NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Monitoring System Performance

Venue: PV Module Reliability Workshop

Presenter: Keith Emery and Ryan Smith

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Outline

Standards

- **National Electric Code**
- IEC 60904-1 **"Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics"**
- IEC 61724 "**Photovoltaic System Performance Monitoring – Guidelines for Measurement, Data Exchange and Analysis"**
- IEC 61829 "**Crystalline Silicon Photovoltaic array – On-site Measurement of I-V Characteristics**"
- ASTM E1036 "**Standard Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells"**
- ASTM E2527 "**Standard Test Method for Electrical Performance of Concentrator Terrestrial Photovoltaic Modules and Systems Under Natural Sunlight"**
- ASTM WK22009 "**Reporting Photovoltaic Non-Concentrator System Performance** "

Sources of Uncertainty

NREL's Approach to Local and Remote System Monitoring

Summary

IEC 60904-1 “Photovoltaic devices – Part 1: Measurement of Photovoltaic Current-Voltage Characteristics

- Voltage and Current measured with ±0.2 % Uncertainty in V_{oc} and I_{sc}
- Test and Reference device coplanar within ±2° and normal to the sun within ±5°.
- Reference cell and test device temperature measured with ±1 °C uncertainty.
- Optionally test device temperature determined via equivalent cell temperature method (IEC 60904-5)
- Spectral mismatch error correction if matched reference cell not used (IEC 60904-7).
- If reference cell >2 °C from calibration temperature corrections applied.
- Use IEC 60891 to translate for temperature and irradiance

ASTM E1036 **“Standard Test Methods for Electrical for Electrical Performance of Nonconcentrating Photovoltaic Modules and Arrays Using Reference cells”**

- Voltage and Current measured with ± 0.1 % Uncertainty and 0.05% Resolution for V_{oc} and I_{sc}.
- Test and Reference device coplanar within $\pm 2^\circ$ and normal to the sun within $\pm 10^\circ$ or report incidence angle.
- Reference cell and test device temperature measured with $\pm 1\,^\circ C$ uncertainty, $0.1\,^\circ C$ resolution.
- Spectral mismatch error correction applied (ASTM E973).
- Temperature and irradiance corrections applied if temperature more than $2^\circ C$ from reference temperature or irradiance > 5% from reference irradiance correct using bilinear method. Otherwise current corrected to constant irradiance.
- Average Wind speed for 5 min prior to test.

IEC 61724 "**Photovoltaic System Performance Monitoring – Guidelines for measurement data exchange and analysis**"

Meteorology

- Total irradiance, in the plane of the array
- Ambient air temperature
- Wind speed

Photovoltaic array

- Output voltage
- Output current
- Output power
- Module temperature
- Mounting / tracker characteristics

Load

- Load voltage
- Load current
- Load power

Energy storage

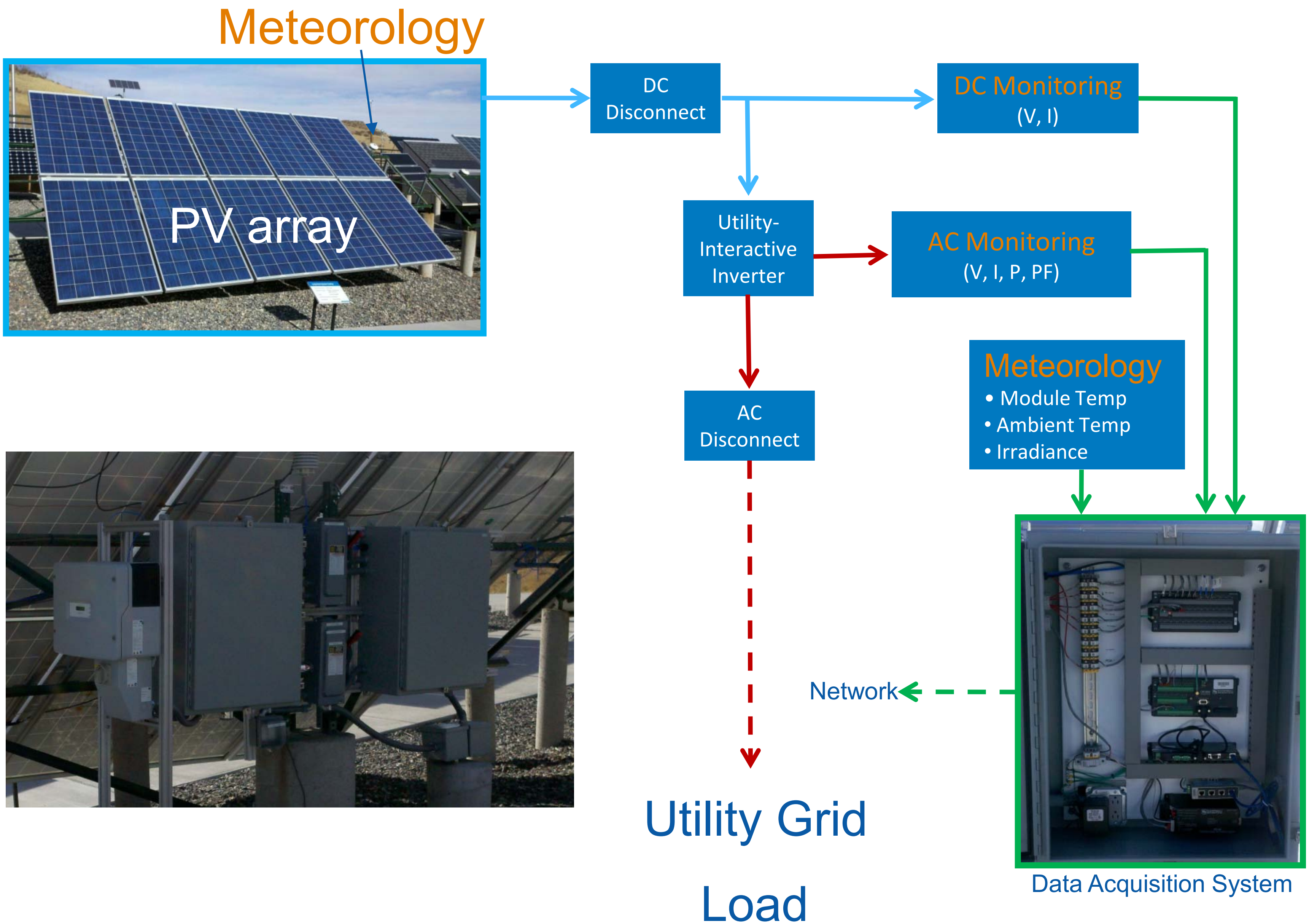
- Operating voltage
- Current to/from storage
- Power to/from storage

