity ($C_{batND/E}$)

Then, multiple linear regression models is developed for estimating the actual daily energy yield (E_{dop}) as a function of latitude and longitude. Also, multiple linear regression models is developed for estimating the actual battery capacity (C_{batAct}) as a function of latitude and longitude. Furthermore, for each of the models, the root mean square error (RMSE), Average absolute percentage prediction error (AAPPE) and the maximum absolute percentage prediction error (MAPPE) are computed.

A. RESULTS AND MODEL FOR THE PEAK SUN HOUR (PSH)

The bar chart of the actual and the predicted Peak Sun Hours (PSH) for the States in Nigeria is shown in Figure 2. First, the case study data was sorted in ascending order based on the actual PSH of the geo-coordinates. Next, the Microsoft Excel Solver is used to derive the coefficients of the parameters in a multiple regression model that can estimate the PSH with the minimum root mean square error (RMSE). The model obtained for estimating the PSH as a function of the latitude (LAT) and longitude (LON) within Nigeria is given as;

$$\mathrm{PSH} = 0.205589476\ (\mathrm{LAT}) + 0.031538797(\mathrm{LON}) + 3.261814358 \quad (16)$$

The model has RMSE value of 0.132480517 h, average absolute percentage prediction error (AAPPE) 2.088229 %and maximum absolute percentage prediction error (MAPPE) of 8.218461 %.

The implication of the model is that within the geo-fenced region (marked by the coordinates 4.293703, 2.662806 and 13.893423, 14.659876) which covers the locations in Nigeria, the PSH can be estimated with ±8% error margin. Then the PSH can be used to determine the PV energy yield and required battery capacity for a solar power system installed at that given geo-location.

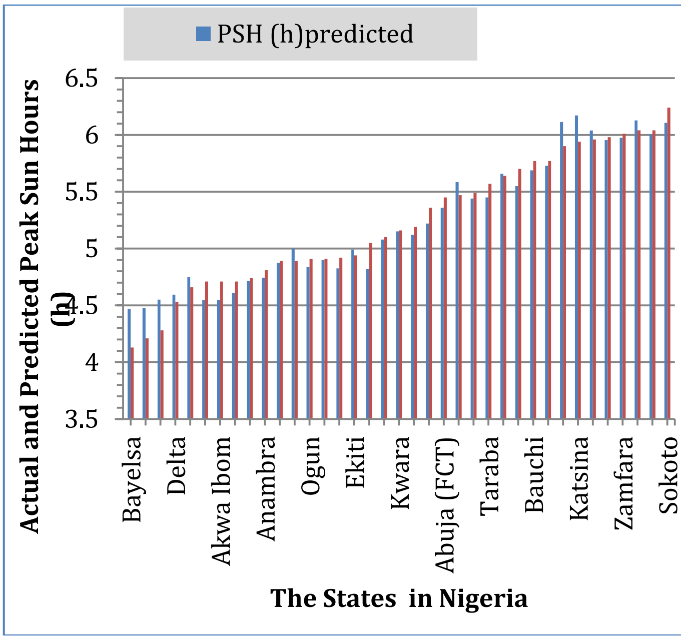

Figure 2 The actual and the predicted Peak Sun Hours for the States in Nigeria

B. *RESULTS AND MODEL FOR THE PV ENERGY YIELD*

The bar chart of the actual and the predicted daily PV energy yield for the States in Nigeria is shown in Figure 3. First, the actual daily PV energy yield is computed based on the case study data which has been sorted in ascending order based on the actual PSH of the geo-coordinates. Next, the Microsoft Excel Solver is used to derive the coefficients of the parameters in a multiple regression model that can estimate the daily PV energy yield with the minimum root mean square error (RMSE). The model obtained for estimating the daily PV energy yield as a function of the latitude (LAT) and longitude (LON) within Nigeria is given as;

$$E_{dop} = E_{(dop)predicted} = 164.4714742\ (LAT) + 25.23033319\ (LON) + 2609.459013 \quad (11)$$

The model has RMSE value of 105.9844139 Wh per day, average absolute percentage prediction error (AAPPE) 2.088214 %and maximum absolute percentage prediction error (MAPPE) of 8.21854 %.

