System Level Reliability Methodologies

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Why Care About Reliability?

Overall impact of a successful Reliability Program:

- Achieve Grid Parity with other electrical generation sources:
  - Costs: Reliable products reduce Levelized Cost of Energy (total lifecycle cost/total energy produced) over the long-term
    - LCOE increases exponentially as system lifetime decreases
    - LCOE increases 10% per 1% increase in degradation rate
    - LCOE increases ~1¢/kWh for each 0.5%/yr of capital cost for O&M
  - Availability: Reliable products over the long-term enhance amount of energy produced and delivered to the grid with reduced O&M costs

Reliability Definition

- Reliability is the probability of simultaneously satisfying:
  - The performance requirement
  - In a specified environment
  - At a particular time
- Reliability is not only about how long something will last
- Systems Approach: Reliability of a component must be addressed with regard to how it fits within the overall system
  - System is defined as all components used to convert sunlight to electricity and deliver it to the grid in a usable form, adhering to all safety and grid quality requirements
- Definition of Failure: inconsistent definition of what constitutes failure--user dependent

PV System Overview

- PV systems Reliability is a function of the components, design, installation, and application
- Must account for interaction among components not just component-level reliability
- Applications-specific issues can also affect lifetime
  - Residential
  - BIPV
  - Commercial
  - Utility scale
  - Grid integrated
  - Stand-alone
- Time is a metric but it must be defined as a function of performance, cost, and reliability

PV System Overview

Component	Materials	Use/Purpose
PV Modules	PV devices, metal interconnects, substrate and superstrate (glass, tedlar, metal foil, polymer), diodes, encapsulant, wires	DC power generation
Junction Box	Wires, diodes	Collect power from module
Module Interconnect	Wires, connectors	Series or parallel string; carries current
Blocking Diode	Si diode	Prevent power backflow
Marshalling Box	Fuses, terminals	Combine PV strings together, protect against power surges
DC disconnect	Mechanical switch, metal box, DC wires	Allow PV strings to be isolated
Inverter	Capacitors, semiconductor devices, wires, LED display, metal box	Convert to AC power
Power Meter	Mechanical or digital output	Monitor power generation

Influencing Factors

What factors influence PV systems reliability?

- We have divided the factors into three categories:
  - Performance is the primary factor

  - Economics enters the picture as we consider when it becomes cost prohibitive to continue to operate a system

  - Social factors are driven primarily by bureaucratic and/or aesthetics factors

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Performance Factors include:

- Technology
  - Module, inverter, tracker, controls, BOS,
  - TF, CPV, and flat plates
- O&M strategy, O&M skill, experience
  - Operation :Is the system being operated optimally or at extremes?
  - Maintenance: how frequently are issues addressed?
- Environment (temp, humidity, dust, wind, hail, cloud)
  - How close is the environment to "Standard Operating Conditions" and qualification-level stresses?
- Application
- Materials
- Quality/Workmanship
- Design (optimized system engineering)
- Installation: site and mounting
- System Monitoring
  - What is the data quality, frequency?
  - What data is being gathered?
- System/component certification
  - Qualification and certification do not "guarantee" lifetime
  - Lack of qual/cert has led to problems in the past
- Grid requirements/behavior
- Vandalism
- Premature degradation/failure

Economic Factors include:

- Incentives: buydowns, rebates, tax credits, feed-in-tariffs
  - When does the maintenance cost of the system outweigh the benefits from the generated power?
  - This will differ based on application
- Cost of ownership
- Owner Business model
  - Does the owner plan to maintain the system?
  - Will the owner use a service contract to maintain the system?
  - Is the business model a Power Purchase Agreement?
- Politics
  - Incentives are driven by politics with economic implications

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Social Factors include:

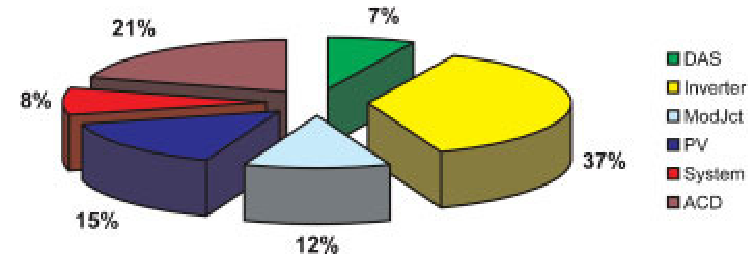
- Politics
  - Is the purpose of using PV politically driven and politically supported?
  - Is it “in” to put PV on your roof or purchase PV power from the local utility?
- Aesthetics: Beauty is in the eye of the beholder
  - Particularly for Residential and Commercial (e.g. facades) applications, aesthetics can make or break the lifetime of the system

    e.g, edge browning after five years may not affect power output, but may influence a homeowners choice of purchasing PV roofing
- Local jurisdictions---codes
  - Solar rights protection codes differ city-by-city
  - Fire protection codes
  - Ease of utility hook-up
- Vandalism
- Safety

