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# Software development for the design of solar energy photovoltaic systems for rural and urban communities in Nigeria

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**ABSTRACT**

***Development of solar photovoltaic (PV) systems is expected to be preceded by accurate pre-installation design. The output power generated and the ability of such a system to meet load demand by a PV system greatly depends on the accurate sizing of its components. This paper developed a new software using JAVA programming language to execute the fundamental equations employed in the development of PV systems. The evaluation metrics employed to assess the performance of this newly developed software include accurate determination of total power of PVs, number of solar panels required, capacity and number of batteries required, size of charge controller and inverter rating, optimum tilt angle, and cable size among others. The software developed was implemented on different load demands to obtain accurate values for the above performance metrics using Ogun State's average daily sunshine and temperature. The results obtained were found not only to be economically viable but also to provide sufficient information about the PV project design before the installation stage. The use of this solar planner software for the design of PV systems gives an effective, faster, cost-effective, and reliable accurate sizing and PV system's improved performance in the Nigerian solar business market.***

## INTRODUCTION

The level of a country's growth can be evaluated by the degree of utilization of energy by its population. Population growth, industrial development as well as urban sprawl lead to growth in energy demand (Ebenezer and Abeeku, 2013; Ibrahim *et al.*, 2013; Ohunakin *et al.*, 2014; Raquibul *et al.*, 2016). Of all the conventional and non-conventional power generation sources that are being explored, only the solar source-photovoltaic system is the most promising; but requires a huge initial capital investment. Solar source-photovoltaic system is a system of obtaining energy from the power of the heat from the sun. This system is a renewable source of energy and the commonest means to harness this energy is by the use of photovoltaic (PV) panels. The dependability of solar PV systems leads to their usefulness in different areas like agriculture, industries, businesses and residential (Olabode *et al.*, 2021).

Many nations in Africa do not have stable electricity and as of 2010, the rate of electrification in African countries is 25% according to the International

Energy Agency, with Nigeria being the second worst electricity supply nation. This is so despite the fact that Africa is the greatest recipient of solar energy, which is the world's richest energy source (Ebenezer andAbeeku, 2013). Nigerians still don't have sufficient electricity and the little supply is not constant. The part of Nigeria tied to the grid only has power for just below 40% of the time based on the Nigerian Energy policy report. This inadequacy and unreliability of power supply has prevented a lot of companies from breaking even due to less production or some even closing down totally (Raquibul *et al.,* 2016).

A considerable number of recent studies give an insight into how supplementation of rural electrification with solar photovoltaic systems results in great benefits such as improvement in health facilities, better health from cleaner air and better electrification (Tarujyoti, 2012). Despite this, the performance of the system of generating solar power is still being hampered due to so many factors like tilt angle, irradiation, shading and inaccurate sizing of the components that make up the system (Olabode *et al.,* 2024), such as battery bank, inverter size, charge controller size, cable size and size of the PV array. All these factors largely affect the output of the system in terms of its ability to meet the load demand which in turn constitute unreliability of the system.

These components need to be accurately sized and catered for during the design stage and failures to accurately size the components of PV systems have been the major challenges in Nigeria's PV solar business market. The consequence of this, results in unsatisfactory output performance, hence, the need for customized software to aid accurate sizing and components selection. However, various types of PV installations are obtainable nowadays which comprise on-grid systems and off-grid systems both containing battery storage systems made up of battery or without battery storage system; mixtures of a PV system and any other source of energy (the mixtures being referred to as hybrid systems) are progressively getting more attention.

The basis of any PV system in electrical design is the accurate sizing and rating of the components needed to meet a certain performance objective (Dinesh *et al.,* 2014; Gurupira and Amp; Rix, 2017; Kebaïli and Benalla, 2015; Mahendra *et al.,* 2010; Majid *et al.,* 2013; Odigwe *et al.,* 2013). Designing a solar photovoltaic system involves some processes that require accuracy such as computing the total load demand, determination of battery capacity needed to meet the load demand, PV arrays required and charge controller sizing.

