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Full Length Research Paper

An Experimental Approach towards PV-Based Solar System Sizing for an Engineering Laboratory

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ABSTRACT

This study aims at providing an experimental sizing procedure for a rooftop PV-based solar power system for an engineering laboratory. This was achieved by monitoring the peak power and energy delivered by an installed 20W solar panel into an 18 Ah battery. Knowledge of the average daily peak power and energy was used to determine the percentage rated capacity available for use and the sun hour. A load consumption comparison was also carried out with and without the connection of a load to inverter. In addition to this, the monitoring of the no-load consumption of the inverter was carried out. This was carried-out to ascertain the contribution of the inverter to the system. With the knowledge of the average daily energy deliverable, sun hour and the no-load power of the inverter, a sample sizing for basic electronic laboratory loads was done. The findings of the study reveal that the average available power is 89.35% of the solar panel rated capacity while the average sun hour is 4.38 h. It has also been shown that an approximate difference of 20 W exists between the power consumption of the load with and without its connection to the inverter. This value (i.e., 20W) has been recorded as the approximate no-load power for the inverter. The sample sizing done has shown that, the solar panel energy requirement of the system with inverter may be considerably higher than that without inverter.

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INTRODUCTION

The adoption of solar photo-voltaic (PV) systems in recent times in most developing countries like Nigeria, has greatly increased due to the epileptic power supply in the country. Despite the efforts being made by the governments of these countries to generate more electricity, the gap between energy generation and demand is too wide as to make these efforts to be visible within a short time. This has caused rationing of energy among the populace, thus, making many to depend on alternative source of energy to meet up with their day-to-day energy requirement. The most popular alternative adopted is the usage of small sized fossil fired generating plants. Though, the initial cost is cheap, it however, has high running fuel cost, and it is not environmentally friendly in terms of noise and emissions. Another emerging alternative being slowly adopted recently is the PV-based solar system. Some of the notable challenges to the practical application of this alternative as narrated by Emmanuel, (2009) are the high **initial equipment costs, large installation space** required for attaining high power loads (large number of solar panels are needed to achieve high power rating). This is one of the major limitations a reason why most industries don't consider it for producing electricity to meet their needs. Home and office owners now install the panels on the roof top of their buildings. Another challenge is the **intermittent nature of the sun** since the energy generated from the panel is a function of the intermittent solar radiation. The intermittent nature of the sun can be cushioned with the introduction of storage system (e.g. battery). Moreover, **inadequate knowledge about appropriate sizing** of a solar system, is one of the key challenges to adoption of this technology. Proper sizing is a key to enjoying uninterrupted power supply from the solar system. Proper sizing requires holistic knowledge of the weather and the components to be used.

Despite all the challenges highlighted, it is still being adopted by few who require stable electrical energy supply. It is also being used to supply power to rural areas that doesn't have access to the grid. Other applications of solar are for street lighting, traffic light and water pumping (Aliyu et al., 2013). The attraction to this adoption in Nigeria for instance, is the good solar radiation that ranges from 4 kWh/m^2 in the South to 7 kWh/m^2 in the North (Oseni, 2012). This radiation is sufficiently above the required threshold average value (of 2.3 kWh/m^2) for electrification (Adeoti et al., 2001).

The power rating of a solar module is an indication of the expected power at a radiation of 1000W/m^2 and a cell temperature of 25oC (Skunponga and Plangklang, 2011). The sun hour and cell temperature are major determinants of the amount of energy deliverable by a solar module. Most installers of PV-based solar system carry out components sizing with the assumption that, there exist a specific average daily sun hour, without due diligence given to specific weather constraints of the location. Most times, these constraints come into play when the system is being put to use. Installers also size with the assumption of some specific components' efficiency which may not be real. Some installers however rely on solar energy estimator software to assume the size of their PV system. The estimator software also works with many assumptions that may not tally with the realities on site. One way to ascertain that the onsite realities are put into sizing consideration is the installation and monitoring of a prototype system at the location where the system is intended for. This work therefore carries out an experimental sizing procedure for a rooftop PV-based solar power system for an engineering laboratory. With this approach, practical realities that affect the performance of the system will be taken care of.

