

Design of Grid Connect PV systems

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INTRODUCTION

- The document provides the minimum knowledge required when designing a PV Grid connect system.
- The actual design criteria could include: specifying a specific size (in kW_p) for an array; available budget; available roof space; wanting to zero their annual electrical usage or a number of other specific customer related criteria.



DESIGNING A SYSTEM SUMMARY

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

- Determining the energy yield, specific yield and performance ratio of the grid connect PV system.
- Determining the inverter size based on the size of the array.
- Matching the array configuration to the selected inverter maximum voltage and voltage operating windows.

Prior to designing any Grid Connected PV system a designer shall either visit the site or arrange for a work colleague to visit the site and undertake/determine/obtain the following:

- Discuss energy efficient initiatives that could be implemented by the site owner. These could include:
 - replacing inefficient electrical appliances with new energy efficient electrical appliances
 - replacing tank type electric hot water heaters with a solar water heater either gas or electric boosted.(If applicable)
 - replacing incandescent light bulbs with compact fluorescents and/or efficient LED lights
- Assess the occupational safety and health risks when working on that particular site.

SITE VISIT 2

- Determine the solar access for the site.
- Determine whether any shading will occur and estimate its effect on the system.
- Determine the orientation and tilt angle of the roof if the solar array is to be roof mounted.
- Determine the available area for the solar array.
- Determine whether the roof is suitable for mounting the array.
- Determine how the modules will be mounted on the roof.
- Determine where the inverter will be located.
- Determine the cabling route and therefore estimate the lengths of the cable runs.
- Determine whether monitoring panels or screens are required and determine a suitable location with the owner

QUOTATION DOCUMENTATION

When providing a quotation to a potential customer, the certified designer should provide (as a minimum) the following information:

- Full Specifications of the system including quantity, make (manufacturer) and model number of the solar modules and inverter.
- An estimate of the yearly energy output of the system. This should be based on the available solar irradiation for the tilt angle and orientation of the array. If the array will be shaded at any time the effect of the shadows must be taken into account when determining the yearly energy output.
- The dollar savings this represents based on existing electrical energy pricing
- A firm quotation which includes all equipment and installation charges
- Warranty information relating to each of the items of equipment

If possible the savings in CO₂ (either tonnes or kg) could also be provided.



STANDARDS for DESIGN

In Australia and New Zealand the following standards are applicable: ...

In Australia and New Zealand the relevant standards include:

- AS/NZ 3000 Wiring Rules
- AS 3008 Selection of Cables
- AS /NZS4777 Grid Connection of energy systems by inverters
- AS/NZS 5033 Installation of PV Arrays
- AS 4509 Stand-alone power systems (note some aspects of these standards are relevant to grid connect systems)
- AS 3595 Energy management programs
- AS 1768 Lightning Protection



STANDARDS for DESIGN 2

In USA the relevant codes and standards include:

- 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
- IEEE 1547, Standards for Interconnecting distributed Resources with Electric Power Systems
- UL Standard 1741, Standard for Inverter, converters, Controllers and Interconnection System Equipment for use with Distributed Energy Resources
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AC ENERGY OUTPUT OF PV ARRAY

The AC energy output of a solar array is the electrical AC energy delivered to the grid at the point of connection of the grid connect inverter to the grid.

The output of the solar array is affected by:

- Average solar radiation data for selected tilt angle and orientation;
- Manufacturing tolerance of modules;
- Temperature effects on the modules;
- Effects of dirt on the modules;
- System losses (eg power loss in cable); and
- Inverter efficiency

ENERGY YIELD

For a specified peak power rating (kW_p) for a solar array a designer can determine the systems energy output over the whole year. The system energy output over a whole year is known as the systems “Energy Yield”

The average yearly energy yield can be determined as follows:

$$E_{sys} = P_{array_STC} \times f_{temp} \times f_{mm} \times f_{dirt} \times H_{tilt} \times \eta_{pv_inv} \times \eta_{inv} \times \eta_{inv-sb}$$

