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DESIGN OF A STANDALONE PHOTOVOLTAIC SYSTEM FOR A RESIDENTIAL BUILDING IN OSOGBO, NIGERIA

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Abstract

Stand-alone photovoltaic (PV) systems have become one of the most promising power solutions for remote areas, which are not connected to the utility grid. In this paper, a stepwise design of a stand-alone PV system for a residential building is presented. A detailed procedure for choosing each system component is mathematically presented and discussed. The cost analysis for the installation and maintenance of the system for 25 years have been outlined. The result reveals that the cost of having a Stand-alone photovoltaic system to power a residential building in Osogbo is high and not yet within the reach of average Nigerians.

Keywords: *Nigeria, Stand-alone, residential, design, Osogbo, power.*

Nomenclature

ED	*average daily energy demand*
η_{INV}	*inverter efficiency*
η_{CON}	*efficiency of the charge controller*
T_{SH}	*peak sun hour*
SF	*safety factor.*
N_A	*Number of days of autonomy*
η_{OUT}	*Battery efficiency X inverter efficiency* = $\eta_B \times \eta_{INV}$

Introduction

Nigeria which is located between longitude 3° and 14° East of Greenwich and latitude 4° and 14° north of the equator has over 170 million people and a total land area of 923,768 km^2. The country generates her electrical power mainly from natural gas-powered and hydro plants, which is just above 3 GW. About 40% of the total households receive energy from the national grid while more than 45% do not have access to any form of electricity. Of this 40 % of households that have access to the grid, 6% use diesel generators as complements while 3% are completely reliant on selfgeneration [1]. The rural electrification program in Nigeria is unproductive because only about
1.1% of rural residents have access to electricity [2]. The quality of electricity services in Nigeria remains pitiable and many Nigerians are still without access to regular electricity [3].

Stand-alone PV systems, have turned into one of the most promising solutions for the urgent electrification problem of numerous remote consumers [4]. A stand-alone PV power system is an interconnected system for converting solar irradiance directly into electricity and generally consists of the PV array, battery bank, charge controller, an inverter and the load. The application of this technology comprises a quite attractive option from a financial point of view, especially for areas with relatively high solar potential [5,6].

Despite this promising future for PV systems, the energy conversion efficiency in practical applications is still relatively low [7]. Therefore, great value has to be set on in designing the components of the PV system because the system works effectively only if all the components connected to the PV array match each other. However, electrical energy generation from PV systems depends on several factors [7]. Foremost of these is the amount of solar radiation impinging on the surface of the PV modules, which also depends on the climatic conditions of the locations [8]. Bhuiyan and Ali Asgar [9] have established that since insolation, temperature and electricity requirements vary according to locations, therefore, designing of PV systems for different locations have to be different. For this reason, many researchers have to design standalone photovoltaic systems for a residential building based on their respective climatic conditions [915], but we are not aware of any published work in scientific journals that report a stand-alone PV system design for Osogbo climate. Therefore, the present study presents a stepwise design of a standalone PV system for a residential building in Osogbo, southwest, Nigeria. The design procedure is similar to those followed by Sandia National Laboratory, USA [16].

Methodology

Geographical location of the selected site

The site meteorological data is required to predict the performance of the PV system of the site under consideration. Osogbo (7.77°N, 4.57°E, 288m), the southwest region of Nigeria under study is a tropical rain forest. The mean annual daily global solar radiation is estimated as 13.110 MJ/m^2 while the mean annual sunshine hours in this location is found to be 5.1 h [17]. The mean yearly temperature of the region is about 27°C and its relative humidity is between 92% and 99% [18].

Residential load estimate

The first task for any photovoltaic system designer is to determine the system load. An estimate of the energy demand of the load is obtained by multiplying the power requirements of each appliance by the average number of hours of use per day. For design purpose, electrical loads are classified as either resistive or inductive. Resistive loads, for example, light bulb, heaters do not have significant surge current when energized. Inductive loads, for example electric motors, transformer requires large amount of current when first energized. Fluorescent lamps should be used instead of incandescent lamps because they provide the same light levels with much lower power demand [16]. In addition, large variable loads for cooking and hot water requirements are normally not part of the PV design, in most cases they are eliminated or operated from another power source [10]. . Based on the above recommendation, the household understudy is a mediumsize resident that requires not a very large quantity of electrical energy demand. The daily energy requirement for the building is given in Table 1.

