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DESIGN AND SIZING OF STAND-ALONE PHOTOVOLTAIC SYSTEMS FOR REMOTE AREAS

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ABSTRACT

As solar photovoltaic technology becomes more affordable globally, Stand-Alone Photovoltaic (SAPV) systems are being recognized as a viable solution for powering essential services in areas lacking grid connectivity. The paper begins with a comprehensive review of SAPV systems, highlighting their categorization, benefits, and typical applications, especially in remote areas. Subsequently, it delves into the design and sizing aspects of these systems, emphasizing the importance of choosing appropriate components, including PV modules, batteries, charge controllers, inverters, and cables. A detailed methodology outlines the intuitive design process, incorporating factors like site selection, solar potential assessment, daily energy needs calculation, and component sizing. This systematic yet straightforward methodology bridges the gap between theoretical design principles and practical implementation. To demonstrate the applicability of the proposed approach, a case study is included, offering real-world insights and best practices for SAPV system deployment. This study contributes to the field of renewable energy by addressing specific challenges associated with SAPV system design in off-grid areas, such as the need for accurate solar irradiation data and precise component sizing. By providing a structured framework and practical guidance, this work serves as a valuable reference for researchers, engineers, and policymakers aiming to optimize SAPV systems for sustainable development and to enhance energy access in remote regions.

Keywords: Stand-Alone Photovoltaic Systems 2, SAPV 3, Remote Areas 4,Solar Irradiation.

1.0 INTRODUCTION

Electricity generated from solar photovoltaic systems is widely used for applications such as street lighting, road-sign illumination, railway and marine signal lighting, and security systems as the prices of photovoltaic modules have declined in the last few years and made them more affordable worldwide. Stand-alone photovoltaic systems (SAPV) are a common choice to power radios, remote repeaters, base stations for cell phone networks and weather-monitoring equipment, telecommunication systems, water pumping, vaccine refrigeration, entertainment appliances, schools, and small businesses in remote areas with no access to power.

Numerous research studies have been published on the design methodologies for off-grid stand-alone solar PV systems, addressing various applications, including residential purposes [1-4], community facilities such as clinics and campuses [5-7], and remote areas [8-11], among others. In these papers, analytical methods have been widely employed for designing and sizing stand-alone solar PV systems due to their ability to provide precise and optimized results. However, these methods often require detailed input data, advanced computational tools, and significant time and expertise, which may not be readily available in all scenarios.

In contrast, the intuitive method offers a simpler and more practical approach, making it particularly beneficial in situations where data availability is limited, resources are constrained, or a rapid preliminary design is needed. Hence, for the context for this paper, the intuitive method is presented as the design methodology in which more preferable for small-scale systems, remote locations with minimal data access, or early-stage feasibility studies, where its efficiency and ease of application outweigh the precision offered by analytical methods.

This paper provides a general guideline for PV installers to size and design a SAPV system, including selecting PV modules and their components. It is organized as follows. Section 2 presents a review of stand-alone photovoltaic systems. Section 3 describes the intuitive methods for designing and sizing a stand-alone photovoltaic system for specific applications. Section 4 explains a case study of a SAPV design. Finally, Section 5 provides the conclusion of the study.

2.0 STAND-ALONE PHOTOVOLTAIC SYSTEMS

The three main categories of photovoltaic operation systems are stand-alone photovoltaic (PV), commonly called off-grid PV, grid-connected or on-grid PV, and hybrid systems. SAPV systems are designed to function independently as a microgrid or source of electricity. It has emerged as an easy method and self-sufficient alternative to deliver electricity, whether for urban residents who want to use this technology for small housing and business communities or remote communities living far from the electric grid in remote locations where grid extension is practically unfeasible.

Utilizing standalone PV systems as a source of energy has numerous benefits, including converting solar energy directly into electricity, achieving energy independence, maintaining security and safety, avoiding electricity bills, making installation quicker and more accessible, providing long-term backup if a storage system fails, and providing power whenever and wherever it is needed.

