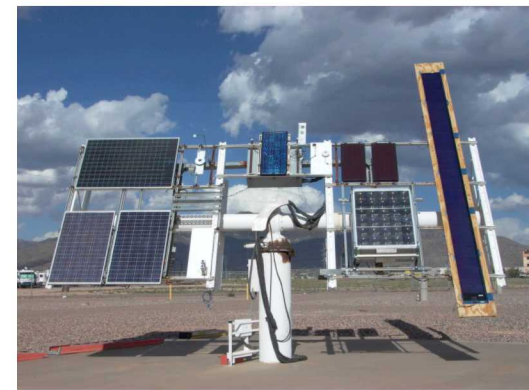
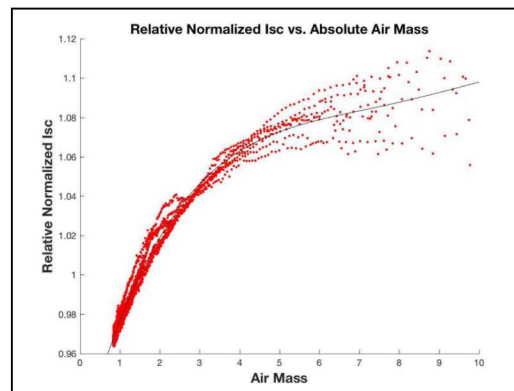


This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.



Application of the Sandia Array Performance Model to Assess Multi-Year Performance of Fielded CIGS PV Arrays

Bruce King, Charles Robinson, Craig Carmignani, Dan Riley and Birk Jones

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Waikoloa, HI

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Acknowledgement

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Outline

- System Descriptions and Instrumentation
- Characterization and Analysis Methods
- STC Flash Test Measurements
- Analyzed System Data

Goals

- Characterize degradation/stability across a range of CIGS products & technology
- Fielded systems
- Common operating environment
- Assess performance model accuracy



System Descriptions

System	Cell	Package	Size (kW)	Installation	Age, months	Status
CIGS-1	discrete	Polymer/Flex	3.36	1/12	18	Inactive
CIGS-2	discrete	Glass-glass	2.2	1/12	45	Active
CIGS-3	discrete	Glass-glass	2.32	6/12	41	Active
CIGS-4	monolithic	Glass-glass	4.8	6/13	20	Inactive
CIGS-5	monolithic	Glass-glass	6	4/15	22	Active
CIGS-6	monolithic	Glass-glass	6	4/15	23	Active

- Grid-tied, 600VDC Central Inverters
- Independent DC monitoring (Voltage, Current), module temperature
- Local POA Irradiance, co-located weather platform
- 5-second sampling => 1 minute averages for analysis
- Nightly automated data screening (PECOS)

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CIGS-2	discrete	Glass-glass	2.2	1/12	45	Active
CIGS-3	discrete	Glass-glass	2.32	6/12	41	Active
CIGS-4	monolithic	Glass-glass	4.8	6/13	20	Inactive
CIGS-5	monolithic	Glass-glass	6	4/15	22	Active
CIGS-6	monolithic	Glass-glass	6	4/15	23	Active

- For this presentation, will focus only on three systems
- CIGS-1 and 4 have been retired
- CIGS-5 and 6 are very similar



Individual modules characterized before and after deployment

Flash Testing

- Spire 4600SLP
- STC characterization
- Modules light-soaked outdoors under natural conditions or removed directly from operational array
- Multiple modules of each type



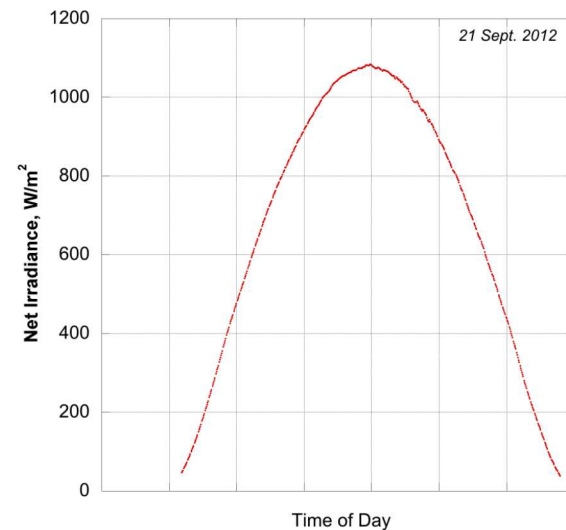
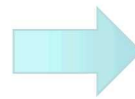
Outdoor Tracker Testing

