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Design Analysis of 7.5KW Stand Alone Solar Photovoltaic Power System for an Intermediate Household

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Authors' contributions

This work was carried out in collaboration among all authors. Author RB designed the study and wrote the protocol. Authors TS and UAK wrote the first draft of the manuscript. Author MA managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Aim: Design Analysis of 7.5KW Stand-alone Solar Photovoltaic Power System for an Intermediate Household.

Methodology: A design analysis of standalone 7.5KW PV system was carried out using PV modeling equations based on load estimated. The analyzed data of the solar photovoltaic components was used to determine the estimated output power of 7.5KW. Therefore, a number of modeling equations and methodologies for designing a PV system based on application have been developed and simplified in order to ensure the optimum performance of the system. The analyzed solar powered 7.5KW system was achieved by designing 24 solar panels of 335W each, 16 deep cycle battery of 200A each, and a pulse width modulation (PWM) charge controller of 60A to monitor the output of the battery for safety operation. The battery will be connected to the inverter circuit (DC-AC) to generate 220V alternating current in its output via a step-up transformer. In this

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paper, design analysis of a standalone PV system enables of producing power to a household with approximate consumption of 7.5KW was conducted.
Results: The standalone PV system along with the cost implications was analysed and designed. In this analysis a sequential design plan of an independent standalone solar powered photovoltaic structure was analysed and overviewed to supply continuous and uninterrupted power to a typical utility with maximum power consumption of 7500W (7.5KVA). The calculated/computed values of all the components yield a result that can serve the purpose. Based on the design analysis, the result implies that the estimate consumption of 7.5KW in a day requires 24 PV panels of 335 Watts each, 16 (12V, 200Ah) batteries, 10KW inverter, (12V, 60A) charge controller and copper wire of cross-sectional area (1.688mm^2) for installation.
Conclusion: In Nigeria, to generate a solar power of 7.5KVA requires almost \$15,585.70 which is equivalent to N 5,965,426.66.

Keywords: Photovoltaic system; stand-alone; inverter; renewable energy.

1. INTRODUCTION

The renewable energy resources such as solar energy for electricity generation are rapidly increasing in most regions of the world. This is because as a result of the uncertainties surrounding the global oil and gas supplies and prices, and the unfavourable environmental impact of fossil fuel exploitation. Energy access, climate change, social and economic improvements are some of the compensation of using renewable energy sources than other sources of energy [1,2]. Photovoltaic effect is the natural reaction of producing electricity by the means of solar cells. Electricity generated using solar cells is more advantageous than the generation using other sources, because it produce electricity by just exposing it to sunlight, it has no any moving part, it is maintenance free and therefore it can last longer. Therefore, improvement of the size of PV system will be necessary in other to come up with possible solution to the energy demand. Designing a PV system will be flexible to suit any kind of utilisation which depends on the operational requirements [3]. These PV systems can be grid-connected system, stand-alone system, or hybrid system [4,5]. Specifically, a stand-alone PV system was analysed and designed in this work.

In most of the developing countries, public and private organizations and some individuals supplement the electricity provided by the national electricity grid with one that is independently supplied using their own diesel generators. It is estimated that about 90% of businesses in these countries own diesel generators [1]. The countries moderate this by depending heavily on electricity supply from diesel engine generators. But it has been shown that small to large electricity power demands can be met by the photovoltaic (PV) power systems [2]. Nafeh designed a standalone PV system to supply electricity to a remote-area household in Egypt [6]. The work studies a stand-alone photovoltaic (PV) system to provide the required electricity for a single residential household in Sinai Peninsula of Egypt. The complete design of the proposed system takes into consideration the site radiation data and the electrical load data of a typical household in the considered site. Ojosu argued that PV energy systems have special role to play in sub Saharan countries like Nigeria power production, because of its substantial solar energy resources with daily solar radiation average of between 4 and 6 kW/m2/day [7].