To further enhance the understanding of SAPV systems, it is essential to address key considerations and precautions during their design. This includes ensuring accurate system sizing to meet energy demands effectively, implementing efficient energy storage management to maintain reliability, conducting thorough site assessments for optimal performance, and adhering to safety standards to guarantee secure and sustainable operation. These aspects are critical to maximizing the benefits of SAPV systems while minimizing potential risks and challenges. However, in this paper, the design methodology for SAPV systems will be covered only through an intuitive approach, focusing specifically on the design of PV modules and their main components.

SAPV systems are generally designed and sized to supply certain DC and/or AC electrical loads. Based on its connection to the electrical loads, the SAPV systems are classified into two types, i.e.: a direct-coupled system, where the DC output of a photovoltaic array is directly connected to a DC load, and an indirect-coupled system where the electrical loads are supplied through a battery system for DC loads and an inverter for AC loads. In a direct-coupled system, the load is directly supplied from the PV modules, as shown in Figure 1 [12].

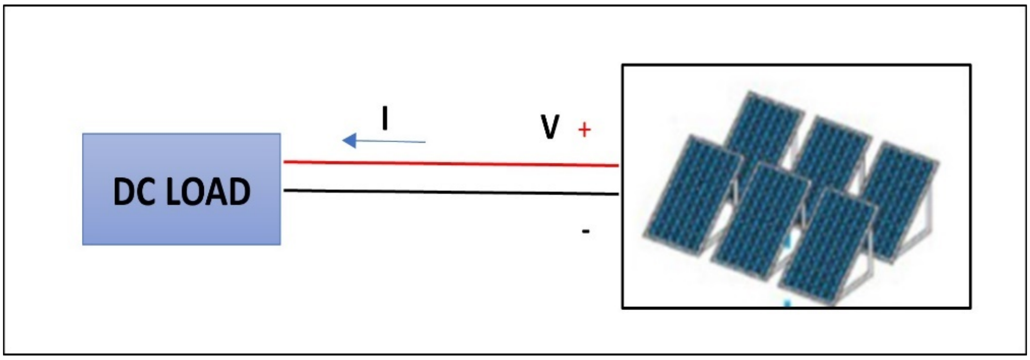


Figure 1. Diagram of direct-coupled SPAV systems

Figure 2 depicts a further connection of a SAPV system. It comprises PV modules, batteries, a charge controller, and an inverter used to change the direct current (DC) produced by the PV modules into alternating current (AC) to supply electricity to AC loads. This allows for the simultaneous supply of both DC and AC loads. In a standalone PV system, a storage battery has three main purposes: to store energy when it is available in excess and to release it when needed; to provide constant current and voltage by eliminating transients; and to release surge currents to loads like motors when necessary. A charge controller is employed to regulate the system and stop overcharging and over-discharging of the battery. Undercharging could result in stratification and sulphation, which reduce the battery's efficacy and lifespan while overcharging could induce gassing.

