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Sustainable Energy

OFF GRID
PV POWER SYSTEMS

SYSTEM DESIGN GUIDELINES
FOR THE PACIFIC ISLANDS

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SYSTEM DESIGN GUIDELINES FOR THE PACIFIC ISLANDS

These guidelines have been developed by the Sustainable Energy Industry Association of the Pacific Islands in Collaboration with the Pacific Power Association
They represent latest industry BEST PRACTICE for the design and installation of Off Grid PV Systems.

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GENERAL

The design of any off-grid system should consider, other than the electrical load, a number of criteria such as:

- Budget
- Power quality
- Environmental impact
- Aesthetics
- Acceptable genset runtime
- Noise levels
- Site accessibility
- Level of automation

Note: This guidelines are based on d.c. bus systems and do not include the new a.c. bus hybrid systems currently available. Guidelines dedicated to hybrid Systems will be developed.

ENERGY SOURCE MATCHING

Heating and lighting should be supplied from the most appropriate source. For example -

- cooking - gas or wood burning stove
- water heating - solar water heating with gas or wood backup
- Lighting - electrical lighting most often used but natural light (daylighting) should be considered.

ENERGY EFFICIENCY

All appliances should be chosen for the lowest possible energy consumption for each desired outcome, such as

- High efficiency lighting
- Energy efficient refrigeration

STANDARDS for DESIGN

System designs should follow any standards that are typically applied in the country or region where the solar installation will occur. The following lists the relevant standards in Australia, New Zealand and USA They are listed because some Pacific island countries and territories do follow those standards. These standards are often updated and amended so the latest version should always be applied.

In Australia and New Zealand the main standards required include:

- AS/NZS3000 Wiring Rules
- AS/NZS4509 Stand-alone power systems
- AS 4086.2 Secondary batteries for stand-alone power supplies
- AS/NZS5033 PV Array
- AS 3010.1 Electrical Installations - Supply Generating set
- AS 1768 Lightning Protection
- AS 3595 Energy management programs
- AS 1359.51 Noise level limits

In USA PV systems must be in accordance with the following codes and standards:

- Electrical Codes-National Electrical Code Article 690:Solar Photovoltaic Systems and NFPA 70 Uniform Solar Energy Code
- Building Codes- ICC, ASCE 7
- UL Standard 1701: Flat Plat Photovoltaic Modules and Panels
- UL Standard 1741: Standard for Inverter, converters, Controllers and Interconnection System Equipment for use with Distributed Energy Resources

INTRODUCTION

Four major issues arise when designing a system:
1. the load (power) required to be supplied by the system is not constant over the period of one day;
2. the daily energy usage varies over the year;
3. the energy available from the PV array may vary from time to time during the day;
4. the energy available from the PV array will vary from day to day during the year.

Since the system is based on photovoltaic modules, then a comparison should be undertaken between the available energy from the sun and the actual energy demands The worst month is when the ratio between solar energy available and energy demand is smallest.

The design of an off-grid power requires a number of steps. A basic design method follows:
1. Determination of the energy usage that the system must supply.
2. Determination of the battery storage required.
3. Determination of the energy input required from the PV array or other sources (eg battery charger/ generator)
4. Selection of the remainder of system components.

LOAD (ENERGY) ASSESSMENT

Electrical power is supplied from the batteries (DC) or via an inverter to produce either 230 volts AC (South Pacific) or 110 / 120 volts AC (North Pacific). 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 of the appliance by 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 DC or AC. An energy assessment should be undertaken for each type, examples of these are shown in tables 1 and 2.

You need to calculate the electrical energy usage with the customer. Many systems have failed over the years not because the equipment has failed or the system was installed incorrectly, BUT BECAUSE THE CUSTOMER BELIEVED THEY COULD GET MORE ENERGY FROM THEIR SYSTEM THAN THE SYSTEM COULD DELIVER. It failed because the customer was unaware of the ***power/energy limitations*** of the system.

The problem is that the customer may not want to spend the time determining their realistic power and energy needs which is required to successfully complete a load assessment form. They just want to know: *How much for a system to power my lights and TV?*

A system designer can only design a system to meet the power and energy needs of the customer. The system designer must therefore use this process to understand the needs of the customer and at the same time educate the customer. Completing a load assessment form correctly (Refer to table 1 and 2 below) does take time; you may need to spend 1 to 2 hours or more with the potential customer completing the tables. It is during this process that you will discuss all the potential sources of energy that can meet their energy needs and you can educate the customer on energy efficiency.