Array Losses/Output

$P_{array-stc}$ = rated output power of the array under standard test conditions, in watts

f_{temp} = temperature de-rating factor, dimensionless (refer next section)

f_{man} = de-rating factor for manufacturing tolerance, dimensionless (refer next section)

f_{dirt} = de-rating factor for dirt, dimensionless (refer next section)

H_{tilt} = yearly irradiation value (kWh/m^2) for the selected site (allowing for tilt, orientation and shading)

SYSTEM LOSSES

H_{tilt} = yearly irradiation value (kWh/m²) for the selected site (allowing for tilt, orientation and shading)

n_{inv} = efficiency of the inverter dimensionless

$n_{\text{pv_inv}}$ = efficiency of the subsystem (cables) between the PV array and the inverter

$n_{\text{inv-sb}}$ = efficiency of the subsystem (cables) between the inverter and the switchboard

Solar irradiation is typically provided as kWh/m². However it can be stated as daily peak Sunhrs (PSH). This is the equivalent number of hours of solar irradiance of 1kW/m².

SOLAR RADIATION DATA

GRID-CONNECTED POWER SYSTEMS
SYSTEM DESIGN GUIDELINES

- Suva, Fiji (Latitude $18^{\circ}08'S$ Longitude $178^{\circ}25'E$)
- Apia, Samoa (*Latitude $13^{\circ}50' S'$ Longitude $171^{\circ}44' W$*)
- Port Vila, Vanuatu (*Latitude $17^{\circ} 44' S$ Longitude $168^{\circ} 19' E$*)
- Tarawa, Kiribati (*Latitude $1^{\circ}28'N$, Longitude $173^{\circ}2'E$*)
- Raratonga, Cook islands(*Latitude $21^{\circ}30'S$, Longitude $160^{\circ}0'W$*)
- Nuku'alofa, Tonga (*Latitude $21^{\circ}14'S$ Longitude $175^{\circ}22'W$*)
- Honiara, Solomon Islands (Latitude $09^{\circ}27'S$, Longitude $159^{\circ}57'E$)
- Koror, Palau (Latitude $7^{\circ}20'N$ Longitude $134^{\circ}28'E$)



SOLAR RADIATION DATA 2

GRID-CONNECTED POWER SYSTEMS
SYSTEM DESIGN GUIDELINES

- Palikir, Pohnpei FSM (*Latitude: 6°54'N, Longitude: 158°13'E*)
- Majuro, Marshall Islands (*Latitude: 7° 12N, Longitude 171° 06E*)
- Alofi, Niue (*Latitude 19°04' S. Longitude 169° 55' W*)
- Nauru (*Latitude 0°55'S, Longitude 166° 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*)



SOLAR RADIATION Sample

Location		Peak Sunlight Hours (kWh/m ² /day)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Suva, Fiji														
Latitude: 18°08' South	0° Tilt ¹	6.29	6.2	5.54	4.67	4.05	3.72	3.89	4.44	5.08	6.04	6.32	6.38	5.21
Longitude: 178°25' East	18° Tilt ²	6.27	5.88	5.55	4.99	4.61	4.38	4.51	4.88	5.22	5.83	6.1	6.41	5.38
	33° Tilt ²	5.95	5.4	5.33	5.03	4.85	4.7	4.8	5	5.1	5.43	5.71	6.12	5.29
Apia, Samoa														
Latitude: 13°50' South	0° Tilt ¹	5.39	5.47	5.16	5.09	4.63	4.46	4.71	5.25	5.77	5.91	5.76	5.51	5.25
Longitude: 171°46' West	13° Tilt ²	5.31	5.24	5.12	5.32	5.07	5	5.24	5.61	5.85	5.72	5.67	5.45	5.38
	28° Tilt ²	5.13	4.86	4.93	5.38	5.36	5.42	5.64	5.81	5.75	5.36	5.45	5.3	5.37
Port Vila, Vanuatu														
Latitude: 17°44' South	0° Tilt ¹	6.68	6.2	5.76	4.98	4.2	3.79	4.04	4.75	5.65	6.47	6.67	6.93	5.5
Longitude: 168°19' East	17° Tilt ²	6.69	5.9	5.78	5.33	4.76	4.42	4.66	5.22	5.82	6.26	6.46	7.01	5.69
	32° Tilt ²	6.38	5.43	5.56	5.39	5.02	4.75	4.98	5.39	5.72	5.83	6.07	6.73	5.61



