iJET International Journal of Engineering & Technology
CENTRE OF PROFESSIONAL RESEARCH PUBLICATIONS
ISSN 2049-3444

International Journal of Engineering and Technology Volume 5 No. 1, January, 2015

Design of a Stand-Alone Photovoltaic System for a Residence in Bauchi

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ABSTRACT

The aim of this paper is to present in detail the design of a stand-alone photovoltaic power system for a typical residential building in Bauchi, Nigeria. A photovoltaic power system can be used to provide alternative and inexhaustible source of electrical power to our homes through the direct conversion of solar irradiance into electricity. The process of acquiring a photovoltaic power system involves designing, selecting and determining the specifications of the different components employed in the system. The success of this process depends on a variety of factors such as geographical location, weather condition, solar irradiance, and load profile. The paper outlines the procedures employed in specifying each component of the stand-alone photovoltaic power system and as a case study, a residence in Bauchi (Nigeria) with medium energy consumption is selected.

Key Words: *Photovoltaic Array, System Sizing, Charge Controller, Inverter, Stand-Alone, Bauchi Residence*

1. INTRODUCTION

Photovoltaic power systems have increasing roles in modern electric power energy mix due to the continuing decline in the world's conventional sources of energy. The major advantages associated with photovoltaic power systems are that [1] and [2]:

- They have no moving parts
- They don't produce any noise
- They require little or no maintenance
- They are non-polluting
- They are renewable
- They are highly modular
- They are highly reliable
- They can be installed almost anywhere

A stand-alone photovoltaic power system is a complete set of interconnected components for converting solar irradiance directly into electricity and generally consists of the array, battery bank, charge controller, an inverter, protection devices and the system load. The total solar irradiance that reaches the surface of the earth varies with the time of day, season, location and weather conditions. Different places on the globe experience different microclimatic conditions; therefore our location is a major factor that affects photovoltaic power system design in the following aspects [2]:

1. The orientation of the array
2. Number of days of autonomy
3. Array tilt angle

In this paper, the design of the various components of a photovoltaic power system for the purpose of residential use will be presented. Thereafter, a residence model with average energy requirements in Bauchi (Nigeria) will be considered as a practical case study for which a detailed a step-by-step design procedure will be provided including cost estimates.

2. PHOTOVOLTAIC POWER SYSTEM COMPONENTS

Photovoltaic power generation is the process of generating electricity directly from sunlight. Most photovoltaic systems being used in a variety of applications are essentially stand-alone. A photovoltaic power system consists of six components that are wired together to form a fully functional stand-alone system capable of generating and supplying electric power. Fig. 1 depicts the interconnection of typical stand-alone photovoltaic power system components and are described hereunder.

