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PV INSTITUTE**

Australian Technical Guidelines for Monitoring and Analysing Photovoltaic Systems

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Jessie Copper¹, Anna Bruce¹, Ted Spooner², Martina Calais³, Trevor Pryor³ and Muriel Watt¹

¹School of Photovoltaic and Renewable Energy Engineering, University of NSW

²School of Electrical Engineering and Telecommunications, University of NSW

³School of Engineering and Information Technology, Murdoch University

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ARENA



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Energy Agency**

GUIDELINE PREPARATION AND CONTACT INFORMATION

Guideline Prepared For:

The Australian Photovoltaic
Institute (APVI)
www.apvi.org.au

Contact:

Muriel Watt
APVA Chair
Chair@apvi.org.au

Guideline Prepared By:

Jessie Copper, Anna Bruce and Muriel Watt, School of Photovoltaic and Renewable Energy Engineering, University of NSW

Ted Spooner, School of Electrical and Telecommunications Engineering, University of NSW

Martina Calais and Trevor Pryor, School of Engineering and Information Technology, Murdoch University

Guideline Reviewed By:

Lyndon Frearson and Paul Rodden, CAT Projects
and additional anonymous reviewers

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Energy Agency**

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1 Executive Summary

Monitoring of photovoltaic systems is required for the detection of operational issues, and to compare the performance of different systems across a range of technologies and climates. Performance and reliability data can therefore facilitate appropriate system design and technology choice, and in the long term, establish credible expectations about PV system performance.

The purpose of this guideline is to provide recommendations for monitoring and analysis of the performance and reliability of flat plate grid connected photovoltaic (PV) systems in Australia.

This guideline was developed primarily with reference to the following documents, with adaptations for current and emerging needs and Australian conditions:

- IEC Standard 61724: Photovoltaic system performance monitoring – Guidelines for measurement, data exchange and analysis
- European Commission 6th Framework Programme: Monitoring guidelines for photovoltaic systems

This document offers guidance on which parameters should be measured, how they should be measured and the frequency of measurement for the following seven uses of PV performance and reliability data:

1. Performance assessment of PV technologies under outdoor conditions
 - a. Basic monitoring
 - b. Detailed monitoring
2. Performance diagnostics
3. Degradation and uncertainty analysis with time
4. Understanding/reducing system losses via comparisons to modelled performance data
5. Forecasting PV performance
6. Interaction of PV systems with the electricity network
7. Integration of distributed generation, storage and load control

Table 6-1 (reproduced below) identifies which parameters should be measured for each of the applications 1-7 listed above, together with their recommended sensor accuracy.

Table 6-1: List of parameters to be measured and recommended sensor accuracy as per IEC 61724

Parameter	Symbol	Unit	1a	1b	2	3	4	5	6	7	Recommended Minimum Sensor Accuracy
In-plane irradiance	G	W/m ²	X	X	X	X	X	X	X		5%
Ambient air temperature	T _{am}	°C		X	X	X	X	X			1°C
Wind speed	WS	m/s		X	X	X	X	X			0.5 m/s for WS<5m/s ±10% for WS>5m/s
Array voltage	V _A	V		X	X	X	X	X	X	X	1%
Array current	I _A	A		X	X	X	X	X	X	X	1%
Array power	P _A	kW		X	X	X	X	X	X	X	2%
Module temperature ²	T _m	°C		X	X	X	X				1°C
Load voltage	V _L	V								X	1%
Load current	I _L	A								X	1%
Load power	P _L	kW								X	2%
Utility voltage	V _U	V			X				X	X	1%
Current to utility grid	I _{TU}	A			X				X	X	1%
Power to utility grid	P _{TU}	kW	X	X	X	X	X	X	X	X	2%
Power from utility grid	P _{FU}	kW							X	X	2%

In order to assist selection of measurement device, Table 6-2 (reproduced below) ranks the performance of different types of measurement sensors for a number of the measurement parameters listed in Table 6-1, highlighting the relative performance of the sensor types, and as appropriate to different monitoring budgets.

Table 6-2: List of parameters and type of measurement device ranked by budget and analysis option [1]

Parameter	Sensor Type	Small	Budget	Large		
		Limited	Analysis Options ¹	Significant		
Meteorology						
1.1.1.1 In-plane irradiance ²	Thermopile Pyranometer					X
	Same-Technology Reference Cell/Module			X	X	X
	Silicon Photodiode Pyranometer	X	X	X	X	
Global horizontal irradiance	Thermopile Pyranometer					X
	Silicon Photodiode Pyranometer			X	X	
Ambient air temperature	Thermocouple, RTD, Thermistor	X	X	X	X	X
Wind speed	Ultrasonic Anemometer				X	X
	Cup Anemometer		X	X		
Photovoltaic Array						
a.c. Energy Generation ³	NMI Class 1 or Class 0.5 energy meter [2]			X	X	X
	Collected from Inverter	X	X	X	X	X
d.c. Energy Generation ³	External Current and Voltage Transducers					X
	Collected from Inverter	X	X	X	X	X
Inverter Status and Errors	Collected from Inverter	X	X	X	X	X
Module Temperature	Thermocouple, RTD, Thermistor		X	X	X	X

¹ Systems which collect higher quality data from a greater variety of sensors allows for more significant analysis and have a greater benefit to PV performance and reliability research.

² The response time of thermopile pyranometers is in the range of 5-30 seconds. Thermopile pyranometers have better accuracy, but slower response times than the same-technology reference cells to changing irradiance conditions.

³ The collection of both inverter and external energy generation data in the large budget scenario allows for comparisons between these two device types.

Table 6-3 suggests appropriate sampling intervals (τ_r) and monitoring periods for each application of monitoring data.

Table 6-3: List of recording interval per use of measured PV data

Use	Use of Measured PV Data	(τ_r)	Monitoring period
1	Performance assessment of PV technologies under outdoor conditions	Max 15 min	Min 1 year
2	Performance diagnostics	Hourly	System lifetime
3	Degradation and uncertainty analysis with time	Hourly	Min 3-5 years
4	Understanding/improving system losses via comparisons to modelled performance data	Hourly	Min 1 year
5	Forecasting PV performance	5min, 30min or hourly**	Min 1 year
6	Interaction of PV systems with the electricity network	1 to 15min**	Min 1 week
7	Integration of distributed generation and load control	1 to 15min**	Min 1 week

** Note: In some applications the recording interval will need to be significantly shorter dependent on the specific nature of the investigation required.

A step by step process in determining the most appropriate monitoring strategy is also provided within this guideline (summarised in the diagram reproduced below).

Step 1: Determine the end use of the measured PV data.

Step 2: Determine the system parameters that should be monitored from Table 6-1, based on selected end use of PV data. Note: All parameters should be monitored if the end use of the measured PV data is unknown.

Step 3: Define the level of accuracy required.
This guideline recommends the sensor accuracy as specified by IEC61724 (Table 6-1). Otherwise sensor type can be defined by budget or sensor type as ranked (Table 6-2).

Step 3: Determine the recording and monitoring intervals required from Table 6-3, based on selected end use of PV data. Note: A recording interval of 5mins over the system lifetime should be implemented if the end use of the measured PV data is unknown.

Procedures for reliability monitoring and recording of data are specified, including a list of events that should be logged, and recommended routine maintenance checks.

The guideline also gives information on how monitored data can be used to identify and diagnose performance and reliability issues within a PV system. Table 8-1 lists performance indices and other derived parameters that are defined within the guideline.

Table 8-1: List of derived parameters

Parameter	Symbol	Unit
Meteorology		
Global irradiation, in the plane of the array	H	kWh/m ²
Electrical Energy Quantities		
Energy from the Array	E _A	kWh
Energy output to Utility grid or load	E _{out}	kWh
System Performance Indices		
Array d.c. energy yield	Y _A	kWh/kW
System a.c. energy yield	Y _f	kWh/kW
Reference solar yield	Y _r	kWh/kW
Array capture losses	L _c	h/d
Performance ratio	PR	
Array d.c. energy efficiency	η _A	
PV system a.c. energy efficiency	η _{pv}	

The guideline describes appropriate use of these performance indices and derived quantities; instructions for checking data quality and for performing basic graphical performance analysis.

It is hoped that these will encourage stakeholders to move toward a common platform that delivers data that is useful, comparable, and of sufficient quality for performance assessment and forecasting, grid integration and other uses.

2 Scope and Objectives

The purpose of this guideline is to provide recommendations for monitoring and analysis of the performance and reliability of flat plate grid connected photovoltaic (PV) systems. It does not cover issues specifically associated with stand-alone, tracking, concentrator or building integrated¹ PV systems. Appropriate parameters to measure, accuracy and frequency of measurement vary for different applications of PV performance and reliability data. This document offers guidance on which parameters should be measured, how they should be measured and the frequency of measurement for the following 7 uses of PV performance and reliability data.

1. Performance assessment of PV technologies under outdoor conditions
 - Either basic or detailed monitoring
2. Performance Diagnostics
3. Degradation and uncertainty analysis with time
4. Understanding/reducing system losses via comparisons to modelled performance data
5. Forecasting PV performance
6. Interaction of PV systems with electricity networks
7. Integration of distributed generation, storage and load control

A step by step process for determining the most appropriate monitoring strategy is provided. Procedures for the analysis of monitored data in order to identify and diagnose performance and reliability issues within a PV system are provided, including agreed definitions for performance indices and other derived parameters; appropriate use of these; instructions for checking data quality and for performing basic graphical performance analysis.

¹ Within this guideline building integrated PV systems refers to PV systems where the PV modules within the system perform additional functions in addition to generating electricity. The design of building integrated systems may compromise on the PV performance to obtain other benefits from the system which would require additional measurement metrics to ascertain both the performance of the PV system electrically and with regards to other functions. PV systems that are mounted on existing building structures are not considered to be building integrated, and hence are covered by the content within this guideline.