In this study, Bayelsa State has the least PSH so it was selected as the reference PSH (PSHref). In essence, the daily energy yield from the PV installed in Bayelsa becomes the reference or required daily energy demand. The normalized energy deficit or excess energy ($E_{ND/E}$) produced per dayis then computed with reference to the daily energy yield from the PV installed in Bayelsa. The bar chart of the normalized energy deficit or excess energy ($E_{ND/E}$) produced per day for the States in Nigeria is shown in Figure 4.

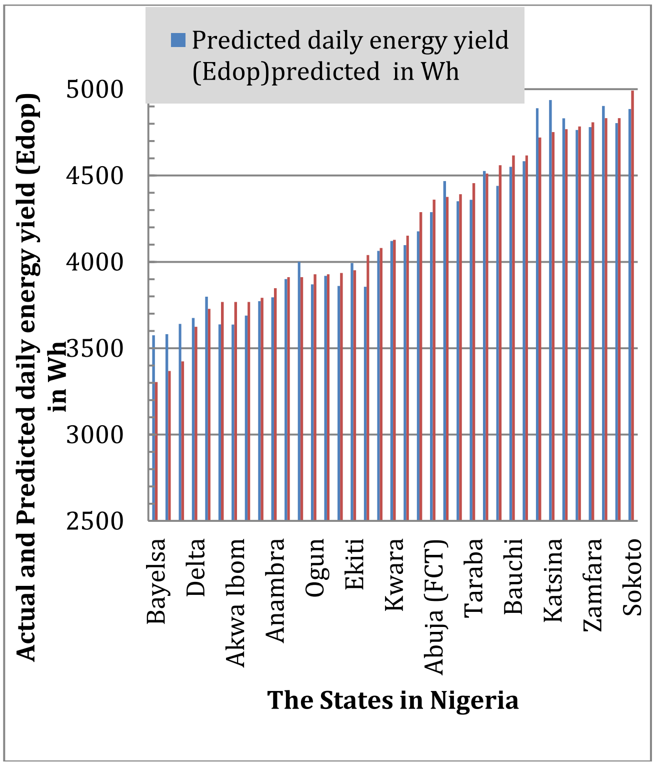

Figure 3. The bar chart of the actual and the predicted daily PV energy yield for the States in Nigeria

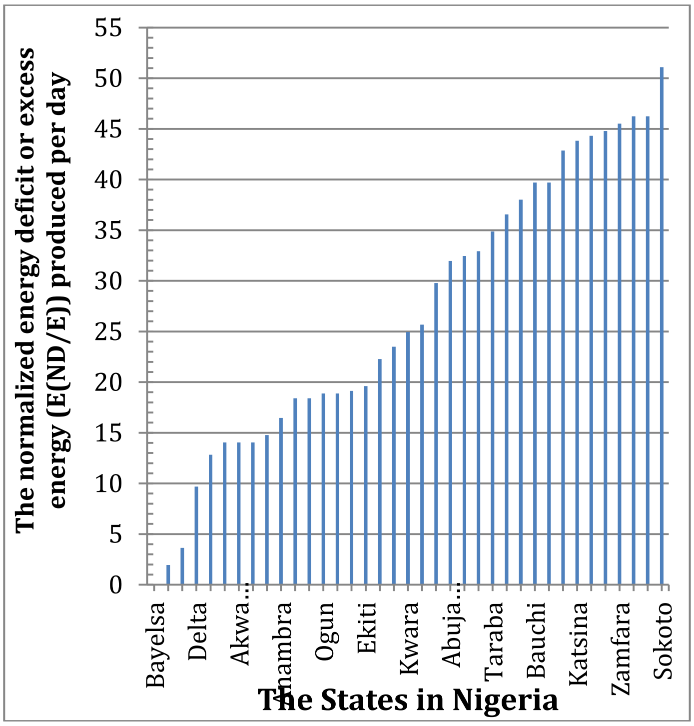

Figure 4. The bar chart of the normalized energy deficit or excess energy ($E_{ND/E}$) produced per day for the States in Nigeria