Worked Example

Table 1 DC Load (energy) Assessment

(1)	(2)	(3)	(4a)	(5a)	(4b)	(5b)	(6)	**Comments**
Appliance	**Number**	**Power**	**dry season**		**wet season**		**Contribution to maximum demand**	
			Usage Time	**Energy**	**Usage Time**	**Energy**		
		W	**h**	**Wh**	**h**	**Wh**	**W**	
Light	4	7	4	112	4	112	28	
Daily Load energy-d.c loads (Wh)			(DC 7a)	112	(DC 7b)	112		
Maximum d.c. demand (W)						(DC 8)	28	

Table 2 AC Load (energy) Assessment

(1)	(2)	(3)	(4a)	(5a)	(4b)	(5b)	(6)	(7)	(8)	(9a)	(9b)	**Comments**
Appliance	**No.**	**Power**	**dry season**		**wet season**		**Power Factor**	**Contribution to max demand**	**Surge Factor**	**Contribution to surge demand**		
			Usage Time	**Energy**	**Usage Time**	**Energy**				**Potential**	**Design**	
		W	**h**	**Wh**	**h**	**Wh**		**VA**		**VA**	**VA**	
TV		**100**	**3**	**300**	**3**	**300**	**0.8**	**125**	**4**	**500**	**125**	
Refrigerator		100	12	**1200**	12	1200	**0.8**	**125**	**4**	**500**	**500**	**Duty cycle of 0.5 included**
Daily Load Energy A.C Loads (Wh)			(AC10a)	**1500**	(AC10b)	1500						
maximum demand (VA)					**(AC11)**			**250**		**1000**		
Surge demand (VA)									**(AC12)**		**625**	

In the worked example on the previous page, the TV and refrigerator are using AC electricity so we have to take into account the efficiency of the inverter. Typically the peak efficiency of the inverter may be over 90% but in many systems the inverter will sometimes be running when there is very little load on the inverter, so the average efficiency is about 85% to 90%. Then we must divide the total AC energy used by this figure to obtain the energy required to be supplied to the inverter from the battery bank.

For the worked example assume the efficiency of the chosen inverter is 90%.

Daily battery load (energy) from AC loads = 1500Wh ÷ 0.9 = 1667 Wh

Daily battery load (energy) from DC loads = 112 Wh

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

1667 + 112= 1779Wh

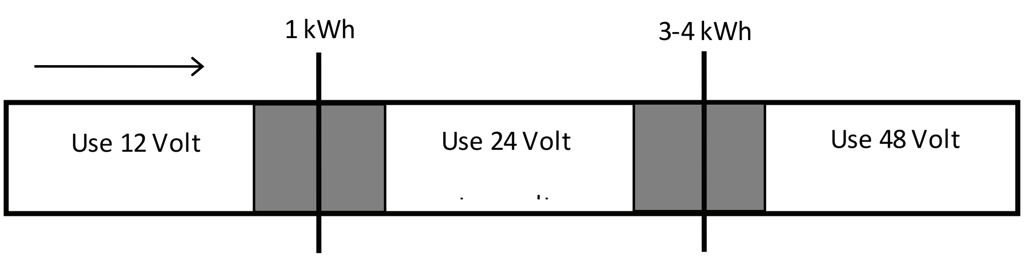
If there are no AC loads, then you only have to work out the load from the DC appliances, and not include the inverter (or the inverter efficiency).

BATTERY SELECTION

DETERMINATION OF SYSTEM VOLTAGE

System voltages are generally 12, 24 or 48 Volts. The actual voltage is determined by the requirements of the system. For example, if the batteries and the inverter are a long way from the energy source then a higher voltage may be required to minimise power loss in the cables. In larger systems 120V or 240V DC could be used, but these are not typical household systems.

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



The changes over points are roughly at daily loads of 1 kWh and 3-4 kWh but this will also be dependent on the actual power profile.

One of the general limitations is that maximum continuous current being drawn from the battery should not be greater than 150A.

BATTERY SIZING

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

For the worked example the daily energy usage was 1779Wh , so we select a battery system voltage of 24 Volts.

