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Design methodology and implementation of stand-alone solar photovoltaic power system for daily energy consumption of 9.16 kWh

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Abstract

This stand-alone solar photovoltaic power system was designed to power a daily energy consumption of 9.16 kWh reliably, by means of photovoltaic only. The design involves different components whose capacities depend on 9.16 kWh daily energy consumption and 1-day autonomy, including several factors that determine the choice of selection. After implementation, the system was put to the test for two days to ascertain the design validity and check if it would be able to sustain the daily load demand for 24 h without failure. The results reveal that the design methodology employed for the stand-alone system in this study is accurate and reliable because the system was able to power the load interminably for 34 h, with a resulting 0.6% DoD at the end of the test. This was due to the complete energy balance that the design methodology offers. Day 1 shows that the overall PV array power was 208% higher than the daytime load power and 61.2% higher than the overall daily load power. While Day-2 shows the overall PV array power to be 130% higher than the daytime load power and 56.3% higher than the overall daily load power, The energy balance between PV array, battery, and load size was completely and sufficiently achieved on both days, as the highest depth of discharge recorded during the test was 48.7%. The study reveals that through a complete energy balance between PV, battery, and load size, a standalone PV system can reliably sustain daily energy demand. It aims to design a stand-alone PV system capable of reliably sustaining daily energy demand without the need for long days of autonomy, so as to help prevent failures in solar PV projects that come as a result of inappropriate sizing, planning, and a lack of technical know-how.

1. Introduction

Solar energy has become the major alternative source of power generation, especially in Nigeria, where epileptic power supply is constantly met [1–3]. This epileptic power problem in Nigeria gave rise to demand for solar electricity, and this has led to so many quick and improperly planned solar projects that later failed or were abandoned [4, 5]. The author in reference [6] reveals that problems like inappropriate charging of batteries, wrong materials, batteries of lesser capacity, lack of careful planning, and lack of technical know-how are all attributed to causes of failure in solar PV projects in Lagos State. Presently, the issues of inappropriate charging of batteries still persist, especially in stand-alone PV system projects, due to the common practice of choosing long days of autonomy, which always result in a larger battery capacity and a very smaller PV array size.

Generally, a stand-alone solar photovoltaic power system is an off-grid solar power system that produces electricity from two sources, namely PV modules and Batteries. It's a system that is not connected to the electric grid; in fact, it is mostly used in countries with extreme epileptic power supplies and in areas that have little or no access to the electric grid [7–9]. This system comprises four major components, which are PV modules (commonly called solar panels), batteries, an inverter, and a charge controller [10]. Out of these four components, batteries and solar panels are the major components that determine the performance of any standalone PV system [11]. In many stand-alone PV system-related publications, days of autonomy are one of the factors used to determine the capacity of batteries, as they are directly proportional to battery capacity and inversely proportional to solar panel capacity [12–15].

Most stand-alone publications show that days of autonomy in a stand-alone PV system should be 3–4 days. As a result, PV professionals are compelled to reduce the capacity of PV array size in lieu of battery size in stand-alone PV system design so as to reduce its high cost implication and the larger space that PV module installation will require. This might lead to battery undercharging, a slow charging rate (ampere), and inappropriate charging of the battery. Hence, using 3–4 days of autonomy in a standalone PV system usually results in a large battery size and a very small PV array size.

Days of autonomy are the number of days the battery bank in a standalone PV system can solely provide power backup for the load connected to the system without being recharged. Days of autonomy range from 1–5 days [12], while the common days range from 3–4 days of autonomy in the design of a stand-alone PV system. In our study, we aim to design a stand-alone PV system capable of sustaining daily load demand interminably and reliably without the need for long days of autonomy.

The author in reference [12] employed the Australian/New Zealand standard method to design a solar electric power system for small islands in Indonesia, using a battery capacity of 783.360 kwh and a PV array capacity of 39 kw for 4-day autonomy, to power a total load capacity of 149.474 kwh. In reference [13], the author estimated the battery and PV array capacity required to power a household load of 6.522 kwh and a base transceiver station of 45.360 kwh in Delhi, India, by considering 3 days of autonomy. For a 6.522 kwh household load, the author estimated 21.6 kwh of battery capacity and 1.95 kw of PV array capacity, while for the 45.360 kwh base transceiver station load, he estimated 189 kwh of battery capacity and 16.25 kw of PV array capacity. The author in reference [14] designed a stand-alone solar power system for a house in Iraq with a total load capacity of 5.7 kwh by using a 24 kwh battery capacity, and 1.980 kw PV array for 3 days of autonomy. These are so evident that long days of autonomy are often considered in stand-alone PV systems with large battery storage sizes and small PV array sizes.

Reviewing the optimal battery storage percentage for grid-tied solar PV systems, the author in reference [15] indicated that when PV array size is equal to load size, the optimal battery size is 18.3% of the residential load demand under South African solar irradiance. This indicates a small battery storage size and a large PV array size for a grid-tied solar PV system.

In this study, batteries were mainly planned for energy storage during the daytime with minimal discharge and for use at night. As noted by the author in reference [11, 16], batteries can cause failure in the PV system if the availability of time to charge the batteries at daytime is insufficient and if battery energy storage is not appropriately sized. For effective energy storage, charging current (Ampere) from the PV array should not be less than 10% of the battery's rated capacity; this we have taken into consideration in this study. Hence, we have sized our PV array capacity and battery capacity in an appropriate ratio for efficient charging of the batteries within a few hours per day. Also, the charge controller was appropriately selected to handle the charging current coming from the solar panels and prevent the batteries from overcharging.