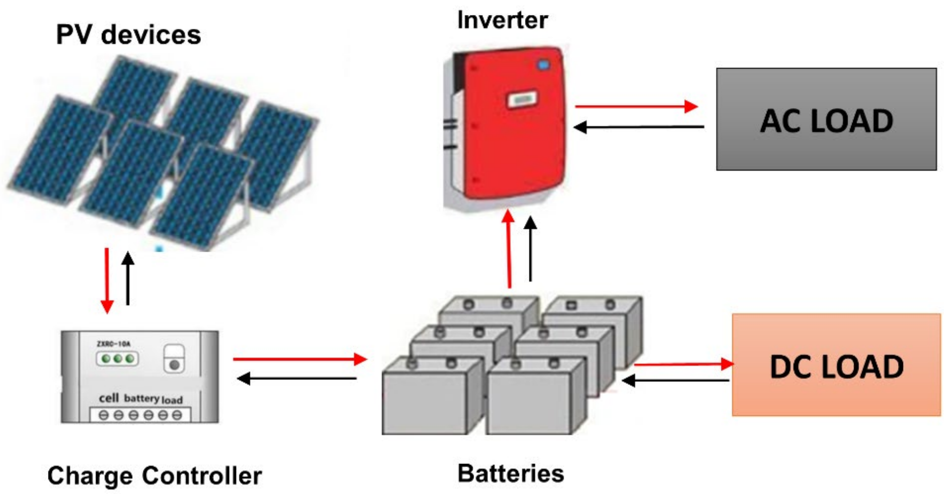


Figure 2. Diagram of a simple SAPV system with battery storage

2.1 Battery Storage for SAPV Systems

Choosing an appropriate battery system is very important for reliable SAPV systems. A battery system is selected based on capacity, depth of discharge, and cycle life [2]. The most commonly used batteries for SAPV systems are lead-acid batteries with thick lead plates, which enhance their ability to tolerate deep discharges. Lead acid batteries have advantages as energy storage devices since they are very inexpensive, have a high energy density, and can be robust and reliable. Aside from its benefits, lead acid batteries require some care in controlling charging and discharging if a long life and a high number of charge/discharge cycles are desired.

Figure 3 depicts a typical charging cycle for a lead-acid battery. The battery is initially charged at a constant current (the bulk charge phase) until the voltage reaches a specific value [13]. The voltage is constant at this point while the charging current decays (the tapered charge phase). After a reasonable period, the charging voltage is decreased or withdrawn to avoid excessive gassing and electrolyte loss. With a PV system, where the available power continually changes, this optimum charging cycle is impossible.

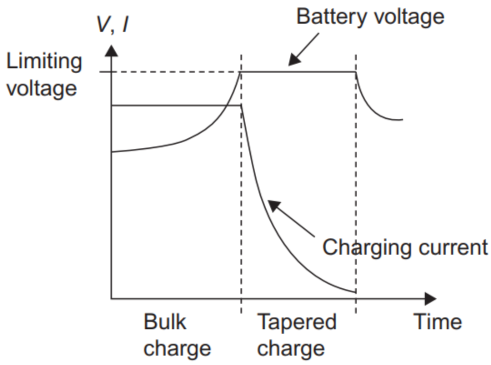


Figure 3. A combination of current and voltage charging techniques for a Lead Acid Battery [2]

The peak charging current can be regulated by a controller during the bulk charge phase and the voltage during the tapered charge phase and cut off the charge if the battery is fully charged. Some charging schemes drop the charging voltage by 5%-10% to provide a trickle charge with a voltage low enough to avoid substantial gassing. Overcharging the battery occasionally with lead-acid cells is also recommended to enhance gassing and stir the electrolyte. All deep-cycle batteries are rated in ampere-hour (Ah) capacity, which measures how much useful energy they can store at nominal voltage. A reasonable charge rate is around 10% of the battery's overall capacity each hour [14]. This will prevent electrolyte losses as well as plate damage [15].

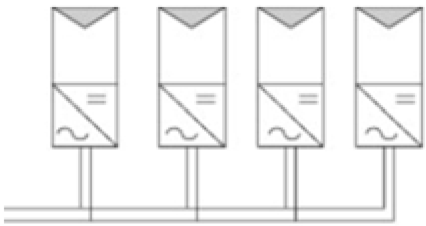
2.2 Inverters for SAPV Systems

Since the generation power of PV modules is in the form of DC, an inverter system is required to convert the DC electricity generated by the panels into AC electricity. A SAPV system requires a standalone inverter to supply AC power for most household appliances. Based on their installation connected to PV arrays, the inverters can be classified into four types, i.e., string inverters, optimized string inverters, microinverters, and hybrid inverters.

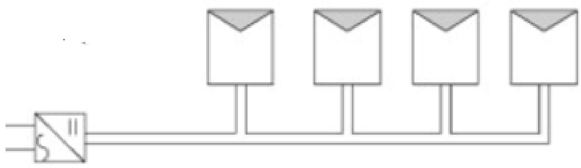
There are some considerations before choosing an inverter for certain applications as follows [14]:

- Efficiency
- Output waves
- Shading mitigation issues
- Warranty
- Type of PV systems

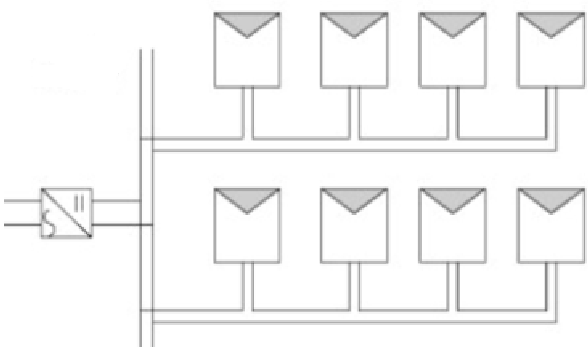
Different configurations of PV inverters are shown in Figure 4 [15].