- Two-axis solar tracker, modules held normal to sun, 2-4 weeks.
- Tracker held on sun from sunrise to sunset, multiple days, clear and cloudy conditions
- IV curves measured at 2 minute intervals
- Approximately 1000 IV curves minimum
- Simultaneous multivariate regression analysis to determine SAPM coefficients for each system

System Performance Modeling

- SAPM – use model coefficients calibrated from outdoor tracker testing
- Inputs – local weather, irradiance
 - 1-minute weather files from onsite weather station
 - Spans period of system operation, 2012-2018
 - Apply filters to remove night-time, low irradiance conditions, bad data
- Calculate Net plane of array irradiance, corrected for angle of incidence

$$E_{net} = E_{POA} - E_{DNI} \cos(AOI) [1 - f_2(AOI)]$$



System Performance Modeling

- Calculate effective cell temperature from net POA irradiance, ambient temperature and wind speed

$$T_c = E_{net} [e^{a+b*WS}] + \frac{E_{net}}{1000} \Delta T + T_a$$

- Calculate effective irradiance from air mass, net POA irradiance

$$E_e = f_1(AM)E_{net}$$

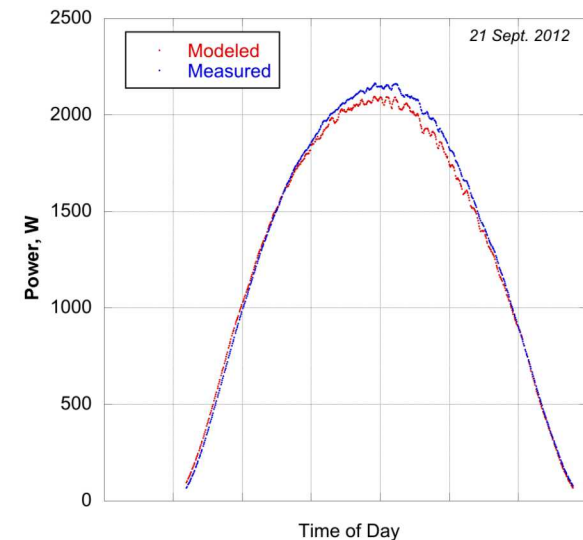
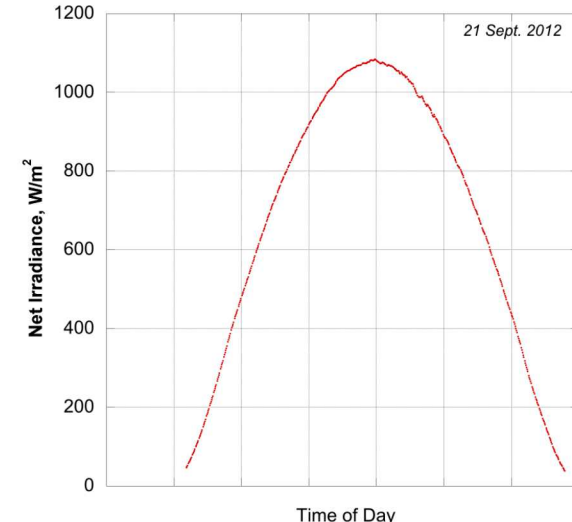
- Calculate current and voltage at max power

$$I_{mp} = I_{mpo} [C_0 E_e + C_1 E_e^2] [1 + \alpha_{I_{mp}} [T_c - T_0]]$$

$$V_{mp} = V_{mpo} + C_2 N_s \delta(T_c) \ln(E_e) + C_2 N_s [\delta(T_c) \ln(E_e)]^2 + \beta_{V_{mp}} [T_c - T_0]$$

$$P_{mp} = I_{mp} V_{mp}$$

- Compare Measured vs Modeled for period of operation (2012-2018)