Systems-Level Reliability Methods

Reliability has both qualitative and quantitative aspects

- Qualitative:
  - Anecdotal evidence:
    - "System X has been in the field for 17 years and is still producing power" suggests this technology will last for at least 17 years, but this provides no capability for predictions
    - "System Y failed after 3 years in the field" suggests this technology will not last long, but does not account for why it failed, design or environmental issues, quality issues, etc.
- Quantitative:
  - Collect aggregate data on failures or working time in the field
    - Does not account for full statistical analysis and/or accuracy



  - Assume system reliability is equal to the reliability of the "weakest" component
    - Does not take into account system-level interactions
  - Predict an "expected lifetime" of a PV system based on scientific data collection methods, statistical analysis, modeling
    - Requires quantifiable metrics and astute, high accuracy metrology

What can be quantified?

- Cost, Performance, and Reliability
  - Performance baseline metrics and performance predictive model
    - Module and inverter baseline performance data, field-level DC (array) or AC (inverter) data
    - Various PV module, inverter and system performance models exist
    - Output relies heavily on quality of input
  - Component/system degradation data: requires long test periods
  - Operational stress levels: Expected environment, application
  - Failure rates
    - Requires knowledge of failure modes
    - Component level (accelerated life testing) and system/field use level
  - Maintenance history
  - Weather
  - Economics: O&M costs, LCOE and market trends

The more detailed the metrology, the better the reliability predictions
Relies on how well metrics are quantified, verified and documented

Failure Modes

- Failure mode information has been collected through anecdotal evidence, papers and presentations, and hands-on experience over the last 20+ years
- NREL and Sandia have summarized the most common failure modes qualitatively: http://www.nrel.gov/pv/performance_reliability/
- Failure Modes and Effects Analysis (FMEA) can be a useful tool to anticipate failure modes at any level of the components or systems
- Combined stresses may cause degradation or catastrophic failure not observed when testing under individual stresses

Failure Modes: Example

Most common power losses in a PV module:

Power Loss Due to:	Example	Parameter Affected	Environmental Stress	How to Test
Solar cell material degradation	a-Si Staebler-Wronski effect Metal migration from contacts into active material	Current, voltage, FF, resistance	Temperature extremes Moisture intrusion Light (UV, visible) Voltage bias	Thermal cycling Damp heat Accelerated UV/light High temperature or bias soak
Mechanical losses	Cell breakage Glass breakage	Current, voltage, FF, resistance	Temperature extremes Moisture intrusion Hail Wind/Snow loading	Thermal cycling Damp heat Ice ball Mechanical loading
Encapsulant degradation	EVA darkening	Current	UV exposure Moisture intrusion	Accelerated UV Damp heat
Loss of electrical conductivity	Solder bond breakage Increased series resistance in cell or interconnects	Current, FF, voltage	Temperature extremes Moisture intrusion	Thermal cycling Damp heat Conductivity over time
Delamination	Encapsulant delamintates from glass or cell Cell delaminates from back metal (e.g. CIGS)	Current, FF	Temperature extremes Moisture intrusion	Thermal cycling Damp heat
Bypass diode failure	Open circuit or short circuit	Voltage	Temperature extremes Voltage bias	Thermal cycling High temperature or bias soak

