



# SOLAR HOME SYSTEMS

## Maximum Array Size 1 kW<sub>p</sub>

### SYSTEM DESIGN GUIDELINES



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These guidelines have been developed for Ugandan Rural Electrification Agency (REA) and the Uganda Energy Credit Capitalisation Company (UECCC)  
They represent latest industry BEST PRACTICE for the Design of Solar Home Systems with a maximum array of 1 kW<sub>p</sub>  
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While all care has been taken to ensure this guideline is free from omission and error, no responsibility can be taken for the use of this information in the design of any Solar Home System.

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## Abbreviations

A	Amps (or Amperes)
a.c.	Alternating Current
Ah	Ampere–Hours
C <sub>x</sub>	Capacity of battery at specified charging rate x in hours
CCC	Current-Carrying Capacity
d.c.	Direct Current
DOD	Depth of Discharge
ERT	Energy for Rural Transformation
IEC	International Electrotechnical Commission
IP	International Protection sometimes known as Ingress protection
IV	Current-Voltage
kW	Kilowatts
LV	Low Voltage
MPPT	Maximum Power Point Tracker
NEP	National Energy Policy
OC	Open Circuit
PSH	Peak Sun-Hours
PV	Photovoltaics
PWM	Pulse-Width Modulated
SC	Short Circuit
SHS	Solar Home System
TS	Technical Specification
UL	Underwriters Laboratories
UV	Ultraviolet
V	Volt
VA	Volt-Ampere
VRLA	Valve-regulated lead-acid battery
W	Watts
Wh	Watt-Hours
W <sub>p</sub>	Watts Peak

## OVERVIEW

This Guideline supports Solar Home Systems with a solar array of maximum 1 kW<sub>p</sub>. It covers the design of installations that deliver only d.c. to the load, and installations that deliver a.c. to the load and use a d.c. bus (charge controller, battery and battery connected inverter).

Larger size solar home systems including installations that deliver a.c. to the load and use an a.c. bus (a.c. inverter connected directly to solar modules, a battery and an inverter that operates off the battery while providing battery charging from the a.c. inverter) will be covered in the design guideline Solar Home Systems greater than 1 kW<sub>p</sub>.

**For simplicity the term Solar Home System when used in this guideline will only refer to systems with a solar array of maximum 1 kW<sub>p</sub>.**

This guideline shall be read in conjunction with the existing Uganda Code of Practice: US:152-2000 Installation of Photovoltaic systems. Where this guideline has a requirement that contradicts a similar requirement within the Code of Practice, the requirement of this guideline shall be followed because this guideline has been based on current best practices.

## 1. Introduction

This guideline provides an overview of the formulas and processes undertaken when designing (or sizing) a Solar Home System, sometimes called a stand-alone power system. It provides information for designing a Solar Home System using d.c. bus (with battery charging directly from the panels) configuration.

The content includes the minimum information required when designing a Solar Home System. The design of a Solar Home System should meet the required energy demand and maximum power demands of the end-user. However, there are times when other constraints need to be considered as they will affect the final system configuration and selected equipment. These include:

- available budget;
- access to the site;
- the need to easily expand the system in the future; and
- availability of technical support for maintenance, troubleshooting and repair.

Whatever the final design criteria, a designer shall be capable of:

- Determining the expected power demand (loads) in kW (and kVA) and the end-user's energy needs in kWh/day;
- Determining the size of the PV array (in kW<sub>p</sub>) and the capacity of the battery bank (in Ah and V or Wh) needed to meet the end-users' requirements;
- Selecting the most appropriate PV array mounting system;
- Determining the appropriate d.c. voltage of the battery bank;
- Determining the rated capacity of the battery bank<sup>1</sup>;
- Determining the size of the battery inverter in VA (or kVA) to meet the end-user's requirements;
- Ensuring the solar array size, battery and any inverters connected to the battery are well matched
- Determining the size of the solar controller<sup>2</sup> (sometimes called regulator) with respect to the PV array
  - For Pulse Width Modulated solar controllers matching the array to the controller so that
    - The controller operating voltage is appropriate for the array voltage is appropriate to the battery voltage;
    - The array current does not exceed the maximum controller input current.
  - For MPPT solar controllers, matching the array configuration to fit the controller's:
    - maximum allowable input voltage
    - input voltage operating window;
    - maximum allowable d.c input power rating; and
    - maximum d.c. input current rating.

**A Solar Home Systems with an a maximum solar array of 1 kW<sub>p</sub> shall have a maximum open circuit voltage of less than 120 V d.c. . Voltage under 120 V d.c. are known as Extra Low Voltage (ELV).**

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<sup>1</sup>For the battery to have a long useful life, the *rated* Ah capacity of the battery will generally need to be substantially larger than the Ah capacity actually needed to reliably operate the load because of losses in the system and to have the reserve needed to handle short term increases in the load. Also, as the battery ages, its effective capacity decreases.

<sup>2</sup> The solar controller could be a fixed input voltage controller—such as a Pulse Width Modulated (PWM) controller—or a Maximum Power Point Tracking (MPPT) controller

## 2. Typical Off-Grid PV Power System Configuration.

Off-grid PV power systems can range from a single module, single battery system providing energy to d.c. loads in a small residence to a large system comprising an array totalling hundreds of kW of PV modules with a large battery bank and an inverter (or inverters) providing a.c. power to the load. Note that those larger systems may integrate a generator using fossil fuel or biofuel. The design of that type of system is covered in a separate guideline titled Design of PV-Fuel Generator Hybrid Power Systems.

Figure 1 shows the configuration of a system that provides d.c. power only. These systems are typically installed on rural housing and village meeting houses where the d.c. power directly feeds lights and small d.c. appliances. Figure 2 shows a solar home system that can also power small a.c. appliances that are powered by an inverter operating off the d.c. power. These installations typically range between about 100 W<sub>p</sub> to 1000 W<sub>p</sub> of solar though smaller or larger installations are possible. The d.c. voltage provided to loads is usually 12 V, 24 V or 48 V. This type of installation is often called a Solar Home System (SHS) and is widely used for remote island village electrification. It is these systems that are covered in this guideline.

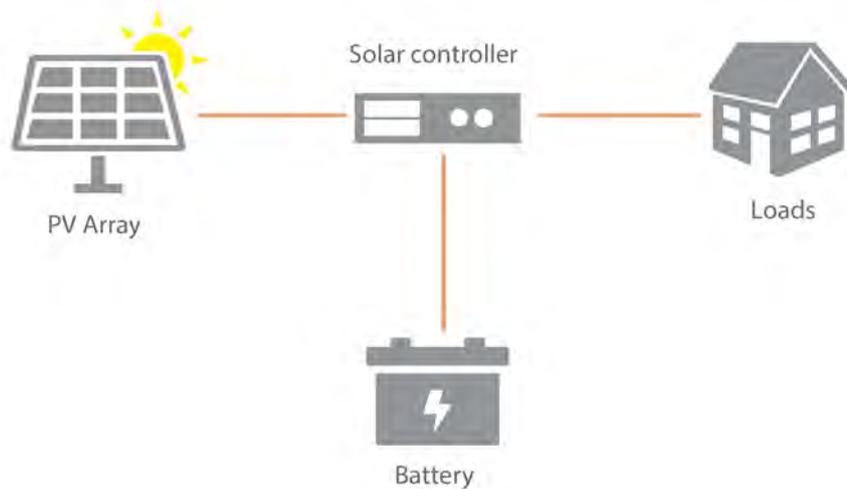


Figure 1: System powering d.c. loads (this is also a simple d.c. bus system)

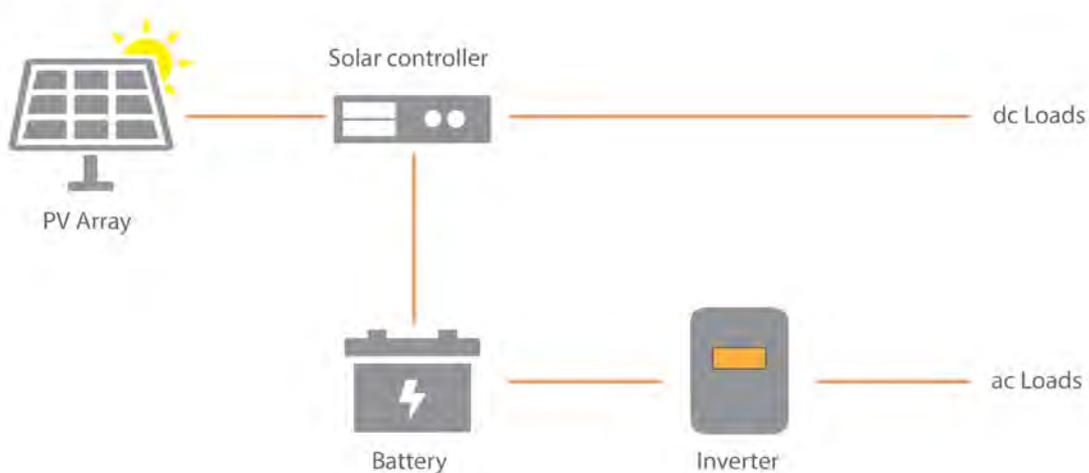


Figure 2: d.c bus system (system providing a.c. and d.c. loads)

This guide contains the basic formulas for d.c. bus systems.

### 3. Standards Relevant to the Design of Solar Home Systems

- IEC 61215 Terrestrial photovoltaic (PV) modules - Design qualification and type approval
  - IEC 61215-1 Part 1: Test requirements
  - IEC 61215-2 Part 2: Test Procedures
- IEC 61730 Photovoltaic (PV) module safety qualification.
  - IEC 61730-1 Part 1: Requirements for construction.
  - IEC 61730-2 Part 2: Requirements for testing.
- IEC 62109 Safety of power converter for use in photovoltaic power systems.
  - IEC 62109-1 Part 1: General requirements.
  - IEC 62109-2 Part 2: Particular requirements for inverters.
- IEC 61427-1 Secondary Cells and Batteries for Solar Photovoltaic Energy Systems - General Requirements and Methods of Test - Part 1: Photovoltaic off-grid application
- IEC 62548 Photovoltaic (PV) Arrays-Design Requirements
- IEC 62619 Secondary cells and batteries containing alkaline or other non-acid electrolytes— Safety requirements for secondary lithium cells and batteries, for use in industrial applications
- IEC 60896 Stationary lead-acid batteries (series)
- UL 1973 Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications
- UL 1642 Standard for Lithium Batteries
- UL 2054 – household and commercial batteries. This standard is typically used for battery packs, whereas UL 1642 is typically applied to cells only.
- IEC 62133-2 – IEC safety standard for lithium-based cells and batteries for portable applications. (IEC 62133 is an older version that is still being phased out; in 2017 it was split into two parts with -1 covering Ni batteries and -2 for Li.)
- UL 62133 – UL version of IEC 62133 (UL 62133-2 is expected to be published shortly)
- IEC 62257-9 Recommendations for small renewable energy and hybrid systems for rural electrification –
  - IEC 62257-9-1 Part 9-1: Micropower systems
  - IEC 62257-9-2 Part 9-2: Microgrids
  - IEC 62257-9-3 Part 9-3: Integrated System-User Interface
  - IEC 62257-9-4 Part 9-4: Integrated System-User installation.
  - IEC 62257-9-5 Part 9-5: Integrated systems - Laboratory evaluation of stand-alone renewable energy products for rural electrification.

### 4. Steps when Designing a Solar Home System

Four major issues arise when designing a Solar Home System:

- 1) the load (power and energy) required to be supplied by the system is not constant over the period of one day;
- 2) the daily usage varies greatly over a week;
- 3) the daily energy usage varies over the year;

- 4) the energy available from the PV array will vary greatly during the day according to the time of day and cloud passages;
- 5) the energy available from the PV array will vary during the year as weather conditions vary over the year and as the sun changes its position in the sky over the year.

Since the system is based on photovoltaic modules, the designer should compare the available energy from the sun over a typical year. If the energy usage varies throughout the year, then the energy usage for each month should be compared with the irradiation for the respective month to determine the design month (refer section 12.1) for sizing the array frame. If the energy demand is relatively constant thorough out the year, the design month will be the month with the lowest monthly average daily irradiation.

The steps in designing a system include:

1. Carrying out a site visit and determining the limitations for installing a system and examining the location where the equipment will be installed (see section 5).
2. Determining the energy needs of the end-user (see section 7).
3. Determining the voltage and capacity of the battery bank (see sections 8 & 9).
4. Determining the size of any inverter connected to systems supplying d.c. power (Section 11).
5. Determining the size of the array (sections 17,18 and 19).
6. Determining the size of the solar controller (Section 20 for PWM controllers and section 21 for MPPT based controllers).
7. Determine cable size and calculate voltage drop (section 22 and 23).
8. Determine system protection and disconnection requirements (Sections 24 and 25).
9. Draw a schematic / single line diagram (Section 26).
10. Prepare bill of quantity (Section 27).
11. Providing a quotation to the end-user. (Section 28).

## 5. Site Visit

If possible, a site visit should be undertaken. The designer should visit the site and undertake/determine/obtain the following:

1. Discuss the energy needs of the end-user. (Section 6 and 7 for more detail).
2. Complete a load assessment form (See Section 7 for more detail).
3. Assess the occupational safety and health risks when working on that particular site.
4. Determine the solar access for the site or determine a position where the solar has the most available sunlight.
5. Determine whether any shading will occur and estimate its effect on the system.
6. Determine the orientation and tilt angle of the roof if the solar array is to be roof mounted. (See the guide for Installation of Solar Home Systems for further information)
7. Determine the available area for the solar array.
8. Determine whether the roof is suitable for mounting the array (if roof mounted).
9. Determine how the modules will be mounted on the roof (if roof mounted).
10. Determine where the batteries will be located.
11. Determine where the solar controller will be located.
12. Determine where the battery inverter will be located (if applicable).
13. Determine the cabling route and therefore estimate the lengths of the cable runs.
14. Determine whether system monitoring panels or screens are required and determine a suitable location with the end-user.