Results: STC Flash Test

STC Flash Test Results

System ID	CIGS-2			CIGS-3			CIGS-6		
# Modules	1			2			5		
Age, months	0	45	76	0	41	70	0	23	38
P_{mp} (mW/cm ²)	12.0	11.1	10.2	13.5	13.7	13.7	12.9	13.0	12.1
I_{sc} (mA/cm ²)	30.1	29.9	30.3	29.2	29.8	30.2	31.3	30.7	30.6
V_{oc} (mV/cell)	595	581	572	639	639	637	591	597	593
I_{mp} (mA/cm ²)	26.0	24.3	23.2	26.0	26.4	26.6	27.9	27.7	27.2
V_{mp} (mV/cell)	464	458	442	519	518	515	461	468	445
$R@I_{sc}$ (W-cm ²)	326	210	143	423	465	423	-	1116	878
$R@V_{oc}$ (W-cm ²)	2.65	2.19	2.54	0.94	1.90	2.01	-	2.74	4.13
Fill Factor	0.67	0.64	0.59	0.72	0.72	0.71	0.69	0.71	0.67

STC Flash Test Results: CIGS-2

System ID	CIGS-2			CIGS-3			CIGS-6		
# Modules	1			2			5		
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- Steady decrease in P_{mp} with age

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- Steady decrease in P_{mp} with age
- Drop in P_{mp} is primarily due to a drop in I_{mp}

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Fill Factor	0.67	0.64	0.59	0.72	0.72	0.71	0.69	0.71	0.67

- Steady decrease in P_{mp} with age
- Drop in P_{mp} is primarily due to a drop in I_{mp}
- Drop in I_{mp} accompanied by a significant drop in Shunt Resistance

STC Flash Test Results: CIGS-2

System ID	CIGS-2			CIGS-3			CIGS-6		
# Modules	1			2			5		
Age, months	0	45	76	0	41	70	0	23	38
P_{mp} (mW/cm ²)	12.0	11.1	10.2	13.5	13.7	13.7	12.9	13.0	12.1
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Fill Factor	0.67	0.64	0.59	0.72	0.72	0.71	0.69	0.71	0.67

- Decrease in V_{mp} tracks with decrease in V_{oc}
- $R@V_{oc}$ doesn't change significantly

STC Flash Test Results: CIGS-3

System ID	CIGS-2			CIGS-3			CIGS-6		
# Modules	1			2			5		
Age, months	0	45	76	0	41	70	0	23	38
P_{mp} (mW/cm ²)	12.0	11.1	10.2	13.5	13.7	13.7	12.9	13.0	12.1
I_{sc} (mA/cm ²)	30.1	29.9	30.3	29.2	29.8	30.2	31.3	30.7	30.6
V_{oc} (mV/cell)	595	581	572	639	639	637	591	597	593
I_{mp} (mA/cm ²)	26.0	24.3	23.2	26.0	26.4	26.6	27.9	27.7	27.2
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Fill Factor	0.67	0.64	0.59	0.72	0.72	0.71	0.69	0.71	0.67

- P_{mp} is flat Year-over-Year

STC Flash Test Results: CIGS-3

System ID	CIGS-2			CIGS-3			CIGS-6		
# Modules	1			2			5		
Age, months	0	45	76	0	41	70	0	23	38
P_{mp} (mW/cm ²)	12.0	11.1	10.2	13.5	13.7	13.7	12.9	13.0	12.1
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Fill Factor	0.67	0.64	0.59	0.72	0.72	0.71	0.69	0.71	0.67

- P_{mp} is flat Year-over-Year
- All other parameters are also flat
- Remarkably stable module

STC Flash Test Results: CIGS-6

System ID	CIGS-2			CIGS-3			CIGS-6		
# Modules	1			2			5		
Age, months	0	45	76	0	41	70	0	23	38
P_{mp} (mW/cm ²)	12.0	11.1	10.2	13.5	13.7	13.7	12.9	13.0	12.1
I_{sc} (mA/cm ²)	30.1	29.9	30.3	29.2	29.8	30.2	31.3	30.7	30.6
V_{oc} (mV/cell)	595	581	572	639	639	637	591	597	593
I_{mp} (mA/cm ²)	26.0	24.3	23.2	26.0	26.4	26.6	27.9	27.7	27.2
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$R@V_{oc}$ (W-cm ²)	2.65	2.19	2.54	0.94	1.90	2.01	-	2.74	4.13
Fill Factor	0.67	0.64	0.59	0.72	0.72	0.71	0.69	0.71	0.67