In-order to fully harness the potentials of the solar energy systems, there is a need for proper and accurate sizing (Al-Najideen and , 2017). Sizing for the solar energy requires the knowledge of the power rating of the load to be supplied, the time of usage of the load, the type of load (alternating current or direct current), components' efficiency, the sun hour, the energy storage required, etc. (Osueke and Obiora, 2011; Guda and Aliyu, 2015; Fardo and Patrick, 2009).

In the recent past, sun hour and unit efficiency have always been premised on assumptions of the installers (Emmanuel, 2009; Ohunakin *et al*., 2014). Most installers size based on the maximum power deliverable by the solar panel and with the assumption that, there exist an average daily sun hour of 4-6 hours without due diligence given to the atmospheric temperature and other factors. It is important to note that, reality on site may not be as assumed. The work of Kumra *et* *al*. (2012) performed a solar sizing for a standalone system to power a small-scale industry with such assumptions. It should be noted that, if the radiation at a particular location is less than 1000 W/m^2, the expected output will be a percentage of the manufacturer's rating. Also, variation in temperature greatly affects the efficiency of the solar module (Parlak, 2014).

There is software that are used for the sizing of standalone PV system for any given location. This sizing is based on knowledge of the sun's energy, geographic distribution, differing terrain and detailed analysis of the available photovoltaic technologies. This software provides a wealth of information about the development of photovoltaic technology across the globe, up-to-date research on photovoltaics and links to world-wide databases of solar technology and data (Chineke and Dike, 2010). In the works of (Jadin*et* al., 2015; Nordin and Rahman, 2017), a procedure for the sizing of a standalone solar PV system was developed using forecasted solar radiation in Malaysia as input, though, the PV system was not implemented to test if the simulation meets the reality on site. It is necessary to note that, before relying on software for sizing, there is need to confirm, if the estimated energy from the software tallies with the reality on site. There is also need to know the percentage difference between manufacturer's rated capacity and the real time measured capacity of a solar panel as the output from a solar panel depends on the angle of inclination and the direction of installation.

In the work of Salim *et al.*, (2013), the real time solar irradiance and ambient temperature are taken for a specific period of time. But the direct relationships that exist between the measured parameters and the energy supplied by the PV system weren't established. The sizing was carried out based on the estimation from the measured parameters. In another similar work (Odigwe *et al.*, 2013), the authors developed software to size PV system and monitor some parameters (voltage, current, solar irradiance, and ambient temperature) of an installed PV system. The aim of the monitoring system was to give the state and performance of an existing solar-PV installation at any given time. The sizing section of the software was also not based on the real time situation of the installation location.

In a closely related work (Chinomi *et al*., 2017) to this present study, the authors set-up well calibrated monitoring devices to acquire and store data that are associated with PV systems in a micro-grid. The experimental set-up has the ability to measure various electrical parameters, to determine power quality parameters, to simulate and analyse the signals, to record parameters and to detect faults. Since the work stated that the measurement and simulation were carried out for just three hours to ascertain the functionality of the set-up, it is clear that the authors only used the set-up for demonstration and not for sizing.

This work carries out an analysis of a small PV-based solar system installed on the rooftop of an Engineering Laboratory in Osun State University, Osogbo. This was done with a view to knowing the energy expectations from the system, so as to be able to perform a proper sizing that can sustain a low-power consuming laboratory in the Engineering building of the University. It is necessary to note that, the power of the system considered in this work is not more than 850VA/680W (i.e., rating of the inverter considered).

MATERIALS AND METHODS

Description of study area

A number of approaches and procedures were undertaken to achieve the study objectives. Initial steps include the determination of energy deliverable by the solar panel to the battery. Secondly, a comparison of the energy consumption by the load, with and without its connection to the inverter is undertaken and lastly, is the determination of the no-load consumption of the inverter.

The components used for this study are: 20 W Middle Star solar PV module, 850 VA Luminous inverter, 20 W DC lamp, 14 W DC-powered incubator, 20 A charge controller unit,18 Ah and 42 Ah Quanta batteries, AC to DC converter and DC multimeter. The solar panel was installed on the rooftop of the Renewable Energy Laboratory of Osun State University, Osogbo, Nigeria. The panel was found to be inclined at an angle of 15^0 to the horizontal (this is the inclination of the roof of the building). Installing solar panel based on the inclination of the building roof is the common practice in Nigeria for rooftops installation. The reason for using 18 Ah and 42 Ah batteries for this work is to allow for a concurrent carrying out of two separate experiments. The 18 Ah battery was used for the monitoring of the energy deliverable to the battery from the solar panel while the 42 Ah battery was used for the rest of the work.