Utility grid

- Utility voltage
- Each phase - Current to/from utility grid
- Power to/from utility grid

Back-up sources

- Output voltage
- Output current
- Output power


Meteorology
PV array
DC Disconnect
DC Monitoring
(V, I)
Utility-Interactive Inverter
AC Monitoring
(V, I, P, PF)
Meteorology
• Module Temp
• Ambient Temp
• Irradiance
AC Disconnect
Network
Utility Grid
Load
Data Acquisition System

IEC 61724 “**Photovoltaic System Performance Monitoring – Guidelines for measurement data exchange and analysis**”

Total Irradiance –

- Measured in plane of array
- Uncertainty including including Instrumentation < 5%
- Pyranometer
- Reference cell or cell in Module Package or Module (IEC 60904-2)

Ambient Temperature –

- Representative of Array Location
- Uncertainty including Instrumentation < 1° C

Wind Speed

- Measured at Height and Location Representative of Array
- Uncertainty including Instrumentation < 0.5 m/s for Speeds < 5 m/s, and <10 % of the reading for Speeds > 5 m/s

IEC 61724 "**Photovoltaic System Performance Monitoring – Guidelines for measurement data exchange and analysis**"

Module Temperature –

- Measured on back of 1 or more modules in representative of location
- Uncertainty including Instrumentation < 1° C
- location on module given in IEC 61829 method A (center of back surface of module in center of array field)
- Based upon V_{oc} and equivalent Cell temperature (IEC 60904-5)

Voltage and Current –

- ac and or dc
- Uncertainty including Instrumentation < 1% of reading

Power

- DC Calculated based upon instantaneous and not averaged readings or directly measured with wattmeter
- AC power accounts for power factor and harmonic distortion
- Uncertainty including Instrumentation < 2%

Appendix A - Data Acquisition - Irradiance, Temperature, Voltage, Current, Power

Sampling

- Parameters which vary directly with irradiance shall be sampled with 1 min or less interval. Parameters with larger time constants, an arbitrary interval may be specified between 1 min and 10 min. Special consideration for increasing the sampling frequency shall be given to any parameters which may change quickly as a function of system load.

Linearity

- The difference between measured and applied signal < ±1 % of full scale value at of 0, 20, 40, 60, 80, and 100 % of full scale.

Stability

- 100 % full scale dc signal applied for 6 h. Should the fluctuation of the input signal exceed ±0.2 %, the results shall be compensated by using a voltmeter with an accuracy better than ±0.2 %.