ORIENTATION and TILT

ANNUAL DAILY IRRADIATION ON AN INCLINED PLANE EXPRESSED AS % OF MAXIMUM VALUE FOR
CAIRNS Latitude: 16 degrees 52 minutes South
Longitude: 145 degrees 44 minutes East

Plane Azimuth (degrees)	Plane Inclination (degrees)									
	0	10	20	30	40	50	60	70	80	90
0	95%	99%	100%	99%	96%	90%	82%	73%	62%	52%
10	95%	99%	100%	99%	95%	90%	82%	73%	62%	52%
20	95%	98%	100%	98%	95%	90%	82%	73%	63%	53%
30	95%	98%	99%	98%	94%	89%	82%	73%	64%	54%
40	95%	98%	99%	97%	94%	88%	81%	73%	64%	55%
50	95%	97%	98%	96%	93%	87%	80%	73%	64%	56%
60	95%	97%	97%	95%	91%	86%	79%	72%	64%	56%
70	95%	96%	96%	94%	90%	84%	78%	71%	63%	55%
80	95%	96%	95%	92%	88%	82%	76%	69%	62%	54%
90	95%	95%	94%	90%	85%	80%	74%	67%	60%	53%
100	95%	95%	92%	89%	83%	78%	71%	64%	58%	51%
110	95%	94%	91%	87%	81%	75%	68%	61%	54%	48%

DERATING MODULES OUTPUT

1. Derating due to Manufacturers Output Tolerance
2. Derating due to dirt
3. Derating due to Temperature

Manufacturers

- The output of a PV module is specified in watts and with a manufacturing tolerance based on a cell temperature of 25 degrees C.
 - Historically $\pm 5\%$
 - recent years typical figures have been $\pm 3\%$
- System design must incorporate this tolerance.

As a worked example, assuming the tolerance is $\pm 5\%$ the “worst case” adjusted output of a 160W PV module is therefore around 152W ($0.95 \times 160\text{W}$), or 5% loss from the rated 160W.

Dirt

- The output of a PV module can be reduced as a result of a build-up of dirt on the surface of the module.
- If in doubt, an acceptable derating would be 5% from the already derated figure that includes manufacturers' tolerances.

Worked example continues: Assuming power loss due to dirt of 5% then the already derated 152 W module would now be derated further to 144.4W ($0.95 \times 152W$).

Temperature

. A solar modules output power decreases with temperature above 25°C and increases with temperatures below 25°C

Minimum Effective Cell Temp
= Ambient Temperature + 25°C

Temperature Cont

Monocrystalline Modules

Monocrystalline Modules typically have a temperature coefficient of $-0.45\%/^{\circ}\text{C}$. That is for every degree above 25°C the output power is derated by 0.45%.

Polycrystalline Modules

Polycrystalline Modules typically have a temperature coefficient of $-0.5\%/^{\circ}\text{C}$.

Thin Film Modules

Thin film Modules have a different temperature characteristic resulting in a lower co-efficient typically around $0\%/^{\circ}\text{C}$ to $-0.25\%/^{\circ}\text{C}$, but remember to check with the manufacturer

Temperature Example

For the worked example, assume the ambient temperature is 30°C.

Therefore the effective cell temperature is

$$30^{\circ}\text{C} + 25^{\circ}\text{C} = 55^{\circ}\text{C}$$

Therefore this is 30°C above the STC temperature of 25°C

Assume the 160W_p module used in the example is a polycrystalline module with a derating of $-0.5\%/^{\circ}\text{C}$

Therefore the output power losses due to temperature would be:

Temperature loss = $30^{\circ}\text{C} \times 0.5\%/^{\circ}\text{C} = 15\% \text{ loss}$

Cont

Assuming power loss due to temperature of 15% then the already derated 144.4 W module would now be derated further to 122.7W ($0.85 \times 144.4\text{W}$).