3 Guidelines and Normative References

This guideline was developed primarily with reference to the following documents, with adaptations for current and emerging needs and Australian conditions:

- **IEC Standard 61724: Photovoltaic system performance monitoring – Guidelines for measurement, data exchange and analysis**
- **European Commission 6th Framework Programme: Monitoring guidelines for photovoltaic systems**

The following documents, have also been used as references:

- DERlab TG 100-01: Technical guidelines on long-term photovoltaic module outdoor tests
- IEC 60904-2: Photovoltaic devices – Part 2: Requirements for reference solar devices
- IEC 60904-6: Photovoltaic devices – Part 6: Requirements for reference solar modules
- IEC 61215: Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval
- IEC 61829: Crystalline silicon photovoltaic (PV) array – On-site measurement of I-V characteristics
- NMI M 6-1 Electricity Meters Part 1: Metrological and Technical Requirements.
- WMO, No. 8: Guide to meteorological Instruments and Methods of Observation: (CIMO guide)

4 Nomenclature

Symbol	Description	Unit
A_a	Active area of PV array	m^2
A_{MD}	Availability of monitored data	%
AST	Apparent solar time (BRL separation model)	
d_t	Diffuse fraction (BRL separation model)	
E_A	Energy from the PV array	kWh
E_{out}	Energy output to Utility grid or load	kWh
G	In-plane irradiance	W/m^2
H	Irradiation	kWh/m^2
I_A	PV array output current	A
I_L	Load current	A
I_{TU}	Current to the utility grid	A
I_{bn}	Direct normal solar irradiance (Perez transposition model (PTM))	W/m^2
I_h	Global horizontal solar irradiance (PTM and BRL)	W/m^2
$I_{h,b}$	Direct normal component of solar irradiance on a horizontal surface (PTM)	W/m^2
$I_{h,d}$	Global diffuse horizontal irradiance (PTM and BRL)	W/m^2
I_{on}	Direct extraterrestrial normal irradiance (PTM and BRL)	W/m^2
k_t	Hourly clearness index (BRL separation model)	
K_t	Daily clearness index (BRL separation model)	
L_c	Array capture losses	kWh/kW
L_{BOS}	Balance of system losses	kWh/kW
P_A	PV array output power	kW
P_L	Load power	kW
P_0	Rated output power of the array under standard test conditions ²	kW
P_{FU}	Power from the utility grid	kW
P_{TU}	Power to the utility grid	kW
PR	Performance ratio	
T_{am}	Ambient air temperature	$^{\circ}C$
T_c	Cell temperature (PVsyst cell temperature model)	$^{\circ}C$
T_m	Module temperature	$^{\circ}C$
U_o	Constant component of heat transfer (module temperature models)	$W/m^2.K$

² Standard test conditions for rating photovoltaic modules are defined in IEC61215

Symbol	Description	Unit
U_1	Convective component of heat transfer (module temperature models)	W/m ² .K
V_A	PV array output voltage	V
V_L	Load voltage	V
V_U	Utility voltage	V
WS	Wind speed	m/s
Y_A	PV array d.c. energy yield over a defined period	kWh/kW
Y_f	System a.c. energy yield over a defined period	kWh/kW
Y_r	Reference solar yield over a defined period	kWh/kW
α	Absorption coefficient (PVsyst cell temperature model)	
α_s	Solar altitude angle (PTM)	
β	Surface tilt angle of PV system from horizon (PTM)	
γ	Orientation of the PV system (PTM)	
γ_s	Solar azimuth angle (PTM)	
η_A	Array d.c. energy efficiency	
η_m	Module efficiency (PVsyst cell temperature model)	
η_{PV}	PV system a.c. energy efficiency	
θ	Incident angle of the PV surface plane (PTM)	
θ_z	Solar zenith angle (PTM)	
ρ	Hemispherical ground reflectance (PTM)	
τ	Reporting period	hours
τ_{MA}	Duration of monitoring activity producing useable/valid data	hours
τ_r	Recording interval	hours
τ_s	Sampling interval	seconds
ψ	Persistence of global horizontal irradiance (BRL separation model)	

5 Applications of PV System Monitoring

This section of the guideline outlines the applications of monitoring PV performance and reliability that are covered in the scope of this guideline. PV performance monitoring generally involves the measurement and recording of the electrical output (primarily a.c. power but d.c. power is also often recorded) of the PV system in conjunction with other parameters such as voltage, current, irradiance, dry bulb temperature, humidity, wind speed and direction and module temperature. On the other hand, monitoring the reliability of PV systems generally involves the upkeep of a maintenance log which records items like the type and frequency of system failures, cause of failure, downtime, scheduled and unscheduled maintenance and the replacement of system components. Measuring and recording these parameters enables system owners to diagnose issues that result in the loss of system performance and reliability. Data collected for performance and reliability monitoring can also be used by researchers and other stakeholders to study a broad range of issues related to PV performance, reliability and integration with energy systems. However, some applications require specific parameters to be measured, measurements to be taken at high frequency, or with an accurate sensor.

- 1) Although the following list is not exhaustive, this guideline is structured around 7 common uses of PV system performance and reliability data, which require differing levels of measurement complexity, as outlined in the Measurement Specifications. The 7 uses are:**Performance assessment of PV technologies under outdoor conditions**
 - a. Basic monitoring – Measured AC power and plane of array irradiance can be used to track the basic performance of a PV system and determine when underperformance has occurred. Fault diagnostics cannot be conducted via basic monitoring.
- 2) Detailed monitoring– Measured PV performance data can be used to assess product quality and the influence of variables such as climatic factors on the performance of different technologies and products.**Performance diagnostics** – Measured PV performance and reliability data can be used to identify when a system is underperforming and the likely cause.
- 3) **Degradation and uncertainty analysis with time** – PV performance data across a number of years (minimum 3-5 years, depending on method used for analysis) can be used to determine the extent of PV performance degradation over time and to identify factors influencing the rate of degradation of different module technologies.
- 4) **Understanding/reducing system losses via comparisons to modelled performance data** – PV system performance models calibrated to measured PV data can be used to investigate the influence on system performance of a number of design, installation and climate factors, including inverter size and partial shading effects. Conversely, accurate and comprehensive system performance data from PV systems can be used to validate PV performance models.
- 5) **Forecasting PV performance** – Forecasting of PV system performance in both the short and long term can be used to predict and manage PV system interactions with electricity networks and markets. Forecasting methods are generally based on characterisation of historical performance of a system or an aggregated cluster of systems under varying climatic and operational scenarios, and then use irradiance and weather forecasts for prediction.
- 6) **Interaction of PV systems with the electricity network** – Measured PV data can be used in conjunction with network models to understand the impact of PV systems on power quality, reliability and protection in electricity systems, including modelling the effects of injection into networks, voltage regulation, stability issues and reactive power control. In this area in particular, sampling and recording rates need to be tailored to the desired data use. Most

challenging in terms of PV data requirements is the study of variability of PV output over very short timeframes, and spatially across large systems or a number of distributed systems, which enables assessment of the impact of climatic effects like sharp cloud boundaries on the stability of the generated power.

- 7) **Integration of distributed generation, storage and load control** – Monitored PV data can be used to examine issues related to the combination of PV systems with other distributed energy technologies into electricity systems. Monitored PV data may be used to assess the need for energy storage and/or load shifting to allow higher values of penetration.

Each of the above mentioned uses of PV data require different levels of measurement complexity. This guideline provides details on the parameters and frequency of measurement for each of the above listed uses of PV data.

6 Measurement Specifications

Table 6-1 provides a list of parameters for PV system monitoring, together with their recommended sensor accuracy, as specified in IEC 61724. The table also highlights the parameters that should be measured for each of the seven uses of PV data listed in section 5. Further recommendations on the measurement of each parameter are provided in the following sections. Parameters to be measured are shown in Figure 6-1 for a) all parameters and b) for the basic monitoring system (listed as 1b in Table 6-1).

Table 6-1: List of parameters to be measured and recommended sensor accuracy as per IEC 61724

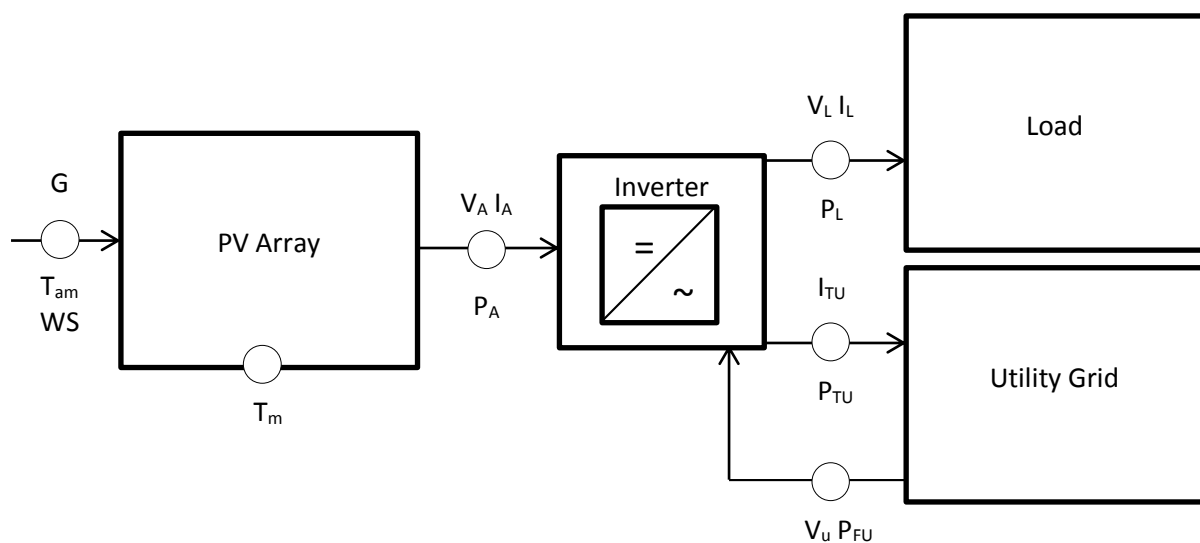
Parameter	Symbol	Unit	1a	1b	2	3	4	5	6	7	Recommended Minimum Sensor Accuracy
In-plane irradiance ¹	G	W/m ²	X	X	X	X	X	X	X		5%
Ambient air temperature	T _{am}	°C		X	X	X	X	X			1°C
Wind speed ²	WS	m/s		X	X	X	X	X			0.5 m/s for WS<5m/s ±10% for WS>5m/s
Array voltage	V _A	V		X	X	X	X	X	X	X	1%
Array current	I _A	A		X	X	X	X	X	X	X	1%
Array power	P _A	kW		X	X	X	X	X	X	X	2%
Module temperature ²	T _m	°C		X	X	X	X				1°C
Load voltage	V _L	V								X	1%
Load current	I _L	A								X	1%
Load power	P _L	kW								X	2%
Utility voltage	V _U	V			X				X	X	1%
Current to utility grid ⁴	I _{TU}	A			X				X	X	1%
Power to utility grid ⁴	P _{TU}	kW	X	X	X	X	X	X	X	X	2%
Power from utility grid ⁴	P _{FU}	kW							X	X	2%

¹ In-plane irradiance, also known as total irradiance, is defined as the sum of direct, diffuse and reflected irradiance, incident upon unit area of an inclined surface.

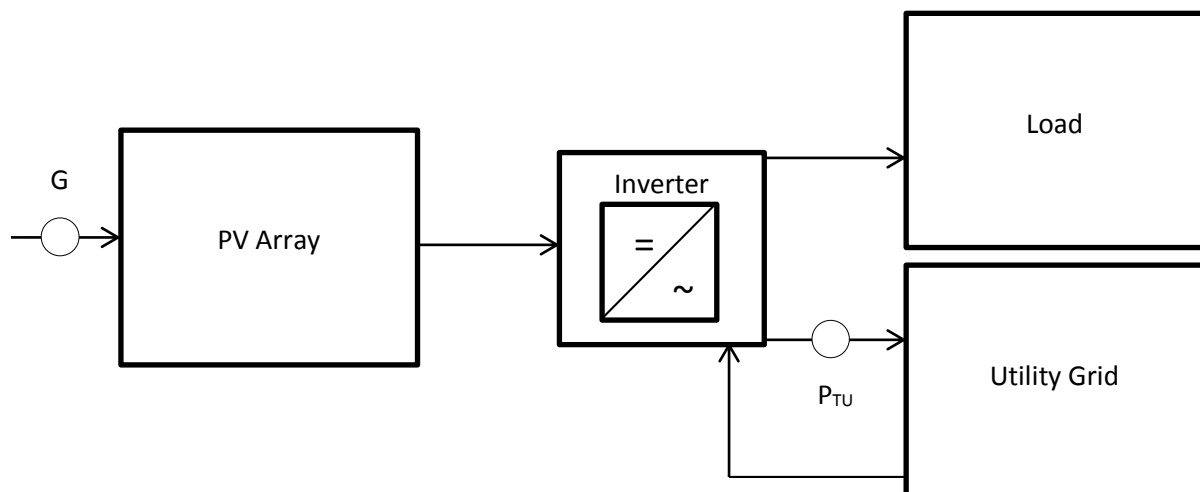
² Parameters such as wind speed and module temperature are optional for most uses of PV data, but may be required by special contract or if the PV array is subject to extreme operating conditions.