Hence, there is a need for software that can accurately carry out the sizing of the aforementioned components and estimate the cost of installation. A substantial number of PV software have been used in the literature which include Photovoltaic System (PV Syst) is PC-based software (Dinesh *et al.,* 2014), Hybrid Optimization Models for Electric Renewables (HOMER)(Majid *et al.,* 2013; Olabode *et al.,* 2024), Photovoltaic Solar Expert (PV expert)(Chel *et al.,* 2009; Eod *et al.,* 2012; Haars, 1997; Kaveri and Sudhakar, 2016; Kebaïli and Benalla, 2015), HOGA (Kebaïli and Benalla, 2015) among others.

The software assists technicians and engineers in the design stage of the solar system installation to accurately determine the quantities and size of all the parameters needed to get maximum yield. These parameters include the total power, design energy, capacity of the solar panel required, number of solar panels required, capacity and number of batteries required, size of charge controller and inverter rating needed for the design, optimum tilt angle and cable size (Amole *et al.,* 2023; Chen *et al.,* 2022; Lee and Shepley, 2020; Ajewole *et al.,* 2020; Onu *et al.,* 2022; Østergaard *et al.,* 2021; Sina and Adeel, 2021).

In this paper, solar photovoltaic system software is developed that can provide useful information on the size and quantity of the PV system's components as well as the installation cost of the PV system. The graphic interface developed is friendly and easy to use with little or no guide. Another astonishing strength of this paper encompasses capability for the design considerations, easy-to-replicate process flow charts and detailed mathematical equations.

## METHODOLOGY

### Method

The development of the software was carried out in stages which included a user-friendly data input interface as well as a calculation algorithm to process the input and give a meaningful result in the output interface. The procedure followed is outlined in the flow of process executions in the flow chart for the proposed software, as presented in Figure 1.

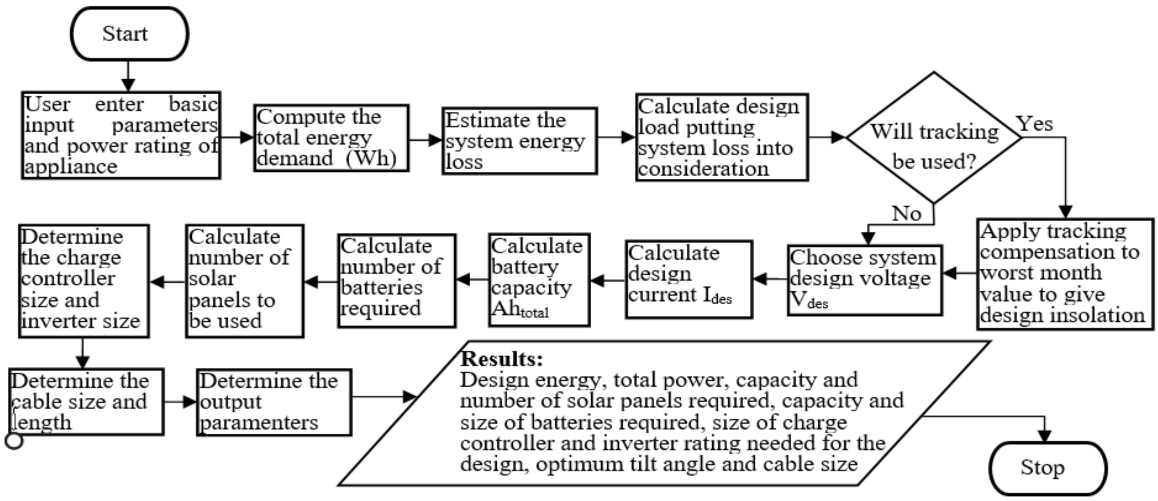


Figure 1. Process flowchart of the Proposed Software

The flow chart is in line with the steps followed in the design; the inputs are first entered into the software which are the power ratings of all appliances and their respective number of hours of usage, average monthly insolation data, autonomy, and peak wattage of a single module, efficiencies of cables, inverter, panel and the desired depth of discharge (DOD). Having obtained all the inputs, the software will process it according to the flow chart and yield the following output: the total load demand of the building, the total battery capacity, the number of batteries and their interconnections, the number of solar panels required, the inverter size, the charge controller size, and the cable size. The steps contained in the flow chart are:

Step 1: Obtaining the basic input parameters such as average sunshine hour per day,
peak watt power of the solar panel to be used etc.