This means that the daily Ah demand on the batteries will be:

Ah = Wh ÷ system voltage 1779Wh ÷ 24 = 74 Ah

So at the moment the minimum size battery to meet the daily energy requirements in the example is: 74Ah

Battery capacity is determined by whichever is the greater of the following two requirements:

1. The ability of the battery to meet the energy demand of the system, often for a few days, sometimes specified as 'days of autonomy' of the system;

OR

2. The ability of the battery to supply peak power demand.

The critical design parameters include:

Parameters relating to the energy requirements of the battery:

a) Daily energy demand
b) Daily and maximum depth of discharge
c) Number of days of autonomy

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

a) Maximum power demand
b) Surge demand

Parameters relating to the charging of the battery:

a) Maximum Charging Current

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

1. <u>Days of Autonomy</u>

Extra capacity is necessary where the loads require power during periods of reduced input. The battery bank is often sized to provide for a number of days autonomy. A common period selected is 5 days.

Where a generator is operating on a regular basis the autonomous period can be reduced.

In other cases, where there is no auxiliary charging source, the period of autonomy is often increased to 7 days or more.

For the worked example assume 5 days autonomy .

ADJUSTED
Battery Capacity = 74 x 5 = 370 Ah

2. 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% or for some solar batteries as high as 80%.

For the worked example Assume a maximum DOD of 70%.

ADJUSTED
Battery Capacity = 370 ÷ 0.7 = 529 Ah

3. Battery Discharge Rate

The actual discharge rate selected is highly dependent on the power usage rates of connected loads. 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.

For small systems this is often impractical.

Where the average rates of power usage are low, the battery capacity for 5 days autonomy is often selected at the 100hr rate of discharge for the battery.

For the worked example

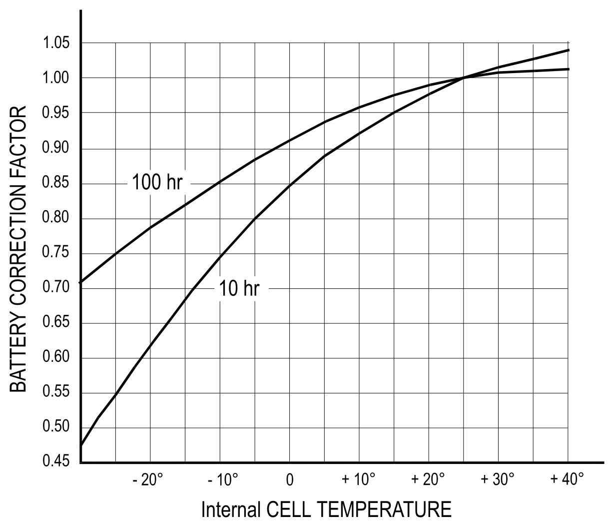
ADJUSTED
Battery Capacity = 529 Ah (@ C_{100})

Where average power usage rates are high, it may be necessary to select the battery capacity for 5 days autonomy at a higher discharge rate. eg. the 10 (C_{10}) or 20hr (C_{20}) rate

4. Battery Temperature derating

Battery capacity is affected by temperature. As the temperature goes down, the battery capacity reduces. The following graph 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 the tropics it is often still 20°C+ in the evenings so unless the system is located in a mountainous region that does get cold then ignore the temperature derating. If you want to be conservative add 5% to the capacity to allow for this factor.



BATTERY SELECTION

Deep discharge type batteries / cells should be selected for the required system voltage and capacity in a single series string of battery cells.

Parallel strings of batteries are not recommended.

Where this is necessary each string must be separately fused.

For the worked example a battery of at least 529 Ah (@C_{100}) should be used.

PV ARRAY SIZING- Standard Switched Controllers

The calculation for determining the size of the PV array is dependent on the type of controller used. Historically standard switched controllers were the most common controllers used. In recent years a number of maximum power point trackers (MPPT) have become available. This section determines how to size the PV array based on switched controllers based on the PV array meeting the daily load requirements all year. Later in the guide is a section on how to size a PV array using a MPPT.

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

- seasonal variation of solar irradiation
- seasonal variation of the daily energy usage
- battery efficiency
- manufacturing tolerance of modules
- dirt
- temperature of array (the effective cell temperature)

Solar irradiation data is available from various sources. Some countries have data available from their respective meteorological department. One source for solar irradiation data is the NASA website: http:/eosweb.larc.nasa.gov/sse/. RETSCREEN, a program available from Canada, incorporates the NASA data and it is easier to use. Please note that the NASA data has, in some instances, had higher irradiation figures than that recorded by ground collection data in some countries. but if there is no other data available it is data that can be used.

Solar irradiation is typically provided as kWh/m^2 however it can be stated as daily peak Sun Hours (PSH). This is the equivalent number of hours of solar irradiance of 1kW/m^2.