³ a.c. and d.c. quantities may be distinguished by the addition of a.c. or d.c. subscripts. In the case of multi-phase systems, parameters V_L , I_L and P_L should be specified for each phase. In the case of large systems with multiple strings, sub arrays or inverters, d.c. and a.c. string/sub array/inverter current, voltage and power should be measured and applied with subscripts 1 ...n.

⁴ A single current or power sensor can normally be used for the measurement of current and/or power for directions of both input and output. A positive sign for the power measurement represents input to the utility grid and a negative sign represents power drawn from the utility grid. Further, it should be noted that any of the power parameters can be calculated from the measured data of current and voltage in real time by the data acquisition software, and does not necessarily require additional sensors to measure these parameters.



a) PV System with all listed measurement parameters



b) PV System with basic monitoring parameters

Figure 6-1: Parameters to be measured for a) all parameters and b) basic monitoring

Table 6-2 Ranks the performance of different types of measurement sensors for a number of the measurement parameters listed in Table 6-1. The table, sourced from [1], highlights the relative performance of the sensor types, and correspondence with relative monitoring budget.

Table 6-2: List of parameters and type of measurement device ranked by budget and analysis option [1]

Parameter	Sensor Type	Small	Budget	Large		
		Limited	Analysis Options ¹	Significant		
Meteorology						
In-plane irradiance ²	Thermopile Pyranometer					X
	Same-Technology Reference Cell/Module			X	X	X
	Silicon Photodiode Pyranometer	X	X	X	X	
Global horizontal irradiance	Thermopile Pyranometer					X
	Silicon Photodiode Pyranometer			X	X	
Ambient air temperature	Thermocouple, RTD, Thermistor	X	X	X	X	X
Wind speed	Ultrasonic Anemometer				X	X
	Cup Anemometer		X	X		
Photovoltaic Array						
a.c. Energy Generation ³	NMI Class 1 or Class 0.5 energy meter [2]			X	X	X
	Collected from Inverter	X	X	X	X	X
d.c. Energy Generation ³	External Current and Voltage Transducers					X
	Collected from Inverter	X	X	X	X	X
Inverter Status and Errors	Collected from Inverter	X	X	X	X	X
Module Temperature	Thermocouple, RTD, Thermistor		X	X	X	X

¹ Systems which collect higher quality data from a greater variety of sensors allows for more significant analysis and have a greater benefit to PV performance and reliability research.

² The response time of thermopile pyranometers is in the range of 5-30 seconds. Thermopile pyranometers have slower response times than the same-technology reference cells/module to changing irradiance conditions.

³ The collection of both inverter and external energy generation data in the large budget scenario allows for comparisons between these two device types.

This guideline recommends that measurement sensors should be selected to meet IEC 61724, particularly for larger PV systems. However lower quality sensors or alternate data sources, particularly for the measurement of the meteorology parameters, may be the only option for

smaller PV systems with lower performance monitoring budgets. It should be noted that use of monitored performance data from systems with higher quality sensors is more valuable for research purposes and improves performance diagnostic capabilities.

Where the inverter has data collection functionality built in, it is important to compare the accuracy of the measurement sensors with the recommendations given here. Modern inverters commonly have capabilities to measure the d.c. and a.c. voltage, current and power from the PV array and power imported from and exported to the grid. This facility may reduce the need for additional sensors and hence the cost of a monitoring system, however the accuracy of the measurement undertaken by the Inverter should be checked against the requirements of IEC 61724. Most modern day inverters do not meet IEC 61724 requirements, hence inverter monitoring will reduce the ability to identify system performance issues. Monitoring of voltage, current and power parameters via an inverter is not recommended if financial decisions/calculations are required from the monitored data for contractual agreements.

6.1 Irradiance

The electrical output of photovoltaic systems is directly correlated to the incident level of irradiance on the surface of the modules. To effectively determine whether the PV system is operating according to design it is essential to have a measurement of the level of irradiance. The definition of irradiance is the instantaneous measurement of solar power on a surface in W/m^2 , whilst irradiation is the sum of solar energy on the surface over a defined period in Wh/m^2 or kWh/m^2 .

For the most rigorous measurements, it is recommended that in-plane irradiance is measured according to IEC 61724. This requires the measurement of irradiance in the same plane as the photovoltaic array by means of a calibrated reference device or pyranometer. If used, reference devices should be calibrated and maintained in accordance with IEC 60904-2 or IEC 60904-6 as appropriate and, where possible, should be spectrally matched to the monitored PV array. The accuracy of the irradiance sensors, including signal condition, according to IEC 61724 should be better than 5%.

The type of sensor used to measure irradiance is largely dependent on the level of monitoring accuracy required and the budget specified for the monitoring system. Table 6-2 ranks the performance of different types of measurement sensors for a number of the measurement parameters listed in Table 6-1. The table, sourced from [1], highlights the relative performance of the sensor types, and correspondence with relative monitoring budget. It should be noted that although the thermopile pyranometers are the most accurate sensors listed in Table 6-2, they have slower response times to changes in irradiance conditions (between 5-30 seconds) in comparison to the same-technology reference devices and PV modules. The choice of irradiance sensor is therefore also dependent on the use of the measured data. Research presented in [3, 4] recommends that thermopile pyranometers should be used for PV performance monitoring. However same-technology reference devices would be the preferred method of irradiance measurement if variability effects of PV are to be investigated (use 6 in Table 6-3).

On-site measurements of irradiance will provide the highest level of accuracy, providing that appropriate calibration, installation and maintenance procedures of the sensors are carried out. Many high quality pyranometers require periodic calibration (approximately every 2 years) which often entails sending the pyranometers away to be calibrated. Such issues must be considered in maintenance planning if data gaps are to be avoided.

Regardless of sensor type and accuracy, the location of any measurement sensor should be representative of the irradiance conditions of the array. The sensor should be co-planar with the modules of the array with a maximum deviation of 2° . The sensor should be positioned where it is unshaded at all times (regardless of whether the PV array is partially shaded at any time) and in a location where it can be accessed for cleaning at regular intervals.

6.1.1 Alternative Methods to Obtain Irradiance Data

This guideline recommends that measurement sensors should be selected to meet IEC 61724, particularly for larger PV systems. However lower quality sensors or alternate data sources, particularly for the measurement of the meteorology parameters, may be the only option for smaller PV systems with lower performance monitoring budgets. It should be noted that use of monitored performance data from systems with higher quality sensors is more valuable for research purposes and improves performance diagnostic capabilities.

For smaller PV systems (typically smaller than 5kWp), in-plane irradiance may be either (1) measured on site (recommended method), (2) measured at another location chosen to be representative or (3) derived from remote measurements and/or synthesised from a combination of ground measured irradiance data and satellite data (e.g. the Australian Bureau of Meteorology gridded solar data set), depending on the accuracy requirements.

Use of satellite derived irradiance data may be used to infer in-plane irradiance for small PV systems where the expense and technical requirements of installing and maintaining on-site irradiance sensor(s) cannot be justified. Satellite derived irradiance is typically reported for a horizontal plane; hence a recognised method of translation to irradiance in the plane of the array must be used. The recommended method for this translation is the Perez model [5, 6] which is detailed in the appendices. It should also be noted that reduced accuracy resulting from estimates of in-plane irradiance via a transposition model, and particularly if satellite derived horizontal irradiance is used as input into the transposition model, will reduce its usefulness, for instance for identifying system loss factors. In addition satellite derived irradiance is unlikely to be reported at a measurement frequency less than an hour.

Note: On-site measurement of in-plane irradiance is the recommended option regardless of system size.

6.2 Ambient air temperature

Ambient air temperature, measured in degrees Celsius ($^{\circ}\text{C}$), in conjunction with in-plane irradiance and wind speed are typically used in PV performance monitoring and modelling to estimate module efficiency losses due to changes in module temperatures in comparison to standard test conditions (25°C).

Again, for the most rigorous level of measurement, it is recommended that ambient air temperature should be measured according to IEC 61724. This requires that ambient temperature should be measured at a location that is representative of the array conditions, by means of temperature sensors housed in solar radiation shields. Radiation shields are required in order to ensure that the temperature sensor measures the air temperature only and is not heated by direct irradiance from the sun or cooled due to wind effects. Temperature sensors should be positioned away from any heat sources and, where possible, at least 1m above the ground. The DERlab TG 100-01 guideline recommends a position of 2m above the ground. The accuracy of air temperature sensors, including signal conditioning, according to IEC 61724 should be better than 1°C .

6.3 Wind speed

Wind speed, measured in m/s, affects the performance of PV systems by increasing convective heat loss, and reducing the temperature of the PV modules. Wind speed is a less significant determinant of system performance than ambient temperature, and it is thus a less important parameter to measure; however it is a useful parameter to improve the accuracy of module temperature estimates and therefore system performance analysis if on-site measurements of module temperatures are not recorded. Wind speed should be measured if the array is subjected to extreme weather conditions.

Again, for the most rigorous level of measurement, it is recommended that wind speed be measured according to IEC 61724. This requires that wind speed should be measured at a height and location that is representative of the array conditions. The accuracy of wind speed sensors should be better than 0.5m/s for wind speeds $\leq 5\text{m/s}$, and better than 10% of the measurement for wind speeds $> 5\text{m/s}$. Ideally installation of a wind speed sensor (anemometer) should be, according to IEC 61215, at 1.2m distance on the East or West side of the system and at 0.7m above the upper edge of the system.

6.4 Module temperature

Module temperature, measured in degrees Celsius ($^{\circ}\text{C}$), is a recommended measurement parameter, as the performance of PV systems is directly correlated to the operating temperature of the modules. The impact of module temperature on PV system performance is dependent on the PV technology employed in the system. Typically crystalline and multi-crystalline silicon technologies suffer significant performance losses due to temperature effects.