a. Micro inverters are used to convert DC power generated by each PV module into AC power



b. String inverters are connected at the end of a string of PC modules



c. Central String inverters are connected at the end of a PV array

Figure 4. Different configurations of inverters in a PV system

The output AC waves of inverters depend on the topology, the number of switches deployed in their internal electrical circuit, and the switching mechanism. Typical output waves of inverters are pure sine waves, square waves, and modified square waves, as shown in Figure 5. Inverters' efficiencies vary from 90% to 96% depending on their harmonic contents and output waves. The square waveform of inverters has a total harmonic distortion of 48.3%.

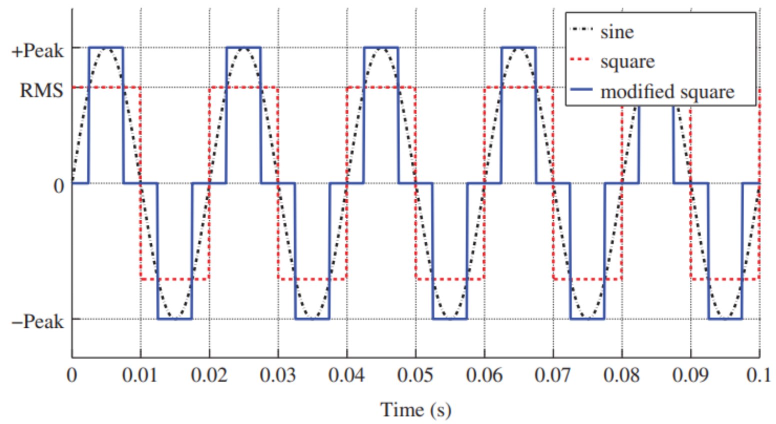


Figure 5. Different output waves of inverters

3.0 DESIGN AND SIZING PROCEDURES

A practical approach introduced in this section for designing and sizing a SAPV system is based on the intuitive method. It involves several key steps to ensure it meets the energy requirement of the user's electrical loads efficiently and safely. The basic steps for sizing and designing a PV system are as follows [16]:

- Defining the site and location for the installation of a SAPV system
- Assessing the solar potential at the selected site based on the local meteorological dataset.
- Calculating the user's daily energy needs based on the operating hours of the wattage of the electrical loads.
- Selecting and sizing the main components of a SAPV system, including the type and size of PV modules, the battery capacity, the charge controller, the cable for connection, and the size of the inverter.

3.1 Defining Site and Meteorological Dataset

As the output power of PV modules varies with time and geographical conditions, selecting a suitable site is a critical step in planning a PV installation system. A site survey is conducted to check the suitability of a site for a SAPV installation. The following information needs to be gathered during a site survey:

- Orientation of the selected site, including the direction of the building for rooftop PV installation.
- The availability of a surface area for mounting the PV modules on the ground or rooftop.
- The structure and type of the roof.
- The location for routing the cables and placing the battery and inverters.
- Identification of shadow-free location to ensure no shadow casting on the PV arrays.

Therefore, access to the relevant information on these parameters is required to perform an optimal PV system design exercise.

3.2 Assessing the Solar Potential at the Selected Site

Due to different topography, the intensities of solar irradiation vary at any location on the earth's surface. Therefore, planning an autonomous photovoltaic system requires the evaluation of the solar energy resource at a chosen site or location. From the sizing perspective, ensuring the designed PV system can efficiently meet the energy demands is crucial.

Solar radiation consists of direct, diffuse, and ground-reflected incident solar radiation, which affects a PV array. The amount of sunshine per year, the average daily global solar radiation, and the average yearly global solar radiation are all significant factors when evaluating solar energy resources. The information on solar irradiation for any typical sites can be accessed online freely, such as in the following links: https://power.larc.nasa.gov/data-access-viewer/, https://everywhere.solar/ or https://www.soda-pro.com/. Another option is to consult the records of a nearby meteorological station. NASA can provide information about the site's solar radiation if the location's latitude and longitude are known.

