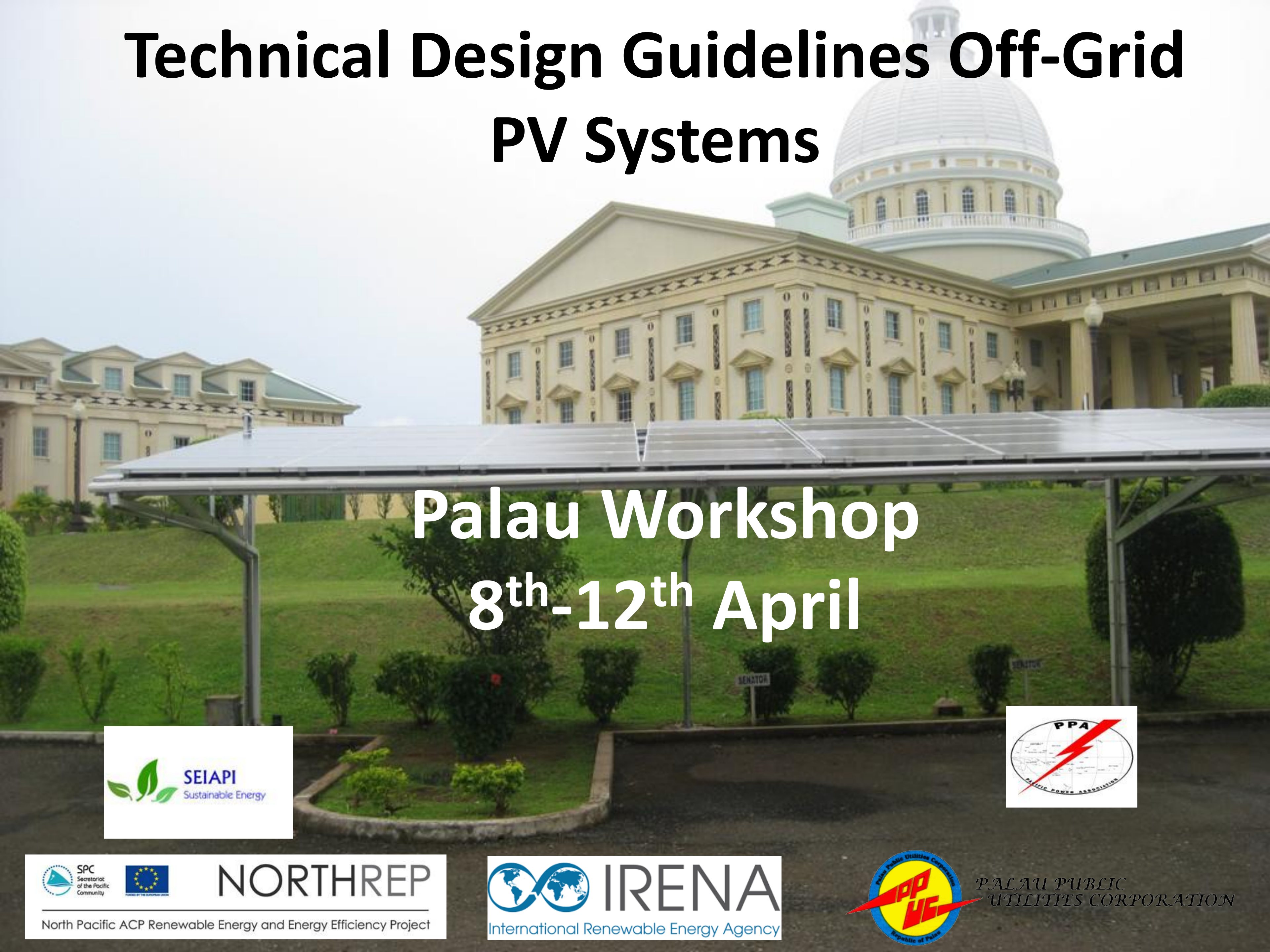
Technical Design Guidelines Off-Grid PV Systems



Palau Workshop

8th-12th April

SEIAPI Sustainable Energy

PPA Pacific Power Association

SPC Secretariat of the Pacific Community

NORTHREP

North Pacific ACP Renewable Energy and Energy Efficiency Project

IRENA

International Renewable Energy Agency

PALAU PUBLIC UTILITIES CORPORATION

GENERAL

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

Budget
Environmental impact
Acceptable genset runtime
Site accessibility

Power quality
Aesthetics
Noise levels
Level of automation

ENERGY SOURCE MATCHING

Heating tasks 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

Electrical lighting is most often used but natural light (day lighting) 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

In Australia and New Zealand the main standards required are …

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

STANDARDS FOR DESIGN 2

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 put on the system is not constant over the period of one day;
2. the daily load varies over the year;
3. the energy available from the renewable energy source may vary from time to time during the day;
4. the energy available from the renewable energy source will vary from day to day during the year.