Attachment 1 provides data on the following sites:

- Suva, Fiji (Latitude 18°08'S Longitude 178°25'E)
- Apia, Samoa (Latitude 13o50' S' Longitude 171o44' W)
- Port Vila, Vanuatu (Latitude 17° 44' S Longitude 168° 19' E)
- Tarawa, Kiribati (Latitude 1°28'N, Longitude 173°2'E)
- Raratonga, Cook islands(Latitude 21°30'S, Longitude 160°0'W)
- Nuku'alofa, Tonga (Latitude 21°14'S Longitude 175°22'W)
- Honiara, Solomon Islands (Latitude 09°27'S, Longitude 159°57'E)
- Koror ,Palau (Latitude 7°20'N Longitude 134°28'E)
- Ponapei, Pohnpei FSM (Latitude: 6°54'N, Longitude: 158°13'E)

- Majuro, Marshall Islands (Latitude: 7º 12N, Longitude 171º 06E)
- Alofi, Niue (Latitude 19°04' S. Longitude 169° 55' W)
- Nauru (Latitude 0º55'S, Longitude 166º 91'E)
- Tuvalu (Latitude 8°31'S, Longitude 179°13'E)
- Hagåtña, Guam (Latitude 13°28'N Longitude: 144°45'E)
- Noumea, New Caledonia (Latitude 22°16'S Longitude: 166°27'E)
- Pago Pago, American Samoa (Latitude 14°16' S Longitude: 170°42'W)

The variation of both the solar irradiation and the load energy requirement should be considered. If there is no variation in daily load between the various times of the year then the system should be designed on the month with the lowest irradiation that is peak sun hours (PSH).

Daily ENERGY REQUIREMENT from the PV Array

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 battery efficiency.

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The average columbic efficiency (in terms of Ah) of a new battery is 90% (variations in battery voltage are not considered).

For the worked example the daily energy requirement expressed in Ah from the battery is 74 Ah. Allowing for the battery efficiency, the solar array then needs to produce…

74 Ah ÷ 0.9 = 82.2 Ah

Assume the worst months PSH is 5.

Therefore the required PV array output current is:

82.2 Ah ÷ 5 PSH = 16.5 A

OVERSIZE FACTOR

If the system does not include a fuel generator which can provide extra charging to the battery bank then the solar array should be oversized to provide the equalisation charging of the battery bank. In Australia and New Zealand this is between 30% and 100%. It is recommended in the Pacific that this is 10%.

For the worked example the adjusted array output current is:

16.5A x 1.1 = 18.1 A

DERATING MODULE PERFORMANCE

The PV array will be de-rated due to:

- Manufacturer's Tolerance: Most manufacturers rate their modules ± a percentage (eg ±3%) or wattage (eg ±2W). Unless every module is tested and its actual rating is known then the modules should be de-rated by the manufacturer's tolerance.
- Dirt: Over a period of time dirt or salt (if located near the coast) can build up on the array and reduce the output. The output of the module should therefore be derated to reflect this soiling. The actual value will be dependent on the site but this can vary from 0.9 to 1 (i.e. up to 10% loss due to dirt).
- Temperature: Modules' output power decreases with temperature above 25°C and increases with temperatures below 25°C. The average cell temperature will be higher than the ambient because of the glass on the front of the module 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 effective temperature of the cell. This is determined by the following formula:

$T_{cell\text{-}eff} = T_{a.day} + 25°C$

Where
$T_{cell\text{-}eff}$ = the average daily effective cell temperature in degrees Celsius (°C)
$T_{a.day}$ = the daytime average ambient temperature for the month that the sizing is being undertaken.

Since the modules are used for battery charging, the current at 14 Volts (a good battery charging voltage) at the effective cell temperature should be used in calculations. If curves are unavailable to determine the current at effective cell temperature then use the Normal Operating Cell temperature (NOCT) provided by the manufacturers.

Therefore the derated module output current is calculated as follows:

The Current of the module at 14V and effective cell temperature (or NOCT current)
multiplied by derating due to manufacturers tolerance
multiplied by derating due to dirt

$$I_{(NOCT)} \times f_{man} \times f_{dirt}$$

If a module has a 3% (0.03) manufacturers tolerance, then the module current is derated by multiplying by 0.97 (1-0.03).

If a module has a 5% (0.05) loss due to dirt then the module current is derated by multiplying by 0.95 (1-0.05).

For the worked example the selected module has a peak rating of $80W_p$.

