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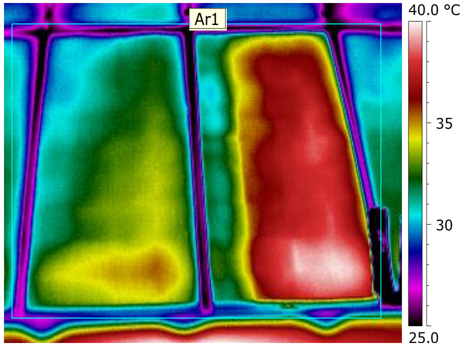

PV System Reliability: An O&M Perspective

NREL PV Module Reliability Workshop

Geoffrey T. Klise
Sandia National Laboratories
February 25, 2016

U.S. DEPARTMENT OF ENERGY

SunShot U.S. Department of Energy

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Overview

- How does O&M impact reliability? Or, reliability impact O&M?
- O&M costs and reliability – goals, trends, and recent insights from PV stakeholders
- System and component "Availability" best practices
  - Availability data standards – improved cataloging of events that impact equipment operational time and performance
- Current efforts to improve O&M with a reliability focus
  - PVROM
  - SAM tool improvements

How does ***O&M*** impact ***Reliability***?
Or, ***Reliability*** impact ***O&M***?

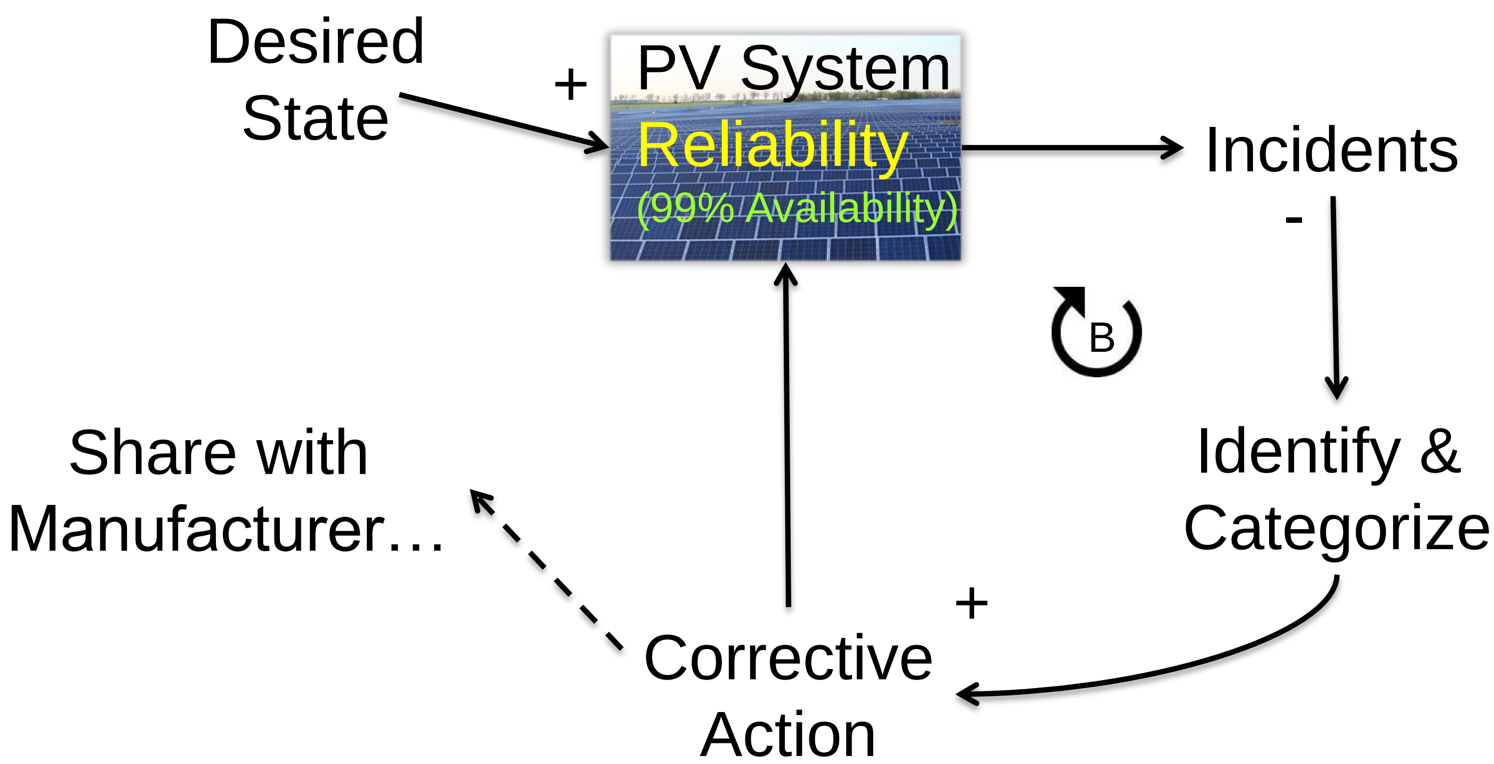
O&M and System Reliability Nexus

- **Operations** provides information to make decisions and triage response activities
- **Maintenance** is the response activity, whether planned or reactive, to ensure that equipment up-time leads to expected system performance and energy generation

Beyond filling tickets… How then does O&M become reliability-focused?

