ISSN 2348-1218 (print)
International Journal of Interdisciplinary Research and Innovations ISSN 2348-1226 (online)
Vol. 6, Issue 1, pp: (96-101), Month: January - March 2018, Available at: www.researchpublish.com

Standalone PV System Design and Sizing for a Household in Gombe, Nigeria

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Abstract: **The aim of this work is to give in detail the standalone PV system for a household in Gombe (Nigeria) with medium energy consumption is selected. The supply of sufficient and sustainable power provision to the country's citizens since the 80's has been an illusion when the signals to improve its power generation capacity to the nation have been neglected. The increase in activities of industry and the rapid growth of population necessitate the solar photovoltaic (PV) technology injection into the nations mix energy. In this study, direct current (DC) and alternative current (AC) appliances were considered. The total load power of these appliances is 3012.5 W. The array to load ratio determined as well as the daily watt-hour load shows that the use of hybrid system in this design is not recommended. To power these appliances, 31 modules, 18 batteries in the battery bank with system battery capacity of 4657.5 Ah and 3 charge controller are required. The use of stand-alone solar photovoltaic technology is recommended for sustainability, reliability and accessibility of power.**

Keywords: **Photovoltaic systems, Stand-alone, Appliances, Power, household.**

1. INTRODUCTION

The energy to sustain life in our solar system is provided by the sun. In our activities daily, energy plays an important role. The amount of utilization of energy by human beings in a country is one of the measured that is been considered the country has development and civilization. In residential establishments, industries and commercial electrical energy is useful. The economy of any country is enhances by the sustainability and availability electrical power of such nation. Due to declining electricity generation from domestic power plants, Nigeria faces serious energy crisis which are basically dilapidated, obsolete, and unreliable and in appalling state of disrepair, reflecting the poor maintenance culture in the country and gross inefficiency of the public utility provider [1]. Despite Nigeria's vast oil wealth, majority of Nigerians have no access to electricity and the supply to those provided is epileptic in nature [2]. According to the Nigerian energy policy report, it is estimated that the population connected to the grid system is short of power supply over 60% of the time [3]. Many industries have been force to reduce their productions in order to break even or they are forced to completely shut down due to inadequate and unreliable power supply. The industries that managed to survive have resorted to make their owned electricity which make them to increases the prices of their products. The use of small generators for electrification purposes has become the order of the day on household or residential bases. The small generating sets cannot power some household appliances such as air conditioners, refrigerators etc. and it release harmful gases to the atmosphere which is a thing of concern. In spite of the expectation that the current reforms in the power sector will boost electricity generation and supply in the country, the injection of solar photovoltaic system in the nation's energy mix is imperative.

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 [4]. This paper is an attempt to design a stand-alone solar photovoltaic system for household building application.

1.1 Case Study – A Typical Residence in Gombe:

Gombe town in Nigeria has an average solar irradiance of 980.7 W/m^2, 600 W/m^2 and 586.7 W/m^2 for clear sunny, cloudy and harmattan microclimatic seasons respectively. This level of solar irradiance has realistically portrayed that Gombe is sufficiently endowed with viable solar energy resource which ought to be exploited maximally to improve the quality of her teaming populace. Gombe is located in the northern hemisphere part of the earth at latitude and longitude of 10° and 11° respectively. This geographical location of Gombe 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.

2. DESCRIPTION OF THE SYSTEM

2.1. Photovoltaic Power System Components:

Solar Photovoltaic system includes different components that should be selected according to your system type, site location and applications. A Balance-of- System that wired together to form the entire fully functional system capable of supplying electric power and these components are:

1- **Photovoltaic (PV) module:** It is made from semiconductor and convert sunlight to electricity. The PV converts sunlight into DC electricity. The most common PV modules include single and polycrystalline silicon and amorphous silicon with other technologies entering the market.

2- **Battery** – stores energy for supplying to electrical appliances when there is a demand. Battery bank, which is involved in the system to make the energy available at night or at days of autonomy (sometimes called no-sun-days or dark days), when the sun is not providing enough radiation. These batteries, usually lead-acid, are designed to gradually discharge and recharge 80% of their capacity hundreds of times. Automotive batteries are shallow cycle batteries and should not be used in PV systems because they are designed to discharge only about 20% of their capacity [5].

3- **Solar charge controller** – regulates the voltage and current coming from the PV panels going to battery and prevents battery overcharging and prolongs the battery life.

4- **Inverter** – converts DC output of PV panels or wind turbine into a clean AC current for AC appliances or fed back into grid line. It is one of the solar energy system's main elements, as the solar panels generate DC voltage. Inverters are different by the output wave format, output power and installation type. It is also called power conditioner because it changes the form of the electric power. The efficiency of all inverters reaches their nominal efficiency (around 90 percent) when the load demand is greater than about 50 percent of rated load [6].

5- **Load** – is electrical appliances that connected to solar PV system such as lights, radio, TV, computer, refrigerator, etc.

2.2. Configuration:

The photovoltaic systems are classified according to how the system components are connected to other power sources such as standalone (SA) and utility-interactive (UI) systems.