Integration

- Apply expected maximum sensor signal for > 6 h. Signal times interval within 1% of expected value. With shorted input integral less than 1% of maximum signal applied times interval.

dc or ac Power Rating to 20°C ambient temperature, 850 W/m^2 total irradiance, 4 m/s wind speed

- Air temperature
  - Resolution 0.1°C, Uncertainty < 1°C
  - 1 to 2 m upwind , > 2m above ground
  - See ASTM D6176 “Standard Practice for Measuring Surface Atmospheric Temperature with Electrical Resistance Temperature Sensors”
- Wind speed
  - Uncertainty less than 0.5 m/s
  - 1 to 2 m upwind , > 2m above ground
- Total direct beam irradiance
  - ASTM E816, “**Standard Test Method for Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers”**
  - **Typical uncertainty < 1.5%**

dc or ac Power Rating to agreed upon Reporting Conditions defined by an Ambient Temperature, Total Irradiance, and Wind Speed

Air temperature

- Resolution 0.1 ° C, Uncertainty < 1 ° C (ASTM D6176)

Wind speed

- Uncertainty less than 0.5 m/s
- ultrasonic preferred since no dead band for <0.5 m/s

Plane of Array irradiance

- Pyranometer
  - ASTM E824 Test Method for Transfer of Calibration From Reference to Field Radiometers "
  - ASTM G167 Test Method for Calibration of a Pyranometer Using a Pyrheliometer
- Matched Reference cell suitable for outdoor use (ASTM E1040)
  - secondary calibration according to ASTM E1362

ac power measured with less than 1.5% uncertainty

PV Irradiance detector

Reference Cells in metal package

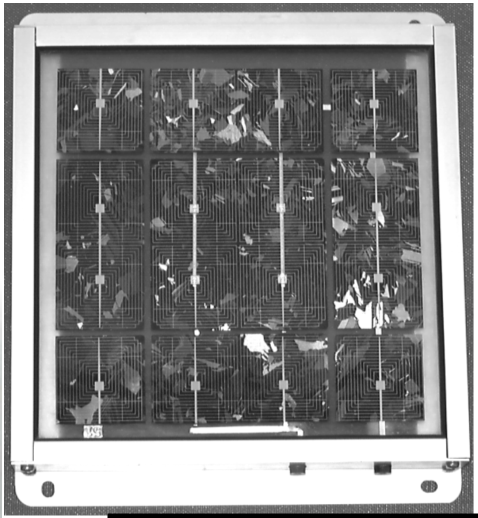
- Uncertainty in measuring the total irradiance of ± 1.5% provided that I_{sc} is temperature corrected and size is less than 2 by 2 cm
- Corrects for spectral effects to the reference spectrum. Exact correction if relative quantum efficiencies of reference and PV system identical
- Multiple intercomparisons among ISO 17025 accredited calibration labs suggest uncertainty less than ±2% for Si reference cells at 25 ° C
- Short-circuit temperature coefficient of Si is 500 to 850 ppm/° C depending on spectra measured under. In systems the temperature range may exceed 60 ° or a 3% error in irradiance if temperature not corrected for.
- Regression analysis of field data has a lower mean square error (less noisy)
- Time constant comparable to PV
- Temperature can be controlled potentially giving lower error in calibration

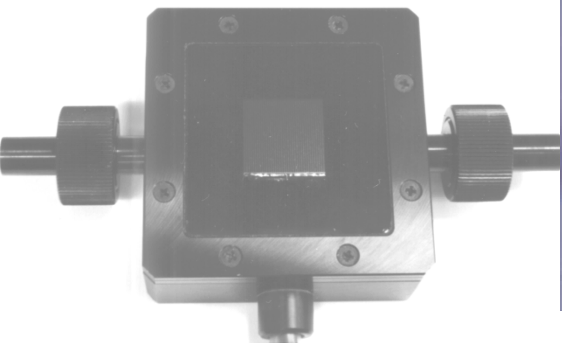
Cell in Module package

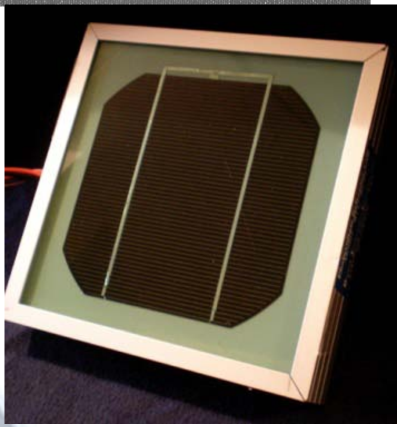
- Angular response similar to PV in system
- Quantum efficiency closer to module because packaging similar
- Thermal characteristics similar to PV system
- Slightly higher uncertainty than small area cells.

