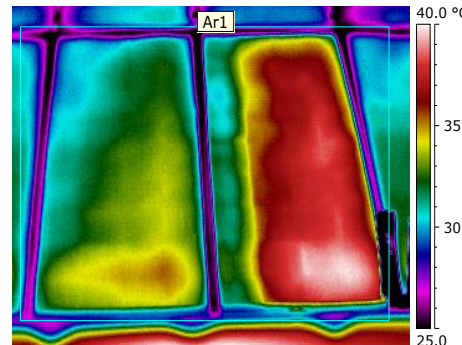


Exceptional service in the national interest



PV System Reliability: An O&M Perspective

NREL PV Module Reliability Workshop

Geoffrey T. Klise
Sandia National Laboratories
February 25, 2016



Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

- 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

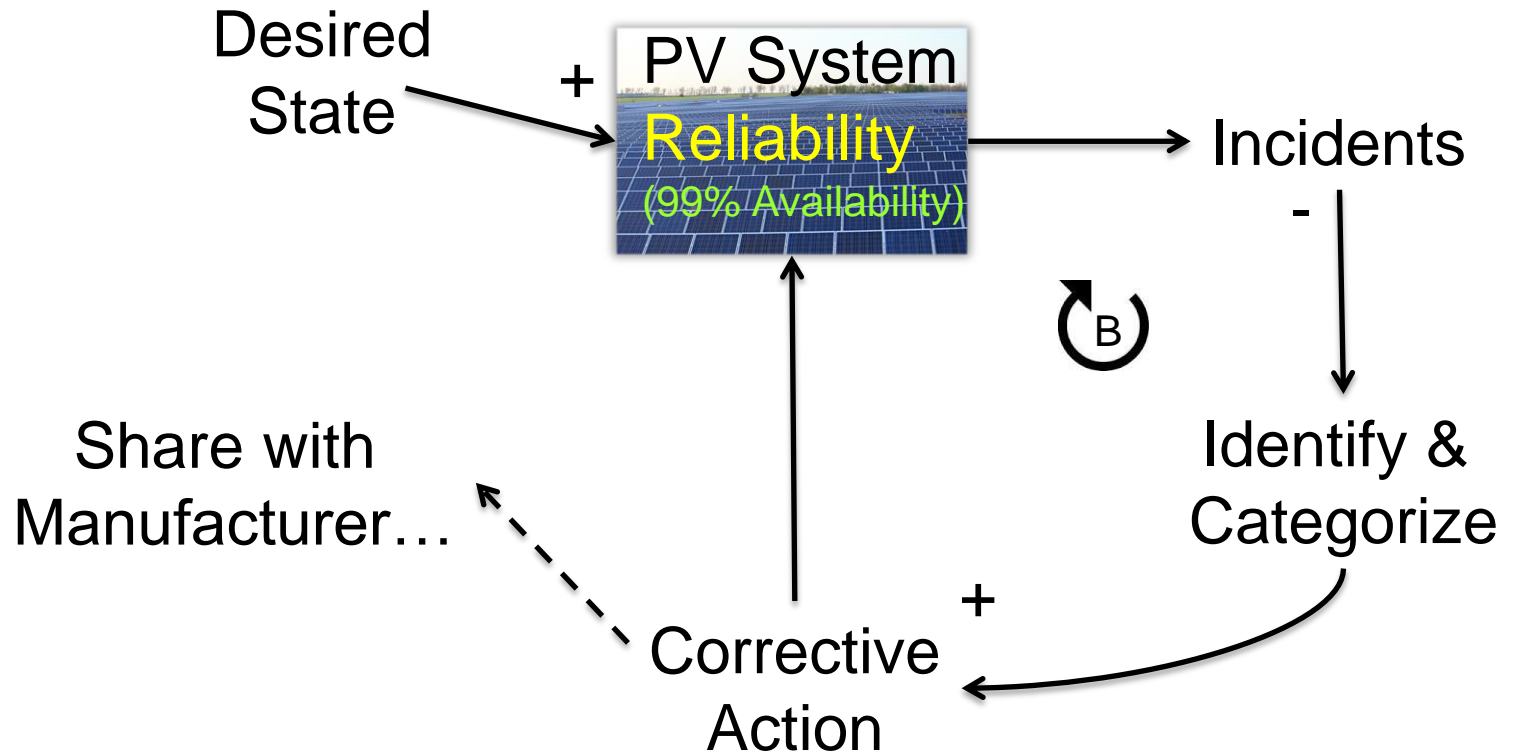
How does ***O&M*** impact ***Reliability***?
Or, ***Reliability*** impact ***O&M***?