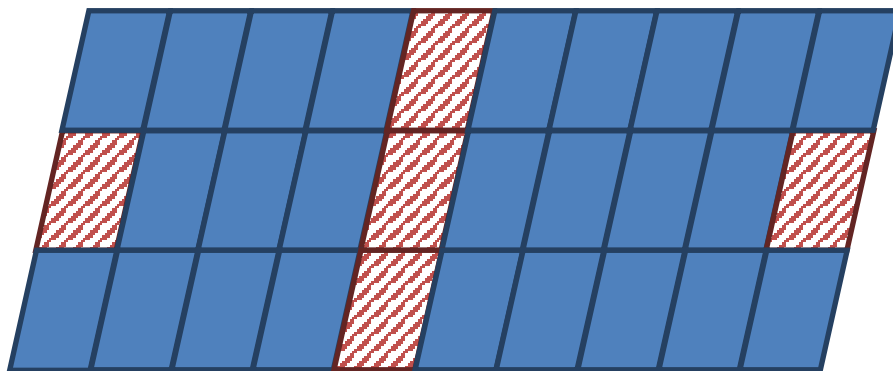
Again for the most rigorous level of measurement, it is recommended that module temperature be measured according to IEC 61724. This requires that module temperature should be measured at locations which are representative of the array conditions by means of temperature sensors located on the back surface of one or more modules. It is noted that care must be taken to ensure that the temperature of the cell in front of the sensor is not substantially altered due to the presence of the sensor. The accuracy of these sensors, including signal processing, according to IEC 61724 should be better than 1°C .

For larger systems or systems that could potentially suffer temperature stratification effects it is recommended that the measurement of module temperature is undertaken across a number of representative modules within the system. The mean of all measurements should then be calculated to give a better representation of the temperature effects of the PV system as a whole. Figure 6-2 presents examples of the recommended representative measurement positions within three typical PV system layouts.

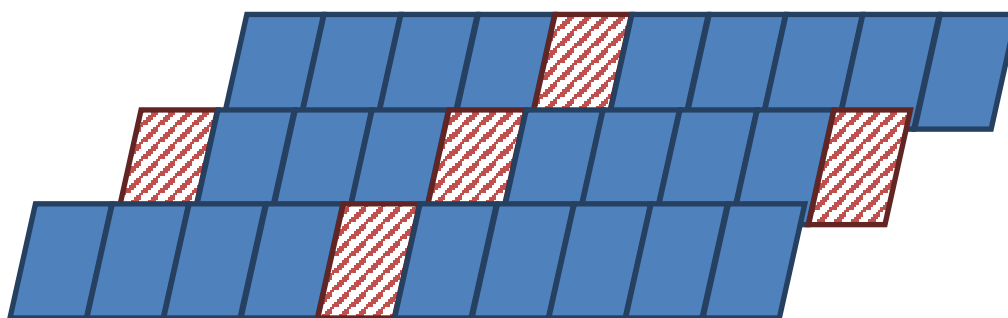
In the absence of measured module temperature(s), ambient air temperature and in-plane irradiance can be used to estimate module temperature. The addition of measured wind speed can be used to further improve the accuracy of the estimation. The appendices provide details of the Sandia and Faiman module temperature models that can be used to estimate module temperature.



c) PV System with one long row of modules. Temperature stratification may occur across the length of the row



d) PV System with multiple stacked rows of modules. Temperature stratification may occur across the length of the row and the height of the system.



e) PV System with multiple staggered rows of modules. Temperature stratification may occur across the length of the rows and may differ between rows.

Figure 6-2: Examples of representative module temperature measurement positions in three different system configurations

6.5 Voltage, Current and Power

Measurement of a.c. and d.c. voltage, current and power are the most important parameters for PV system performance monitoring. These parameters can be used, in combination with irradiance measurements, to directly determine when a PV system is underperforming. For large PV systems where the array is comprised of a number of sub-arrays (systems or strings), it is beneficial to measure the a.c. and d.c. parameters of each sub-array separately, which enables faults to be more easily isolated. The number of sub-arrays to be measured depends on the level of diagnostic capability desired. The total output of the array must always be measured.

The measurement of d.c. parameters allows for additional diagnostic capabilities when a system fault is detected. For example the ratio of d.c. to a.c. power is a measurement of the inverter efficiency, while d.c. power can also be used to calculate the array yield and is the parameter

recommended for use in PV degradation rate calculations. In addition measurements of d.c. voltage can be compared to the theoretical d.c. voltage of the system/string to check for shunting (diagnostic of potentially induced degradation (PID)). On the a.c. side, the measurement of a.c. power in addition to a.c. current and voltage can be used to obtain a basic estimate of the power factor. In addition the a.c. voltage (i.e. the utility voltage) can be used within system diagnostics to determine whether an inverter driven system failure was caused via high or low voltage trip points.

Power can either be calculated in real time as the product of sampled voltage and current quantities or measured directly using a power sensor. It is recommended that power be measured directly, however if power is calculated from the product of voltage and current, the calculation must use the simultaneously sampled voltage and current quantities and not averaged voltage and current quantities. Under this scenario particular attention must be given to the sampling interval of the measured voltage and current parameters.

Again for the most rigorous level of measurement, it is recommended that voltage, current and power be measured according to IEC 61724. This requires that the accuracy of voltage and current sensors, including signal conditioning, should be better than 1%, whilst the accuracy of power sensors, including signal conditioning, should be better than 2%. Sensors should be selected to ensure they have a measurement range that is compatible with the output of the PV array (i.e. upper voltage limit $> 1.3 \times V_{oc}$ and upper current limit $> 1.5 \times I_{sc}$) and selected to have minimal impact on the electrical operation of the array. Where monitoring is being conducted to validate output as required under a Power Purchase Agreement, or similar investment requirement, Class 1 and Class 0.5 energy meters, as defined by the Australian National Measurement Institute Electricity Meters Metrological and Technical Requirements [2], are appropriate for measuring a.c. voltage, current and power.

Note: Modern inverters commonly have capabilities to measure the d.c. and a.c. voltage, current and power from the PV array and power imported from and exported to the grid. This facility may reduce the need for additional sensors and hence the cost of a monitoring system, however the accuracy of the measurement undertaken by the Inverter should be checked against the requirements of IEC 61724. Most modern day inverters do not meet IEC 61724 requirements, hence inverter monitoring will reduce the ability to identify system performance issues. Monitoring of voltage, current and power parameters via an inverter is not recommended if financial decisions/calculations are required from the monitored data.

6.6 Measurement Sampling

Monitoring of PV performance and reliability involves the measurement of a number of individual parameters. The measurement of each of these parameters requires a sensor that provides an output that varies with the quantity being measured. The robustness of the measurement process is dependent not only on the accuracy of the measurement sensor but also on the data acquisition and conversion systems employed in the measurement process. In general the data acquisition and conversion process is dependent on the data sampling interval and any data filtering processes employed. This section of the document focuses on the issue of data sampling. Refer to [7] for further information on the principles of data acquisition and conversion.

This guideline recommends that the maximum sampling interval (τ_s) for all averaged parameters should be set at 1 second. Data can then be averaged and logged over the recording interval (discussed in the following section). In the case where power measurements are calculated from sampled currents and voltages the sampling interval needs to be significantly shorter than 1 second.

Note: Separate power transducers which calculate power and internally average it appropriately for the sampling interval are one method of measuring average power at a specified accuracy. The resulting power measurement may then be sampled at a rate appropriate to the averaging period.

Alternatively, fast sampling and calculation of power by multiplying voltage and current and averaging is also a good method and can be done by many data acquisition systems.

The most important details to consider when determining sampling intervals and/or filtering are:

- the rate of change of the parameter to be measured;
- the use of the sampled data (for example whether the data will be used in further calculations that involve other sampled datasets, as is the case when calculating power from sampled current and voltage measurements); and
- the ultimate end use of the sampled data.

In some cases a sampling interval of 1 second may be longer than required. The sampling interval can be set lower than 1 second to increase the level of accuracy in the recorded data for uses that have very short recording intervals (τ_r). Such a scenario could occur if the PV data is being used to assess short term behaviour of PV systems under fast-varying irradiance caused by clouds, where the rate of change of irradiance and PV output can be significant over a period of seconds.

Note: Very high sampling rates of data can require significant data storage capabilities, particularly for long term studies.

The World Meteorological Office (WMO) recommends that irradiance observations should be made at a sampling interval (τ_s) less than $1/e$ (0.368) of the time-constant of the measurement instrument, where the time-constant of a sensor is the time taken, after a step change in the measured variable, for the instrument to register 63.2% of the step change in the measured parameter [8].

Another important factor when determining the sampling frequency is the aliasing error, which is the error associated with information lost by not taking a sufficient number of sampled data points. Figure 6-3 presents an example of a constant sinusoidal signal and the resultant first order reconstructed and zero order interpolation of the signal generated from the sampled data points. In this example the sample frequency used is inadequate to generate a true reflection of the underlying signal. Both the zero and first order interpolations would indicate that the underlying measured parameter has a variable moving average, which is not reflective of the constant moving average of the original signal. To avoid aliasing error the Nyquist sampling theorem suggests that a minimum of two samples per cycle of the data bandwidth (the data bandwidth is synonymous with the inverse of the time constant of a measurement instrument as referred to by the WMO) is required to reproduce the sampled data with no loss of information [7].

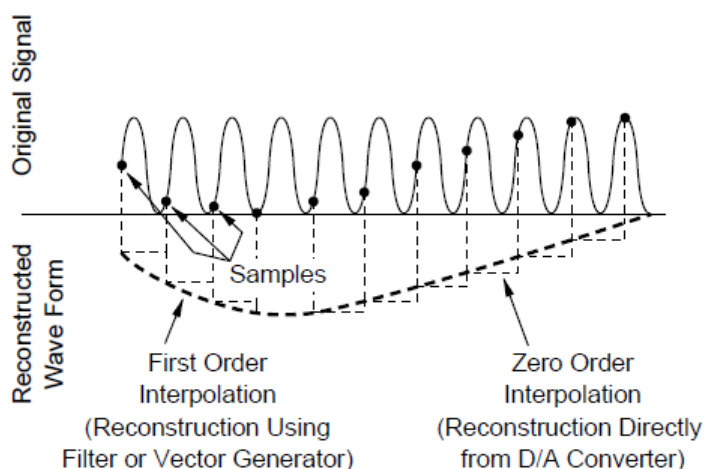


Figure 6-3: Aliasing Error versus Sampling frequency (Source: Burr Brown [7])

For example, the Nyquist theorem suggests that if the highest frequency in the signal to be sampled is f_{max} then the minimum sampling frequency would be $2f_{max}$. However, this sampling frequency still does not achieve a very accurate reproduction of the original signal (average error between the reconstructed signal and the original signal is 32% at $2f_{max}$) and an increase in the sampling frequency to $200f_{max}$ is required to achieve an accuracy of 1% in the reconstructed signal.

An alternative option is to filter the signal before sampling. This is a very effective method of reducing the maximum frequency of the signal, but filtering also results in the loss of information. This is not an issue if the ultimate use of the data is to calculate simple averages over a period of time. However if the data is to be used in a calculation involving other sampled parameters (for example the calculation of power from sampled voltage and current measurements) then analogue filtering before sampling removes fundamental elements of the time-dependent variation of the signal and may lead to the loss of accuracy in the calculated data. When determining the appropriate filtering level and sampling interval it is first necessary to consider the purpose for which the data is to be used and the rate at which the original signal may change.

