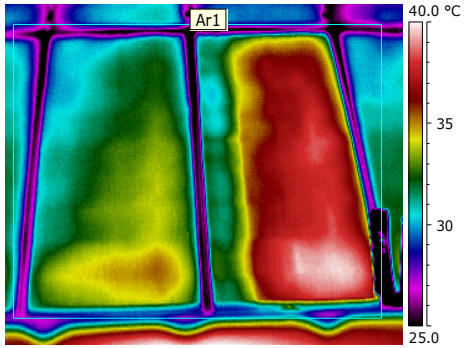
SAND2017-1138C



Reliability Impacts to PV Plant Performance: Methods and Tools for O&M Insight

EPRI Generation Advisory and Council Meeting

Geoffrey T. Klise
Sandia National Laboratories
February 7, 2017

SAND2016-XXXXC

U.S. DEPARTMENT OF ENERGY

SunShot U.S. Department of Energy

Acknowledgements

- Michael Bolen – EPRI, for the invitation to present Sandia's research efforts in PV system reliability

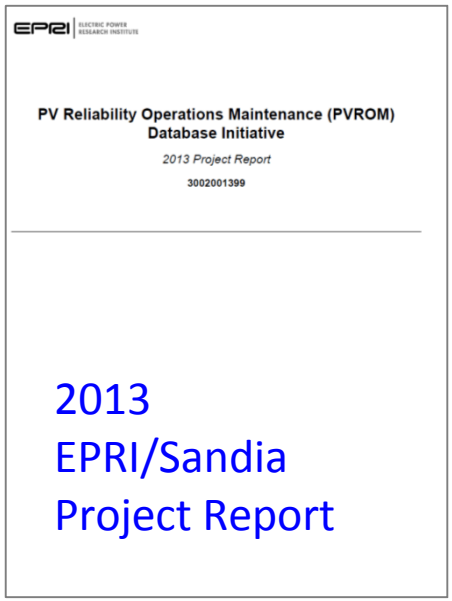
- Olga Lavrova from Sandia for reliability analysis
- Janine Freeman from NREL for implementing Sandia's PV-RPM algorithm into SAM
- DOE SunShot PV and Soft Costs Programs for funding this research

Outline

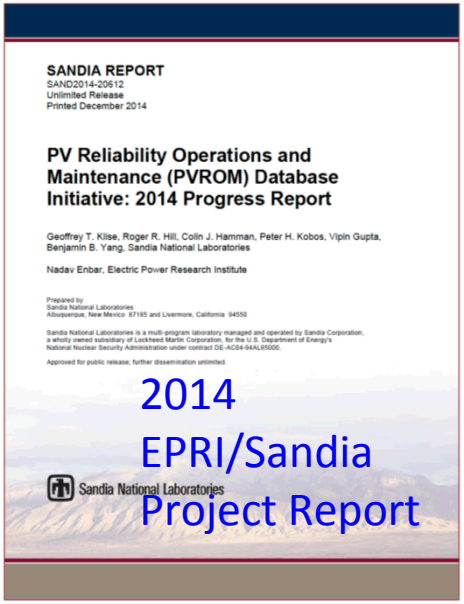
- EPRI and Sandia Relationship
- What does reliability help provide insight to?
- Process for evaluating reliability impacts to performance
- Levels of Data Collection & Storage efforts
- Data Analysis
  - Summary Statistics
  - Energy Impacts from Inverter Events
- Data Application – Further Analysis
  - PV Performance Modeling
  - Proforma O&M Cost Modeling

EPRI and Sandia Relationship

- Formal CRADA agreement from 2012 through June 2017 in the area of Reliability and O&M. Collaborative research includes:
  - Budgeting for Solar PV Plant O&M: Practices and Pricing
  - PVROM effort, laying foundation for best practices in reliability data collection



2013
EPRI/Sandia
Project Report



2014
EPRI/Sandia
Project Report

EPRI and Sandia Relationship

Additional CRADA activities:

- 2016 PV Systems Symposium
  - PV Performance Modeling Workshop
  - PV Life Cycle Reliability Workshop
- 2014 PV Systems Symposium
  - PV Performance Modeling Workshop
  - PV Distribution System Modeling Workshop
  - PV Operations & Maintenance Workshop
  - EPRI Smart Inverter Workshop
- 2013 PV Systems Symposium
  - Operations and Maintenance Workshop
  - Inverter Reliability Workshop
  - PV Performance Modeling Workshop

All held in Santa Clara, CA

Events well attended each year and received positive feedback from industry participants

EPRI and Sandia Relationship

Other Projects:

- PREDICTS 2 Project (DOE funded, EPRI Awardee, SNL partner)
  - EPRI led with SNL as the sub. Goal: validate a new Qual+ Accelerated lifetime testing protocol to improve IEC 61215
  - No CRADA
- California Solar Initiative (EPRI Awardee, SNL partner)
  - CSI 3: Screening Distribution Feeders: Alternatives to the 15% Rule
  - CSI 4: Analysis to Inform California Grid Integration Rules for PV
  - All Under different CRADA
- SUNRISE (DOE funded, SNL partner)
  - Transmission and Distribution Grid Integration
  - Under different CRADA

