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LONG-TERM PERFORMANCE AND RELIABILITY ASSESSMENT OF 8 PV ARRAYS AT SANDIA NATIONAL LABORATORIES

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OUTLINE

- Motivation
- Background
- Array field overview
- Test method
- Initial data
- Trouble-shooting the arrays
- Summary

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MOTIVATION

- Use Sandia's 95 kW array field to understand:
  - System-level performance degradation
  - System-level reliability issues seen in the field
  - Operations and Maintenance
- Apply a process to assess each of these in this "microcosm" of a larger, multi-array, multi-inverter system
- Transfer knowledge to PV community

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BACKGROUND

- Sandia's Solar Energy Systems team brings a *systems approach* to PV performance, degradation and reliability
  - The PV Systems Evaluation Lab (PSEL) focuses on module issues and how they fit into a system
  - The Distributed Energy Technologies Lab (DETL) focuses on inverters and the balance-of-systems aspects
  - Working together provides AC and DC expertise for most aspects of PV systems

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Array Field Overview

- DETL array field used primarily to assess *fielded* performance and reliability of inverters
  - DETL array field currently uses ~95 kW (STC) from 9 different systems
  - Strings are reconfigurable to test various inverter sizes and configurations
  - All but one system at fixed latitude tilt
- PSEL performs initial DC “acceptance test” and periodic DC performance assessments on arrays

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Array Field Overview

Array #	Tech	Strings	Modules /String	Instl. Date	Name Plate Rating (kW)
1	a-Si	70	1	2002	3.06
2	c-Si	4	20	2004	6.00
3	mc-Si	4	22	2005	7.04
4	mc-Si	4	22	2005	7.04
5	c-Si	6	7	2005	9.31
6	c-Si	3	28	2005	7.04
7	a-Si	3	2	2006	3.26
8	c-Si	3	21	2006	7.92
9	c-Si	24	12	2008	50.50

Primary focus of this presentation:
Six silicon-based PV arrays at Sandia's DETL

Array DC Test Method

- 2-3 modules baselined prior to installation
  - Full outdoor electrical performance testing and thermal response on a tracker and indoor dark IV
  - Analyzed according to Sandia PV Performance Model
- DC string-level testing
  - Thermocouples on backside of two modules per array
  - Measured during spring or autumn: solar incident angles < 50 degrees during AMa 1.5
  - Two c-Si reference cells at POA to measure irradiance and soiling effects
  - Daystar data acquisition system and thermocouple data logger to gather data
  - Collect IV curves and temp data every 2 minutes over a mostly clear sky day
  - Estimated measurement error is +/- 2.5%