Example of “Raw” Failure & Maintenance Data

September Notes:
Planned power outage on 09/19/2003 to connect construction power for Bechtel kept SGS-20kW off line all day. Energy Loss = 133 kWh.
C-3 tripped with DC Disconnect Interlock Fault at 19:15 on 09/20/2003. Discovered and reset at 08:30 on 09/21/2003. Loss of energy = 60 kWh.
C-3 tripped with DC Disconnect Interlock Fault at 19:21 on 09/21/2003. Discovered and reset at 20:02 on 09/21/2003. Loss of energy = 0 kWh.
C-3 inspected on 09/23/2003. No obvious source of problem found. Wires and switch were shaken to check for bad connections. Nothing found.
TF-4 lost data communications at 10:00 on 09/22/2003. On 09/23/2003 found the CAT5 cable had pulled out of the data switch. Retaining clip was fixed and reinserted with proper latching action. Loss of energy 0 kWh.
TF-3 Module vendor testing created a ground fault trip at 10:36 on 09/25/2003 Reset remotely at 11:06. Loss of energy 20 kWh. Vendor did not close row fuses on row 24, 25, 26, 27 & 28 prior to leaving site. Global Solar closed all fuses at 14:00 Loss of energy of 30 kWh. Ground fault blew row fuses in Row 1 & 2. Discovered from daily log review on 09/25. Fuses replaced at 13:22 on 09/27/2003. Loss of energy 115 kWh.
C-8 Data communications computer lost synch with the revenue meter at 15:07 on 09/26/2003. Computrer reset at 14:01 on 09/27/2003. Loss of energy 0 kWh.
During September, C-7 and C-32 exhibited intermittent high matrix temprature readings. Inspection of C-32 fan on 09/27/2003 indicated it exhibits high vibration, needs a new cooling unit.

Maintenance data log sample from 4.6 MW PV plant

Failure events, failure modes, and failure rates evaluated from these data logs

Failure Rates: Calculations

How to calculate failure statistics once data is collected

- There is an entire field of science dedicated to reliability and failure statistics
- Requires failure data to calculate failure rates, failure distribution functions F(t), Mean Time To Failure (MTTF), Mean Time Between Failure (MTBF), etc.
- Requires a basic understanding of the material system, failure mode and environment to determine the correct statistics to use to model failure rates and hence extrapolate long-term reliability
- Life distribution statistics include: Exponential (one or two parameter), Weibull (two or three parameter – the classic "bathtub" curve), Lognormal

Failure rates determined from ALT results and from field failures

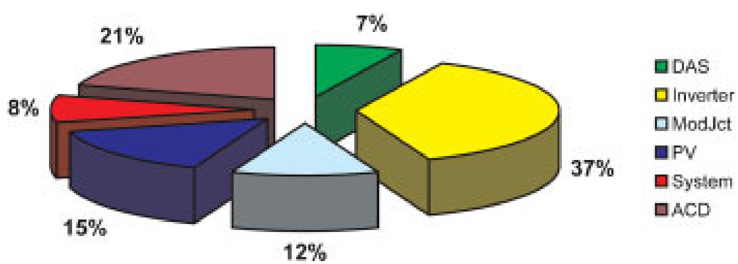
Predictive Model

- What does it take to make a systems-level predictive model?
  - Collect high quality field data
    - ✓ Detailed system-level design information
    - ✓ Performance over time
    - ✓ O&M records including: what failed, time to failure, time to repair, power lost during downtime
    - ✓ Weather, unexpected outages, lightning
  - Degradation rates for each component under various environments
  - Accelerated life test data for each component and expected failure mode