- P_{mp} was initially flat but is now showing some degradation

STC Flash Test Results: CIGS-6

System ID	CIGS-2			CIGS-3			CIGS-6		
# Modules	1			2			5		
Age, months	0	45	76	0	41	70	0	23	38
P_{mp} (mW/cm ²)	12.0	11.1	10.2	13.5	13.7	13.7	12.9	13.0	12.1
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Fill Factor	0.67	0.64	0.59	0.72	0.72	0.71	0.69	0.71	0.67

- P_{mp} was initially flat but is now showing some degradation
- Both I_{mp} and V_{mp} contribute to drop in P_{mp}

STC Flash Test Results: CIGS-6

System ID	CIGS-2			CIGS-3			CIGS-6		
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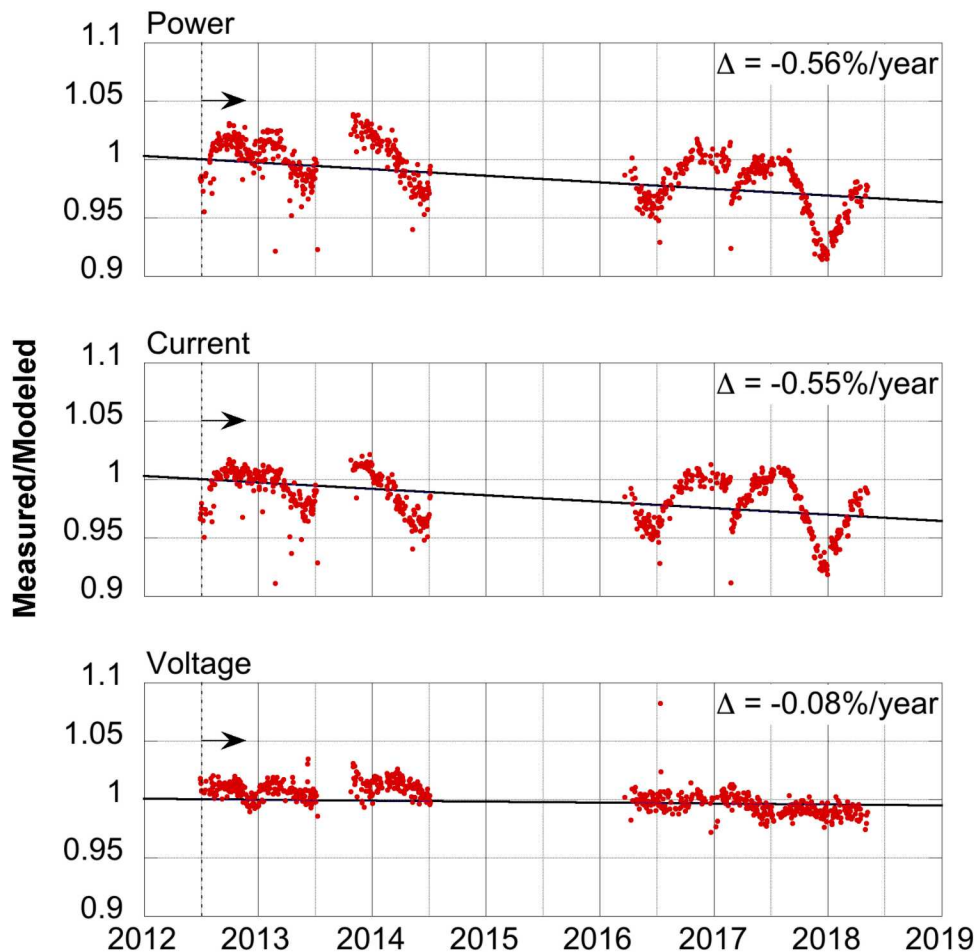
- P_{mp} was initially flat but is now showing some degradation
- Both I_{mp} and V_{mp} contribute to drop in P_{mp}
- Changes in I_{mp} and V_{mp} are accompanied by a drop in Shunt Resistance and an increase in $R@V_{oc}$