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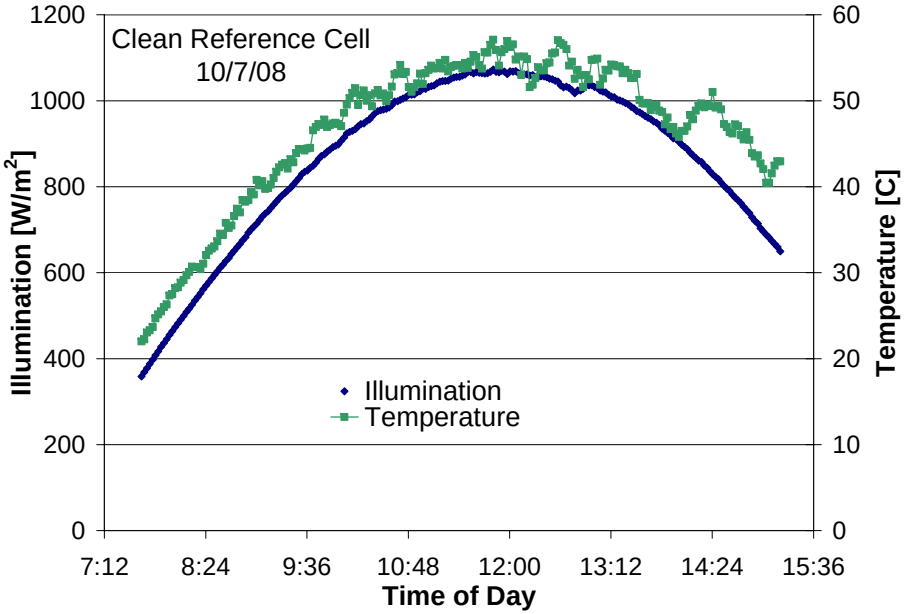
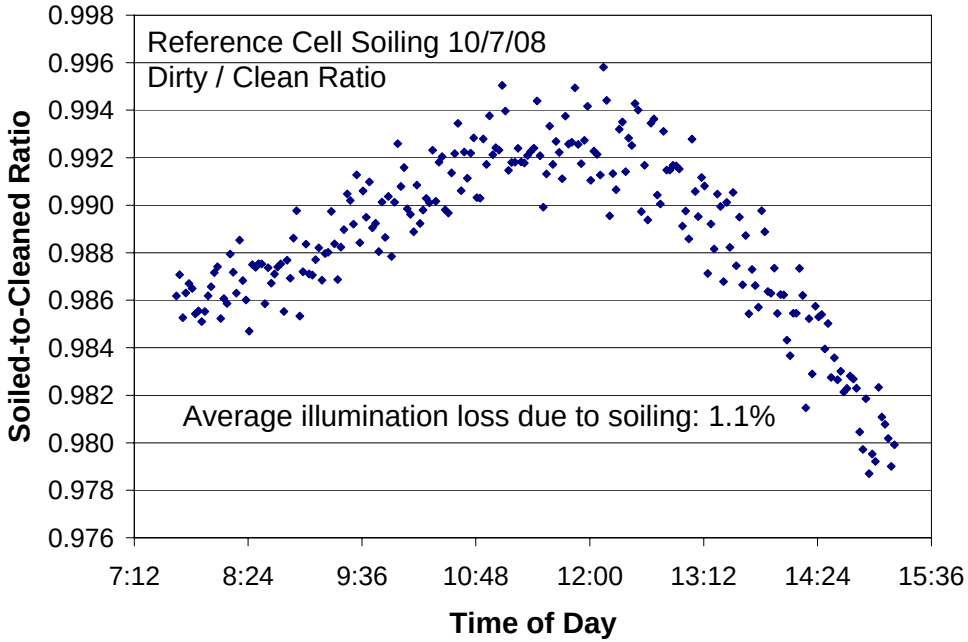
Array DC Test Method

- Periodic DC performance assessments on arrays
  - Date of re-measure for this assessment: October 2008
  - Same method used as outlined for DC performance after disconnecting from inverter



Illumination and module temperature during October 2008 testing



Effect of soiling on arrays

Included in data translation to SRC

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Array Performance Change

Array	Test Date	Isc [A]	Imp [A]	Voc [V]	Vmp [V]	Pmp [W]	FF
System #1, a-Si, 3.06 kW Installed 2002	% diff*	-45.3	-45.9	-4.4	-3.6	-47.9	-0.4
	%/year	*-7.0*	*-7.1*	*-0.7*	*-0.6*	*-7.4*	*-0.1*
System #2, mc-Si, 5.42 kW Installed 2004	% diff	+2.1	+1.5	-0.9	-2.1	-0.7	-1.8
	%/year	*+0.5*	*+0.4*	*-0.2*	*-0.5*	*-0.2*	*-0.4*
System #3, mc-Si, 6.87 kW Installed 2005	% diff	-24.6	-24.9	-2.2	-1.0	-25.6	+1.0
	%/year	*-8.0*	*-8.1*	*-0.7*	*-0.3*	*-8.3*	*+0.3*
System #4, mc-Si, 7.00 kW Installed 2005	% diff	-1.9	-1.8	+0.9	+0.6	-1.2	-0.1
	%/year	*-0.6*	*-0.6*	*+0.3*	*+0.2*	*-0.4*	*-0.0*
System #5, mc-Si, 7.99 kW Installed 2005	% diff	-17.2	-16.7	-0.2	-0.3	-17.0	+0.6
	%/year	*-5.6*	*-5.4*	*-0.1*	*-0.1*	*-5.5*	*+0.2*
System #6, mc-Si, 6.93 kW Installed 2005	% diff	-0.3	-2.0	-0.1	-2.3	-4.3	-3.8
	%/year	*-0.1*	*-0.7*	*-0.0*	*-0.8*	*-1.4*	*-1.3*
System #7, a-Si, 3.26 kW Installed 2006 (Roof mount)	% diff*	-2.6	+0.4	-1.0	+0.3	+0.9	+4.3
	%/year	*-1.2*	*+0.2*	*-0.5*	*+0.1*	*+0.4*	*+2.0*
System #8, c-Si, 5.69 kW Installed 2006	% diff	-1.1	-9.8	+0.4	+3.3	-6.9	-6.2
	%/year	*-0.5*	*-4.9*	*+0.2*	*+1.6*	*-3.5*	*-3.1*