- **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

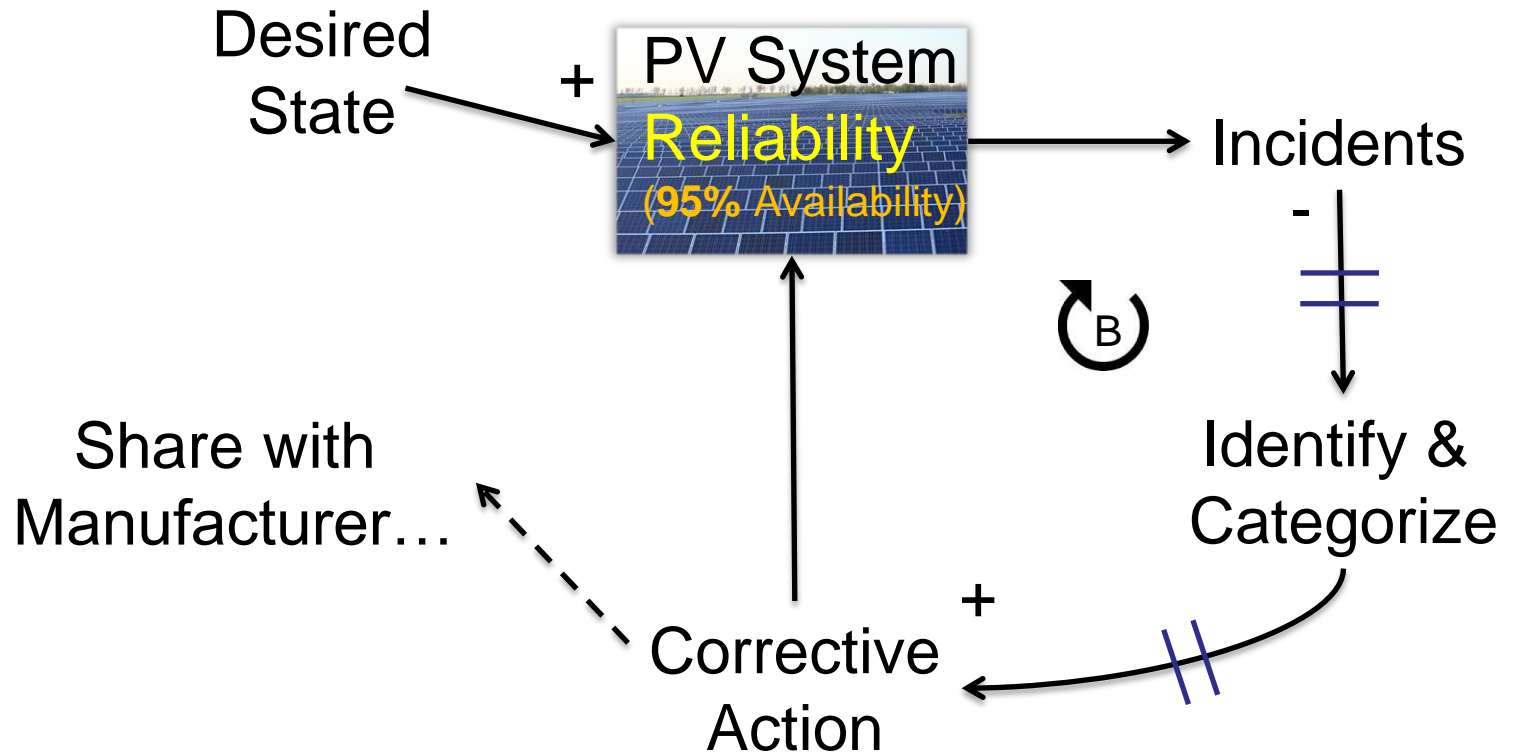
Beyond filling tickets... How then does O&M become reliability-focused?