The implication of the model is that within the geo-fenced region which covers the locations in Nigeria, a PV array rated at 1000 W peak power will yield about 3304 Wh per day in Bayelsa State and about 4885.18424 Wh per day in Sokoto State . This is about 51 % excess power generation from the same PV array for Sokoto State when compared to

the reference required energy yield in Bayelsa State. The implication is the more energy will be produced for the same PV installation in Sokoto and this will lead to lower unit cost of solar energy in Sokoto State. Also, the higher energy output in Sokoto means that a smaller battery capacity will be required to satisfy the days of autonomy required by the system. This will lead to further reduction in the installation cost of the PV power system.
The bar charts in Figure 3 shows the daily energy yield for the various States in Nigeria while the bar chart in Figure 4 shows the excess energy yeilr for each of the State in respect of the reference State (Bayelsa State) energy yield.

C. RESULTS AND MODEL FOR THE BATTER CAPACITY

The bar chart of the actual and the predicted battery capacity for the States in Nigeria is shown in Figure 5.

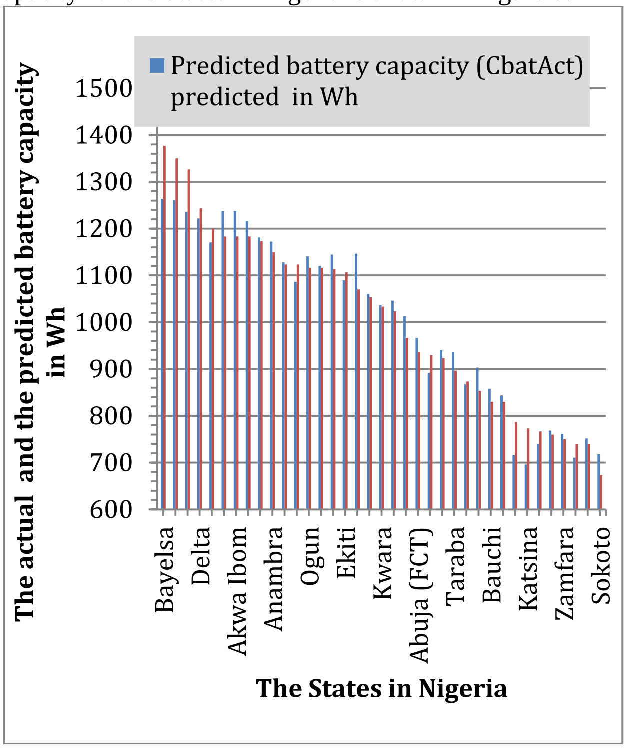

Figure 5 The bar chart of the actual and the predicted battery capacity for the States in Nigeria

The actual battery capacity is computed based on the case study data which has been sorted in ascending order based on the actual PSH of the geo-coordinates. Next, the Microsoft Excel Solver is used to derive the coefficients of the parameters in a multiple regression model that can estimate the battery capacity with the minimum root mean square error (RMSE). The model obtained for estimating the battery capacity as a function of the latitude (LAT) and longitude (LON) within Nigeria is given as;

C_{batAct}) = -68.5290658 (LAT) + -10.512059 (LON) + 1666.046552(12)