An 80 watt solar module (still used in many small off-grid systems) typically has the following data:

Table 3: 80 W module data

Rated Power	80W
Power Tolerance	± 5%
Nominal Voltage	12V
Maximum Power Voltage, V_{mp}	17.6V
Maximum Power Current, I_{mp}	4.55A
Open Circuit Voltage, V_{oc}	22.1V
Short Circuit Current, I_{sc}	4.8A
NOCT	47±2°C
Current at 14V and NOCT	4.75A

Assuming a 5% dirt derating then the adjusted output current of the above module is:

ADJUSTED
Module current = $I_{(NOCT)}$ x 0.95 (¬ minus 5% for manufactures tol) x 0.95 (¬ minus 5% for dirt)
= 4.75A x 0.95 x 0.95 = 4.29A

NUMBER OF MODULES REQUIRED IN ARRAY

First determine number of modules in series, To do this divide the system voltage by the nominal operating voltage of each module. In our example:

For the worked example Number of modules in series = 24V ÷ 12V = 2

Therefore the array must comprise of series connected strings of 2 modules.

To determine the number of strings in parallel, the PV array output current required (in A) is divided by the output of each module (in A).

For the worked example Number of strings in parallel =18.1A ÷ 4.29A = 4.22

Do we round up or down? If you want to be conservative you would round up. However in this example we suggest you round down since this calculation was based on the worst month and we allowed an oversize of 10%.This does need to be determined for each system.

For the worked example The number of modules in the array = 4 x 2 = 8

The peak rating of the array is : 8 x $80W_P$ = $640W_P$

INVERTER SELECTION

The type of inverter selected for the installation depends on factors such as cost, surge requirements, power quality and for inverter/chargers, a reduction of the number of system components necessary. Inverters are available in 3 basic output types - Square wave, modified square wave and sine wave.
There are few square wave inverters used today.

Modified square wave inverters generally have good surge and continuous capability and are usually cheaper than sine wave types. However, some appliances, such as audio equipment, television and fans can suffer because of the output wave shape.

Sine wave inverters often provide a better quality power than the 230V (or 110V or 120V) grid supply.

INVERTER SIZING

The selected inverter should be capable of supplying continuous power to all AC loads
AND
providing sufficient surge capability to start any loads that may surge when turned on and particularly if they turn on at the same time.

Where an inverter cannot meet the above requirements attention needs to be given to load control and prioritisation strategies.

For the worked example

From the load (energy) assessment on page 3, a selected inverter must be capable of supplying 250VA continuous with a surge capability of 625VA.

CONTROLLERS- Standard Switched Controller

PV controllers on the market range from simple switched units that only prevent the overcharge (and discharge) of connected batteries to microprocessor based units that incorporate many additional features such as …

- PWM and equalisation charge modes
- DC Load control
- Voltage and current metering
- Amp-hour logging
- Generator start/stop control

Unless the controller is a model that is currently limited these should be sized so that they are capable of carrying 125% of the array short circuit current and withstanding the open circuit voltage of the array. If there is a possibility that the array could be increased in the future then the controller should be oversized to cater for the future growth.

(Note: sometimes the controller is called a regulator)

For the worked example
The controller chosen must have a current rating
$> 1.25 \times 4 \times 4.8$ A = 24A at a system voltage of 24V.

GENERATORS & BATTERY CHARGING

To reduce system costs, it is common for some form of auxiliary charging to be used to provide energy when daily energy requirements are greater than the daily PV input into the system. This is usually a diesel/petrol/gas powered generator. Where the electrical output is 230V AC (or 110V or 120V) a battery charger is required.

An inverter/charger can be used; otherwise a separate charger unit is needed.

Factors that must be considered when using internal combustion generators are

- Fuel storage and spillage precautions
- Noise emission control
- Ventilation
- Generator loading

With regards to generator loading, a generator should supply greater than 50% of its maximum rating while running. Loading of less than 50% increases running and maintenance costs and reduces generator life.
(refer to genset manufacturers' information)

BATTERY CHARGER SIZING

A charger must be capable of supplying voltage greater than the nominal system voltage.
The maximum charging current must not be greater than that recommended by the battery manufacturer but a usable estimate is a maximum charge current of around 10% of the C_{10} rate.

PV ARRAY SIZING- MPPT

Daily ENERGY REQUIREMENT from the PV Array

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

- seasonal variation of solar irradiation
- seasonal variation of the daily energy usage
- battery efficiency (wh)
- Cable losses
- MPPT efficiency
- manufacturing tolerance of modules
- dirt
- temperature of array (the effective cell temperature)

With the standard controller the only sub-system losses was the battery efficiency and the calculations are undertaken using Ah. When using a MPPT the calculations are in Wh and the sub-system losses in the system include:

- Battery efficiency (watthr)
- Cable losses
- MPPT 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.