The energy balance between the energy produced by the PV array and the energy consumed by the load is another important area of concern in stand-alone PV systems [17]. When the energy produced by the PV array is less than the energy consumed by the load and is not sufficient to charge the batteries as well, this will result in an energy imbalance, thereby causing rapid draining of the energy stored in the battery. Therefore, we have ensured that the energy produced from our PV array is sufficient to sustain the load consumption while charging the batteries simultaneously during the daytime.

Similar to the procedure mentioned by the author in reference [18], the procedures in our design involve a site survey and climatic condition assessment, load energy consumption assessment, and sizing of components. The design was implemented in Ibadan, Nigeria, and the results obtained were analyzed by considering battery depth of discharge, state of charge, and energy balance between PV array and load power. The results were also compared with previously cited references of stand-alone PV systems with 3–4 days of autonomy.

Table 1. Details of the daily load schedule.

Load details	Load power (W)	Load quantity	Total load power (W)	Daily load plan (Hours)		Daily energy consumption (kWh)
				Day	Night	
Lighting Bulbs	5 W	5	25 W	—	12 h	0.3 kWh
Security Bulbs	15 W	4	60 W	—	12 h	0.72 kWh
CCTV Security System	80 W	1	80 W	12 h	12 h	1.92 kWh
LED TV	100 W	1	100 W	6 h	6 h	1.2 kWh
Fan	60 W	2	120 W	6 h	12 h	2.16 kWh
Laptop	60 W	1	60 W	6 h	6 h	0.72 kWh
Refrigerator	200 W	1	200 W	6 h	—	1.2 kWh
Water Pump Machine	940 W	1	900 W	1 h	—	0.94 kWh
TOTAL			1545 W			9.16 kWh

2. Methodology

The daily load demand is the combination of daytime and nighttime loads. The loads were purposely scheduled for daytime and nighttime so as to allow energy balance. Hence, batteries were mainly planned for energy storage during the day with minimal discharge and for sufficient use at night. The solar PV array converts sunlight into direct current electricity during the day to sustain daytime loads and charge the batteries simultaneously. A charge controller was used to regulate the charging of the batteries, while an inverter was used to power the load by converting the output DC electricity (either from the PV array or battery) to alternating current. The implementation of the system is divided into six different running heads, as given below:

2.1. Site survey and energy consumption assessment

The site location was in Ibadan (latitudes 7.3775°N and 3.9470°E). The site was first surveyed to check if the building roof was not covered with shade from neighboring trees and tall buildings within the vicinity. The slope of the roof facing south was also checked to see if it met the required tilt angle of the solar panel for efficient solar energy collection. An average of 4 h of bright sunlight were observed at the site, and the average solar irradiance per day ranged from 3.6 kW m^{-2} to 4.0 kW m^{-2} [NREL]. After the site survey, a load audit and power consumption assessment were carried out at the installation site by using a power analyzer to determine the power consumption of appliances that will be connected to the stand-alone solar system. The power analyzer measures the voltage, current, frequency, and power of each appliance. Most of the appliances with high power consumption were scheduled for use in the daytime, while low-power appliances were scheduled for use at night so as to minimize energy consumption from batteries at night and allow energy balance between load and battery. Table 1 displays the details of energy consumed (in kWh) for the planned stipulated duration per day.

The total power consumption of appliances that were planned to be put to use in the Daytime is given as:

$$D\_time = \sum_{t=1}^{12} (P_{D\_time} \times t) \tag{1}$$

Where P_{D_time} = Load power in the Daytime, t = time in hours

$$D\_time = 4.780 \text{ kWh}$$

The total power consumption of appliances that were planned to be put to use at Night-time is give as:

$$N\_time = \sum_{t=1}^{12} (P_{N\_time} \times t) \tag{2}$$

Where PN_time = Load power in the Night-time, t = time in hours

$$N\_time = 4.380 \text{ kWh}$$

2.2. Inverter sizing

Based on the total load power (1545 W) and the surge power of the water pump machine and refrigerator, the inverter capacity was rated twice the load power [19, 20]. Hence, by taking the power factor into consideration,

$$\text{Inverter Size} = \frac{\textit{Total Load Power}}{\textit{Power factor}} \times 2 \tag{3}$$

Table 2. 3500 VA, inverter specification.

Inverter description	Output specification
Brand Name	Soccer Power
Capacity (VA/Watts)	3.5 kVA or 3,500 VA
Battery Voltage	24 Vdc
Output voltage	220–230 Vac ±2%
Output Phase	1 Phase
Output wave form	Sine Wave
Output Power Factor	0.8
Output frequency	50/60 Hz (±0.05%)

$$= (1545 \div 0.8) \times 2 = 3862.5 \text{ VA}$$

= **3500 VA (Approx)**. The nearest rated capacity.

Therefore, a 3500 VA Soccer Power inverter size was used to power the required load power of 1,545 W The output voltage specification of the 3,500 VA inverter for this design is shown in table 2 [21].

2.3. Battery sizing and connection

The total daily energy consumption of 9.16 kWh and 1-day autonomy were used to determine the battery capacity. Considering the battery depth of discharge (DoD), all battery manufacturers recommend keeping battery DoD below the maximal limits of 100%, ideally, 80% or less is recommended [22].