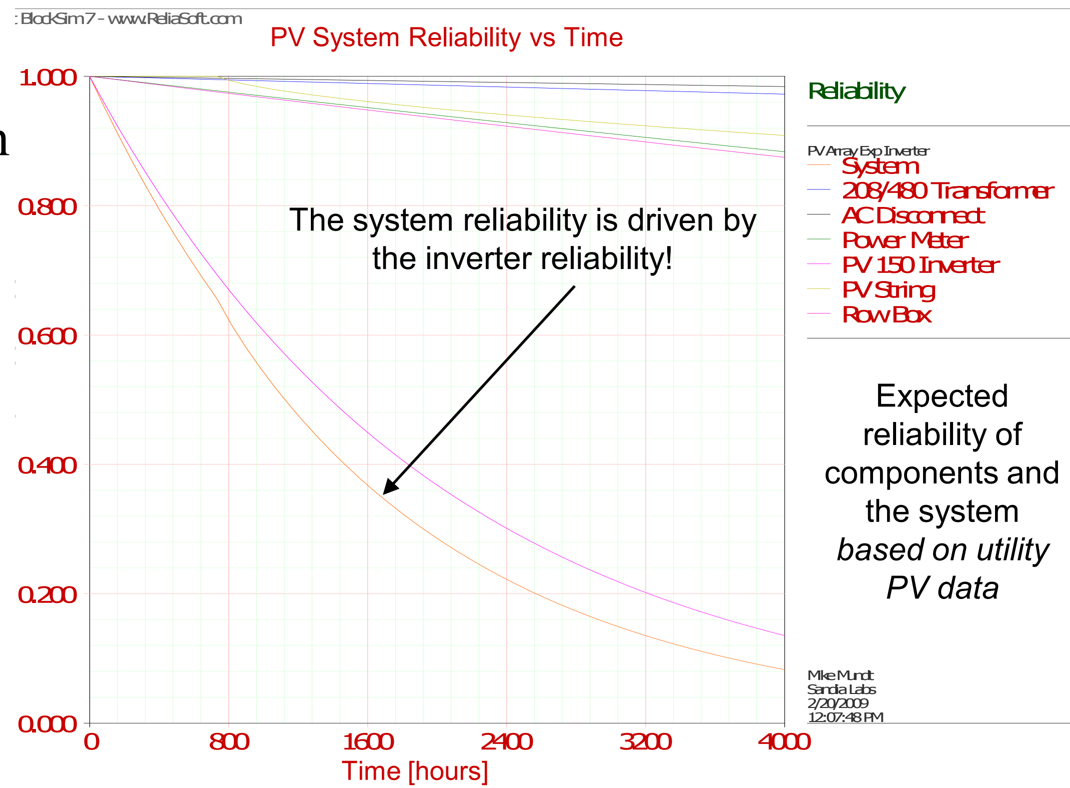
Predictive Model Systems Approach

Systems Approach: Reliability of a component must be addressed with regard to how it fits within the overall system

- Understand how each component fits into the system
- The overall reliability of the system is dominated by the least reliable component(s)
- Two views of the data:
  - Summarize most likely failures
  - Use data to predict reliability



Unscheduled maintenance events by component for PV system for five years in the field



Example shown for calculated reliability of a PV system for one year in the field

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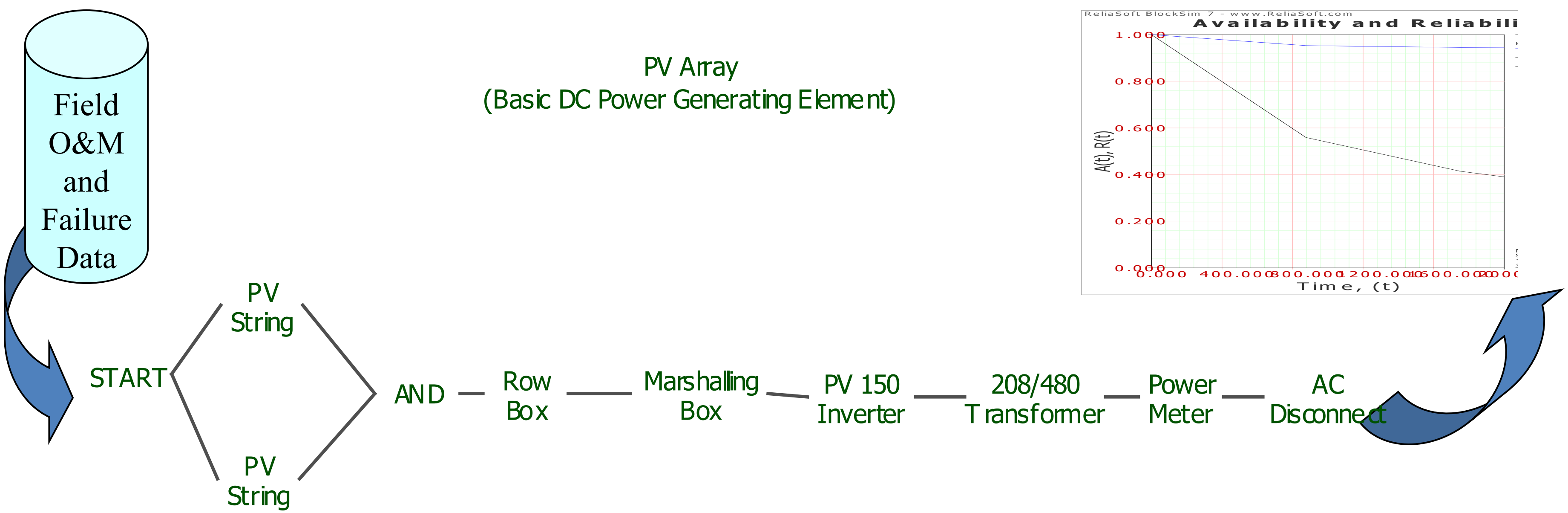
Predictive Model Development
Sandia's PVRAM