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

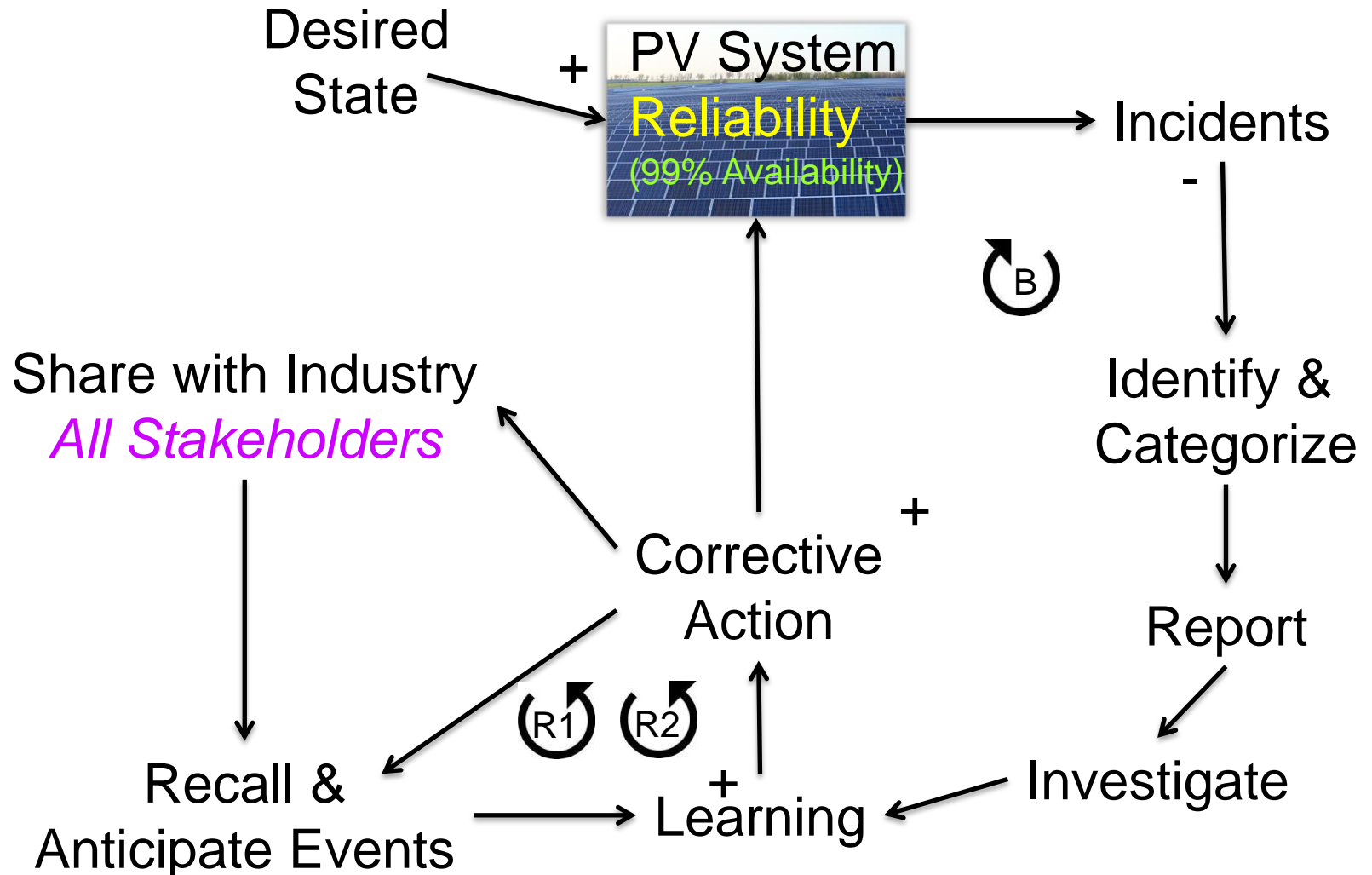
Simple Incident Response



Simple Incident Response



Incident Response - Reliability Focus



O&M Costs and Reliability:

Trends, Goals, and Recent Insights from PV Stakeholders

Recent PV O&M white paper – 2015

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.

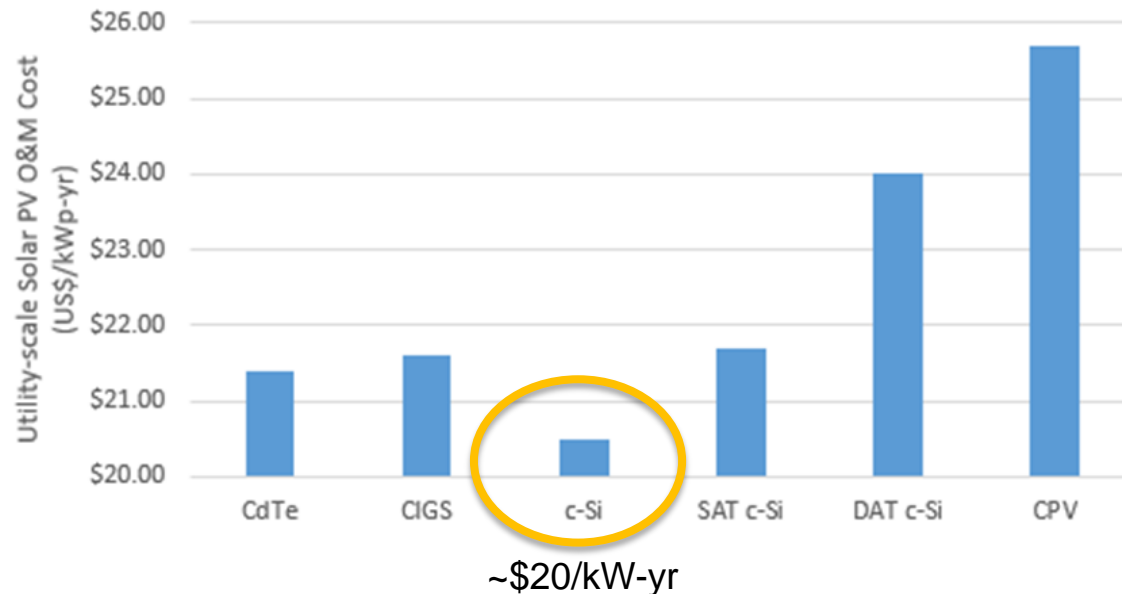
** Inverter replacement metrics based on a \$/kW, cover one-time equipment replacement and installation activity over the course of a plant's lifetime.