Table 1: The daily energy requirement for a residential building

Electrical load type	Quantity	Load power (W)	Hours of operation(h)	Energy consumption (Wh)
Fluorescent lamps	10	40	6	2400
TV	1	100	5	500

Refrigerator	1	100	8	800
Fan	3	60	6	1080
Washing machine	1	250	0.5	125
Cell phone	3	2.5	6	45
Presing iron	1	1000	0.5	500
Clipper	1	15	0.25	3.75
Total		1567.5		5453.75

PV System Design

The operating voltage selected for a stand-alone PV system depends on the voltage requirements of the largest loads. When loads require ac power, the dc system voltage should be selected after studying available inverter characteristics. DC loads are mostly 12V or multiple of 12V.The efficiency and power handling capacity are better for system operating at higher dc voltage because of low current required to produce the required power. However, low DC voltage have been recommended [10] as this will significantly reduce the capacity of the inverter, even though expensive and hard to get switches, fuses and connectors will be required. Based on these factors, the operating voltage of the system is selected to be 24V DC

Sizing of solar PV module

A PV array is a combination of several solar cells. A single module of solar cell rarely provides the amount of the required energy needed for a residential building. The modules are connected together to get the desired energy. Generally, the modules in a PV array are connected in series to obtain the desired voltage and the individual strings are connected in parallel to produce the desired current. In this design, the module tilt angle is taken as the latitude of the location. The selection of a particular PV module for PV system is dependent on some characteristics and warranty in case of any failure. For this design, a Sunpower E20 A grade module has been selected. Detailed specifications of the module are given in Table 2.

Table 2. Solar module specification (www.kara.com.ng/solar-panel-140W-for-12V)

Module specification	
module capacity	140W
Nominal Voltage	12V
Nominal Current	5.79A
Open Circuit Voltage (Voc)	28.6V
Short Circuit Current (Isc)	6.25A
Cell Conversion Efficiency	20.80%
Operating Temperature	-40 to +85°C

The required average peak power of the PV array is determined by the following expression [10]:

$$PV_{peak\ power} = \frac{E_D}{\eta_{INV}\,\eta_{CON}\,T_{SH}}S_F \qquad (1)$$

=5453.75 x 1.2/0.9 x 0.85 x 5.1 = 1677.43175W

The number of PV modules in series [13]

$$NM_S = \frac{System\ Nominal\ voltage}{Module\ voltage} \qquad (2)$$

= 24/12 = 2 modules

and the number of modules in parallel

$$NM_P = \frac{PV_{peak\ power}}{NM_S\ X\ Module\ capacity} \qquad (3)$$

= 1677.4317/2 X 140 = 5.99 =6 modules

Thus, 12 modules will be required for the design 2 modules will be connected in series and 6 strings (each of 2 modules in series) will be connected in parallel.

Sizing of the battery

The battery is a vital part of the designed solar home system, as it should supply the adequate power to run all the loads at night, overcast and dusty days.

Batteries used in all solar systems are sized in ampere-hours under standard test condition of 25°C. Battery manufacturers usually specify the maximum allowable depth of discharge (DOD). In this design, the day of autonomy has been taken to be 4 days and the maximum allowable depth of discharge to be 80%. Assuming the battery efficiency is 85%. The storage capacity can be determined according to the following expression.

$$Storage\ Capacity = \frac{E_D\ X\ N_A}{DOD\ X\ System\ Nominal\ Voltage\ X\ \eta_{OUT}} \qquad (4)$$

= 5453.75 x 4/0.80 x24x0.765

=1485.23Ah

The battery selected for the design is Exide solar 6LMS200L. The specification of the selected battery is given in Table 3.

Table 3.specifications of battery [19]

Parameters	
Battery type	Lead acid type
Depth of discharge (DOD)	80%
Each battery voltage	12V
Each battery capacity	200Ah
C-rating	C-10

The number of batteries required (N_{BRE}) can be determined from the following expression

$$N_{BREQ} = \frac{Storage\ Capacity}{Capacity\ of\ selected\ battery} \qquad (5)$$

=1485.23/200
=7.43
= 8 batteries

The number of batteries connected in series and parallel can be obtained from the following equation

Battery in series = $\frac{System\ Nominal\ Voltage}{Voltage\ of\ a\ single\ battery}$ (6)

= 24/12
= 2 batteries

And battery in parallel = $\frac{N_{BREQ}}{Battery\ in\ series}$ (7)
=8/2
=4

The battery arrangement would be 2 batteries connected in series of 4 string of a parallel connection to give an overall number of 8 batteries.