Therefore, the battery DoD considered in this design was 80%. A Flooded Lead-Acid (FLA) battery type was used.

$$\text{Battery Capacity} = \frac{E_{Daily} \times D_{Autonomy}}{DoD} \tag{4}$$

$$\text{E}_{Daily} = \textit{Daily energy consumption}$$

$$D_{Autonomy} = 1day \quad DoD = 0.8$$

$$\text{Battery Capacity} = 9.16 \text{ kWh} \div 0.8 = 11.45 \text{ kWh.}$$

2.3.1. Number of batteries

The number of batteries used to achieve the 11,450 Wh battery storage capacity was calculated as follows:

$$\text{No of Batteries} = \frac{\textit{Battery Storage Capacity}}{\textit{Watts of one Battery}} \tag{5}$$

The battery used was rated at 12 V, 220 Ah; hence, the watts of one battery = 12 V × 220 Ah = 2640 Wh

$$\text{Number of Batteries} = 11,450 \text{ Wh} \div 2640 \text{ Wh}$$

$$= 4.34 \quad = 4(\text{Approx.})$$

4 batteries of 220 Ah at 12 V were therefore connected together to achieve a total battery size of 11,450 kWh (at fully charged capacity).

2.3.2. Batteries connection

Based on the 24 Vdc rating of the 3.5 kVA inverter as shown in the specification, the 4 batteries were connected both in series and parallel to give a voltage of 24 Vdc so as to match the input dc voltage of the inverter (24 Vdc).

Since one battery is rated at 12 V/220 Ah, two batteries will be connected in series and then in parallel to give a total battery storage rating of 24 V/440 Ah, which is equivalent to 10,560 Wh at nominal battery storage capacity. The connection is shown in figure 1.

2.4. Solar PV array

Solar PV array capacity depends on the charging duration, while charging duration was determined using the hours of sunshine per day at the installation site. During site survey, a 4-hours bright sunshine was observed, hence a 4 h charging duration was scheduled for the charging of the four batteries per day.

$$\text{PV Array Capacity} = \frac{\textit{Battery Storage Capacity}}{\textit{Charging Duration}} \tag{6}$$

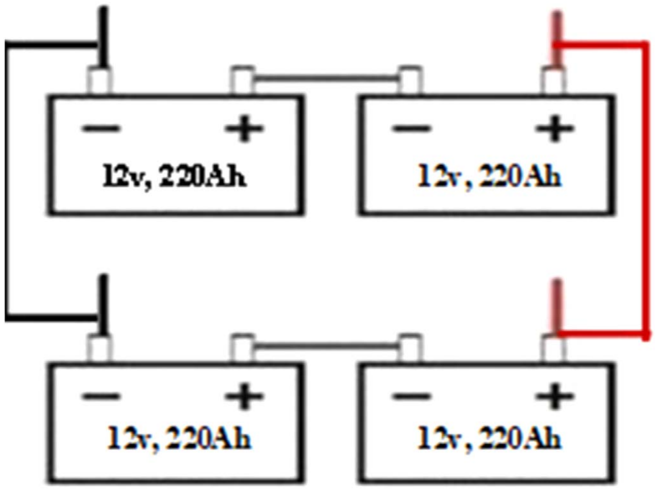

Figure 1. Connection of the 4 batteries.

Table 3. Specification of the 330 W PV module at standard test condition [23, 24].

330 W PV module specification at STC	Rating
Maximum Power (Pmax)	330 W
Open Circuit Voltage (Voc)	45.9 Vdc
Short Circuit Current (Isc)	9.31 A
Maximum Power Voltage (Vmp)	37.5 Vdc
Maximum Power Current (Imp)	8.80 A
Weight	49.4 lbs
Dimensions	77.2″ × 39.1″ × 1.57″
Maximum System Voltage	1000 Vdc

$$= 10,\ 560\ \text{Wh}\ \div\ 4\ \text{h}\quad = 2640\ \text{W}$$

Since solar panels are not 100% efficient, an inefficiency of 20% of the total capacity was added. Hence, PV Array Capacity = 2640 W × 1.2

$$= \mathbf{3000\ W}(\text{Approx.})$$

2.4.1. Number of solar panels to yield 3000 W capacity

$$\text{Number of Solar Panels} = \frac{Solar\ PV\ Array\ Capacity}{Watt\ of\ one\ Solar\ Panel} \tag{7}$$

To minimise cost, a fairly used Canadian solar panel rated 330 W was selected for use in this design

$$\text{Number of Solar Panel} = \quad 3000\ \text{W}\ \div\ 330\ \text{W} = 9$$

Therefore, nine solar panels of 330 W each were connected to yield a total solar PV array of 2970 W for charging the 10,560 Wh of battery storage within 4 h.

The specification of the 330 W solar panel at standard test condition is as follows in table 3.

2.5. Charge controller sizing

A PWM charge controller was used in order to reduce costs. The charge controller size was calculated to match the battery voltage and the PV array output current as follows:

i. Charge Controller Voltage = Battery VoltageBattery storage capacity voltage is 24 Vdc. Hence the voltage rating of the charge controller will be 24 V

$$\text{ii.}\quad Charge\ Controller\ Current\ Rating = Isc \times Nsp \times Sf \tag{8}$$