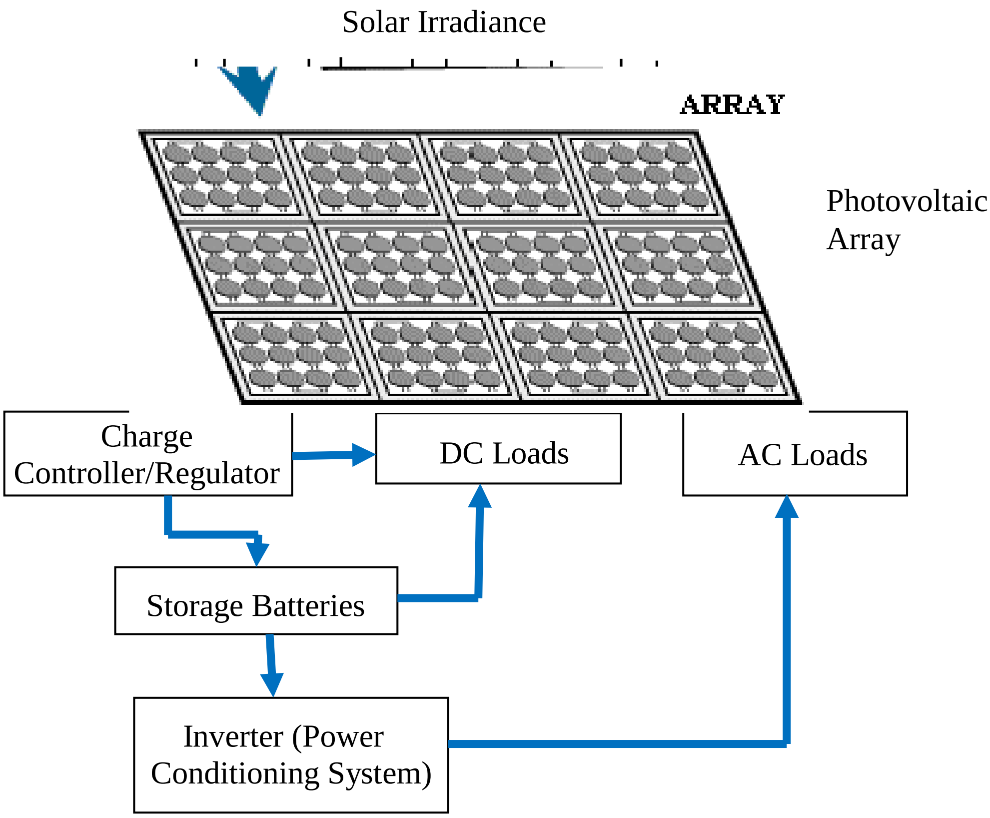

Figure 1: Stand-Alone Photovoltaic Power System Components

2.1 Photovoltaic Array

Referring to fig. 1, the photovoltaic array is the heart, and therefore indispensable, component of any stand-alone PV system. It is responsible for the conversion of sunlight into electricity. The fundamental power conversion units are the solar cells, which typically produce less than 2 Watts of power. In order to produce increased power output, the solar cells are normally connected in series and parallel to form modules. Modules are then also connected in series and parallel architecture to form an array so as to meet the desired power output [3].

2.2 Storage Batteries

The storage batteries are used to supply the load during non-sunshine hours whilst being charged by the PV array during periods of high solar radiation. The recommended batteries that should be used in stand-alone photovoltaic power system are deep-cycle lead-acid batteries because of their high performance [2].

2.3 Charge Controller

The charge controller (also known as voltage regulator) coordinates the power flow between the components of the system and the load, and ensures that the system voltage is regulated to specified range. The basic function of a charge controller is to prevent the storage battery from
being overcharged and also prevents it from being over discharged [4].

2.4 Inverter

An inverter (also known as a power conditioning system) is essential for meeting the load requirements. The power from the PV array is in dc form; therefore a dc to ac inverter is necessary if the load requires an alternating current supply [5].

2.5 Balance of System Components

Components such as protective devices, blocking & bypass diodes, lightning-protection system and cable wiring constitute what is known as balance of system components [2]. Such components are necessary to keep the PV power system safe and reliable. In particular, selecting the correct size and type of cable will enhance the performance of the system while selecting inadequate cable size will cause voltage drop from the source to the load. In low voltage systems, such voltage drops will lead to inefficiencies.

2.6 Loads

Loads are the power consuming units of the PV system. There are two types of loads (ac and dc) depending on the type of electrical power that they require for their operation. For the purpose of this design, electrical loads may be broadly classified as either resistive or inductive. Resistive loads do not have any significant inrush of current when energized. Examples of resistive loads include light bulbs and electric heaters. Inductive loads on the other hand, pull a large amount of current (inrush) when first energized and examples include transformers, electric motors and coils.

3. PV SYSTEM DESIGN

PV system design is the process of determining the capacity (in terms of voltage and current) for each component of the stand-alone photovoltaic power system with the view to meeting the load profile of the residence for which the design is made. For the sake of completeness, we are also calculating the total cost implication of the complete system.

