DESIGN OF A STAND-ALONE PHOTOVOLTAIC POWER SYSTEM: CASE STUDY OF A RESIDENCE IN OGWASHI-UKWU, DELTA STATE

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Abstract

Stand-alone Photovoltaic (PV) system is increasingly finding application as a means of generating electricity. This system converts solar energy directly into electricity using photovoltaic principle in PV panel arrays. The electricity produced can be used to power most ac and dc electrical appliances. Inverter is used to convert the dc generated by the PV panels to ac for most domestic and industrial use. For continuous availability of power during days of autonomy (low insolation or cloudy days), battery storage system and charge controller (for battery charge and discharge control) are required. This paper considered the design of a stand-alone PV system that would be adequate to power a single residence and estimate the appropriate size of the solar panel, inverter, charge controller, battery, components interconnection wires and the system cost estimated. The sizing processes considered the quality of solar irradiation of the geographical location, effect of temperature de-rating, efficiency of components, system voltage selection, days of autonomy and load demand (in watt-hour). A residence in Ogwashi-Uku town was chosen as a case study. The minimum electrical load of 7.875kWh per day, household *wattage of 2.471kW was estimated. And 18 units of 24V 180W solar panels, 12 batteries of 12V/200AH, 60Amps charge controller, 3.5kW solar inverter are the designed components ratings for the case study.*

Keywords: Photovoltaic system, Stand-alone, Electrical load demand, Solar irradiation, System sizing, Component cost.

The enormity of solar power and its unrestricted availability to vast part of the earth surface makes it possible to harness this form of energy to meet the world energy demand. This would not only meet the energy need of the world, but can also become more and more attractive especially with the constant fluctuation in fossil fuel prices and its pollution risk to the preservation of the ecological cycle of the bio-systems on the earth. The direct conversion of solar energy into electricity using the photovoltaic (PV) system is considered as one of the important alternatives to this regard because its production is clean, freely infinitely available, highly reliable and also a very attractive power source for many applications, especially in rural and remote areas. Although it is very expensive to design or purchase, it is very cost effective to maintain and seen as more efficient than all other sources of renewable energy [5]. The present energy crisis in Nigeria is so alarming that poor services have forced most domestic and industrial customers to install their own power generators with very high running costs to themselves and the Nigerian economy [6]. Nigeria is situated between 3^o and 14^o East Longitude and 4^o and 14^o North Latitude and lies within a high sunshine belt where solar radiation is fairly well distributed.

The annual average of total solar radiation is varies from about 12.6 MJ/m2-day (3.5 kWh/ m2-day) in the coastal latitudes to about 25.2 MJ/ m2-day (7.0 kWh/ m2-day) in the far north. On the average, the country receives about 18.9 MJ/m^2 – day (5.3kWh/ m^2/day), and therefore has an estimated 17,459,215.2 million MJ/day (17.439 TJ/day) of solar falling on its 923,768 km^2**.** This is a good indication of the countries solar potential [6, 7].

Harnessing solar energy to power electrical appliances starts by converting the energy from the sun to electricity. A photovoltaic (PV) cell converts sunlight into electricity. These cells are quite small and are connected together to form larger units called modules which can be connected to form even a larger unit called array. These arrays are connected in parallels and series formations to meet the required electricity demand. PV arrays produce electricity only when illuminated and is therefore necessary to employ a large energy storage system, most commonly a series of rechargeable batteries. Also to prevent harmful battery over-charge and over-discharge conditions and to drive AC loads and a charge controller and converters have to be implemented [2]. PV systems can be used to exploit the solar energy in almost all applications. A stand-alone PV Systems are systems which use photovoltaic technology only and are not connected to a utility grid. The systems use the DC output of the PV modules to power DC loads, while a bank of battery is used to store energy for use when there is demand. The DC output of the batteries can be used immediately to run certain low DC Voltage loads such as lighting bulbs or refrigerators or it can be converted by an inverter to AC voltage to run AC-loads that constitutes most appliances. Off-grid PV system provides affordable electricity in area where conventional electricity grids are unreliable or non-existing [8].