6.7 Recording and Monitoring Intervals

All parameters should be continuously sampled at the sample interval (τ_s) rate during the specified recording interval (τ_r). The sampled data for each measured parameter should be processed into time-weighted averages.

The recording interval is dependent on the final use of the PV system data. Table 6-3 presents the recommended recording interval and monitoring periods required per use of measured PV data as listed in section 6. The recording interval should be synchronised to midnight, so that data, which may be collected from multiple devices or sites, will be logging on the minute or hour, and can easily be synchronised.

The monitoring period should be sufficient to provide operational data that is representative of the PV performance, load and ambient conditions. The minimum period of continuous monitoring should be chosen in accordance with the end use of the collected data as recommended in Table 6-3. For on-going performance diagnostics it is recommended that the monitoring period be continued until the PV system is decommissioned.

Table 6-3: List of recording interval per use of measured PV data

Use	Use of Measured PV Data	(τ_r)	Monitoring period
1	Performance assessment of PV technologies under outdoor conditions	Max 15 min	Min 1 year
2	Performance diagnostics	Hourly	System lifetime
3	Degradation and uncertainty analysis with time	Hourly	Min 3-5 years
4	Understanding/improving system losses via comparisons to modelled performance data	Hourly	Min 1 year
5	Forecasting PV performance	5min, 30min or hourly**	Min 1 year
6	Interaction of PV systems with the electricity network	1 to 15min**	Min 1 week
7	Integration of distributed generation and load control	1 to 15min**	Min 1 week

** Note: In some applications the recording interval will need to be significantly shorter dependent on the specific nature of the investigation required.

6.8 Summary - Selecting the Appropriate Monitoring Strategy

This section of the guideline provides a summary of the details presented within section 6 with the aim to help select an appropriate monitoring strategy. This guideline was framed based on 7 typical uses of PV data and the method defined in Figure 6-4 determines the appropriate monitoring strategy based on the end use of the PV data.

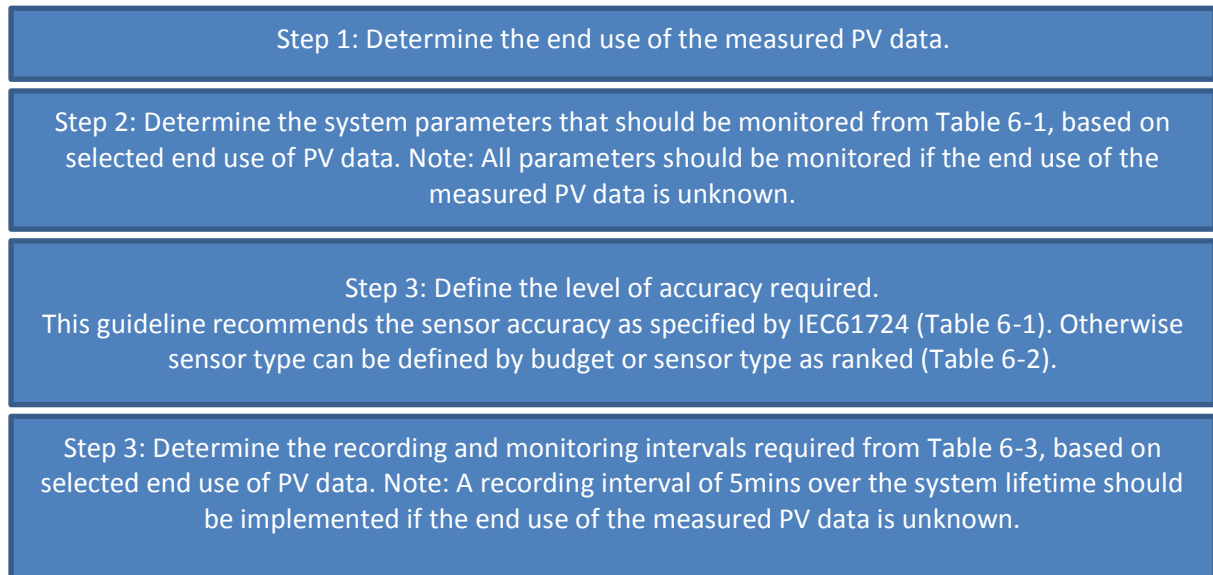


Figure 6-4: Steps required for selecting an appropriate monitoring strategy

The first step in selecting an appropriate monitoring strategy is to determine the use of the monitored PV data from the list of the 7 typical uses listed below.

1. Performance assessment of PV technologies under outdoor conditions
2. Performance diagnostics
3. Degradation and uncertainty analysis with time
4. Understanding/reducing system losses via comparisons to modelled performance data
5. Forecasting PV performance
6. Interaction of PV systems with the electricity network
7. Integration of distributed generation, storage and load control

Once the end use for the data is known, the second step in selecting an appropriate monitoring strategy is to determine what system parameters should be monitored. Table 6-1 (reproduced below) lists the parameters that are required for measurement based on the 7 typical uses of PV data.

Note: If the final use of the PV system data is unknown then all of the parameters reported in Table 6-1 should be monitored.

Table 6-1: List of parameters to be measured and recommended sensor accuracy as per IEC 61724 (reproduced)

Parameter	Symbol	Unit	1a	1b	2	3	4	5	6	7	Recommended Minimum Sensor Accuracy
In-plane irradiance ¹	G	W/m ²	X	X	X	X	X	X	X		5%
Ambient air temperature	T _{am}	°C		X	X	X	X	X			1°C
Wind speed ²	WS	m/s		X	X	X	X	X			0.5 m/s for WS<5m/s ±10% for WS>5m/s
Array voltage	V _A	V		X	X	X	X	X	X	X	1%
Array current	I _A	A		X	X	X	X	X	X	X	1%
Array power	P _A	kW		X	X	X	X	X	X	X	2%
Module temperature ²	T _m	°C		X	X	X	X				1°C
Load voltage	V _L	V								X	1%
Load current	I _L	A								X	1%
Load power	P _L	kW								X	2%
Utility voltage	V _U	V			X				X	X	1%
Current to utility grid ⁴	I _{TU}	A			X				X	X	1%
Power to utility grid ⁴	P _{TU}	kW	X	X	X	X	X	X	X	X	2%
Power from utility grid ⁴	P _{FU}	kW							X	X	2%

The third step in selecting an appropriate monitoring strategy is to determine the level of accuracy required for the monitoring process. 6-2 presents a range of measurement devices for each parameter ranked by budget and analysis option. For a best practice monitoring strategy, sensor accuracy as defined by IEC61724 and listed in 6-1 should be selected.

Table 6-2: List of parameters and type of measurement device ranked by budget and analysis option [1] (reproduced)

Parameter	Sensor Type	Small	Budget	Large		
		Limited	Analysis Options ¹	Significant		
Meteorology						
6.8.1.1 In-plane irradiance ²	Thermopile Pyranometer					X
	Same-Technology Reference Cell/Module			X	X	X
	Silicon Photodiode Pyranometer	X	X	X	X	
Global horizontal irradiance	Thermopile Pyranometer					X
	Silicon Photodiode Pyranometer			X	X	
Ambient air temperature	Thermocouple, RTD, Thermistor	X	X	X	X	X
Wind speed	Ultrasonic Anemometer				X	X
	Cup Anemometer		X	X		
Photovoltaic Array						
a.c. Energy Generation ³	NMI Class 1 or Class 0.5 energy meter [2]			X	X	X
	Collected from Inverter	X	X	X	X	X
d.c. Energy Generation ³	External Current and Voltage Transducers					X
	Collected from Inverter	X	X	X	X	X
Inverter Status and Errors	Collected from Inverter	X	X	X	X	X
Module Temperature	Thermocouple, RTD, Thermistor		X	X	X	X

¹ Systems which collect higher quality data from a greater variety of sensors allows for more significant analysis and have a greater benefit to PV performance and reliability research.

² The response time of thermopile pyranometers is in the range of 5-30 seconds. Thermopile pyranometers have slower response times than the same-technology reference cells/module to changing irradiance conditions.

³ The collection of both inverter and external energy generation data in the large budget scenario allows for comparisons between these two device types.

The final step in selecting an appropriate monitoring strategy is to define the appropriate recording and monitoring periods. Table 6-3 presents a list of the recommended recording and monitoring intervals based on the list of 7 typical uses of PV data as defined in this guideline. If the final use of the PV system data is unknown then a recording interval of 5min over the systems lifetime should be implemented.

Table 6-3: List of recording interval per use of measured PV data (reproduced)

Use	Use of Measured PV Data	(τ_r)	Monitoring period
1	Performance assessment of PV technologies under outdoor conditions	Max 15 min	Min 1 year
2	Performance diagnostics	Hourly	System lifetime
3	Degradation and uncertainty analysis with time	Hourly	Min 3-5 years
4	Understanding/improving system losses via comparisons to modelled performance data	Hourly	Min 1 year
5	Forecasting PV performance	5min, 30min or hourly**	Min 1 year
6	Interaction of PV systems with the electricity network	1 to 15min**	Min 1 week
7	Integration of distributed generation and load control	1 to 15min**	Min 1 week

** Note: In some applications the recording interval will need to be significantly shorter dependent on the specific nature of the investigation required.

7 Reliability Specifications

For measurement of system reliability a maintenance/monitoring log should be kept to record any of the following:

1. Scheduled and unscheduled maintenance
2. Unusual or extreme events such as weather events or grid outages
3. Component changes, failures or faults
4. Sensor issues, recalibration or change
5. Module and Sensor cleaning
6. Data acquisition system issues or changes
7. System operation issues or changes
8. Load issues or changes

All system maintenance must be explicitly documented. The maintenance/monitoring record should include dates and times for the start and end of each event. Table 7-1 presents an example of a maintenance log as recommended by the European Commission PV performance monitoring guidelines.

In addition, the following list identifies a number of items that should be visually inspected for on a regular basis and after extreme weather events. Any observations should be recorded in the maintenance/monitoring log.

1. PV modules –
 - 1.1 Check for mechanical damage to glass or frame
 - 1.2 Soiling
 - 1.3 Delamination
 - 1.4 Any visual changes i.e. colour, bubbles, uniformity or encapsulation, uniformity of surface
 - 1.5 Any changes in shading from the external environment i.e. new buildings, tree growth
2. Mounting structure –
 - 2.1 Check for mechanical damage or corrosion
 - 2.2 Missing or loose connections/fixings
3. Electrical connections/earthing, cabling and junction boxes –
 - 3.1 Inspect for damage by corrosion, wildlife etc.
 - 3.2 Secure connections
 - 3.3 Discolouration
 - 3.4 Moisture ingress
 - 3.5 Support of the cables and conduits
4. Inverter
 - 4.1 Inspect external conditions i.e. damage to seals
 - 4.2 Discolouration
 - 4.3 Excessive noise

Table 7-1: Example maintenance record form (as taken from the European Commission PV performance guidelines [9])

Date and Time	Action³	Description of action	Person undertaking action	Material used⁴	Time taken for action	State of completion⁵	Counter readings⁶	Down time⁷	Comments and further action⁸

³ Action category: scheduled maintenance, fault inspection, fault diagnosis, repair

⁴ Material used: note any material or equipment used for repair or replacement, including serial numbers of old and new components if applicable

⁵ State of completion: indicate the state of completion of overall intervention resulting from this action

⁶ Counter readings: the energy counter reading (or equivalent measure of system output) should be recorded at the beginning and end of each action. This allows estimated of the amount of energy loss (if any) resulting from the cause of the intervention or the action itself

⁷ Down time: record any shutdowns of all or part of the system required to complete the action, including start time and period

⁸ Comments: any additional comments regarding the action and record all further actions required to complete the intervention, including schedule where possible.