3.1 Factors Affecting PV System Design

Although PV power systems have numerous advantages as already highlighted, it is important to understand that high initial capital cost is still a major limitation to their use. During the design phase therefore and in order to reduce the overall system cost, a number of factors are normally considered as discussed in the following subsections:

3.1.1 Reasonable load profile

Energy conservation principles should be strictly observed when estimating the required average energy demand in watt-hour per day. This is usually estimated by listing all the loads and their corresponding daily hours of use. Hours for which a particular load is not put to use must be excluded.

3.1.2 PV power system installation site

The geographic location of the installation site is an important factor because it is used in determining the array orientation, tilt angle and the average sun hour per day of the site. Furthermore, the installation site should be free from all sorts of shadows throughout the solar day.

3.1.3 Optimizing building design

In order to minimize the amount of energy that may be required to meet the desired home heating, the residential building should be provided with adequate insulation while its windows should be designed to face south so as to keep the house as warm as possible. Furthermore, the southern part of the house should be free from all types of solar irradiance obstacle since the array will be oriented towards the south.

3.1.4 Use of energy efficient loads

Lighting devices should be of the compact fluorescent lamp (CFL) types usually referred to as energy savers so as to reduce energy consumption. Furthermore, cooking and hot water are normally not part of a residential PV power system design. A separate solar thermal system is normally employed to provide energy for cooking and hot water requirements.

3.1.5 Use of low-voltage dc powered loads

Low-Voltage dc powered loads should be used wherever possible as this will significantly reduce the capacity of inverter and therefore a corresponding reduction of its cost.

3.1.6 Accounting for inductive loads

The normally large starting current of inductive residential loads such as water pumps and refrigerators must be accounted for during the design phase.

3.2 Determining the size of the PV array

A photovoltaic array is a linked collection of solar modules. The power that one module can produce is seldom enough to meet a residential power requirements, so the modules are linked together to form an array. The modules in a PV array are usually first connected in series to obtain the desired voltage; the individual strings are then connected in parallel to allow the system to produce more current as desired. The following information should be determined before the actual sizing of the PV array begins:

- The dc voltage of the system (V_{dc})
- The average sun hours of the installation site per day (T_{sh})
- The daily average energy demand in watt-hours (E_d)

Sizing the array begins by first determining the required daily average energy demand (E_{rd}) which is obtained by dividing the daily average energy demand by the product of the efficiencies of all system components as given in equation (1).

$$E_{rd} = \frac{E_d}{\eta_b \eta_i \eta_c} \quad (1)$$

Where η_b = battery efficiency
η_i = inverter efficiency
η_c = charge controller efficiency

The average peak power ($P_{ave,peak}$) is then obtained by dividing the required daily average energy demand by the average sun hours of the site per day (T_{sh}) as in equation (2).

$$P_{ave,peak} = \frac{E_{rd}}{T_{sh}} \quad (2)$$

The total dc current of the system (I_{dc}) is then obtained by dividing the average peak power by the dc voltage of the system as in equation (3).

$$I_{dc} = \frac{P_{ave,peak}}{V_{dc}} \quad (3)$$

The number of modules in series (N_{sm}) is then obtained by dividing the system dc voltage by the rated voltage of each module (V_{rm}) as expressed in equation (4).

$$N_{sm} = \frac{V_{dc}}{V_{rm}} \quad (4)$$

Next, we obtain the number of parallel number of module strings (N_{pm}) by dividing the total dc current of the system by the rated current of one module (I_{rm}) as in equation (5).

$$N_{pm} = \frac{I_{dc}}{I_{rm}} \quad (5)$$

The total number of modules (N_{tm}) that form the array is then finally determined by multiplying the number of modules in series by the number of parallel modules as in equation (6), thus giving the required array size.

$$N_{tm} = N_{sm} x N_{pm} \quad (6)$$

3.3 Determining the size of the Battery Bank

The battery type recommended for use in solar PV power system is deep cycle battery, specifically designed such that even when it is discharged to low energy level it can still be rapidly recharged over and over again for years. The battery should be large enough to store sufficient energy to operate all loads at night, cloudy, rainy and dusty days.