Following the site visit, the designer shall estimate the available solar irradiation for the array based on the available solar irradiation for the site and the tilt, orientation and effect of any shading. (See section 12.1, 12.2 and 12.3.)

If the site is too remote, then all the above information might need to be obtained through discussions with the end-user and the final location of all equipment selected at the time of installation.

Some small systems might be provided as plug-and-play systems (sometimes called pico-solar systems).

## 6. Energy Efficiency

Discuss energy efficient initiatives that could be implemented by the site owner. These could include:

- i. replacing inefficient electrical appliances with new energy-efficient electrical appliances;
- ii. replacing incandescent light bulbs with efficient LED lights;
- iii. using laptop computers instead of desktop units;
- iv. using energy-efficient flat-screen TVs instead of older units with picture tubes.

## 7. Load (Energy Assessment)

Electrical power is supplied from the batteries (d.c.) or via an inverter to produce 240 volts a.c. (Electrical energy usage is normally expressed in watt hours (Wh) or kilowatt hours (kWh).

To determine the daily energy usage for an appliance, multiply the power required by the appliance in watts times the number of hours per day it will operate. The result is the energy (Wh) consumed by that appliance per day.

Appliances can either be d.c. or a.c.. An energy assessment should be undertaken for each type. Examples of these are shown in tables 1 and 2.

You need to discuss the electrical energy usage in detail with the end-user. Many systems have failed over the years not because the equipment has failed or the system was installed incorrectly, BUT BECAUSE THE END-USER BELIEVED THEY COULD GET MORE ENERGY FROM THEIR SYSTEM THAN THE SYSTEM COULD DELIVER. It failed because the end-user was unaware of the **power/energy limitations** of the system and attempted to use more energy than the system was designed to provide.

The problem is that the end-user may not want to spend the time determining their realistic power and energy needs, which are required to successfully complete a load assessment form. They typically just want to know: *“How much for a system to power my lights and radio or TV?”*

A system designer can only design a system to meet the power and energy needs as stated by the end-user. The system designer must therefore use this process to clearly understand the needs of the end-user and at the same time educate the end-user regarding the capacity of the system to be installed. Completing a load assessment form correctly does take time (refer to table 1 and 2 below); you may need to spend 1 to 2 hours or more with the potential end-user completing the tables. It is during this process that you will need to discuss all the potential sources of energy that can meet their energy needs and you can educate the end-user about energy efficiency.

Tables 1 and 2 are used throughout the guideline as a worked example. If the loads are d.c. then table 1 will be used. If the loads are a.c. then table 2 will be used. The tables show d.c. lighting loads and a.c. appliance loads.

Uganda straddles the equator and therefore has little year-round fluctuation in temperature and no real winter or summer but does have wet/rainy seasons. In some countries that have distinct seasons there can be with large variations in temperature and also differences in the length of the nights between different seasons. This can result in differences in energy consumption between the different seasons.

When that happens it is advisable to prepare a load assessment that includes estimating the energy usage for possibly two seasons.

When this is undertaken the season with the highest average daily energy usage is used to determine the size of the battery bank. A comparison is undertaken between available solar irradiation for each month and the pattern of seasonal energy use to determine the month that has the greatest disparity between energy needed by the end-user and the energy available from the sun. The kWh/day energy requirement of that month is then used to determine the size of the solar array needed to provide the required kWh of electrical energy during that month. (refer to sections 18 and 19)

The worked example assumes that the energy usage remains the same throughout the year,

Though the total load energy might be high for some installations, it can also be small for other installations; a careful survey for each installation has to be carried out. The table also shows both d.c. lighting loads and a.c. appliance loads for a single site. In real life this could be the case, or all the loads might be d.c. or all a.c. The principle of this guideline is to summarise how you use a load assessment form to design any Solar Home System.

Tables 1 and 2 show the daily energy usage for each appliance. The daily energy usage of each appliance are added together to provide the daily load energy for the d.c. loads and daily load energy for the a.c. loads.

For the a.c. table a term called power factor is introduced. This is from the formula:

True power (W) = Apparent power (VA) x Power factor (sometimes expressed as  $\cos \phi$  where  $\phi$  is the angle between true power and apparent power or between voltage and current)

The power factor is used in table 2 to determine the apparent power. Inverters sold on the market have a power factor rating of 1. That is the true power in W is the same as the apparent power in VA. The maximum demand, that is maximum apparent power is calculated in the table to help select the inverter. The inverter must have a continuous power rating in VA equal to but probably greater than the maximum demand determined in table 2.

The maximum demand column contains all the appliances that will operate at the exact same time. In table 2 all appliances are shown to operate however that is expected when there are only 3 appliances. If a house contains many appliances, the designer in consultation with the home owner must determine what are the loads that might all operate at same time and hence determine the maximum demand.

**Worked Example 1`**

Table 1: d.c. Load (energy) Assessment

Appliance	Number	Power	Daily usage		Contribution to maximum demand	Comment
			Usage time	Energy		
		W	h	Wh	W	
Light	4	7	4	112	28	--
<b>Daily load energy-d.c. loads (Wh)</b>				112	--	--
Maximum d.c. demand (W)					28	--

Table 2: a.c. Load (energy) Assessment

Appliance	No.	Power	Daily Usage		Power factor	Contribution to max demand	Surge factor	Contribution to surge demand		Comment
			Usage time	Energy				Potential	Design	
		W	h	Wh	VA	VA	VA			
TV	1	25	4	100	0.8	31	1	31	31	
Refrigerator	1	100	14	1400	0.8	125	4	500	500	Duty cycle of 0.58 included
<b>Daily load energy a.c. loads (Wh)</b>				1500						
Maximum a.c. demand (VA)						154				
Surge demand (VA))								531		

Some appliances, such as motors, require a higher current to start and hence have a surge power rating as well as a continuous power rating. The inverter must be able to provide sufficient surge power (typically for 1 to 3 seconds) to start a motor or other appliances that might have higher currents at the start.

For every appliance that operates at the same time, the surge power should be added into column titled “potential surge”. These are added together to determine the maximum surge demand which must be supplied by the inverter. However, when there are a lot of appliances they will not all be on at the same time and they definitely will not start at the same time. The designer must determine the actual surge demand that will be used when selecting an inverter—that is the design surge.

When there are many appliances the designer must try many combinations when determining the maximum and surge demands.

In the worked example of a load assessment (previous page), the TV, fan and refrigerator are using a.c. electricity so we have to take into account the efficiency of the inverters used. Typically, the peak efficiency of an inverter may be over 95% but in many systems the inverter will sometimes be running even when there is very little load on the inverter and some energy will be used by the inverter even though it is not operating a load, so the average efficiency is typically about 90% to 96%. Then we must divide the total a.c. energy used by the load plus the losses in the inverter to obtain the total energy required to be supplied to the inverter from the battery bank.

### **Worked Example 2**

(Based on the load tables shown on page 8)

This example shows how to determine the energy at the battery bank for both the humid season and the rest of the year.

Assume the overall efficiency of the chosen inverter is 90%.

Daily battery load (energy use) from d.c. loads = 112 Wh

Daily battery load (energy use) from a.c. loads =  $1500 \text{ Wh} \div 0.90 = 1667 \text{ Wh}$

To estimate the total load (energy) as seen by the battery, you add the two figures together:

$$1667 + 112 = 1779 \text{ Wh}$$

If there are no a.c. loads, then just work out the load from the d.c. appliances, and do not include any calculations for an inverter (inverter efficiency)

## **8. Selecting Battery Voltage**

System battery voltages are generally 12, 24 or 48 volts. The actual voltage is determined by the requirements of the system.

As a general rule, the recommended system voltage increases as the total daily energy usage increases. For small daily loads, a 12 V system voltage can be used. For intermediate daily loads, 24 V is used and for larger loads 48 V is used.

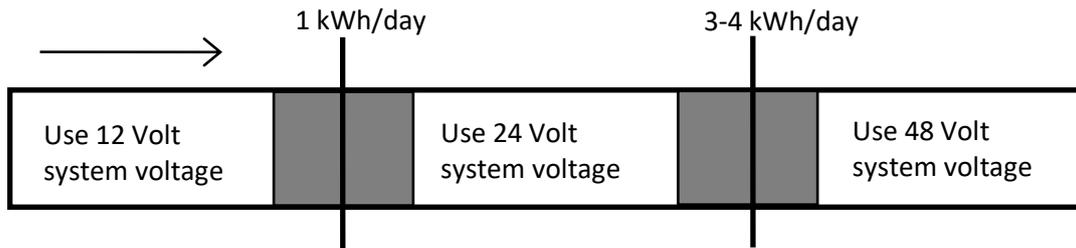


Figure 3: Guideline to selecting battery voltage

The changeover points are roughly at total energy usage of 1 kWh/day and 3-4 kWh/day, but this will also be dependent on the actual power profile. These are only a guide and there will be certain systems where this guide might not be applied. For example, assume a radio transmitter has a 100 W of continuous power demand. A 12 V system could still be used even though the total energy usage is 2400 Wh/day. The current being drawn from the battery bank is only 8.33 A (100 W/ 12 V). On the other hand, a pump drawing 800 W that only operates 3 hours a day will also use 2400 Wh but will draw almost 67 A when it runs, requiring very large wires and high Ah capacity batteries at 12V. If operated at 48 V, the current draw will be approximately 17 A and much smaller wiring can be used without excessive losses, plus the battery Ah requirement will be  $\frac{1}{4}$  that of using a 12 V battery.

It is good design practice to aim to have the maximum continuous current being drawn from the battery bank not greater than 150 A. This is to reduce the size of the required cable and minimise any problems with voltage drop.

Note: The term battery bank is being used in the guideline; in Solar Home Systems a battery bank may be a single 12 V monobloc battery.

## 9. Determining the Required Capacity of the Battery Bank

If the load energy assessment is undertaken based on two different weather seasons, the highest daily energy usage is used to determine the installed battery capacity.

Some people in the industry might argue that if some of the loads are working during the day the battery bank capacity does not need to be based on the total daily energy usage; it can be reduced due to the daytime loads being supplied directly by the PV array. However, the available solar irradiation can vary greatly from day to day so the best practice – and the recommendation of this guideline – is to determine the required battery capacity based on the total daily energy usage. This not only helps ensure that the system operates reliably, it also extends the battery life since it is less stressed during cloudy periods.

Lithium-ion batteries are typically supplied based on their watt-hour (Wh) capacity.

Lead-acid batteries are typically supplied based on their ampere-hour (Ah) capacity.

To convert watt-hours (Wh) to ampere -hours (Ah) you need to divide by the battery system voltage.

### Worked Example 3

From example 1: the energy usage is 1779 Wh/day, so select a battery system voltage of 24 V.

This means that the Ah/day usage on the battery bank will be:

$$\text{Ah/day} = \text{Wh/day} \div \text{system voltage} = 1779 \text{ Wh/day} \div 24 \text{ V} = 74 \text{ Ah/day}$$

The minimum size battery to meet the daily energy requirements in the example is: 74 Ah (for lead-acid battery) or 1779 Wh (for a lithium-ion battery).

However, for long-life, lead-acid batteries should not regularly be discharged more than 50% or 60%, with 20-30% being a common daily average discharge level for Solar Home System installations. So the actual Ah of the battery installed will be at least double and often five times the calculated one-day Ah requirement to account for a potential string of cloudy days.

In addition, battery capacity is determined by whichever is the greater of the following two requirements:

1. The ability of the battery to meet the energy usage of the system, typically for one to five days, sometimes specified as “days of autonomy” of the system;

OR

2. The ability of the battery to supply maximum power demand in delivered watts (amperes delivered times volts at the battery terminals). (Refer to maximum demand values in Tables 1 and 2)

How to determine the daily energy usage of the system was shown in example 3.

### Worked Example 4.

The maximum d.c. demand in table 1 is 28 W.

The maximum a.c. demand in table 2 is 154 VA. This is the demand out of the inverter so at the battery terminals the maximum demand would be  $154/0.9 = 171.1 \text{ VA}$ .

The maximum current that will be discharged from the batteries =  $(171.1 + 28)/24 = 8.3 \text{ A}$

Parameters relating to the energy requirements of the battery include:

1. Daily energy usage.
2. Daily average depth of discharge and maximum depth of discharge.
3. Number of days of autonomy.

Parameters relating to the discharge power (current) of the battery:

1. Maximum power demand (maximum demand discharge current).
2. Surge demand (surge demand discharge current).

Parameters relating to the charging of the battery:

1. Maximum charging current.

Based on these parameters there are a number of factors that will increase the required battery capacity in order to provide satisfactory performance. These factors must be considered when specifying the system battery.

### **Days of Autonomy**

Extra capacity is necessary where the loads require power during periods of reduced solar input. The battery bank is often sized to provide for a number of days of autonomy (days of operation without solar charging). A common period selected is between two to five days, but it depends on how critical the loads are. For example, a site could provide critical services and therefore more than 5 days of autonomy might be required to ensure continuous operation. For example, an important telecommunications station may require a solar installation with sufficient battery capacity for 14 days of autonomy.

The minimum that should be used is 1 ½ days (with no generator as back-up), and 3 to 5 days is preferred for remote sites because battery life may be significantly increased relative to a 1 1/2-day period of autonomy.

#### **Worked Example 5**

Assume 1 ½ days autonomy .

Adjusted battery capacity = 74 Ah x 1.5 = 111 Ah for lead-acid batteries.

and

Adjusted battery capacity = 1.5 x 1779 Wh = 2669 Wh for lithium-ion batteries

### **Maximum Depth of Discharge**

Battery manufacturers recommend a maximum depth of discharge (DOD). If this is regularly exceeded the life of the battery is severely reduced. This could be 50% for some residential sized lead-acid batteries or as high as 80% for some large industrial quality solar batteries

In lithium-ion batteries the term usable power is applied. This may be between 60% and 100% of the rated capacity.

