Sandia's Approach to Reliability

Utility-Scale Grid-Tied PV Inverter Reliability Workshop

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Sandia National Laboratories

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
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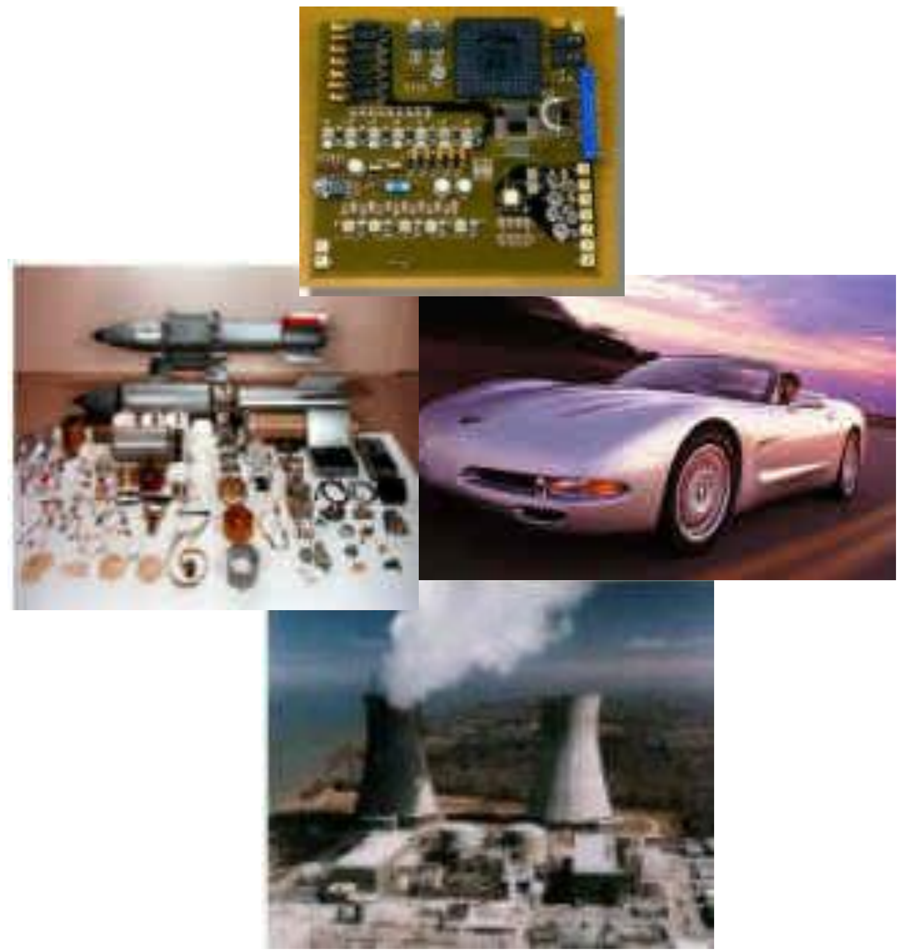
Sandia's Reliability Program

- **SNL has broad historical roots in reliability**
- **Nuclear Weapons Program**
  - Independent reliability predictions and assessments on nuclear weapon components, subsystems, and systems throughout the conceptual design-to-retirement life cycle
- **The Center for System Reliability (CSR) started in 1998**
  - CSR develops methodologies and software tools (Pro-Opta) to address a wide range of reliability issues
  - Application areas ranging from nuclear power and missile systems to aviation, automotive, energy, and manufacturing



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Sandia's Reliability Program

- Sandia has a reputation and the infrastructure to solve problems
- Sandia has extensive reliability expertise, focus on leveraged research and technology development, and a culture of information protection
- As a National Laboratory, Sandia is in a unique position to engage with a broad spectrum of industry players

Using analysis based on statistically significant data, Sandia works with stakeholders to reduce the risks to investors, developers, operators, utilities, manufacturers and their customers.