When designing a SAPV system for a typical site, a set of one full year of solar irradiation data for all months is required to evaluate the availability of solar resources at the site. The solar irradiation data is provided in kilowatt hours per square meter per day (kWh/m^2/day). Sometimes, the daily insolation in peak sun hours (PSH) per day is defined for solar irradiation. It measures the time that the sun irradiates its light intensity at an irradiance of 1 kW/m^2 in a day on a typical site. It is written as:

$$PSH = \frac{G(kWh/m^2)}{1kW/m^2} \tag{1}$$

Where G is daily irradiation at a chosen site.

The month with the lowest mean daily insolation value overall is chosen as a basic calculation for sizing the PV system components. It aims to ensure that the system will function even when the sun is not as accessible due to weather. To obtain the maximum irradiation level, i.e., when the sun is placed at the zenith in the sky, the orientation of fixed mounting PV modules must be adjusted according to the local site's latitude. Therefore, sizing the number of PV arrays must account for the plane of the array 's irradiation in its calculation procedures.

3.3 Calculating Daily Energy Needs

The size of a standalone PV system relies entirely on the load of appliances or other devices and the time of use. This factor should be calculated precisely. Therefore, determining the system load is the next phase in the design of a SAPV system. One of the most critical aspects of the design is the daily energy balance between the daily electrical loads and the energy generated by the PV arrays. The power consumption of each appliance is measured in watts, and its operational duration is taken into account in hours. Each appliance has a different load and operating duration. The average daily energy consumption of the loads is calculated as Wh (watt-hours) by multiplying the appliances' wattage by the amount of time they have been used, as shown in Equation 2.

$$E(i) = P(i) \times t(\mathrm{i}) \tag{2}$$

Where:
E(i) is the energy demand per day of individual load in watt-hours
P(i) is the rating of individual load in watts.
t(i) is the time of use of that load per day in hours

The total daily energy demand in Wh is calculated by adding the individual energy demand of each appliance, as shown in Equation 3.

$$E_T = E(i) \tag{3}$$

Where E_T is the total energy demand per day of individual load in watt-hours

The estimated loads for both AC and DC appliances are added together. The peak load values are employed if the loads have significant seasonal variation or are crucial.

3.4 Selecting and Sizing the Main Components of a SAPV System

Designing an optimal SAPV system requires a well-sized of SAPV components. It comprises photovoltaic arrays, charge controllers, battery banks, inverters, and cables connecting these components, as shown in Figure 6.

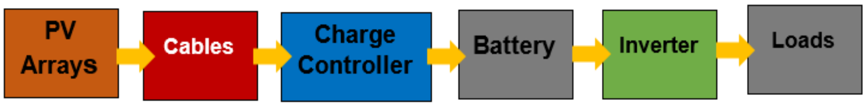


Figure 6. Components of a SAPV systems

Each component in the SAPV system may contribute some losses in the PV energy generation. Therefore, it is crucial to secure the PV-generated power to meet the load demands. To increase system performance, the PV array should be sized by considering the efficiency factor of each component in the SAPV system. The total size of PV Arrays is computed as follows [16]:

$$P_{T,PV} = \frac{L}{\eta_{cables} \times \eta_{CC} \times \eta_{Bat} \times \eta_{Inv} \times PSH} \quad (4)$$

Where:
$P_{T,PV}$ is the total size of a PV array rated in Watt peak (Wp)
L is the total daily energy demand in kWh
η_{cables} is the efficiency of cables
η_{CC} is the efficiency of the charge controller
η_{Bat} is the efficiency of the battery
η_{Inv} is the efficiency of the inverter
PSH is the Peak Sun Hour

Different sizes of PV modules produce different amounts of power. Generally, they are rated in peak-watts (Wp), which define the amount of power generated at the standard test conditions (STC), i.e., at an irradiance of 1000 W/m^2, a module temperature at 25°C, the incidence of light at 0° and AM1.5g. The rated peak watts produced by the chosen PV module are required to calculate the number of PV modules needed for specific loads and the DC operating voltage of a PV array. There are three general classifications of the DC operating voltage determined by the battery voltage, as shown in Table 1 [17].