Standalone solar photovoltaic system mainly includes three parts: solar components; power electronic equipment such as charge-discharge controller, inverter, test instrumentation and computer control; battery or other energy storage and auxiliary power generation equipment, as shown in Fig. 1. The working principle of photovoltaic power supply system is that the electricity produced from the solar component will charge for the battery controlled by the controller, directly to the load power supply in the context of meeting the load demand under the sunlight. The battery supply power for the DC load under the control of the controller if the sunlight is lack or at night. The converter needs to translate AC into DC for the photovoltaic system with AC load [8].Therefore, the main aim of this analysis was to design and compute a cost effective PV system that can produce about 7.5KW, which can be able to power a small household.

2. METHODOLOGY

2.1 Photovoltaic System Design Analysis

The photovoltaic system development mainly entails the design analysis and cost analysis of the system. These are now considered in the following sub-sections.

2.2 System Description

The Photovoltaic (PV) system is composed of a variety of components in addition to the photovoltaic modules, a balance-of-system that wired together to form the entire fully functional system capable of supplying electric power; and these system elements are: [9,10].

- PV cells represent the fundamental power conversion units. They are made from semiconductors and convert sunlight to electricity. To increase the power output of PV cells, they are connected together to form larger units called modules. Modules, in turn, are connected in parallel and series to form a larger unit called panel.
- A storage medium (battery bank): stores the electrical energy produced by the PV cells, and makes the energy available at night or on dark days (days of autonomy or no sun days).
- A voltage regulator (or charge/discharge controller), reverses current and prevents battery from getting overcharged and over discharged.
- An inverter converts a low DC voltage into usable AC voltage; it may be a standalone installation or grid connected installation.
- AC and DC loads, appliances and devices, which consume the power generated by the PV system.

Fig 1. above, shows the interfacing arrangement of the standalone photovoltaic system with all the functional components.

2.3 System Design Analysis

The PV system analysis involve system sizing, which is the process of estimating the required voltage and current (power) rating for each component of the photovoltaic system to meet the electrical demand of the load estimated.

In this 7.5KW stand-alone PV system analysis, the quantity and size of the components involved will be computed to meet the requirement of the estimated power demand. The following investigations were carried out in other to design the load estimated PV system.

- **Location assessment:** this is the most significant aspect in designing a PV power system, because it facilitate in determining the possibilities of existence of PV system. The two quantities that influence the power generation from the PV system are solar irradiation and temperature. Before initiating any PV system these two quantities must be necessary. At constant temperature power generation from PV System increases with increasing solar irradiation therefore, the site location should be assessed in order to understand the amount of sun days in a year.