PV Reliability and Availability predictive Model Goal: Predict for any component and any level of the system -
Degradation*, *Reliability* and *Availability versus time

PV Reliability and Availability predictive Model (PVRAM) progress to date:

- Partnered with utility: multi-MW system characteristic of fastest growing sector of PV market, in the field for >5 years
- Created data-driven Reliability Block Diagram (RBD) based on utility partner's multi-MW systems
- 5 years of O&M data from utility partner used to generate failure statistics for each block



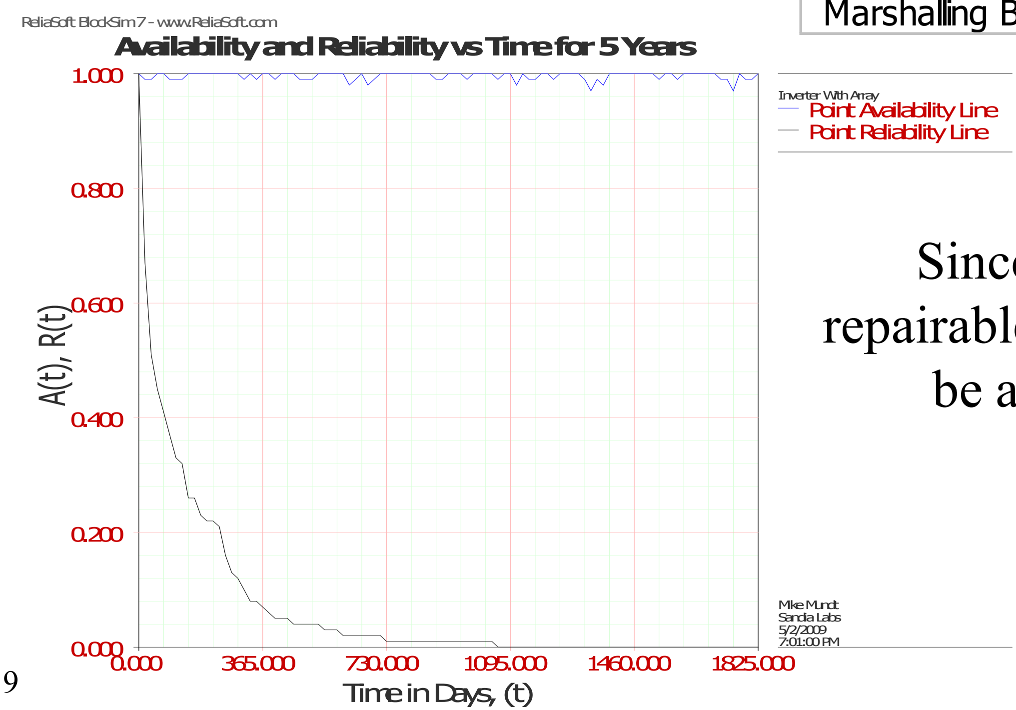
Model ready to use O&M data to generate system Reliability & Availability predictions

PVRAM: Failure Stats and System Availability

Apply a rigorous reliability methodology for each component and determine failure statistics

Summary of Time to Failure Analysis for Components that are Replaced

PV Component/ RBD Block	Distribution	Beta or Log SD (Shape)	Eta or Log Mean or Lambda (Scale)	Gamma (Location)
AC disconnect	Weibull 3-RRX	0.35	11000	3.9
Lightning	Exponential 1-RRX		0.00022	
Row Box	Weibull 2-RRX	0.51	1.2E+06	
PV Module	Weibull 3-RRX	0.28	5.2E+12	17
480/34.5 KV	Weibull 2-RRX	0.58	7100	
208/480 Transformer	Weibull 3-RRX	0.15	1.3E+10	28
Marshalling Box	Lognormal 2-RRX	2.3	10	



Since the PV system is repairable, high availability can be achieved with low reliability.