Table 1. The DC Voltage System of a SAPV system [17]

Operating Voltage System (V)	12	24	48
Daily Energy Demands (kWh)	1	1-4	>4
Load Power (W)	< 300	<1000	<3000
Inverter size (kW)*	< 1	<5	< 15
Corresponding current (A)	25	42	62

*The inverter is connected directly to the battery units.

Thus, the total number of PV modules required to meet the energy demands is calculated by using the chosen PV module that is available on the PV market [16]:

$$N_{PVmod} = \frac{P_{T,PV}}{P_{max}} \quad (5)$$

Where P_{max} is the maximum power output of the chosen PV module.

The configuration of PV modules in terms of series and parallel connections is determined based on the DC operating voltage system, the maximum voltage of the chosen PV module for series connections, and the peak power rating of the chosen PV module as follows [16]:

$$N_s = \frac{V_{DC}}{V_{max}} \quad (6)$$

$$N_p = \frac{P_{T,PV}}{P_{max} \times N_s} \quad (7)$$

Where:
N_s is the number of PV modules in series connections (in one string)
N_p is the number of strings or parallel connections of PV modules
V_{DC} is the DC operating voltage system
V_{max} is the maximum voltage of the chosen PV module

The charge controller is used to regulate the charging and discharging state of the battery. Therefore, it should be sized to overcome the maximum current generated by the PV arrays and to safeguard the battery from charging the PV arrays at night. The charge controller is sized based on the short circuit current rating of selected PV modules and the DC operating Voltage system. Thus, the size of the PV charge controller is determined as [16]:

$$I_{PV,CC} = 1.3 \times I_{SC,mod} \times N_p \quad (8)$$

$$V_{PV,CC} = V_{DC} \quad (9)$$

Where:
$I_{PV,\ CC}$ is the current rating for choosing a solar charge controller
$I_{SC,}$ the mod is the short circuit current of the chosen PV module
N_p is the number of PV parallel connections.
The value of 1.3 represents the safety factor.

The sizing of the battery units for a SAPV system has been explained in the Institute of Electrical and Electronics Engineers (IEEE) standard (IEEE Std 1013–1990). As a battery unit is intended to store the output power of PV arrays to meet power demands at night or during several days of cloudy weather, known as "days of autonomy," days of autonomy become a vital factor for sizing battery units as well as the battery's nominal voltage and its depth of discharge. The Ampere-hour (Ah) unit is used as a measure to represent a battery capacity. It is calculated as [16]:

$$C_{T,Bat} = \frac{n \times L/\eta_{inv}}{DoD \times V_{DC}} \quad (10)$$

Where:
$C_{T,Bat}$ is the total battery capacity in Ampere-hours
n is days of autonomy; a standard for the number of autonomy days is usually 3.

The battery's total capacity can determine the number of battery units to serve energy demands. It is given as [16]:

$$N_{Bat} = \frac{C_{T,Bat}}{C_{1,bat}} \quad (11)$$

Where:
$C_{1,\ bat}$ is the capacity of one battery on the PV market.

Inverters of a SAPV system are sized based on the power rating of AC loads. Its capacity should meet the peak power of the load demands. If the AC loads comprise motors, the inverters are sized 3-5 times larger than the power demands of the appliances. a correction factor is used to accommodate the reliability issue of a SAPV system. If the AC loads are motor, the valuer of 3 is applied for the CF, while the simple AC loads use the value of 1.3 for CF. The size of inverters is determined as:

$$(VA)_{Inv} = CF \times \sum (VA)_i \quad (12)$$

Where:
(VA)Inv is the power rating of the inverter in Volt-Ampere.
(VA)i is the power rating of individual AC load power in Volt Ampere
CF is the correction factor.

The last component of the SAPV system is the cables, which connect different components in certain configurations to the electrical loads. It is sized based on the maximum current carrying capacity. Choosing appropriate cable sizes is crucial for minimum voltage drop and resistive losses. The permissible voltage drop in the cables should be very minimum of less than 2 %. For outdoor applications, cables should be UV and water-resistant. The size of the cables is determined as follows:

$$A = \frac{\rho \times l \times I_{max} \times 2}{V_d} \tag{13}$$

Where:
A is the cross-sectional area of the cable in mm^2.
l is the cable length, which is physically measured on-site between the components of the SAPV system.
ρ is the resistivity of the wire material in ohm-meters. It is 1.68x10^{-8} Ωm at 20°C for copper wire with a temperature coefficient, α of 4.29x10^{-3}/°C.
V_d is the maximum permissible voltage drop in cable (2% to 5%).
I_{max} is the maximum current flowing in the cables. It varies from component component depending on their section components' voltage and power rating.