Sizing the battery begins by first determining the estimated energy storage (E_{est}) required which is equal to the product of the daily average energy demand and the number of autonomy days (D_{aut}) as in equation (7).

$$E_{est} = E_d x D_{aut} \quad (7)$$

A safe energy storage (E_{safe}) is then computed by dividing the obtained estimated energy storage by maximum allowable depth of discharge (D_{disch}) as given by equation (8).

$$E_{safe} = \frac{E_{est}}{D_{disch}} \quad (8)$$

The total capacity of the battery bank in ampere-hours (C_{tb}) is then determined by dividing the safe energy storage by the rated dc voltage of one battery (V_b) as in equation (9).

$$C_{tb} = \frac{E_{safe}}{V_b} \quad (9)$$

At this point, the total number of batteries (N_b) can then be obtained by dividing the total capacity of the battery bank in ampere-hours by the capacity of one of the selected batteries in ampere-hours (C_b) as given by equation (10).

$$N_{tb} = \frac{C_{tb}}{C_b} \quad (10)$$

The number of batteries in series (N_{sb}) can now be determined by dividing the system dc voltage by the rated dc voltage of one battery as in equation (11).

$$N_{sb} = \frac{V_{dc}}{V_b} \quad (11)$$

At this point, we can then determine the number of parallel battery strings (N_{pb}) by dividing the total number of batteries by the number of batteries in series as in equation (12).

$$N_{pb} = \frac{N_b}{N_{sb}} \quad (12)$$

Finally, since the number of batteries in series (N_{sb}) and the number of parallel battery strings (N_{pb}) are now known, then the size of the battery bank is fully determined and consists of $N_{sb} x N_{pb}$ batteries.

3.4 Determining the Capacity of the Charge Controller

The solar charge controller is generally sized in a way that will enable it perform its function of current control. A good charge controller must be able to withstand the array current as well as the total load current and must be designed to match the voltage of the PV array as well as that of the battery bank.

The standard practice of sizing the charge controller is to ensure that it is able to withstand the product of the total short circuit current of the array ($I_{sc}^{A} = I_{sc}^{M} x N_{pm}$) and a certain safe factor (F_{safe}). The safe factor is necessary in order to allow for a reasonable system expansion. Thus, the desired charge controller current (I_{cc}) is as given by equation (13).

$$I_{cc} = I_{sc}^{M} x N_{pm} x F_{safe} \quad (13)$$

Where I_{sc}^{M} = the short circuit current of the selected module

3.5 Determining the Capacity of the Inverter

An inverter is used in the PV power system when an ac power output is needed. The input rating of the inverter should never be lower than the total power of the different loads and must have the same nominal voltage as that of the battery bank. In practice, the capacity of the inverter is taken to be the sum of the total power of all loads running simultaneously and 3 times the total power of all inductive loads with large surge currents. Furthermore, the obtained value is then multiplied by a factor of 1.25 to make it 25% larger in capacity [6] in order to allow for a reasonable system expansion. Thus, the inverter power is determined using equation (14) as follows:

$$P_{inv} = 1.25(P_{sum} + 3P_{ind}) \qquad (14)$$

Where P_{inv} = Power of the inverter
P_{sum} = Power of all loads running simultaneously
P_{ind} = Power of all inductive loads with large surge currents