Process for Evaluating Reliability Impacts to Performance

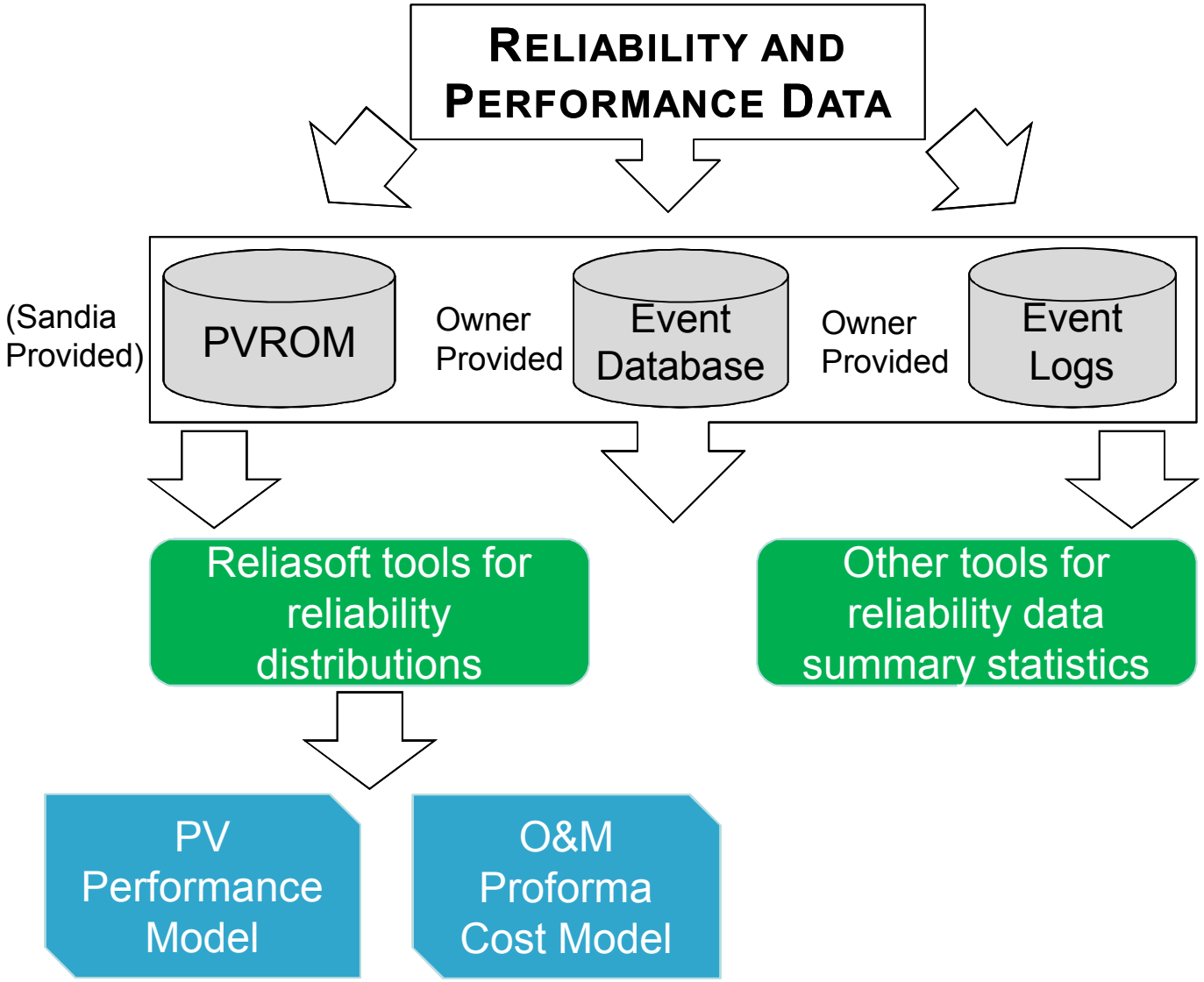
Sandia National Laboratories

Raw Data Generation

Data Collection & Storage

Data Analysis

Data Application and Further Analysis

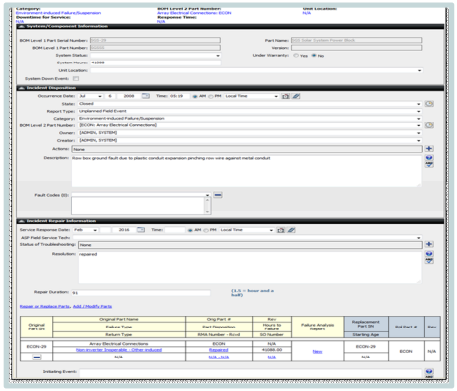


Reliability Spectrum of Data Collection & Storage Efforts

Designed for Reliability Analysis

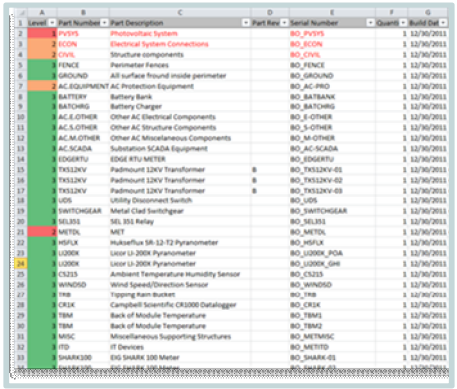
Yes — **Somewhat** — **No**

PVROM



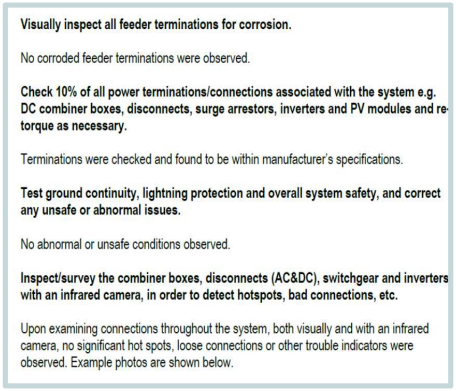
- Highly structured series-parallel component dependencies
- Allows for less data manipulation for reliability analysis
- Component downtime and energy lost

Event Database



- Somewhat structured based on component tickets
- Dependent tickets
- Component downtime and energy lost

Event Logs



Visually inspect all feeder terminations for corrosion.

No corroded feeder terminations were observed.

Check 10% of all power terminations/connections associated with the system e.g. DC combiner boxes, disconnects, surge arrestors, inverters and PV modules and re-torque as necessary.

Terminations were checked and found to be within manufacturer's specifications.

Test ground continuity, lightning protection and overall system safety, and correct any unsafe or abnormal issues.

No abnormal or unsafe conditions observed.

Inspect/survey the combiner boxes, disconnects (AC&DC), switchgear and inverters with an infrared camera, in order to detect hotspots, bad connections, etc.

Upon examining connections throughout the system, both visually and with an infrared camera, no significant hot spots, loose connections or other trouble indicators were observed. Example photos are shown below.

- Not structured
- Monthly reports and event details are compiled into database
- Incomplete information for downtime and energy lost

PV Reliability Operations & Maintenance (PVROM)

- Pros
  - Component downtime and energy lost
  - Highly structured series-parallel component dependencies
  - Allows for less data manipulation for reliability analysis
- Cons
  - Resides on a Sandia Server (security protocols for partner entering data)
  - Serializing PV system is not a trivial effort
  - Time and effort for entering data into PVROM forms, outside of data partner's own ticketing system
- 13.2 MW in the PVROM highly structured category
  - 4.7 MW is older data – fixed tilt (AZ)
  - 1.75 MW is older data – tracking system (AZ)
  - 0.45 MW is newer, DG data – fixed tilt (AZ)
  - 6.3 MW with new IPP partner (*240 MW potential*), soon to be entering event data (East Coast)

PVROM Input and Output Data Fields

Sandia National Laboratories

Base Installation Detail
PV System Owner
PV System Installer
PV System Location
As-built drawing
Commissioning Date
In Service Date
O&M Contract
dc Nameplate Capacity
Array Size
Array Operating Voltage
Configuration/Application
Utility/Grid Details
BOS components
Component Bill-of-Materials

PV System Performance
Measured site solar insolation
Estimated site solar insolation
Weather data
dc kWh production
ac kWh production
Other test data
Energy Yields
Yield Losses
Performance Ratio
Efficiencies (array, BOS and plant)
Model used for developing lifetime performance estimates
Degradation rates of components

O&M Cost Metrics
Budgeted O&M cost
O&M service contract
Installed cost
Component and activity cost estimates
Labor rates
Component and activity cost - actual
NPV of components (lifetime)
Lost revenue
Warranty items
Insurance policy

Reliability Metrics
Incident Title
Incident Description
Occurrence Date
Creation Date
Warranty Repair
Service Response Date
Incident Status
Service Response Date
System Status
Incident Report Type
Incident Categories
Restored to Duty
Active repair duration
Incident Resolution
Initiating Event
System Hours
Operating Time Prior to Failure
Severity to System
System Down Event
Warranty Repair
ac kWh Loss
Tables of Reliability Data
Availability
Logistical Downtime
Failure Modes
Incident Frequency
Repair Duration
Downtime
Service Downtime
Component Labor Hours
Component Contribution to Energy Loss

Incident Categories
Hardware failure
Software problem
Hardware upgrade required to operate
Software upgrade required to operate
Equipment installation problem
Grid-induced failure/suspension
Lightning-induced failure/suspension
Environment-induced failure/suspension
Hardware application problem
Vandalism
Unknown
Hardware upgrade
Software upgrade
Planned maintenance
Troubleshooting issue
System upgrade
End of useful life failure

Additional PVROM Output

Component Metric Summary - Example

	Summary Maintenance Metrics				*Summary Availability Metrics*		*Failure Metrics in Percentile - Failure Time*			*Repair Metrics in Percentile – Repair Time*		
Component	**CUM. MTBM**	**CUM. MTBF**	**Avg. Active Repair Time**	**Total Comp. Downtime**	**Total Power Lost (kWh)**	**Total Comp. Downtime**	**10th**	**50th**	**90th**	**10th**	**50th**	**90th**
Inverters	18,500	140,000	0.75	400	26	50	1,550	10,220	33,950	0.2	0.5	1.4
Photovoltaic Modules	54M	54M	4	10	4	0	5.7 E+06	3.7 E+07	1.2 E+08	0.4	2.8	9.2
Hydraulic Cylinders	10,560	10,560	4.5	0	80	0	6,500	12,680	16,000	3.6	4.4	5.2
Programmable Logic Controller	20.5 M	20.5 M	1.2	0	15	0	2,590	274,200	2.9 E+07	0.2	0.8	2.6
Data Acquisition system	14,112	21,168	0.3	0	1	0	1,490	9,780	32,490	N/A	N/A	N/A

Repairable failure distribution parameters

Component	Beta (Shape)	Lambda (Scale)
DC Disconnect Switch	0.470	0.0496
Array Electrical Connections	1.239	3.486×10^{-5}
Inverter – Corrective and Preventative Maintenance	1.029	2.264×10^{-3}
Inverter - Induced Outages	1.041	4.799×10^{-3}

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	$\beta = 0.825$	$\eta = 4.498\times10^{6}$
480/34.5 kV Transformer	Weibull	$\beta = 0.668$	$\eta = 2{,}554$

Structured Event Database

- Pros
  - Somewhat structured based on component tickets
  - Dependent tickets
  - Component downtime and energy lost
  - Can be analyzed in different platforms
- Cons
  - Only two years of data
  - Not serialized for component dependency

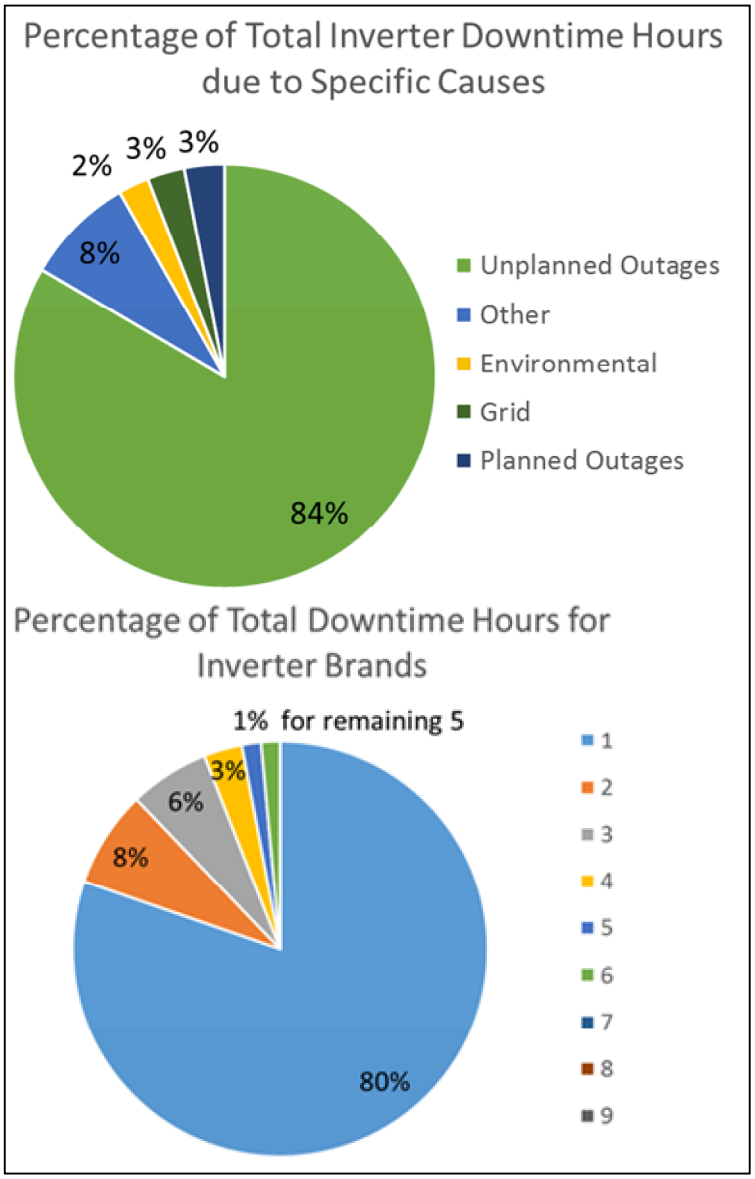
- 570 MW in the Structured Event Database category
  - Mixed between Utility-scale and DG. Mostly Utility Scale
  - Located in AZ, CA, CT, IN, MA, NC, NJ, NY
  - Primarily inverter events under analysis