Schematic of a typical stand-alone photovoltaic system is shown below in fig1

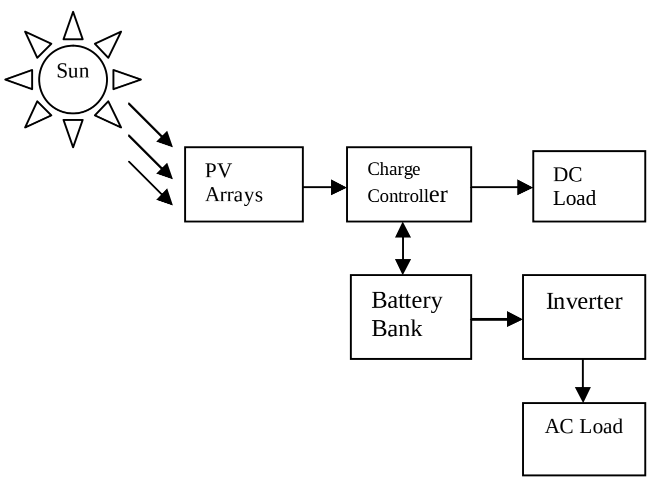

Fig 1 Block Diagram of Stand-alone Photovoltaic System

Site Meteorological Data

The site meteorological data is needed to predict the performance of the PV system of the site under consideration [1,10]. The site is located on; Latitude: 6°10'59" North, Longitude: 6°31'27" East and Elevation: 197 m a.s.l. This elevation in this means it is on a high topographical location to receive high enough sunshine suitable for good irradiation. Fig. 2 shows the solar irradiation (insolation) at different orientations. Table 1 showing the Monthly Average Daily Solar Irradiation for Ogwashi-Uku viz: when placed at horizontal (H_h), optimal inclination angle of 12degree (H_{opt}) and at 90 degree $H_{(90)}$. From the graph of the monthly global irradiation it shows that the average for the year is 4.64kWh/m^2/day and has a minimum of 3.45kWh/m^2/day in the month of September [8]. The lowest insolation month was considered in this design. By this, the Stand-alone PV system design will meet the load and keep the battery fully charged in the worst month of the average year [13]. These figures could be improved if a tracking system is incorporated in the design. This would increase the cost of system installation however.