Step 2: Computation of the total energy demand

Step 3: Estimation of energy losses in the system

Step 4: Calculation of the design load of the system with the use of losses and the load factor.

Step 5: Choosing the design voltage of the system for the system (mostly the system's maximum DC voltage).

Step 6: PV array Sizing

Step 7: Storage battery Sizing

Step 8: Charge controller Sizing

Step 9: Sizing of the Wire and cable

Step 10: Sizing of the Inverter

Step 12: Show results obtained

Step 13: Generate result in text format

***Load Audit Calculation***

The approach presented in this paper is a stepwise approach that is based on daily or monthly average sunshine hours with the assumption that the energy demand is constant. The load data, hours of usage and sunshine data are collected through the input interface. The first step in the design of a solar PV system is to obtain the daily consumption of energy of the electrical appliances to be powered by the PV system. Equation (1) gives the linear relationship between the daily energy demand and time (Haars, 1997).

$$E_T = t \times \sum_i^n P_i \quad (1)$$

$$\sum_i^n P_i = P_1 + P_2 + P_3 \quad (2)$$

$$E_L = E_T + XE_T \quad (3)$$

Where $P_i$ is the power of the ith appliances**,** $E_i$ is the energy demand of the $i^{th}$ appliances, $\sum_i^n P_i$ represents the total power rating of all the appliances, t represents the proposed hours of the appliances' usage per day, $E_T$ is the appliances' total energy per day, $E_L$ represents total daily energy demand after the inclusion of the load factor, where X is the load factor. The solar panel's anticipated generated quantity of energy is denoted by $E_{DES}$ and given by:

$$E_{DES} = \frac{E_L}{\eta_{SYS}} \quad (4)$$

System loss,

$$(\eta_{SYS}) = \eta_{GEN} \times \eta_{CAB} \times \eta_{BAT} \quad (5)$$

Where, $\eta_{GEN}$ includes all the losses due to temperature, spectral variations etc and is usually taken as 0.9, $\eta_{CAB}$ is the cable and charge controller loss and$\eta_{BAT}$ =is the battery efficiency, $E_L$ =Total daily energy demand, and $E_{DES}$ =Design energy consumption.

***PV Array Sizing***

The generator (PV array) size, ($P_{GEN}$) is calculated using Equation 6 defined as ;

$$P_{GEN} = \frac{E_{DES}}{S_{DES}} \text{ W} \quad (6)$$

Where; $S_{DES}$is the average sunshine hour data and $P_{GEN}$ is the solar panel size in Watts

$$\text{Number of solar panels (N)} = \frac{P_{GEN}}{W_P} \quad (7)$$

Number of solar panels to be connected in parallel

$$N_P = \frac{N}{N_S} \quad (8)$$

Number of panels to be joined in series ($\boldsymbol{N_S}$) =

$$\frac{V_{DES}}{\text{Nominal voltage}} \quad (9)$$

***Sizing of the Tilt Angle***

The optimum solar panels' tilt angle depends upon the latitude of the location [15] and can be approximated to be the same as the latitude of the location. If the latitude is denoted by$\phi$, then the optimum tilt angle is determined by;

$$\theta = \{0.9\phi + 29 \quad \phi < 25^0 \quad (10)$$

***Sizing of the Battery Bank***

$$C_{BAT} = \frac{E_D \times \text{Autonomy}(D) \times (1+\text{DOD})}{V_{inv}} \text{ Ah} \quad (11)$$

$$\text{Number of batteries} = N_{BAT} = \frac{C_{BAT}}{Ah_{BAT}} \quad (12)$$

$$\left.\begin{aligned} B_s &= \frac{V_{DES}}{V_{BAt}} \\ B_P &= \frac{N_{BAT}}{B_S} \end{aligned}\right\} \quad (13)$$

$V_{BAT}$ = rated battery bank voltage (V)

$N_{BAT}$ = Total required number batteries

$V_{INV}$ = inverter efficiency

$B_S =$ number of batteries to be connected in series

$B_P =$ number of strings to be connected in parallel

$Ah_{BAT}$ Represents the amp-hour of the battery selected.