8 Performance Assessment

This section of the guideline provides direction on how the recommended monitored data can be used to analyse PV system performance.

The extent to which losses and performance issues can be identified will be dependent on the accuracy of and uncertainty in of the measured data. The first step in the performance analysis is to check all recorded data for consistency and gaps to identify obvious anomalies in the dataset. The following procedure is based on the recommendations as presented in IEC 61724 and the European Commission PV performance guideline.

8.1 Check of Data Quality

A reasonable set of limits should be defined for each recorded parameter, based on the known characteristics of the parameter, the PV plant and the environment. The limits should define the maximum and minimum allowable values for the parameter. Data that falls outside these limits or are otherwise inconsistent with other data should not be included in the subsequent analyses. Suggested limits for maximum and minimum values of the main parameters are given below:

- Irradiance – Values between 0 and 1500 W/m²
- Ambient temperature – values between -40 and 60°C
- Module temperature – values between ambient and ambient plus 40° C for open rack mounted systems and plus 60°C for roof mounted/integrated systems.
- Array voltage – values between 0 and 1.3 x V_{oc} of the array under STC
- Array current – values between 0 and 1.5 x I_{sc} under STC

The results of these data quality checks should normally include the following information:

5. A list or quantity of data points falling outside the pre-set ranges.
6. The duration of monitoring activity τ_{MA} (expressed in hours) in the reporting period τ (commonly one month, but expressed in hours), for which monitoring data have been recorded and checked.
7. The total number of hours of data passing through the quality check should also be stated if different from the duration of the actual check period selected
8. The availability of monitored data A_{MD} (expressed as a fraction of the reporting period), as given by:

$$A_{MD} = \tau_{MA} / \tau$$

8.2 Derived Parameters

Table 8-1 provides a list of the derived parameters that can be calculated based on the measured parameters that were listed in Table 6-1. The listed parameters can be calculated for any period that is longer than the recording interval. Typically these values are calculated on a daily basis. The equations used to calculate the parameters in Table 8-1 are detailed in the following sections.

Note: IEC 61724 contains an extended list of parameters in comparison to the parameters presented in Table 8-1. Only the parameters relevant for performance diagnostics are included in Table 8-1. It is outside of the scope of this document to list and describe the methodology for use of the measured data for each of the uses of PV measured data as listed in section 5.

Table 8-1: List of derived parameters

Parameter	Symbol	Unit
Meteorology		
Global irradiation, in the plane of the array	H	kWh/m ²
Electrical Energy Quantities		
Energy from the Array	E _A	kWh
Energy output to Utility grid or load	E _{out}	kWh
System Performance Indices		
Array d.c. energy yield	Y _A	kWh/kW
System a.c. energy yield	Y _f	kWh/kW
Reference solar yield	Y _r	kWh/kW
Array capture losses	L _c	h/d
Performance ratio	PR	
Array d.c. energy efficiency	η _A	
PV system a.c. energy efficiency	η _{pv}	

8.3 Global Irradiation

Plane of array irradiation (also commonly known as insolation) is calculated from the recorded irradiance G by

$$H = \tau_r \times \sum_{\tau} G$$

where H_r (expressed in kWh/m²) is the irradiation over the reporting period (τ), where τ_r is the recording interval of the irradiance readings in hours and G are the measured irradiance readings in kW/m².

The symbol \sum_{τ} denotes the summation over the reporting period τ

8.4 Electrical Energy Quantities

To calculate any energy quantity (E_A or E_{out}) from their corresponding measured power parameters (P_A or P_{TU}) over the reporting period (τ) the following equation is used:

$$E_i = \tau_r \times \sum_{\tau} P_i$$

where E_i (expressed in kWh) is the energy over the reporting period (τ) for the parameter i , where τ_r is the recording interval of the power readings in hours and P_i are the measured power readings for parameter i in kW.

The symbol \sum_{τ} denotes the summation of each power parameter over the reporting period (τ).

8.5 System Performance Indices

PV systems of different technologies, configurations and at different locations can be compared by calculating their normalised system performance indices such as yields, losses and efficiencies. Yields are energy quantities normalised to rated array power. System efficiencies are normalised to array area and losses are the differences between the yields. These parameters can be compared and tracked against parameters derived historically for the same system, allowing for identification of significant changes.

8.6 Yields

Yields are the ratios of energy quantities over the installed array's rated output power P_0 (kW). Yields indicate actual array operation relative to its rated capacity.

Note: Yields can be calculated over any time period. Daily, monthly and annual yields are the most frequently reported.

1. The array yield (Y_A) is the energy output of the PV array (E_A) per kW of installed capacity.

$$Y_A = E_A / P_0$$

where P_0 is the rated output power of the array under standard test conditions.

2. The final yield (Y_f) is the net energy output of the entire PV system (E_{out}) expressed per kWh/kW of installed capacity over the reporting period. The reporting period should be recorded with the yield to avoid misinterpretation of the figures.

$$Y_f = E_{out} / P_0$$

3. The reference yield (Y_r) can be calculated by dividing the total daily in-plane irradiation by the module's reference in-plane irradiance G_{ref} (kW/m²), where $G_{ref} = 1\text{ kW/m}^2$. For a reporting interval of 24 hours, Y_r is effectively the number of peak sun-hours (PSH)⁹ per day (h/d).

$$Y_r = H / G_{ref}$$

8.6.1 Normalised Losses

Normalised losses can be calculated by finding the difference between reference, array and final yields. Two types of losses can be calculated once yields are determined. These are capture losses and system losses.

- 1) The array capture losses (L_c) represent the losses due to the array operating below what would be expected at STC. Typical losses include the effect of temperature, high incidence angles, shading, array circuit losses, including mismatch, low irradiance and soiling of the array.

$$L_c = Y_r - Y_A$$

Using these loss measures, maximum power point tracking (MPPT) losses will also appear as array capture losses, although they are not related to the array. However, in modern inverters, MPPT losses are generally very small. In most cases, inverter failures will also be counted as L_c , since no power (or reduced power if limited) will be measured at the input to

⁹ PSH is the equivalent number of hours per day of irradiance of 1kW/m² (the reference irradiance level) required to equal the actual irradiation.

the inverter. Care should be taken to prepare data for analysis in order to attribute losses appropriately.

- 2) The balance of system losses (L_{BOS}) represent the losses that occur in the rest of the PV system other than the array including losses due to wiring and the inverter.

$$L_{BOS} = Y_A - Y_f$$

Note: No power will be measured at the input to the inverter, if a malfunction or inverter failure occurs. This will usually be reflected as a large L_c , rather than L_{BOS} . Unreliable inverters and complete system breakdowns appear statistically as high capture losses and relatively low system losses.

8.6.2 Performance Ratio

The performance ratio (PR), defined as the ratio of the final yield to the reference yield, indicates the overall effect of losses on the array's rated output due to array temperature, incomplete utilisation of the irradiation and the system component inefficiencies or failures:

$$PR = Y_f / Y_r$$

PR is widely used for simple comparison of different grid-connected PV systems.

8.6.3 System Efficiencies

Efficiencies can be calculated for the whole system or for individual components within the system. In general efficiencies are the ratio of energy out to energy in represented as a percentage.

- 1) The array d.c. energy efficiency over the reporting period τ is defined by

$$\eta_A = E_A / (A_a \times H)$$

where A_a is the active area of the array in m^2 .

This efficiency represents the average d.c. energy conversion efficiency of the PV array, which is useful for comparison with the array efficiency η_{A0} at its rated power, P_0 .

- 2) The PV system a.c. energy efficiency over the reporting period τ is defined by

$$\eta_{pv} = E_{out} / (A_a \times H)$$

Other efficiencies can also be calculated for example the inverter efficiency could be calculated as the a.c. energy output of the inverter to the d.c. power input into the inverter.

Note: The efficiency figures can be severely affected by poor BOS performance e.g. poor MPPT performance, by inverter failures or grid unavailability.

8.7 Identifying Performance Issues

This section of the guideline provides more details on the performance indices described previously, and provides a context for their use in identifying performance issues in PV systems, including when they are useful, and issues associated with their use. The information described in this section is based on information provided in [10, 11] and the European Commission's performance monitoring guideline.

Reduction in system output caused by operational problems within the PV system will be reflected in the yields, efficiencies and ratios described earlier. The performance parameters can be compared against historically measured metrics for the same system or compared against predicted performance values. It should be noted however that each of these metrics has limitations in their

use due to the influence of weather on the calculated metric. For example the final PV system yield (Y_f) is strongly influenced by its dependence on irradiance, so systems with a good solar resource will perform well on this measure. Y_f essentially normalises the system performance with respect to system size so it is useful for comparing systems of different sizes and technologies to quantify the benefits of design components, or locations but it is not useful for identifying operational issues. Y_f can only be used to identify issues within different sub-systems of the same array if separate monitoring of each sub-system has taken place.

The PR is typically used to diagnose system issues as it quantifies losses on the rated output of the PV system, and is influenced less by solar resource than Y_f as it is normalised to solar radiation incident on the array (reference yield). It should, however, be noted that because the PR reflects losses due to module temperature, PR values tend to be greater in the winter than in the summer, and also for cold climates compared to hot climates. Other seasonal effects, like soiling, may also impact on the PR, where they vary significantly with the season. Decreasing yearly values of PR may be used to indicate a permanent loss in system performance, i.e. degradation in PV performance or worsening of shading problems. Large reductions in the PR indicate events that significantly impact the system performance, such as inverter failure or circuit breaker trips. Small or moderate decreases in PR can identify the existence of a problem, but not the cause. The European Commission guideline recommends that when the PR is less than 0.75, especially where a significant reduction in PR is observed in comparison with a previous period of similar operating conditions, then the reason for this reduction should be investigated. The approach is to consider the variation in the system output with time and/or irradiance level. This can most clearly be observed graphically.

The PV system a.c. -energy efficiency (η_{PV}) is a simple metric to calculate as it only requires the measurement of in-plane irradiance and the a.c. power of the PV system. The advantage of the η_{PV} metric is that it provides a more accurate method for comparing the performance of widely different PV technologies as it is not dependent on the various reference conditions used to rate the different technologies [11].

8.7.1 Graphical Analysis

The following details a set of recommended graphical analyses that can be undertaken to help diagnose system performance issues when low PR values have been identified. This analysis has been taken from the European Commission's Performance Monitoring Guidelines [9].

Note: It is worthwhile undertaking the following analysis on the sub-array data, if monitored, as issues on one or a section of the sub-arrays can be obscured when the total array output is plotted.