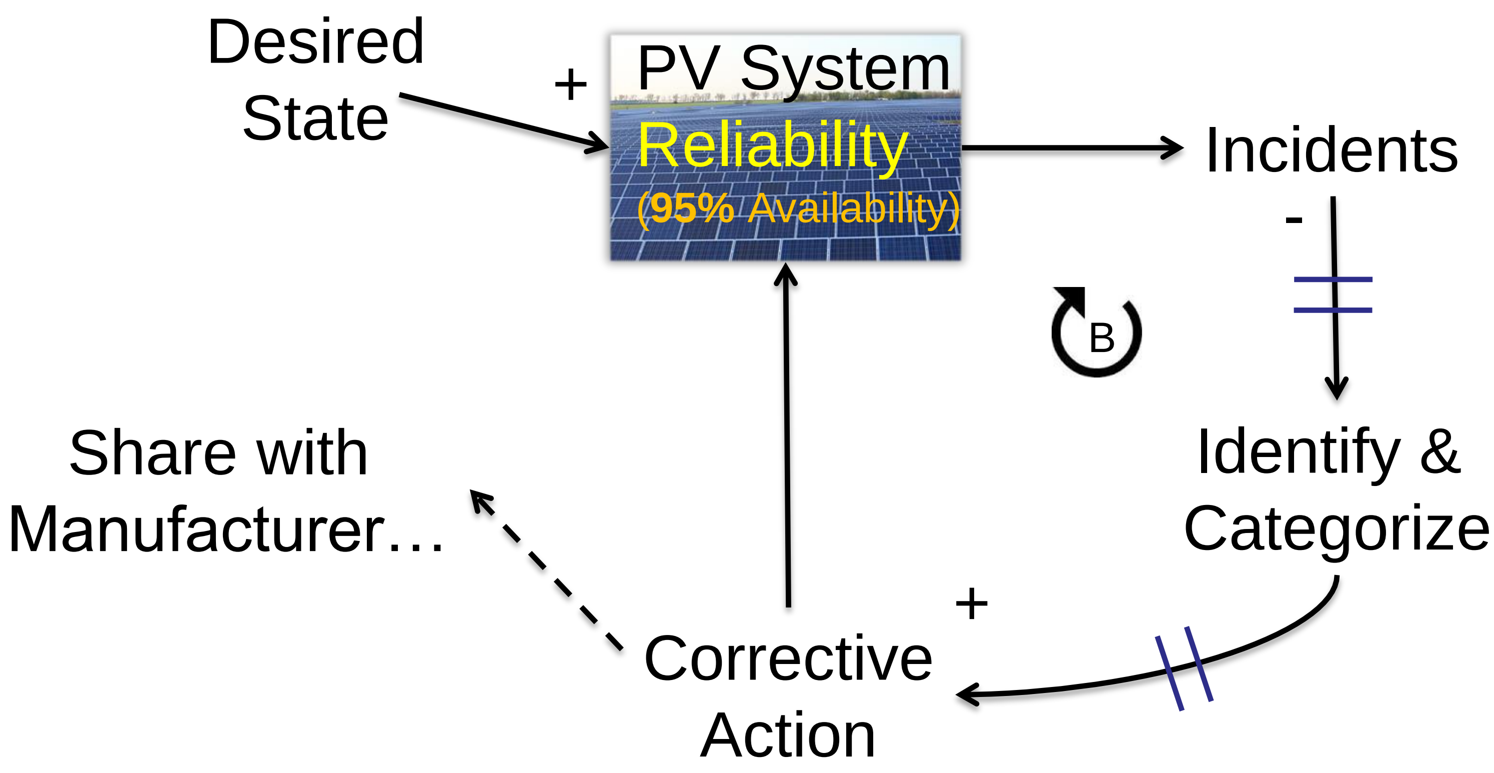
- By increasing preventative maintenance?
- Through faster response times?
- Through more intelligent machine-learning algorithms?

Simple Incident Response



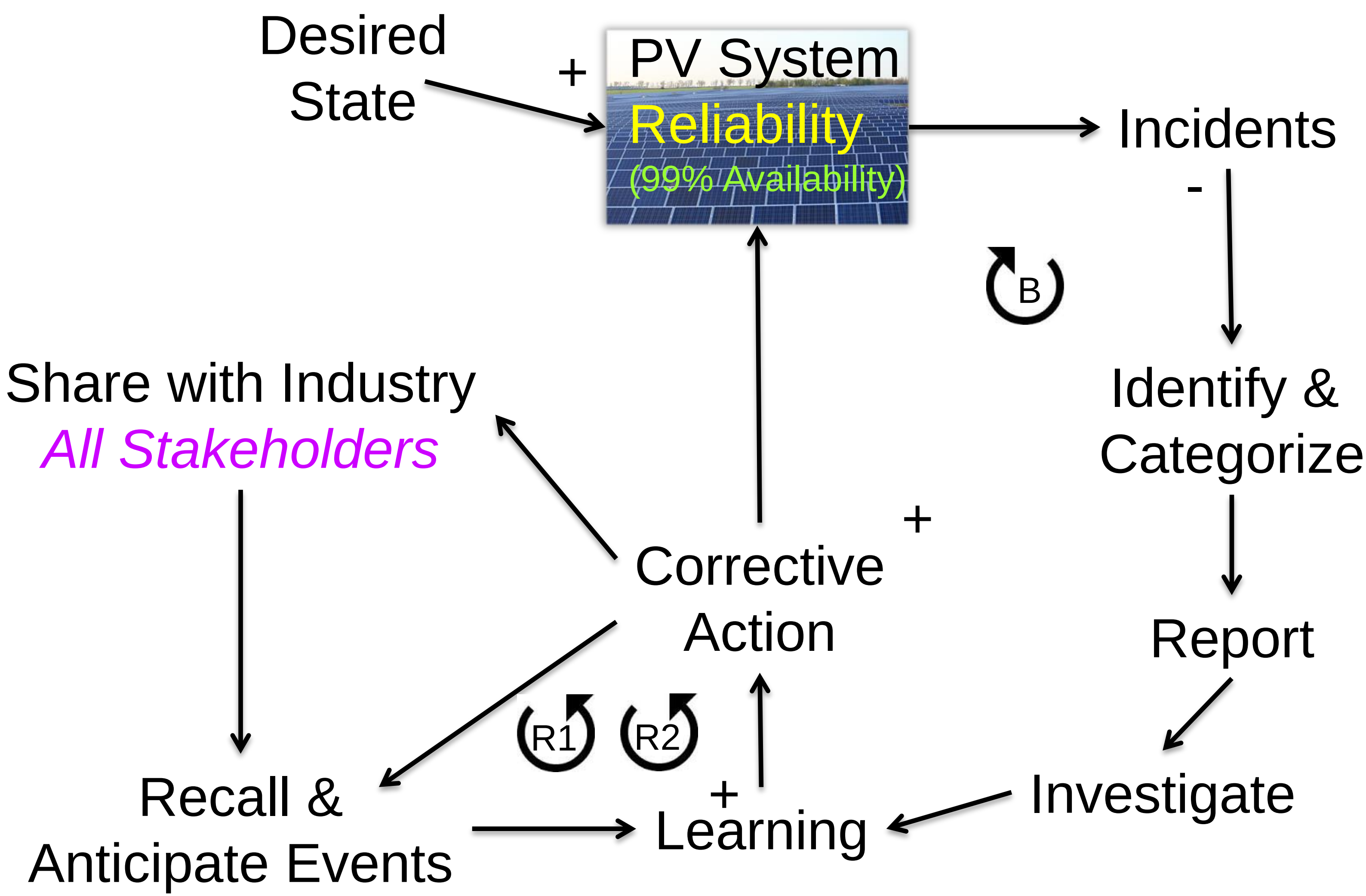
Adapted from Cooke, D.L., 2003, "Learning from Incidents"