***Sizing of the Inverter***

The inverter is specified according to the load estimation of the design. (Raquibul *et al.*, 2016).

$$P_{INV} = \frac{E_L}{t \times \eta_{INV} \times \cos\phi} \text{ VA} \quad (14)$$

Where; $P_{INV}$ is the inverter rating in KVA, $n_{INV}$ is the inverter efficiency, and $E_L$ =Total daily energy demand.

***Sizing of the Charge Controller***

A charge controller with a higher rating than the maximum PV system and load current should be selected. Raquibul *et al.* (2016) give the charge controller rating as;

$$I_{CT} = 1.25 \times N_p \times I_{sc} \text{ A} \quad (15)$$

***Sizing of the Cable***

Table 1 is provided by the Institute of Electrical Electronics Engineering as a guide to cable selection for solar photovoltaic systems.

Cable size for the inverter to distribution board section is calculated by;

$$I = \frac{E_L}{t \times 220} \times 1.25 \quad (16)$$

Where, $E_L$ =Total daily energy demand, t = hours of usage, and I= current in amperes.

The range of values $I$ is used to select the cable size. The cable is selected following Table 1

**Table 1. Maximum Allowable Current of the Conductor (IEEE Standard Table)**

| Max. Current | Alternating | CSA (mm$^2$) |
|---|---|---|
| 13-15 | | 1.5 |
| 15-21 | | 2.0 |
| 21-28 | | 2.5 |
| 28-38 | | 4.0 |
| 37-49 | | 6.0 |
| 48-67 | | 10.0 |
| 66-89 | | 16.0 |
| 90-118 | | 25.0 |

***Cost Estimation for PV System***

The estimation for the cost is given by (Eod *et al.*, 2012) as highlighted thus:

Solar Panel Cost = Cost per module x Number of modules (N)

Battery cost = Cost per battery x Number of Battery (N bat)

Charge controller cost = Cost per unit charge controller chosen x number of charge controller

Inverter cost = Cost per unit Inverter x Number of inverters (N)

Subtotal = cost of solar panel + cost of battery + cost of charge controller + cost of inverter

The equation for the Balance of the System is given by(Majid *et al.*, 2013 ; Chel *et al.*, 2009 ; Pandey *et al.*, 2012) as;

Balance of System (BOS) = Subtotal x 0.2

## RESULTS AND DISCUSSIONS

The graphic user interface developed in this new software includes the welcoming interface, the basic input parameters interface for executing the desired tasks, the load selection interface, the output interface and the cost estimation interface. These user interfaces are as shown in Figure 2(a) to 2(f) thus;