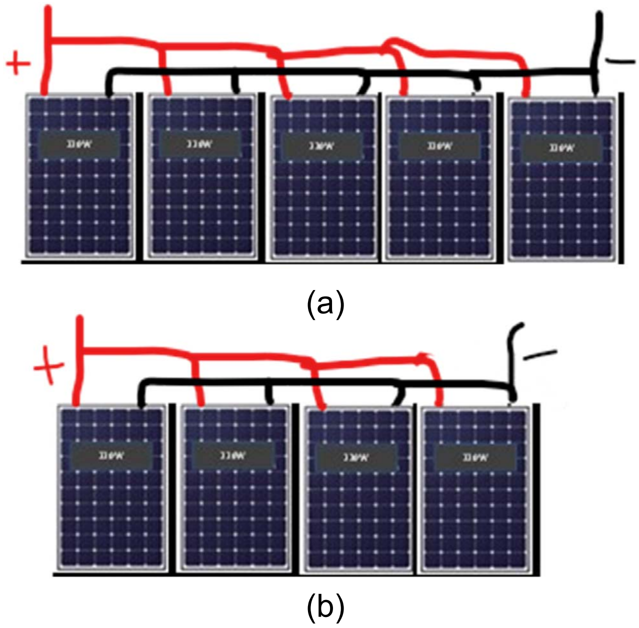

Figure 2. (a) Connection of 5 solar panels in parallel, (b) connection of 4 Solar Panels connected in parallel.

Isc = Short Circuit Current of solar panel
Nsp = Number of Solar panel connected in parallel
Sf = Safety factor). where Safety factor is 1.25
$= (9.31 \text{ A} \times 9 \times 1.25) = 104.7 \text{ A} = 105 \text{ A}$ (Approx.)

2.5.1. Number of charge controller

Due to the unavailability of a single PWM charge controller in the market that has a rating of 24 V 105 A, as calculated, two charge controllers with a rating of 24 V 60 A each were used. The resulting capacity of the two PWM charge controllers used in this design was 120 A at 24 V.

2.5.2. Connection of the solar panels

Since two PWM charge controllers rated at 24/60 A each were employed in this work, the solar panels were connected in parallel and separated into two output circuits. The first output circuit consists of 5 solar panels connected in parallel to one of the 24 V 60 A charge controllers, as shown in figure 2(a), while the second output circuit, which consists of the remaining 4 solar panels, is also connected in parallel to the second 24 V 60 A charge controller, as shown in figure 2(b).

2.6. DC/AC cable sizing

The diameter of the DC cable used for the batteries, solar panels, charge controller, and inverter was calculated as follows: (Compute depend on 1 mm^2 copper core to 5 A current, i.e. 5 A current per 1 mm^2 diameter cable [25, 26])

2.6.1. Battery cable diameter for series connection

$$Battery\ cable\ diameter \quad (series) = \frac{P_{Inverter}}{vdc_{Inverter} \times 5Amm^2} \tag{9}$$

$P_{Inverter\ =}$ rated inverter power (VA)
$Vdc_{Inverter\ =}$ rated inverter dc voltage(v)
Battery cable diameter = 3500 VA ÷ (24 V × 5 A mm^{-2})
= 29.2 mm^2 = 25 mm^2 (Approx.)
29.2 mm^2 cable does not exist, hence, 25 mm^2 which is the nearest available cable, was used to connect the batteries together in series.

2.6.2. Battery cable diameter for parallel connection

$$\text{Battery cable diameter (parallel)} = \frac{I_{controller}}{5A\ \text{mm}^2} \quad (10)$$

$I_{Controller}$ = *rated* charging current of charge Controller

$= 120\ \text{A} \div 5\ \text{A mm}^{-2} = 24\ \text{mm}^2 = 25\ \text{mm}^2$ (Approx.)

Since 24 mm^2 cable is not also available, 25 mm^2, which is the closest available cable, was used to connect the batteries together in parallel.

2.6.3. Solar panel cable diameter for the first 4 solar panels connected in parallel =

$$\frac{Isc \times Nsp \times Sf}{5A\ \text{mm}^2} \quad (11)$$

Isc = Short Circuit Current of solar panel

Nsp = Number of Solar panel connected in parallel

S_f = Safety factor). where Safety factor is 1.25

$= (9.31\ \text{A} \times 4 \times 1.25) \div (5\ \text{A mm}^{-2})$

$= 46.55\ \text{A} \div 5\ \text{A mm}^{-2} = 9.31\ \text{mm}^{-2} = 10\ \text{mm}^{-2}$ (Approx.)

9.31 mm^2 is not available; therefore, 10 mm^2 of DC cable was used to connect the four solar panels to the charge controller.

2.6.4. Solar panel cable diameter for other five 5 solar panels connected in parallel =

$$\frac{Isc \times Nsp \times Sf}{5A\ \text{mm}^2}$$

$= (9.31\ \text{A} \times 5 \times 1.25) \div (5\ \text{A mm}^{-2})$

$= 58.1\ \text{A} \div 5\ \text{A mm}^{-2} = 11.6\ \text{mm}^{-2} = 12\ \text{mm}^2$ (Approx.)

12 mm^2 DC cable was used to connect the 5 solar panels to the charge controller.

2.6.5. Cable size from each of the solar charge controllers to the battery

$$\textit{Cable diameter for each solar charge controllers} = \frac{Icontroller \times Sf}{5A\ \text{mm}^2} \quad (12)$$

$I_{Controller}$ = charge controller current rating for each

$$= (60A \times 1.25) \div 5A\ \text{mm}^{-2} = 15\ \text{mm}^2 = 16\ \text{mm}^2 (Approx.)$$

A 16 mm^2 DC cable was used to connect each of the two solar charge controllers to their respective terminals on the batteries.

2.6.6. AC cable size

$$\text{AC cable diameter for inverter output voltage} = \frac{P_{Inverter}}{Vac_{Inverter} \times 5Amm^2} \quad (13)$$

$P_{Inverter}$ = rated inverter power(VA)

$Vac_{Inverter}$ = rated AC voltage(v)

$= 3500\ \text{VA} \div (220\ \text{V} \times 5\ \text{A mm}^{-2})$

$= 3500\ \text{VA} \div 1100\ \text{VA} = 3.2\ \text{mm}^2 = 4\ \text{mm}^2$ (Approx.)