Sizing of the inverter

The selected inverter must be able to handle the maximum expected power of the AC loads. When specifying an inverter, it is necessary to consider the requirement of the DC input and the AC output [16]. The DC input voltage of the inverter shall be compatible with the output of the storage bank voltage and should operate within the range of charge controller voltage. The output will be either single phase or three phase 230V/440V and 50HZ compatible to the AC loads. In most cases, the capacity of the inverter is taken to be the sum of the total power of all loads (inductive and resistive loads) running simultaneously and 3.5 times the total power of all inductive loads with large surge current. The total power output of all loads in the residential building is given as

P_{TOT} = Inductive load + Resistive load
The power delivered by inverter [11]

P_{INT} = P_{TOT} + 3.5(Inductive load)

The power delivered by the inverter is multiplied by a factor of 1.25 to make it 25% larger in capacity in order to allow for system expansion.

$$P_{INT} = 1.25[P_{TOT} + 3.5(\text{Inductive load})] \tag{8}$$

$$P_{INT} = 1.25[2052.5 + 1032.5]$$
$$= 3856.25W$$
$$= 4.0KVA$$

An inverter, EP30-4KW have been selected for this design. Detailed information about the inverter is given in Table 4.

Table 4. Inverter specification [20]

Parameter	**Power**	**4KVA**
Voltage	24V	
Frequency	50HZ/60HZ±0.3HZ	
Max Efficiency	>88%	

Design of battery charge controller

The function of a charge controller in a stand-alone PV system is to maintain the battery at the highest possible state of charge while protecting it from overcharging by the array and from over discharge by the loads. It has to be capable of carrying the short circuit current of the PV array. Some stand-alone PV system can be designed without the use of a charge controller [21]. In this design, a charge controller is required because the control strategy of a battery charge controller determines the effectiveness of battery charging and PV array utilization, the ability of the system to meet the load demands and extend the life of the battery. Charge controllers are generally selected by their size or ability to control a given amount of current and by their operating voltage [15].

The rated maximum current (I_R) of the charge controller is determined by the following expression.

$$I_R = NM_P \ X \ I_{SC} \ X \ F_{safety} \tag{9}$$

= 6x6.25x1.25
= 46.88 A

Based on this calculation, the TK50D charge controller has been selected. The detailed specification is given in Table 5.

Table 5. Charge controller specification [22]

Parameter	
Voltage	24VDC
Max battery charge current	50A

Number of voltage regulator required $=\frac{rated\ maximum\ current}{selected\ controller\ current}$

$=\frac{46.88}{50}$

. =0.94

=1

A charge controller will be required for the design

Sizing of the DC cable

Selection of appropriate cable size and type enhances the reliability and performance of the PV system design. The size of the wire must be able to carry the current at the operating temperature without excessive losses [16]. Two types of DC cables are required; battery to inverter DC cable and PV module and battery through charge controller DC cable. The dc-wires between the photovoltaic modules and batteries through the voltage regulator must withstand the maximum current produced by these modules. This current is given as the rated maximum current (I_R) of the charge controller determined in Eq (9).

The cross-sectional area of the cable is given by the following expression [11]

$$A = \frac{2\rho l I_R}{V_D} \qquad (10)$$

ρ is the resistivity of the cable material, taken as 1.724 x $10^{-8}\Omega m$, *is* the length of the cable, taken to be 1m, VD is a voltage drop, which is 4% of the PV module voltage.

A = 2 X 1.724 X 10^{-8} X 1 X 46.88/0.48

$=3.4 \text{ X } 10^{-6} m^2$

This implies that any copper cable of the cross-sectional area of $3.4 \text{ X } 10^{-6} m^2$, 46.88A can be used for the wiring between PV modules and batteries through the charge controller.

The DC wire from the battery to the inverter must withstand the maximum current at the input of the inverter. The maximum current carrying capacity of the cable is the continuous inverter input current rating when the inverter produces rated power at the lowest input voltage. The maximum continuous input current (I_M) is given as

$$I_M = \frac{P_{INVT}}{\eta_{INVT} \text{ X System nominal voltage}} \quad (11)$$

$= 4KVA/0.9X24$

$= 185.19A$

The cross-sectional area of the cable is given by the following expression [11]

$$A = \frac{2\rho l I_M}{V_D} \quad (12)$$

l is the length of the cable, taken to be 5m, VD is a voltage drop, which is 4% of the system nominal voltage.