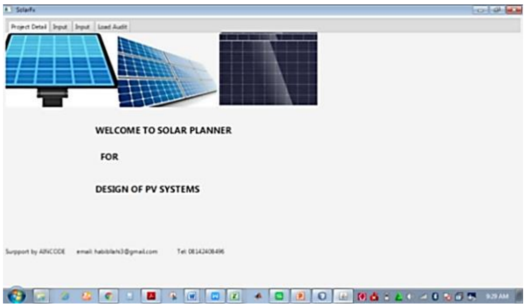


Figure 2(a). Welcome Interface

Figure 2(b): First Input Interface

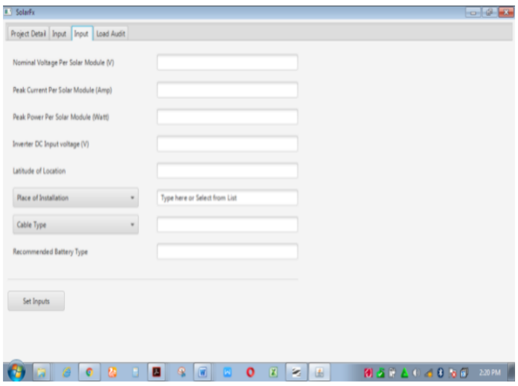

Figure 2(c): Second Input Interface

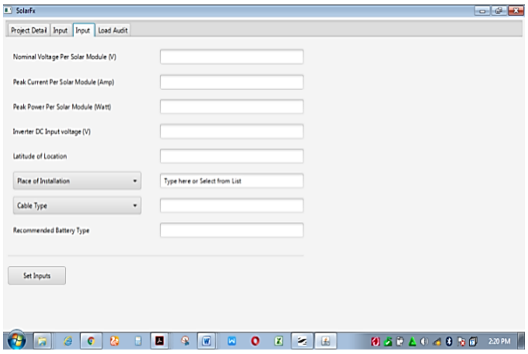


Figure 2(d): Load Selection interface

Figure 2(e): Output Interface

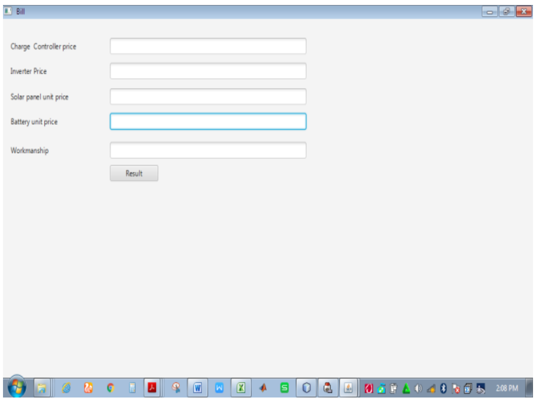


Figure 2(f): Cost estimation Interface

This interface in Figure 2(a) is the first that will pop up when one double clicks on the application from the desktop and it is a welcoming interface displaying 'Welcome to Solar Planner for design of PV systems. Figures 2(b) and 2(c) are the input interfaces where the basic input parameters required by the software are supplied. These inputs include hours of usage, days of autonomy, sunshine hours per day, inverter efficiency, battery efficiency, amp hour per battery, battery voltage, depth of discharge, solar panel efficiency, load audit factor, and tracking factor.

In a bid to reduce the stress of inputting all the aforementioned parameters, some of the inputs such as battery efficiency, cable and generator efficiency, load audit factor etc. were given a default value. The software is so flexible that the default values can be edited to suit the user's needs. The interface shown in Figure 2(d) deals with the selection of loads and their wattage as input for the software to work with and several home appliances are available for selection. The interface consists of three fields one of which shows a drop-down box containing several appliances, another field is meant for selecting the quantity and the last one is meant for specifying the power rating of the appliances so selected. The user will be required to press the 'ok' button to tell the software that all loads have been finally selected while the 'calculate' button finally does the necessary calculation and displays the result in the output interface shown in Figure 2(d).

Figure 2(e) shows the output interface where all the generated results are shown. The generated results include the total power, design energy, capacity of the solar panel required, number of solar panels required, capacity and number of batteries required, size of charge controller and inverter rating needed for the design, optimum tilt angle and cable size. Figure 2(f) represents the interface for the estimation of the cost of items required for the design. It consists of battery unit price, solar panel unit price, workmanship, inverter price and charge controller price which are used to estimate the total cost. Each field displays the information required to be known by the user in a black dropdown box when the cursor is placed in the field; for instance, when the cursor is placed in the solar panel unit price field, it automatically displays the quantity of solar panel required for the design.

The software was tested by using it to design for various loads ranging from 1000W to 64000 W and the result obtained is shown in Table 2. The parameters of the PV system produced at the output interface are observed and the following variations occur. The parameters of the PV system produced at the output interface were observed and the following variations occur as shown in Figures 3-7. The output parameters such as optimum tilt angle and the number of solar panels vary with geopolitical regions because the tilt angle is a function of the geographical location of the area of installation i.e. the latitude of the area plays a big role in determining tilt angle while the number of solar panels is dependent upon both the loads and the level of sunshine of the area. The lower the sunshine hour per day (e.g. in the south-south region of Nigeria), the more the number of solar panels that would be required to provide sufficient energy to drive the given load.