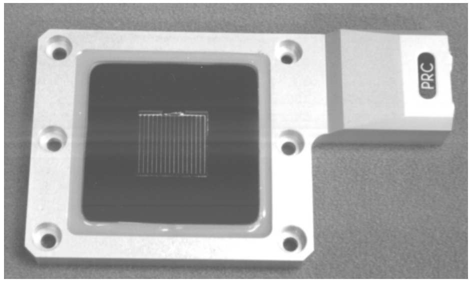
Reference Cell Packages

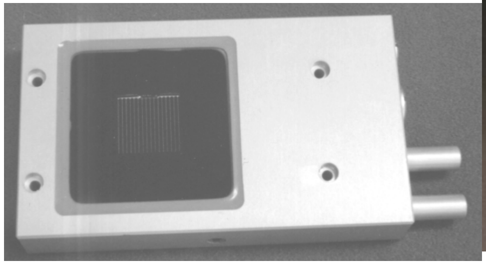
- Encapsulated
- Temperature sensor attached or other means to correct for temperature
- Packaged cell or cell in module package

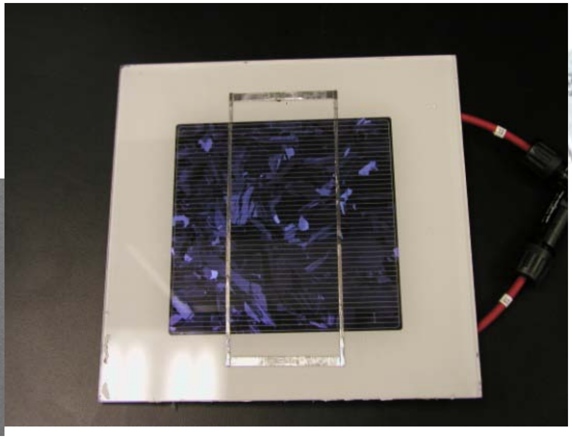










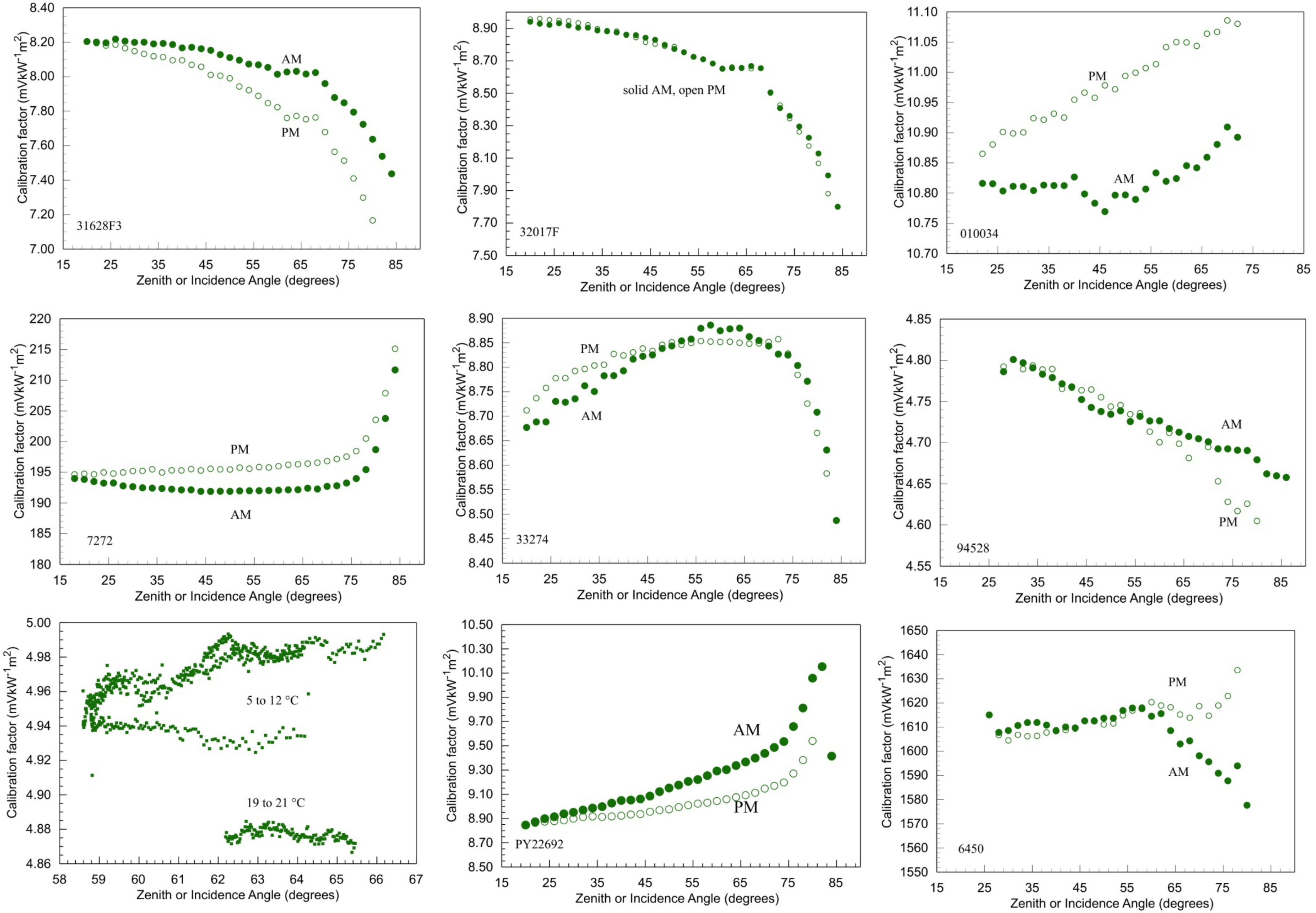


Pyranometer

- Wide range of uncertainties depending on how calibrated (indoors using a sphere vs. outdoors, how mounted, and if corrections for temperature and angular response applied
- 1.5 % to >5% for WMO first class, potentially >20% for other units.
- "**WMO GUIDE TO METEOROLOGICAL INSTRUMENTS AND METHODS OF OBSERVATION**" http://www.WMO.int/pages/prog/www/IMOP/publications/CIMO-Guide/CIMO_Guide-7th_Edition-2008.html