For the worked example assume cable losses is 3% (transmission efficiency of 97%), MPPT efficiency of 95% and battery efficiency of 80%

Subsystem efficiency = 0.97 x 0.95 x 0.8 = 0.737

Energy required from the PV array = 1779Wh ÷ 0.737 = 2413Wh

Assume the worst months PSH is 5.

Therefore the required peak PV array output power is:

$2413\text{Wh} \div 5\ \text{PSH} = 482\text{W}_\text{P}$

OVERSIZE FACTOR

If the system does not include a fuel generator which can provide extra charging to the battery bank then the solar array should be oversized to provide the equalisation charging of the battery bank. In Australia and New Zealand this is between 30% and 100%. It is recommended in the Pacific that this is 10%.

For the worked example Therefore the adjusted array output current is:

$482\text{W}_\text{P} \times 1.1 = 530\text{W}_\text{P}$

DERATING MODULE PERFORMANCE

The PV array will be de-rated due to:

- Manufacturer's Tolerance: Most manufacturers rate their modules ± a percentage (eg ±5%) or wattage (eg ±2W). Unless every module is tested and its actual rating is known then the modules should be de-rated by the manufacturer's tolerance.
- Dirt: Over a period of time dirt or salt (if located near the coast) can build up on the array and reduce the output. The output of the module should therefore be derated to reflect this soiling. The actual value will be dependent on the site but this can vary from 0.9 to 1 (i.e. up to 10% loss due to dirt).
- Temperature: Modules' output power decreases with temperature above 25°C and increases with temperatures below 25°C. The average cell temperature will be higher than the ambient temperature because of the glass on the front of the module 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 effective temperature of the cell. This is determined by the following formula:

  $T_{cell\text{-}eff} = T_{a.day} + 25°C$

  Where
  $T_{cell\text{-}eff}$ = the average daily effective cell temperature in degrees Celsius (°C)
  $T_{a.day}$ = the daytime average ambient temperature for the month that the sizing is being undertaken.

With switched controllers the temperature effect was used to determine the operating current of the module/array. With MPPT's the derating power factor must be calculated.

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

- Monocrystalline: Modules typically have a temperature coefficient of –0.45%/°C. That is for every degree above 25°C the output power is derated by 0.45%.
- Polycrystalline: Modules typically have a temperature coefficient of –0.5%/°C.
- Thin Film: Modules have a different temperature characteristic resulting in a lower co-efficient typically around 0%/°C to -0.25%/°C, but remember to check with the manufacturer

The typical ambient daytime temperature in many parts of the Pacific is between 30 and 35°C during some times of the year. So it would not be uncommon to have module cell temperatures of 55°C or higher.

For the worked example Assume the ambient temperature is 30°C..

Therefore the effective cell temperature is

30°C +25°C = 55°C
Therefore this is 30°C above the STC temperature of 25°C.

The 80 W_p module used in this example is a polycrystalline module with a derating of -0.5%/°C

Therefore the losses due to temperature would be:

Temperature loss = 30°C x 0.5%/°C = 15% loss

This is a temperature derating factor of 0.85

Assuming a 5% dirt derating then the adjusted output power of the 80W module is:

Adjusted module power = 80 x 0.95 x 0.95 x 0.85 = 61.4W

NUMBER OF MODULES REQUIRED IN ARRAY

To calculate the required number of modules in the array, divide the required array power by the adjusted module power.

For the worked example
Number of modules in array =530 ÷ 61.4 = 8.63

(Note for the switch regulator we had 4.29 parallel strings of 2 modules in series)

The actual number of modules will be dependent on the MPPT selected. If it was 9 then the rating of the array is : 9 x $80W_P = 720W_P$

SELECTING MPPT

The following table gives some examples of MPPT's currently available on the market:

Table 4: MPPT Data

Model	d.c. battery Voltage (V)	Input voltage range (V)	Max d.c. Battery Current (A)	Max(W) Solar Array	Max Load Current (A)
STECA Solarix MMP2010	12/24	17 to 100	20	250/500	10
Phocos MMPT 100/20-1	12/24	Max 95	20	300/600	10
Morningstar SS-MPPT-15L	12/24	Max 75	15	200/400	15
Outback Flex Max 80	12/24/36/48/60	Max 150	80	1250(12) 2550(24) 5000(48) 7500 (60)	
Outback Flex Max60	12/24/36/48/60	Max 150	60	900(12) 1800(24) 3600(48) 4500 (60)	

For the worked example
Allowing for 125% oversizing then the required rating of the MPPT is:

1.25 x 720Wp = 900 W

From the table we would select the Outback Flexmax60 which has an array rating of 1800W @ 24V

We could possibly use two of the others e.g. Phocos or Steca.