Event Logs

- Pros
  - Not structured
  - Incomplete information for downtime and energy lost
- Cons
  - Monthly reports and event details are compiled into database
  - Not serialized for component dependency
  - Most time consuming process for reliability data set-up

- 29 MW in the Event Log category
  - 15 MW (commercial DG) under this system
  - 14 MW (commercial and industrial DG) to be added shortly in Hawaii

Data Analysis – Summary Statistics



Portfolio A – "Structured Event Database"

- 570 MW_{dc}
- Snow, water, lightning
- Utility planned/unplanned repair & grid disturbance
- Annual PM, coolant check, filter cleaning, module replacement, thermal imaging

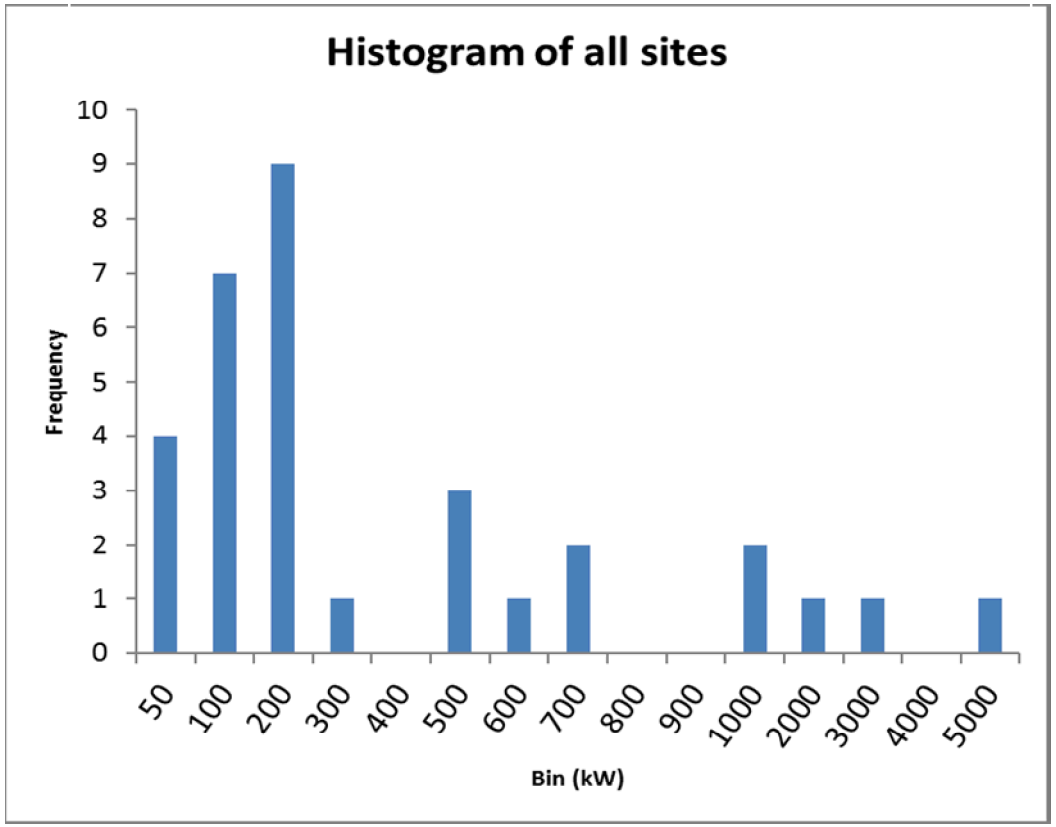
Data Reduction – 374 to 187 short descriptions

Event Name Modified	New Order by Event Frequency	Event Name Original	Original Order by Event Frequency
Unknown Fault	1	Unknown Reason & Unknown Fault	5 and 16
Fan Failure	2	Fan Failure	1
DCS Fault	3	DCS Fault & DC Subsystem Fault	4 and 14
Preventative Maintenance	4	Due to and for Preventative Maintenance	9 and 12
Grid Fault	5	Grid Disturbance	20
LVRT Fault	6	LVRT Fault	3
Engine Failure	7	Engine Failure	2
Critical Faults	8	Critical faults	6
Cycling Fault	9	Cycling Fault	7
Array Fault	10	Array Fault	8

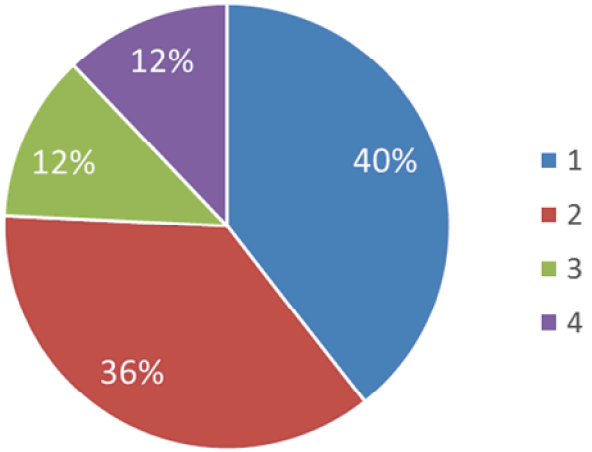
Data Analysis – Summary Statistics

Portfolio B – "Event logs"

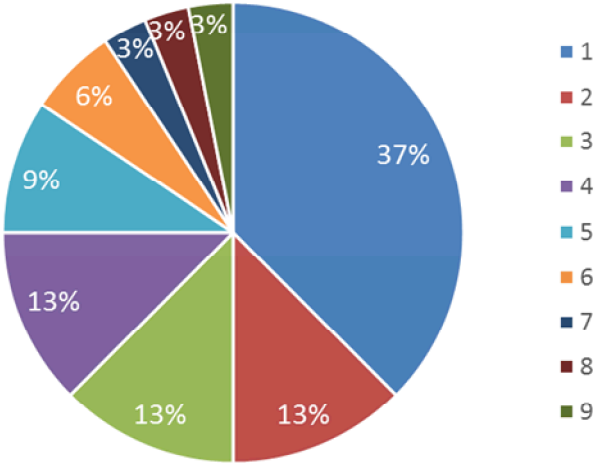
- 14 MW_{dc}
- 32 DG sites, distribution below
- Compilation of events is currently underway