8.7.1.1 Clear Sky Day Analysis

For a clear sky day plot the a.c. output and in-plane irradiance as a function of time of day. If the a.c. output does not follow the same curve of the in-plane irradiance then the shape of the curve should be noted and compared to expected behaviour for different fault mechanisms.

- 1) Array shading – a.c. output curve will show a marked reduction for part of the day. If shading is suspected, then check similar curves for different days in the same period to see if the behaviour is consistent and check the site for possible shading sources. Figure 8-1 presents an example of a system that has significant morning shading observed in winter, with the shading effect reduced in March and September and not present in summer.
- 2) Inverter limitations – If the output curves follow the in-plane irradiance when irradiance is low but levels out to a plateau at high irradiance levels, the inverter output may be limiting.

- 3) Inverter dropouts – If there are repeated period during the day where the output curve drops to zero or is substantially lower than would be expected from following the irradiance curve, the inverter may be dropping out. Example presented in Figure 8-3

8.7.1.2 Variable Day Analysis

For a day with variable irradiance levels, plot the a.c. output and in-plane irradiance as a function of time of day. If the a.c. output does not follow the rapid changes in irradiance there may be problems with the maximum power point tracking, especially if the output drops to zero when there are rapid decreases in irradiance.

For a number of days in the period being considered, plot the a.c. output against in-plane irradiance. In the ideal case this should result in a linear plot. i.e. output is directly proportional to irradiance.

- Operational threshold – If the a.c. output remains zero until irradiance levels above 100 W/m² are reached, the operating threshold on the inverter may be set too high
- Inverter limitations – If the output levels out at high irradiance levels, the inverter capacity may be too small. (Note the output reduction can also be a result of overheating the inverter and temperature monitoring of the inverter would be need to discern this effect). Example presented in Figure 8-2
- Module heating/poor module ventilation – If two separate lines are observed, as in Figure 8-2, with the morning values of output higher than the afternoon values for the same irradiance level, then this indicates heating of the modules. This issue may need further investigation if there is a large difference between the morning and afternoon curves. The effect can be confirmed by inspecting the variation in module temperature if it is measured.

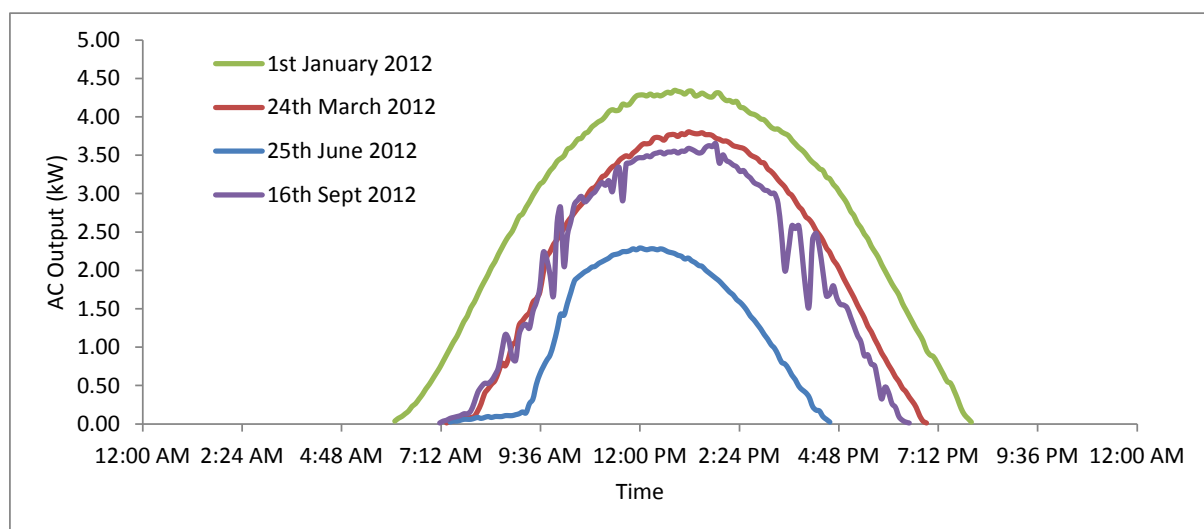


Figure 8-1: Example of seasonal change in shading losses.

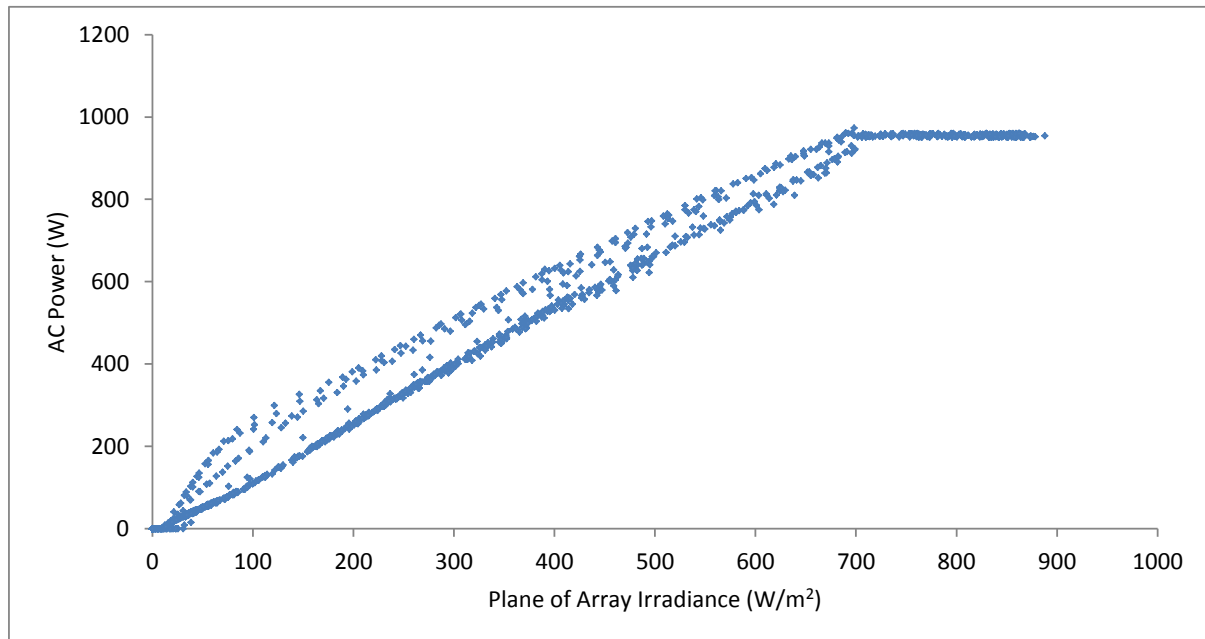


Figure 8-2: Plot of a.c. output vs. irradiance showing limiting of the output at high irradiance due to the inverter capacity

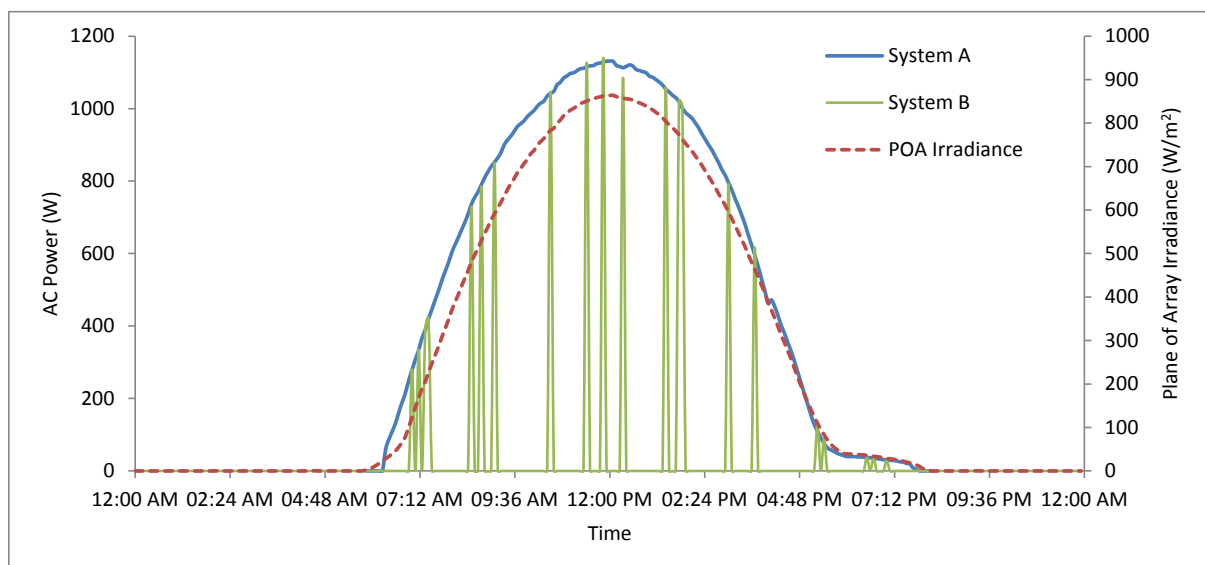


Figure 8-3: Plot of a.c. output from two systems vs. in-plane irradiance. Performance of system B impacted by inverter dropout

9 Appendices

9.1 Transposition Method of Horizontal Irradiance to In-plane Irradiance

The following methodology is presented to enable the estimation of in-plane irradiance G (W/m^2) in the absence of measured in-plane irradiance. The method presented is the Perez transposition model [5, 6]. This model is valid for data with hourly time steps or shorter, it cannot be used for daily values. It should be noted that this method requires the input of the following parameters,

- I_{bn} – direct normal solar irradiance (W/m^2)
- I_h – global horizontal solar irradiance (W/m^2)
- $I_{h,b}$ – direct normal component of solar irradiance on the horizontal surface (W/m^2)
- $I_{h,d}$ – global diffuse horizontal irradiance (W/m^2)
- I_{on} – direct extraterrestrial normal irradiance (W/m^2)
- α_s – solar altitude angle ($^\circ$)
- β – surface tilt angle from horizon ($^\circ$)
- θ – incident angle of the surface ($^\circ$)
- θ_z – zenith angle of the sun ($^\circ$)
- ρ – hemispherical ground reflectance (typical value of 0.2 or 0.3 can be used if value is unknown)
- γ – orientation of the PV system (topocentric N=0, E=90, S=180 and W=270) ($^\circ$)
- γ_s – solar azimuth angle (topocentric N=0, E=90, S=180 and W=270) ($^\circ$)

Ideally global horizontal solar irradiance and direct solar irradiance are measured. The diffuse horizontal irradiance component can then be calculated from the following standard relation:

$$I_h = I_{h,d} + I_{h,b}$$

where $I_{h,b} = I_{bn} \sin \alpha_s$

The solar position parameters can be calculated using NREL's solar position calculator <http://www.nrel.gov/mid.c./solpos/spa.html> with inputs of date range, latitude, longitude, elevation and Greenwich Time zone. The algorithms in NREL calculator are documented in full in [12].