Determination of the Total Deliverable Solar Energy and Power

The experimental setup to determine the total amount of energy deliverable by the solar panel to the battery is further elaborated in this section. The energy delivered by the 20 W solar panel was monitored via the multimeter from 14^{th} November to 17^{th} December, 2020. The 20 W DC lamp was connected to the setup through the controller to ensure night time discharge of the battery in preparation for the next day's charging. The setting of the controller was done in a way as to allow for the discharge of the battery only at night. The setup of this arrangement is shown in Figure 1. Energy at the end of each day and the peak power were recorded daily for the period. A daily reset was done on the multimeter prior to taking readings for the next day to ensure fresh readings are taken for daily experiments. Here, only one DC meter was utilized for taking daily readings.

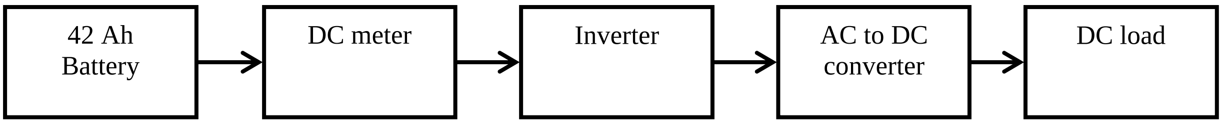
Determination of Energy Consumption by a DC Load

The goal of this experiment is to determine the amount of energy consumed by a DC load with and without its connection to a power inverter. A DC load was considered for this work because most low power consuming equipment in an Engineering laboratory are always supplied through the rectification of AC to DC. Here, a 14 W DC-powered incubator has been used as the load. Figure 2a shows the set-up for monitoring the energy consumed by the load from the battery when connected to an inverter through an AC to DC adapter while Figure 2b shows the set-up for monitoring the energy consumed by the load from the battery when connected directly to the battery. Prior to the start of each experiment, the 42 Ah battery is fully charged. The energy and the power consumed for the set-ups in Figures 2a and 2b for four hours are, respectively, taken.

Determination of No-Load Energy Consumption of an Inverter

This section monitors the energy consumed from the battery when the inverter is on no-load. The set-up used for this is shown in Figure 3. Just like other set-ups aforementioned in this work, this experiment makes use of a DC meter connected in-between a fully charged 42 Ah battery and inverter as shown in Figure 3. In this set-up, no-load was connected to the inverter unit. During the course of the experiment, no form of charging was carried out on the battery. The components used to determine the energy consumption by the DC load with and without its connection to an inverter are shown in Figure 4.

Meter readings were taken for a four hour period for individual set-up shown in Figures 2 and 3. The essence of this is to investigate the impact of inverter on the consumption pattern of a load in a standalone PV-based solar energy system.



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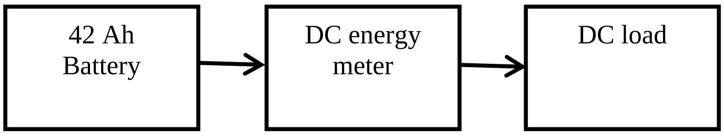
(a) Through Inverter and Converter



(b) When connected directly to battery

Figure 2: Block diagram for the set-up to determine the energy consumed by load from the battery

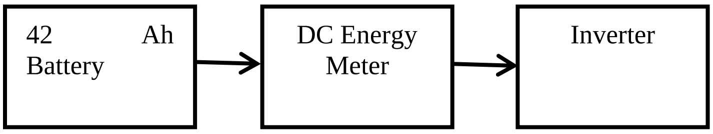


Figure 3: Block diagram for the set-up to determine the no-load consumption of an inverter

RESULTS AND DISCUSSIONS

The study findings presented include the recorded results from the experiments carried out in this work and the implications of the presented results.