$A = 2 \text{ X } 1.724 \text{ X } 10^{-8} \text{ X } 5 \text{ X } 185.19/1.92$

$=1.7 \text{ X } 10^{-5} m^2$

This implies that any copper cable of cross-sectional area of $1.7 \text{ X } 10^{-5} m^2$, 185.19A can be used for the wiring between the battery bank and the inverter.

The ac-wire from the inverter to the ac appliance in the residence must be determined. The cable must withstand the maximum current that the inverter can produce at full load. The maximum current from inverter at full load on the phase (line) is obtained by the following expression for a rated ac-voltage (Vac) of 220V.

$$I_{PHASE} = \frac{P_{INVT}}{V_{OUTPUT} \text{ X } \sqrt{3}} \quad (13)$$

$= 4000/220 \text{ X } \sqrt{3}$

$=10.50A$

The cross-sectional area of the cable is given by the following expression.

$$A = \frac{2\rho l I_{PHASE}}{V_D} \qquad (14)$$

l is the length of the cable, taken to be 20m, VD is a voltage drop, which is 4% of the AC voltage.

$A = 2 \times 1.724 \times 10^{-8} \times 20 \times 10.50/8.8$

$= 8.2 \times 10^{-7} m^2$

This also implies that any copper cable of the cross-sectional area of $8.2 \times 10^{-7} m^2$, 10.50A can be used for the wiring between the battery bank and the inverter.

Cost Estimate of the System

The price of the PV system and its installation are important factors in the economic assessment of a PV system. The life cycle cost (LCC) of the PV system includes the sum of all the present worth of the costs of the PV modules, storage batteries, charge controller, inverter, the cost of the installation, and the maintenance cost of the system. The details of the used cost data for all items are shown in Table 6.

Table 6. System component models and cost estimate

Components Model	Qty	Unit price(Naira)	Cost of components
Module			
Sunpower E20	12	25, 800	309, 600
Batteries			
Exide solar 6LMS200L	8	84,160	673, 280
Inverter EP30-4KW	1		180, 000
Charge controller TK500	1		21, 790
Sub total			1,184,670
Auxiliaries(cost of wire, fuses, breakers) 20% of the subtotal			236, 934
Total			1,421,604

For this design, the life cycle of the components will be considered as 25 years, except that for the batteries which will be considered to have a lifetime of 8 years. Thus, an extra 2 groups of batteries (each of 8 batteries) have to be purchased, after 8 years and 16 years, assuming an inflation rate i of 5% and a discount rate d of 6%.[23]

The cost of the first group of batteries (C) is given in Table 6

The present worth of the second group of batteries, after 8 years = $\frac{C(1+i)^{N-1}}{(1+d)^{N}}$

$$=\frac{673{,}280(1+0.05)^{7}}{(1+0.06)^{8}}$$

= N594,393

The present worth of the second group of batteries, after 16 years = $\frac{673{,}280(1+0.05)^{15}}{(1+0.06)^{16}}$

= N550, 987

The installation cost of a PV system can be estimated as 10% of the initial cost (Table 6) while the annual operation and maintenance cost is about 2% of the initial cost.

Life cycle cost = initial cost of PV system + cost of second and third groups of batteries + installation cost + operation and maintenance cost

= 1,421,604 + (594, 393 + 550, 987) + (0.1 x 1,421,604) + (0.02 x 25years x 1,421,604) = N3, 419,946

The study shows that to provide a residential building in Osogbo, Southwest Nigeria with energy, the building will require a PV system of a life-cycle cost of approximately 3.4 million naira which is about 9, 500 $ at an exchange rate of three hundred and sixty naira to a dollar.

Conclusion

This study presents the design and the life cycle cost analysis of the stand-alone PV system for a residential building in Osogbo, Nigeria. The study indicates that electrifying a residential building using PV systems is expensive and beyond the reach of average homeowners in Nigeria. It is recommended that government should provide policies that encourage and support the use of an alternative source of energy (solar technology) other than dependence on oil and gas via subsidizing the cost of system components. We also appeal to the manufactures of the PV system components to cut down the prices of the system components so as to make it affordable for domestic applications especially in rural and suburbs areas where there is no electricity grid.

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