**Note:** If the usable energy of a lithium-ion battery is specified at say 80%, it is recommended that the battery does not go more than 70%. This is because if some lithium-ion batteries reach their lowest value, they might “lock-up” and then become unusable. The cut-off point though is usually based on a specified minimum voltage.

### Worked Example 6

Assume a maximum DOD of 60% for a lead-acid battery, and the usable capacity with a lithium-ion battery is 90% but 80% is applied.

Adjusted battery capacity =  $111 \div 0.6 = 185$  Ah for the lead-acid battery

and

Adjusted battery capacity =  $2669 \div 0.8 = 3336$  Wh for the lithium-ion battery

### Battery Discharge Rate

For lead-acid batteries, the actual discharge rate selected for the capacity rating is highly dependent on the power consumption of connected loads. For lead acid type batteries, this is indicated by the capital letter C (for capacity) and small numbers that follow representing the hours of charge available at that discharge rate. (See below for examples of other notations). The Ah capacity of solar batteries, particularly a small 12 V solar battery, is typically given a discharge rate of  $C_{100}$  – that means the time it takes to fully discharge the rated Ah capacity of the battery at the given current is 100 hours. For deep-cycle batteries, often used in Solar Home Systems, the Ah capacity is often provided at the  $C_{20}$  discharge rating. Many appliances operate for short periods only, drawing power for minutes rather than hours. This affects the battery selected, as battery capacity varies with discharge rate. Information such as a power usage profile over the course of an average day is required for an estimate of the appropriate discharge rate to use in the design. For many systems, and particularly smaller systems, this is often impractical to obtain.

Table 3: Example of varying battery capacities (in V/cell) based on discharge rates

Type	Capacities $C_1 - C_{100}$ (20°C)				
	$C_1$ 1.70 V/C	$C_5$ 1.70 V/C	$C_{10}$ 1.70 V/C	$C_{20}$ 1.75 V/C	$C_{100}$ 1.80 V/C
SB12/60 A	34	45	52	56	60
SB12/75 A	48	60	66	70	75
SB12/100 A	57	84	89	90	100
SB12/130 A	78	101	105	116	130
SB12/185 A	103	150	155	165	185
SB6/200 A	104	153	162	180	200
SB6/330 A	150	235	260	280	330

Source: GNB Sonnenschein Batteries

Where the average rates of power usage are low, such as for most residential loads, the battery capacity for 5 days of autonomy is often selected at the 100 h ( $C_{100}$ ) rate of discharge for the battery while for 1 ½ days of autonomy is often selected at the 20 h ( $C_{20}$ ) rate of discharge for the battery.

For lithium-ion batteries, the battery capacity is only slightly reduced at higher discharge currents. So the battery can be selected based on the rating provided by the manufacturer without consideration of the discharge rate.

Though lead acid batteries typically have a capacity rated stated with the  $C_x$  notation, Lithium Ion batteries capacities are often quoted using the XC notation. The hours for this notation is determined as 1/X.

Examples include:

1C is the 1 hour rating (1/1)

2C is the ½ hour rating (1/2)

0.5C is the 2 hour rating (1/0.5)

0.01C is the 100 hour rating (1/0.01)

### Battery Temperature Derating

The capacity of lead-acid batteries is affected by temperature. As the temperature goes down, the battery capacity also goes down. Figure 4 gives a battery correction factor for low-temperature operation. Note that the temperature correction factor is 1 at 25°C, as this is the temperature at which battery capacity is specified in some standards, while the European standards now uses 20°C as the test temperature.

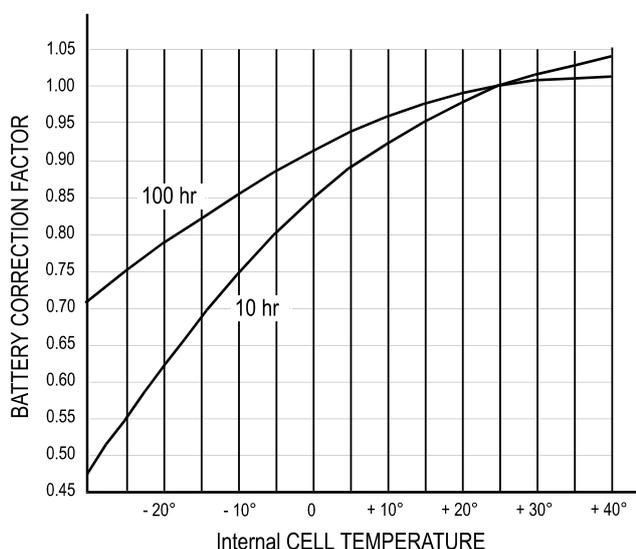


Figure 4: Temperature Correction Factor

The minimum temperatures in some locations in Uganda can be 10°C; however, at other locations 15°C is common. If you want to be conservative, add 5% to the battery capacity to allow for this factor.

#### Worked Example 6

Allow 5% to the capacity to allow for effect of temperature.

Adjusted battery capacity =  $185 \times 1.05 = 195$  Ah for the lead-acid battery

and

Adjusted battery capacity =  $3336 \times 1.05 = 3502$  Wh for the lithium-ion battery

### Battery Selection

For lead-acid batteries, a deep discharge type battery/cells must be selected and they must provide the required system voltage and capacity in a single series string of battery cells.

Parallel strings of batteries are not recommended.

Where paralleling strings cannot be avoided, each string must be separately fused.

**For the worked example** a battery of at least 24 V and 195 Ah (at  $C_{20}$ ) or 3502 Wh is recommended

## 10. Selecting a Battery

For lead acid batteries, the deep-cycle type batteries/cells selected should be rated for the required system voltage and capacity. Batteries designed for solar installations do exist even as single 2V cells and if purchasing 2V batteries for the battery bank, it is preferable that solar type batteries are selected. In any case, batteries must be designed for deep discharge applications; engine starting batteries have a short life when used in solar installations.

Parallel strings of batteries are not recommended. However, it is accepted that for some systems use of parallel strings is unavoidable, though as a rule, the more batteries there are connected in parallel, the shorter the battery life. If parallel batteries are unavoidable, then follow the manufacturer's recommendation for the maximum number of parallel strings. It is usually only 3 to 5 and some manufacturers void their battery warranty if more than 2 batteries are placed in parallel. For solar home systems with less than 1 kW<sub>p</sub> array, it is recommended that 3 strings of batteries in parallel should be the maximum and to ensure all the requirements for wiring parallel battery strings are followed as specified in the installation guideline.

Lead Batteries should meet one of the following standards:

- IEC 61427-1 Secondary Cells and Batteries for Solar Photovoltaic Energy Systems - General Requirements and Methods of Test - Part 1: Photovoltaic off-grid application.
- IEC 60896 Stationary lead-acid batteries (series).
- UL 1973 Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications.

Lithium Ion batteries should meet either

- IEC 62619 Secondary cells and batteries containing alkaline or other non-acid electrolytes— Safety requirements for secondary lithium cells and batteries, for use in industrial applications.

or

- UL 1642 Standard for Lithium Batteries; and
- UL-2054 Safety Standard for household and commercial batteries.

## 11. Selecting a Battery Inverter

When selecting a battery inverter to power an a.c. appliance that is to be connected to a Solar Home System, the inverter must have an input d.c. voltage rating that is the same as the voltage of the d.c. power provided by the battery and should meet one of the following standards:

- IEC 62109 Safety of power converters for use in photovoltaic power systems
  - IEC 62109-1 Part 1: General requirements.
- UL Standard 1741: Standard for Inverters, Converters, Controllers and Interconnection System Equipment for use with Distributed Energy Resources.

The type of inverter selected for the installation depends on factors such as availability, cost, surge requirements and power quality requirements. Inverters are available in three basic output types: square wave, modified square wave (sometimes called modified sine wave) and sine wave. There are few square wave inverters used today since most a.c. equipment works poorly on square wave a.c. power and modified square wave inverters are comparable in price.

Modified square wave inverters generally have good surge capacity, are available in a wide range of power capacities and are usually cheaper than sine wave types. However, many appliances, such as some audio equipment, some televisions and all appliances that have a.c. motors (e.g. fans) can be damaged or provide poor service because of the non-sine-wave power input.

Sine wave inverters are increasingly affordable and often provide even better quality power than the urban grid supply.

### **BATTERY INVERTER SIZING**

For systems where there are only a few a.c. appliances (e.g. as shown in table 2) the selected battery inverter should be capable of supplying continuous power to all loads that are connected to it and must have sufficient surge capacity to start all loads that may surge when turned on, should they all be switched on at the same time. Electric motors are particularly likely to have a large surge capacity requirement.

For households with many a.c. loads where some loads, e.g. microwave and power tools, are only operating occasionally it is not practical to select an inverter based on the total power rating of all the loads. The inverter should be selected based on determining what loads would typically be operating at the same time. Attention might need to be given to load control and prioritisation strategies. For example, if the inverter has surge capacity sufficient for only one motor but there are several motors that it powers, the motor switching design should make it impossible for two or more of the connected motors to be switched on at the same time.

#### **Worked Example 7**

From the load (energy) assessment on page 8, the selected inverter must be capable of supplying 154 VA continuously with a surge capability of 531 VA for a short period of time-typically only a few seconds.

## 12. Solar Irradiation

Solar irradiation is typically provided as kWh/m<sup>2</sup>, however, it can be stated as daily peak sun-hours (PSH). This is the equivalent number of hours to equal the kWh/m<sup>2</sup> listed if the solar irradiance always equals 1 kW/m<sup>2</sup>.

One important source for solar irradiation data that is available at no cost is the following site established through funding from the European Commission:

<http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?lang=en&map=africa>

With this site, latitude and longitudes can be entered and irradiation data can be obtained for horizontal, optimum tilt, and also for a specified array tilt angle.

Table 4 provides irradiation data obtained from this site for four locations around Uganda.

Table 4: Irradiation Data for Uganda

Region	Near Kampala	Southwest	Northwest	Northeast
Latitude	0° 4'35" North	1° 9'13" South	2° 50'38" North	3° 30'07" North
Longitude	32° 44'23' East	30° 19'22" East	31° 25'17' East	34° 05'01' East
Month	Irradiation (kWh/m <sup>2</sup> ) 10° Tilt Angle			
Jan	6.050	4.570	6.950	6.830
Feb	6.280	4.810	6.820	6.850
Mar	6.290	4.910	6.650	6.670
Apr	5.270	4.690	5.960	5.690
May	4.970	4.730	5.680	5.380
Jun	4.600	5.220	5.250	4.920
Jul	4.790	4.570	4.950	4.790
Aug	5.160	4.810	5.320	5.270
Sep	5.660	4.910	5.940	6.070
Oct	5.900	4.690	5.860	6.310
Nov	5.610	4.730	6.080	6.420
Dec	5.590	5.220	6.540	6.550
<b>Year</b>	<b>5.510</b>	<b>4.800</b>	<b>6.000</b>	<b>5.970</b>

PV arrays in Solar Home Systems ideally should be installed facing the optimum orientation/azimuth. The optimum tilt direction is generally true (not magnetic) north in the Southern Hemisphere and true south in the Northern Hemisphere—that is the PV array should face towards the equator. However, this can change due to local climatic conditions (clouds that consistently form at a particular time of the day) or topographical conditions (mountains or structures causing shading at consistent times in the mornings or afternoons). In latitudes between 10° south and 10° north the array can be oriented either north or south with little change in output. Also, orientations that are as much as 90° away from the optimum direction have a relatively small impact on daily irradiation totals when the latitude of sites are less than 10° as is the case for Uganda.

If the PV array is mounted on the roof of a building, the roof may not be facing the optimum direction of true north (Southern Hemisphere) or true south (Northern Hemisphere) or may not be at the optimum tilt angle. The irradiation data for the actual roof orientation (true installed azimuth) and pitch (true tilt angle) shall be used when preparing the design. Please see the discussion on tilt and orientation (Section 12.2) for determining peak sun hours for sites not facing the ideal direction.

### 12.1. Irradiation for Design Month

If the daily energy usage varies throughout the year, then a comparison should be undertaken between the average daily irradiation and the average daily load energy. The design month is the month where the ratio of available irradiation (PSH) to daily load energy for that month is the smallest. The irradiation of the design month is then used when determining the size of the required PV array.

If the energy usage stays relatively constant throughout the year, then the design month will be the month with the lowest irradiation.

**Worked Example 8**

The energy usage(at the battery bank) = 1779 Wh= 1.78 kWh

Assume that the site is near Kampala.

Using the irradiation data in Table 4, the ratio of available irradiation (which is proportional to of PV energy output) to load energy is shown in Table 5:

Table 5: The ratio of available irradiation to load energy requirement

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Irradiation (kWh/m <sup>2</sup> )	6.05	6.28	6.29	5.27	4.97	4.60	4.79	5.16	5.66	5.90	5.61	5.59
Daily Energy used (kWh)	2.21	2.21	2.21	1.78	1.78	1.78	1.78	1.78	1.78	2.21	2.21	2.21
irradiation / daily energy	3.40	3.53	3.53	2.96	2.79	2.58	2.69	2.90	3.18	3.31	3.15	3.14

The lowest ratio is 2.58 so June will be the design month and the available irradiation in June is 4.60kWh/m<sup>2</sup> or 4.60 Peak Sun hours. Note that since the load energy was constant all year the lowest ratio did correspond with the lowest monthly irradiation

For Solar Home Systems in Uganda, the daily energy usage will typically not vary much throughout the year. As shown in worked example 8 when the load energy remains constant throughout the year the design month is the month where the available irradiation (PSH) is the lowest. The irradiation of the design month is then used when determining the size of the required PV array.