Simple Incident Response



Adapted from Cooke, D.L., 2003, "Learning from Incidents"

Incident Response - Reliability Focus



Adapted from Cooke, D.L., 2003, "Learning from Incidents"

O&M Costs and Reliability:
Trends, Goals, and Recent Insights from PV Stakeholders

Recent PV O&M white paper – 2015

Sandia National Laboratories

Research rationale: Little information exists regarding the budgeting process, actual metrics ($/kW-yr), consensus best practices, and industry gaps

- Joint effort by EPRI and Sandia National Labs
- Focus: Utility-scale solar PV
- Data/insights derived from:
  - In-depth interviews & on-line survey

Respondent Type	Respondents
Interview Sample	
Utility / IPP	6
Turnkey Solar Company	2
O&M Provider	5
Insurance / Bank	4
Independent Engineer	1
Total	**18**
Survey Sample	
O&M Provider	8
Owner	5
EPC	3
Asset manager	4
Total	**20**

The publicly-available white paper is available for download at:
http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002006218

PV O&M *Budget* – Utility Scale

Caveats

- $/MW or kW-yr metric can skew perspectives
  - Other metrics can be more instructive
- Normalizing O&M budget figures for comparison can be difficult
- The constituent parts of O&M budget don't always add up to overall average budget
- $/kW-yr O&M costs tend to decrease as system size increases
  - Returns diminish as plant size grows
  - O&M of smaller systems can be 2-4x more expensive than for larger sites

Budget Item	Budget Range ($/kW-yr)
Overall Budget	$10.00 - $45.00/kW-yr*
General Site Maintenance	$0.20 - $3.00/kW-yr
Wiring Electrical Inspection	$1.40 - $5.00/kW-yr†
Panel Washing	$0.80 - $1.30/kW-yr†
Vegetation Management	$0.50 - $1.80/kW-yr†
Inverter Maintenance	$3.00 - $7.50/kW-yr†
Inverter Replacement	$6.00 - $10.00/kW**
Racking / Tracker Maintenance	Insufficient data
Spares	$2.00 - $20.00/kW-yr***

Source: EPRI

Notes: Budget numbers for utility-scale plants; encompass an entire range of baseline, cost-plus, and warranty terms.

** Constituent O&M budget components are non-linear; will not necessarily add up to overall budget on a $/kW-yr basis.*

*** Inverter replacement metrics based on a $/kW, cover one-time equipment replacement and installation activity over the course of a plant's lifetime.*

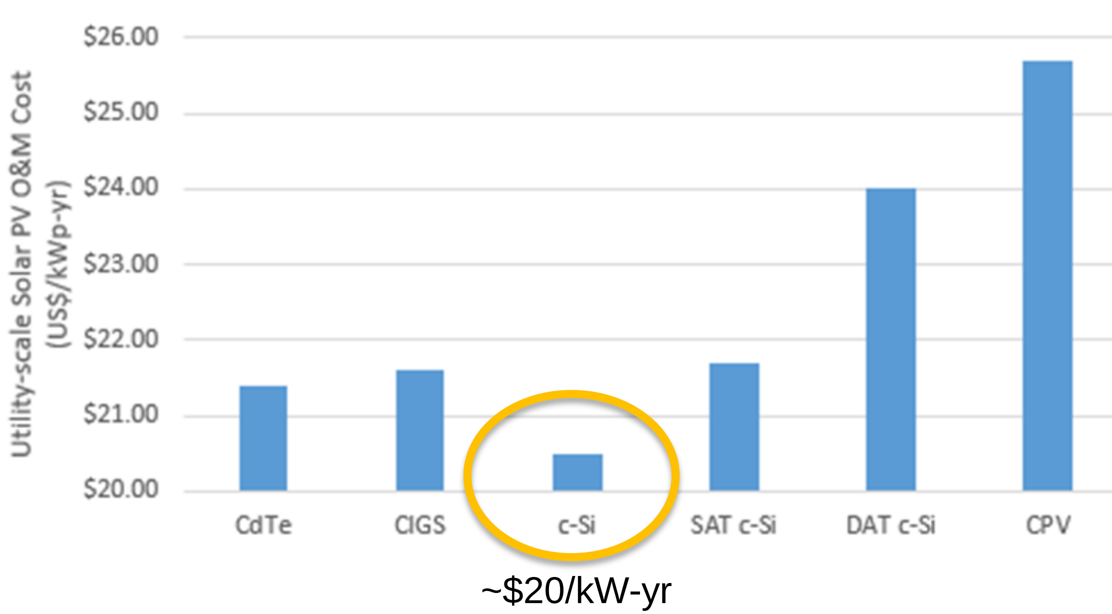
**** Budget range for spares primarily encompasses equipment procurement and storage costs.*

† Price points based on a 1x annual frequency (i.e., per event)

PV O&M *Costs* – Utility Scale

- Budgets historically low (and remain so)
- No one-size-fits-all approach
  - Budgets typically 1-5% of MW-scale plant's $/kW-yr price tag
  - Variation based on
    - System / fleet characteristics
    - Business interests
    - O&M approaches (scope)
    - Contractual arrangements
    - Miscellaneous: labor rates, local energy prices, project volume, profit taking
  - Broad structure guides budgeting process that is informed by multiple factors/attitudes