All DG sites, by Inverter Brand



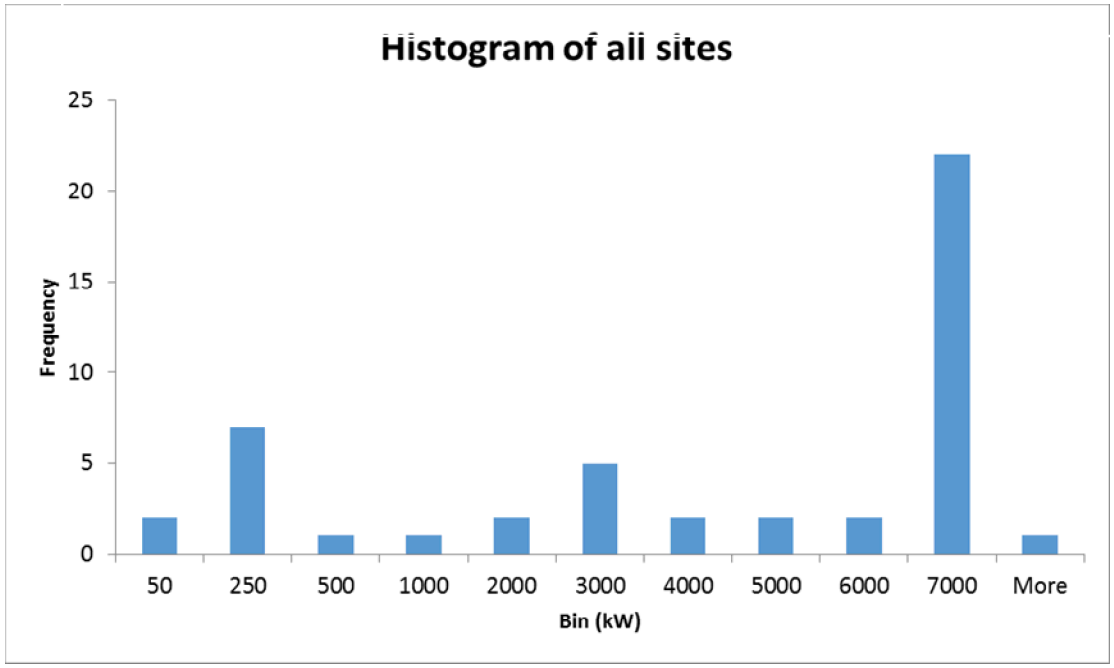
All DG sites, by Module Brand

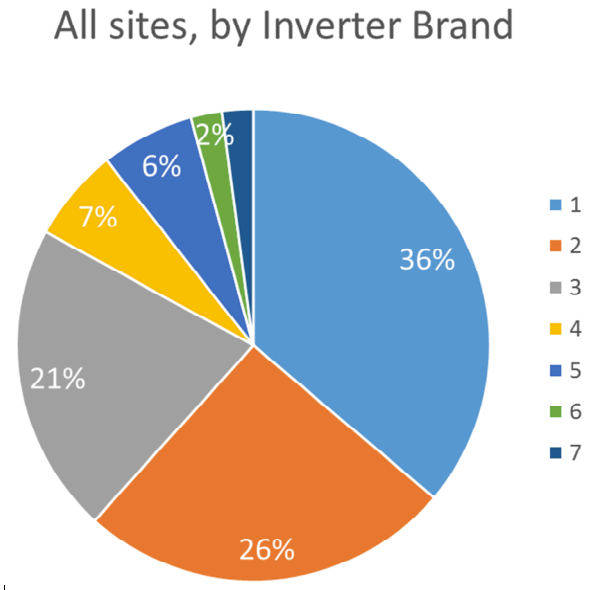


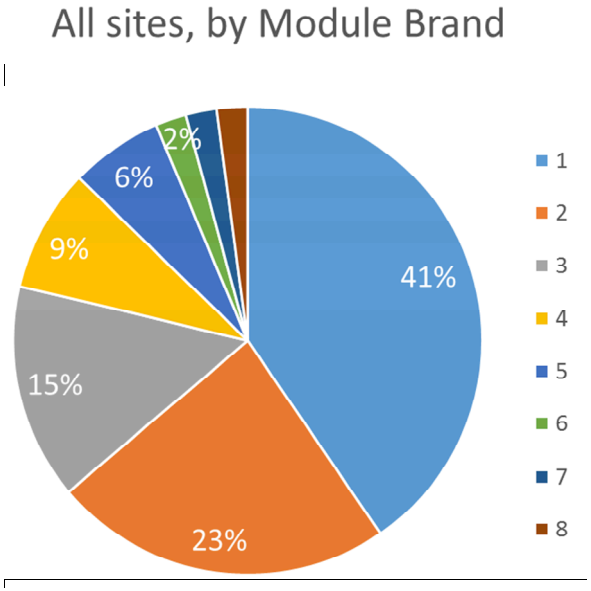
Data Analysis – Summary Statistics

Portfolio C – "Structured Event Database & PVROM Database"

- 240 MW_{dc}
- 47 Utility and DG sites, distribution below
- PVROM Bill of Materials development (6 MW system)
- Compilation of events is currently underway





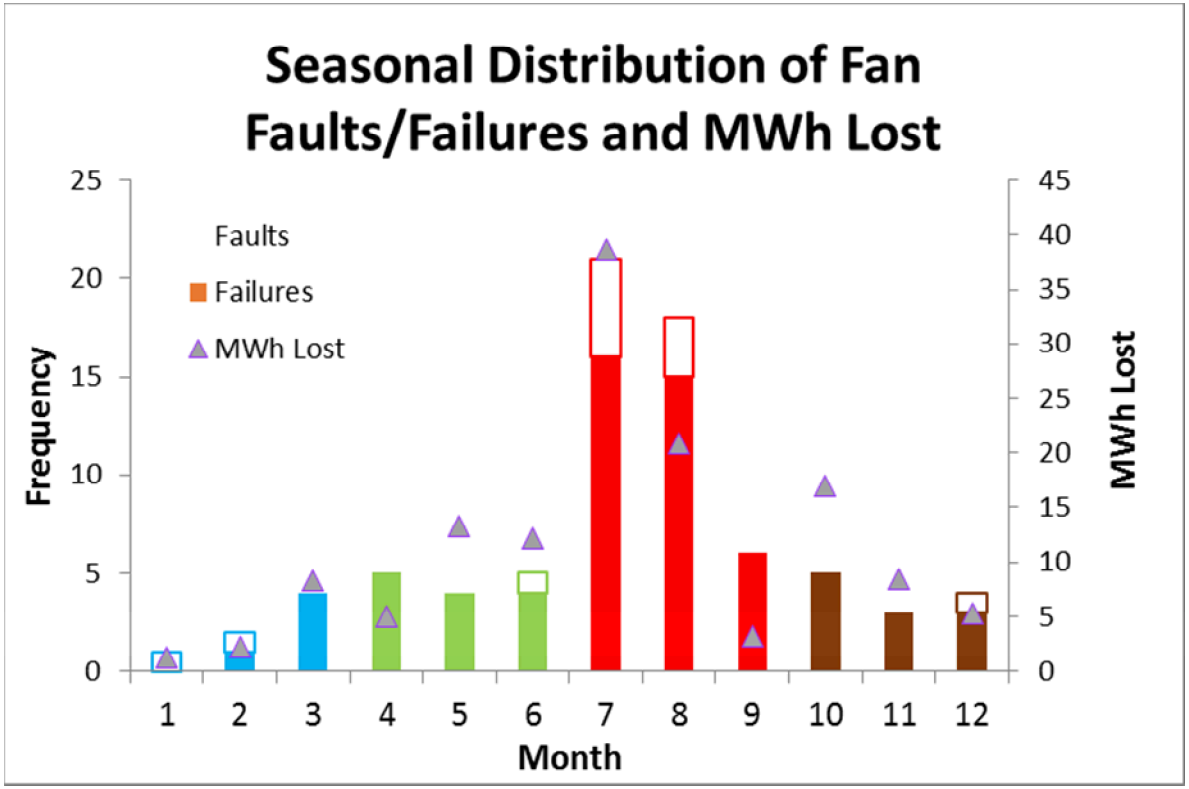


Data Analysis – Specific Component

Sandia National Laboratories

Inverter Fan Analysis

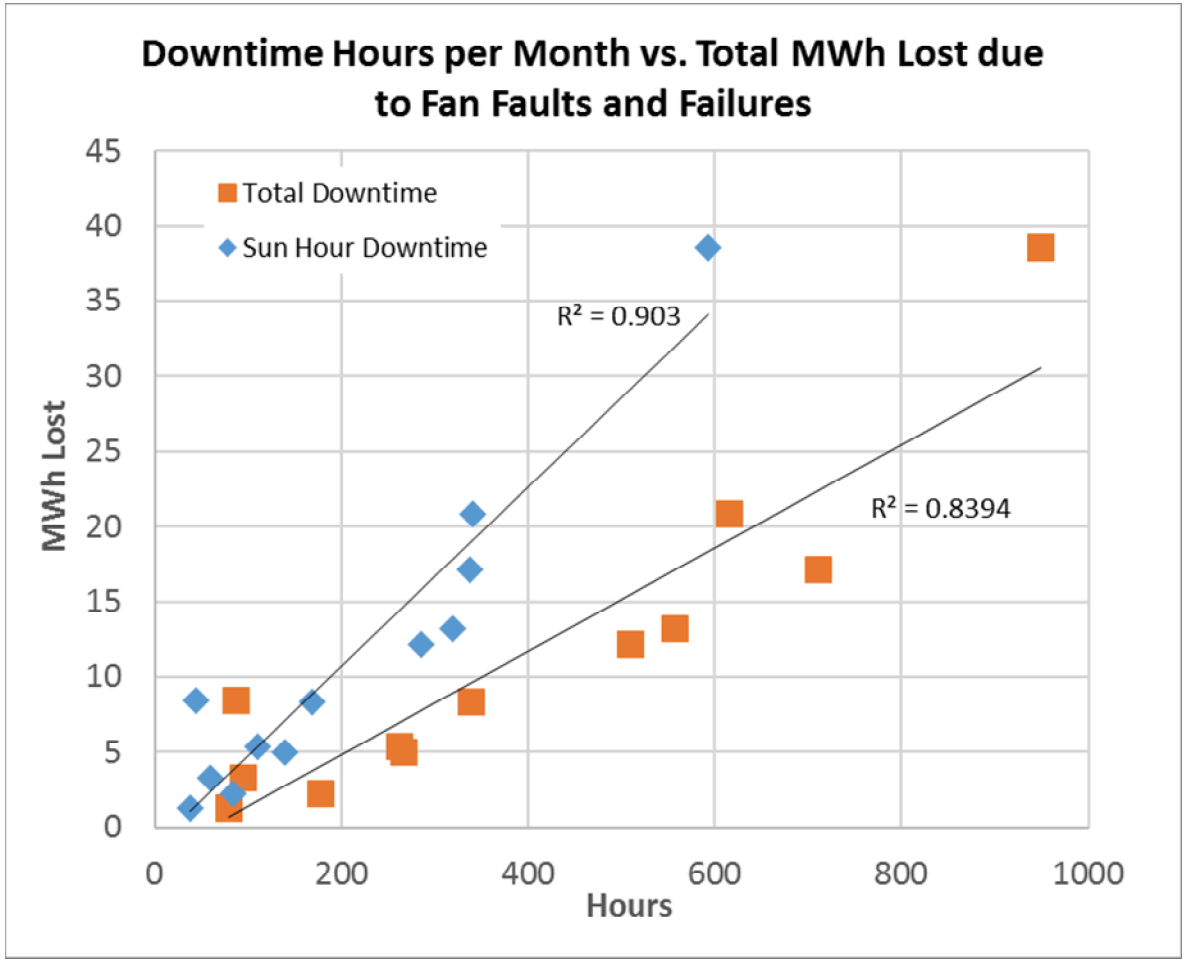
- 78 fan events over two-year period (17 locations, 3 states)
  - 49 inverters (out of 222) with events representing *potential* to impact 160 MW_{ac}
  - 3 different model numbers
  - In-service dates primarily 2013-2015 (~2 years of data)
  - **11 faults – power cycle**
  - **67 faults leading to failure – replaced**