**Worked Example 9**

Using Table 4 the lowest irradiation values for the 4 locations are:

Kampala Region: 4.6 kWh/m<sup>2</sup> (or PSH) in June

South West Region: 4.57 kWh/m<sup>2</sup> (or PSH) in January and July

North West Region: 4.95 kWh/m<sup>2</sup> (or PSH) in July

North East Region: 4.79 kWh/m<sup>2</sup> (or PSH) in July

## 12.2. Effect of Orientation and Tilt

If the array is mounted not oriented true north (Southern Hemisphere) or south (Northern Hemisphere) and/or not at the optimum tilt angle (inclination), the daily output from the array will generally be less than the maximum possible.

Roofs often have pitch of 20° to 30° degrees. Since Uganda only ranges from latitudes approximately 2° South to 3° North, irradiation would only decrease by maximum of 5% if the array tilt ranged between 10° and 30° and independent of the orientation.

If the roof is flat or a shallow tilt angle (< 5°) the array should be tilted at 10°.

## 12.3. Shading of the Array

In rural areas and villages where Solar Home Systems will be used, the PV array may be shaded part of the day by local vegetation, e.g. nearby trees, or landforms such as mountains. This may greatly affect the output of the array if it occurs between about 9 am and 3 pm.

There are many survey devices and computer programs to help determine the effect on irradiation due to shading. The result of shading will be a lower value of solar irradiation that reaches the array. That lower irradiation level must be used when determining the size of the solar array required to provide the calculated daily energy needs of the end-user.

## 13. Factors that Affect a Solar Module's Output Power

The output of the solar module is affected by temperature, foreign materials on its surface (dirt, leaves, pollution products, etc.) and possibly manufacturer's tolerances and/or module mismatches (connecting modules of different characteristics together). This means that the outputs of the solar modules will need to be adjusted relative to their standard rated values when estimating the actual energy output of the solar array. The rated output is determined with a solar cell temperature of 25°C (with an irradiance of 1000 W/m<sup>2</sup>); cell temperatures when exposed to the sun are typically greater than the standard 25°C. Actual solar array outputs are always less than the standard rated values so modules must be "derated" when estimating their actual outputs.

### Derating Due to Temperature

A solar module's output power decreases with a solar cell temperature above 25°C and increases with temperatures below 25°C. When exposed to the sun, the average cell temperature will be higher than the ambient temperature because of the glass on the front of the module insulates it from the cooler air around it and the fact that the module absorbs some heat from the sun. The output power and/or current of the module must be based on the actual temperature of the cell. This is estimated by the following formula:

$$T_{\text{cell-eff}} = T_{\text{a.day}} + T_r$$

Where

$T_{\text{cell-eff}}$  = the average daytime effective cell temperature in degrees Celsius (°C)

$T_{\text{a.day}}$  = the average daytime ambient temperature for the month that the sizing is being undertaken.

$T_r$  = rise in temperature due to the type of installation used for the array

The value of  $T_r$  is selected from Table 6.

Table 6: Values of  $T_r$

Installation of Array Frame	$T_r$
Ground-mounted array	25°C

Array on roof where array tilt angle is at least 20 degrees different from the tilt of the actual roof	25°C
Array structure is parallel to the roof with an air gap between the array and the roof greater than 150 mm	30°C
Array structure is parallel to the roof with an air gap less than 150 mm	35°C

The three major types of solar modules available on the market each have different temperature coefficients of power. These are:

A) Monocrystalline Modules

Monocrystalline Modules typically have a temperature coefficient between -0.3%/°C and -0.45%/°C. Assuming it is -0.45%/°C, for every degree above 25°C, the rated output power must be derated by 0.45%.

B) Polycrystalline Modules

Polycrystalline Modules typically have a temperature coefficient of -0.4 %/°C to -0.5 %/°C

C) Thin Film Modules

Thin film modules have a quite different temperature characteristic, resulting in a lower coefficient, typically around 0 %/°C to -0.3 %/°C.

Note: On a solar module data sheet three temperature coefficients will be provided. The different temperature coefficients provided are for maximum (or peak) power ( $W_p$ ), open circuit voltage ( $V_{oc}$ ) and short circuit current ( $I_{sc}$ ). Some brochures might also include a temperature coefficient for maximum power voltage.

Always check with the product manufacturer for the exact temperature coefficient for the module being used in the system design. That data should be available in the product brochure and must be available if the product has been tested and approved in accordance with the IEC and UL standards.

The symbol used for temperature coefficient of power is  $\gamma$  and it is expressed on data sheets as a negative number (e.g.  $\gamma = -0.5 \text{ %/}^\circ\text{C}$ ).

Note : As a fraction -0.5 %/°C is expressed as 0.005/°C (derived from 0.5/100)

The derating of the array due to temperature will be dependent on the type of module installed, the average ambient maximum temperature for the location and the type of module mounting system used.

The typical ambient daytime temperature in most parts of Uganda is between 25°C and 30°C, so it would not be uncommon to have module cell temperatures of over 50°C.

The percentage power loss due to the effective cell temperature is the Cell Temperature Coefficient multiplied by the difference between the cell effective temperature and the Standard Test Condition (STC) temperature ( $T_{STC}$ ) of 25°C.

This loss is generally expressed as a temperature derating factor ( $f_{temp}$ ) which is calculated as follows:  
 $f_{temp} = 1 - (\gamma \times (T_{STC} - T_{cell-eff}))$

**Worked Example 10**

The solar array is mounted parallel to a pitched roof with an air gap of 100mm.

The solar module has a power temperature coefficient of  $-0.39\%/^{\circ}\text{C}$ .

The average daytime ambient temperature is  $28^{\circ}\text{C}$ .

What is the percentage (%) power loss due to temperature for this solar?

What is the temperature derating factor?

From table 6 the rise in temperature ( $T_r$ ) is  $35^{\circ}\text{C}$ .

The effective cell temperature is therefore:

$$\begin{aligned} T_{\text{cell-eff}} &= T_{\text{a.day}} + T_r \\ &= 28^{\circ}\text{C} + 35^{\circ}\text{C} \\ &= 63^{\circ}\text{C} \end{aligned}$$

As a fraction  $-0.39\%/^{\circ}\text{C}$  is represented as  $-0.0039/^{\circ}\text{C}$ .

The temperature derating factor ( $f_{\text{temp}}$ ) is calculated as follows:

$$\begin{aligned} f_{\text{temp}} &= 1 - (\gamma \times (T_{\text{STC}} - T_{\text{cell-eff}})) \\ &= 1 - (-0.39\%/^{\circ}\text{C} \times (25^{\circ}\text{C} - 63^{\circ}\text{C})) \\ &= 1 - (-0.0039 \times -38) \\ &= 1 - (0.148) \\ &= 0.852 \end{aligned}$$

This means that the array actually provides only 85.2% of its rated output power due to its operation at  $63^{\circ}\text{C}$  instead of STC ( $25^{\circ}\text{C}$ ).

**Derating Due to Dirt and Other Foreign Materials on the Module Surface**

The output of a PV module can be reduced as a result of a build-up of dirt on the surface of the module. The actual value of this loss will be dependent on the conditions at the actual location of the modules, but in some city locations this could be high due to the amount of car pollution and dust in the air. It can also be high in coastal regions during long periods of no rain when salt may build up on the module surface.

In dusty or salty environments this loss could be as high as 20%.

For most rural areas, the typical loss will be no more than 5% though installations adjacent to factories, quarries or unpaved roads may be much higher if modules are not regularly cleaned by the end-user.

This loss is generally expressed as a dirt derating factor ( $f_{\text{dirt}}$ ).

$$f_{\text{dirt}} = 1 - \text{the loss due to temperature}$$

**Worked Example 11**

If the loss due to dirt is 5% what is the dirt derating factor?

As a decimal fraction 5% converts to  $5/100 = 0.05$

$$\begin{aligned} f_{\text{dirt}} &= 1 - \text{the loss due to dirt} \\ &= 1 - 0.05 = 0.95 \end{aligned}$$

## Manufacturer's Output Tolerance

The output of a PV module is specified in watts and with a manufacturing tolerance based on a cell temperature of 25°C. Historically this has been  $\pm 5\%$  though in recent years typical figures have been 0% to +3%. However, in small print on the data sheet there is often the statement: *Measuring tolerance:  $\pm 3\%$* . This effectively means the module could have a manufacturer's tolerance which leads to a loss of up to 3% (though there could also be a gain of 3%).

When designing a system, it is important to incorporate the actual figure for the selected module and take into account any measuring tolerances and to assume the worst-case conditions so the resulting design will not be underpowered.

This manufacturer's tolerance loss is generally expressed as a manufacturer's derating factor ( $f_{\text{man}}$ ).  
 $f_{\text{man}} = 1 - \text{manufacturer's tolerance (or measuring tolerance loss)}$

### Worked Example 12

If the loss due to *Measuring tolerance* is 3% what is the manufacturer's derating factor?

As a fraction 3% converts to  $3/100 = 0.03$

$$\begin{aligned} f_{\text{man}} &= 1 - \text{the measuring tolerance loss} \\ &= 1 - 0.03 = 0.97 \end{aligned}$$

## Solar Module Ageing Factor

Another factor that could be included in the derating of the solar array is ageing of the solar modules. When in service, solar modules gradually lose some capacity over time, though quite slowly. Manufacturers generally will provide a warranty that their solar module will not fall more than 15% below the rated value for 25 years. For the designer, it is reasonable to assume the useful life of the Solar Home System is 20 years, so the array needs to continue to service the design load for those 20 years and may last longer. This means that the initial rating of the modules used will need to be at least 10% higher than the value that will be sufficient to serve the load when new.

However, in section 17.4 an oversizing factor of 30% is recommended for system comprising lead acid batteries. This 30% takes into account the ageing of the module and it is for this reason that the ageing factor is not applied when derating that solar array (and module) but it is applied within the oversizing of the array. For Lithium Ion batteries an oversizing factor of 10% is included to take into account the ageing factor of the solar modules.

To determine the total derating factor for the solar modules, it is necessary to multiply all the derating factors together and then apply the result to the rated output of the modules.

**Worked Example 13:**

For a system comprising lead acid batteries where the temperature derating factor is 0.852, the dirt derating factor is 0.95 what is the overall derating factor for the modules?

$0.858 \times 0.95 = 0.81$  which means that the actual output from the module is expected to be 0.81 times the rated output. Thus a  $100 W_p$  panel can be expected to provide at least:

$$100 W_p \times 0.81 = 81 W.$$

## 14. Selecting a Solar Module

When selecting a solar module to be used in a Solar Home System the solar modules when the array is greater than  $100W_p$  shall meet either one of the following design qualification and type approval standards

- IEC 61215 Terrestrial photovoltaic (PV) modules - Design qualification and type approval and
  - IEC 61730 Photovoltaic (PV) module safety qualification
    - IEC 61730-1 Part 1: Requirements for construction
    - IEC 61730-2 Part 2: Requirements for testing

or

- UL Standard 1703: Flat Plat Photovoltaic Modules and Panels

For solar arrays greater than  $100W_p$  the modules with IEC certification must be certified as Class II per IEC 61730 (or Application Class A per IEC 61730:2004).

Note: IEC 61215 and IEC 61730 are also available as European Standards (EN) and Underwriters Laboratories (UL) Standards

For Solar Home Systems, with an Array Peak Watt Rating equal to or less than  $100W_p$  with an Array Open Circuit Voltage less than 35V d.c., modules that are not tested and certified in accordance with the IEC and UL standards specified above can be used if they have been tested in accordance with the solar module test requirements specified in:

- IEC TS 62257-9-5:2018: Recommendations for renewable energy and hybrid systems for rural electrification - Part 9-5: Integrated systems - Laboratory evaluation of stand-alone renewable energy products for rural electrification.

The test results must indicate that the solar module meets the relevant requirements specified in the Lighting Global SHS Kit Quality Standards (available at <https://www.lightingglobal.org/quality-assurance-program/our-standards/>).

## 15. Selecting an Array Structure

The array structure and module attachment system selected for the PV modules shall be designed to resist the ultimate wind actions for the site where the array will be located and be constructed of material suitable for the location.

## 16. Relationship Between Solar Controllers and Solar Modules

Historically, switched solar controllers were the most common solar controllers.

The initial version applied “on-off” type switching between the solar array and the battery using relays. These operated such that the solar array was either directly connected to the battery and charging the battery with the relay in the “on” (or closed) state or the solar array was disconnected from the battery with the relay in the “off” (or open) state.

The modern switched type controllers employ Pulse Width Modulation (PWM) technology. PWM controllers use electronic switches to rapidly turn on and off the direct connection between the solar array and battery to provide an average charging current necessary to maintain the required battery voltage.

Traditionally solar modules were designed to charge a 12 V battery. To effectively charge the 12 V battery the solar module comprised 36 solar cells and manufacturers data sheets specified the module as a nominal 12 V module.

To have an efficient system the switched type controllers should be connected to a solar array which has a “nominal” voltage equivalent to the nominal battery voltage. That is, a solar system using a switch type controller with a 12 V battery should be connected to a 36cell module with a “nominal” voltage of 12 V. A 24 V battery should be connected to 72 cells while a 48 V battery should be connected to 144 cells.

In the current market the great majority of solar modules are used for grid-connected systems and the number of cells depends more on the power desired than the voltage required of the module. The solar module designed for the grid connect market typically comprise 60 or 72 cells though there have been some with 48 or even 96 cells. Therefore, many solar modules that are readily available should not be used with switching type solar controllers because they have more than the 36 cells and the module voltage does not match the voltage of the battery bank. If a 60 cell module is connected to a switched controller and a 12 V battery, the solar module will charge the battery however 40% (24 of the solar cells) of the module capacity would never be used resulting in an inefficient system.

The result is that in recent years’ solar controllers known as maximum power point trackers (MPPT) have become more common. These can have an input voltage range much greater than the charging voltages of the battery. These are d.c. to d.c. power converters where the controller is designed to track the maximum power point of the solar array. This maximum power point voltage will (and should) be greater than the voltage of the battery connected to the output of the MPPT controller. Since the battery must be charged at a voltage applicable to its voltage rating, the extra power available, due to the input voltage being higher than the battery voltage, is converted into a battery charging current greater than that which would be available if the solar array was directly connected to the battery.