STC Flash Test Results: CIGS-6

System ID	CIGS-2			CIGS-3			CIGS-6		
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Age, months	0	45	76	0	41	70	0	23	38
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Fill Factor	0.67	0.64	0.59	0.72	0.72	0.71	0.69	0.71	0.67

- I_{sc} and V_{oc} largely unchanged

Results: Analyzed System Data

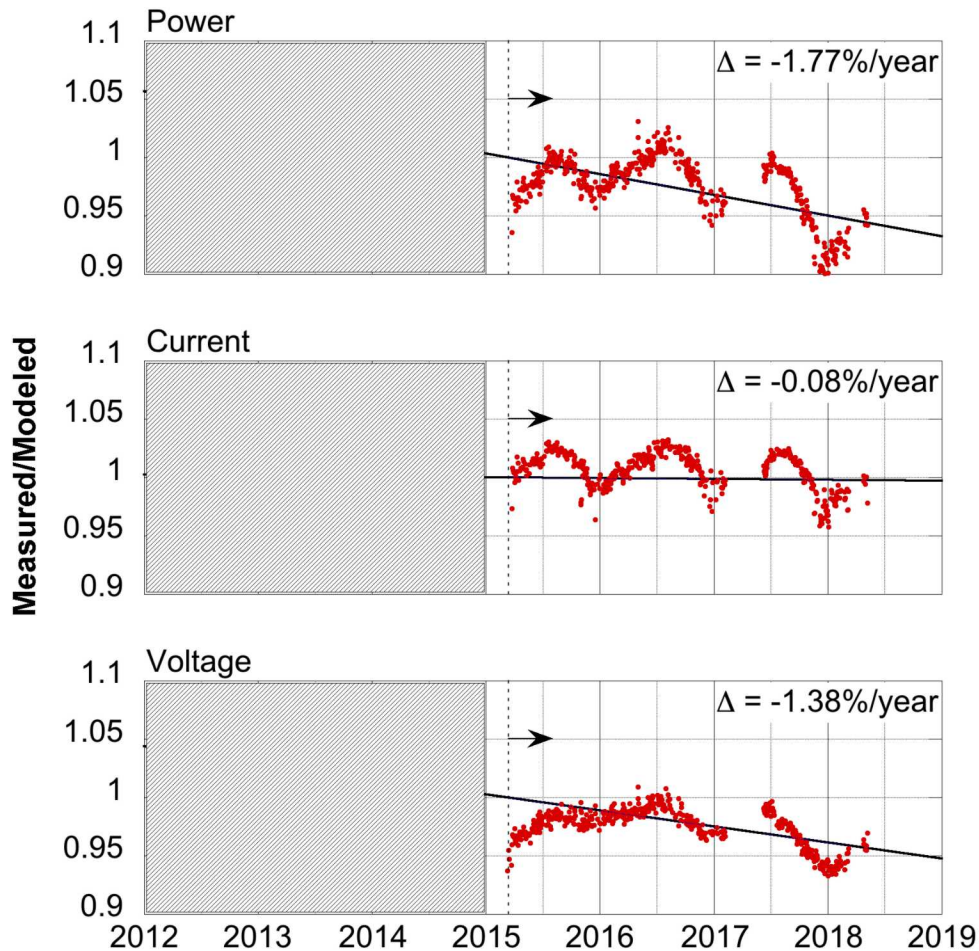


Annual Change, %/Year

	Flash	Array
P_{mp}, W	+0.3%	-0.6%
I_{mp}, A	+0.4%	-0.6%
V_{mp}, V	-0.1%	-0.1%

- Distinct seasonal behavior in current that is not captured by the model.
- Low seasonal variation in voltage indicating good prediction accuracy
- Array data suggests there might be degradation not captured by STC flash test.