% difference calculated from initial measured data or from Name Plate*

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A-Si Systems: #1, #7

- A-Si System #1: Nothing of interest to be learned
  - Older technology, known to degrade quickly
  - No longer being manufactured
- A-Si system #7: Behaving as expected
  - Not tested upon installation
  - First DC test October 2008
  - Has reached the name plate values to within measurement error after 2.5 years in the field
  - A-Si stabilization expected within the first year
    - No additional degradation is being observed in the early years for this system

Array	Test Date	Isc [A]	Imp [A]	Voc [V]	Vmp [V]	Pmp [W]	FF
System #1, a-Si, 3.06 kW Installed 2002	% diff	-45.3	-45.9	-4.4	-3.6	-47.9	-0.4
	%/year	*-7.0*	*-7.1*	*-0.7*	*-0.6*	*-7.4*	*-0.1*
System #7, a-Si, 3.26 kW Installed 2006 (Roof mount)	% diff	-2.6	+0.4	-1.0	+0.3	+0.9	+4.3
	%/year	*-1.2*	*+0.2*	*-0.5*	*+0.1*	*+0.4*	*+2.0*

Note data is not corrected for a-Si seasonal effects

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Systems #2, #4 and #6

- System #2, c-Si: Behaving as expected
  - Oldest of the crystalline silicon systems, installed mid 2004
  - Demonstrated consistent performance over nearly five years in the field, with no measurable change in parameters
- Systems #4 (mc-Si) and #6 (c-Si): Behaving as expected
  - Both installed in October 2005
  - Showing little to no degradation within measurement error

Array	Test Date	Isc [A]	Imp [A]	Voc [V]	Vmp [V]	Pmp [W]	FF
System #2, mc-Si, 5.42 kW Installed 2004	% diff	+2.1	+1.5	-0.9	-2.1	-0.7	-1.8
	%/year	***+0.5***	***+0.4***	***-0.2***	***-0.5***	***-0.2***	***-0.4***
System #4, mc-Si, 7.00 kW Installed 2005	% diff	-1.9	-1.8	+0.9	+0.6	-1.2	-0.1
	%/year	***-0.6***	***-0.6***	***+0.3***	***+0.2***	***-0.4***	***-0.0***
System #6, mc-Si, 6.93 kW Installed 2005	% diff	-0.3	-2.0	-0.1	-2.3	-4.3	-3.8
	%/year	***-0.1***	***-0.7***	***-0.0***	***-0.8***	***-1.4***	***-1.3***

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System #3, mc-Si

- System #3, mc-Si: One failed module = 25% power loss
  - System #3 demonstrated much greater losses than expected
  - A 4-string module, 25% power and current loss was likely due to one lost string
  - Trouble-shooting included:
    - Visual Inspection
    - Fuse and Interconnect check
    - IR Imaging in the field
    - Module-by-module Voc and IV check

Array	Test Date	Isc [A]	Imp [A]	Voc [V]	Vmp [V]	Pmp [W]	FF
System #3, mc-Si, 6.87 kW	% diff	**-24.6**	**-24.9**	**-2.2**	**-1.0**	**-25.6**	**+1.0**
Installed 2005	*%/year*	***-8.0***	***-8.1***	***-0.7***	***-0.3***	***-8.3***	***+0.3***