4. CASE STUDY – A TYPICAL RESIDENCE IN BAUCHI

Bauchi town in Nigeria has an average solar irradiance of 950.8 W/m^2, 600 W/m^2 and 586.7 W/m^2 for clear sunny, cloudy and harmattan microclimatic seasons respectively [7]. This level of solar irradiance has realistically portrayed that Bauchi is sufficiently endowed with viable solar energy resource which ought to be exploited maximally to improve the quality of her teaming populace. This has become necessary particularly in view of the large number of hard to reach rural communities that cannot be easily reached by the conventional national grid even when current improvement efforts in the energy sector have become successful. Bauchi is located in the northern hemisphere part of the earth at latitude and longitude of 10.313° and 9.843° respectively. This geographical location of Bauchi implies that the solar array should be inclined at an optimal angle of about 30° facing southward for all year round maximum solar energy harvest if it is to be of fixed orientation and at a location devoid of overcasts from nearby trees and buildings.

4.1 The Proposed Residence

The residence depicted in Fig. 2 is a typical floor plan of a three bedroom bungalow in Bauchi. A 10 m^2 of land devoid of shading between the hours of 9:00 am to 4:00 pm near the residence is required for ground installation of the solar array.

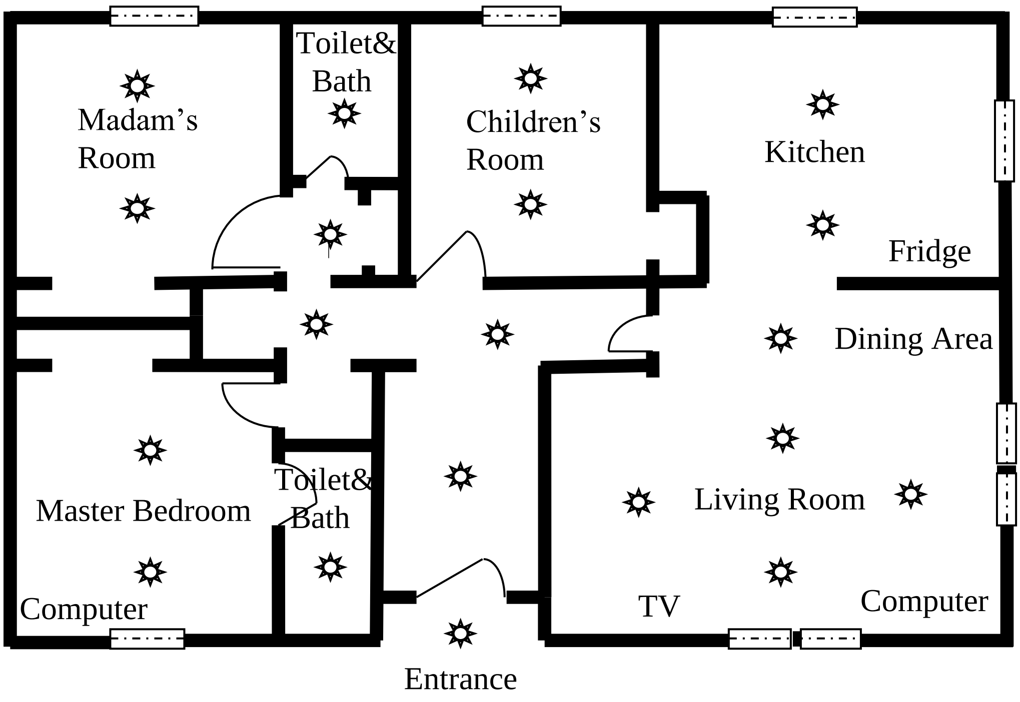

Figure 2: Floor Plan of a Typical 3 Bedroom Bungalow in Bauchi

4.1.1 Residence load profile

The residence load profile is determined by itemizing all the residence appliances with their corresponding power ratings and hours of operation to obtain the total average energy demand in watt-hours (residence load profile) per day as indicated in Table 1.