INTRODUCTION -Cont

- If 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.

INTRODUCTION -Cont

The design of a off-grid power requires a number of steps. A basic design method follows …

1. Determination of the system load (energy usage).
2. Determination of the battery storage required.
3. Determination of the energy input required.
4. Selection of the remainder of system components.

LOAD ASSESSMENT

Table 1 DC Loads

(1)	(2)	(3)	(4a)	(5a)	(4b)	(5b)	(6)	Comments
			dry season		r wet season			
Appliance	**Number**	**Power**	**Usage Time**	**Energy**	**Usage Time**	**Energy**	**Contribution to maximum demand**	
		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 Loads

(1)	(2)	(3)	(4a)	(5a)	(4b)	(5b)	(6)	(7)	(8)	(9a)	(9b)	
			dry season		r wet season					Contribution to surge demand		
Appliance	**No.**	**Power**	**Usage Time**	**Energy**	**Usage Time**	**Energy**	**Power Factor**	**Contribution to max demand**	**Surge Factor**	**Potential**	**Design**	**Comments**
		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**	

Important!

- *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.***

Determining the d.c. Energy Usage

In the worked example, the TV and refrigerator are using AC electricity so we have to take into account the efficiency of the inverter.

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

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

Daily battery load from DC loads = 112 Wh

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

1667 + 112= 1779Wh

Battery Selection

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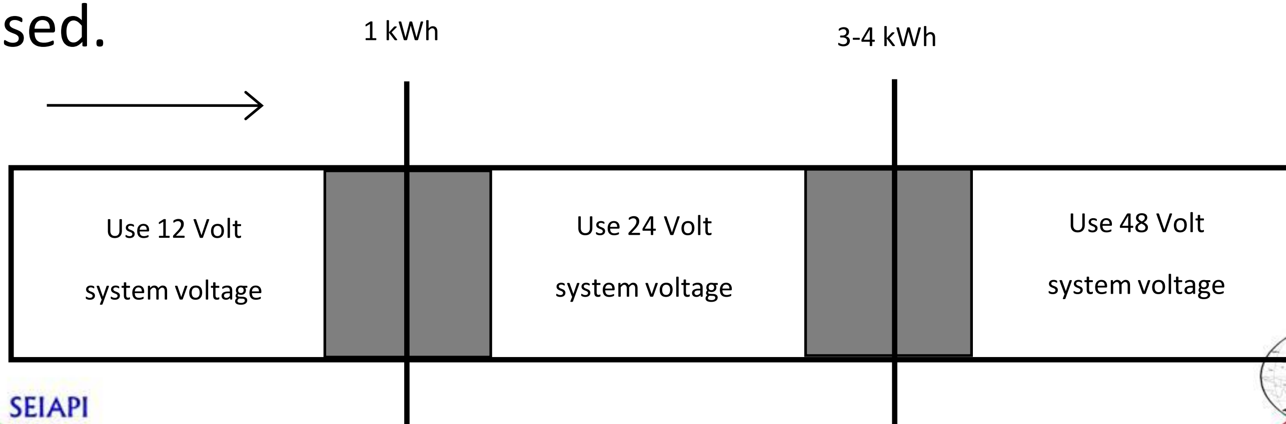
Determining System Voltage

System voltages are generally 12, 24 or 48 Volts and the actual voltage is determined by the requirements of the system. In larger systems 120V or 240V DC could be used, but these are not the 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.



Daily Load in Ah

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 will be:

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

Battery Capacity

Determined by whichever is the greater of the following two requirements:

- 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

- The ability of the battery to supply peak power demand

Battery Design Parameters 1

Parameters relating to the energy requirements of the battery:

- Daily energy demand
- Daily and maximum depth of discharge
- Number of days of autonomy

Battery Capacity-Example

Maximum Depth of Discharge

Recommended by the manufacturer

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

ADJUSTED Battery Capacity = 74 Ah ÷ 0.7 = **105.8 Ah**

Days of Autonomy

5 days often used

No generator & days +

Generator readily available and used maybe less than 5 days

For the worked example assume 5 days autonomy .