4 mm^2 AC cable was used to connect the output AC voltage of the 3500 VA inverter to the distribution board, where the electrical load wires were connected.

The procedures employed during implementation and installation are as follows:

i. The 4 batteries were connected together both in series and parallel using a battery cable diameter of 25 mm^2 for series and parallel connections, as shown in figure 1.

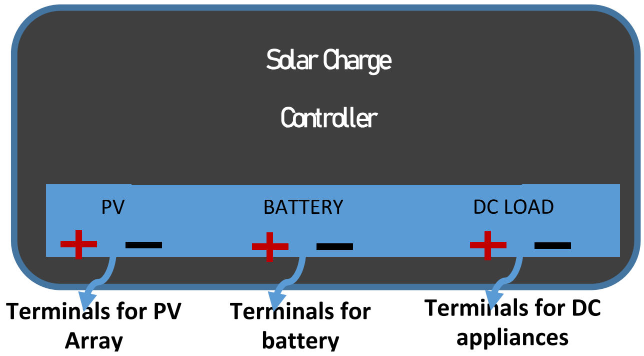

Figure 3. Solar charge controller terminal.

ii. The 3.5 kVA inverter was connected to the batteries taking the inverter polarity into consideration, i.e., positive to positive and negative to negative.

iii. The two (2) solar charge controllers were mounted on the wall and connected to the batteries using a 16 mm^2 dc cable. The positive terminal meant for battery on the solar charge controller was connected to the battery positive terminal, while the negative terminal, which is also meant for battery on the solar charge controller, was connected to the battery negative terminal accordingly, as described in figure 3.

iv. The nine solar panels were mounted on the roof and connected together in parallel in two output circuits, as shown in figures 2(a) and (b).

v. The solar panels were then connected to the two charge controllers separately using 10 mm^2 and 12 mm^2 dc cables as calculated, with their polarity taken into consideration.

vi. The 1545 W electrical load was connected through the distribution board to the inverter AC output using a 4 mm^2 AC cable.

vii. The battery terminals, wires, and other terminal connections were inspected and retightened to ensure a tight connection. The strength of the battery was also checked using a battery analyser to ensure that it was still strong and suitable for this work.

viii. The batteries were left to charge for 8 h before testing.

The 9.16 kWh stand-alone solar photovoltaic power system was implemented and tested in Ibadan, Nigeria. The testing took 34 h. The test begins at 9 a.m. in the daytime after the batteries have been fully charged from the previous day. Then the following data were measured and recoded per hour:

i. Energy produced from solar PV array

ii. Battery state of charge

iii. Battery depth of discharge

The energy produced from the solar PV array was measured by converting the PV array output current (A) displayed by the two PWM charge controllers into kilowatt hours (kWh) as follows:

$$\mathrm{E_{PV}} = \frac{I_{PV} \times V_{PV} \times t}{1000} \tag{14}$$

$\mathrm{E_{PV}}$ = Energy Produced from PV array in kWh
$\mathrm{I_{PV}}$ = PV array output Current in Ampere , t = 1-hour
VPV = PV array voltage. (Due to the PWM charge controller, PV array voltage equals Battery Voltage during charging) A digital multi-meter was used to measure the battery voltage per hour
The battery state of charge (SoC) and Depth of discharge (DoD) were calculated as follows:

$$\mathrm{DoD} = \frac{P_{Load}}{P_{Battery}} \times 100\% \tag{15}$$

$$\mathrm{SoC} = 100\% - \mathrm{DoD} \tag{16}$$

P_{Load} = load power per hour (kWh)

Table 4. First 12-hours data obtained from 9.00 am to 21.00 pm, July 6.

Day Time	July 6, 9.00 AM to 21.00 PM											
Backup Time (Hour)	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00	21.00
Load Energy per hour (kWh)	0.56	0.56	0.56	1.46	0.56	0.56	0.08	0.08	0.08	0.08	0.45	0.45
PV Array Energy per Hour (kWh)	1.48	1.65	2.29	2.43	2.54	2.15	1.29	0.57	0.26	0.11	0	0
Battery Depth of Dis-charge(%)	0	0	0	0	0	0	0	0	0	0.6	5.7	11
Battery State of Charge(%)	100	100	100	100	100	100	100	100	100	99.4	94.3	89

Table 5. Second 12-hours data obtained from 21.00 pm July 6 till 9.00 am July 7.

Night Time	July 6–7, 21.00 PM to 9.00 AM											
Backup Time	22.00	23.00	00.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00
Load Energy per hour (kWh)	0.45	0.45	0.45	0.45	0.29	0.29	0.29	0.29	0.29	0.29	0.08	0.08
PV Array Energy per Hour (kWh)	0	0	0	0	0	0	0	0	0	0	0.27	0.78
Battery Depth of Discharge(%)	16.5	22.2	28.1	34.3	36.2	38.3	40.6	43.1	45.8	48.7	48.5	41.3
Battery State of Charge(%)	83.5	77.8	71.9	65.7	63.8	61.7	59.4	56.9	54.2	51.3	51.5	58.7

Table 6. Last 10-hours data obtained from 9.00 am to 19.00 pm, July 7.