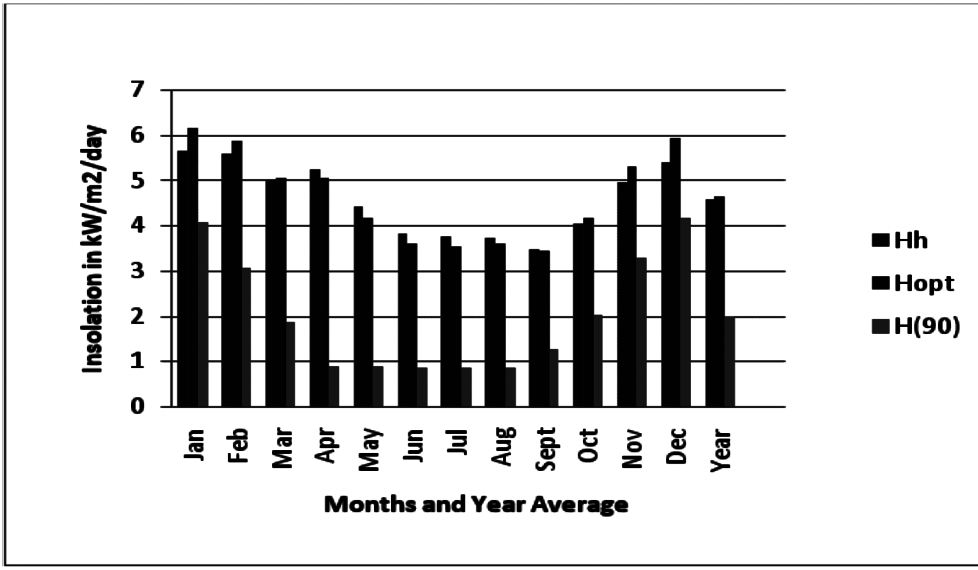

Fig 2 Incident Global Irradiation for Ogwashi-Ukwu Town

Table 1: Monthly Average Daily Solar Irradiation for Ogwashi-Uku

	H_h	H_{opt}	$H_{(90)}$
Jan	5.63	6.15	4.06
Feb	5.57	5.86	3.06
Mar	5.01	5.05	1.86
Apr	5.24	5.06	0.889
May	4.42	4.16	0.876
Jun	3.83	3.58	0.84
Jul	3.74	3.52	0.838
Aug	3.73	3.59	0.853
Sept	3.48	3.45	1.25
Oct	4.05	4.16	2.03
Nov	4.94	5.3	3.28
Dec	5.38	5.92	4.15
Year	4.58	4.64	1.99

Methodology

The first task was to determine the system load. This load estimate is one of the key factors in the design and costing of the stand-alone PV system. The electrical loads available at the resident were profiled with their respective power ratings and average operation hours during the day noted to obtain the power demand in watt-hour per day. The result of the analysis obtained was used to determine the proposed stand-alone photovoltaic system components sizes.

Resident Electrical Demand

The household is a medium size resident not requiring very large quantity of electrical energy. Table 2 below shows the various electrical appliances and their load chat.

Table 2: Electrical Load Demand for Residence

Load Description	Qty	Load Power(w)	Hours use (Hrs)	Load Power (W-h)
Refrigerator	1	260	6	1560
Television	2	120	5	1200
Toaster	1	750	0.4	300
Fan	4	65	4	1040
DVD Home Theater	1	60	4	240
Sat Decoder	2	25	4	200
Laptop	2	140	6	1680
Light	8	36	4	1152
Electric Iron	1	1000	0.5	500
Clipper	1	15	0.18	2.7
Total Power		**2,471**		**7,874.7**

The residence under consideration consumes an approximate electrical load of 7.875kWh/day of electricity and daily watt power of 2.471kW.

System Voltage Selection

The operating voltage selection for a stand-alone system is dependent on the voltage requirement of the loads and the total current. However in a standalone PV system, the voltage is also dependent on the inverters that are available. When loads require ac power, the dc system voltage should be selected after studying available inverter characteristics and ensuring it can provide the total and instantaneous ac power required. Since the total ac-load is greater than 2471W, the system voltage selected is 48vdc [13].

Pv Module Selection

The selection of a particular PV module for PV system is dependent on some characteristics and warranty in case of any failure; so as to enable replacement. It must also be compliant with some natural electrical and building codes. ENP Sonne High Quality 180Watt 24V monocrystalline is the solar PV panel proposed for this design.

Pv Array Sizing

The output power of PV array ($P_{Pv\ array}$) is determined by Equation. (1) [2]

$$P_{Pv\ array} = \frac{E_{ld}}{\eta_{B.O} \times K_{Loss} \times I_s} \times PSI \qquad (1)$$

Where

E_{ld} = Average daily load energy in kWh/day,

I_s = Average solar radiation in peak sun hour's incident for specified tilt angle in kWh/m^2/day.