*** 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

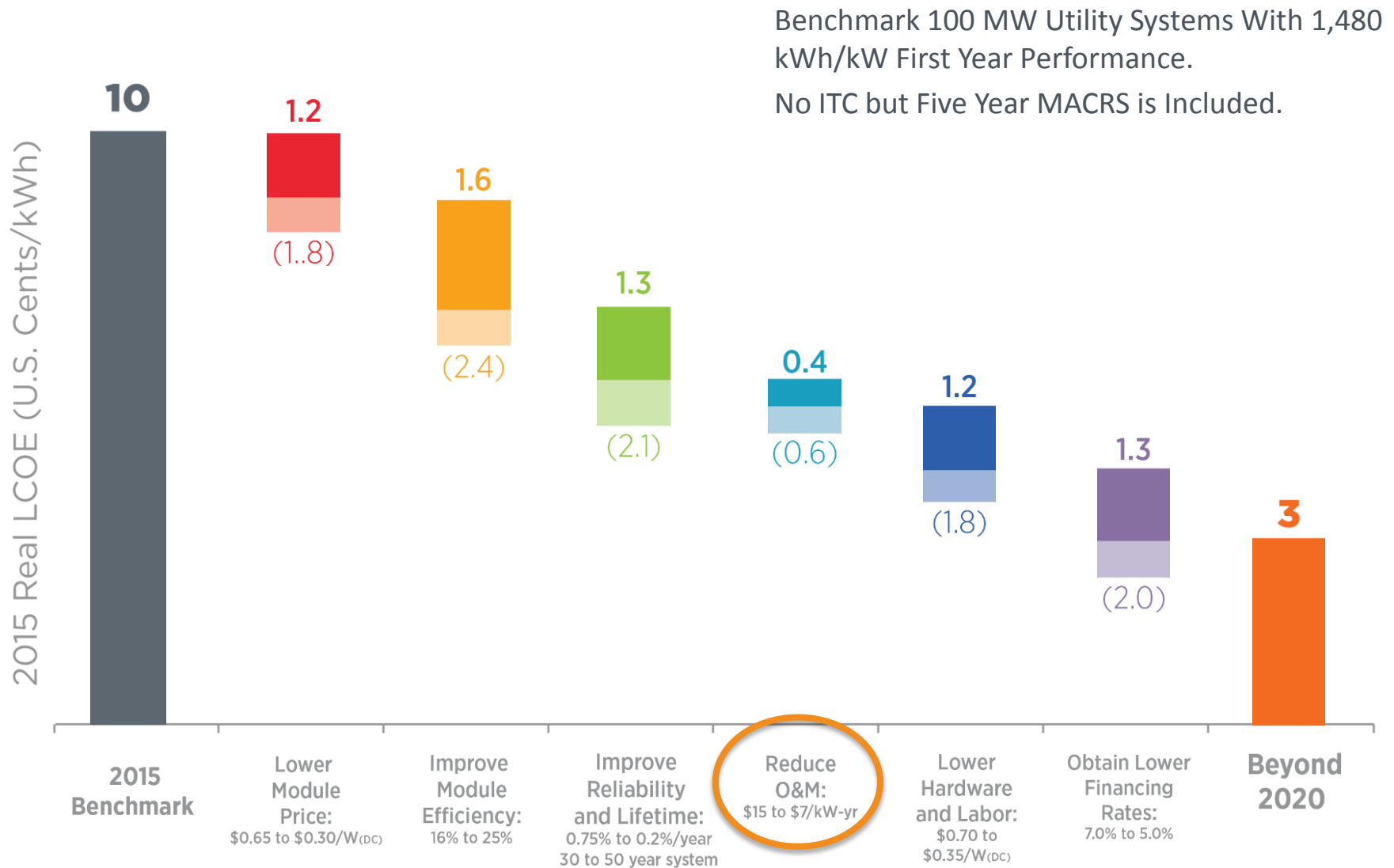
- Budgets historically low (and remain so)
- No one-size-fits-all approach
 - Budgets typically 1-5% of MW-scale plant's \$/kW-yr price tag
 - Variation based on
 - System / fleet characteristics
 - Business interests
 - O&M approaches (scope)
 - Contractual arrangements
 - Miscellaneous: labor rates,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