Data Analysis – Specific Component

Sandia National Laboratories

Inverter Fan Analysis



- Data can be analyzed for Total Downtime or Sun Hour Downtime
- Sun Hour Downtime correlates better with energy loss
- Use of one or the other depends on the research question
- pvlib.solarposition* used to estimate Sun Hours at each site (not a function of inverter start threshold)

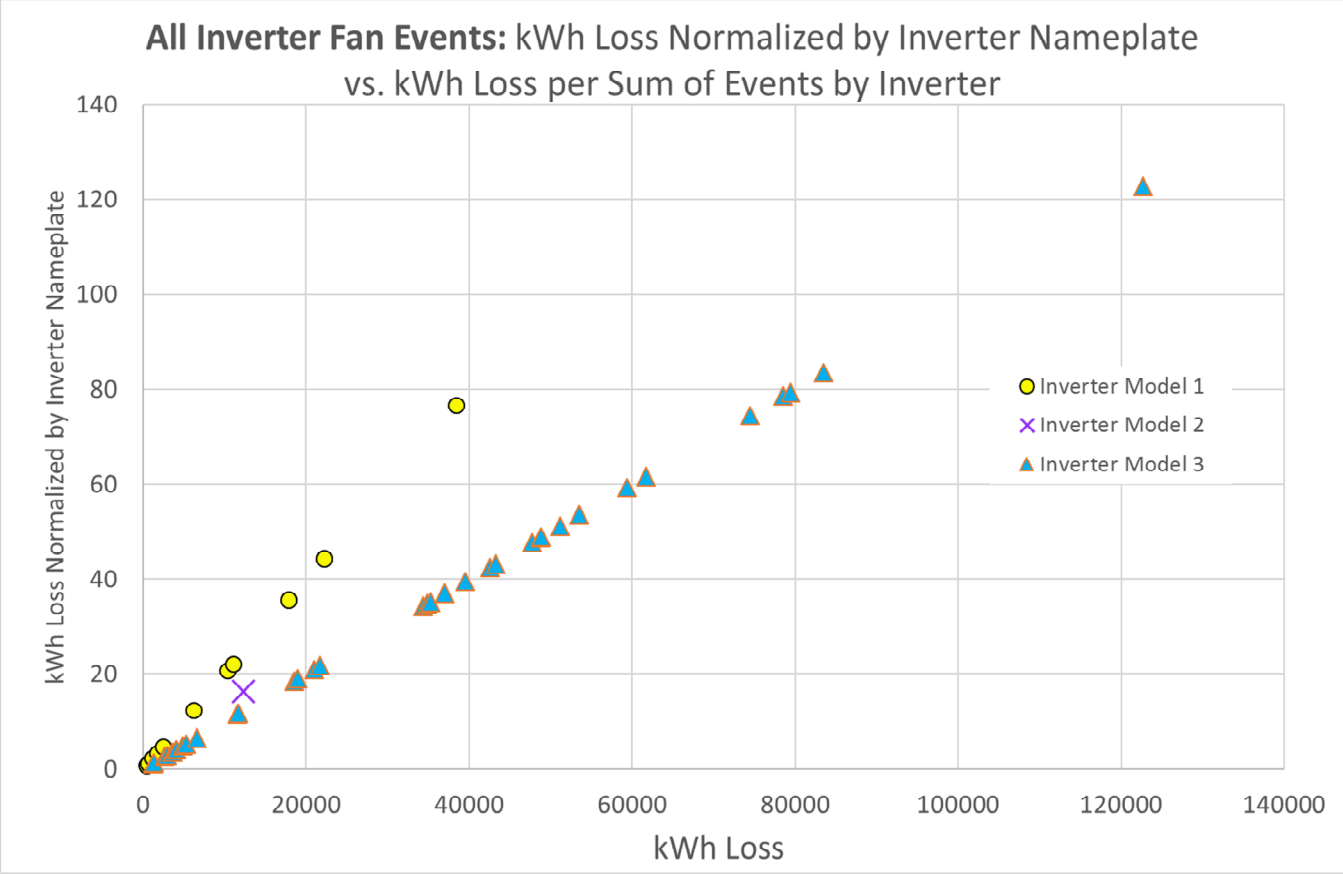
*http://pvlib-python.readthedocs.io/en/latest/_modules/pvlib/solarposition.html

Data Analysis – Specific Component

Sandia National Laboratories

Inverter Fan Analysis

- Normalizing fan energy losses by inverter nameplate separates the losses by inverter size
- When considering the same loss amount, impact is greater for the smaller inverter (Inverter Model 1)