## 17. Sizing a Solar Array-General

The calculations for determining the size of the PV array are dependent on the type of controller used.

The size of the PV array shall be selected to take account of:

- a) seasonal variation of solar irradiation

- b) manufacturing tolerance of modules
- c) dirt accumulation
- d) temperature of array (the effective cell temperature)
- e) inverter efficiency (if applicable)
- f) battery efficiency
- g) controller efficiency
- h) cable losses
- i) oversize factor to allow for effective charging and allowing for the module efficiency decreasing over time(aging)

The points a through to d have been covered in sections 12 and 13. This section looks at points e through to i. Points e, f, g and h, when grouped together, are commonly known as the sub-system efficiency, the sub-system being defined as the components between the solar array and the associated loads.

### 17.1. Sub-System Losses in a Solar Home System

The sub-system losses are all those in the circuit from the output of the PV array to the load.

If the system is only providing d.c. loads, then the sub-system losses are:

- cable losses (due to voltage drop);
- solar controller losses; and
- battery losses.

If the system is only providing a.c. loads, then the sub-system losses are:

- cable losses (due to voltage drop);
- solar controller losses (d.c. bus system);
- battery losses; and
- battery inverter losses.

The battery losses can be based on either coulombic efficiency (in terms of Ah) or watt-hour efficiency.

The average coulombic efficiency of a new lead-acid battery is typically 90% while the average watt-hour (Wh) efficiency of a new battery is typically 80%. As the battery ages, the coulombic and watt-hour efficiency both decline slowly.

When determining the PV array size for systems using switching solar controllers, the calculations are based on Ah and coulombic efficiency is used.

When determining the PV array size for systems using a MPPT controller, Wh efficiency is used.

All these losses are expressed as percentages which are then converted into a fraction when applied in determining the PV array output.

#### **Worked Example 14**

If a battery has a coulombic efficiency of 90%, then the fraction used in determining the required PV array power output would be 0.9.

## 17.2. Determining the Energy Requirement of the PV Array

The design month's daily load energy is used for determining the size of the PV array.

In order to determine the energy required from the PV array these sub-system losses need to be taken into account. That means that the output of the PV array must be greater than the daily load it is supplying. The total required output is calculated by dividing the required daily load energy by all the sub-system losses in the system expressed as decimal fractions.

## 17.3. What about the loads that operate during the day?

When sizing the array, convention has been to be conservative and assume that all the loads are supplied by the battery bank so that the battery efficiency was taken into account for all loads when determining the size of the solar array required to meet the daily energy demand.

However, some of the load energy will be supplied directly during the day since typically the available output from the controller will be directly connected to both the battery and the input terminals of the battery inverter. To determine exactly how much, a detailed interval analysis would be required whereby the load power profile is compared to the available solar power profile. However, the available solar power and the loads will vary during the day and from day to day so the percentage of the load during the day that is directly powered by the array can only be estimated.

Though in practice some of the loads will be met directly during the day this guideline assumes none of the load is being supplied directly during the day. The difference is that some of the solar energy will not pass through the battery and at that time the sub-system losses will be less than assumed. However, since there are so many things that can vary each day such as irradiation, loads and also that both the efficiency of the solar module and battery decreases with time, this guideline has taken the conservative approach for solar home systems that all of the solar array power does pass through the battery bank.

## 17.4. Oversize Factor

If the system does not include a fuel generator which can provide extra charging to the battery bank, if the system includes lead acid batteries then the solar array should be oversized to enable equalisation charging of the battery bank (lead-acid). Otherwise, the battery life will be shortened due to its having to remain in a partially charged condition for many days during cloudy periods. That leads to sulfation of the battery and the loss of some battery capacity unless an equalizing charge is carried out shortly after the sulfation occurs.

Therefore, when designing a solar system that includes lead acid batteries, the array should be oversized by at least 30% to allow for rapid full charging of the battery and to provide equalizing charging when needed. An oversize factor of 30% should also effectively cover the ageing of the solar module.

This oversize factor of 30% is required for Solar Home Systems comprising of lead-acid batteries. An oversize factor of 10% , to effectively cover the aging of the solar module should be included with systems that include lithium-ion batteries.

## 18. Sizing a PV Array—Switching Type PWM Solar Controller

When using a PWM solar controller, the calculations are all based on determining the required Ah from the array. The losses in the cable and the solar controller are only reflected as voltage drops, which therefore dictates the operation point on the IV curve of the solar array. That is, if the battery is at 12V then the PV array will be operating at 12V plus the voltage drop in the connecting cable plus any voltage drop across the controller. Since the maximum power point of a nominal 12V module will be at 17-18V and the maximum charge voltage of a lead acid battery is between 14.4V and 15V, then the typical voltage drop of around 1V that occurs between the array and the battery is not an issue for most of the time the battery is being charged.

The only losses that need to be taken into account are any battery inverter losses (when a.c. appliances are powered by an inverter connected to the system) so the battery losses are assumed to be the average coulombic efficiency (in terms of Ah in and Ah out) of a new battery. That is typically 90% (variations in battery voltage are not considered).

### Worked Example 15

Figures used in this example are from table 1 and 2. Assume the site is near Kampala and the lowest irradiation is 4.6 kWh/m<sup>2</sup> or 4.6 PSH.

Assume all the loads are supplied by the PV array charging the battery bank

Assume The efficiency of the chosen inverter is 90%.

(Note the actual inverter efficiency varies depending on the load connected. Many good quality inverters will have an efficiency equal to or greater than 90% for most of their operating power range)

Daily battery load (energy) due to a.c. loads = 1500Wh ÷ 0.9 = 1667 Wh

Daily battery load (energy) due to d.c. loads = 112 Wh

To get the total load (energy) as provided by the battery, you add the two figures together:

$$1667 + 112 = 1779 \text{ Wh}$$

The system voltage is 24 V.

The daily energy requirement expressed in Ah from the battery is 74.1 Ah (1779 Wh/24 V).

Allowing for the battery efficiency, the solar array then needs to produce:

$$74.1 \text{ Ah} \div 0.9 = 82.33 \text{ Ah}$$

The PSH in the design month is 4.6

Therefore the required PV array derated output current is:

$$82.33 \text{ Ah} \div 4.6 \text{ PSH} = 17.9 \text{ A}$$

The oversize factor then needs to be applied. A minimum of 30% is recommended for Uganda when using lead acid batteries and 10% when using lithium ion batteries.

#### Worked Example 16

Since the worked example has been based on lead acid batteries he adjusted required PV array derated output current is:

$$17.9 \text{ A} \times 1.3 = 23.3 \text{ A}$$

The PV array will be derated due to:

- Manufacturer's Tolerance
- Dirt
- Module Temperature greater than 25°C
- and potentially for ageing of the module that results in decrease in efficiency and hence power output; however, the oversizing takes this into account.

The designer, when using a **switching type PWM solar controller, should use solar modules that have a nominal voltage rating that is appropriate for the battery voltage**. In the market today these are either 36 cell modules for 12 V batteries or 72 cell modules suitable for 24 V battery banks. Today 36 cell modules are typically costlier than 60 cell or 72 cell modules when compared on a per  $W_p$  basis because they have become a specialty item and are no longer mainstream. For rural residences, 36 cell panels matched with a simple switching controller still provides the simplest and most cost effective solution for lighting and basic entertainment but locating a source of low cost 36 cell modules is not always easy. A few manufacturers provide 72 cell modules that are internally split into two 36 cell units which can be electrically connected as paralleled 36 cell modules for 12 V battery charging or series connected as a 72 cell module for 24 V battery charging.

The typical charge voltage range for different lead acid battery banks is as follows:

- 12 V battery bank- charge range 12 V to 15 V(wet cells/flooded) or 12 V to 14.4 V (Valve regulated battery)
- 24 V battery bank- charge range 24 V to 30 V(wet cells/flooded) or 24 V to 28.8 V (Valve regulated battery)
- 48 V battery bank- charge range 48 V to 60 V(wet cells/flooded) or 48 V to 57.6 V (Valve regulated battery)

To allow for temperature and the various charge voltages the module effective current used when determining the size of an array using crystalline type modules are as follows:

- For 12 V module: current at 14 V and at the effective cell temperature
- For 24 V module: current at 28 V and at the effective cell temperature.
- For 48 V module: current at 56 V and at the effective cell temperature

Unless the current vs voltage (IV) curves for different temperatures are available for the module selected, it is difficult to obtain this information. The module manufacturer's data sheets usually only provide short circuit current ( $I_{sc}$ ) and maximum power point current ( $I_{mp}$ ); the operating current will be between these two values. The published values are usually only provided for Standard Test Conditions and for cells at the Nominal Operating Cell Temperature (NOCT).

If the IV curves at different temperatures are not available, it is recommended that the current half way between  $I_{sc}$  and  $I_{mp}$  be used as the module current.

That is: Calculated Module Current =  $(I_{sc} + I_{mp})/2$

Also allowing for dirt and manufacturer's tolerance:

Derated Module current = Module effective current x manufacturer's tolerance derating factor x dirt derating factor

Or

Derated Module current = Calculated module current x manufacturer's tolerance derating factor x dirt derating factor

The number of modules in a string is determined by dividing the battery voltage by the nominal voltage of the module. It is reasonable to assume the nominal voltage of a module is number of cells per module divided by three. Thus a 36 cell module has a nominal voltage of 12V, a 60 cell module has a nominal voltage of 20V and a 72 cell module has a nominal voltage of 24V.

The number of module strings that need to be in parallel is determined by dividing the adjusted required array current by the derated module current.

#### **Worked Example 17**

A module with the following characteristics is selected:

STC Electrical Data

$$P_{mp} = 220 \text{ W}_p$$

$$V_{oc} = 46.2 \text{ V}$$

$$V_{mp} = 37.8 \text{ V}$$

$$I_{sc} = 6.18 \text{ A}$$

$$I_{mp} = 5.82 \text{ A}$$

Power Temperature coefficient =  $-0.39 \text{ \%}/^{\circ}\text{C}$

$V_{oc}$  temperature coefficient =  $-0.29 \text{ \%}/^{\circ}\text{C}$

Manufacturer's Tolerance = 0 to +5 %

Test Tolerance  $\pm 3\%$

Note for this example the oversize factor has taken into account the ageing factor.

Module has 72 cells and hence provides a nominal 24 V.

The number of modules in a string

= the battery voltage / nominal voltage of the module.

$$= 24 \text{ V} / 24 \text{ V} = 1$$

$$\text{Module current} = (5.82 + 6.18) / 2 = 6 \text{ A}$$

Manufacturers Tolerance = test tolerance = 3%

This is a derating factor of 0.97

Assume dirt derating is 5% and hence derating factor of 0.95.

Therefore the derated current =  $6 \times 0.97 \times 0.95 = 5.53 \text{ A}$  per module string

Adjusted required array current = 23.3 A

$$\text{Number of module strings in parallel} = 23.3 \text{ A} / 5.53 \text{ A} = 4.21$$

Round up to 5. In reality a smaller module could be selected if one is available but the smaller modules will need to have either 72 cells or 36 cells.

## 19. Sizing a PV Array- MPPT Solar controller

When using a MPPT controller the calculations are in Wh and the d.c. sub-system losses in the system include:

- Battery losses (Watt-hour efficiency)
- Cable losses
- MPPT losses (controller efficiency); and
- Inverter losses (inverter efficiency)

In order to determine the energy required from the PV array, it is necessary to increase the energy from the battery bank to account for all the sub-system losses.

### Worked Example 18

The energy supplied by the battery bank allowing for the inverter efficiency = 1779 Wh

Assume

- cable losses is assumed to be 3% (transmission efficiency of 97%),
- MPPT efficiency of 95% and
- battery efficiency of 80%
- All the load energy is provided by the battery.

d.c. Subsystem efficiency =  $0.97 \times 0.95 \times 0.8 = 0.737$

Energy required from the PV array =  $1779 \text{ Wh} \div 0.737 = 2414 \text{ Wh}$

The design month PSH is 4.6

Therefore the required PV array derated output power is:

$$2414 \text{ Wh} \div 4.6 \text{ PSH} = 525 \text{ W}$$

Allowing for an oversize factor of 30%, the adjusted required derated array output is:

$$525 \text{ W} \times 1.3 = 683 \text{ W}$$

The output of the solar module is affected by temperature, dirt, possibly manufacturer's tolerances and/or module mismatches and module ageing. This means that the power output of the solar module should be derated when determining the energy output of the solar array.

Solar modules have a rated output measured at Standard Test conditions (STC). Based on the factors affecting the power output of the module ( $P_{\text{mod}}$ ) as detailed in section 13 the derated power output ( $P_{\text{derated}}$ ) of the module is determined as follows:

$$P_{\text{derated}} = P_{\text{mod}} \times f_{\text{temp}} \times f_{\text{dirt}} \times f_{\text{man}}$$

Ageing has been taken into account with the 20% oversize.

### Worked Example 19

In the worked example

- Derating due to temperature  $f_{temp} = 0.883$
- Derating due to dirt  $f_{dirt} = 0.95$
- Derating due to manufacturer's tolerance  $f_{man} = 0.97$

Module rating is  $220W_p$

Derated module output =  $220 \times 0.883 \times 0.95 \times 0.97 = 179 \text{ W}$

The adjusted required derated array output =  $683 \text{ W}$

The required number of modules =  $683 \div 179 = 3.82$  which must be rounded up to 4 modules.