DERATING MODULES SUMMARY

A solar module has an derated output power = Module power @ STC x Derating due to manufacturers tolerances x derating due to dirt x derating due to temperature.

For the worked example:

Derated output power = $160 \times 0.95 \times 0.95 \times 0.85 = 122.7\text{W}$

DC ENERGY OUTPUT FROM ARRAY

The actual DC energy from the solar array = the derated output power of the module x number of modules x irradiation for the tilt and azimuth angle of the array.

For the worked example assume that the average daily PSH is 5 and that there are 16 modules in the array.
Therefore the DC energy output of the array = $122.7 \times 16 \times 5 = 9816\text{Wh}$

DC SYSTEM LOSSES

The DC energy output of the solar array will be further reduced by the power loss (voltage drop) in the DC cable connecting the solar array to the grid connect inverter.

For the worked example assume that the cable losses for the DC cables is 3%. This is a DC subsystem efficiency of 97%. Therefore the DC energy from the array that will be delivered to the input of the inverter will be = $9816 \times 0.97 = 9521 \text{ Wh}$

INVERTER EFFICIENCY

The DC energy delivered to the input of the inverter will be further reduced by the power/energy loss in the inverter.

For the worked example assume that the inverter efficiency is 96%. Therefore the AC energy delivered from the output of the inverter will be = $9521 \times 0.96 = 9140 \text{ Wh}$

AC SYSTEM LOSSES

The AC energy output of the inverter will be further reduced by the power loss in the AC cable connecting the inverter to the grid, say switchboard where it is connected.

For the worked example assume that the cable losses for the AC cables is 1%.

the AC energy from the inverter (and originally from the array) that will be delivered to the grid will be = $9140 \times 0.99 = 9048 \text{ Wh}$

Energy Yield of example

The worked example included an array of 16 modules each with a STC rating of 160W_p. Therefore the array is rated 2560W_p.

The average daily AC energy that was delivered by the array to the grid was 9048Wh or 9.05kWh.

Therefore over a typical year of 365 days then Energy Yield of the solar array is = 365 days x 9.05kWh/day = 3303kWh/year

SPECIFIC ENERGY YIELD

The specific energy yield is expressed in kWh per kW_p and it calculated as follows:

For the worked example: The AC energy from the array was 3303kWh/year and the array was rated at 2560W_p

Therefore the specific energy yield is 3303/2.560= 1,290kWh per kW_p

$$SY = \frac{E_{sys}}{P_{array_STC}}$$

PERFORMANCE RATIO

The performance ratio (PR) is used to assess the installation quality. The PR provides a normalised basis so comparison of different types and sizes of PV systems can be undertaken. The performance ratio is a reflection of the system losses

$$PR = \frac{E_{sys}}{E_{ideal}}$$

Where

E_{sys} = actual yearly energy yield from the system

E_{ideal} = the ideal energy output of the array.

Ideal Energy

$$E_{ideal} = P_{array_STC} \times H_{tilt}$$

Where

H_{tilt} = yearly average daily irradiation, in kWh/m²
for the specified tilt angle

P_{array_STC} = rated output power of the array
under standard test conditions, in watts

Performance Ratio Example

The average daily PSH was 5. Therefore the yearly irradiation (or PSH) would be $5 \times 365 = 1825 \text{ kWh/m}^2$ (that is 1825 PSH).

The rated power of the array at STC is 2560 W_p (@ kWh/m^2)

Therefore the ideal energy from the array per year would be: $2.56 \text{ kW} \times 1825 \text{ h} = 4672 \text{ kWh}$

The AC energy from the solar array was 3303 Kwh per year.

Therefore the performance ratio is $3303/4672 = 0.71$

INVERTER SELECTION

The selection of the inverter for the installation will depend on:

- The energy output of the array
- The matching of the allowable inverter string configurations with the size of the array in kW and the size of the individual modules within that array
- Whether the system will have one central inverter or multiple (smaller) inverters

INVERTER SIZING

Inverters currently available are typically rated for:

- Maximum DC input power. i.e. the size of the array in peak watts;
- Maximum DC input current; and
- Maximum specified output power. i.e. the AC power they can provide to the grid;

Inverter Sizing Example

The array comprises 16 of the $160W_p$ crystalline modules.