Avg. Utility-Scale PV O&M *Costs*, by Technology



Source: EPRI, PID 3002005779

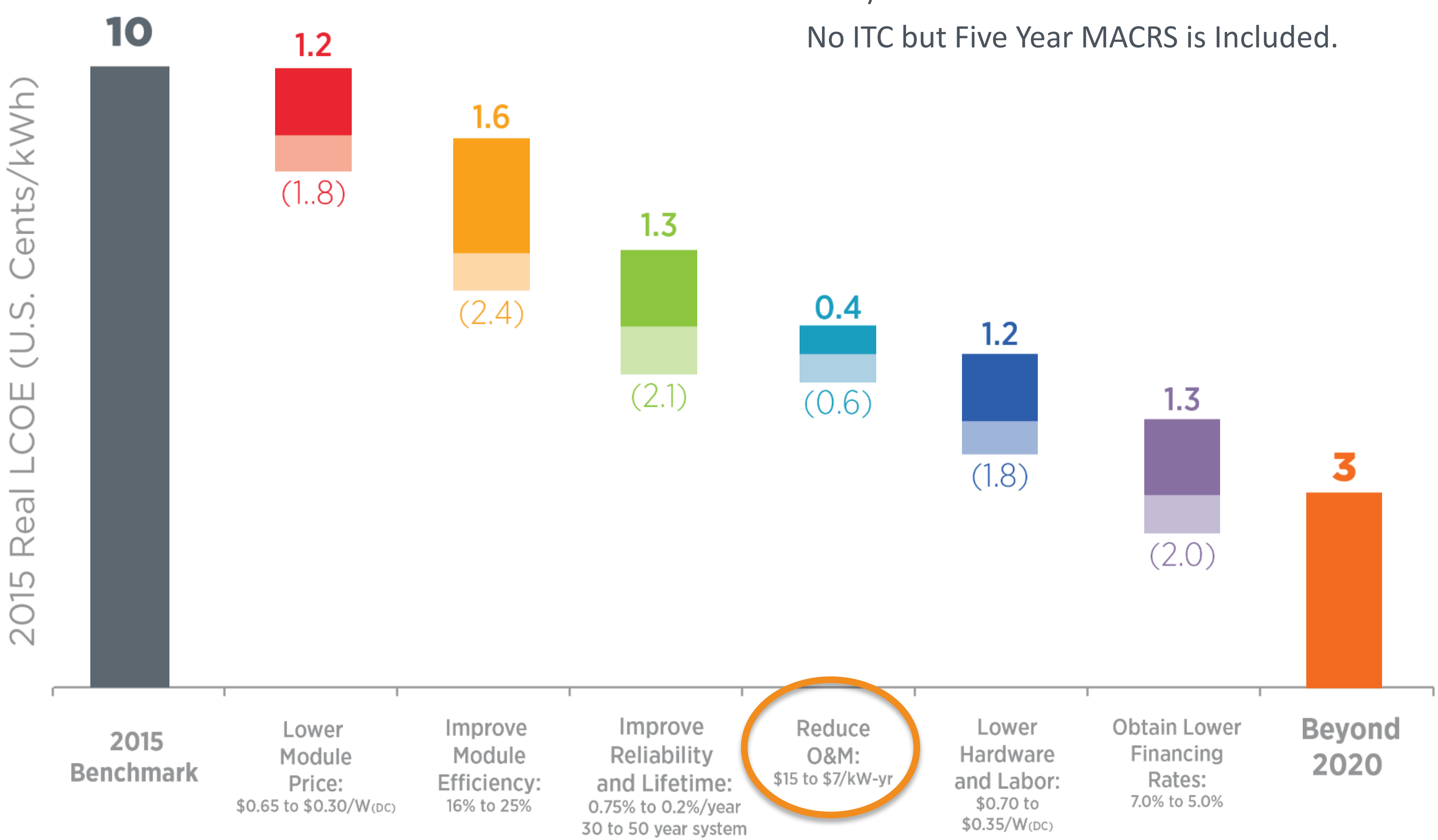
Note: O&M estimates developed using bottoms-up approach; incorporates detailed info from EPCs, and input from industry data (i.e. equipment cost and labor indices), market analyst info, and developer feedback. Estimates for conceptual 10-MW$_{dc}$ plants

Towards 2030: A Pathway To 3¢/kWh

SunShot
U.S. Department of Energy
energy.gov/sunshot

Benchmark 100 MW Utility Systems With 1,480 kWh/kW First Year Performance.

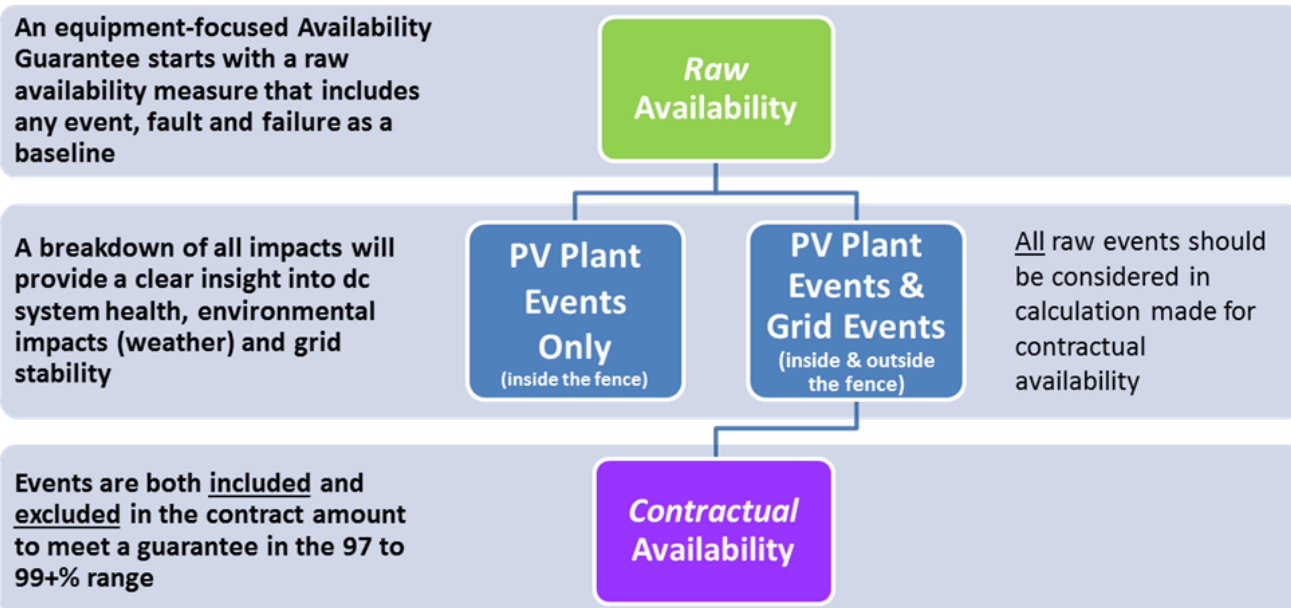
No ITC but Five Year MACRS is Included.