PSI = Peak solar intensity at the earth's surface (1kW/m^2),

η_{BO} = Efficiency of balance of system

$$\eta_{B.O} = \eta_{inverterloss} \times \eta_{wiringloss} \qquad (2)$$

In this design, $\eta_{inverterloss}$ and $\eta_{wiringloss}$ are taken as 94% and 97% respectively

K_{Loss} = Factor determined by the different losses such as module temperature losses, circuit losses, dust, etc [4].

$$K_{Loss} = f_{man} \times f_{temp} \times f_{dirt} \qquad (3)$$

Where,

f_{man} = manufacturer's tolerance

f_{temp} = Temperature de-rating factor

f_{dirt} = De-rating due to dirt if in doubt, an acceptable de-rating would be 5% and is given by equation below, [4]

$$f_{temp} = 1 - \left(\gamma\left(T_{cell.eff} - T_{stc}\right)\right) \qquad (4)$$

Where,

γ = Power temperature co-efficient per °C

T_{stc} = Cell temperature at Standard Test Conditions, in °C

$T_{cell\text{-}eff}$ = the average daily effective cell temperature in degrees Celsius (°C) [14]

$$T_{cell.eff} = T_{a.day} + 25 \qquad (5)$$

Where,

$T_{a.day}$ = Daytime average ambient temperature in °C
This average is about 28°C
Substituting this value into equation 5 above, we have 53°C

From equation 4 above,

$$f_{temp} = 1 - \left(\gamma\left(T_{cell.eff} - T_{stc}\right)\right)$$

Using the selected manufacturers specification for the module, $T_{cell.eff}$ = 53°C, γ = 0.48%/°C T_{stc} = 25°C

$$f_{temp} = 1 - \left[\frac{0.48}{100}(53 - 25)\right] = 0.8656$$
$$f_{man} = 97\%$$

f_{dirt} = 95%

Substituting these into equation (3) we have

$$K_{Loss} = f_{man} \times f_{temp} \times f_{dirt}$$
$$= 0.97 \times 0.8656 \times 0.95$$

$$= 0.7976$$

From equation 2,

$\eta_{inverterloss}$ = 94% and $\eta_{wiringloss}$ = 97%

$$\eta_{B.O} = \eta_{inverterloss} \times \eta_{wiringloss}$$

$$= 0.94 \times 0.97 = 0.912$$

Substituting the above values into equation (1)

$$P_{Pv\ array} = \frac{E_{ld}}{\eta_{B.O} \times K_{Loss} \times I_s} \times PSI$$

$$= \frac{7.875}{0.912 \times 0.7976 \times 3.45} \times 1$$

$$= 3.14kW$$

Number of Modules in Series

Determining the number of modules that would be in series N_{ms} is designed to accommodate the system voltage required to power the entire load. This is achieved by dividing the designed system voltage V_{system} (usually determined by the battery bank or the inverter) with the nominal module voltage V_{module} at Standard Test Condition (STC) [2,14].

$$N_{ms} = \frac{V_{System}}{V_{module}} \qquad (6)$$

$$N_{ms} = \frac{V_{System}}{V_{module}} = \frac{48}{24} = 2 \text{ modules}$$

Numbers of Modules in Parallel

The number of modules in parallel N_{mp} is found using the equation below, and is determined by the dividing the designed array output $P_{Pv\ array}$ by the selected module output power P_{power} and the number of module in series N_{ms} [2].

$$N_{mp} = \frac{P_{pv\ array}}{N_{ms} \times P_{module}} \qquad (7)$$

$$N_{mp} = \frac{3.14 \times 10^3}{2 \times 180} = 8.7 \cong 9 \text{ modules}$$

The total number of modules is given by the product of the series and parallel modules, which is

$N_{mt} = N_{ms} \times N_{mp} = 2 \times 9 = 18$ modules

Storage (Battery) System Sizing

In the design of the capacity of the battery bank, it is necessary to consider some very important factors that determine the availability of power at all times, proper operation of the batteries, they include, the days of autonomy-days where there is little or no solar irradiation or cloudy days, allowable depth of discharge, possible battery loss, nominal system voltage of selected battery and estimated load energy in W-h [14]. The storage capacity can be calculated using the equation below [3,9].

$$C_B = \frac{E_{ld} \times N_a}{DOD \times V_{system} \times \eta_{bat}} \quad (8)$$

Where,
C_B = Required minimum battery capacity
N_a = Number of days of autonomy
DOD= Depth of discharge
E_{ld} = Average daily load energy in kWh/day
V_{system} = System voltage
η_{bat} = Battery efficiency

The battery selected is Rolls Series 4000 Deep Cycle batteries, T12 250, having the following characteristics, a capacity of 200AH, and a voltage of 12Vdc.