- U_{95} for pyranometer calibration at NREL on a horizontal surface ±3 to 4% depending on multiple factors. Often different from indoor based calibrations by over 5%.
- Calibrated outdoors with respect to incident spectrum so calibration is **not** with respect to a reference spectrum Error for Si pyranometer not as large an error for thermopile based units.
- Usually calibrated on a horizontal surface. Calibration varies with tilt angle.
- Calibration dependent on cable orientation. Cable should face to north away from sun in northern hemisphere.
- Manufacturers often calibrate indoors with integrating sphere against a reference pyranometer.

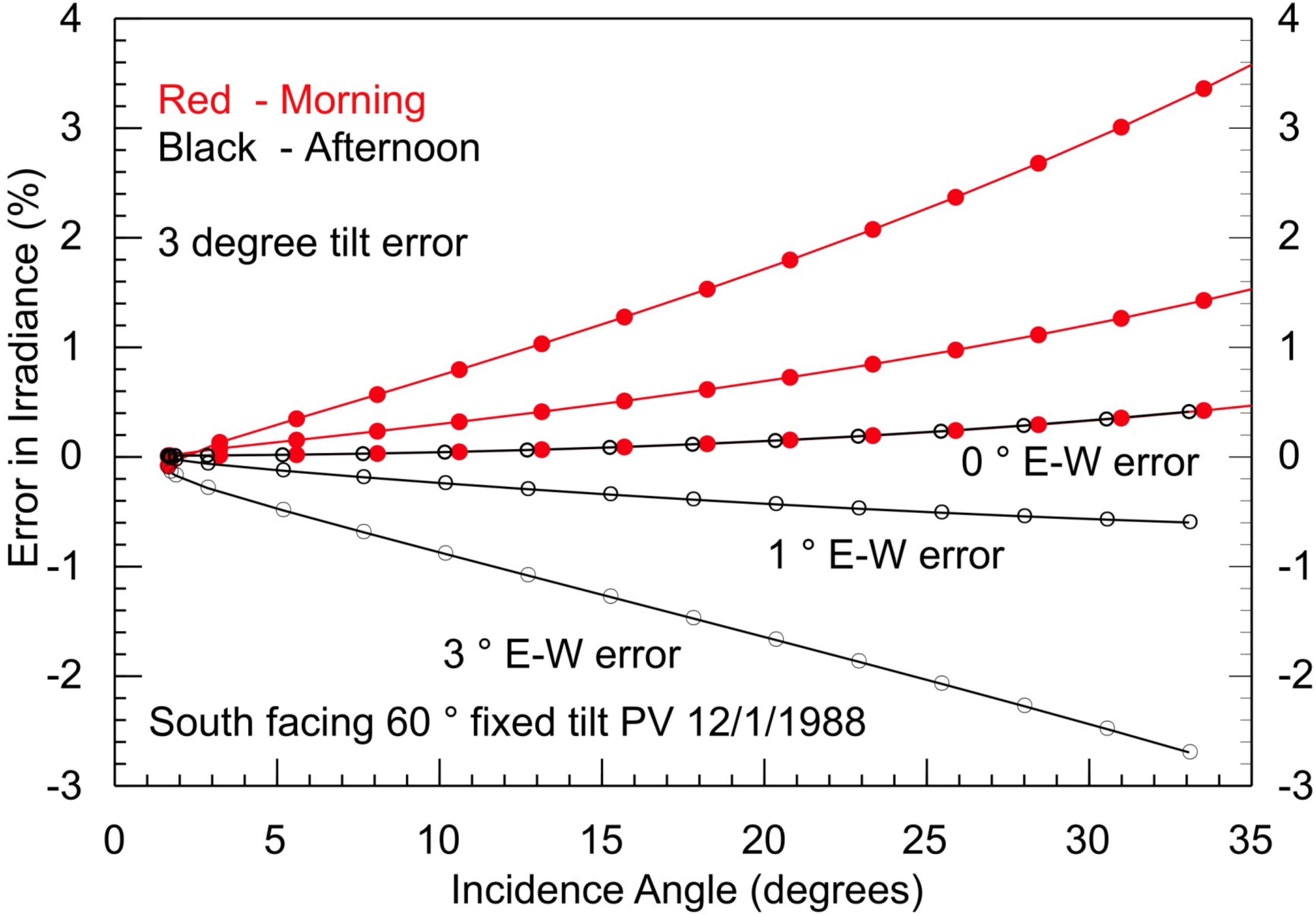
NREL single day Pyranometer calibrations, 2 degree bins