## 20. Selecting a Solar Controller: - PWM controllers

When selecting a PWM solar controller to be used in a Solar Home System the controller should meet one of the following standards

- IEC 62509 Battery charge controllers for photovoltaic systems - Performance and functioning
- IEC 62109 Safety of power converters for use in photovoltaic power systems
  - IEC 62109-1 Part 1: General requirements
- IEC 60335-1 (Household and similar electrical appliances - Safety - Part 1: General requirements) **and** 60335-2-29 (Household and similar electrical appliances - Safety - Part 2-29: Particular requirements for battery chargers).
- UL Standard 1741: Standard for Inverters, Converters, Controllers and Interconnection System Equipment for use with Distributed Energy Resources

PV controllers on the market range from simple switched units that only prevent battery overcharge (and usually also excessive discharge) to microprocessor based units that incorporate many additional features such as:

- Boost and equalisation charge modes.
- d.c. load control.
- Voltage and current metering.
- Amp-hour logging.
- Priority load connections (low priority connections shut down when the normal discharge limit for the battery is reached. Priority loads can continue running until the battery is more deeply discharged).
- Generator start/stop control (for a back-up generator to automatically start if the battery reaches its pre-set discharge limit).

Unless the controller is a model that is internally current limited, these should be sized so that they are capable of carrying at least 125% of the array short circuit current and withstanding the temperature corrected open circuit voltage of the array. If there is likelihood that the array may need to be increased in the future, then the controller should be oversized to allow for future growth.

(Note: sometimes the controller is called a regulator)

**Worked Example 20**

If three modules in parallel are selected, the controller chosen must have a current rating  $> 1.25 \times 5 \times 6.18 \text{ A} = 38.6 \text{ A}$  at a system voltage of 24 V if the controller is not current limited.

If it is current limited it needs to be rated at  $5 \times 6.18 \text{ A} = 30.9 \text{ A}$  at a system voltage of 24 V

## 21. Selecting a solar controller- MPPT type controller

When selecting an MPPT controller to be used in an Solar Home System the controller should meet one of the following standards:

- IEC 62509 Battery charge controllers for photovoltaic systems - Performance and functioning.
- IEC 62109 Safety of power converters for use in photovoltaic power systems.
  - IEC 62109-1 Part 1: General requirements
- UL Standard 1741: Standard for Inverter, converters, Controllers and Interconnection. System Equipment for use with Distributed Energy Resources

The MPPT controller must be matched with the array in relation to:

- Maximum Solar Rating in watts;
- Input voltage; and
- Input current if specified by the manufacturer.

**Worked Example 21**

The number of modules required was 3.82 so unless a different size module was chosen select a MPPT which will be suitable for 4 modules.

The module rating is 220  $W_p$ .

$$4 \times 220W_p = 880 W_p$$

The MPPT controller should also have an input current rating of  $1.25 \times$  short circuit of the array if the MPPT controller is not current limited.

### 21.1. Matching the PV array to the Voltage Specifications of the MPPT

The MPPT typically will have a recommended minimum nominal array voltage and a maximum input voltage. In the case where a maximum input voltage is specified and the array open circuit voltage is above the maximum specified, the MPPT could be damaged.

The maximum power point voltage of a solar module decreases as the cell temperature rises. A 36 cell module is required for effective charging of a 12V battery connected to the module via a switched controller. For the MPPT to work effectively the maximum power point voltage of the array must always be greater than the maximum charge voltage of the battery. So though a 36 cell module could be connected to a battery via an MPPT, the MPPT will work more efficiently if the number of solar cells in the array is greater than 36 for a 12V battery.

Some MPPT controllers may allow the minimum array nominal voltage to be equal to that of the battery bank. However, the MPPT will work better when the minimum nominal array voltage is higher than the nominal voltage of the battery.

Table 7 shows the recommended minimum number of cells in a string for the different nominal battery voltages when using a MPPT controller however always follow the manufacturers recommendation.

Table 7: Minimum Number of Cells in a String

Nominal Battery voltage (V)	Recommended Minimum Number of Cells per string of modules
12	54
24	90
48	162

**Worked Example 22**

Battery voltage is 24 V so the array should have at least 90 cells in series. The module selected for the worked example has 72 cells so a minimum of two of these in series will be required per string.

The output voltage of a module is affected by cell temperature changes in a similar way to the output power. The manufacturers will provide a *voltage temperature coefficient* on the panel specification sheet. It can be specified in V/°C (or mV/°C) but it generally expressed as a percentage %/°C .

To ensure that the  $V_{oc}$  of the array does not reach the maximum allowable voltage of the MPPT the coldest temperatures for that specific site are required.

In early morning at first light the cell temperature will be very similar to the ambient temperature because the sun has not had time to heat up the module. Though the energy from the sun at sunrise is very low and therefore the current (amperes) that can be generated from the module will be very low, the solar module reaches almost maximum open circuit voltage as soon as the sun is on the horizon. In Uganda, the minimum temperature can vary from 10°C to 20°C and, unless specific site data provides a lower temperature, it is recommended that 10°C be used to determine the maximum  $V_{oc}$ . The maximum open circuit voltage is determined similarly to the temperature derating factor for module power.

When modules are connected in series the maximum  $V_{oc}$  of the string shall always be less than the maximum allowable voltage of the MPPT; however, for Solar Home Systems with an array rated at 1kWp or less than the maximum array voltage should be less than 120V d.c. .

So once the module  $V_{oc}$  at coldest temperature is calculated then the maximum number of modules allowed in series is determined by dividing the maximum MPPT allowable voltage divided by module  $V_{oc}$  at coldest temperature.

### Worked Example 23

The selected module has the following characteristics:

$$V_{oc} = 46.2 \text{ V}$$

$$V_{oc} \text{ temperature coefficient} = -0.29\%/^{\circ}\text{C}$$

$$\text{The temperature coefficient in } V/^{\circ}\text{C} = -0.29 \div 100/^{\circ}\text{C} \times 46.2 \text{ V} = -0.134 \text{ V}/^{\circ}\text{C}$$

If the minimum temperature is  $10^{\circ}\text{C}$  this is  $15^{\circ}\text{C}$  below the STC temperature of  $25^{\circ}\text{C}$ . Therefore the effective variation in voltage is:

$$15 \times 0.134 = 2.01 \text{ V}$$

$$\text{So the maximum open circuit voltage of the module} = 46.2 \text{ V} + 2.01 \text{ V} = 48.21 \text{ V}$$

Based on the example the MPPT should be selected to be suitable for four modules. To achieve the required power, these could either be installed four in series or two parallel strings of two modules in series. Each configuration meet the minimum voltage requirement of at least 90 cells in series, but if there are four in series, the array would have a maximum  $V_{oc}$  of  $4 \times 48.21 = 192.84 \text{ V}$ . This is greater than the maximum allowed voltage of  $120 \text{ V}$ .

So the solution is two parallel strings of two modules in series

## 22. PV Array Cabling

The formulas in this section are from IEC62548: Photovoltaic (PV) Arrays-Design Requirements.

Figure 5 helps explain the various cables and components within a PV array.

PV string cables are those that interconnect modules in a string. The PV array cable is the cable between the array and the solar controller.

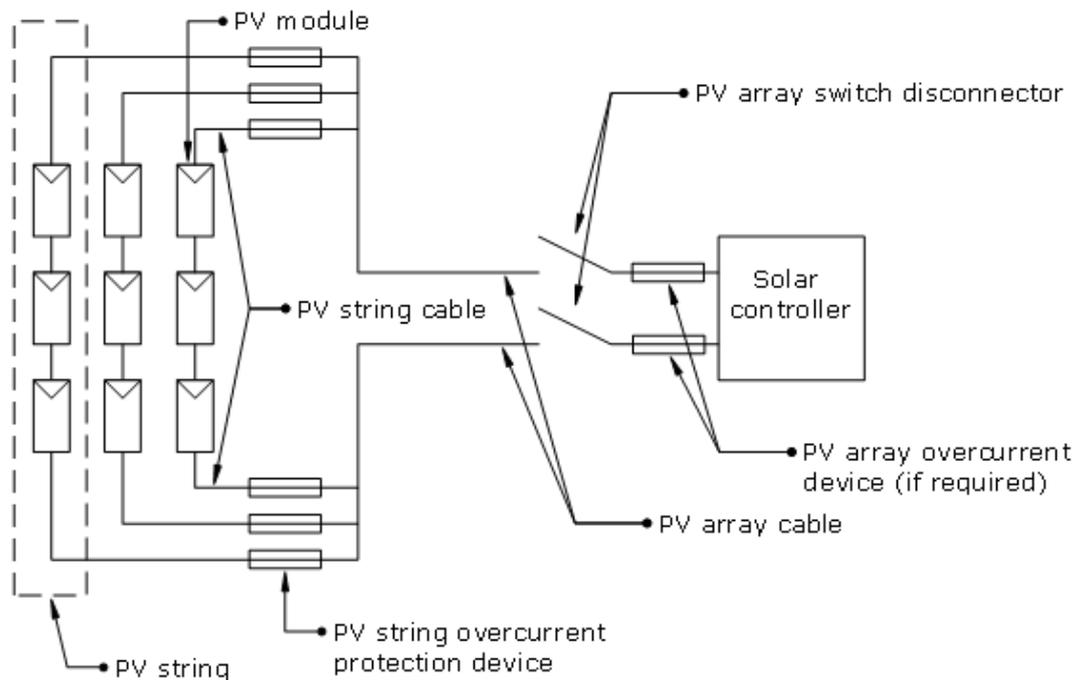


Figure 5: PV Array diagram showing multiple strings

### 22.1. Selection of d.c. cable for PV Array

Cables used within the PV array wiring shall:

- Be suitable for d.c. applications.
- Have a voltage rating equal to or greater than the PV array maximum voltage.
- Have a temperature rating appropriate for the application.
- Be water resistant.
- It is recommended that string cables be sufficiently flexible to allow for thermal/wind movement of arrays/modules.
- Be UV resistant or housed in appropriate conduit.
- Have appropriate insulation and marking.

Correctly sized cables in an installation will produce the following outcomes:

- No excessive voltage drops (which equates to an equivalent power loss) in the cables.
- The current in the cables will not exceed the safe current handling capability of the selected cables [known as current carrying capacity (CCC)]

### 22.2. Selection of Current Carrying Capacity of PV String Cables

If a fault current protection device is located in the string cable (as shown in figure 5), the string cable must have a rating equal to or greater than the current rating of the fault current protection device. For example, if the fault current protection device is rated at 8 A, the string will need to be rated with a current carrying capacity (CCC) of 8 A at minimum.

If no fault current protection is provided, the current carrying capacity (CCC) of the string cable will be rated according to:

$$CCC \geq 1.25 \times I_{SC\ MOD} \times (\text{Number of parallel connected strings} - 1) + I_n$$

where

$I_n$  is the current rating of the nearest downstream overcurrent protection device.

In summary this is saying that each string cable must be capable of carrying all the current from the other parallel strings (hence number of parallel connected strings – 1) plus any current that could be supplied upstream before a protection device trips. In figure 5 this is the protective device shown near the solar controller.

### 22.3. Selection of Current Carrying Capacity of PV Array Cables

If a fault current protection device (as shown in figure 5) is located in the array cable, the array cable must have a current rating equal to or greater than the current rating of the fault current protection device.

If no fault current protection device has been included, the current carrying capacity of the PV array cable will be rated according to:

$$CCC \geq 1.25 \times I_{SC\ ARRAY}$$

## 23. Voltage Drop

- The voltage drop between the PV array and the battery bank should never exceed 5%.
- The voltage drop between the battery bank and any D.C. load should never exceed 5%.
- The voltage drop between the PV array and MPPT should never exceed 3%.

### 23.1. Calculating Voltage Drop for Systems that include PWM Solar controllers

This section is for systems that are using standard pulse width modulated (PWM) solar controllers.

Voltage drop is calculated using Ohm's law:

$$V = I \times R$$

Combining this with the formula for calculating resistance, the voltage drop along a cable is given by:

$$V_d = \frac{2 \times L_{CABLE} \times I \times \rho}{A_{CABLE}}$$

$$\text{Voltage drop (in percentage)} = \frac{V_d}{V_{batt}} \times 100$$

Where:

- $V_d$  = voltage drop in cable in volts.
- $L_{CABLE}$  = route length of cable in metres (multiplying it by two adjusts for total circuit conductor length since a complete circuit requires a conductor out and another conductor back along the route).
- $I$  = current in amperes.
- $\rho$  = resistivity of the wire in  $\Omega/m/mm^2$
- $A_{CABLE}$  = cross-sectional area (CSA) of cable in  $mm^2$ .
- $V_{batt}$  = the nominal voltage of the battery, which is the d.c. system voltage, in volts.

For PV arrays connected to a switching type controller, the current is the short circuit current ( $I_{sc}$ ) of the string, sub-array or array. The battery voltage is the nominal battery voltage of the battery bank.

**Worked Example 24 :**

A solar array has been installed and the distance between the output of the array and the solar controller is 10 metres. The short circuit current of the array is 9.6 A.

The cable has a cross-sectional area of 10 mm<sup>2</sup>

The cable is copper with a resistivity of 0.0183 Ω/m/mm<sup>2</sup>

The battery voltage of the system is 12 V.

$$V_d = \frac{2 \times L_{\text{CABLE}} \times I \times \rho}{A_{\text{CABLE}}}$$

$$= 2 \times 10 \text{ m} \times 9.6 \text{ A} \times 0.0183 \Omega/\text{m}/\text{mm}^2 \div 10 \text{ mm}^2$$

$$= 0.35 \text{ V}$$

$$\text{Voltage Drop in percentage} = \frac{V_d}{V_{\text{Batt}}} \times 100$$

$$= 0.351 \text{ V} \div 12 \text{ V} \times 100$$

$$= 2.9\%$$

### 23.2. Calculating Voltage Drop for Systems that include a MPPT

This section is for systems that are using Maximum Power Point Trackers (MPPT) type solar controllers.