In this design, the days of autonomy is taken as 5 days, maximum allowable depth of discharge (DOD) taken as 50% and efficiency (η_{bat}) of 85%. Computing the battery capacity using the above variables gives us as below,

$$C_B = \frac{7.875 \times 10^3 \times 5}{0.5 \times 48 \times 0.85} = 1930\text{Ah}$$

Calculating the number of battery units required can be done using the equation below

$$N_{breq} = \frac{C_B}{C_{sel}} \quad (9)$$

C_B = 1930Ah
C_{sel} = 200Ah

$$N_{breq} = \frac{1930}{200} = 9.6 \cong 12 \text{ batteries}$$

The approximate number of batteries required would be 12 batteries.
To determine the number of batteries in series, we divide the nominal system voltage with the battery voltage

$$N_{bs} = \frac{V_{system}}{V_{bat}} \quad (10)$$

Applying the above expression gives us the series as

$$N_{bs} = \frac{48}{12} = 4 \text{ batteries}$$

We also have to calculate the number of parallel by applying the formula below.

$$N_{Pb} = \frac{N_{breq}}{N_{bs}} \qquad (11)$$

$$N_{Pb} = \frac{12}{4} = 3$$

The battery arrangement would be 4 series and 3 parallel combinations of 12Vdc 200AH Rolls 4000 series.

Inverter Sizing

When designing a system inverter size, the actual power drawn from the appliances that will run at the same time must be determined as a first step. Also, we must consider the possibility of having large motors with very high starting current by multiplying their power by a factor of 3. Also to allow the system to expand, we multiply the sum of the two previous values by 1.25 as a safety factor [3].

$$P_{invt} = (P_{rs} + P_{lsc}) \times 1.25 \qquad (12)$$

Where,

P_{invt} = Inverter power rating

P_{rs} = Power of appliances running simultaneously

P_{lsc} = Power of large surge current

This design does not have large surge current machines and as such, P_{lsc} is zero and

$$P_{rs} = 2.471\text{kW from table Table 2.0}$$

$$P_{invt} = (2471 + 0) \times 1.25 = 3088.75\text{W} \cong 3.50\text{kW} = 3.5\text{kVA}$$

From the above calculation, an inverter of 3.5kVA and 48VDC capacity was chosen. LS-3548 3500-W, 48-VDC, 220-Vac

Charge Controller Sizing

The charge controller regulates the flow of electricity from the solar modules to the battery bank. When the battery bank is low, the charge controller feeds all of the electricity from the array to the batteries. When the batteries reach a state of full charge, the charge controller stops or redirects the supply of electricity to prevent overcharging. Charge controllers are generally selected by their size or ability to control a given amount of current and by their operating voltage [4,10]. The rated maximum current of the charge controller is obtained by multiplying the short circuit current I_{sc} of the modules connected in parallel by a safety factor f_{safety} to allow for short periods of high irradiance produced by momentary cloud enhancement. The rated maximum current is given by this expression below [12,13].

$$I_{max} = N_{mp} \times I_{sc} \times F_{esafety} \qquad (13)$$

We consider a safety factor $F_{safety} = 1.25$

$$I_{max} = 9 \times 5.38 \times 1.25 = 60.525\text{Amps}$$

Xantrex C60 Charge Controller was considered for this design. The number of charge controllers needed is given by the equation below

$$N_{CC} = \frac{I_{max}}{I_{selected}} \qquad (14)$$

Where,
$I_{max} = 60.525$Amps and

$I_{selected} = 60$Amps

Therefore,

$$N_{CC} = \frac{60.525}{60} = 1.00875 \cong 1$$

Hence, 1 charge controller was selected

Sizing of System Cables

After sizing and selecting the major components, the interconnections wires are next. Selection of appropriate wire size and type enhances the reliability and performance of the photovoltaic system. The size of the wire must be capable of carrying the current at the operating temperature without excessive losses [13].