http://www.nrel.gov/aim/



Leveling Error

How closely must irradiance sensor be aligned to PV array?
What is impact of PV modules in system misaligned with respect to each other?

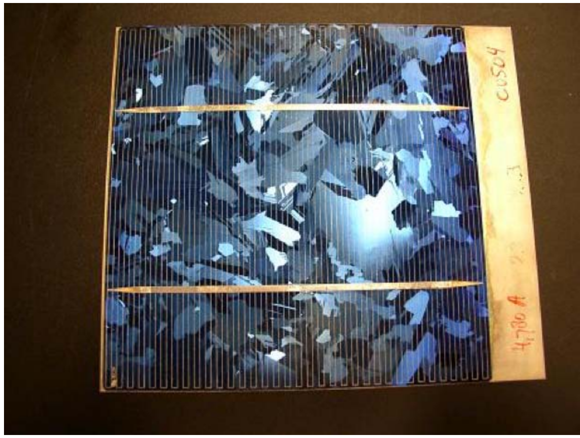


K.A. Emery, et al, "SERI Results from the PEP 1987 Summit Round Robin and a Comparison of Photovoltaic Calibration Methods," SERI tech. rep. TR-213-3472, March 1989.

Si secondary calibrations

Formal and informal secondary reference cell intercomparisons among ISO 17025 accredited or equivalent calibration labs suggest that the uncertainty is ±2% or less.

Cell	Calibrated	Isc (A)	Isc,ECN	ΔI (%)
100-A	ESTI 2002	3.020 ± 1.9%	3.032	+0.4
100-B	ESTI 2002	3.006 ± 1.9%	3.019	+0.4
100-B	NREL 2003	3.023 ± 2.0%	3.019	-0.1
125-A	ESTI 2002	4.780 ± 1.9%	4.816	+0.8
125-B	ESTI 2002	4.731 ± 2.0%	4.716	-0.3
125-C	NREL 2004	5.311 ± 2.0%	5.311	---
125-D	NREL 2004	5.380 ± 2.0%	5.393	+0.2
125-E	PTB 2004	4.752 ± 2.9%	4.724	-0.6
150-A	ESTI 2002	6.858 ± 1.9%	6.808	-0.7
150-B	PTB 2004	7.247 ± 2.8%	7.122	-2.2



Arvid van der Heide, Stefan Winter, Keith Emery, and Wim Zaaiman, "Comparison Between Large Reference Cells Calibrated by ESTI-JRC, NREL and PTB, Performed at ECN", Proc. 20th EU PVSEC, June, 2005.

NREL's Approach to Local and Remote System Monitoring

Successful monitoring requires understanding the entire data acquisition system.