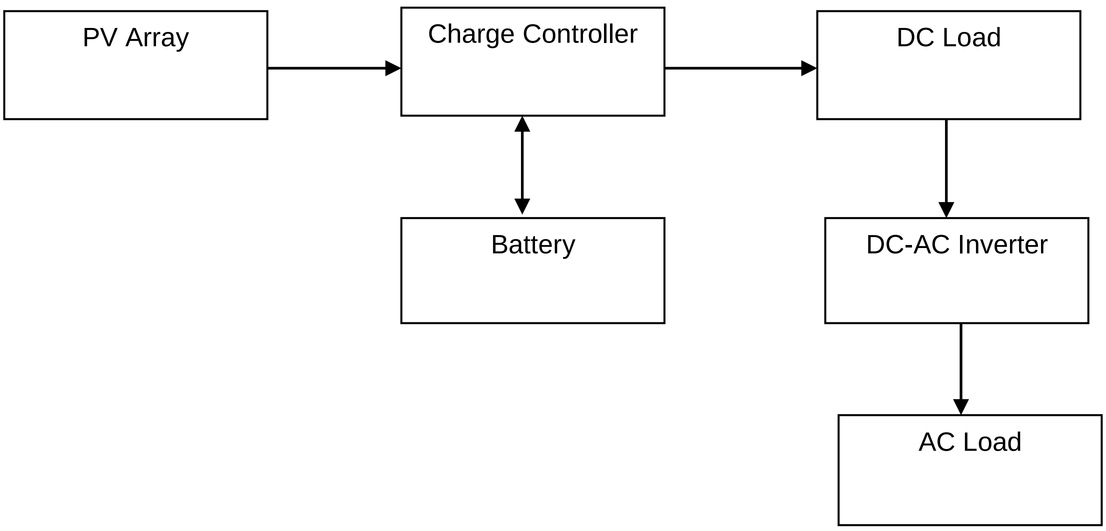

Fig. 1. Stand-alone photovoltaic system block diagram

- **Designing required load:** this is also another important aspect in designing PV system. It gives the total power rating of all the electrical appliances operated in the proposed designed household. The total load will be known by listing all appliances with their power ratings and operation hours and adding it to acquire the total average electric power demand in watt per hours or kilowatt per hours.
- **PV Panels quantification:** as soon as the total load required for the proposed household has been determined the next step is to know the quantity of PV module required to produce the power that perfectly operate all the electric appliances in the household. the following quantities need to calculated before knowing the number of PV panels going to be use:

  Total power use in a day = Total power of the appliances use per day.

  Total energy consumption in a day = Number of appliances use in watt-hours per day.

  The total energy required from PV panel = total energy utilization per day x 1.3.

Where, 1.3 is the factor of energy lost in PV system [11]. The lowest amount of PV module required is going to be equal to the total energy essential from PV module divided the product of power fact generation and watt-peak of PV module available.

- **Solar charge controller selection:** the appropriate charge controller that can match the voltage of PV module and storage battery must be selected for smooth operation of designed PV system. The function of charge controller is to prevent discharges and overloads in the battery bank, it can also protect the load under severe operating conditions and prevent charge in the battery from over-discharge.
- **Batteries Bank:** This is also very important components of a standalone solar PV system because in the night or cloudy days there will be no solar energy to operate the appliances. The battery system is essential for the storage of energy supplied by the photovoltaic system. For the battery to be used in solar PV system, it must be charged during the sun hours, there is need to find out the battery capacity that can store the required amount of energy estimated for consumption.
- **Inverter Selection:** Since the photovoltaic panels only supply direct current (DC) when enlighten by sunlight, it is required to convert this DC electric current into alternating current (AC). For the purpose of this conversion, an inverter is necessary; it acts as a combination component between the continuous electricity generated by the PV solar panel and the charge that requires alternating current. The power rating of an inverter must be greater than the total power of the estimated load, to make the system functioned appropriately. So the inverter rating should be 25% - 30% larger than the power of estimated load.
- **Cable designing:** the function of this stage is to analysed the appropriate type of wire that can be suitable for the current which will pass through it in order to maintain the consistency and the performance of our system.
- **Cost estimation:** Is to forecast the cost and other resources needed to complete the system design within the defined scope. This accounts for each components required for the this PV solar system. In PV systems the cost evaluation equal to the sum of cost of components, cost of stability of system component and the maintenance cost of the PV system per annum.

2.4 Load Estimation/Power Demands

To design the PV solar system, there is need to identify the total power of the loads which can be connected to the system and the energy consumption by the system also must be determined. These quantities can be determined as:

Total power use per day = Total power of appliances use per day.

Total energy consumption per day = Total appliances use in watt-hours per day.

Total energy of PV panels = Total energy consumption per day x 1.3 (1)

The power needed by the load in small household = 7500W

Energy consumption in one day = 20941wh/day

Total Energy required from the PV panel = 20941wh/day x 1.3 = 27223wh/day

2.5 Solar Photovoltaic Panels

In other to find out the number of solar panels, there is need to calculate the total watt-peak rating needed from the PV panel to generate the operational power of the appliances in the household, and the panel generation factor for the site location must to be taken in to consideration. In Nigeria, the average panel generation factor is 3.62 according to the reviewed literature.

Number of system PV modules = Total watt-peak rating require to operate the appliance divided by watt- peak of the PV module available for you.

$$Nm = 1 \text{ module} \times \frac{\text{watt–peak rating}}{\text{rated output peak of the PV available}} \quad (2)\ [11]$$

Where: Nm = number of PV modules

The total power required for the appliances = Total PV power required from panel divided by panel generation factor.

$$\text{The total watt- peak rating} = \frac{\text{total energy required}}{\text{module generation factor}} \quad (3)$$

The panel generation factor was used for calculating the number of solar photovoltaic cells. It was a unstable factor that depends on climate of the site location. For instance, in Nigeria it is 3.62, in European countries it is 2.93 and in Indian it is 4.32. [12,8]