MATCHING THE PV ARRAY TO THE MAXIMUM VOLTAGE SPECIFICATIONS OF THE MPPT

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

Some MPPT controllers might allow that the minimum array nominal voltage is 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. The Outback range of MPPT's requires that the minimum nominal array voltage is greater as shown in Table 5. Please check with the MPPT manufacturer because these could vary.

Table 5 Minimum Nominal Array Voltages (Outback MPPT's)

Nominal Battery Voltage	Recommended Minimum Nominal Array voltage
12V	24V
24V	36V
48V	60V

It is important that the output voltage of the string is matched to the operating voltages of the MPPT and that the maximum voltage of the MPPT is never reached.

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*. It is generally specified in V/°C (or mV/°C) but it can also be expressed as a % .

To ensure that the V_{oc} of the array does not reach the maximum allowable voltage of the MPPT the minimum day time 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. In the Pacific Islands the average minimum temperature is 20^{0}C (this could be lower in some mountain areas) and it is recommended that this temperature is used to determine the maximum $V_{oc.}$ (Note: If installing in the mountains then use the appropriate minimum temperature. Many people also use 0°C, if appropriate for the area). The maximum open circuit voltage is determined similar to the temperature derating factor for the power.

For the worked example Assume the voltage co-efficient is 0.07V/^{o}C.

If the minimum temperature is 20^{o}C this is 5^{o}C below the STC temperature of 25^{o}C. Therefore the effective variation in voltage is:

5 x 0.07 = 0.35V

So the maximum open circuit voltage of the module = 22.1V + 0.35V =22.45V

Maximum number of modules that you can have in series = 150V ÷ 22.45V = 6.68 this is rounded down to 6.

So the MPPT will allow between 3 and 6 modules in a string.

The actual number of modules required was 8.68. If we round down to 8 (since an oversize factor of 10% and also worst month for PSH was used) then the array would be 2 parallel strings of 4 modules in series. If we round up to 9 then the solution could be 3 parallel strings with 3 modules in series.

ATTACHMENT 1: : Table showing Peak Sunhrs for various sites and tilt angles.

***Longitude**: 134°28′ East*	7° Tilt[2]	5.4	5.7	6.16	6.22	5.7	5.01	5.11	5.15	5.49	5.45	5.44	5.16	5.5
	22° Tilt[2]	5.75	5.86	6.06	6.01	5.66	5.03	5.1	5.03	5.3	5.51	5.74	5.54	5.55

Ponape, Pohnpei FSM		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
***Latitude:** 6°54′ North*	0° Tilt[1]	4.97	5.57	5.91	5.79	5.44	5.33	5.51	5.54	5.66	5.29	5.03	4.83	5.4
***Longitude**: 158°13′ East*	6° Tilt[2]	5.12	5.65	5.88	5.72	5.42	5.33	5.51	5.49	5.59	5.33	5.16	5	5.43
	21° Tilt[2]	5.43	5.82	5.8	5.55	5.4	5.39	5.53	5.39	5.41	5.39	5.43	5.36	5.49

Majuro, Marshall Islands		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
***Latitude:** 7°12′ North*	0° Tilt[1]	5.26	5.86	6.11	5.89	5.66	5.31	5.35	5.63	5.42	5.15	4.88	4.84	5.44
***Longitude**: 171°06′ East*	7° Tilt[2]	5.47	5.99	6.09	5.81	5.65	5.32	5.35	5.58	5.35	5.2	5.03	5.05	5.49
	22° Tilt[2]	5.83	6.16	5.99	5.62	5.61	5.35	5.35	5.46	5.16	5.25	5.27	5.4	5.53

Alofi, Niue		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
***Latitude:** 19°04′ South*	0° Tilt[1]	6.47	6.2	5.67	4.8	4.26	3.86	4.01	4.61	5.35	6.02	6.53	6.46	5.34
***Longitude**: 169°55′ West*	19° Tilt[2]	6.43	5.88	5.7	5.2	4.96	4.47	4.75	5.14	5.53	5.81	5.98	6.47	5.53
	34° Tilt[2]	6.06	5.4	5.47	5.24	5.24	4.78	5.08	5.29	5.42	5.41	5.35	6.15	5.41