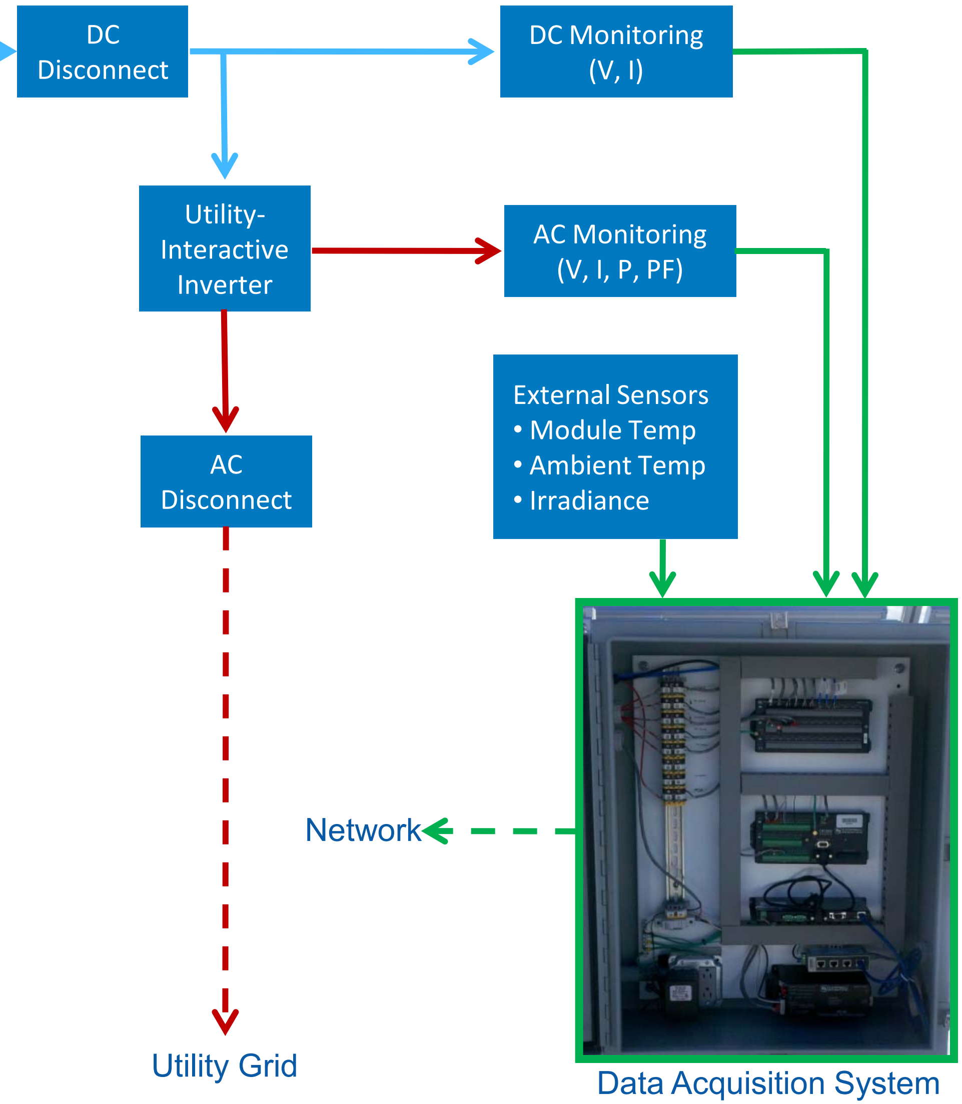
Budget constraints may dictate to what extent monitoring is possible.

Local and remote monitoring applications can require different approaches.

Primary concepts for either monitoring application include:

- Select highly reliable hardware suitable for the end-use environment
- Decrease the susceptibility to external noise
- Choose sensors with low uncertainties and low drift
- In general, a simple system design is better
- Calibrate! Calibrate! Calibrate! - Calibration drift adversely impacts data quality and interpretation (next talk).

Typical NREL Installation



Choices

Reliable hardware is worth the cost!

- If the data is to be used for modeling or analysis than it needs to be as accurate and complete as possible. Unreliable hardware can impact results because of missing, inaccurate, or noisy measurements.
- Limit external noise by using good quality signal wires.
  - Foil shielded with drain wire or dense braided shield; one side only!
  - Transition between different thermal environments may require PTFE jacket
- Protect DAS hardware by using reliable fuses (especially on DC side of system)
- Use equipment rated for the worst-case temperature (usually 90° C).
- Monitoring equipment rated for range of ambient temperatures where deployed.
- A hardware suite of preference comes with experience (and from failures)
- A trustworthy communications interface and large internal storage is essential.

"Simple is better" - In our experience this is a true statement.

- Unnecessary signal conditioning increases uncertainty and creates more failure points.
- Passive devices with low thermal coefficients work very well.

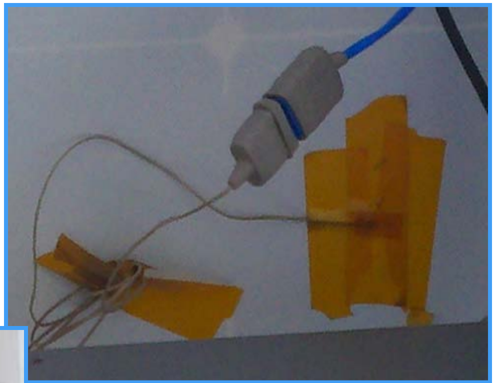
Calibrate

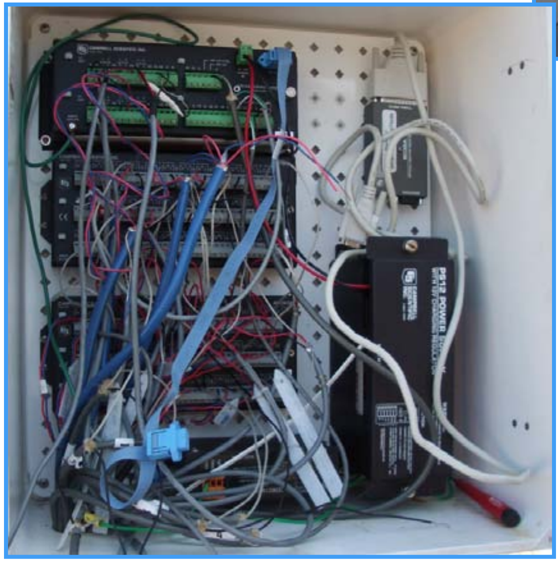
- Failure to do so impacts system rating uncertainty and degradation rates
- Don't blindly trust data sheets.
  - Often, the manufacturer calibration is valid for only one year.
- A complete end-to-end calibration, when possible, limits systematic errors.
- Periodic pyranometer calibrations (such as NREL's BORCAL) are essential!
  - 24 month schedule is normal, periodic inspection / cleaning of sensors