Day Time	July 7, 9.00 AM to 19.00 PM									
Backup Time	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00
Load Energy per hour (kWh)	0.56	0.56	0.56	1.46	0.56	0.56	0.08	0.08	0.08	0.08
PV Array Energy per Hour (kWh)	1.31	1.49	2.04	2.15	2.24	2.10	1.16	0.44	0.21	0.13
Battery Depth ofDischarge(%)	26.3	14.5	8.2	0	0	0	0	0	0	0.6
Battery State of Charge(%)	73.7	85.2	91.8	100	100	100	100	100	100	99.4

$P_{Battery}$ = Nominal battery capacity or capacity of energy stored in battery (kWh)

The Nominal battery capacity is 10.56 kWh or 440 Ah. During discharge hours, the capacity of energy stored in the battery decreases with time. The depth of discharge is expressed in percentages. A 100% DoD means battery energy capacity is empty, and a 0% DoD means battery energy capacity is full.

Battery state of charge is also expressed in percentage; 100% SoC means battery energy storage is full, and 0% SoC means battery energy storage is empty.

The test was carried out on July 6 and 7, 2022, in Ibadan, Nigeria, for a duration of 34 h. The 34-hour duration was used to ascertain the validity of the design and to check if the system would be able to sustain the daily load demand for 24 h without failure.

3. Result and discussion

The measured data obtained during the 34-hour testing are presented in tables 4, 5, and 6, and the results were evaluated as follows:

i. Energy balance between PV array power and load power.

ii. Battery depth of discharge, state of charge and charging rate.

iii. Comparative analysis with previous published papers.

3.1. Energy balance between PV array power and load power flow

The peak load power, PV array peak power, PV array average power, and overall PV array power obtained were discussed to analyse the energy balance between PV Array Power and Load Power Flow. July 6 is referred to as Day 1 and July 7 as Day 2. The daily flow of 9.16 kWh of load power is shown in figure 4 to clearly display the

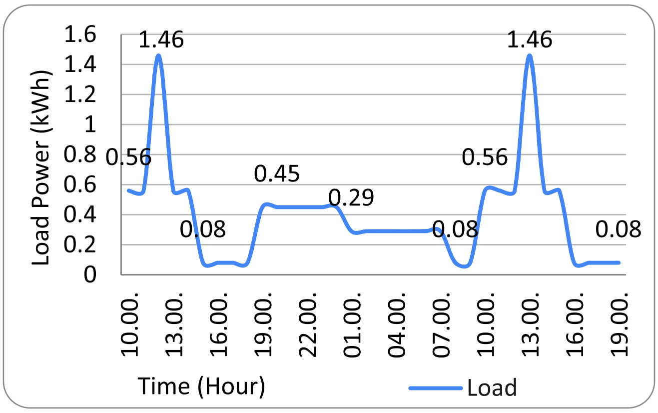

Figure 4. Histogram of load power flow.

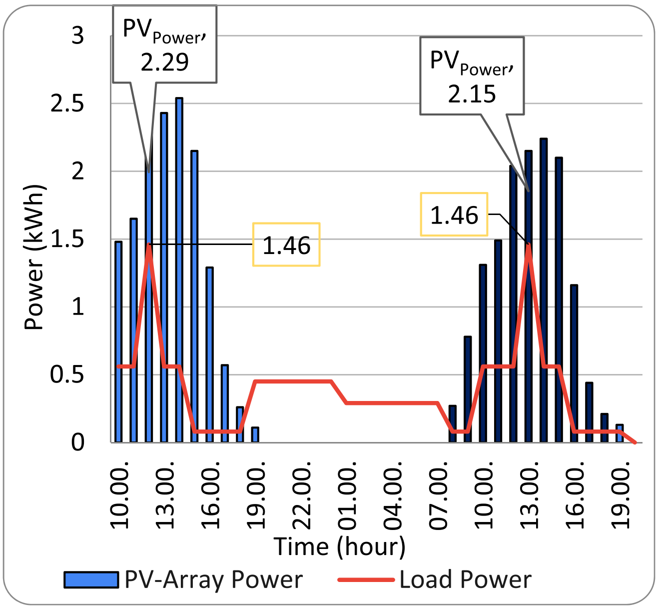

Figure 5. PV array power obtained per hour.

schedule of peak and off-peak load periods. The peak load time falls between 11 a.m. and 14 p.m. daily, while off-peak load begins from 14 p.m. until 11 a.m. the following day.

Figure 5 shows the PV array power obtained. As shown in figure 5(a) 4 h period of peak power from the PV array was recorded on each day between 10 o'clock and 15 o'clock. The highest peak power obtained on Days 1 and 2 was 2.54 kWh and 2.24 kWh, respectively, at 14.00 p.m. The average PV power obtained on Day 1 from 10 a.m. to 19 p.m. was 1.48 kWh and the overall PV array power was 14.77 kWh. On Day 2, the average PV power obtained was less: 1.19 kWh was the average PV power obtained within the hours of 8 a.m. to 19 p.m.; notwithstanding, 14.32 kWh overall power from the PV array was obtained, which is very sufficient for load power as well.