Cable Size: PV Module through Charge Controller to Battery

The maximum current produces by the PV panels is given by equation 13 [12],

$$I_{max} = N_{pb} \times I_{sc} \times F_{safety}$$

The cross section that would be adequate for this current would be given by equation 15 [11]

$$S = \frac{L \times I}{\gamma \times V_d} \qquad (15)$$

Where,
V_d = 2% of maximum allowed voltage drop for the 2 series array PV

$= \frac{2}{100} \times$ System Voltage at maximum power $= 0.02 \times 35.8 \times 2 = 1.432V$

L = distance from the PV array to the battery through the charge controller

$= 2 \times 15m = 30m$

$I_{max} = 9 \times 5.38 \times 1.25 = 60.525Amps$
$\gamma = 58m/\Omega.mm^2$ = Conductivity of copper
The cross section becomes

$$S = \frac{30 \times 60.525}{58 \times 1.432} = 21.86mm^2$$

The optimum wire size for this current is #3copper wire (AWG) which is equivalent to $25mm^2$ copper.

Cable Sizing between Battery Bank and Inverter (Inverter Input Circuit Current)

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 is producing rated power at lowest input voltage and is given by equation 16 below [12].

$$I = \frac{P_{invt}}{V_{DC} \times \eta_{invt}} \qquad (16)$$

Where,

η_{invt} = inverter efficiency = 94%
P_{invt} = 3.5kw
V_{DC} = 48V, at lowest possible of -2Vdc,

$$I = \frac{3.5 \times 10^3}{46 \times 0.94} = 80.9Amps$$

A minimum wire of #2 copper wire (AWG) equivalent to $35mm^2$ is required to terminate the battery and inverter. This selection takes into consideration the possibility of having 2Vdc drop at the inverter input.

Cable Size between Inverter and Load

The ac-wire from the inverter to the electric panel of the residence must withstand the maximum current that the inverter can produce at full load. This current is given by the following formula for a rated ac-voltage (V_{ac}) of 220V [12].

$$I_{maxinv} = \frac{P_{invt}}{V_{ac} \times pf} \qquad (17)$$

Where,

pf = power factor = 0.8

$$I_{maxinv} = \frac{3500}{220 \times 0.8} = 19.9\text{Amps}$$

An optimum wire size of #10 copper wires (AWG), equivalent to 6mm^2 was considered for this design.

Table 3: Results Obtained from Equipment sizing for the Proposed Off-Grid PV System

Component	Description of Component	Result
Load Estimate	Total Load Estimated	7.875 kWh/day
PV Array	PV module Capacity	3.14 kW
	Number of modules in series	2
	Number of modules in parallel	9
	Total Number of Modules	18
Battery Bank	Battery Bank Capacity	1930AH
	Number of batteries in series	4
	Number of batteries in parallel	3
	Total Number of batteries	12
Charge Controller	Capacity of Charge Controller	60.525Amps
	Number of charger controllers	1
Inverter	Capacity of inverter	3.5kVA
Wire	From module through charge controller to Battery	25mm^2
	Between Battery and Inverter unit	35mm^2
	From inverter to Load circuit	6mm^2

System Components Details

Table 4: Shows the System Component Model and Cost Estimate for Each

Component	Model	Qty	Unit Price (₦)	Component Cost (₦)
PV Module	ENP Sonne High Quality 180Watt 24V	18	30,000	540,000
Battery	Rolls Series 4000, T12 250, 200AH	12	30,000	360,000
Inverter	Ls-3548 3500-W 48Vdc	1		118,000
Controller	Xantrex C60 12/24/48Vdc Charge Controller	1	50,000	50,000
Sub-total				1,068,000
Other BOS costs (wires, fuses, circuit breakers etc) 20% of Sub-total				213,600
Capital cost				**1,281,600**
Running Cost 0.5% of Capital Cost				6,408
Total Cost				**1,288,008**

Cost per component = Qty × Unit price

Other balance of system cost around 20% of sub-total.