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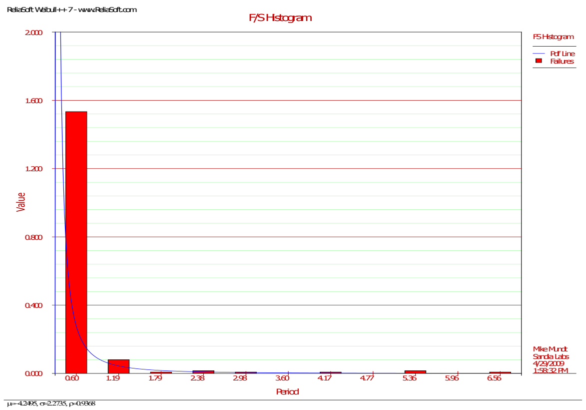
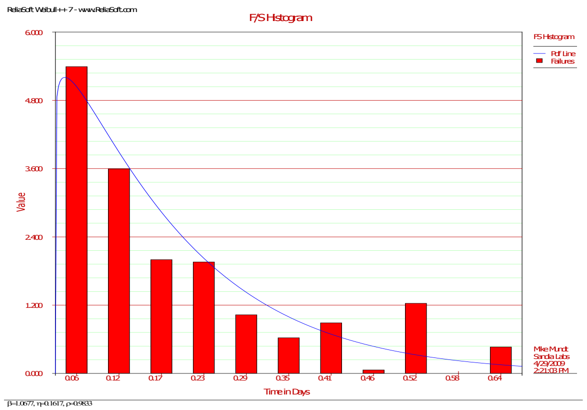
PVRAM: Inverter Down Time Data Analysis

- Inverter downtime analysis was performed for corrective maintenance, grid-induced shutdowns, and preventive maintenance.
- Observed data on downtime causes was fit to best distribution based on engineering knowledge and goodness of fit metrics.
  - Lognormal
  - Weibull
  - Exponential

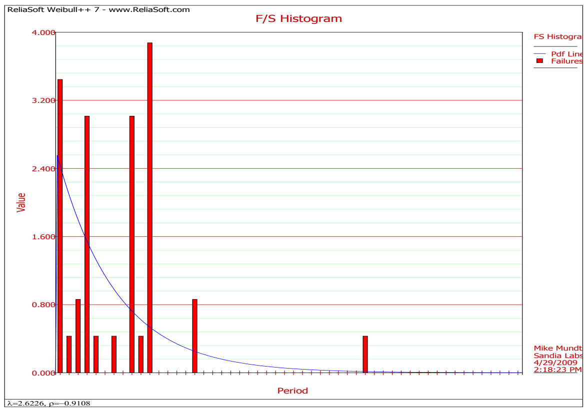
Corrective Maintenance pdf and Histogram
lognormal



Grid Downtime pdf and Histogram
Weibull



Preventive Maintenance pdf and Histogram
exponential



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PVRAM: Predicted Failures for 4.6 MW PV System

Expected Number of Failures for 20 Years

Component	Actual # of Failures in 5 yrs. Cumulative	Expected # of Failures in 5 yrs. Cumulative	Expected # of Failures in 10 yrs. Cumulative	Expected # of Failures in 20 yrs. Cumulative
PV 150 Inverter (26 cSi arrays)	125	132	231*	429*
PV Module	29	26	31	38
AC Disconnects	22	17	23	31
Lightning Event	16	10	20	41
208V/480V Transformer	4	3	3	3
Row Box	34	25	35	50
Marshalling Box	2	4	7	11
480V/34.5KV Transformer	5	4	5	9

For the first 5 years the repair rate was < 1 per inverter per year, and the replacement rate was < 5 per 10,000 PV modules per year

***Inverter predictions for 10 and 15 years assume no further reliability growth.**

Predicted results could be used to forecast spares and to plan resources for maintenance. In this forecast the effects of degradation and wear-out mechanisms are not considered because no accelerated test (ALT) data is available.

Without ALT data, predictions beyond the 5 years of field data are increasingly uncertain.

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PVRAM: What's Next

- Degradation rates and ALT data currently being collected will be added to PVRAM to reduce the uncertainties
- Dynamic performance and weather modeling will be added
- Economic factors (cost of ownership, O&M costs) will be added
- Expand to other operational systems/partners

Summary

- System level reliability is influenced by many factors, including performance, economic and social
- Reliability can be viewed as qualitative or quantitative
- Quantitative reliability can come in different levels of accuracy
  - The better the data collection precision and accuracy, the better the predictive capability
- System level reliability requires component level reliability, but component level is not sufficient for system reliability predictions
  - Must include interactions
- Sandia's PVRAM has demonstrated reliability and availability predictive capability based on field data; additional capability to be added to address performance and cost
- The recent awareness of the need for quantitative reliability methods in PV is driving the implementation of reliability growth
- Bottom line: Reliability growth reduces LCOE