In a stand-alone system depicted, the system is designed to operate independent of the electric utility grid, and is generally designed and sized to supply certain DC- and/or AC electrical loads.

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.

3.1. Residence Device

As a first step, the electrical devices available at the residence are itemized with their power ratings and time of operation during the day to obtain the average energy demand in Watt-hour per day as shown below in Table 1. The total average energy consumption is used to determine the equipment sizes and ratings starting with the solar array and ending with system wiring.

3.2 Sizing of the PV array

Before sizing the array, the total daily energy in Watt-hours (E), the average sun hour per day Tmin, and the DC-voltage of the system (VDC) must be determined. Once these factors are made available we move to the sizing process. To avoid under sizing, losses must be considered by dividing the total power demand in Wh.day-1 by the product of efficiencies of all components in the system to get the required energy Er. To avoid under sizing we begin by dividing the total average energy demand per day by the efficiencies of the system components to obtain the daily energy requirement from the solar array:

$$E_r = \frac{daily\ average\ energy\ consuption}{product\ of\ components\ effeciencies} = \frac{E}{\eta_b \eta_i \eta_c} = \frac{E}{\eta_{overall}} \quad (1)$$

Where

η_b = battery efficiency

η_i = inverter efficiency

η_c = charge controller efficiency

The previous result is divided by the average sun hours per day for the geographical location T_{min} to obtain the peak power.

$$p_p = \frac{daily\ energy\ requirement}{minimum\ peak\ sun-hours\ per\ day} = \frac{E_r}{T_{min}} \quad (2)$$

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.

$$I_{DC} = \frac{peak\ power}{system\ DC\ voltage} = \frac{p_p}{V_{DC}} \quad (3)$$

The number of parallel modules which equals the whole modules current divided by the rated current of one module I_r.

$$N_p = \frac{whole\ module\ current}{rated\ current\ of\ one\ module} = \frac{I_{DC}}{I_r} \quad (4)$$

The number of series modules which equals the DC voltage of the system divided by the rated voltage of each module V_r.

$$N_s = \frac{system\ DC\ voltage}{module\ rated\ voltage} = \frac{V_{DC}}{V_r} \quad (5)$$

The total number of modules (N_m) that form the array is then finally determined by multiplying the number of modules in series by the number of parallel modules which gives the required array size:

$$N_m = N_s \times N_p \quad (6)$$

3.3 Sizing of the Battery Bank:

The amount of rough energy storage required is equal to the multiplication of the total power demand and the number of autonomy days:

$$E_{rough} = E \times D \quad (7)$$

A safe energy storage (E_{safe}) is then computed by dividing the obtained estimated energy storage by maximum allowable depth of discharge (MDOD):

$$E_{safe} = \frac{energy\ storage\ required}{maximum\ depth\ of\ discharge} = \frac{E_{rough}}{MDOD} \quad (8)$$

The capacity of the battery bank needed in ampere-hours can be evaluated by dividing the safe energy storage required by the DC voltage of one of the batteries selected:

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

The total number of batteries is obtained by dividing the capacity C of the battery bank in ampere hours by the capacity of one of the battery C_b selected in ampere-hours:

$$N_{batteries} = \frac{C}{C_b} \quad (10)$$

The number of batteries in series equals the DC voltage of the system divided by the voltage rating of one of the batteries selected:

$$N_s = \frac{V_{DC}}{V_b} \quad (11)$$

Then number of parallel paths Np is obtained by dividing the total number of batteries by the number of batteries connected in series:

$$N_p = \frac{N_{batteries}}{N_s} \quad (12)$$

We proceed to the next system component once the sizing of the battery bank is made available [7].

3.4 Sizing of the Capacity of the Charge Controller:

The function of the charge controller is the controls flow of current. To withstand the maximum current produced by the array as well as the maximum load current, there must be a good voltage regulator. To obtain the sizing of the voltage regulator, you multiply the short circuit current of the modules connected in parallel by a safety factor F_{safe}. The result obtained gives the rated current of the voltage regulator I:

$$I = I_{SC} \times N_p \times F_{safe} \quad (13)$$

To make sure that the regulator handles maximum current produced by the array that could exceed the tabulated value, the factor of safety is employed. For instance, to handle a load current more than that planned due to addition of equipment. This safety factor allows the system to expand slightly.

To obtain the number of controller, we divide the Array short current Amps by current rating of one controller:

$$\boldsymbol{N_{controller}} = \frac{\boldsymbol{I}}{current\ of\ one\ controller} \quad (14)$$

3.5. Sizing of the Inverter:

The actual power drawn from the appliances that will run at the same time must be determined as a first step when sizing the inverter.

3.6. Sizing of the System Wiring:

Because of loses (about 3%) through cables, it is recommended that thicker cables be used.