***Variation of Parameters with Change in Geopolitical Area***

A residential PV system was designed using the developed software for loads of different sizes and the following output parameters were observed to vary while others remained constant throughout the selected area in each of the six geopolitical regions of Nigeria. The parameters of the PV system produced at the output interface were observed and the following variations occur as shown in Figures 3-7. Figure 8 shows the relationship between the number of solar panels with the orientation of the geopolitical region. It can therefore be inferred from Figure 8 that the required solar panels number for 2500 W-load in the south-south zones of Nigeria is greater than any of the remaining geopolitical zones. This also implies an increase in the cost of installing solar PV systems in such areas of Nigeria.

Table 2. Variation of parameters with various loads in Ogun State using 200Ah, 12V battery, 200W panel, and the loads are powered for 24 hours

| S/N | PT(W) | V DES | Nominal Voltage | Lat | V storage | E design (Wh) | P GEN(W) | N | NS | NP | C BAT | N BAT | BS | BP | I CT (A) | P inv | cable size(mm) | Tilt angle |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1000 | 24 | 24 | 7.1 | 12 | 31,189.08 | 4,455.58 | 22.28 | 1.00 | 22.28 | 1,689 | 8.45 | 2.00 | 4.22 | 189.36 | 1.56 | 1.50 | 35.43 |
| 2 | 2240 | 24 | 24 | 7.1 | 12 | 69,863.55 | 9,980.51 | 49.90 | 1.00 | 49.90 | 3,784 | 18.92 | 2.00 | 9.46 | 424.17 | 3.50 | 1.50 | 35.43 |
| 3 | 2500 | 24 | 24 | 7.1 | 12 | 77,972.71 | 11,138.96 | 55.69 | 1.00 | 55.69 | 4,224 | 21.12 | 2.00 | 10.56 | 473.41 | 3.91 | 2.00 | 35.43 |
| 4 | 3000 | 24 | 24 | 7.1 | 12 | 93,567.25 | 13,366.75 | 66.83 | 1.00 | 66.83 | 5,068 | 25.34 | 2.00 | 12.67 | 568.09 | 4.69 | 2.50 | 35.43 |
| 5 | 4500 | 24 | 24 | 7.1 | 12 | 140,350.88 | 20,050.13 | 100.25 | 1.00 | 100.25 | 7,602 | 38.01 | 2.00 | 19.01 | 852.13 | 7.03 | 4.00 | 35.43 |
| 6 | 5000 | 24 | 24 | 7.1 | 12 | 155,945.42 | 22,277.92 | 111.39 | 1.00 | 111.39 | 8,447 | 42.24 | 2.00 | 21.12 | 946.81 | 7.81 | 4.00 | 35.43 |
| 1 | 2240 | 24 | 24 | 7.1 | 12 | 69,863.55 | 9,980.51 | 49.90 | 1.00 | 49.90 | 3,784 | 18.92 | 2.00 | 9.46 | 424.17 | 3.50 | 1.50 | 35.43 |
| 2 | 6,400 | 24 | 24 | 7.1 | 12 | 199,610.14 | 28,515.73 | 142.58 | 1.00 | 142.58 | 10,812 | 54.06 | 2.00 | 27.03 | 1,211.92 | 10.00 | 10.00 | 35.43 |
| 3 | 76,800 | 24 | 24 | 7.1 | 12 | 2,395,321.64 | 342,188.81 | 1,710.94 | 1.00 | 1,710.94 | 129,747 | 648.73 | 2.00 | 324.37 | 14,543.02 | 120.00 | 70.00 | 35.43 |
| 9 | 64,000 | 24 | 24 | 7.1 | 12 | 1,996,101.36 | 285,157.34 | 1,425.79 | 1.00 | 1,425.79 | 108,122 | 540.61 | 2.00 | 270.31 | 12,119.19 | 100.00 | 50.00 | 35.43 |
| 10 | 54,400 | 24 | 24 | 7.1 | 12 | 1,696,686.16 | 242,383.74 | 1,211.92 | 1.00 | 1,211.92 | 91,904 | 459.52 | 2.00 | 229.76 | 10,374.02 | 85.00 | 35.00 | 35.43 |