ADJUSTED Battery Capacity = 105.8 x 5 = **529 Ah**

Battery Design Parameters 2

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

- Maximum power demand
- Surge demand

Battery Capacity Example Cont

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

For the worked example

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

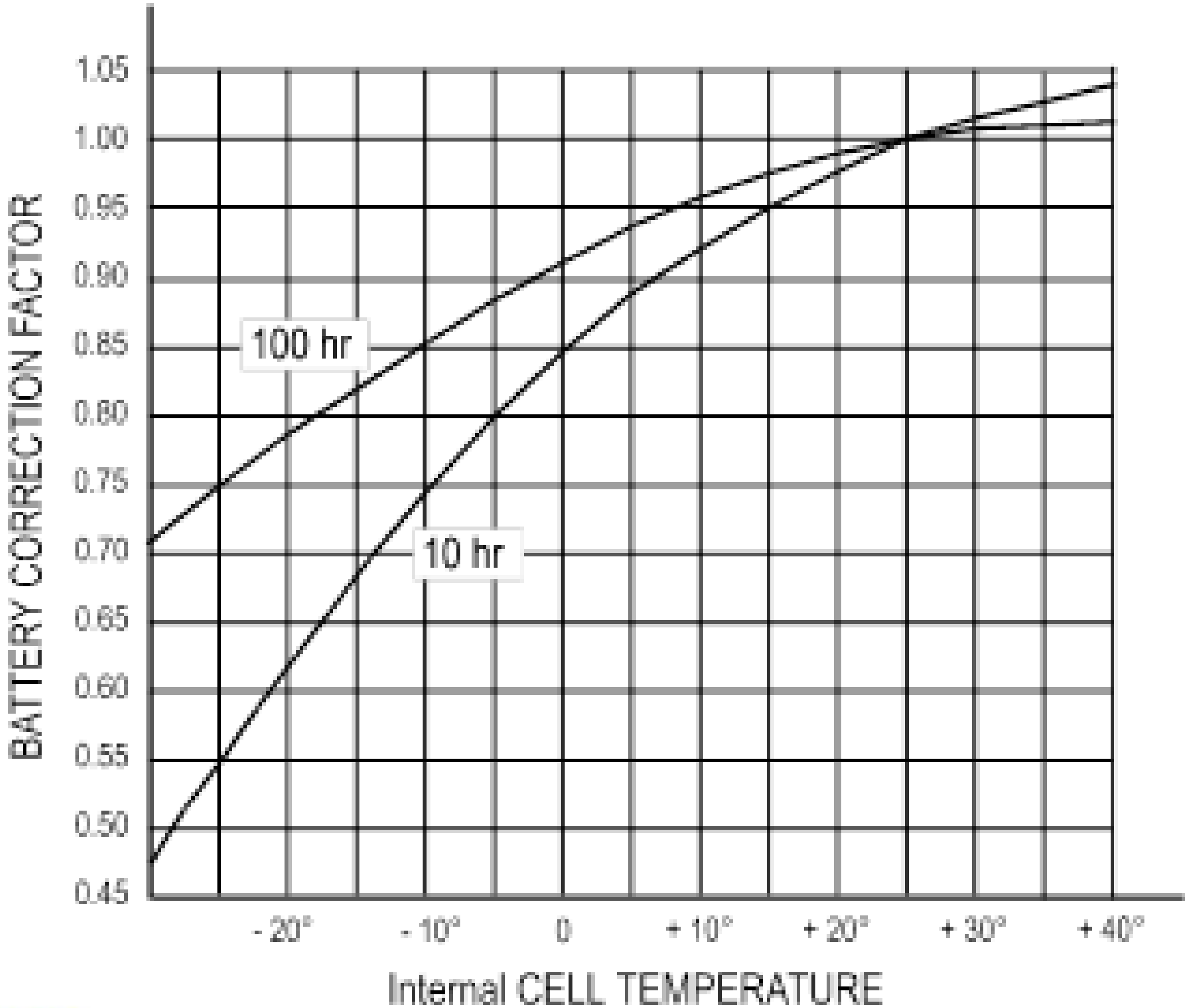
Where average power usage rates are high, it may be necessary to select the battery capacity for 5 days autonomy at a higher discharge rate. eg. the 10hr (C_{10}) or 20hr (C_{20}) rate

Battery Temperature derating

- Battery capacity is affected by temperature.
- As the temperature goes down, the battery capacity reduces.

- In the Pacific it is often still 20°C+ (68 F) 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 Temperature derating



Battery Design Parameters 3

Parameters relating to the charging of the battery:

- Maximum Charging Current

Typically 0.1 x C_{10} capacity

For example:

Battery of 100Ah (C_{10}) maximum charging current is 10A

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 (@C100) should be used.