4. RESULT

4.1 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 Energy Consumption

S\N	Appliance	Quantity	Power Rating (w)	Usage (h\d)	Usage (d\w)	Energy per Day (AC)
1.	32’’ Plasma TV	2	125	7	7	1750
2.	Satellite Receiver	1	25	7	7	175
3.	Fridge	3	150	12	7	5400
4.	Computer	2	65	4	7	520
5.	Electric Iron	1	1000	2	4	457
6.	Fluorescent Lamps	15	15	5	7	1125
7.	Cell Phone	5	2.5	5	7	63
8.	Ceiling Fan	6	120	7	7	5040
9.	DVD	2	25	7	7	350
10.	Blender	1	120	0.2	7	24
Total			3012.5			14904

Thus, the load profile of the residence is 14904 watt-hours per day and will be used to determine the stand-alone PV power system component sizes as detailed below.

4.1.1 Sizing of the Solar Array

The select panel is (Mitsubishi - MF180UD4, 180- W, V_{DC} = 24-V, I_r = 7.45-A).

The Specification of PV panel

Manufacturer: MITSUBISHI ELECTRIC.

Model name: PV-MF180UD4.

Cell type: Poly-crystalline Silicon.

Number of cells: 50 cells.

Maximum power rating STC (P_{max}): 180 watts.

V_{oc} (Open circuit voltage): 30.4V.

I_{sc} (Short circuit current): 8.03A.

V_{mp} (Maximum power voltage): 24.2V.

I_{mp} (Maximum power current): 7.45A.

Daily average demand (E) from table 1 = 14904 Wh.

Battery efficiency (η_b) = 0.85.

Inverter efficiency (η_i) = 0.90.

Charge controller efficiency (η_c) = 0.90.

The daily energy requirement from the solar array can be determined as following:

$$E_r = \frac{E}{\eta_b \eta_i \eta_c} = \frac{E}{\eta_{overall}} = \frac{1490}{0.68} = 21917.6\ Wh\backslash day.$$

To obtain the peak power of the PV: $p_p = \frac{E_r}{T_{min}} = \frac{21917.6}{4} = 5479.4\ W = 5.4\ kW.$

The total current needed can be calculated by: $I_{DC} = \frac{p_p}{V_{DC}} = \frac{5479.4}{24} = 228.31\ Amp.$

The number of parallel modules required: $N_p = \frac{I_{DC}}{I_r} = \frac{228.31}{7.45} = 30.6 \approx 31\ panels.$

The number of series modules required: $N_s = \frac{V_{DC}}{V_r} = \frac{24}{24} = 1\ panel.$

The total number of modules: $N_m = N_s \times N_p = 31 \times 1 = 31\ panels.$

The PV array of the system consists of 31 panels in parallel.

4.1.2. Sizing of the Battery Bank:

Total average energy needed is 14904 Wh\day.

Dark days = 3 days.

According to the selected battery (UB-8D AGM - 250 AH, 12V-DC) MDOD = 80%.

The amount of energy storage required is, $E_{rough} = E \times D = 14904 \times 3 = 44712\ Wh.$

For Energy safety, $E_{safe} = \frac{E_{rough}}{MDOD} = \frac{44712}{0.8} = 55890\ Wh.$

The capacity of the battery bank needed can be evaluated: $C = \frac{E_{safe}}{V_b} = \frac{55890}{12} = 4657.5\ Ah.$

The total number of batteries is obtained by: $N_{batteries} = \frac{C}{C_b} = \frac{4657.5}{250} = 18.63 \approx 18$

The number of batteries in series equals to: $N_s = \frac{V_{DC}}{V_b} = \frac{24}{12} = 2$

Then number of batteries parallel is obtained by: $N_p = \frac{N_{batteries}}{N_s} = \frac{18}{2} = 9$

The number of batteries needed is = 18 batteries. 9 parallel branches and 2 series batteries.

4.1.3. Sizing of the Voltage Controller:

According to selected controller (Xantrex C-60, 24- V, 60-A), the rated current of the voltage Controller

I: $I = I_{SC} \times N_p \times F_{safe} = 8.03 \times 18 \times 1.25 = 18.675\ Ah.$

The number of controller equals to $\boldsymbol{N_{controller}} = \frac{I}{current\ of\ one\ controller} = \frac{\mathbf{180.675}}{\mathbf{60}} = 3.011 \approx 3.$

We need 3 regulators connected in parallel.

4.1.4. Sizing of the Inverter:

Total power of the devices is 3012.5 W. inverter with 24 V, 3000 W – 3500 W, 220 V_{ac} output.

5. CONCLUSION

The geographic location of Gombe makes it to have 3 major microclimatic seasons namely harmattan, cloudy and clear sunny seasons with an average solar irradiance annually of 2167.4 W/m^2. It is enough alternative if efficiency tapped and it can provide clean source of energy, especially to the many rural community that cannot be reached through the conventional national electric grid. In this design, to meet the power demand of 3012.5 W of the appliances, the solar photovoltaic system with 18 batteries and 31 modules are required. The stand-alone solar photovoltaic has high initial cost but its durability, reliability, sustainability, ease of maintenance, environmental friendliness, and make the system attractive for residential and other pertinent applications.

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