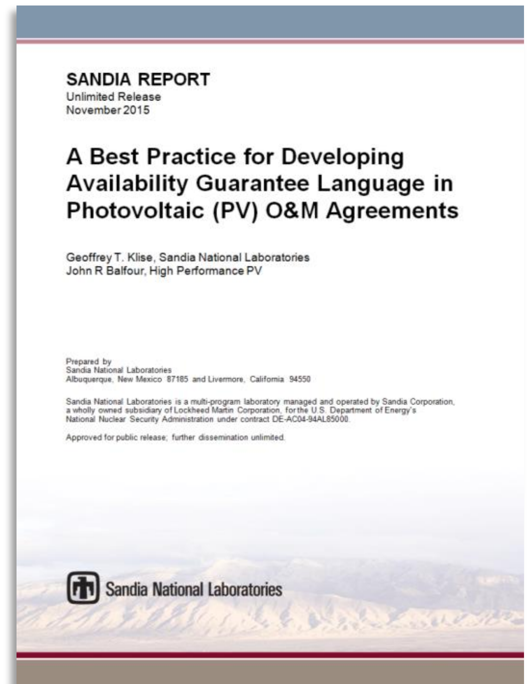


System and Component "Availability" Best Practices

Availability Guarantee Best Practices

Methods, equations and classifications for collecting data to support availability calculations





SANDIA REPORT
Unlimited Release
November 2015

A Best Practice for Developing Availability Guarantee Language in Photovoltaic (PV) O&M Agreements

Geoffrey T. Klise, Sandia National Laboratories
John R Balfour, High Performance PV

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Approved for public release; further dissemination unlimited.

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http://energy.sandia.gov/download/35866/

- Reviewed 11 O&M contracts for their "Availability Guarantees"
- Categorized contractual elements

Availability Guarantee Best Practices

New availability data collection & analysis classification

Raw Component Availability

$$A_{raw\_i} = 1 - \frac{DownTime_i}{TotalTime_i}$$

Raw System Availability

$$A_{raw\_sys} = \frac{\sum_{i=1}^{n} A_{raw\_i} \times NP_i}{\sum_{i=1}^{n} NP_i}$$

Irradiance-Weighted Raw Availability

$$A_{raw\_irr} = 1 - \sum \left(\frac{DownTime_{i\_irradiance}}{\sum irradiance} \right)$$

Contractual Availability

$$A_{exclude\_i} = 1 - \frac{DownTime_i - ExcludedTime_i}{TotalTime_i - ExcludedTime_i}$$

Data Area/System Class	A	B	C
Data Granularity	High	Medium	Low
Components measured and potentially subject to availability calculation	Inverter, combiners (ac, dc), disconnects, modules, transformer, DAS, SCADA	Inverter, Combiners (dc), disconnects, DAS	Inverter
Necessary Instrumentation	DAS, SCADA, POA irradiance, Utility grade meter, inverter	DAS, SCADA, inverter, irradiance	DAS, inverter
Timestep	1 to 15 minutes	15 minutes	15 minutes
External Grid Events	Grid outage, curtailment, grid support	Grid outage, curtailment	Grid outage

- Suggested best practices for improved language for **raw** and **contractual** availability
- Developed equations and examples for determining component and system availability

Collecting time-based event data and maintenance response supports reliability analysis

Current Efforts to Improve O&M with a Reliability Focus:
- PV Reliability Operations Maintenance *Process*

Time-Based Data Collection

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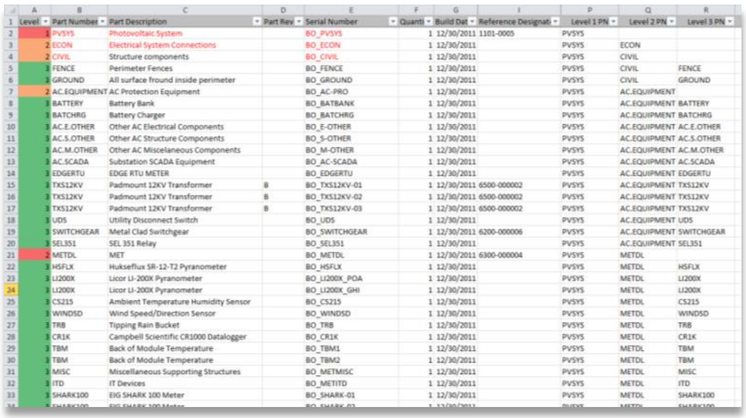
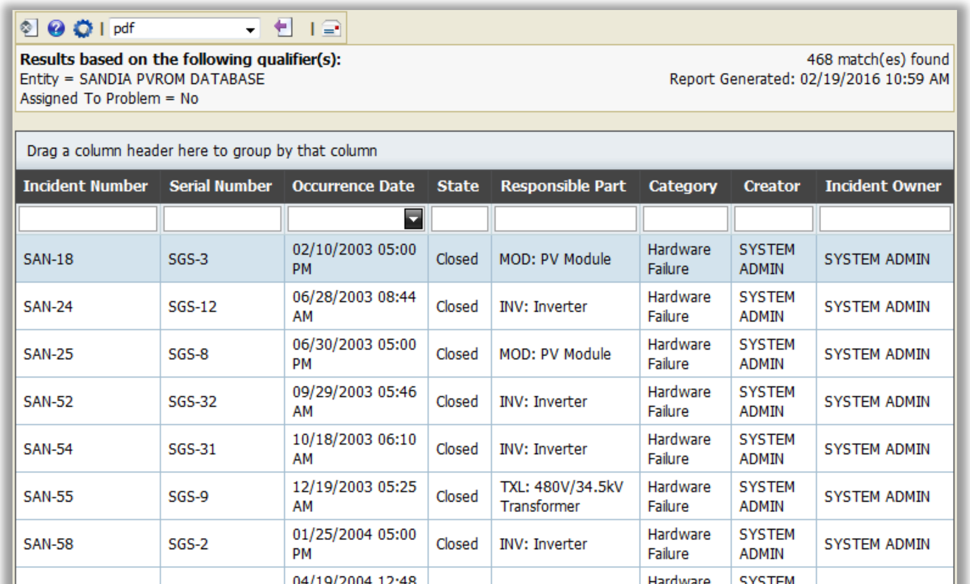
- PV System Serialized