Figure 6 analyses the energy balance between load power and PV array power. Figure 6 showed that there is sufficient energy balance per hour between the PV array power and load power, such that during peak load power (1.46 kWh) on Day 1, the PV array power was 56.8% (0.839.16 kWhkWh) higher than the peak load power at 12.00 p.m., while on Day 2, the PV array power was 47.3% (0.69 kWh) higher than the peak load power at 1.00 p.m. Also, the highest peak power of the PV array on Day 1 was 73.9% (1.08 kWh) greater than the 1.46 kWh peak load power, and 53.4% (0.78 kWh) greater than the peak load power on Day 2. This energy balance is also evident between the PV average power and peak load power. On Day 1, the average power from the PV array was 1.37% (0.02 kWh) greater than peak load power, but on Day 2, the average PV array power was 18.5% (0.27 kWh) less than peak load power. Although the average PV array power on Day 2 was less than the peak load power, the overall power from the PV array on Day 2 was 130% (6.25 kWh) higher than the 4.78 kWh

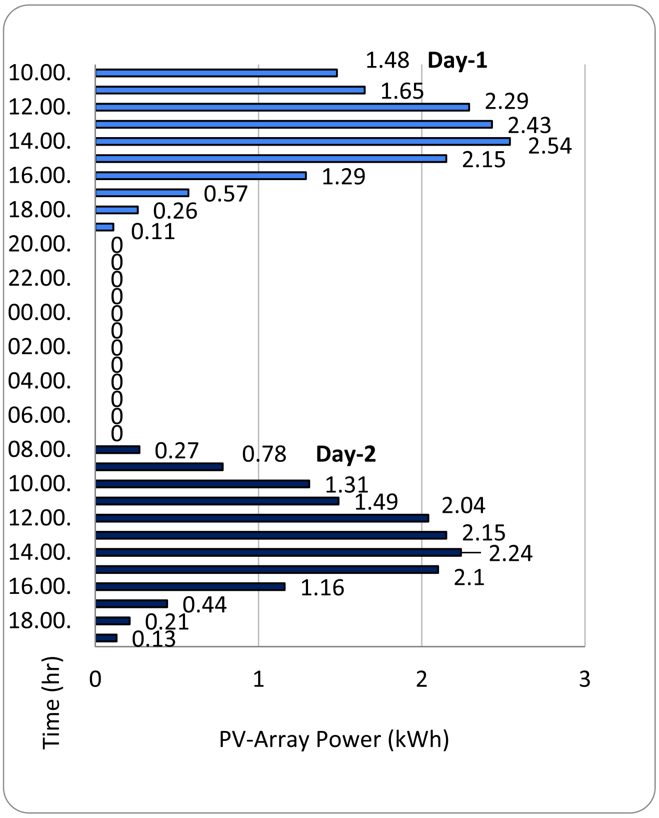

Figure 6. Energy balance between load power and PV array power.

total load power at daytime. Also, a higher overall PV array power was obtained on Day 1, as the overall PV array power was 208% (9.99 kWh) higher than the 4.78 kWh total load power at daytime. In comparison with the total daily load power of 9.16 kWh, the overall PV array power was 61.2% (5.61 kWh) higher than the total daily load power of 9.16 kWh on Day 1 and 56.3% (5.16 kWh) higher on Day-2. This percentage indicates a good energy balance between PV array power and load power. This energy balance conforms with the recommendation of author in [11].

3.2. Battery discharge and state of charge

Figure 7 and figure 8 show the battery's depth of discharge and state of charge. The depth of discharge and state of charge obtained on Day 1 from 9.00 a.m. until 18.00 p.m. were 0% and 100%, respectively. This was due to a sufficient energy balance between the PV array power and the load power during the daytime.

At 19.00 p.m., when PV array power was down, the battery state of charge started reducing and the depth of discharge increased; this continued until Day 2 at 7.00 a.m. During this 12-hour discharge period, the total load power was 4.38 kWh (night-time load), the depth of discharge increased to 48.7%, and the state of charge was reduced to 51.3%. This depth of discharge of 48.7% indicates that half of the energy stored in the battery was used and that the energy consumption from the battery storage was minimal both during the day and at night. This also indicates a sufficient energy balance between nighttime load power and battery power. At 8 a.m. on Day 2, battery recharging begins, and the state of charge starts increasing from 51.3%, while the depth of discharge also begins to reduce from 48.7%. This recharging process took a duration of 6 h; the count began at 8 a.m., and the batteries became fully charged at 14 p.m., with the resulting SoC equal to 100 % and DoD equal to 0 %. From 14 p.m. until 18 p.m., the batteries SoC and DoD remain at 100 % and 0 %, respectively. This indicates that, there is sufficient power from the PV array to effectively charge the batteries and maintain the batteries in a fully charged state while supporting the load power. This 48.7 % DoD obtained at night is appropriate for the battery's life span and cycle life for long-term operation. Battery life span depends on the cycle life of the battery, the more frequently a battery is cycling, the shorter its lifespan will be [27–29]. A battery that is frequently discharged at 50 % DoD, will sustain a longer cycle life than a battery that is frequently discharged at 80 % DoD [30–32]. Hence, this shows that at 48.7 % DoD, the batteries will sustain a longer cycle life and lifespan.

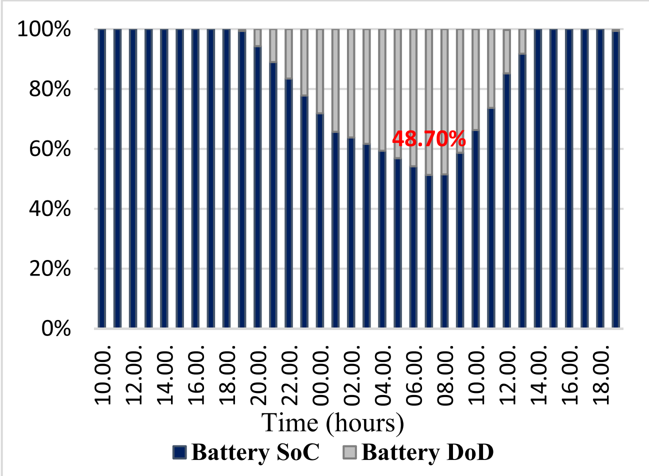

Figure 7. PV battery state of charge and depth of discharge.