Voltage drop is calculated using Ohm's law:

$$V = I \times R$$

Combining this with the formula for calculating resistance, the voltage drop along a cable is given by:

$$V_d = \frac{2 \times L_{\text{CABLE}} \times I \times \rho}{A_{\text{CABLE}}}$$

$$\text{Voltage drop (in percentage)} = \frac{V_d}{V_{\text{MAX}}} \times 100$$

Where:

- **L<sub>CABLE</sub>** = route length of cable in metres (multiplying it by two adjusts for total circuit wire length since a complete circuit requires a wire out and another wire back along the route).
- **I** = current in amperes.
- **ρ** = resistivity of the wire in Ω/m/mm<sup>2</sup>
- **A<sub>CABLE</sub>** = cross sectional area (CSA) of cable in mm<sup>2</sup>.
- **V<sub>MAX</sub>** = maximum line voltage in volts

For PV arrays connected to a MPPT type solar controller (d.c. bus), the current is the short-circuit current (*I<sub>sc</sub>*) of the string, sub-array or array. The maximum line voltage in volts is the maximum power point voltage of the string, sub-array or array (*V<sub>mp</sub>*).

**Worked Example 25:**

A solar array has been installed and the distance between the output of the array and the solar controller is 10 metres. The short circuit current of the array is 9.6 A.

The cables have a cross sectional area of 4 mm<sup>2</sup>

The cable is copper with a resistivity of 0.0183 ohms/metres/mm<sup>2</sup>

The array comprises two 72 cell modules in series and have maximum power point voltage of 77.2 V.

$$V_d = \frac{2 \times L_{\text{CABLE}} \times I \times \rho}{A_{\text{CABLE}}}$$

$$= \frac{2 \times 10 \times 9.6 \times 0.0183}{4} \text{ V}$$

$$= 0.88 \text{ V}$$

$$\text{Voltage Drop in percentage} = \frac{V_d}{V_{\text{MAX}}} \times 100$$

$$= \frac{0.88}{77.2} \times 100$$

$$= 1.14\%$$

### 23.3. Tables Providing Route Lengths for twin cables for a specified voltage drop

Table 8: Maximum Distance in metres to produce 5% voltage drop (12 V system)

Current (A)	Cable Size						
	1 mm <sup>2</sup>	1.5 mm <sup>2</sup>	2.5 mm <sup>2</sup>	4 mm <sup>2</sup>	6 mm <sup>2</sup>	10 mm <sup>2</sup>	16 mm <sup>2</sup>
1	16.4	24.6	41	65.6	98.4	163.9	262.3
2	8.2	12.3	20.5	32.8	49.2	82	131.1
3	5.5	8.2	13.7	21.9	32.8	54.6	87.4
4	4.1	6.1	10.2	16.4	24.6	41.0	65.6
5	3.3	4.9	8.2	13.1	19.7	32.8	52.5
6	2.7	4.1	6.8	10.9	16.4	27.3	43.7
7	2.3	3.5	5.9	9.4	14.1	23.4	37.5
8	2.0	3.1	5.1	8.2	12.3	20.5	32.8
9	1.8	2.7	4.6	7.3	10.9	18.2	29.1
10	1.6	2.5	4.1	6.6	9.8	16.4	26.2
11	1.5	2.2	3.7	6.0	8.9	14.9	23.8
12	1.4	2.0	3.4	5.5	8.2	13.7	21.9
13	--	1.9	3.2	5.0	7.6	12.6	20.2
14	--	1.8	2.9	4.7	7.0	11.7	18.7
15	--	1.6	2.7	4.4	6.6	10.9	17.5
16	--	1.5	2.6	4.1	6.1	10.2	16.4
17	--	--	2.4	3.9	5.8	9.6	15.4
18	--	--	2.3	3.6	5.5	9.1	14.6
19	--	--	2.2	3.5	5.2	8.6	13.8

20	--	--	2.0	3.3	4.9	8.2	13.1
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Table 9: Maximum Cable Lengths in Metres for 12 V System 3% Voltage Drop

Current (A)	1 mm <sup>2</sup>	1.5 mm <sup>2</sup>	2.5 mm <sup>2</sup>	4 mm <sup>2</sup>	6 mm <sup>2</sup>	10 mm <sup>2</sup>	16 mm <sup>2</sup>
1	9.8	14.8	24.6	39.3	59.0	98.4	157.4
2	4.9	7.4	12.3	19.7	29.5	49.2	78.7
3	3.3	4.9	8.2	13.1	19.7	32.8	52.5
4	2.5	3.7	6.1	9.8	14.8	24.6	39.3
5	2.0	3.0	4.9	7.9	11.8	19.7	31.5
6	1.6	2.5	4.1	6.6	9.8	16.4	26.2
7	1.4	2.1	3.5	5.6	8.4	14.1	22.5
8	1.2	1.8	3.1	4.9	7.4	12.3	19.7
9	1.1	1.6	2.7	4.4	6.6	10.9	17.5
10	1.0	1.5	2.5	3.9	5.9	9.8	15.7
11	0.9	1.3	2.2	3.6	5.4	8.9	14.3
12	0.8	1.2	2.0	3.3	4.9	8.2	13.1
13		1.1	1.9	3.0	4.5	7.6	12.1
14		1.1	1.8	2.8	4.2	7.0	11.2
15		1.0	1.6	2.6	3.9	6.6	10.5
16		0.9	1.5	2.5	3.7	6.1	9.8
17			1.4	2.3	3.5	5.8	9.3
18			1.4	2.2	3.3	5.5	8.7
19			1.3	2.1	3.1	5.2	8.3
20			1.2	2.0	3.0	4.9	7.9

### 23.4. Location for Protection and Isolation in a Solar Home System

All electrical standards state that all cables shall be electrically protected from fault currents that could occur. However because of the difficulty in some situations of installing protection equipment at the start of a cable some electrical wiring standards allow 2 to 3 metres of cable to be unprotected. This guideline adopts that philosophy.

#### 23.4.1. Solar Home System with d.c. loads only

The cables in a d.c.-only solar home system are as follows:

- Cable between the battery and the solar controller.
- Cable between the controller and the PV array.
- Cable between the controller and the loads such as d.c. lights and d.c. appliances.

Any fault current in this system would come from the battery and even with a small 100 Ah battery the fault current can be as high as 2000 A. If this fault current flows in any of the cables, the cables will catch on fire.

Figures 6 show the possible options for protection and isolation (switch-disconnection) requirements in the solar home system with d.c.-only loads. It shows isolation and protection in positive and negative cables for each of the three cables using circuit breakers performing both isolation and protection. This is the ideal, but it is also the most expensive.

The minimum requirement for the electrical protection of the cables is summarised as follows:

- If the cable between the battery and the controller is less than 2 metres in length, then no protection is required to be installed in that cable.
- The cables to the PV array and the loads shall be protected.
- If the solar controller includes fusing that protects both the PV array and load cables, then no further protection is required.
- If the solar controller only protects one of the cables, either the loads or the PV array, then the other cable shall be protected.
- If protection is installed between the batteries and controller and it is suitably sized to protect the smallest of all the cables installed, then that protection will meet the protection requirement for the system.

When protection devices (suitably rated d.c. circuit breakers or fuses) are installed they should be installed in both the positive and negative cables.

For maintenance and fault finding (troubleshooting) purposes it is preferable that each cable: PV array, loads and battery to controller, can be individually isolated as shown in Figure 5. However, it is accepted that due to costs the isolation is achieved by removing the cable from the solar controller.

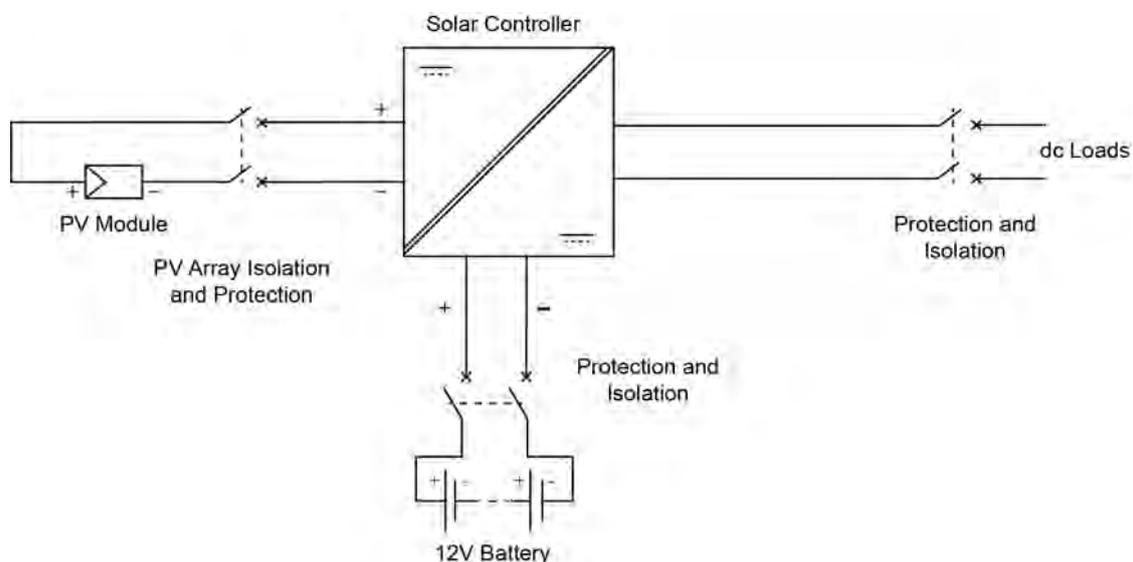


Figure 6: Solar Home System with d.c. loads only

#### 23.4.2. Solar Home System with d.c. and a.c. loads

The additional cables in solar home system with both d.c. and a.c. loads compared to a solar home system with d.c. loads only (as detailed in section 23.4.1) are as follows:

- d.c. cable between the battery and the inverter

- Possible a.c. cables from the inverter to a switchboard or distribution board.

As with the d.c. only system any fault current in this system would come from the battery.

Figures 7 show the possible options for protection and isolation (switch-disconnection) requirements in the solar home system with d.c. and a.c. loads.

In addition to the requirements of section 23.4.1 , the minimum requirements for the electrical protection of the extra cables required for the a.c loads is summarised as follows:

- Protection (either double pole suitable rated d.c. circuit breaker or fuses) shall be located in the cable between the battery and the inverter.
- If the inverter is only providing loads directly connected to power points located on the inverter, then no further protection is required between the inverter and the loads.
- If the inverter a.c. output is being hardwired to a switchboard or distribution board and the inverter does not have circuit protection on the output (a.c. side) of the inverter, then a double pole a.c. circuit breaker should be installed for the cable going to the switchboard (distribution board).

When protection devices (suitably rated d.c. circuit breakers or fuses) are installed they should be installed in both the positive and negative cables.

For maintenance and fault finding (troubleshooting) purposes it is preferable that the additional battery to inverter cable can be individually isolated as shown in Figure 7. The battery to inverter protection device should meet the isolation requirement for that cable.

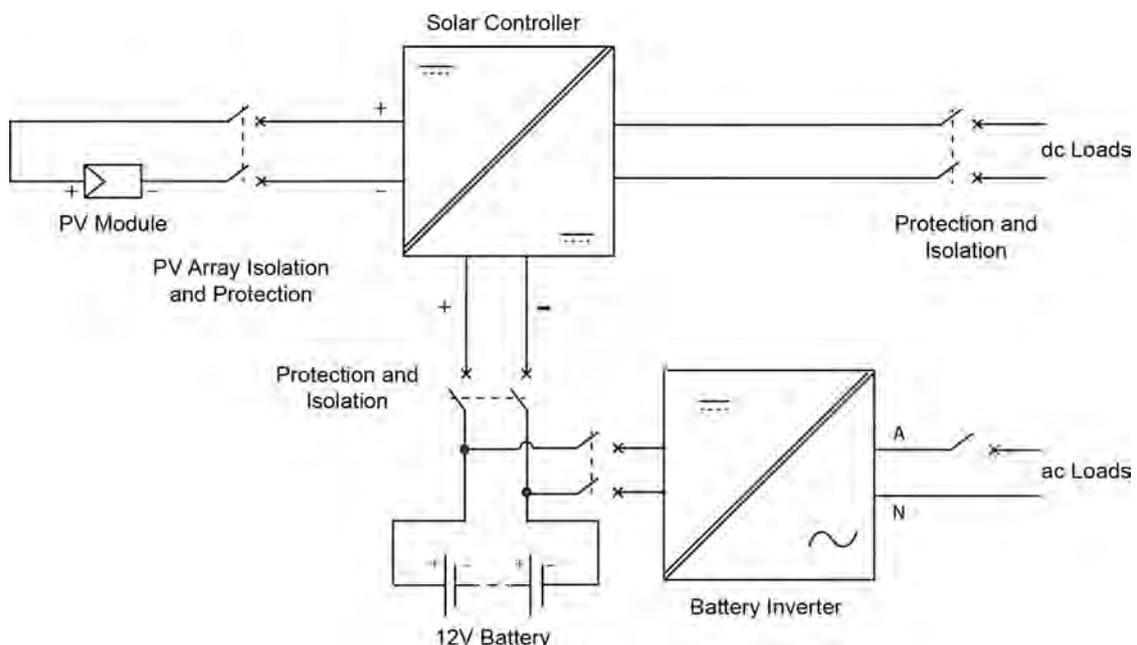


Figure 7: Solar Home System with d.c and a.c. loads

### 23.4.3. Arrays with Parallel Strings

Figure 7 shows the location of string and array isolators when the array has parallel strings.