Table 1: Residence Appliances and Daily Load Profile

S/N	Appliance	Quantity	Power Rating (Watt)	Hours of use per Day	Energy per Day
1	32" Plasma TV	1	125	6	750
2	Satellite Receiver	1	25	6	150
3	Refrigerator	1	150	8	1200
4	Computer	2	65	4	520
5	Printer	1	700	0.5	350
6	Pressing Iron	1	1000	0.4	400
7	Washing Machine	1	250	0.5	125
8	Compact Fluorescent Lamps	20	15	5	1500
9	Cell phone	4	2.5	5	50
10	Rechargeable Lamp	4	9.5	5	190
11	Electric Fan	3	70	6	1260
12	Shaver	1	15	0.4	6
Total Load Profile				**6501**	

Thus, the load profile of the residence is 6501 watt-hours per day and will be used to determine the stand-alone PV power system component sizes as detailed hereunder.

4.1.2 PV array sizing

The first step toward sizing the PV array is to determine the daily energy requirement from the array. The required energy obtained is then divided by the average sun-hours per day for Bauchi to obtain the peak power. The peak power is then divided by the selected system dc voltage to obtain the total dc current. Finally, the number of series and parallel modules can then be determined to give the array size. From the cost of an individual module (M_{cost}), the total cost of the PV array (A_{cost}) can then be determined. Table 2 presents the summary of the PV array sizing and cost determination procedure.

Table 2: Summary of PV Array Sizing and Cost Estimate

Required Information:

Solar Module: SUNTECH STP200-18-UB-1, $V_{rm} = V_{mp} = 26.2$ V, $I_{rm} = I_{mp} = 7.63$ A, $I_{sc} = 8.12\ A$, M_{cost} = ₦ 96,000.00
System Voltage (V_{dc}) = 24 V
Average Sun-hours for Bauchi (T_{sh}) = 4
Daily Average Demand (E_d) from Table 1 = 6501 Watt-hours
Battery Efficiency (η_b) = 0.85
Inverter Efficiency (η_i) = 0.90
Charge Controller Efficiency (η_c) = 0.90

Parameter Being Determined	Working Formula	Computed Parameter Value
Required Daily Energy Demand (E_{rd})	$E_{rd} = \frac{E_d}{\eta_b \eta_i \eta_c}$	9.4423 kWh.Day^{-1}
Average Peak Power ($P_{ave,peak}$)	$P_{ave,peak} = \frac{E_{rd}}{T_{sh}}$	2360.58 W
Total dc Current (I_{dc})	$I_{dc} = \frac{P_{ave,peak}}{V_{dc}}$	98.36 A
Number of Series Modules (N_{sm})	$N_{sm} = \frac{V_{dc}}{V_{rm}}$	1
Number of Parallel Modules (N_{pm})	$N_{pm} = \frac{I_{dc}}{I_{rm}}$	13
Total Number of Modules (N_{tm})	$N_{tm} = N_{sm} x N_{pm}$	13
Total Cost of Array in Naira (A_{cost})	$A_{cost} = N_{tm} x M_{cost}$	1,248,000.00

4.1.3 Battery bank sizing

In order to size the battery bank, the estimated energy storage is first determined. The obtained energy value is then divided by the allowable depth of discharge of the battery to give a safe energy storage value of the required battery bank. At this point, the particular battery to be used is selected and using its specifications, the capacity of the entire battery bank in Ampere-hours is computed, and subsequently the total number of batteries in the bank is computed. Finally, the number of batteries in series and parallel branches of the bank are determined and an estimate of the cost of the battery bank (B_{bcost}) is made from the knowledge of the cost the selected single battery (B_{cost}). The procedure for sizing the battery bank and cost estimate is presented in Table 3.