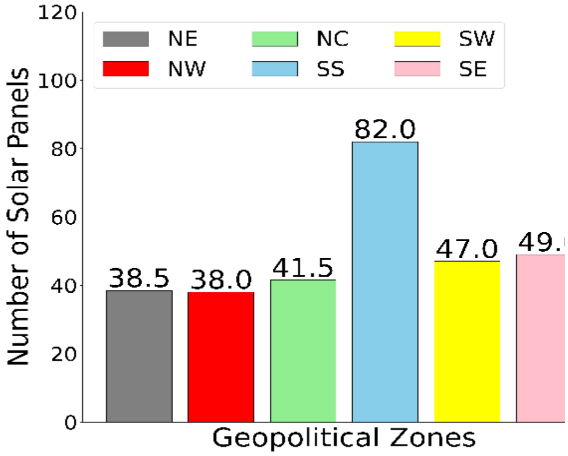


Figure 3. Number of solar panels required in different regions of Nigeria for a load of 2500W.

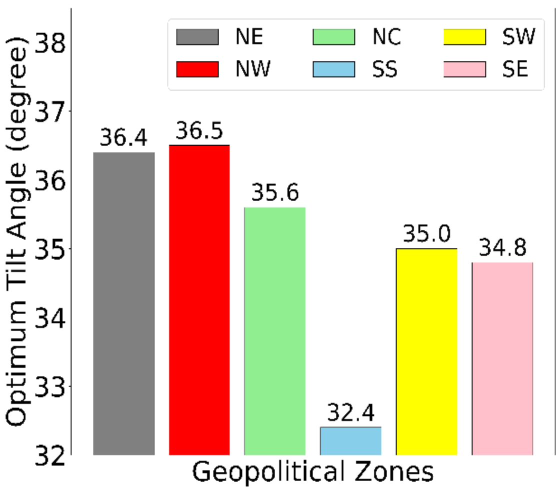


Figure 4. shows how the optimum tilt angles for the solar panels vary for different regions of the country (Nigeria).

Also, from Figure 4 the North-west region of the country requires the highest optimum tilt angle for a reliable solar installation than the other regions. It can be inferred that the optimum tilt angle depends on the geopolitical region's Latitude.

***Variation with Load***

Some of the outputs produced by the software vary with the load demand. These variations with load can be explained using the graph of Figure 5 it can be concluded that the more the loads demand the more the required battery number of such PV systems. This is because the graph has a positive slope. Figure 5 depicts that the required batteries' number for a given load, varies as the load increases.