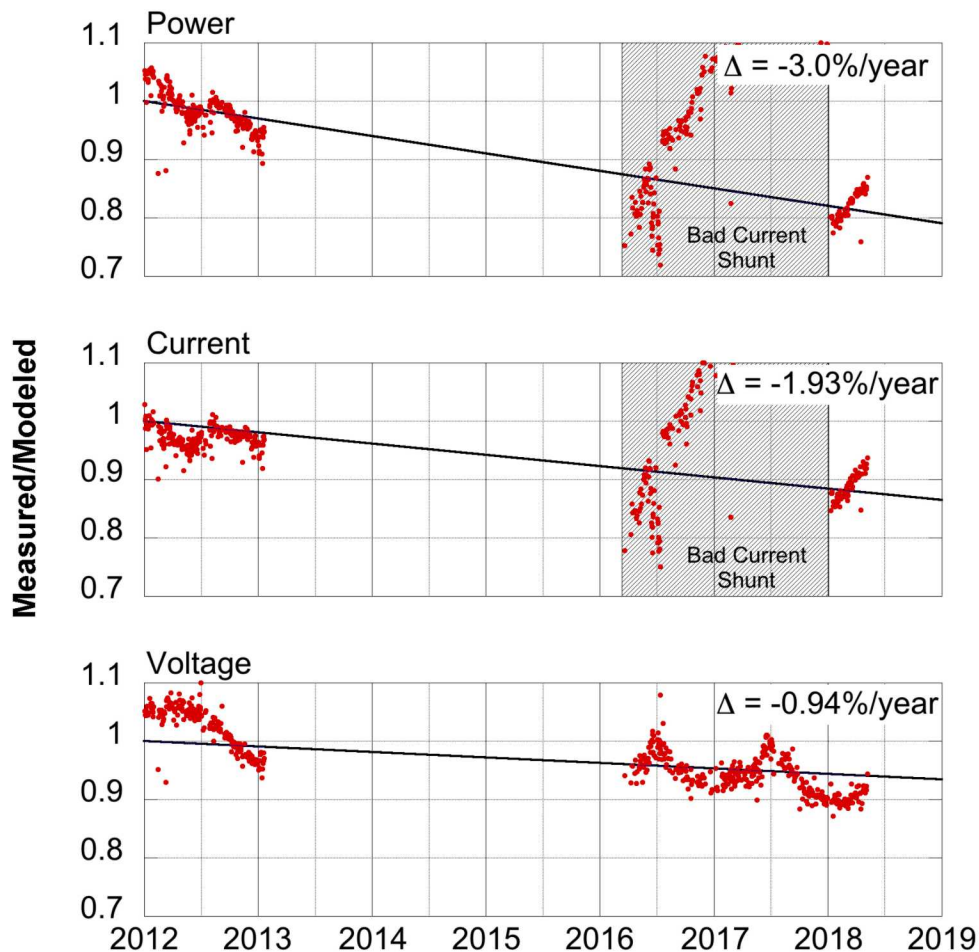
V-shaped dip in P_{mp} centered about 2018 solstice visible in all systems.



Annual Change, %/Year

	Flash	Array
P_{mp} , W	-1.8%	-1.8%
I_{mp} , A	-0.7%	-0.1%
V_{mp} , V	-1.1%	-1.4%

- Distinct seasonal behavior in current that is not captured by the model.
- Greater seasonal variation in voltage than observed for CIGS-3
- Array degradation rate mostly consistent with STC flash.



Annual Change, %/Year

	Flash	Array
P_{mp}, W	-2.4%	-3.0%
I_{mp}, A	-1.7%	-1.9%
V_{mp}, V	-0.7%	-0.9%

- Failed current shunt obscures seasonal variation in current/power
- Pronounced seasonal variation in voltage is consistent with variable diode factor observed during model calibration
- Array degradation rate consistent with STC flash.

Summary

- STC flash testing and performance modeling using the Sandia Array Performance Model were used to track degradation of three CIGS PV arrays
- Flash test data revealed;
 - One system displayed a consistently high degradation rate of $>2\%/year$
 - One system that was initially stable now has a high $\sim 2\%/year$ degradation rate
 - One system did not appear to degrade
- Comparison between flash test data, measured system data and model predictions indicated that the SAPM was effective at tracking field degradation
- In one case, field data+SAPM indicated degradation that was not observed in indoor flash data
- Seasonal variations (3-10%) were observed in comparisons between measured system data and model predictions for all systems.
- The most dramatic seasonal variation occurred in voltage for one system known to have a variable diode factor