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



System and Component “Availability” Best Practices

Availability Guarantee Best Practices

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

An equipment-focused Availability Guarantee starts with a raw availability measure that includes any event, fault and failure as a baseline

**Raw
Availability**

A breakdown of all impacts will provide a clear insight into dc system health, environmental impacts (weather) and grid stability

**PV Plant
Events
Only**
(inside the fence)

**PV Plant
Events &
Grid Events**
(inside & outside
the fence)

All raw events should be considered in calculation made for contractual availability

Events are both included and excluded in the contract amount to meet a guarantee in the 97 to 99+% range

**Contractual
Availability**

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

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.

 Sandia National Laboratories

<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

PV System Serialized

Incidents Recorded

Database of stored incidents

Level	Part Number	Part Description	Part Rev	Serial Number	Quant	Build Date	Reference Designator	Level 1 PN	Level 2 PN	Level 3 PN
1	PVSVS	Photovoltaic System		BO_PVSVS	1	12/30/2011	1181-0005	PVSVS		
2	ECON	Electrical System Connections		BO_ECON	1	12/30/2011		PVSVS	ECON	
3	CIVL	Structure components		BO_CIVL	1	12/30/2011		PVSVS	CIVL	
4	FENCE	Perimeter Fences		BO_FENCE	1	12/30/2011		PVSVS	CIVL	FENCE
5	GROUND	All surface found inside perimeter		BO_GROUND	1	12/30/2011		PVSVS	CIVL	GROUND
6	AC.EQUIPMENT	AC Protection Equipment		BO_AC_PRO	1	12/30/2011		PVSVS	AC.EQUIPMENT	
7	BATTERY	Battery Bank		BO_BATBANK	1	12/30/2011		PVSVS	AC.EQUIPMENT	BATTERY
8	BATCHRG	Battery Charger		BO_BATCHRG	1	12/30/2011		PVSVS	AC.EQUIPMENT	BATCHRG
9	AC.E.OTHER	Other AC Electrical Components		BO_E-OTHER	1	12/30/2011		PVSVS	AC.EQUIPMENT	AC.E.OTHER
10	AC.S.OTHER	Other AC Structure Components		BO_S-OTHER	1	12/30/2011		PVSVS	AC.EQUIPMENT	AC.S.OTHER
11	AC.M.OTHER	Other AC Miscellaneous Components		BO_M-OTHER	1	12/30/2011		PVSVS	AC.EQUIPMENT	AC.M.OTHER
12	AC.SCADA	Substation SCADA Equipment		BO_AC-SCADA	1	12/30/2011		PVSVS	AC.EQUIPMENT	AC.SCADA
13	EDGERTU	EDGE RTU METER		BO_EDGERTU	1	12/30/2011		PVSVS	AC.EQUIPMENT	EDGERTU
14	TKS12KV	Padmount 12KV Transformer		BO_TKS12KV-01	1	12/30/2011	6500-000002	PVSVS	AC.EQUIPMENT	TKS12KV
15	TKS12KV	Padmount 12KV Transformer		BO_TKS12KV-02	1	12/30/2011	6500-000002	PVSVS	AC.EQUIPMENT	TKS12KV
16	TKS12KV	Padmount 12KV Transformer		BO_TKS12KV-03	1	12/30/2011	6500-000002	PVSVS	AC.EQUIPMENT	TKS12KV
17	UDS	Utility Disconnect Switch		BO_UDS	1	12/30/2011	6200-000006	PVSVS	AC.EQUIPMENT	UDS
18	SWITCHGEAR	Metal Cask Switchgear		BO_SWITCHGEAR	1	12/30/2011	6200-000006	PVSVS	AC.EQUIPMENT	SWITCHGEAR
19	SEL351	SEL 351 Relay		BO_SEL351	1	12/30/2011	6300-000004	PVSVS	AC.EQUIPMENT	SEL351
20	METDL	MET		BO_METDL	1	12/30/2011	6300-000004	PVSVS	AC.EQUIPMENT	METDL
21	HFLX	HuaweiFlux 18-12 T3 Pyranometer		BO_HFLX	1	12/30/2011		PVSVS	METDL	HFLX
22	L1200X	Licor Li-1200X Pyranometer		BO_L1200X_PDA	1	12/30/2011		PVSVS	METDL	L1200X
23	L1200X	Licor Li-1200X Pyranometer		BO_L1200X_G4H	1	12/30/2011		PVSVS	METDL	L1200X
24	C3215	Ambient Temperature Humidity Sensor		BO_C3215	1	12/30/2011		PVSVS	METDL	C3215
25	WINWSD	Wind Speed/Direction Sensor		BO_WINWSD	1	12/30/2011		PVSVS	METDL	WINWSD
26	TRB	Tipping Rain Bucket		BO_TRB	1	12/30/2011		PVSVS	METDL	TRB
27	CR1K	Campbell Scientific CR1000 Datalogger		BO_CR1K	1	12/30/2011		PVSVS	METDL	CR1K
28	TBM1	Back of Module Temperature		BO_TBM1	1	12/30/2011		PVSVS	METDL	TBM1
29	TBM2	Back of Module Temperature		BO_TBM2	1	12/30/2011		PVSVS	METDL	TBM2
30	MISC	Miscellaneous Supporting Structures		BO_METMISC	1	12/30/2011		PVSVS	METDL	MISC
31	ITD	IT Devices		BO_METITD	1	12/30/2011		PVSVS	METDL	ITD
32	SHARK100	SHARK100 Meter		BO_SHARK100	1	12/30/2011		PVSVS	METDL	SHARK100
33	SHARK100	SHARK100 Meter		BO_SHARK100	1	12/30/2011		PVSVS	METDL	SHARK100