Nauru		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
***Latitude:** 0°32′ South*	0°Tilt[1]	5.77	6.24	6.27	6.04	5.99	5.75	5.85	6.25	6.7	6.5	6.12	5.5	6.07
***Longitude**: 166°56′ East*	15° Tilt[2]	5.94	6.26	6.07	6.06	6.28	6.16	6.21	6.4	6.52	6.45	6.27	5.69	6.19

Vaiaku, Tuvalu		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Latitude: *8°31′ South*	0° Tilt[1]	5.16	5.27	5.33	5.29	4.93	4.66	4.76	5.3	5.72	5.8	5.57	5.23	5.25
Longitude*: 179°13′ East*	8° Tilt[2]	5.14	5.2	5.26	5.37	5.14	4.92	5	5.45	5.71	5.71	5.54	5.22	5.31
	23° Tilt[2]	5.09	5.05	5.08	5.43	5.42	5.3	5.33	5.62	5.61	5.49	5.47	5.21	5.34

Hagåtña, Guam		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Latitude: *13°28′ North*	0° Tilt[1]	5.33	5.87	6.73	7.12	7.04	6.44	6	5.3	5.42	5.46	5.16	5.05	5.9
Longitude*: 144°45′ East*	13° Tilt[2]	5.95	6.27	6.86	6.88	6.97	6.43	5.95	5.06	5.38	5.7	5.66	5.7	6.07
	28° Tilt[2]	6.41	6.49	6.75	6.4	6.7	6.27	5.76	4.68	5.19	5.78	6.01	6.2	6.05

Noumea, New Caledonia		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Latitude: *22°16′ South*	0° Tilt[1]	7.31	6.7	5.73	4.97	3.94	3.47	3.91	4.73	6.05	7.09	7.41	7.6	5.73
Longitude*: 166°27′w East*	22° Tilt[2]	6.61	6.34	5.83	5.56	4.76	4.19	4.69	5.51	6.44	6.88	6.77	7.53	5.93
	37° Tilt[2]	5.75	5.8	5.6	5.63	5.03	4.48	5	5.7	6.33	6.38	5.94	7.03	5.72

Pago Pago, American Samoa		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Latitude: *14°16 South*	0° Tilt[1]	5.87	5.93	5.54	5.18	4.63	4.4	4.59	5.2	5.78	6.05	6.11	5.93	5.43
Longitude*: 170°42 West*	14° Tilt[2]	5.79	5.66	5.51	5.43	5.11	4.99	5.15	5.59	5.88	5.84	6.01	5.87	5.57
	29° Tilt[2]	5.57	5.22	5.3	5.49	5.4	5.39	5.52	5.77	5.77	5.46	5.75	5.68	5.53

[1] *Monthly Averaged Insolation Incident On A Horizontal Surface (kWh/m²/day)*

[2] *Monthly Averaged Irradiation Incident On An Equator-Pointed Tilted Surface (kWh/m²/day)*

Source: NASA Surface meteorology and Solar Energy (http://eosweb.larc.nasa.gov)

Appendix 1 – Table of Abbreviations and Acronyms

d.c.	Direct current
a.c.	Alternating current
AS/NZS	Australia Standard/New Zealand Standard
UL	Underwriters Laboratory
ICC	International Code Council
NFPA	National fire Protection Association
ASCE	American Society of Civil Engineers
IEEE	Institute of Electrical and Electronics Engineers
Wh	Watt hours
kWh	Kilowatt hours
W	Watts
W_p	Watts peak
H	hours
V	Volts
A	Amps
VA	Volt amps
Ah	Amp hours
DOD	Depth of discharge
C_{100}	Battery capacity when battery is discharged over 100 hours
PV	Photovoltaic
MPPT	Maximum power point tracker
PSH	Peak sun hours(kWh/m^2)
kWh/m^2	Kilowatt hours/metres squared
°C	Degrees Celsius
NOCT	Nominal operating cell temperature
$T_{cell-eff}$	the average daily effective cell temperature (degrees Celsius)
$T_{a.day}$	the daytime average ambient temperature for the month that the sizing is being undertaken (degrees Celsius)
f_{man}	Derating due to manufacturers tolerance (dimensionless)
f_{dirt}	Derating due to dirt (dimensionless)
PWM	Pulse Width Modulation
V_{oc}	Open circuit voltage (volts)
V_{mp}	Maximum power point voltage (volts)
I_{sc}	Short circuit current (amps)
I_{mp}	Maximum power point current (amps)
STC	Standard test conditions