Incidents Recorded



- Database of stored incidents



pdf

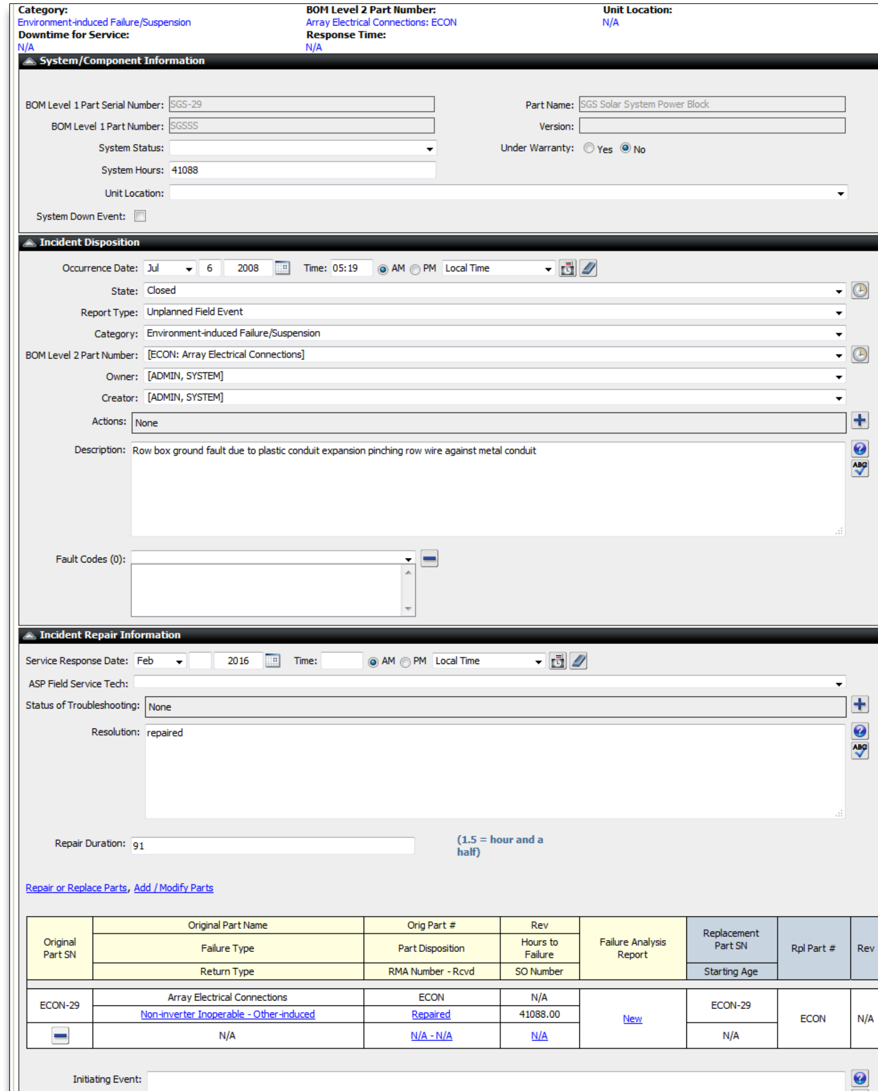
Results based on the following qualifier(s): 468 match(es) found

Entity = SANDIA PVROM DATABASE Report Generated: 02/19/2016 10:59 AM

Assigned To Problem = No

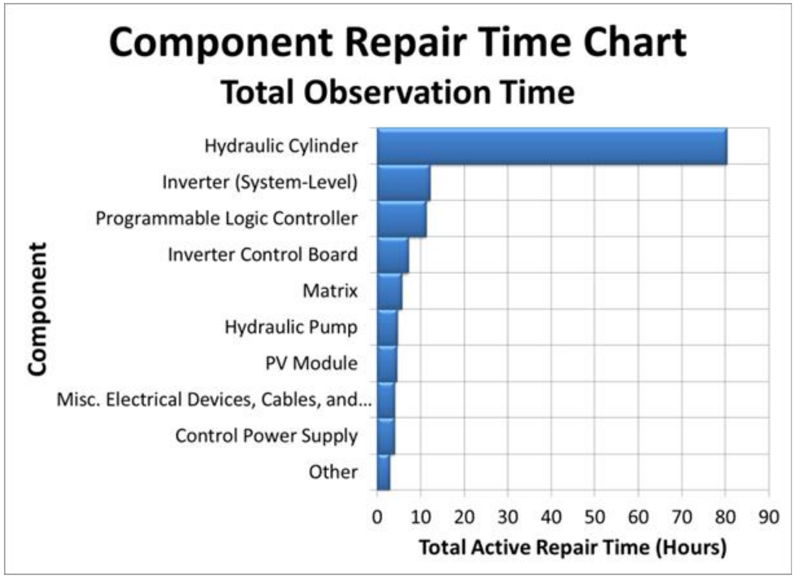
Drag a column header here to group by that column

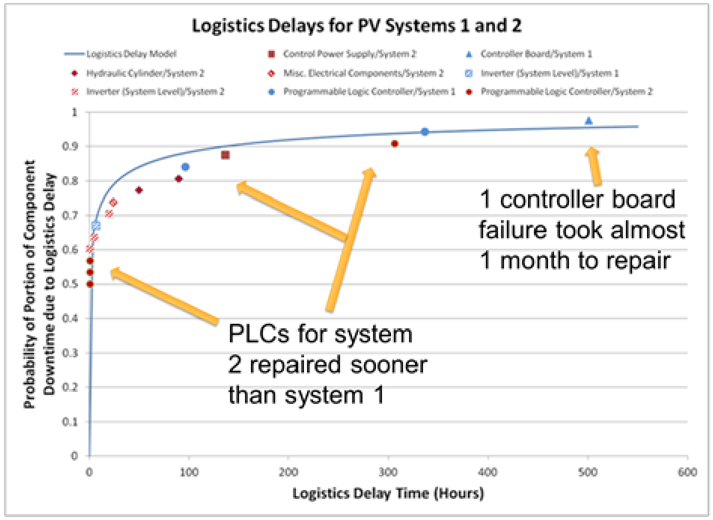
Incident Number	Serial Number	Occurrence Date	State	Responsible Part	Category	Creator	Incident Owner
SAN-18	SGS-3	02/10/2003 05:00 PM	Closed	MOD: PV Module	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN
SAN-24	SGS-12	06/28/2003 08:44 AM	Closed	INV: Inverter	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN
SAN-25	SGS-8	06/30/2003 05:00 PM	Closed	MOD: PV Module	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN
SAN-52	SGS-32	09/29/2003 05:46 AM	Closed	INV: Inverter	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN
SAN-54	SGS-31	10/18/2003 06:10 AM	Closed	INV: Inverter	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN
SAN-55	SGS-9	12/19/2003 05:25 AM	Closed	TXL: 480V/34.5kV Transformer	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN
SAN-58	SGS-2	01/25/2004 05:00 PM	Closed	INV: Inverter	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN
SAN-61	SGS-32	04/19/2004 12:48	Closed	INV: Inverter	Hardware	SYSTEM	SYSTEM ADMIN