The model has RMSE value of 44.16012828 Wh per day, average absolute percentage prediction error (AAPPE) 2.088209 % and maximum absolute percentage prediction error (MAPPE) of 8.21858 %.
In this study, the battery capacity in Bayelsa is the reference or required battery capacity for the case study. The normalized battery capacity deficit or excess battery capacity ($C_{batND/E}$) is then computed with respect to the reference battery capacity of Bayelsa. The bar chart of the normalized battery capacity deficit or excess battery capacity ($C_{batND/E}$) for the States in Nigeria is shown in Figure 6.
The implication of the model is that within the geo-fenced region which covers the locations in Nigeria, the battery capacity required for 3 days of autonomy and with daily load demand of 3304 Wh per day is 1376.6653 AH in Bayelsa State . In view of the higher PSH in Sokoto, the battery capacity required for the same daily energy demand and days of autonomy is about 49 % of the one in Bayelsa. That means there is about 51% reduction (as shown in Figure 6) in the required battery capacity for Sokoto State when compared to that of Bayelsa State. In essence, in Sokoto State, smaller battery capacity will be required to satisfy the days of autonomy required by the system. This will lead to significant reduction in the installation cost of the PV power system, since battery is a major contributor to the cost of PV power systems.

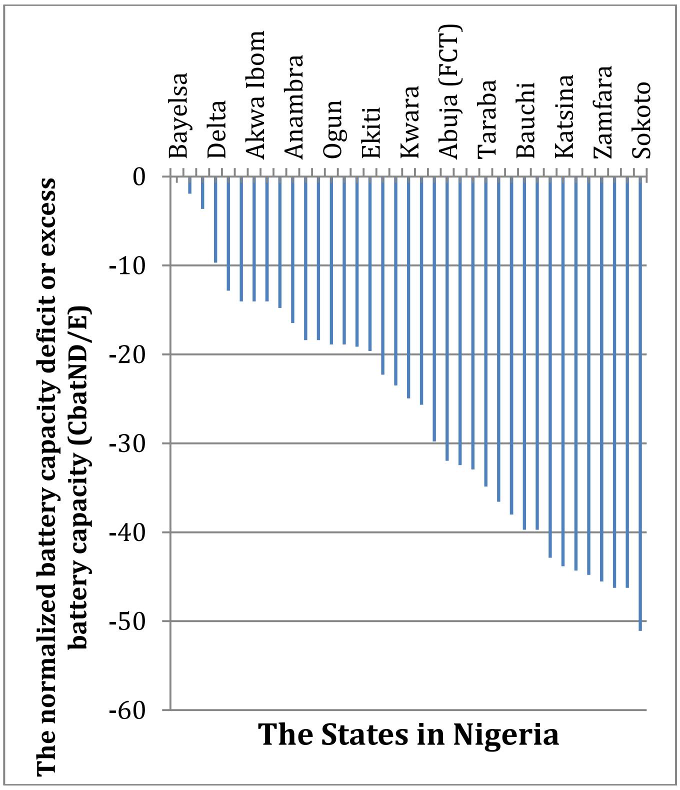

Figure 6 The bar chart of the normalized battery capacity deficit or excess battery capacity ($C_{batND/E}$) for the States in Nigeria

IV . CONCLUSION

In this paper, regression models that use geo-coordinates (latitude and longitude) to determine the spatial distribution of peak sun hours (PSH), the daily energy output of photovoltaic array and the required battery capacity for a given days of autonomy are developed. The models are based on the solar radiation data obtained from NASA portal for the locations in the various State in Nigeria. The Microsoft Excel Solver tool was used to determine the coefficients of the model parameters which gives minimum root mean square error. The models will assist PV system designers for Nigerian climatic condition to select appropriate PV array size and battery capacity that will meet the daily energy demand of the load at minimal cost for the individual States in Nigeria. The results showed that for any given power system, the battery storage capacity required for any given days of autonomy need to be adjusted with respect to the prevailing solar radiation data in the installation site. This will help the designers to cut cost; both installation and maintenance cost as well as the unit energy cost of the system.

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