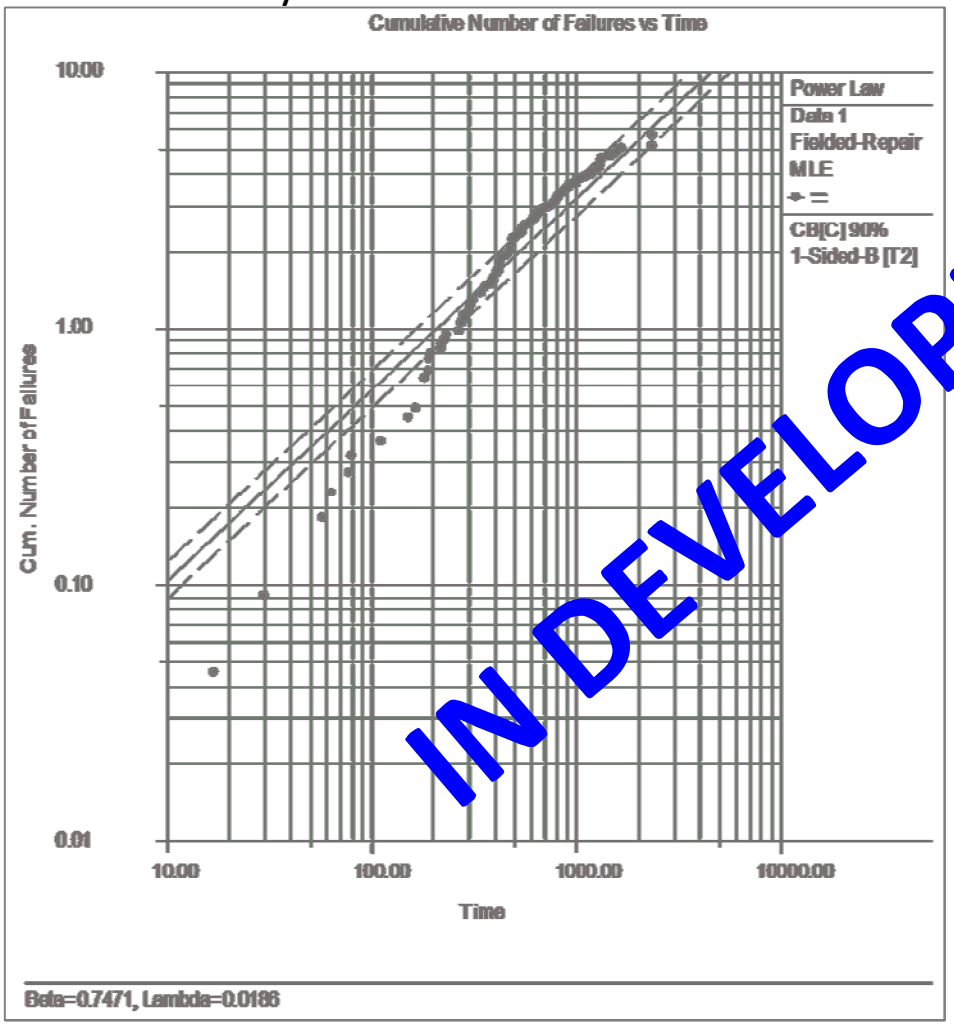


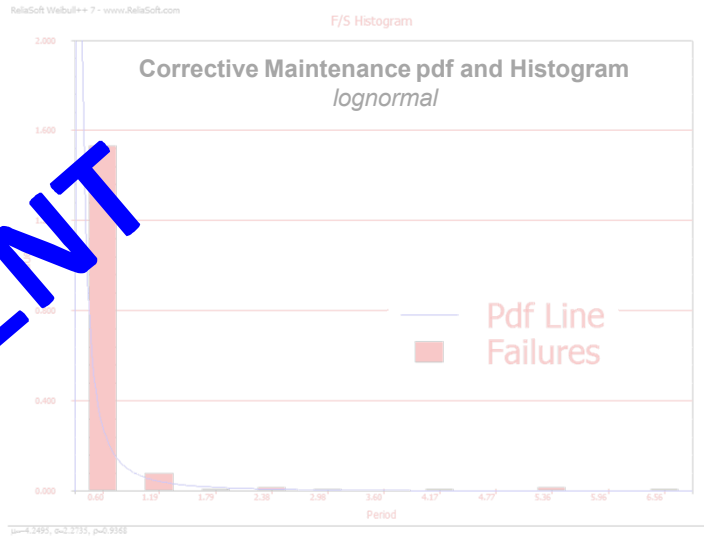
Data Analysis – Specific Component

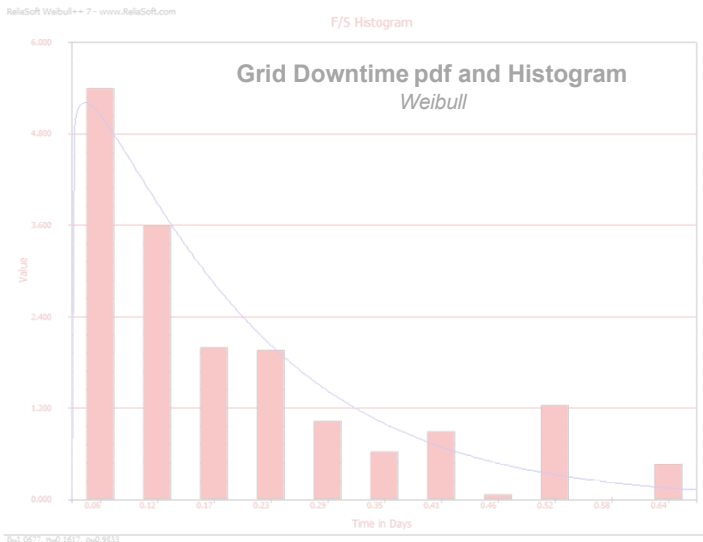
Sandia National Laboratories

Inverter Fan Analysis

- Reliability Distributions







IN DEVELOPMENT

Data Analysis – Developing Reliability Distributions

Database of Stored Incidents

pdf

Results based on the following qualifier(s):
Entity = SANDIA PVROM DATABASE
Assigned To Problem = No

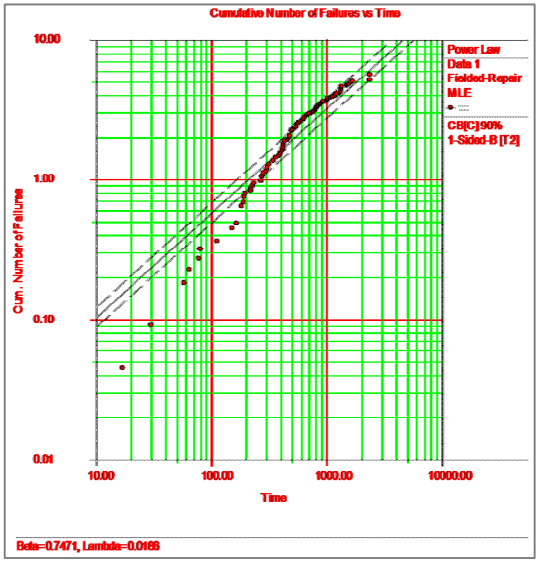
468 match(es) found
Report Generated: 02/19/2016 10:59 AM

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

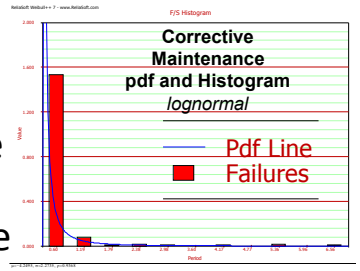
Inverter Parametric Recurrence Data Analysis – Cumulative Failures vs. Time

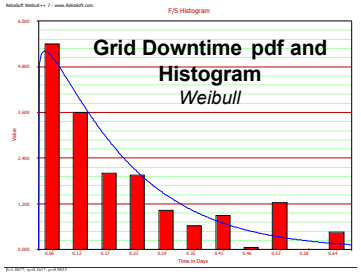
- Power law analysis of inverter failure data indicates reliability growth
- Red markers are observed cumulative times, and solid line is power law fit using Maximum Likelihood Estimation



Inverter Down Time Data Analysis

- Inverter downtime analysis performed for corrective maintenance and grid-induced shutdowns, for example
- Observed data on downtime causes is fit to best distribution. Lognormal and Weibull for this example





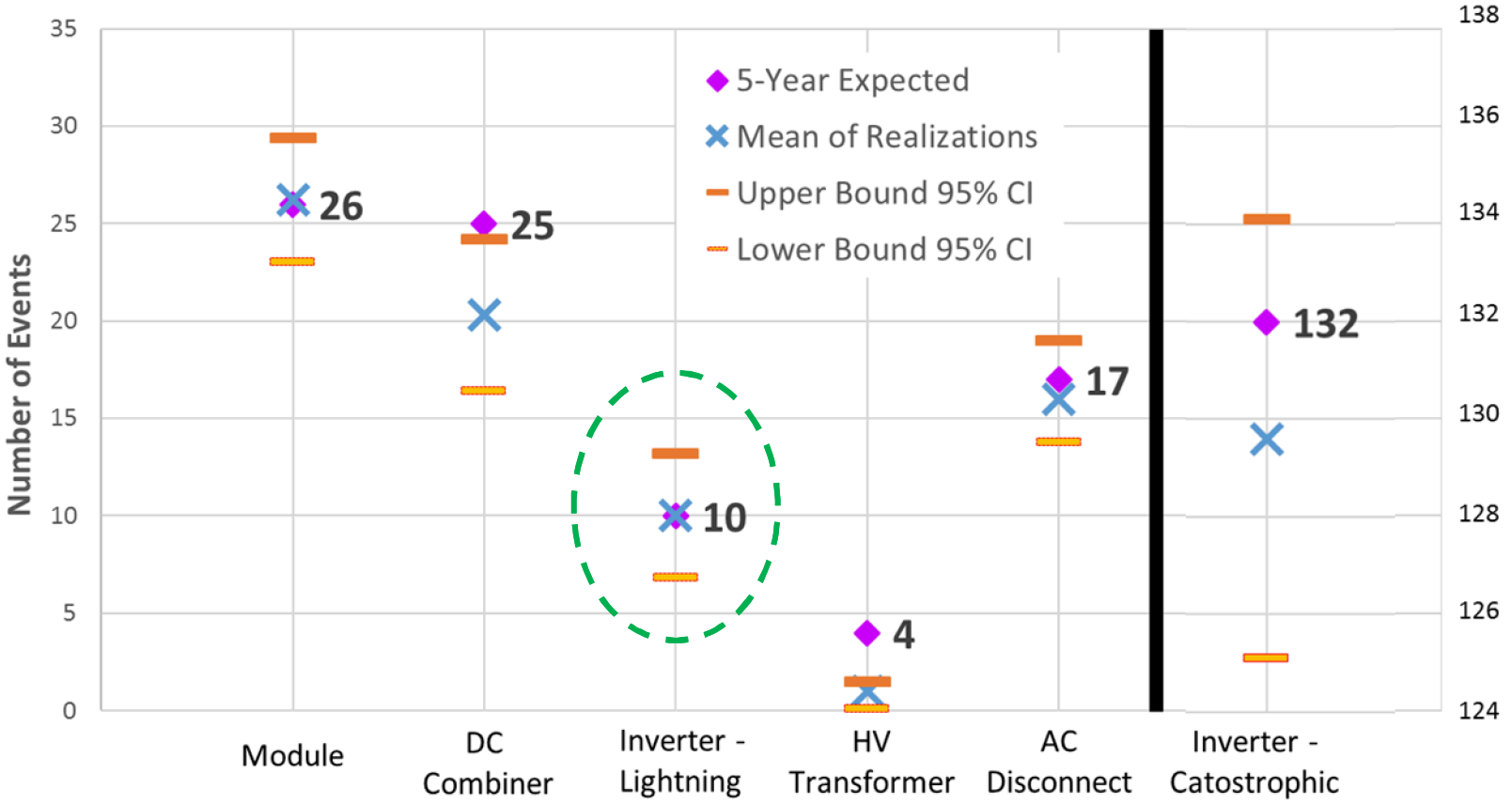
Development of Failure and Repair Distributions for Components