The total Power required = 27223wh/day/ 3.62 = 7520.2W

Power of Solar PV panels use = 335W

The number of PV modules for the system = 7520.2W/335W

= 22.448 panels = 23 Panels

The number of PV panels required = 23 PV panels

Therefore, the system required at least 23 PV panels of 335W PV module.

$$N_{ms} = \frac{\text{V system}}{\text{Vmodule}} \quad (4)\ [13,14,15]$$

= 1 module x $\frac{48V}{24V}$ = 2 panels required in series PV modules

$$N_{mp} = \frac{N_{mt}}{N_{ms}} \quad (5)\ [13,14,15]$$

= 1 module x $\frac{23}{2}$ = 11.5 Panels = 12 Panels required in parallel PV array

$N_{mt} = N_{ms} \times N_{mp}$

$= N_{ms} \times N_{mp} \times P$ module (7)[13,15]

= 2 x 12 x 335W

= 8040W = 8.04KW

Where: N_{mt} = Total number PV panels
N_{mp}= Number of PV panels in parallel
N_{ms} = Number of PV panels in series.

Therefore, total of 24 PV can generate the required power for the system. Two (2) panels are to be connected in series and twelve (12) panels connected in parallel.

2.6 Determining Photovoltaic Inverter Size

The inverter will be taking into account because the power required by the system is AC. The power rating of the inverter must be greater than the total power of the appliances and also, the inverter must have the same nominal voltage as the storage battery. The input power of the inverter should be 25-30% larger than the power of the appliances in household.

For the grid connected system, the input power of the inverter should be the same as PV panel's power in other to allow smooth and efficient operation [11].

The total power required for the appliances = 7500W

Inverter size = total power ×130% (8) [11]

Inverter size = 7500 x 130% = 975000W

Therefore, the appropriate inverter size is 975000W or little bit bigger than 975000W. One unit inverter with power rating of 10KVA was selected for this system.

2.7 Number of Storage Batteries Determination

To find out the size of the storage battery of PV system, it is necessary to calculate the number of days that the system being able to operate in the absence of sunlight and the maximum discharge rate of the battery. The battery size must be big enough to handle the load coming from the PV panels and store enough power for the appliances when there is no solar radiation/sunshine. The voltage of the battery bank can be 12V, 24V, 48V or 96V which depends on the amount of voltage produce by PV system. For the PV system battery of 12V and 105Ah (storage capacity) the energy stored for the battery = 12V x 105 AH = 1260Wh. That means it can power 100W appliance for 1260wh/100W=12.6 hours on fully charged battery.

The battery capacity should be large enough to store sufficient energy to operate the appliances when there is no solar radiation.

$$\text{Size of battery} = \frac{\text{C x n}}{\text{0.85 x 0.6 x V system}} \quad (9)\ [11]$$

Where: 0.85 = battery loss
0.6 = depth of discharge
V_{system} = 48V,
C = Battery capacity
n = non-sunshine days.

Battery size of 3 non-sunshine days = $\frac{\text{24990Wh x 3days}}{\text{0.85 x 0.6 x 48v}}$ = 3062.5Ah

For the reference battery capacity = 200Ah

$$N_{bt} = \frac{\text{battery bank capacity}}{\text{capacity of reference battery}} \quad (10)\ [13]$$

$$= \frac{\text{3062.5Ah}}{\text{200Ah}} = 15.3215 \text{ batteries} = 16 \text{ batteries}$$

So the PV system requires 16 batteries.

$$N_{bs} = \frac{\text{Vsystem}}{\text{Vbattery}} = \frac{\text{48V}}{\text{12V}} = 4 \text{ batteries} \quad (11)\ [14]$$

$$N_{bp} = \frac{N_{bt}}{N_{bs}} = \frac{16}{4} = 4 \text{ batteries} \quad (12)\ [15]$$

$$N_{bt} = N_{bs} \times N_{bp} = 4 \times 4 = 16 \quad (13)\ [15]$$

Where: N_{bt} = number of total battery
N_{bs} = number of battery in series
N_{bp} = number of batteries in parallel.

The PV system required 16 storage batteries, 4 batteries connected in series and also 4 batteries connected in parallel.