Time-Based Data Analysis

System Component	Abbreviation	Quantity	Maintenance Actions	Active Repairs	Avg. Active Repair Time (hrs)
AC Disconnect Switch	ADS	69	0	0	0.00
Combiner Box	CB	142	0	0	0.00
Data Acquisition System	DAS	43	4	3	0.13
DC connectors, e.g. MC4	DCCON	41	0	0	0.00
DC Disconnect Switch	DDS	97	0	0	0.00
Misc. Electrical Devices, Cables, and Connectors	ECON	43	1	1	2.00
Fuses, ac and dc	FUSE	41	1	1	0.00
DC Home Runs	HOMERUN	41	0	0	0.00
Utility Power Meter	MET	61	0	0	0.00
PV Module	MOD	15957	4	4	2.08
Module Mounting System	MOUNT	41	0	0	0.00
Programmable Logic Controller	PLC	35	10	8	1.13
HV Transformer	TXL	31	0	0	0.00
Utility Disconnect Switch	UDS	44	0	0	0.00
Inverter Equipment					
Inverter	INV	54	9	0	0.68
Control Power Supply	CPS	39	1	1	2.00
Inverter Control Board	CRTLBRD	41	4	2	1.79
Inverter Control Software	CTRLSW	54	1	1	0.63
Cooling Fan	FAN	54	1	1	0.66
Inverter fuses, wires, etc	IECON	47	1	1	0.00
Power Matrix	MAT	61	4	4	0.71
LV Transformer	TXS	27	0	0	0.00





- Development of non-repairable failure distribution parameters

Component	Distribution	1st Model Parameter	2nd Model Parameter
AC Disconnect Switch	Lognormal	$\mu = 7.048$	$\sigma = 3.863$
Photovoltaic Modules	Weibull	$\beta = 0.825$	$h = 4.498 \times 10^6$
480/34.5 kV Transformer	Weibull	$\beta = 0.668$	$h = 2{,}554$

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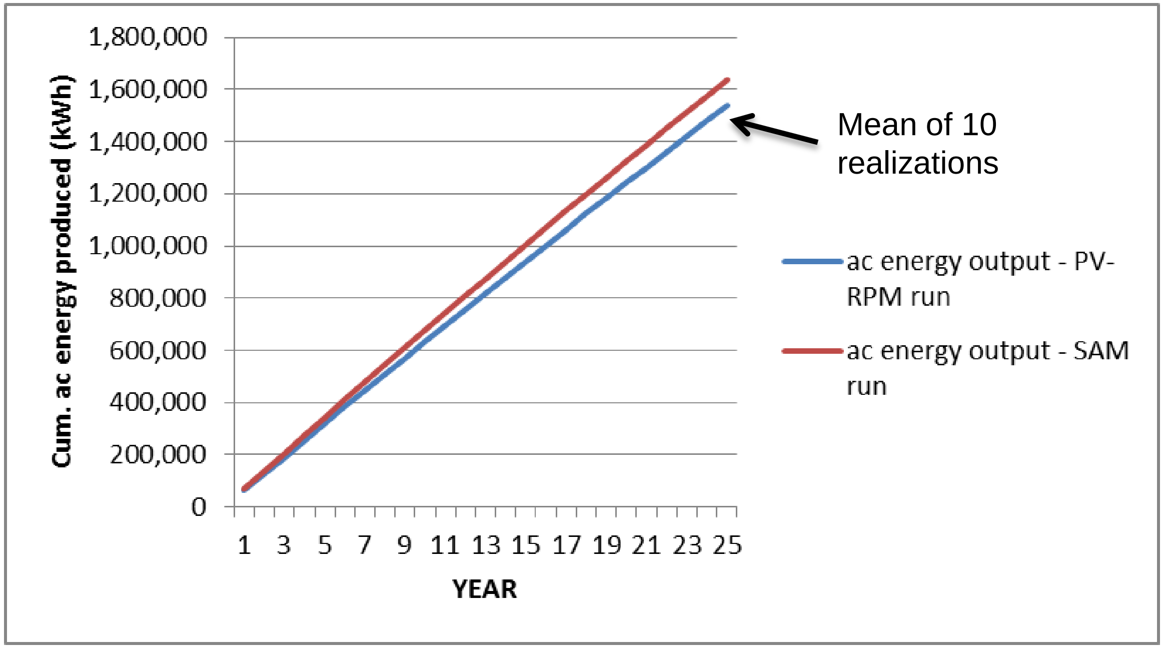
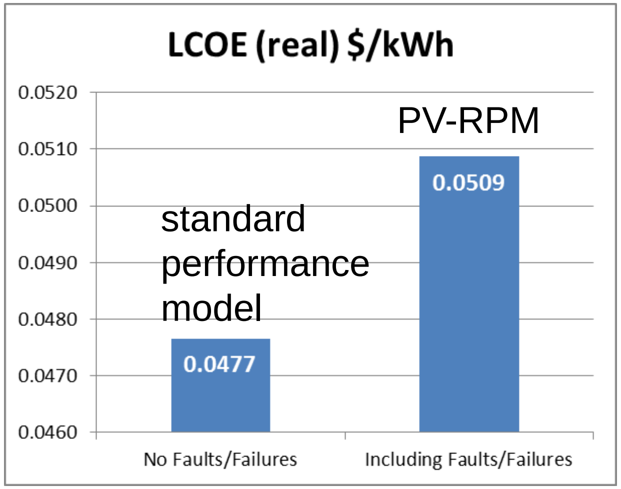
Current Efforts to Improve O&M with a Reliability Focus:
- Adding probability distributions to the System Advisor Model