Component	Distribution	1st Model Parameter	2nd Model Parameter
Inverter Corrective Maintenance	Lognormal	$\mu = -4.25$	$\sigma = 2.27$
Grid Effects	Weibull-2 parameter	$\beta = 1.07$	$h = 0.16$

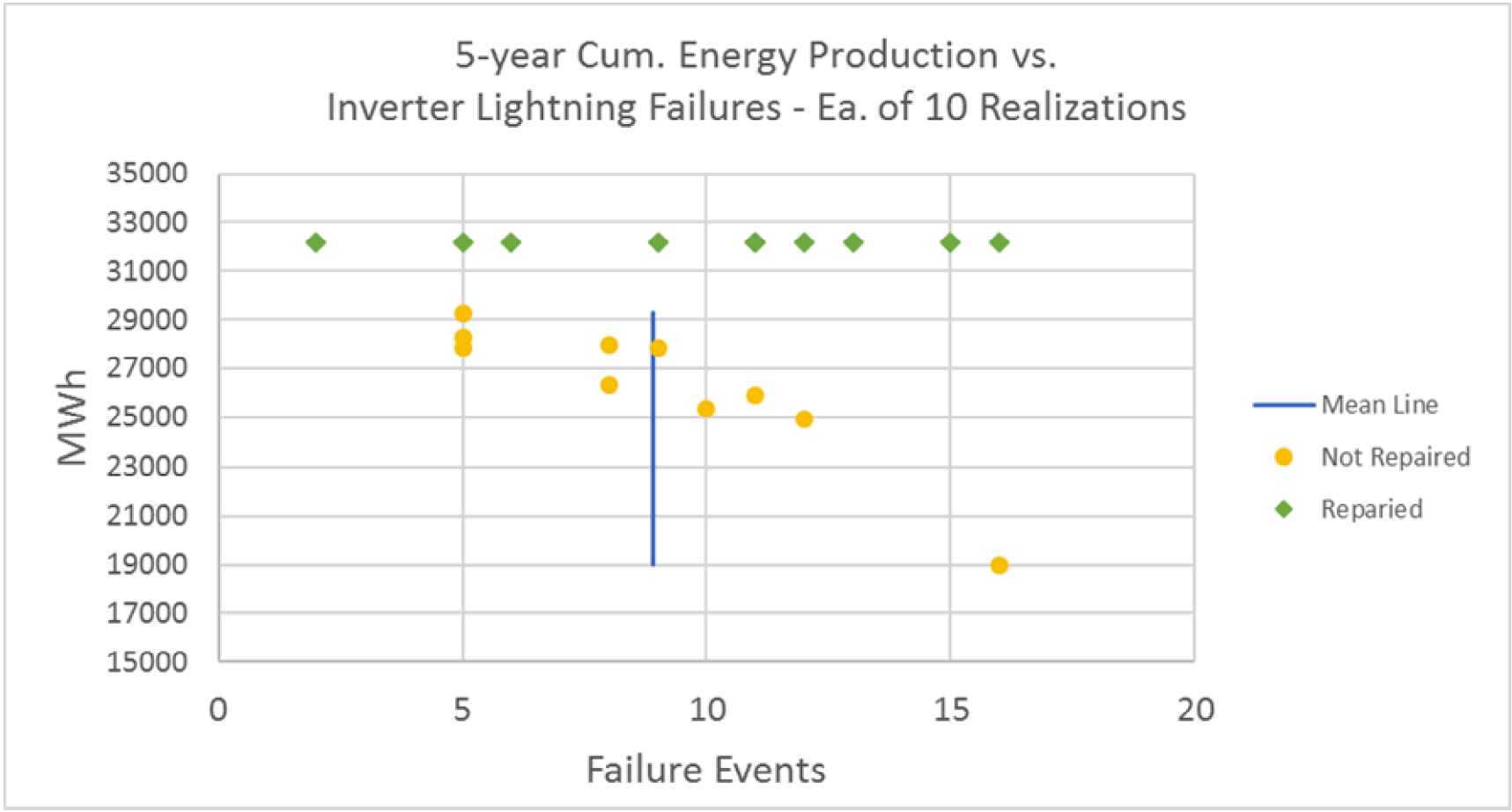
- Data can then be used in O&M cost model or other model, such as the new Reliability feature currently under development in the System Advisor Model

Data Application – Further Analysis

- 5-year dataset used in proof-of-concept and new System Advisor Model (SAM) version to validate implementation of representative failure distributions
- Proof-of-concept results generally fall within or near the 95% confidence interval from the newer SAM implementation (Mean 10 of Realizations)

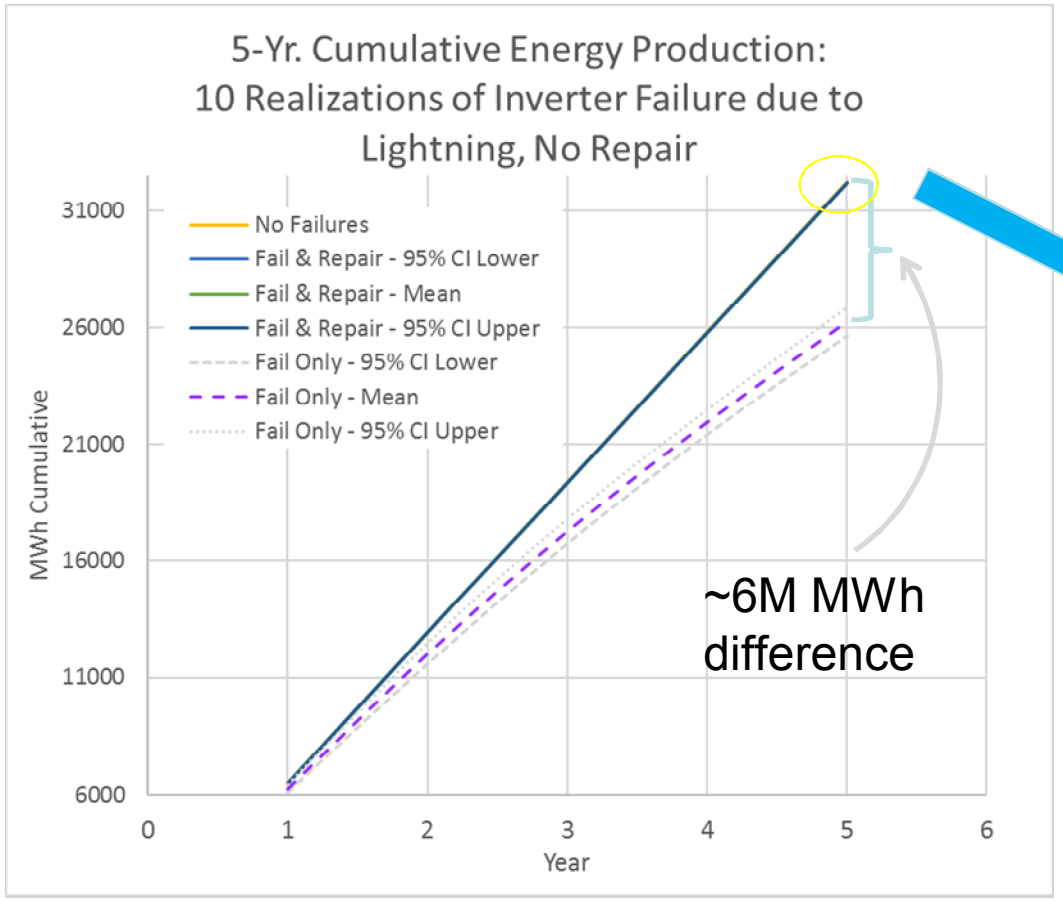


Data Application – Further Analysis

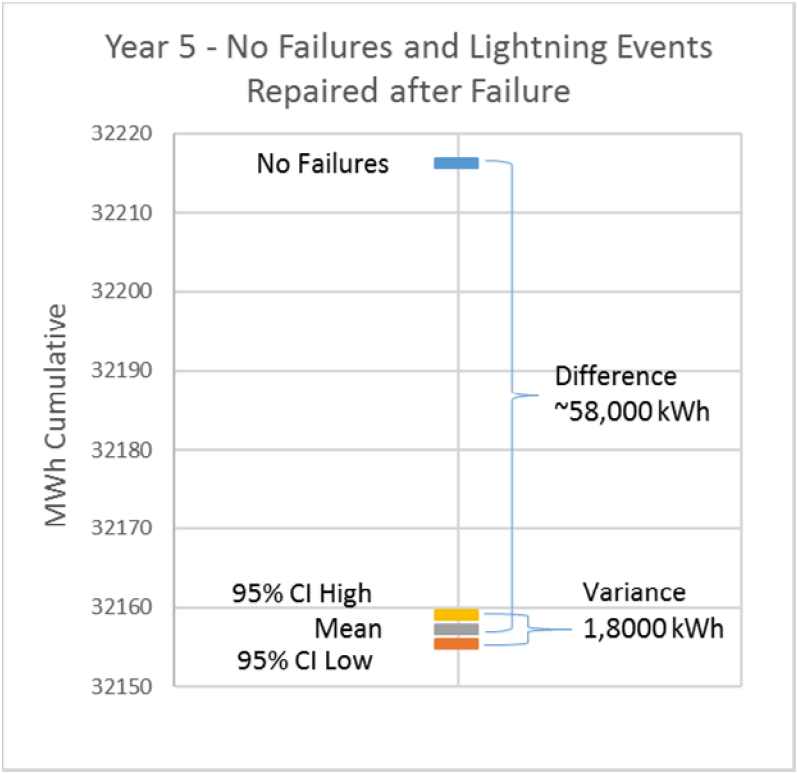


- Top green diamonds are system total 5-year cumulative energy results from 10 realizations when inverter fails and is repaired based on a failure and repair distribution
- Bottom orange circles represent the range of results from the same failure distribution, but inverter is not repaired after lightning event