Keep it Clean

- Use devices designed and rated for the end-use environment
- Limit access to weather and vermin
- Use good wire management practices; label signal lines
- Make sure all measurement equipment is grounded


Lizard living within enclosure


Degraded polyimide tape; potential for poor thermal contact


Poor wire management; lack of labeling.


Corroded signal connections

vs.


Clean installation; good wire management; rated devices.


Tight contact with module; limited ability for corners to lift.

Recommendations

Topic	Recommendation	Reason
Measurement Interval	5-sec scans into 1-min averages	15-minute data (standard) cannot capture many system issues; 1-minute data provides the resolution needed for capturing transient system events such as inverter shutdown. 1-minute data also supports analysis which require more data points (degradation rate calculations, for instance). With the cost of hardware and storage decreasing there is no reason to avoid 1-minute (or sub-minute) data collection.
Analog Signal Lines	High quality PTFE Jacket; Shielded w/ drain wire	Experience has shown that PTFE jacketed signal lines are less susceptible to noise when going between different temperature environments. Also, PTFE has superior resistance against weather (UV, moisture, temperature) when used outdoors.
Outdoor Connectors	Rated for the environment; Use of protective boots.	Use all means to limit connector corrosion. Sunlight resistant boots must be used; unrated boots can crack and actually trap moisture within the connector housing.
Equipment Temperature Ratings	-55° C to 85° C	Equipment enclosures can see dramatic temperatures, especially if exposed to direct sunlight. Equipment must handle these extremes.
Enclosure Locations	In the shade	Direct exposure to sunlight can raise the interior temperature of an enclosure dramatically.
Thermocouple Attachment	Clean location and hands; Silicone adhesive; Round shape	Silicone adhesive has withstood outdoor testing very well. Limit contamination of the adhesive by cleaning the attachment location (w/ IPA) and your hands. Avoid touching the adhesive by using tape with a split carrier film. Square corners are prone to lifting; round dots limits lifting.
Inspection Interval	Visual checks quarterly	Check for: 1)Thermocouple detachment or tape embrittlement 2)Damage to exterior sensors (pyranometers, ambient temp sensors) 3)Evidence of moisture or vermin in enclosures 4)Loose connections at DAS / sensors
Calibration Interval	End-to-End Calibration Annually -Ambient temp above 15° C -Wind speeds below 3 m/s	Bench calibrations are done in an atypical environment (indoor is not equivalent to outdoor conditions). Calibration equipment can be affected by the surrounding environment. Limit temperature extremes and high winds which may cause offsets in the calibration hardware. End-to-end calibrations are necessary to limit uncertainties and systematic errors.

Monitoring Budget

As budgets for monitoring increase, the measurement data sources can be expanded.

- Allows for additional analysis options and backups

Component or Measurement	Data Source	Small		Budget		Large
		Limited		Analysis Options[2]		Significant
AC Energy Generation[1]	ANSI C12.20 Revenue Grade Meter			•	•	•
	Collected from Inverter	•	•	•	•	•
DC Energy Generation[1]	External Current and Voltage Transducers					•
	Collected from Inverter	•	•	•	•	•
Inverter Status and Errors	Collected from Inverter	•	•	•	•	•
Global Horizontal Irradiance	Thermopile Pyranometer					•
	Silicon Photodiode Pyranometer			•	•	
Plane-of-Array Irradiance	Thermopile Pyranometer					•
	Same-Technology Reference Cell / Module			•	•	•
	Silicon Photodiode Pyranometer	•	•	•	•	
Ambient Temperature	Thermocouple, RTD, Thermistor	•	•	•	•	•
Module Backsheet Temperature(s)	Thermocouple, RTD, Thermistor		•	•	•	•
Wind Speed	Ultrasonic Anemometer				•	•
	Cup Anemometer		•	•		

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

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

Summary

- The dominant error source in determining the system power is determining the plane-of-array irradiance
- Performance monitoring is significantly affected by the quality of the measurement hardware and the professionalism of the installation.
- Results of performance modeling have greater meaning if the measurement hardware is calibrated regularly.
- Calibration drift can invalidate all data since the previous calibration.
- No standards for system Energy rating, minimal standards for system power rating