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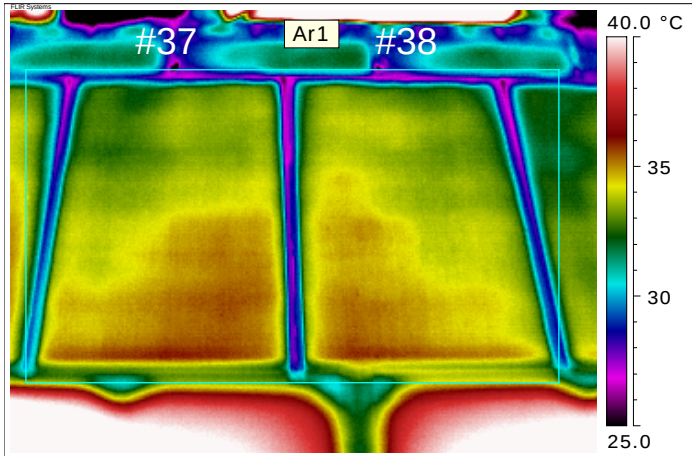
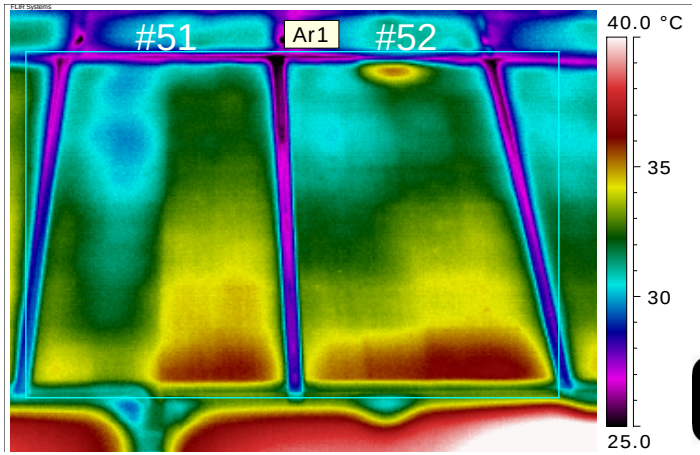
System #3, mc-Si

- Trouble-shooting results:
  - Visual Inspection showed no cracked or discolored modules
  - All fuses and interconnects operating
  - All strings hooked up correctly
  - No obvious lost modules under IR Imaging in the field
  - All modules operative based on module-by-module Voc check
  - Found one intermittent module under module-by-module IV sweep in the field

Sample IR images in the field



IR images in the field with issues observed; module on left intermittent



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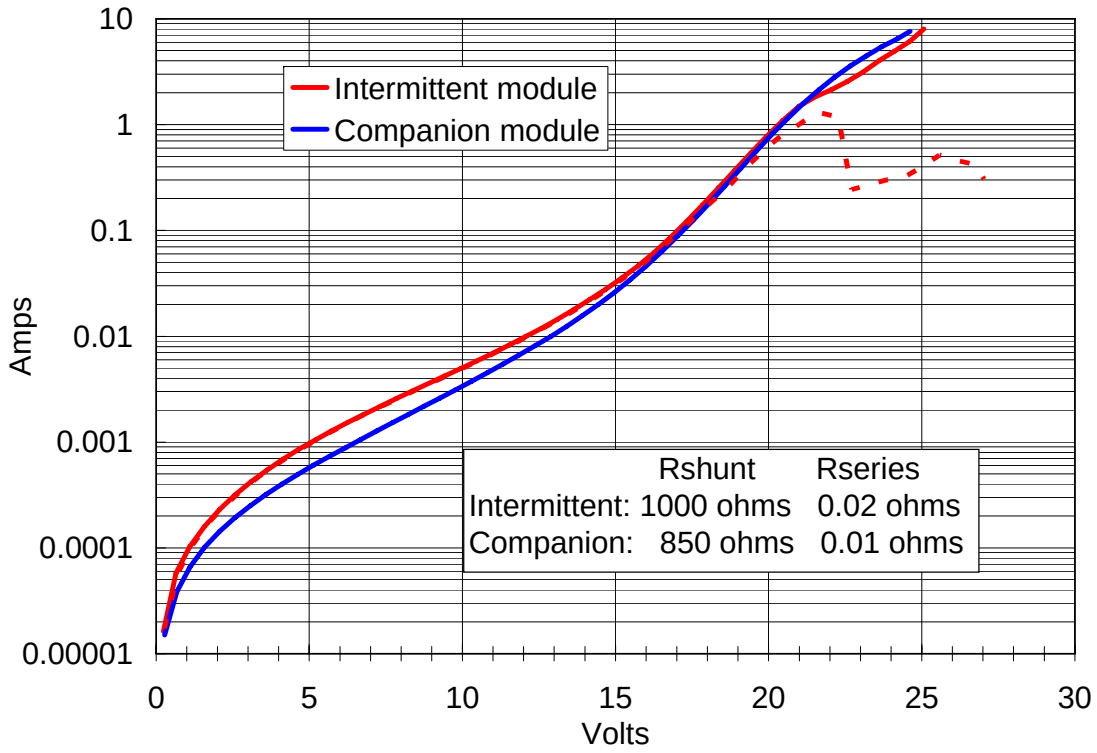
System #3, mc-Si