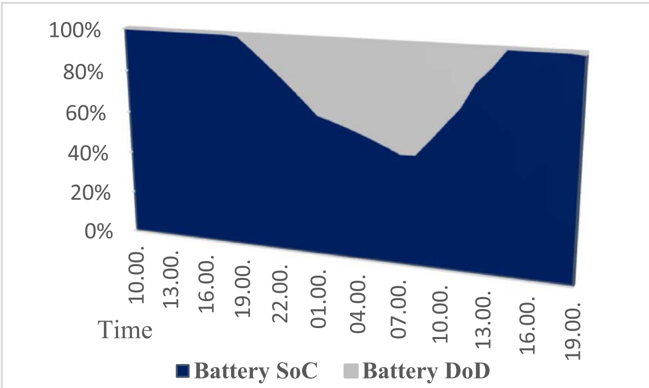

Figure 8. PV battery state of charge and depth of discharge.

Table 7. Comparative analysis of result with previous study.

Comparative parameter	Current study	Previous study				
		[15]	[13]		[14]	[12]
Load (kWh)	9.16	60.0	6.522	45.360	5.70	149.474
Battery Capacity (kWh)	10.56	11.0	21.600	189.0	24.0	783.360
PV Array Capacity (kW)	2.97	60.0	1.95	16.25	1.98	39.0
Days of Autonomy	1	N/A	3	3	3	4
% of Battery Capacity to Load	115%	18.3%	331%	417%	421%	524%

3.3. Comparative analysis with previous published papers

The energy balance between PV array size, load size, and battery size was compared with four previous studies. The percentage of battery capacity is the only parameter that is analyzable from the previous study. Table 7 presents the comparison of results with other studies, with a focus on the percentage of battery to load capacity and energy balance. In comparison with the study [15], when the PV array capacity was hugely sized to match the load power, the optimal battery capacity in a grid-tied solar photovoltaic system was achieved at 18.3% of load demand. The 18.3% optimal battery size achieved is quite small and was therefore supported by a larger PV array size. This reveals that an energy balance between PV array size, battery size, and load size is also required in grid-tied solar photovoltaic systems.

In the study [13, 14], a stand-alone PV system for 3-days of autonomy was designed. In the study [13], the battery size for each of the two standalone PV systems was 331% and 417% of load power, respectively. In Study

[14], the battery size was 421% of load demand. These high percentages of battery size in the study [13, 14] indicate that a high energy balance between battery size and load size was allowed in order to achieve the 3 days of autonomy. The energy balance between PV array size and load size cannot be ascertained because it was not discussed in the reference study. Study [12] as well uses a larger battery capacity, which was 524% of load capacity, to achieve a 4-day autonomy. The energy balance between PV array and load power was also not revealed, but the battery capacity indicates a sufficient energy balance between battery size and load size.

In comparison, our study also indicated an energy balance between battery size and load size, as our resulting battery capacity was also more than 100% of total daily load power, like the previous study. This shows that the method employed in this study is appropriate, as all results compared indicate a sufficient energy balance either between the battery size and load size or between the PV array size and load size. Our result showed an energy balance between the three, i.e., PV array size, load size, and battery size. The battery size was able to meet the nighttime load demand of 4.38 kWh and the PV array power was enough to meet the daytime load demand of 4.78 kWh and sufficiently recharge the batteries in a few hours. This shows a complete energy balance between PV array, load, and battery size in sustaining the 9.16 kWh daily energy demand reliably.

4. Conclusion

The parts comprising the design and implementation of the stand-alone solar photovoltaic power system are described. A full technical account with connection diagrams of the components employed in this work is given, and where necessary, factors involved in the parameters dictating the choice of the components are discussed.

The parameters evaluated during testing were energy balance between PV array power and load power, battery depth of discharge, state of charge, and comparative analysis of the results with previous published papers. The results obtained show that the design is a reliable stand-alone solar PV system because a sufficient energy balance was achieved between the PV array size, load size, and battery size.

Previous study results revealed that there should be a high energy balance between battery size and load size to achieve a reliable standalone PV system for 3–4 days of autonomy [12–14]. Our methodology agrees with this, and also reveals that, through a complete energy balance between PV size, battery size, and load size, a standalone PV system can reliably sustain daily energy demand, without long days of autonomy. In our study results, the energy balance between the PV array power and load power was evident on Days 1 and 2. On Day 1, the overall PV array power was 208% higher than the daytime load power and 61.2% higher than the overall daily load power. On Day 2, the overall PV array power was 130% higher than the daytime load power and 56.3% higher than the overall daily load power. The energy balance between battery size and load size was also sufficiently achieved on both days. The battery capacity was 115% of load power, and the highest depth of discharge recorded throughout was 48.7% DoD. These results confirmed that the design methodology in this work is accurate and reliable, as it offers sufficient and complete energy balance to sustain the daily energy demand with a good percentage of battery DoD and SoC, which will help prolong the battery life span and make the entire standalone solar PV system efficient and reliable. That notwithstanding, the system designed and reported here has been implemented and demonstrated to work. The study exposes readers and authors to adequate technical knowledge of stand-alone solar power generation for daily energy consumption. This work will also serve immensely as a guide to future standalone PV projects of different capacities anywhere, as it contains in-depth information and illustrations that will be helpful to forestall the problems of improper sizing, planning, and lack of technical know-how in future solar PV projects.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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