The running costs for PV solar system are negligible, but the annual maintenance cost may amount to 0.5% to 1% of capital cost of system [9].

Using 0.5%, this would amount to

= 0.5% of 1,281,600= ₦ 6,408.00

Overall cost of the system is

= ₦1,281,600+ ₦ 6,408.00= ₦ 1,288,008.00

Discussion

The proposed stand-alone PV system was designed based on estimated load demand in watt-hour rating of appliances. The result of the estimated daily demand is shown in Table 2. The result of which amounted to 7.875kWh/day. The detailed result of the design and component sizes are in Table 3 comprising of 18 ENP Sonne 180W, 24V PV modules which is capable of producing an array power of 3.14kW. The PV array design is composed of 9 parallel and 2 series so as to meet the desired current and voltages for the load system. The storage system consideration was designed to meet the load demand. Total of 12 numbers of 12Vdc 200AH Rolls 4000 series T12 250 with a bank capacity of 1930AH, having 4 series and 3 parallel battery combinations. The total current from the PV arrays is 60.525Amps and Xantrex C60 Charge Controller was selected for this design. The rating of the designed inverter for the conversion of dc to ac is 3.5kW, and Latronic Ls-3548 3500-W 48Vdc inverter was selected. The wire sizing considered the current carrying capacity of each of the components. Between the PV panel through Charge controller and the battery which carries a current of 60.525Amps, #3copper wire (AWG) which is equivalent to 25mm^2 copper wire was selected. From the design calculation, the optimum wire of #1 copper wire (AWG) equivalent to 35mm^2 is required to terminate the battery and inverter. While feeding the load distribution would require an optimum wire size of #10 copper wires (AWG), an equivalent of 6mm^2 which is adequate to carry the 19.02Amps the inverter is capable of delivering at full load. The complete system cost was also estimated to □1,288,008.00; the breakdown is highlighted in Table 4 and it also indicates that the bulk of the cost is tied to the PV modules and Batteries because of their numbers.

Conclusion/Recommendation

This study evaluated the sizing of a typical photovoltaic stand-alone system for a residence in Ogwashi-uku. The town is located on Latitude: 6°10'59" North and Longitude: 6°31'27" East and its Optimal inclination angle (tilt) is 12 degrees. The average solar irradiation for the case study is 4.64kW/m^2/day and the least which usually occurs in the month of September is 3.45kW/m2/day was used for the system design. By this, the Stand-alone PV system design would meet the load and keep the battery fully charged in the worst month of the average year. The system components are rated and their cost estimated based on the appliances electrical load demand in watt-hour. Sizes of cables for the various components interconnections are also design for the stand-alone system. The cost of system installation is on the high side, beyond the reach of the average home owners on the short term because of the initial cost implication, but it becomes more economical on a longer term bases since it has a lifespan of between 25-30years and other very important benefits to the environment should not be underestimated.

It is recommended that government should provide policies that encourage, support and consider other alternative outside the present dependence on oil and gas to renewable sources, particularly solar because of its abundance nature in Nigeria to meet some of the energy need of the populace and also ensuring that the cost of these components are subsidized so as to make it a lot more affordable for other small scale business and domestic applications especially in rural and suburbs areas where there are no electricity grid at all. The system should also be considered grid-interactive so as to enable disposition of excess power and policies that encourages it be put in place for producers.

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