4.0 A CASE STUDY OF SAPV DESIGN

This section explains an example calculation for designing and sizing a SAPV system. A house located at latitude of 5.56 North and longitude 95.29 East will be planned to use a solar power system as a source of electrical energy. Based on the location chosen, this area has the potential for solar radiation of 2503.41 kWh/m^2 per year or 6.86 kWh/m^2 per day. Daily average solar irradiation at the chosen site is shown in Figure 7. The minimum daily irradiation at the chosen site is at 6.14 kWh/m^2. This value will be used for sizing the PV modules at the site.

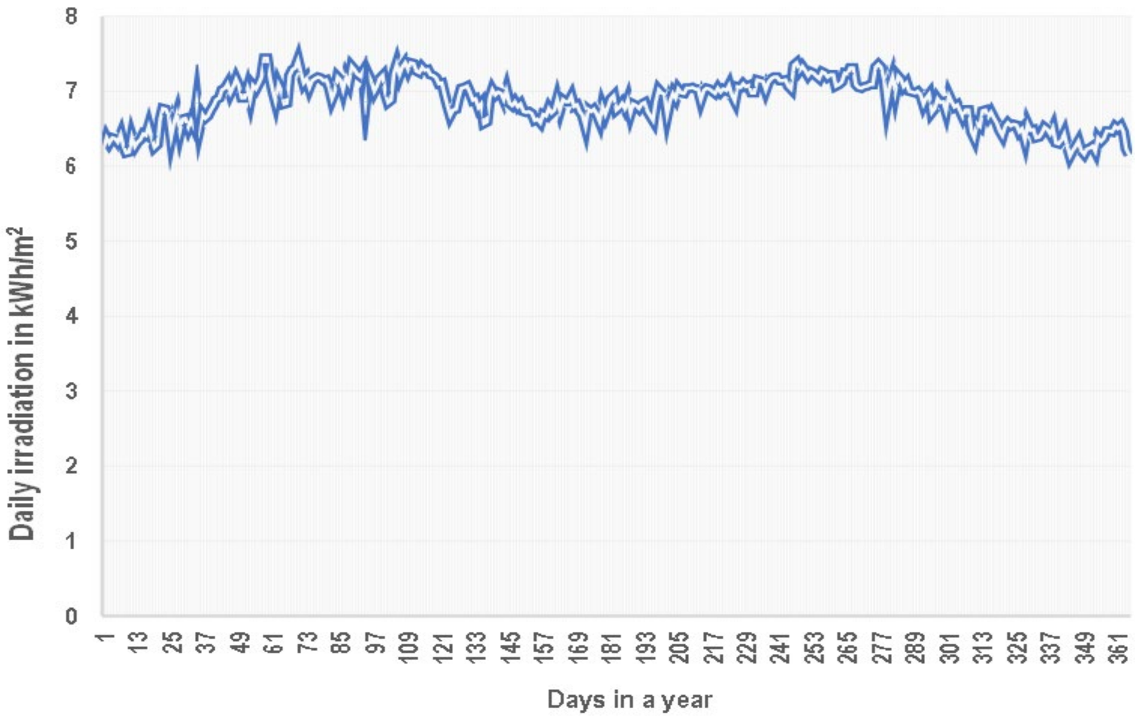


Figure 7. Daily average solar radiation at the selected site

The daily energy consumption in the household is 10.433 kWh, as shown in Table 2. After having the daily load demands, the next step is determining the size of PV arrays. It is calculated based on the lowest irradiation value in PSH and losses in each component, as shown in Table 3. A Monocrystalline PV module with a peak rating power of 250 Wp is selected for the SAPV system. Its module specification is shown in Table 4. Other parameters used in the sizing procedure are shown in Table 5.