Table 3: Summary of Battery Bank Sizing and Cost Estimate

Required Information:
Number of Days of Autonomy (D_{aut}) = 3 Days
Battery: 8A8DLTP-DEKA, $C_b = 250$ Ah, $V_b = 12$ V, $D_{disch} = 80\%$, B_{cost} = \$679.00 = ₦108,640.00

Parameter Being Determined	Working Formula	Computed Parameter Value
Estimated Energy Storage (E_{est})	$E_{est} = E_d x D_{aut}$	19.503 kWh
Safe Energy Storage (E_{safe})	$E_{safe} = \frac{E_{est}}{D_{disch}}$	24.379 kWh
Total Capacity of Battery Bank (C_{tb})	$C_{tb} = \frac{E_{safe}}{V_b}$	2031.58 Ah
Total Number of Batteries in Bank (N_{tb})	$N_{tb} = \frac{C_{tb}}{C_b}$	8
Number of Batteries in Series (N_{sb})	$N_{sb} = \frac{V_{dc}}{V_b}$	2
Number of Batteries in Parallel (N_{pb})	$N_{pb} = \frac{N_b}{N_{sb}}$	4
Cost of Battery Bank in Naira (B_{bcost})	$B_{bcost} = N_{tb} x B_{cost}$	869,120.00

4.1.4 Charge controller sizing

Sizing a suitable charge controller starts by computing the required total current that the controller should withstand. From the results of the required current, the total number of charge controllers can then be computed and once the cost of a single charge controller is known, the total cost of the controllers can then be determined. Table 4 presents the summary of the Charge Controller sizing procedure and its cost estimate

Table 4: Summary of Charge Controller Sizing and Cost Estimate

Required Information:
Charge Controller: Xantrex XW-MPPT60-150, V_{cc}= 24, I_{cc}= 60 A (dc), C_{cost} = ₦ 81,600.00
Safety Factor (F_{safe}) = 1.25

Parameter Being Determined	Working Formula	Computed Parameter Value
Required Charge Controller Current (I_{rcc})	$I_{rcc} = I_{sc}^{M} x N_{pm} x F_{safe}$	131.95 A
Number of Charge Controllers (N_{cc})	$N_{cc} = \frac{I_{rcc}}{I_{cc}}$	2
Cost of Charge Controllers in Naira (C_{tcost})	$C_{tcost} = N_{cc} x C_{cost}$	163,200.00

4.1.5 Inverter sizing

The required solar inverter should have a power rating that is equal to 125% of the sum of the power of all non-inductive appliances and 3 times the sum of the power of all inductive appliances. Thus the power of all non-inductive appliances (P_{nia}) is first determined, then the power of all inductive appliances scaled by a factor of three ($3P_{ia}$) is computed. The total inverter power is now simply the sum of the two previous powers (P_{nia}+$3P_{ia}$) but however, scaled by a factor of 1.25 to take care of reasonable future expansion. The inverter with such power rating is then sourced from the manufacturer at a suitable cost (I_{cost}). Table 5 presents the summary of the inverter sizing procedure and its cost estimate.

Table 5: Summary of Inverter Sizing Procedure and Cost Estimate

Required Information:
Inverter: UNIV 5000P, DC Voltage = 24 V, AC Voltage = 230 V, P_i = 5000 W, I_{cost} = ₦80,960.00

Parameter Being Determined	Working Formula	Computed Parameter Value
Power of Non-inductive Appliances (P_{nia})	$P_{nia} = \sum_{l=1}^{l} P_{nia_l}$	2553 W
Power of Inductive Appliances Scaled by 3 ($3P_{ia}$)	$3P_{ia} = 3\sum_{k=1}^{k} P_{ia_k}$	1200 W
Total Inverter Power (P_i)	$P_i = 1.25(P_{nia} + 3P_{ia})$	4691.25 W
Cost of Inverter in Naira (I_{cost})	Contact Appropriate Sellers	80,960.00

l = Number of Non-inductive Appliance and **k** = Number of Inductive Appliances

4.1.6 System wiring sizing

The design of a PV power system is incomplete until the correct size and type of cable is selected for wiring the components together. The following cables links in the PV system must be appropriately selected:

- The dc cable from the PV array to the battery bank through the charge controller.
- The ac cable from the inverter to the distribution board (DB) of the residence.