Results based on the following qualifier(s):
 Entity = SANDIA PVROM DATABASE
 Assigned To Problem = No
 468 match(es) found
 Report Generated: 02/19/2016 10:59 AM

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-22	04/19/2004 12:48	Closed	INV: Inverter	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN

Category:
 Environment-induced Failure/Suspension
Down Time for Service:
 N/A

BOM Level 2 Part Number:
 Array Electrical Connections: ECON
Response Time:
 N/A

Unit Location:
 N/A

System/Component Information

BOM Level 1 Part Serial Number: SGS-29

Part Name: SGS Solar System Power Block

BOM Level 1 Part Number: SGSSS

Version:

System Status:

System Hours: 41088

Unit Location:

Under Warranty: ☐ Yes ☒ No

System Down Event:

Incident Disposition

Occurrence Date: Jul 6 2008

Time: 05:19 AM Local Time

State: Closed

Report Type: Unplanned Field Event

Category: Environment-induced Failure/Suspension

BOM Level 2 Part Number: [ECON: Array Electrical Connections]

Owner: [ADMIN, SYSTEM]

Creator: [ADMIN, SYSTEM]

Actions: None

Description: Row box ground fault due to plastic conduit expansion pinching row wire against metal conduit

Fault Codes (0):

Incident Repair Information

Service Response Date: Feb 2016

Time: AM PM Local Time

ASP Field Service Tech:

Status of Troubleshooting: None

Resolution: repaired

Repair Duration: 91 (1.5 = hour and a half)

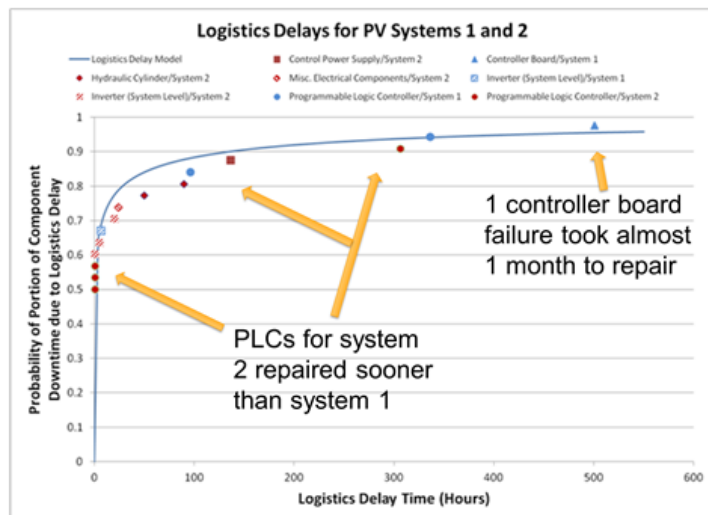
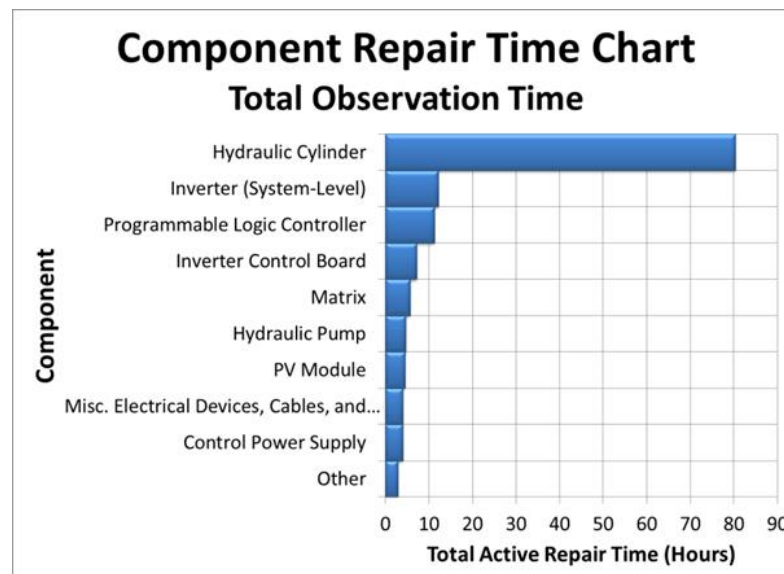
Repair or Replace Parts, Add /Modify Parts