- Assess intermittent (“IM”) module:
  - Dark IV performed on “IM” module and on a companion module from the array
  - No major differences in performance, other than intermittency and difficulty reaching high voltage



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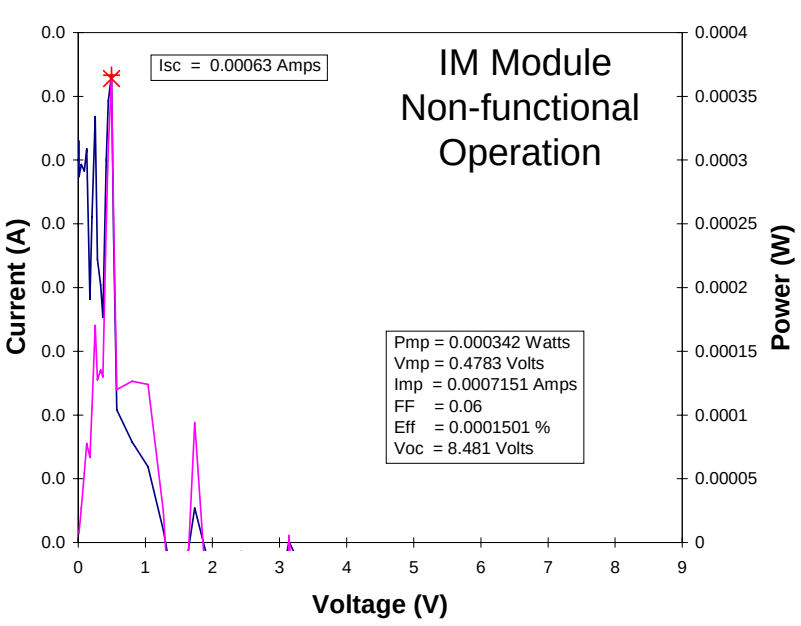
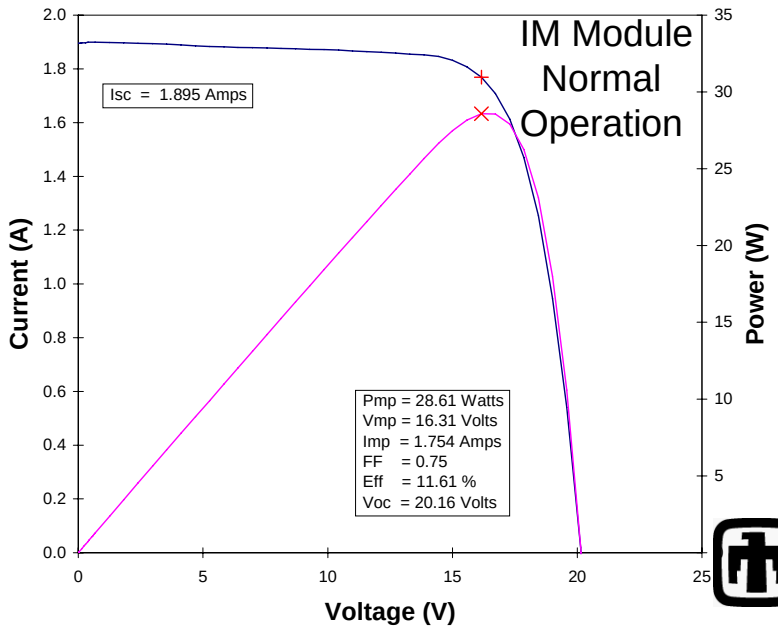
System #3, mc-Si

- Assess intermittent (“IM”) module:
  - Outdoor performance on “IM” module and on a companion module from the array
  - Companion module performed as expected
  - “IM” module had complete drop-outs unrelated to time, temperature, or illumination level
  - No major differences in performance, other than intermittency





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System #3, mc-Si

- Assess intermittent (“IM”) module:
  - It was possible to induce the intermittency by manipulating the pigtails, suggesting the failure mechanism is in the attachment of the pigtail to the circuit.
  - Remaining steps to prove this hypothesis include:
    - Non-destructive imaging techniques of the module to look for damage
    - Take the junction box apart
- DC test repeated in February 2009 after replacing intermittent module
    - Recovered to within measurement error of initial test