Deliverable Peak Power and Energy by the Solar Panel

The daily peak power and energy delivered to the battery for a 30 days period was recorded and the average values of these two quantities estimated. Figures 5 and 6, respectively, show the daily peak power (in comparison to the rated power of the solar panel) and energy recorded during the period. The peak power recorded ranges from 15.7 W to 20.1 W. The slight increase from the rated power seen in Figure 5 is a result of the solar panel power tolerance. The energy delivered ranges from 91.1Wh to 66.5Wh. A close observation of Figures 5 and 6 shows that the values of the energy are not proportional to the peak power values. For example, the days with the minimum and maximum peak power give energy of 81.4 Wh and 72.8 Wh, respectively. Also, the days with the minimum and maximum energy have a peak power of 19.3 W and 16.6 W, respectively. Peak power depends on the peak sun radiation, while energy depends on the duration the panel is exposed to the radiation. The average solar panel peak power (ASPPP) and average deliverable solar panel energy (ADSPE) can be determined using Equations (1) and (2), respectively. The ASPPP and ADSPE are estimated to be 17.87 W and 78.32 Wh, respectively. The estimated value for ASPPP is an indication that the solar panel available average power (i.e., 17.87 W) is 89.35% of the rated power (i.e., 20 W). The average sun hour (ASH) is estimated as the ratio of ADSPE and ASPPP as shown in Equation (3). The estimated ASH is 4.38 hours.

In summary, to achieve the calculated ADSPE from 20 W solar panel, the panel will deliver 89.35% of its capacity for 4.38 hours. This was the guide used to size the PV-based solar power system for the laboratory loads.

$$ASPPP = \left(\sum_{i=1}^{N} P_i \right) \Big/ N \quad (1)$$

$$ADSPE = \left(\sum_{i=1}^{N} E_i \right) \Big/ N \quad (2)$$

$$ASH = (ADSPE)/(ASPPP) \quad (3)$$

where P_i and E_i are, respectively, the recorded peak power and energy delivered for day *i* and N is the total number of days the observation was done.

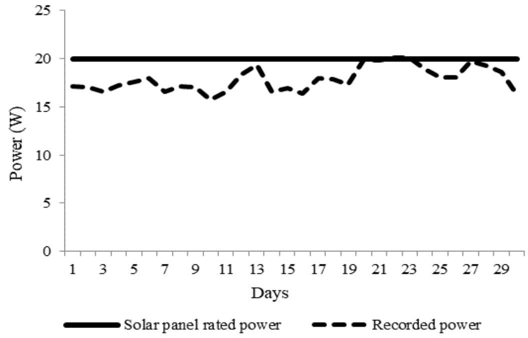


Figure 5: Comparison between the solar panel rated and recorded power

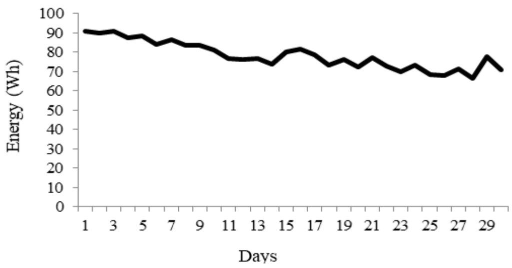


Figure 6: Energy delivered into the battery

Load Energy Consumption

The energy, power and voltage recorded when the DC load is connected directly to the battery is shown in Table 1 while Table 2 shows similar parameters for DC load but with its connection to the inverter through an AC to DC converter. A close look at Tables 1 and 2 clearly show the energy consumption advantage derivable from a DC load being used without an inverter and converter. The battery voltage level recorded on both tables is an indication of the loading effect on the battery. The loading effect when the load is used with battery directly is lighter than when the load is connected through converter and inverter. The implication of this is that, low voltage cut-off mark will be quickly reached when inverter and converter is involved than when these two devices are not used. The average power consumptions of the load without and with inverter are, respectively, 13.93 W and 34.56 W. Table 3 shows the energy and power waste introduced due to the use of the converter and inverter. After the fourth hour, energy and average power of 83 Wh and 20.65 W, respectively, have been wasted with the introduction of the two devices.