Original Part SN	Original Part Name	Orig Part #	Rev	Failure Analysis Report	Replacement Part SN	Rpl Part #	Rev
	Failure Type	Part Disposition	Hours to Failure				
	Return Type	RMA Number - Rcvd	SO Number		Starting Age		
ECON-29	Array Electrical Connections	ECON	N/A		ECON-29	ECON	N/A
	Non-inverter Inoperable - Other-induced	Repaired	41088.00	New			
	N/A	N/A - N/A	N/A		N/A		

Initiating Event:

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

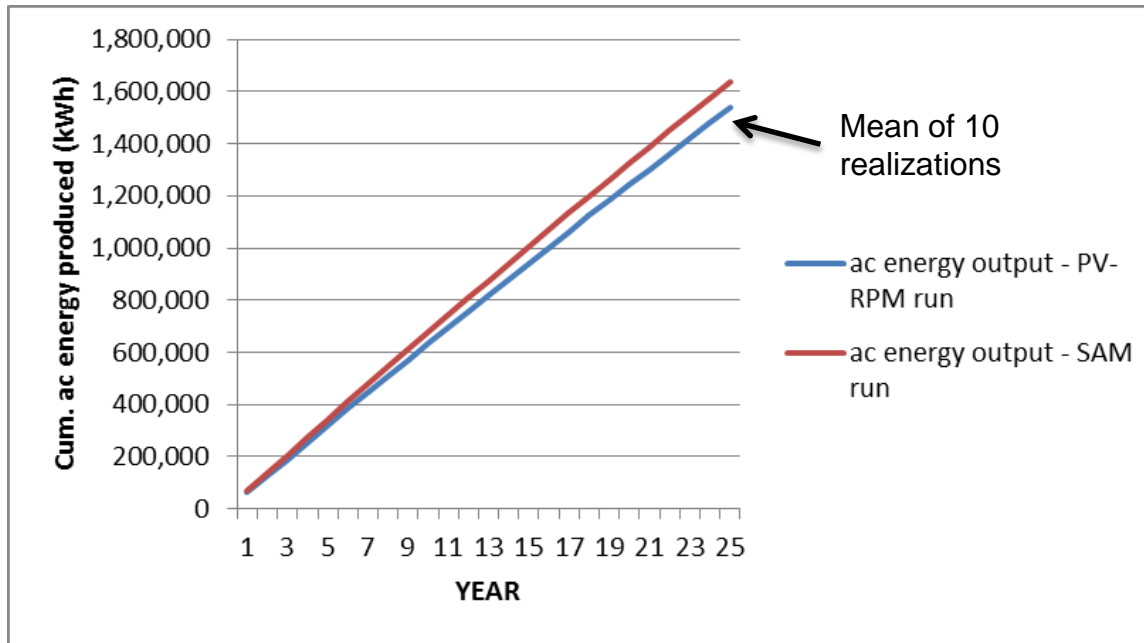
Component	Distribution	1 st Model Parameter	2 nd Model Parameter
AC Disconnect Switch	Lognormal	$\mu = 7.048$	$\sigma = 3.863$
Photovoltaic Modules	Weibull	$\beta = 0.825$	$h = 4.498 \times 10^6$
480/34.5 kV Transformer	Weibull	$\beta = 0.668$	$h = 2,554$

Current Efforts to Improve O&M with a Reliability Focus:

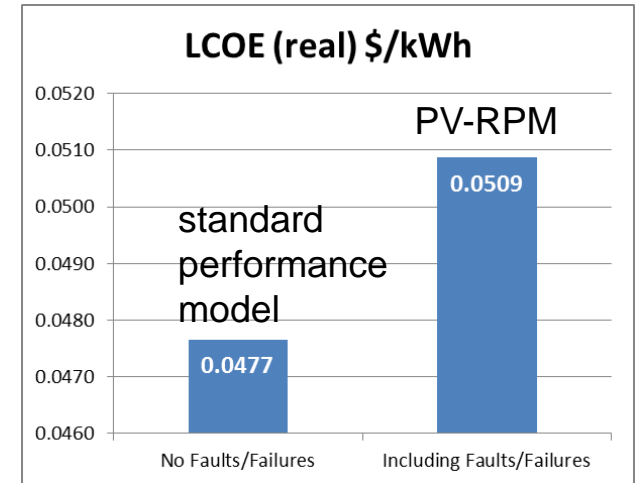
- Adding probability distributions to the System Advisor Model