Sizing PV Arrays

Different for:

- Standard Charge Controllers
- MPPTs

Sizing PV Arrays Standard Controller

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

- seasonal variation of solar radiation
- seasonal variation of the load
- battery efficiency
- manufacturing tolerance of modules
- dirt
- temperature of array (the effective cell temperature)

DAILY AH 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).

DAILY AH REQUIREMENT FROM THE PV ARRAY-EXAMPLE

For the worked example the daily load requirement 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**

DAILY A REQUIREMENT FROM THE PV ARRAY-EXAMPLE

For the worked example

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**

Module Derating

Same as covered in grid connect design:

- Manufacturer's Tolerance
- Dirt
- Temperature
    - 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 or If curves are unavailable to determine the current at effective cell temperature then use the Normal Operating Cell temperature (NOCT) provided by the manufacturers.

Calculated Derated Module Current

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

Example

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

Normal Operating Cell temperature (NOCT)

Example Cont

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

ADJUSTED

$I_{(NOCT)}$ = 4.75 A

Module current = I $_{(NOCT)}$ x 0.95 (← minus 5% for manufactures tolerance) x 0.95(← minus 5% for dirt)

= 4.75A x 0.95 x 0.95 = **4.29A**

Number of Modules in Series String

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.

Number of Strings in Parallel

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**

ADJUSTED *array output current* / ADJUSTED Module current

Do we round up or down?

For the worked example: round down to 4

=> Already conservative in calculation. (worst month and over sized)

Number of Modules in The Array

For the worked example The number of modules in the array = 4 (parallel) x 2 (series) = **8**

The peak rating of the array is : $8 \times 80W_P = \mathbf{640W_P}$

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-
- Sine wave- .

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 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.

Sizing Inverter Example

Table 1 DC Loads

(1)	(2)	(3)	(4a)	(5a)	(4b)	(5b)	(6)	Comments
			dry season		r wet season			
Appliance	Number	Power	Usage Time	Energy	Usage Time	Energy	Contribution to maximum demand	
		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		
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			dry season		r wet season					Contribution to surge demand		
Appliance	No.	Power	Usage Time	Energy	Usage Time	Energy	Power Factor	Contribution to max demand	Surge Factor	Potential	Design	Comments
		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	

CONTROLLER SIZING

Also sometimes referred to as a “Regulator”.

These should be sized so that they are capable of carrying 125% of the array **short circuit current** (unless the controller is current limited)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 regulator should be oversized to cater for the future growth

For the worked example …

The controller chosen must have a current rating

> 1.25 x 4 x 4.8 A (Isc) = **24A** at a system voltage of 24V.

Sizing PV Arrays MPPT

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

- seasonal variation of solar radiation
- seasonal variation of the load
- battery efficiency (Wh)
- Cable losses
- MPPT efficiency
- manufacturing tolerance of modules
- dirt
- temperature of array (the effective cell temperature)

DAILY ENERGY REQUIREMENT FROM THE PV ARRAY

When using a MPPT then the sub-system losses in the system include:

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

DAILY ENERGY REQUIREMENT FROM THE PV ARRAY-EXAMPLE

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**

DAILY W_P REQUIREMENT FROM THE PV ARRAY-EXAMPLE

For the worked example

Assume the worst months PSH is 5.

Therefore the required peak PV array output power is:

$$2413\text{Wh} \div 5 \text{ PSH} = \mathbf{482W_P}$$

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:

$$482W_P \times 1.1 = 530W_P$$

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Module Derating

Same as covered in grid connect design:

- Manufacturer's Tolerance
- Dirt
- Temperature
  - 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

Temperature Derating

For the worked example Assume the ambient temperature is 30°C (86 F)..

Therefore the effective cell temperature is
30°C +25°C = 55°C (131 F)
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

Temperature Derating

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

Example Cont

Assuming a 5% dirt derating and 5% manufacturers tolerance 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 in The 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**

The actual number of modules will be dependent on the MPPT selected. If it was 9 then the rating of the array is :

$9 \times 80W_P = \mathbf{720W_P}$

Selecting MPPT

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)	

GENERATOR & BATTERY CHARGING

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

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

GENERATOR & BATTERY CHARGING

Factors that must be considered when using internal combustion generators are

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

On this last point, 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)

GENERATOR & BATTERY CHARGING Cont

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 maximum charge current of around 10% of the C10 rate.