Table 1: Energy consumed by the load without inverter

Hour	Energy (Wh)	Power (W)	Battery Voltage (V)
1	14.3	14.4	12.79
2	27.8	13.9	12.68
3	41.7	13.8	12.59
4	55.3	13.6	12.50

Table 2: Energy consumed by the load with inverter

Hour	Energy (Wh)	Power (W)	Battery Voltage (V)
1	33.6	35.5	12.38
2	68.6	34.4	12.19
3	103.7	34.3	12.04
4	138.3	34.1	11.91

Table 3: Loss due to consumption through inverter

Hour	Energy Loss (Wh)	Power Loss (W)
1	19.3	21.1
2	41.3	20.5
3	62.0	20.5
4	83.0	20.5

No-load Assessment of an Inverter

Table 4 shows the no-load consumption of an inverter for four hours. The average no-load power for the four-hour period is 19.53 W. Comparing the no-load power values of Table 4 with the power loss of

Table 3 shows that, their values are closely similar. The likely reason for the slight difference might be the contribution of the AC to DC converter. *By implication, it could be approximated that, the power consumption of load through an inverter is the addition of the power rating of the load and the no-load power of the inverter*. As a result of this, an approximate value of 20 W (as against 19.53 W) has been considered in this work as the no-load power.

Table 4: No-load consumption of an inverter

Hour	Energy (Wh)	Power (W)
1	15.6	19.8
2	34.7	20.0
3	53.5	20.0
4	72.1	18.3

Sizing Procedure

The procedure involved in sizing using this experimental approach is summarized in the flow chart of Figure 7. The explanation of the flow chart is itemised below:

i. The power rating of the load and the expected time of using the system need to be known.
ii. Identify if the load is of AC type or DC. If AC, the power rating of the load must be added to the no-load power of the inverter.
iii. Multiply load power by time of usage to determine the energy to be consumed from the system.
iv. Divide the energy (in iii) by the ASH (i.e., 4.38 hours) to obtain the needed total power rating of the solar panel.
v. Divide the obtained total power rating by the calculated percentage panel power available (i.e., 0.8935). This is done to determine the actual power rating of panel needed.
vi. Select the size of the solar panel to be used (80 W, 100 W, 150 W, 180 W, etc.)
vii. Divide the actual power rating of panel needed in (v) by the selected size of solar panel to be used to determine the quantity of solar panel needed.
viii. To size for battery, subtract average sun hour from time of usage to know the time needed for storage.
ix. Multiply the time needed for storage by the load power to know the energy needed for storage.
x. Divide the storage energy needed by an assumed value of depth of discharge (DOD) of battery to know the total capacity of the battery needed. In this work, a DOD of 70% is considered.
xi. Multiply the quantity of solar panel needed by the current at maximum power (I_{mp}) of the selected solar panel, to determine the maximum allowable charging current from the panels.
xii. Assuming 20% of the rated battery current capacity as the maximum allowable charging current, determine the minimum battery capacity to be used by dividing the maximum allowable charging current in (xi) by 0.2.

To further understand this procedure, a sample sizing for an average total power of 200 W AC/DC laboratory equipment was done. This equipment is expected to be used from 9:00 AM to 4:00 PM (i.e., for seven hours) daily. This period includes the sun time. Two separate sizing procedures were carried out for this load. First is the sizing with the assumption that, the load is DC and there may be no need for inverter. Secondly is the sizing with the assumption that the load is AC, hence, inverter is needed.

Sizing without the consideration of an inverter

i. Sizing for the load as a DC device means that, this device is directly connected to the battery/solar panel.
ii. Its usage for seven hours implies that, 200 W x 7h = 1400 Wh of energy will be consumed.
iii. This energy is expected to be supplied by the solar panel. Recall that, the calculated sun hour is 4.38 hours, so, assuming 100% efficiency, 319.63 W

(i.e., 1400 Wh /4.38 h) capacity of solar panel is required.

iv. Also recall that, 89.35% of the rated capacity of the solar panel is available for use. So, the actual rating of the solar panel to be used is 357.73 W (i.e., 319.63 W/0.8935).

v. If a 150 W solar panel is to be used, the quantity of panels to be used can be calculated as 357.73W/150W = 2.38. Approximately, 3 pieces of the panels rated 150 W are needed.