Array	Test Date	Isc [A]	Imp [A]	Voc [V]	Vmp [V]	Pmp [W]	FF
System #3, mc-Si, 6.87 kW	% diff	**-24.6**	**-24.9**	**-2.2**	**-1.0**	**-25.6**	**+1.0**
3 year Assessment	*%/year*	***-8.0***	***-8.1***	***-0.7***	***-0.3***	***-8.3***	***+0.3***
Retest after module replacement	% diff	**+0.6**	**+0.3**	**+1.4**	**+1.8**	**+2.0**	**+0.0**
	%/year	***+0.2***	***+0.1***	***+0.5***	***+0.6***	***+0.7***	***+0.0***

System #5, c-Si

- System #5, c-Si: Loss due to Balance-of-Systems Error
  - System #5 demonstrated much greater losses than expected
  - A 6-string module, 17% power and current loss was likely due to one lost string
  - Trouble-shooting included:
    - Visual Inspection
    - Fuse and Interconnect check
    - IR Imaging in the field
    - Module-by-module Voc and IV check

Array	Test Date	Isc [A]	Imp [A]	Voc [V]	Vmp [V]	Pmp [W]	FF
System #5, mc-Si, 7.99 kW Installed 2005	% diff	-17.2	-16.7	-0.2	-0.3	-17.0	+0.6
	%/year	*-5.6*	*-5.4*	*-0.1*	*-0.1*	*-5.5*	*+0.2*

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System #5, c-Si

- Trouble-shooting results:
  - Visual Inspection showed no cracked or discolored modules
  - All fuses and interconnects operating
  - No stand-outs under IR Imaging in the field
  - All modules operative based on module-by-module Voc check
  - String-level hookup check revealed 6th string connected incorrectly
    - Corrected string hookup
  - DC test repeated in February 2009
    - Recovered to within measurement error of initial test

Array	Test Date	Isc [A]	Imp [A]	Voc [V]	Vmp [V]	Pmp [W]	FF
System #5, mc-Si, 7.99 kW 3 year Assessment	% diff	-17.2	-16.7	-0.2	-0.3	-17.0	+0.6
	%/year	*-5.6*	*-5.4*	*-0.1*	*-0.1*	*-5.5*	*+0.2*
Retest after string polarity change	% diff	-0.6	+0.0	+0.3	-0.3	-0.3	+0.1
	%/year	*-0.2*	*+0.0*	*+0.1*	*-0.1*	*-0.1*	*+0.0*

System #8, c-Si

- System #8, c-Si: Loss due to Balance-of-Systems Error
  - System #8 technology requires positively-grounded inverter for optimal performance
  - Quick check found it was hooked to a negatively-grounded inverter
  - DC test repeated after one week on correct inverter
    - Recovered from 34% power loss to 7% power loss
  - DC test repeated in February 2009 after 4 months on correct inverter
    - Recovered to within measurement error of initial test

Array	Test Date	Isc [A]	Imp [A]	Voc [V]	Vmp [V]	Pmp [W]	FF
System #8, c-Si, 5.69 kW	% diff	-1.1	-9.8	+0.4	+3.3	-6.9	-6.2
2 year Assessment	*%/year*	*-0.5*	*-4.9*	*+0.2*	*+1.6*	*-3.5*	*-3.1*
Retest after 4 months on +grounded inverter	% diff	-3.7	-3.7	+1.6	+1.2	-2.5	-0.3
	%/year	*-1.8*	*-1.8*	*+0.8*	*+0.6*	*-1.2*	*-0.1*

RELIABILITY

- The fielded arrays were examined for reliability issues and/or potential for failure. The following are issues observed in modules that contribute to reduced reliability:
  - Performance loss >1% per year
  - Encapsulant/backsheet discoloration (2 c-Si technologies)
  - Burn marks/arcing (2 c-Si technologies)
  - Backsheet delamination visible under visual inspection
  - Hot spots seen in IR images
  - Broken glass
  - Breakdown in polymer outer sheet
  - Corrosion of interconnect regions

RELIABILITY

- Of the reliability issues discovered, some are easily classified as failures, others may be considered failures based on aesthetics, and some are indicators of likely premature failure
- There is still too little data for statistical reliability assessments on these arrays
- The issues observed will be followed in coming years, particularly to look for early indicators of module failure