Table 2. The details of the appliances used and the operating hours

Load description	Units	Power rating (W)	Load (W)	Operating time (Hours/day)	Energy used (Wh)
Electric water pump machine	1	120	120	1	120
Rice cooker	1	390	390	1	390
Dispenser	1	180	180	24	4320
Fan	2	45	90	2	180
Electric oven	1	600	600	0.25	150
Washing machine	1	500	500	0.25	125
Blender	1	350	350	0.08	28
Laptop	2	80	160	1	160
Lighting 1	4	40	160	10	1600
Lighting 2	2	20	40	4	160
Air conditioner	2	400	800	4	3200
Total daily load (W)			**3390**		
Total energy in a day (kWh/d)					**10.433**

Table 3. Efficiency factor of SAPV components

Efficiency Factor	
Cable	0.95 [18]
Charger controller	0.95 [19]
Battery	0.80 [20]
Inverter	0.90 [20]

The battery units are sized with the assumption that PV arrays cannot supply the electric loads within 2 days. The operating DC voltage is selected at 48 Volts as the daily load demands are greater than 4 kWh. The battery's capacity is calculated with the assumption that the Depth of Discharge of the battery is 70%.

Table 4. Selected PV module for the SAPV system

Electrical Parameters of PV Module	
Maximum power at STC (Wp)	250
Open circuit voltage (V)	37.72
Maximum power voltage (V)	30.31
Short circuit current (A)	8.76
Maximum power current (A)	8.25
Efficiency	15.29
Temperature coefficient of Isc	+0.059%/°C
Temperature coefficient of Voc	-0.33%/°C
Temperature coefficient of Pmpp	-0.410%/°C

Table 5. Parameters used for PV panel

Other Parameters for PV Sizing	
Operating Vdc (V)	48
DoD	0.7
N (days)	2
Imax (A): Output current of PV arrays	49.50
ΔV: Percentage of permissible voltage drop	0.03
Vpv (V): String DC voltage	60.62
ρcu (Ωm) @ 20°C	0.0000000168
length	50
Operating temperature @ 50°C	50
Temperature coefficient of copper wire (/°C)	0.0040366

It is assumed that the operating temperature of the SAPV system is at 50°C. This operating condition affects the resistivity value of the selected cable. Generally, the resistivities of any metals are provided at a temperature of 20°C. The type of cable used in the design is Copper wire with a resistivity of 1.883×10^{-8} Ωm at 50°C. The permissible voltage drop of 3% in the cable is taken for calculating the cable size.

The overall size of each component for the designed SAPV system to satisfy the daily electrical demands of 10.4 kWh is shown in Table 6.

Table 6. The size of each component for the designed SAPV system

PV modules (kWp)	2.61
Ns	2
Np	6
Total number of PV modules	12
Area (m^2)	19.50
Battery (Ah)	621.01
N (Battery unit no.)	4
If one battery is 200Ah, 24V	
Inverter (W)	7875
Vin (V)	48
Cable – PV (mm^2)	51.27
Diameter (mm)	8.08
Charger controller, I (A)	68.328
Voltage (V)	48

5.0 CONCLUSION

In conclusion, this study highlights the critical role of Stand-Alone Photovoltaic (SAPV) systems in delivering reliable energy solutions for remote areas without grid connectivity. By providing a thorough review of SAPV system components, design principles, and sizing methodologies, the research underscores the importance of accurate solar potential assessment, precise energy demand calculations, and proper component selection for achieving optimal system performance. The case study demonstrates the practical applicability of these concepts, offering valuable guidance for real-world SAPV implementations. Ultimately, this work contributes to advancing renewable energy deployment, supporting sustainable development, and addressing energy access challenges in underserved regions. In the future, further work can be explored on the comparison study between the intuitive and numerical methods on SAPV. Exploring hybrid systems with wind or micro-hydro sources and innovative energy storage solutions, like advanced batteries or hydrogen systems, can enhance reliability and performance. Studies on resilience to extreme weather, sustainable recycling of components, and application-specific designs for sectors like agriculture and healthcare are essential. IoT integration for real-time monitoring and policy frameworks to encourage adoption are also critical. These efforts will drive SAPV advancements, supporting energy access and sustainable development in off-grid areas.

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