Sandia's PV Reliability Program

Objective of the PV Reliability Program: Team with industry to develop and apply tools for predictable PV system reliability and provide identification and prioritization of reliability issues

- Reliability is the probability of simultaneously satisfying:
  - The performance requirement
  - In a specified environment
  - At a particular time

- Availability is the probability of successful operation when the system is requested for use:
  - The system has not yet failed or if it has failed, it is not undergoing repair and has been restored
  - Accounts for both reliability and maintainability

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

Major Activities

- Real-Time Reliability
- Failure Modes and Effects Analysis
- Accelerated Life Testing
- Diagnostics
- Predictive Model Development
- Standards Development

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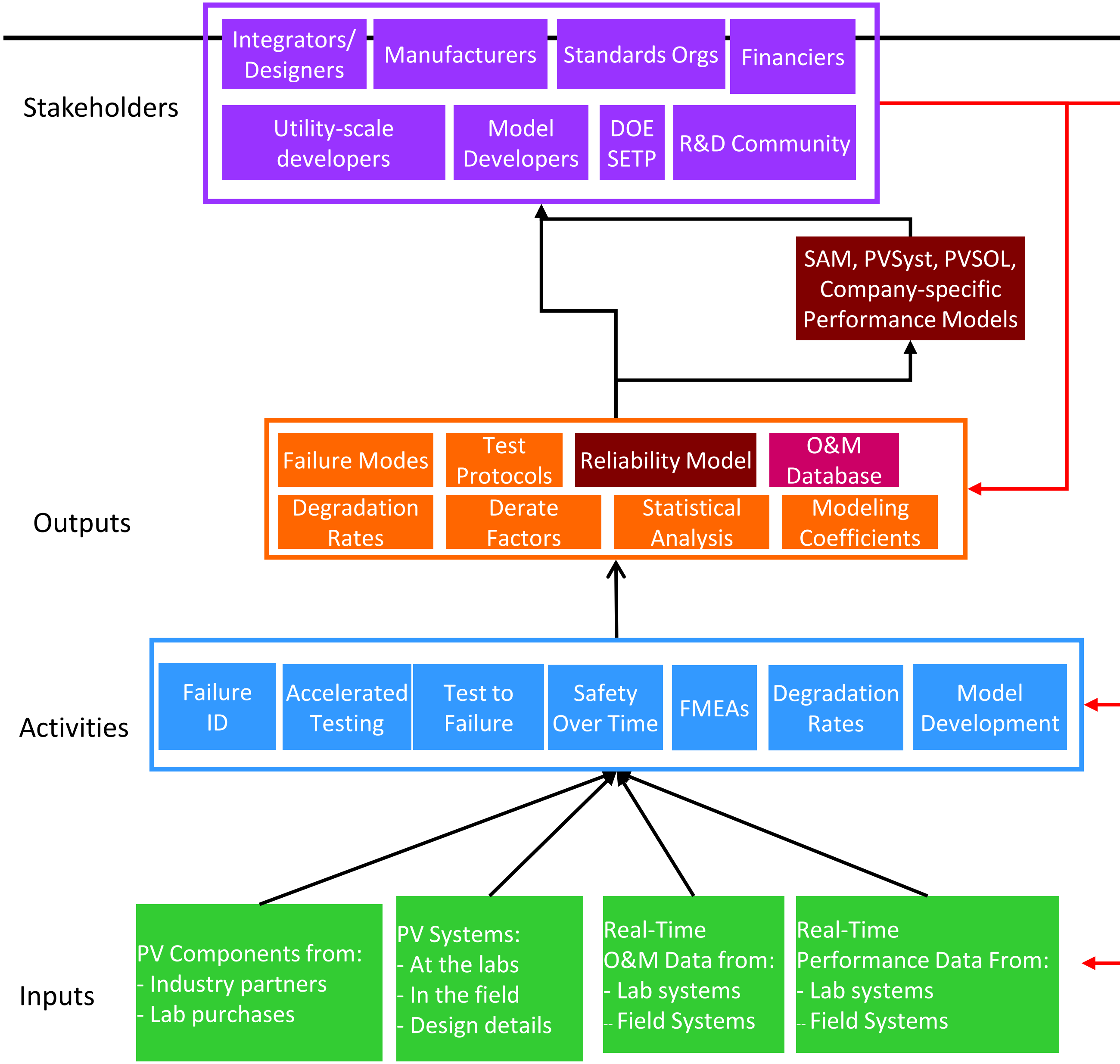
Sandia's PV Reliability Program