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Next Steps

1. Additional failure analysis of IM module from System #3
2. Investigate the AC data to look for patterns and early indicators of degradation
3. Remeasure modules from each system on the 2-axis tracker to document any module-level degradation
4. Further investigation of data trends for degradation beyond measurement error
5. Annual or bi-annual DC testing on each system to continue monitoring any long term degradation and follow progression of noted reliability concerns

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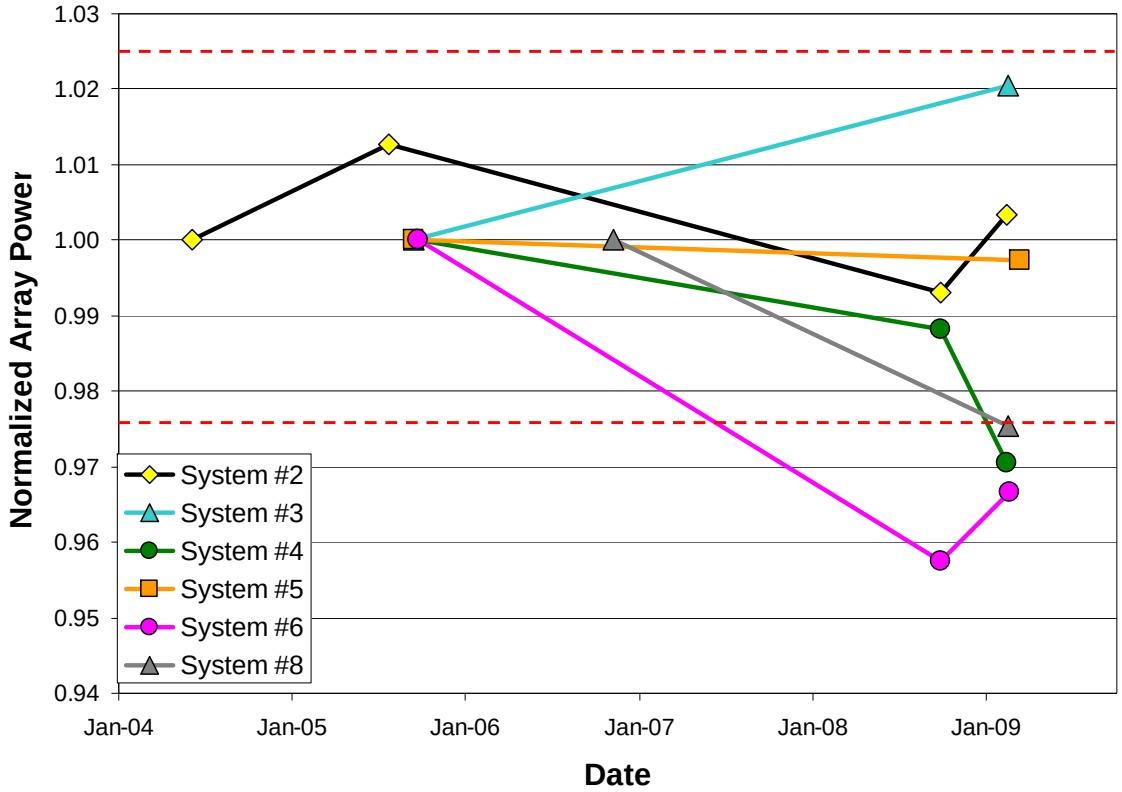
Next Steps

- Further investigation of data trends for degradation beyond measurement error
- Normalized power versus time after restoring arrays shows likely true power degradation in System #6 and possibly System #4



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Conclusions and Lessons Learned

- Only System #6 showed true power degradation beyond experimental error at 4.3%±2.5%, (ave. 1.4%±0.8%/year)
- In all other cases, the degradation rate was less than the experimental error
- Lessons learned:
  - Proper commissioning is essential to detect installation errors
  - Acceptance testing should also be performed following any maintenance work
    - Testing and checking against expected array output would have quickly caught loss mechanisms for Systems #5 and #8
  - Sufficiently sensitive string-level monitoring might have detected the string degradation due to failed module in System #3
  - Peer to peer (string to string) monitoring at the string level would have certainly detected string degradation due to the failed module

Contact Information

Thank You!

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