Reliability for PV Performance Modeling

- Adding fault and failure impact into the System Advisor Model from Sandia PV-Reliability Performance Model (RPM)
- Example analysis below, with LCOE differences when faults and failures are represented probabilistically





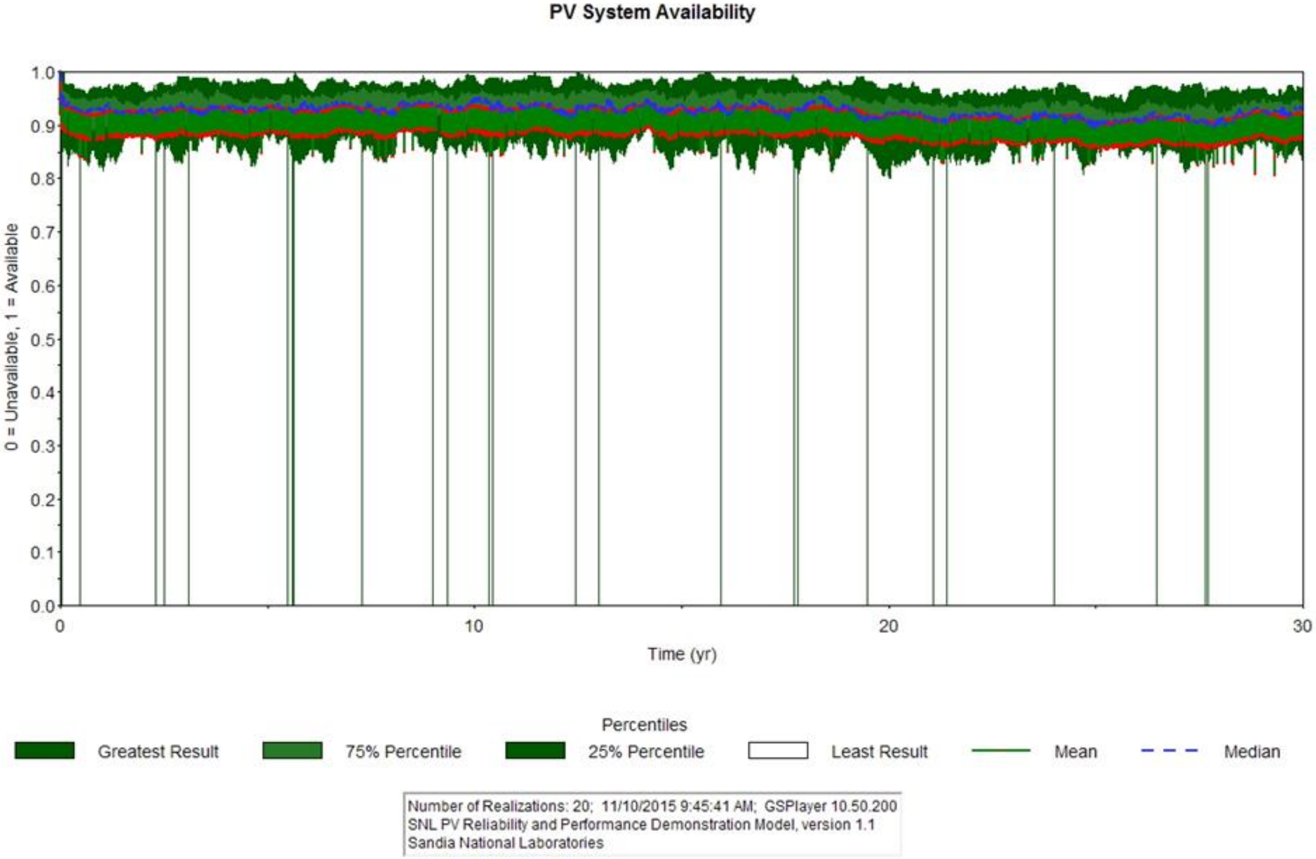
Hypothetical analysis shows 3/10 of a cent difference in LCOE

6% difference in cumulative ac energy production over 25 years

Reliability for PV Performance Modeling

- Instead of forcing Availability into a performance model with scheduled maintenance and ‘guesses’ on when components fail…

- Estimates of equipment availability can be represented probabilistically and used to improve contractual expectations and compliance



- Grid events (Availability of 0 due to external event, in this example) can also be expressed as probabilities

EPRI-Sandia PV Systems Symposium

May 9-11th at the Biltmore Hotel in Santa Clara, CA

Sandia National Laboratories

EPRI ELECTRIC POWER RESEARCH INSTITUTE

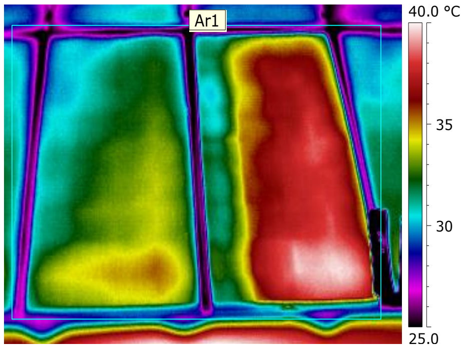
A symposium, comprised of three one-day workshops, on the technical challenges and opportunities related to solar PV systems and technologies

Registration opens 2/28
Submit abstract until 3/4

- **5th PV Performance Modeling Workshop** — May 9
  - Solar Resource Data Sources and Uncertainty
  - Spectral Corrections for PV Performance Modeling
  - Modeling Challenges for New PV Techs
  - PV Modeling Tools Update
- **Side Meeting: PVLIB for Matlab and Python** — May 10
  - Current status of the PVLIB and future plans
  - Gaps to focus on for new development
- **PV Grid Integration into Distribution Workshop** — May 10
  - Distribution Modeling for Planning and Screening
  - Advanced Inverter Functionality
  - Challenges of High-Pen PV on Distribution
  - Distributed Control and Operation Mgmt
- **PV Life Cycle Workshop** — May 11
  - Improving Current and Future PV System Design
  - Budgeting for PV O&M
  - Reliability Analysis of PV Plus Storage
  - Reliability and Lifetime of PV Systems




http://energy.sandia.gov/wp-content/uploads/2012/04/2016-PV-Systems-Symposium-Save-the-Date-final.pdf



Thank You

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