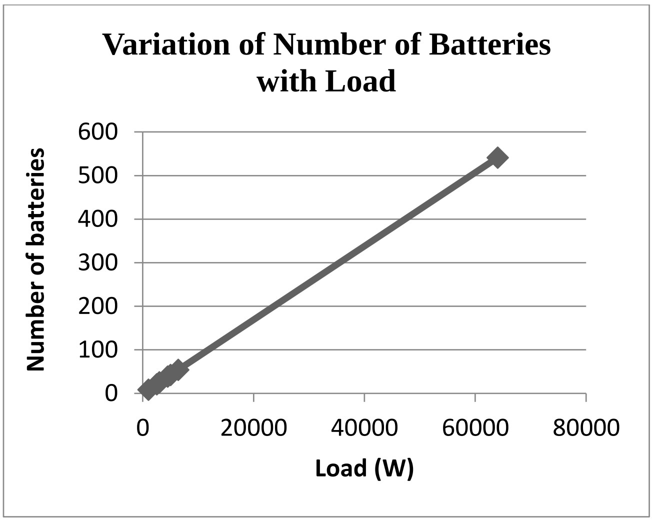


Figure 5. Variation of the Number of batteries required with load

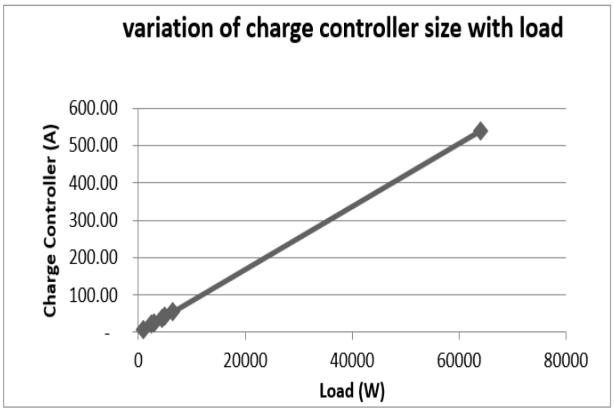


Figure 6. Variation of charge controller ratings with load

Figure 6 shows a linear relationship between the charge controller rating and the PV load of the system; this is because of the increased number of solar panels for an increase in the PV load, which corresponds to increased charge controller capacity in Ampere. It can be deduced that the inverter size increases directly with the load i.e. both parameters are proportional to each other.

The graph of Figure 7 depicts that inverter ratings vary in proportion to the load demand. It can be deduced from Figure 7 that the inverter size increases directly with the load, that is, both parameters are proportional to each other.

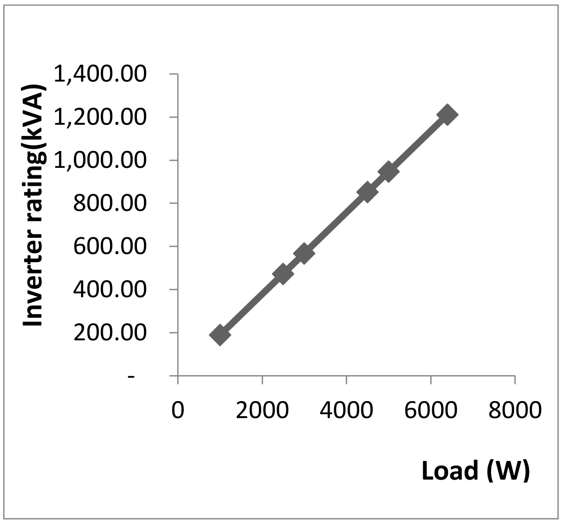


Figure 7. Variation of inverter ratings with load

## CONCLUSIONS

The application software for the design of PV systems was successfully developed and named Solar Planner. The execution of the equations was carried out with JAVA codes following the process flow chart developed without any error, in contrast to the conventional method (manual sizing) of design of photovoltaic systems operational in Nigeria's solar business market. The software was subjected to testing by using it for the design of PV systems for loads of 1 kW, 2.5 kW, 3kW, 4.5kW, 5kW and 6.4 kW.

The results obtained were observed to vary with two major factors namely, the load demand and the change in geopolitical region. The result obtained when the software was used to design a PV system of 2.5kW load with change in the geopolitical region shows that there is a noticeable variation in the number of solar panels required for such system across all the six geopolitical regions in Nigeria with the northeastern part of Nigeria requiring the least and the south southern part of Nigeria requiring the highest number of solar panels.

The implication is that the cost of installation in the southern part of Nigeria is costlier than that of the northern part. This is because the Northern part has high sunshine. The result obtained when the load is varied and the location kept constant using Ogun State at latitude 7.14 as a case study showed that the number of batteries, the inverter rating and the charge controller are the only parameters that vary with the load and are of optimal value. The result obtained and the ability of the software to easily determine the energy demand of a sample building and accurately size the component of the PV system yielded useful technical parameters such as the total power, design energy, capacity of the solar panel required, number of solar panels required, capacity and number of batteries required, size of charge controller and inverter rating needed for the design, optimum tilt angle, cable size and cost of installation lead to a conclusion that the software facilitates easier, faster and accurate design of PV systems for adaptation in Nigeria solar market for promotion of use and applications of PV system in rural and urban communities and attainment of sustainable development goal.

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