vi. To size the battery, the sun hour is subtracted from the time of usage. This means that there is need for 2.62 h (i.e.,7 h – 4.38 h) of storage.

vii. Multiplying 2.62 h with 200 W (i.e., the load), the storage energy needed is 524 Wh.

viii. Assuming this represent 70% depth of discharge (DOD), the energy of the battery needed is 748.57Wh (i.e., 524 Wh/0.7).

ix. To determine the minimum size of battery needed, the peak current available for a 150W panel (i.e., 8.33 A) is multiplied by three (which is the quantity of panels considered) to give 25 A. This means that 25 A is the peak available charge current from the panels. If this value is expected to be the current at a maximum recharge rate of 0.2C, where C is the Ah rating of the battery (Luptak, 2014), the minimum capacity of the battery (in Ah) to be used for three panels is 125 Ah (i.e., 25A/0.2).

If 12 V, 125 Ah battery is considered, from (viii), the number of batteries needed is 748.57 Wh /125 Ah x 12V) = 0.5. Approximately, one battery is needed.

The size of the proposed system if load is to be connected directly to the battery is 3 pieces of 150W panel and 1 piece of 125Ah battery.

Sizing with the consideration of an inverter

i. Sizing for the load as an AC device means that, this device uses inverter. In this case, the brand of inverter used for this work is still being considered.

ii. Adding the no-load power value of 20W, the total expected consumption from the battery is 220 W (i.e., 200 W + 20 W).

Using the procedure stated in section 3.4.1, from point (ii) to (x), the sizing technique proposes the same quantity of solar panels and battery for a system that will be powered through inverter.

Though, the same quantity of solar panels and battery is suggested for the system with and without the use of inverter, at some load levels, the size of components will be different for both cases. For example, using excel sheet to implement the flow chart of Figure 7, it has been discovered that the number of 150 W solar panel needed for a 250 W load for the same duration without inverter remains three while with inverter, it is four. With three panels, 125 Ah battery can be used, but higher capacity is needed for four panels. Tables 5 and 6, respectively, show the number of solar panels and the battery size to be used with and without the usage of an inverter. Cases A and B in the table, respectively, stand for the number of solar panels and the battery size without and with inverter. It can be seen that the number of solar panels and size of battery needed for both cases are the same for some load requirements and different for others.

Table 5: Number of solar panels for different load requirements

Load (W)	Case A	Case B
200	3	3
250	3	4
300	4	4
350	5	5
400	5	6
450	6	6
500	6	7
550	7	7
600	8	8
650	8	8

Table 6: Battery capacity for different load requirements

Load (W)	Case A	Case B
200	125	125
250	125	167
300	167	167
350	209	209
400	209	250
450	250	250
500	250	292
550	292	292
600	334	334
650	334	334

Figure 3 shows the Lactide and PLA formed during ring open polymerization process using sisal boles purified LA. The crude lactide contained yellow-like colour which is attributed to the colour of LA used. The residual sugar composition in the sisal bole LA (only 64% were removed during purification (Msuya *et al.*, (2018c)), could have contributed to the colour change as it is concentrated and decomposes when higher temperatures were used during lactide formation. The lactide crystals obtained were whitish in colour which suggests that the solvent used was able to remove the colour containing compounds in the sisal bole crude lactide. From each 1.0 g of sisal bole LA used, it was possible to produce 0.73 g of Lactide. Low yield can also be attributed to the residual sugars in LA used.

CONCLUSION AND RECOMMENDATION

This work has carried out an analysis of the energy expectation for a standalone PV-based solar system for an Engineering laboratory. This analysis was able to establish the average deliverable daily energy and power from a solar panel. It has also established the effect of the inclusion of the inverter in the system. In addition to increasing the cost of installation, inverter contributes significantly to the energy wastage in the system. The analysis carried out in this work was used for the solar power system sizing for a laboratory. The essence of this work is to have a proper sizing that put the installation environment's conditions into consideration. It has been shown that, to power a 200 W load for seven hours, it requires a minimum of 357.73 W solar panel power if inverter won't be connected. If inverter is to be connected, it requires 576.4 W solar panel power. Using excel sheet to implement the sizing procedure, it has been shown that the number of solar panels and the size of battery needed to power a load with and without its connection to the inverter are the same for some load requirements and different in others. If the procedure carried out in this work is used for installation sites evaluation, it will allow for an optimum powering of the needed loads. It is recommended that further works should involve a real time data logging of the measured parameters to further improve the sizing procedure.