Data Application – Further Analysis



- Graph at bottom is the energy production range between No Failures & Fail and Repair. Results won't show on same graph



Data Application – Further Analysis

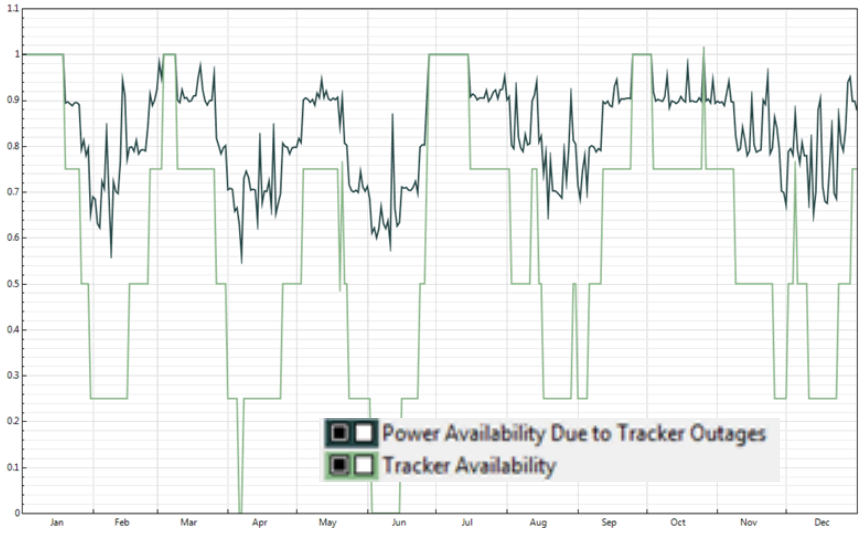
System Advisor Model

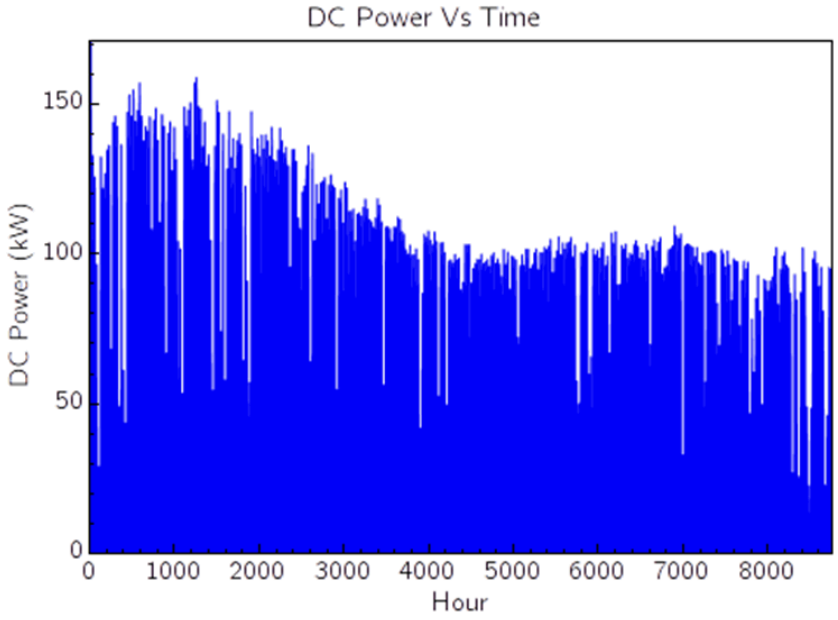
- Tracker Failure

  1. Worst case scenario- tracker is assumed to fail at its rotation limit facing north. In the case of a north-south axis, facing west

  2. Average case scenario- tracker is assumed to fail flat

- Module Degradation
  - When running a reliability scenario, module degradation changes can be analyzed as a result of different failure and replacement rates

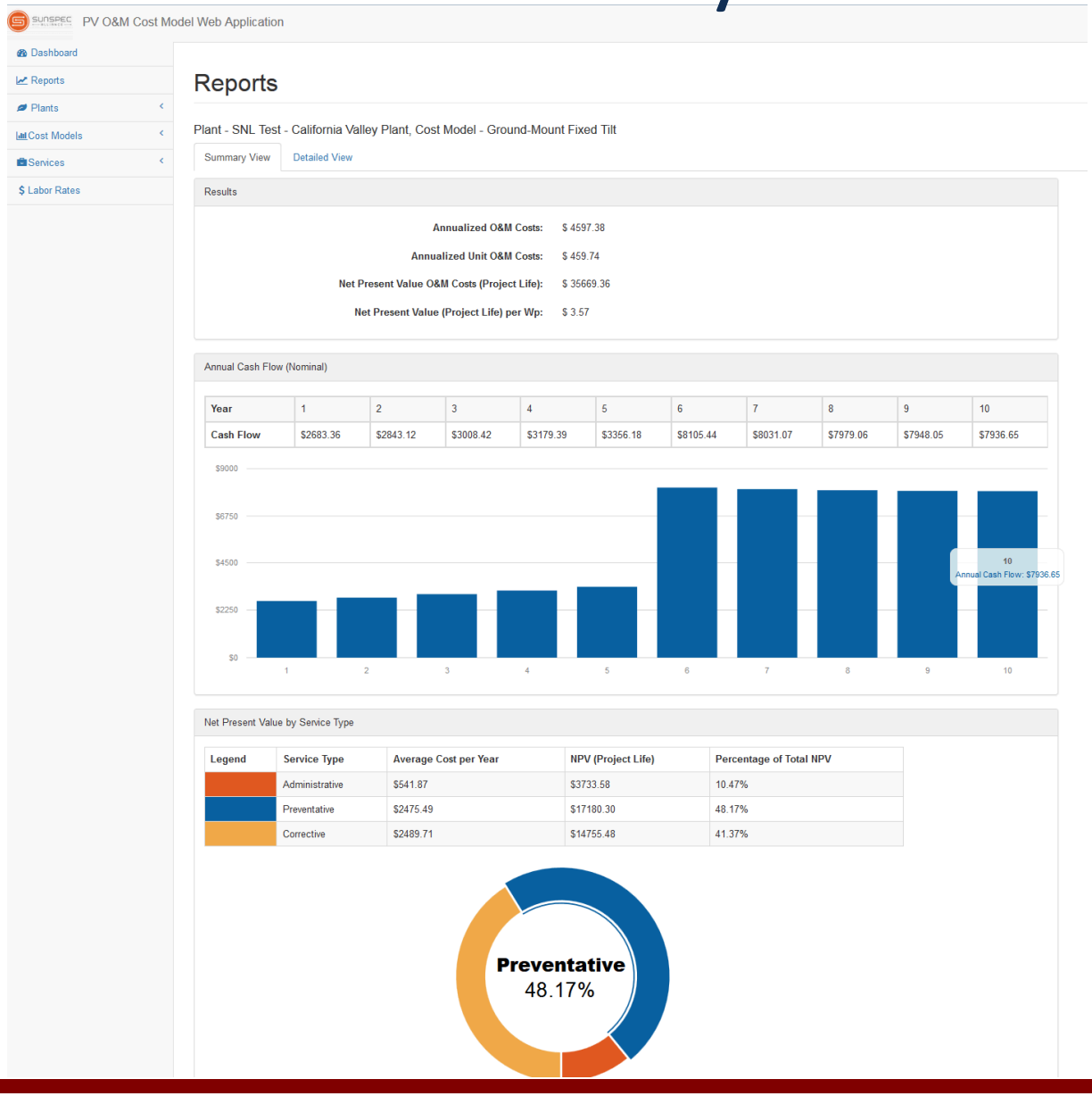


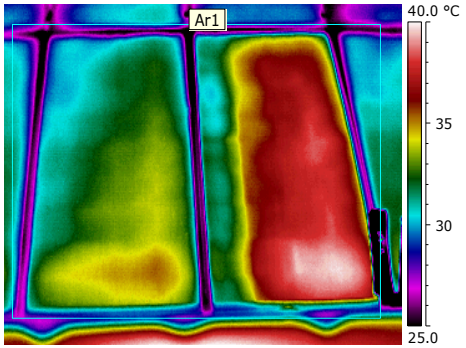


Data Application – Further Analysis

PV O&M Cost Model

- Project led by NREL, with SunSpec and Sandia as partners
- Started as Spreadsheet model
- Currently testing Beta of online O&M cost model





Thank You

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