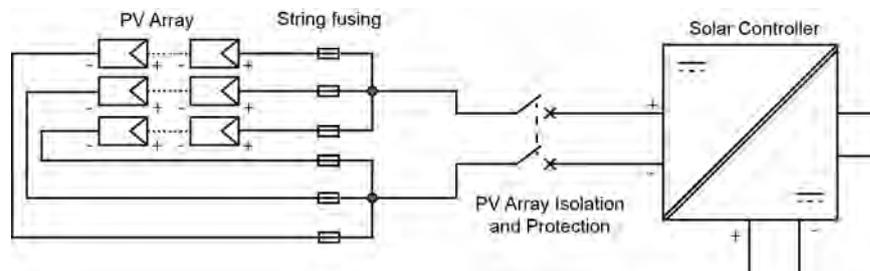


Figure 8: Array with Parallel strings

The minimum requirement for the electrical protection of the cables in an array with parallel strings is summarised as follows:

- String fusing is required if the potential fault current is greater than the reverse current rating of the PV module. (Refer section 24.1).
- PV array cable protection is required if the cable is not protected by either the solar controller or protection device located between the battery and the controller

For maintenance and fault finding (troubleshooting) purposes it is preferable that the PV array cable can be individually isolated as shown in Figure 8. However, it is accepted that due to costs the isolation for the PV array cable could be achieved by just disconnecting the cable from the solar controller instead of installing a separate isolator as shown in figure 8.

## 24. Ratings and types of protection Devices

The formulas and requirements in this section are from IEC62548: Photovoltaic (PV) Arrays-Design Requirements.

This section specifies how to determine the ratings of the protection devices when they are installed.

### 24.1. Solar Array d.c. Cable

Each solar module has a maximum reverse current rating provided by the manufacturer. If the array consists of parallel strings such that the reverse current that flows into one string, resulting from a fault in that string can be greater than the maximum reverse current for the modules in that string, then protection shall be provided in each string. The protection to be used shall be d.c. rated fuses that meet the specification shown in 24.2.

### Worked Example 26

The reverse current rating for a module is 15 A while the short circuit current is 8.9 A. If the array consists of two (2) parallel strings and a fault occurs in one (1) string, then the potential fault current will come from the other one (1) string which is only 8.9 A and is less than the reverse current rating so no protection is required. However, if the array consists of three (3) parallel strings and a fault occurs in one (1) string then the fault current could come from the other two (2) strings. This current is 17.8 A (2 x 8.9 A) and is now greater than the reverse current rating of the module. Protection is now required.

A formula for determining the maximum number of strings allowed before fuses are required is:

Maximum number of strings without string protection  
= reverse current rating of a module/ $I_{sc}$  of the module

The answer must always be rounded up because it is the maximum number of strings.

So in the above example; Max number of strings = 15 A / 8.9 A = 1.69 A rounded up to 2.

## 24.2. PV fuses

Fuses used in PV arrays shall —

- (a) be rated for d.c. use;
- (b) have a voltage rating equal to or greater than the PV array maximum voltage;
- (c) be rated to interrupt fault currents from the PV array; and
- (d) be of an overcurrent and short-circuit current protective type suitable for PV complying with IEC 60269-6 (i.e. Type gPV).

## 24.3. String Protection

The fuses shall have the following current rating:

$$1.5 \times I_{sc \text{ of module}} < I_{TRIP} < 2.4 \times I_{sc \text{ of module}}$$

and

$$\text{Fuse Rating} < I_{RC \text{ of module}}$$

Where

$I_{sc \text{ of module}}$  = module short-circuit current

$I_{TRIP}$  = rated trip current of the fault current protection device

$I_{RC \text{ of module}}$  = module reverse current rating

## 24.4. Array Cable Protection

Array overcurrent protection is designed to protect the entire PV array from external fault currents. For solar home systems this can only occur when the solar controller (PWM type solar controller or MPPT) allows fault current from the battery bank to back-feed through the controller.

If array overcurrent protection is required for a system, the nominal rated current for the overcurrent protection device will be as follows:

$$1.25 \times I_{SC-ARRAY} \leq I_{TRIP} \leq 2.4 \times I_{SC-ARRAY}$$

Where:

$I_{SC\_ARRAY}$  = short-circuit current of the array

$I_{TRIP}$  = rated trip current of the fault current protection device

The protection device that is physically located within the solar controller shall meet the above rating or separate protection will need to be installed.

The protective device installed to meet the above rating, can either be installed in the PV array cable or in the battery-to-controller cable.

#### 24.5. Battery Cable Protection- battery to controller

As stated in section 23.4.5 : If the cable between the battery and the controller is less than 2 metres in length, then no protection is required to be installed in that cable. However, if protection is installed it should meet the requirements as specified in this section.

For Solar Home Systems with d.c. loads, as shown in Figures 6 and 7, when a protection device is installed in the cables between the battery bank and the controller, the protection devices will be rated to allow the maximum charge current provided by the solar controller and the maximum d.c. load current that is to be provided by the solar controller.

#### 24.6. Battery Cable Protection- Battery to Inverter

To select the appropriate battery protection for the cable to the battery inverter:

1. Obtain the battery inverter manufacturer's data of:
  - Continuous power rating (watts)
  - 3 to 10 second surge rating (watts)
  - Average inverter efficiency (%)

2. Obtain Time-Current characteristics for the overload protection to be used.

[All manufacturers publish time-current information for their circuit breaker and HRC fuse ranges]

3. For each inverter power rating, determine the current drawn from the battery bank using ...

$$I = \frac{\text{Inverter Power Rating (W)}}{(\text{inverter efficiency} \times \text{nominal battery voltage})}$$

4. Consult the Time-Current characteristic of available overload protection devices to determine the device with an appropriate rating that matches the maximum load and maximum load surge characteristics.

## 25. Disconnection Requirements

This guideline does not specify that separate isolation devices are installed in a solar home system. However, if an installer (designer) decides to install these devices, then they should meet the requirements of this section. Isolation devices are sometime called switch disconnectors. Switch disconnectors or isolators are load-breaking devices

### 25.1. Within the Array

No separate disconnection devices are required within an array because the solar module connectors will meet the isolation of the array requirement. However PV modules should never be disconnected under load.

## 25.2. PV Array switch disconnecter near Solar Controllers

If a switch disconnecter is installed, it should meet the following requirements:

- All PV array switch-disconnectors shall be capable of being reached for inspection, maintenance or repairs without necessitating the dismantling of structural parts, cupboards, benches or the like.
- Where the switch-disconnector is exposed to the weather, it shall have an IP rating of at least IP56; however, it is recommended that they are rated to IP66.
- It is recommended that there are no top cable entries into the switch-disconnector and cable drip loops are utilised at the bottom of the switch-disconnector to minimise risk of water ingress.
- PV array switch-disconnectors shall meet the requirements of section 25.5.

## 25.3. Battery bank disconnecter Device

If disconnection devices are installed they could be installed between the battery and controller, and if applicable, between the battery and inverter, and also when there are parallel batteries on each of the battery strings. If switch disconnectors, are installed these should meet the following requirements:

- All battery isolating devices shall be d.c. rated switch disconnectors capable of breaking the maximum current for the particular equipment the battery is connected to.
- All battery switch-disconnectors shall be capable of being reached for inspection, maintenance or repairs without necessitating the dismantling of structural parts, cupboards, benches or the like.
- Where the switch-disconnector is exposed to the weather it shall have an IP rating of at least IP56, however it is recommended that they are rated to IP66.
- Battery switch-disconnectors shall meet the requirements of section 25.5.

## 25.4. Load Disconnection Devices

Load disconnection devices could be connected on the d.c. load cable from the controller and the a.c. load cable from the inverter. However, the disconnection might be able to be performed at the controller or at the inverter, depending on the isolation that is provided on those devices. If switch disconnectors are installed, they should meet the requirements of 25.5. In addition:

- All load switch disconnectors devices shall be capable of breaking the maximum load current possible on the cable.
- All d.c. load switch disconnection devices shall be d.c. rated switch disconnectors and meet the requirements of 24.5.
- a.c. load switch disconnectors shall meet the standard requirements for a.c. switch disconnectors as required in the country of installation and have minimum current ratings equivalent to the rated output current of the inverter

## 25.5. d.c Switch disconnection Devices Requirements

The d.c. switch-disconnectors shall:

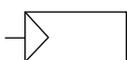
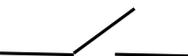
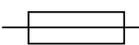
- be rated for d.c. use.
- be rated to interrupt the full load and prospective fault currents.
- not be polarity sensitive.
- interrupt all live conductors simultaneously.
- shall not have exposed live parts in the connected or disconnected state.
- shall comply with the requirements of IEC 60947-3 and shall have a utilization category of at least D.C.-21B (as per IEC 60947-3).

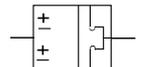
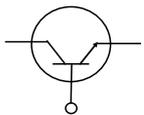
- For PV array switch connectors, the switch disconnectors shall have voltage ratings as follows:
  - For PWM controller and separated MPPT controllers: the sum of the voltage rating of both poles together of the switch-disconnector shall be at least the PV array maximum voltage ( $V_{oc}$  of the array adjusted for the lowest ambient temperature at the site).
  - For non-separated MPPT controllers: the voltage rating of each pole of the disconnector shall be at least the PV array maximum voltage ( $V_{oc}$  of the array adjusted for the lowest ambient temperature at the site).
- For battery switch disconnectors, the switch disconnectors shall have voltage ratings as follows:
  - For non-separated MPPT: the voltage rating of each pole of the disconnector shall be at least the PV array maximum voltage ( $V_{oc}$  of the array adjusted for the lowest ambient temperature at the site).
  - For all PWM controllers, separated MPPT controllers and battery inverters connected to battery banks that are not earthed/grounded the voltage rating of the sum of the two poles (positive and negative) of the switch-disconnector shall be at least the maximum battery voltage expected when under charge.
  - For all PWM controllers, separated MPPT controllers and battery inverters connected to battery banks that are earthed/grounded, the voltage rating of each pole of the switch disconnector shall be at least the maximum battery voltage expected under charge.
- Battery switch disconnectors shall be rated to withstand the prospective fault current for a time at least equal to the operating time of the associated over-current protective device.

## 26. Draw Schematic/ Single Line Diagram

A schematic circuit diagram is the representation of a power system using the simple symbol for each component. This diagram should show the main connections and arrangement of the system components along with their data such as current rating, voltage, power rating, cable size, etc. Table 10 shows universally accepted electrical symbols to represent the different electrical components are generally applicable for Solar Home System circuit diagram. A designer must prepare this diagram and include it as part of design document. This will help in procuring and installing the right components and wiring the system correctly.

Table 10: Electrical Schematic Symbols

Symbol	Identification	Explanation
	PV Module	Represents solar PV modules
	Circuit breaker	Represents a fixed mounted low voltage circuit breaker
	Disconnect switch	Represents a switch (open position shown)
	Fuse	Represents fuses in d.c. circuit
	Ground (earth)	Represents a grounding (earthing) point
	Battery	Represents a battery in an equipment package

	Ammeter	Represents ammeter
	Voltmeter	Represent voltmeter
	Inverter	Represents inverter
	MPPT	Represents Maximum Power Point Tracker
	PWM Controller	Represents PWM Controller

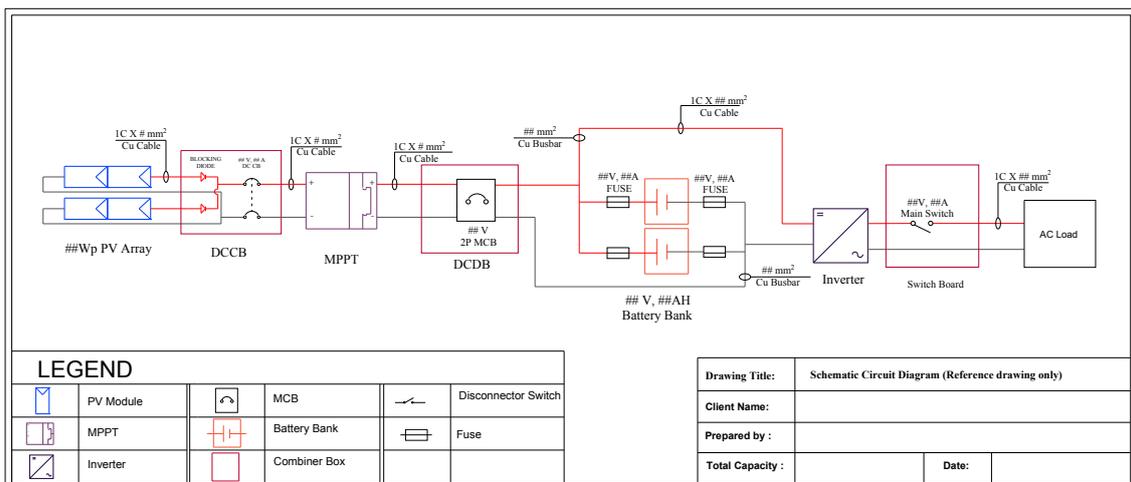


Figure 9: A schematic circuit diagram for an example large Solar Home System

## 27. Prepare Bill of Materials

After design is complete, a bill of materials or bill of quantity should be prepared to estimate the system cost. An example of a bill of materials for a typical Solar Home System is presented in table 11.

Table 11: Bill of materials and costings for a typical Solar Home System

Sl. No.	Description	Specification	Qty.
1.	Poly-crystalline solar PV module		

Sl. No.	Description	Specification	Qty.
2.	Storage battery		
3.	Battery inverter		
4.	MPPT		
5.	Mounting structure for roof		
6.	Battery rack		
7.	Single core d.c. cable		
8.	Two core a.c. cable		
9.	Battery fuses		
10.	d.c. switch to disconnect PV modules		
11.	d.c. switch to disconnect battery		
12.	a.c. switch to disconnect a.c. loads		
13.	d.c. combiner box		
14.	d.c. combiner box		

## 28. Providing a Quotation

When providing a quotation to a potential end-user, the designer should provide (as a minimum) the following information

- Full specifications of the system proposed including quantity, make (manufacturer) and model number of the solar modules, full specifications of any inverter(s) and drawings and specifications of the array mounting structure where applicable.
- A copy of the load assessment sheet showing the details of how the load was calculated.
- The expected performance of the system and how it will meet the power and energy requirements specified in the load assessment sheet.
- A firm quotation, which shows the installed cost of the complete system.
- Warranty information relating to each of the items of equipment and the overall system performance.
- A complete listing of the regular maintenance requirements for the installation.