Therefore the array peak power = 16×160
= 2.56kW

Should the inverter be rated 2.56kW?

Inverter with Crystalline Module

Based on figures of :

- 0.95 for manufacturer,
- 0.95 for dirt and
- 0.85 for temperature (Based on ambient temperature of 30° C)

The derating of the array is: $0.95 \times 0.95 \times 0.85 = 0.77$

MATCHING ARRAY VOLTAGE TO THE MAXIMUM AND MINIMUM INVERTER OPERATING VOLTAGES

TEMPERATURE EFFECT ON ARRAY VOLTAGE

The output power of a solar module is affected by the temperature of the solar cells.

This variation in power due to temperature is also reflected in a variation in the open circuit voltage and maximum power point voltage.

VOLTAGE WINDOWS OF INVERTERS

- With the odd exception grid interactive inverters include Maximum Power Point (MPP) trackers.
- Many of the inverters available will have a voltage operating window.
- If the solar voltage is outside this window the inverter might not operate or the output of the solar array might be greatly reduced.
- In the case where a maximum input voltage is specified and the array voltage is above the maximum specified then the inverter could be damaged.

Minimum Voltage of Inverter

- When the temperature is at a maximum then the Maximum Power Point (MPP) voltage (V_{mp}) of the array should never fall below the minimum operating voltage of the inverter.
- It is recommended that maximum effective cell temperature of 70°C is used.

Minimum Voltage of Inverter

Example

The module selected has a rated MPP voltage of 35.4V and a voltage (V_{mp})co-efficient of-0.177V /°C.

An effective cell temperature of 70°C is 45° above the STC temperature of 25°C.

Therefore the V_{mp} voltage would be reduced by $45 \times 0.177 = 7.97V$

The V_{mp} @ 70°C would be $35.4 - 7.97 = 27.4V$

Example Cont

If we assume a maximum voltage drop in the cables of 3% then the voltage at the inverter for each module would be

$$0.97 \times 27.4 = 26.6 \text{ V}$$

This is the effective minimum MPP voltage input at the inverter for each module in the array.

Minimum Voltage of Inverter

Example Cont 2

Assume that the minimum voltage window for an inverter is 140V.

Recommended that a safety margin of 10% is used.

Minimum inverter voltage of $1.1 \times 140V = 154V$ should be used.

The minimum number of modules in a string is
 $= 154 / 26.6 = 5.79$ rounded up to 6 modules

Maximum Voltage of Inverter

At the coldest daytime temperature the open circuit voltage of the array shall never be greater than the maximum allowed input voltage for the inverter. .

Therefore the lowest daytime temperature for the area where the system is installed shall be used to determine the maximum V_{oc} .

Maximum Voltage of Inverter

Example

assume the minimum effective cell temperature is 15°C , with the open circuit voltage (V_{oc}) of 43.2 V and a voltage (V_{oc})co-efficient of $-0.14\text{V}/^{\circ}\text{C}$.

An effective cell temperature of 15°C is 10° below the STC temperature of 25°C .

Therefore the V_{oc} voltage would be increased by $10 \times 0.14 = 1.4\text{V}$

The V_{oc} @ 15°C would be $43.2 + 1.4 = 44.6\text{V}$

Maximum Voltage of Inverter

Example Cont

Assume the maximum voltage allowed by the inverter is 400V.

The maximum number of modules in the string, is

$$= 400 / 44.6 = 8.96$$

rounded down to 8 modules

.

Array Solution for Example

we required 16 modules. Therefore we could have two parallel strings of 8 modules.

Effect of Shadows

In towns and cities where grid connect systems will be predominant the roof of the house or building will not always be free of shadows during parts of the day.

Care should therefore be taken when selecting the number of modules in a string because the shadow could result in the maximum power point voltage at high temperatures being below the minimum operating voltage of the inverter.

End of Presentation