Table 6 presents the summary of the procedure for selecting the correct cable sizes for these two important links.

Table 6: Summary of Procedure for Selecting Cable Sizes

PV System Cable Link	Current Rating of Cable (I_{cab})	Selected Cable Size and Type
PV Array to Battery Bank through Charge Controller	$I_{cab} = I_{rcc} = I_{sc}^{M} x N_{pm} x F_{safe}$ = 131.95 A	3x35 mm^2 Insulated Flexible Copper Cable
Inverter to DB of Residence	Current Produced by Inverter Output $I_{oi} = \frac{P_i}{V_{oi} x pf} = \frac{5000}{230x0.8}$ = 27.17 A	3x4 mm^2 Insulated Flexible Copper Cable

Where
I_{cab} = Cable Current between Array and Battery Bank;
I_{oi} = Current at Inverter Output;
P_i = Power rating of Inverter;
V_{oi} = Inverter Output Voltage;
pf = Power Factor

4.1.7 Summary of PV system components and cost estimate

The PV power system components that have been sized and needed to setup a complete stand-alone power system for the suggested Bauchi residence of Fig. 2 are summarized in Table 7. The cost of equipment (Modules, Batteries, Charge Controller and Inverter) is ₦ 2,361,280.00 while the costs of Cables, Design, Labour, Metering and Control Devices are lamped together as 20% of equipment cost and add up to ₦ 472,256.00. Thus, the total cost of the stand-alone PV power system is ₦ 2,833,536.00.

Table 7: List of PV System Components and Cost Estimate

Component	Qty	Model	PV Component Rating			Unit Cost (Naira)	Total Cost (Naira)
			Power (W/Ah)	Current (A)	Voltage (V)		
Module	13	SUNTECH STP200-18-UB-1	200 W	7.63	26.2	96,000.00	1,248,000.00
Battery	8	8A8DLTP-DEKA	250 Ah	-	12	108,640.00	869,120.00
Controller	2	XANTREX XW-MPPT60-150	-	60	24	81,600.00	163,200.00
Inverter	1	UNIV 5000P	5000 W	-	24/230	80,960.00	80,960.00
Cables	Lot	Array to Battery	3x35 mm^2 Insulated Flexible Copper Cable				472,256.00
		Inverter to DB	3x4 mm^2 Insulated Flexible Copper Cable				
		Design, Labour, Metering and Control Devices					
Total Stand-alone PV System Cost							**2,833,536.00**

5. CONCLUSION

The geographic location of Bauchi makes it to have 3 major microclimatic seasons namely harmattan, cloudy and clear sunny seasons with an average solar irradiance of 586.7 W/m^2, 600 W/m^2 and 950.8 W/m^2 respectively. If efficiently tapped, this is enough to provide enough alternative and clean source of energy, particularly to the many hard to reach rural communities that cannot be reached through the conventional national electric grid. Stand-alone PV power systems have become more relevant particularly in the conflict ridden areas of North Eastern Nigeria and other parts of the world where the electric grid infrastructure are continuously being destroyed by conflict. A cost estimate of the whole system including cabling, design, labour and control devices has also been provided. The same design procedure can be extended to other locations and applications involving higher energy consumptions. Government involvement in providing financial support for PV system equipment procurement and installation is highly recommended in view of the high capital intensive nature of this alternative and renewable source of energy. Government should also encourage local production of these PV system components so as to reduce their costs in the long term. There is the need to create institutional research centers that will research into fabrications of solar cells of different technologies most especially the emerging technologies such as organic solar cells. Obviously, this will require collaborative research work amongst Chemists, Physicists and Engineers. The penetration of photovoltaic systems should be fast tracked to meet the huge energy supply gap that currently exists in Nigeria and other developing countries. This could be achieved through very smart Government subvention and reduction of import duties for solar modules and other critical PV system components. In this regard, the German renewable energy model is worthy of emulation.

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