The Perez in-plane irradiance model is:

$$G = I_{h,b} R_b + I_{h,d} \left[(1 - F_1) \left(\frac{1 + \cos \beta}{2} \right) + F_1 \frac{a}{b} + F_2 \sin \beta \right] + I_h \rho \left(\frac{1 - \cos \beta}{2} \right),$$

where R_b is a variable geometric factor which is the ratio of tilted to horizontal beam irradiance, F_1 and F_2 are circumsolar and horizontal brightness coefficients, respectively, and a and b are terms that take the incidence angle of the sun on the considered slope into account. The terms a and b are computed by the following:

$$a = \max(0^\circ, \cos \theta)$$

$$b = \max(\cos 85^\circ, \cos \theta_z)$$

$$\cos \theta = \sin \beta \sin \theta_z \cos(\gamma_s - \gamma) + \cos \beta \sin \theta_z$$

The brightness coefficients F_1 and F_2 depend on the sky condition parameters clearness ε and brightness Δ . These factors are defined by,

$$\varepsilon = \frac{\frac{I_{h,d} + I_n}{I_{h,d}} + 5.535 \cdot 10^{-6} \theta_z^3}{1 + 5.535 \cdot 10^{-6} \theta_z^3}$$

$$\Delta = m \frac{I_{h,d}}{I_{on}}$$

F_1 and F_2 are then computed by,

$$F_1 = \max \left[0, \left(f_{11} + f_{12}\Delta + \frac{\pi\theta_z}{180} f_{13} \right) \right]$$

$$F_2 = f_{21} + f_{22}\Delta + \frac{\pi\theta_z}{180} f_{23}$$

Where the coefficients f_{11} , f_{12} , f_{13} , f_{21} , f_{22} and f_{23} were derived based on statistical analysis of empirical data for specific locations. Two different sets of coefficients were derived for this model [5, 6] where the coefficients from [6] are presented in Table 9-1.

Table 9-1: Coefficients used in the Perez model [6]

$\epsilon_i(\text{bins})$	1	2	3	4	5	6	7	8
Lower Bound	1.000	1.065	1.230	1.500	1.950	2.800	4.500	6.200
Upper Bound	1.065	1.230	1.500	1.950	2.800	4.500	6.200	-
F_{11}	-0.0083	0.1299	0.3297	0.5682	0.8730	1.1326	1.0602	0.6777
F_{12}	0.5877	0.6826	0.4869	0.1875	-0.3920	-1.12367	-1.15999	-0.3273
F_{13}	-0.0621	-0.1514	-0.2211	-0.2951	-0.3616	-0.4118	-0.3589	-0.2504
F_{21}	-0.0596	-0.0189	0.0554	0.1089	0.2256	0.2878	0.2642	0.1561
F_{22}	0.0721	0.0660	-0.0640	-0.1519	-0.4620	-0.8230	-1.1272	-1.3765
F_{23}	-0.0220	-0.0289	-0.0261	-0.0140	0.0012	0.0559	0.1311	0.2506

9.2 Separation of Global Horizontal Irradiance into Direct and Diffuse Irradiance

A number of mathematical models have been developed to estimate direct and diffuse irradiance from global horizontal irradiance in the absence of measured data. This section presents two of the mathematical models presented within the literature. The primary author of this document recommends the BRL model [13] as data from two locations within Australia (Adelaide and Darwin) were used in the development of the model. The Maxwell DISC [14] model from NREL is also presented as it is a model frequently cited within the academic literature. Again these models are valid for data in hourly time steps.

9.2.1 BRL Model

The method presented is the BRL model [13]. The BRL model calculates diffuse irradiance ($I_{h,d}$) via the calculation of the diffuse fraction (d_t).

$$I_{h,d} = d_t \times I_h$$

Direct irradiance can then be calculated as the difference between global and diffuse horizontal irradiance.

$$I_h = I_{h,d} + I_{h,b}$$

The BRL model requires the following parameters as input:

- AST - apparent solar time
- I_h - global horizontal solar irradiance (W/m^2)
- I_0 - extraterrestrial irradiance (W/m^2)
- k_t - hourly clearness index
- K_t - daily clearness index
- α_s - solar altitude angle ($^\circ$)
- ψ - persistence of global irradiance

$$k_t = \frac{I_h}{I_{0n}}$$

$$I_{0n} = I_0 \times \sin \alpha_s$$

$$\psi = \begin{cases} \frac{k_{t-1} + k_{t+1}}{2} & \text{sunrise} < t < \text{sunset} \\ k_{t+1} & t = \text{sunrise} \\ k_{t-1} & t = \text{sunset} \end{cases}$$

$$d_t = \frac{1}{1 + e^{\beta_0 + \beta_1 k_t + \beta_2 AST + \beta_3 \alpha_s + \beta_4 K_t + \beta_5 \psi}}$$

where β_0 to β_5 are the fitted coefficients with global values of -5.38, 6.63, 0.006, -0.007, 1.75 and 1.31 respectively.

9.2.2 Maxwell DISC Model

The second method presented is the Maxwell DISC [14] model from NREL. An excel version of the Maxwell DISC model can be downloaded from NREL via the following link. The user needs to input global horizontal irradiance and adjust the site location parameters of Latitude, Longitude, time zone and pressure for this excel document to work correctly. <http://rredc.nrel.gov/solar/models/DISC/>

9.3 Module Temperature Models

9.3.1 Sandia Model

The Sandia National Laboratories proposes the following model to estimate module temperature, T_m :

$$T_m = G(e^{a+bWS}) + T_{am}$$

where a and b are parameters of the model that depend on the module construction as well as the mounting configuration of the modules. Table 9-2 lists representative values of the coefficients a and b for various common module types and configurations.

Table 9-2: Coefficients of Sandia module temperature model

Module Type	Mounting Configuration	a	b
Glass/cell/glass	Open rack	-3.47	-0.0594
Glass/cell/glass	Close roof mount	-2.98	-0.0471
Glass/cell/polymer sheet	Open rack	-3.56	-0.0750
Glass/cell/polymer sheet	Insulated back	-2.81	-0.0455
Polymer/thin-film/steel	Open rack	-3.58	-0.113

9.3.2 Faiman Model

David Faiman presented a module temperature model [15] based on simple heat transfer concepts. His model is:

$$T_m = T_{am} + \frac{G}{U_o + U_1 \times WS}$$

where U_o is the constant component of the heat transfer in $W/m^2.K$ and U_1 is the convective component of the heat transfer in $W/m^2.K$.

Values reported in [15] for modules with front glass covers and tedlar backing varied between:

9. 23.5 to 26.5 with an average value of 25 $W/m^2.K$ for U_o
10. 6.25 to 7.68 with an average value of 6.84 $W/m^2.K$ for U_1

NB: The model presented by Faiman is similar to the cell temperature model used in PVsyst which defines cell temperature T_c as:

$$T_c = T_{am} + \frac{G}{U_o + U_1 \times WS} \alpha(1 - \eta_m)$$

where α is the absorption coefficient of the module (PVsyst default is 0.9) and η_m is the efficiency of the PV module (PVsyst default is 0.1). For free standing arrays U_o default is 29 $W/m^2.K$ and for fully insulated arrays (close roof mount) the default is 15 $W/m^2.K$.

Note: The current default values in PVsyst assume no dependence on the wind speed hence $U_1 = 0$.

9.4 Measurements at Installation

When first setup it is important to ensure that the measurement system installed is operating as expected. This section provides a lists of checks that should be undertaken on the measurement system as recommended based on Annex A of IEC 61724 and the European Commission Performance Monitoring guidelines for Photovoltaic systems [9]. It should be noted that the number of checks that should be made will depend on the complexity of the monitoring system installed.

- Check the linear response of sensors. IEC 61724 indicates that differences between the results measured by the data acquisition system and the products of the input signal and the scaling factor should be less than $\pm 1\%$.
- Check of stability of sensors. IEC 61724 recommends that the fluctuation of the measured value of the signal should be kept within $\pm 1\%$ of full scale.

- Check all channels are recording correctly and investigate the reasons for any missing data
- Check that data values are within an appropriate range for the parameter being measured as per section 8.1.
- If any parameters are not within the correct range:
 - o Check any calculations that are made to determine the logged values are correctly implemented
 - o Check the operation connections and positioning of the sensor
 - o Check for electromagnetic noise disrupting the signal from the sensor (Note: this would often be expected to affect more than one sensor)

The European Commission performance monitoring guidelines recommends the following analyses should be undertaken over a period of time at the beginning of operation of the system to determine the typical performance of the PV system and to identify any major losses existing at installation.

9.4.1 Analysis 1 – Clear Day Analysis

The aim of this analysis is to determine the typical output of the PV system under high irradiance conditions.

On a clear, sunny day, measure the energy output, the solar irradiation and the average ambient temperature and calculate final yield, system efficiency and performance ratio for the day. Record all values and keep as a record. Verify that the performance parameters are within the expected range. If the parameters fall outside the expected range, follow the instructions in section 8.7 to identify the cause of the issue.

9.4.2 Analysis 2 – Variation of Output across a Typical Day

The aim of this analysis is to determine the expected level of variation of the system performance across a typical sunny day.

On a clear, sunny day, record the energy output and solar irradiation at the recording interval that is to be used for long term monitoring (i.e. the first use of PV data as listed in section 0). On the same graph plot both quantities against time and follow the procedure detailed in section 8.7 to identify whether any performance issues exist. Record all values and the analysis and keep as a record.

9.4.3 Analysis 3 – Other Days Analysis

The aim of this analysis is to determine the typical output of the PV system under a range of possible weather scenarios.

Repeat Analysis 1 for a number of days where each day has a different weather profile. Ideally include days with a range of irradiation levels and ambient temperature conditions. Record all values and keep as a record. Verify that the performance parameters are reasonable given the weather conditions for that day.

Note: The range of levels and weather scenarios possible will depend on the prevailing climate at the location and the time of year the initial analysis is undertaken. Date of the analysis should be included in all the analysis records.

9.4.4 Analysis 4 – Inverter Measurements

The aim of this analysis is to determine the expected behaviour of the inverter under different operating conditions.

Performance data, both on the d.c. input side and a.c. output side of the inverter, should be measured and kept on record for each of the following scenarios. A minimum test period of 200ms is recommended to avoid system instability/disturbance.

- Conditions of zero solar irradiance in order to get information on self-consumption in idling conditions and at night time.
- With increasing solar radiation the variation in voltage and current on the d.c. side and the a.c. power flow in both directions should be monitored for the moment at which the inverter starts full operation. Repeat test over a day to detect inverter/MPPT start-up and shut-down thresholds
- In the course of the day several measurements should be done at a range of power levels.
- If the inverter is rated lower than the PV array, establish the reaction to overload if irradiance permits.
- With inverter connected to the grid, monitor for current harmonics.
- If possible, disconnect inverter and measure grid current, voltage and harmonics.
- With the inverter connected to the grid, disconnect the array and measure a.c. power backflow into the inverter (check if inverter is in a 'night-time' or 'standby' mode).
- During operation the inverter should be switched off and on in order to get information on the starting procedure after shut down.
- The starting procedure should also be tested by switching off and on the grid when the inverter is under normal operation.

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