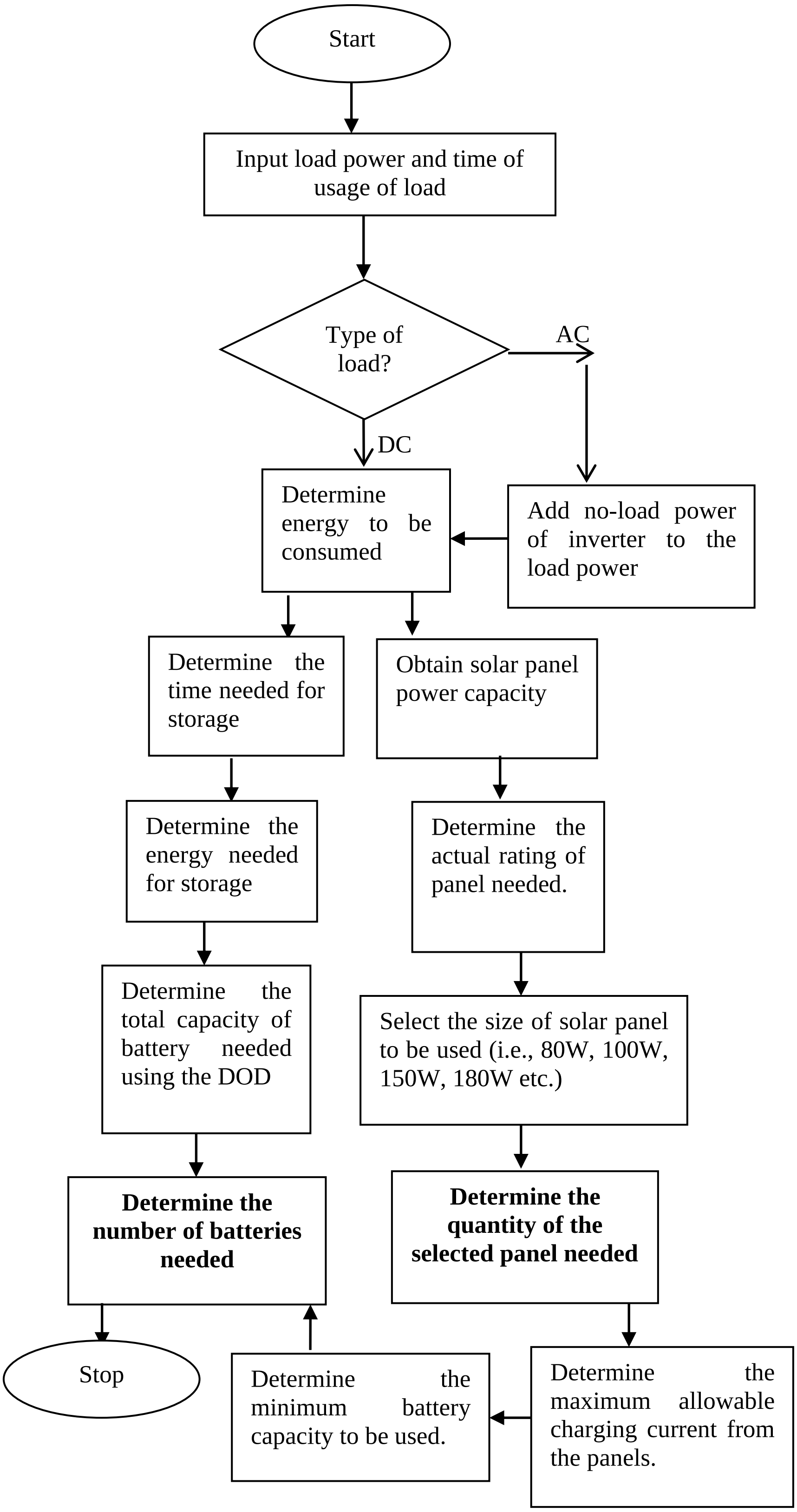


Figure 7: Flow chart for the sizing procedure

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