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



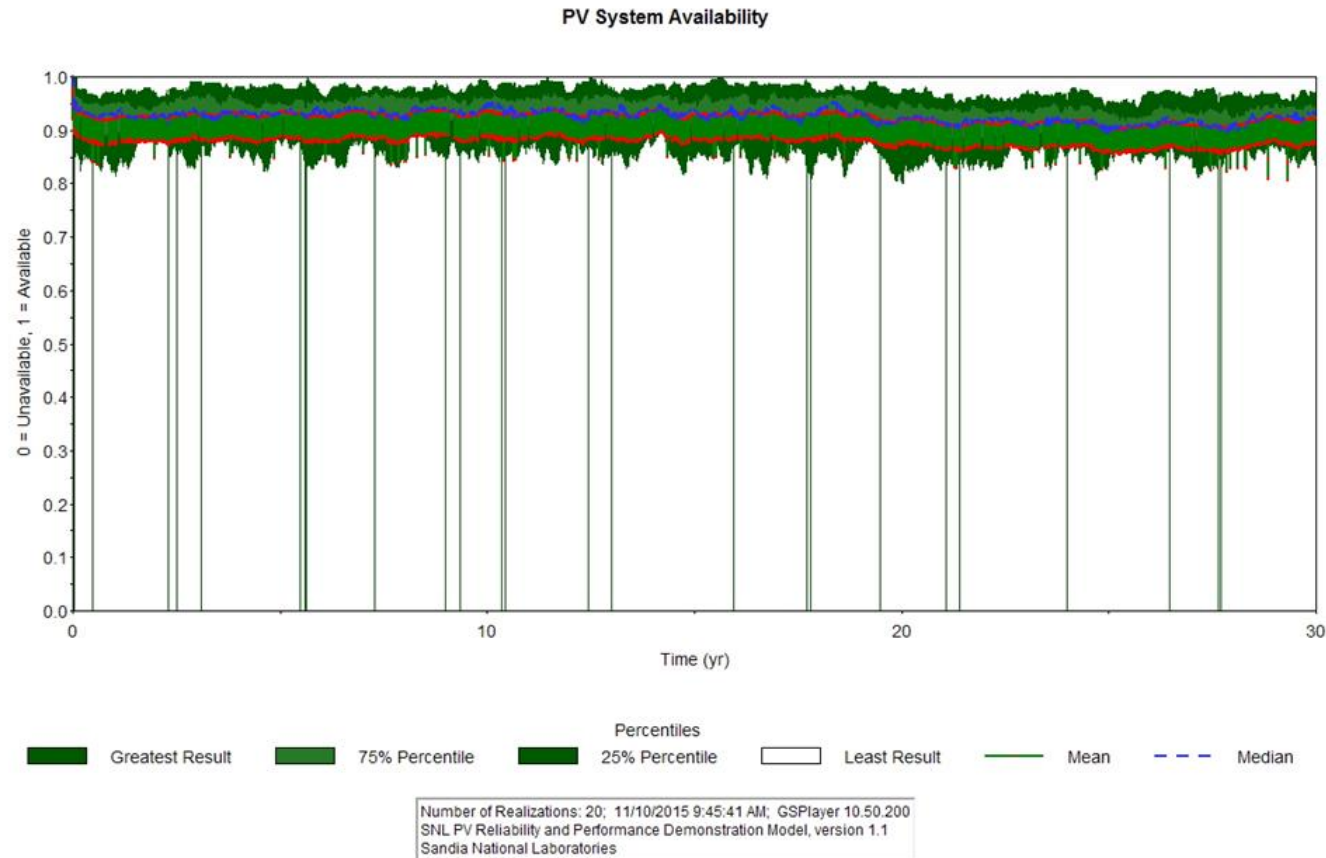
6% difference in cumulative ac energy production over 25 years



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

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



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

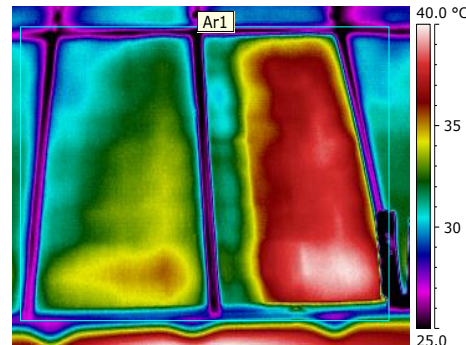
■ PV Life Cycle Workshop

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



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Thank You
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