2.8 Estimation PV Charge Controller

The purpose of a charge controller is to regulate the charge in the battery, stop overcharging and reverse current flow during night. The Pulse width modulation (PWM) or Maximum power point tracing (MPPT) are the suitable controllers for smooth and efficient operation. The determination of charge controller size depends on the total PV input current which delivered to the controller and also depends on PV panel arrangement (series or parallel arrangement). The following equation represents the calculation of the charge controller's capacity:

$$I_{rated} = (N_{bp} \times I_{sc}) \times 1.3 \quad (14)\ [15]$$

In this analysis, the short circuit current of PV panels = 8.96A

$$= 4 \times 8.96 \times 1.3 = 46.592\text{A} = 47\text{A}$$

Where: I_{rated} = solar charge controller current rating
I_{sc} = short circuit current
N_{bp}= number of parallel batteries
1.3 is safety factor.

Therefore, the charger controller should be rated 47A or little bit larger. One unit of solar charge controller of 60A rating is required.

2.9 Calculating Required Wire Size

In order to calculate the required wiring, it is significant to consider the length of the cables (in order to avoid losses caused by the Joule Effect), where the shortest possible length, voltage drops and wiring resistance can be minimized. When the size and type of wire are well selected this improves reliability and performance of PV system. Equation 15 was used in determining the cross sectional area of the wire.

$$S = \frac{PXL}{R_{PV}} \quad (15)\ [14]$$

Where:

S = Conductor's section (mm2)
L = Conductor's length (m)
P = Conductor's resistance (Ω.mm2/m)
R_{pv}= Photovoltaic system's resistance (Ω)

3. RESULTS

Table 1. Determined components sizes of the PV system

Components	Components descriptions	Components ratings
Estimated Load	Daily estimated load consumption	27223wh/day
Solar PV Panels	Solar PV power	8040W
	PV panels connected in series	2
	PV panels connected in parallel	12
	Total PV panels	24
Battery bank	Battery bank capacity	3062.5W
	Number of batteries in series	4
	Number of batteries in parallel	4
	Total number of batteries required	16
Charge controller	Current rating of charge controller required	47A
	Number of charge controller	1
Solar Inverter	Power rating of inverter required	11KVA
Connecting wires	An AWG14 multi-core copper wire	47A, 1.628mm^2

Table 2. Cost estimated of the analyzed PV system's components (1$ = N382.75) [16]

Device	Model	Quantity	Unit price ($)	Cost ($)	Cost (N)
Solar panel	Panasonic VBHN335SA17 Mono solar panel	23	336	7,728.00	2,957,892.00
Battery	UPG 45965 UB-4D 12V 200Ah	16	395.95	6,335.20	2,424,797.80
Charge controller	SUNTANT ZHC 60A PWM	1	173.50	173.50	66,407.125
Inverter	GROWATT 12KW 3 Phase	1	899	899.00	344,092.25
Wires, fuses	Copper wire, 15A,20A,30A and 45A fuses	Many		250.00	95,687.50
Installation cost				200.00	76,550.00
Total				15,585.70	5,965,426.66

4. DISCUSSION AND CONCLUSION

The standalone PV system along with the cost implications has been analysed and designed. In this analysis a sequential design plan of an independent standalone solar powered photovoltaic structure was analysed and overviewed to supply continuous and uninterrupted power to a typical utility with maximum power consumption of 7500W (7.5KVA). The calculated/computed values of all the components yield a result that can serve the purpose. The system analysed parameters that yields a load estimation of approximately 7.5KW involved 24 PV Panels of 335Watts each, 16 units of (12V, 200Ah) batteries, 10KW inverter, (12V, 60A) charge controller and copper wire of cross-sectional area (1.628mm^2) for installation. Generally this work was aimed to analysed a designing of standalone solar PV system to supply a single utility. This design analysis of a stand-alone PV System was conducted according the environmental conditions of Nigeria; stand-alone PV systems are a good solution that contributes to problems arising from climate change and the development of alternative energy resources. In Nigeria, to generate a solar power of 7.5KVA requires almost $15,585.70 which is equivalent to N 5,965,426.66.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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