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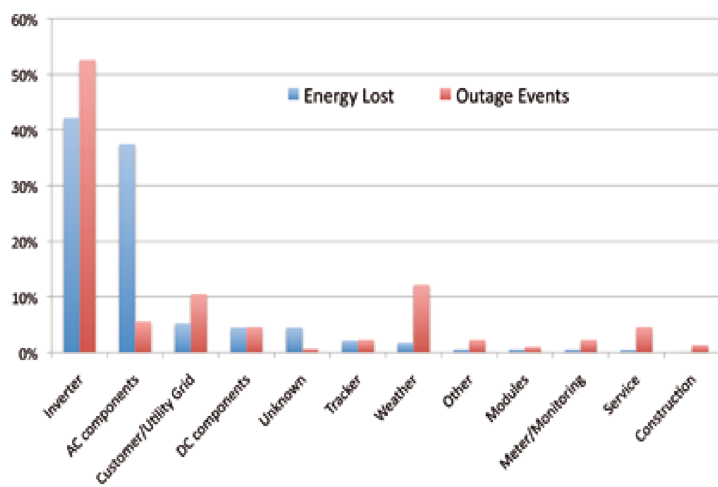
Inverter Reliability

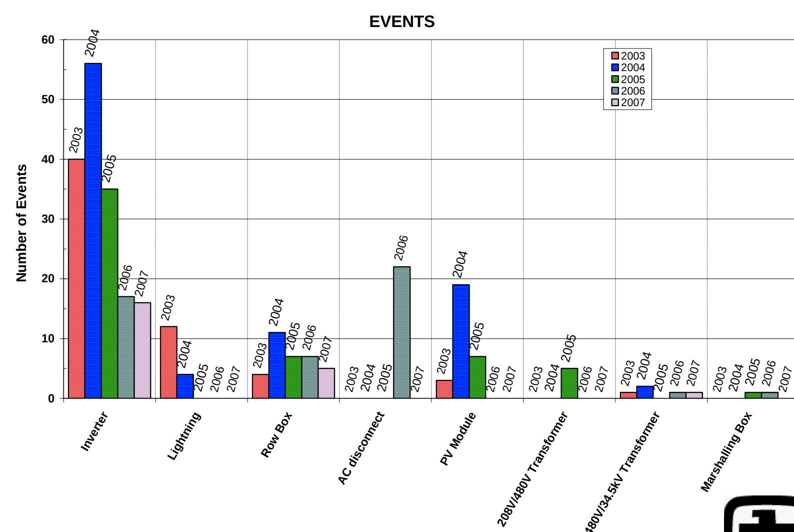
Why focus on inverter reliability?

- Reliability (O&M cost, degradation, lifetime) is one of the factors that contributes directly to LCOE and the ability to reach DOE's targeted cost goals and grid parity.
- High system reliability leads to high system availability for all energy generators
- For PV installations, recent studies demonstrating the inverter associated with a disproportionate fraction of PV system repair events (Collins et al, 2009 PVSC; Voss et al, Journal Article P173-179 PV International Edition 5 Sep 16, 2009)
- As modules have improved, the impact of inverter lifetime, downtime and cost to repair is becoming a more significant fraction of the total system cost
- There is currently no accepted baseline or standard process for assessing inverter reliability; each company has a unique approach

Inverter failure is the largest contributor to reduced system availability



* From Voss, 2009 (based on 78% of SunEdison's fleet surveyed through June 2009)



* From Collins, 2009 (TEP Springerville System)

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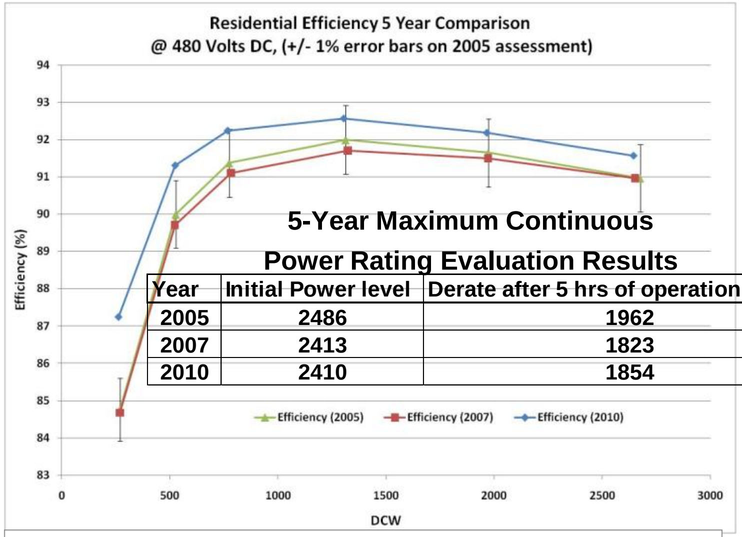
Real-Time Reliability

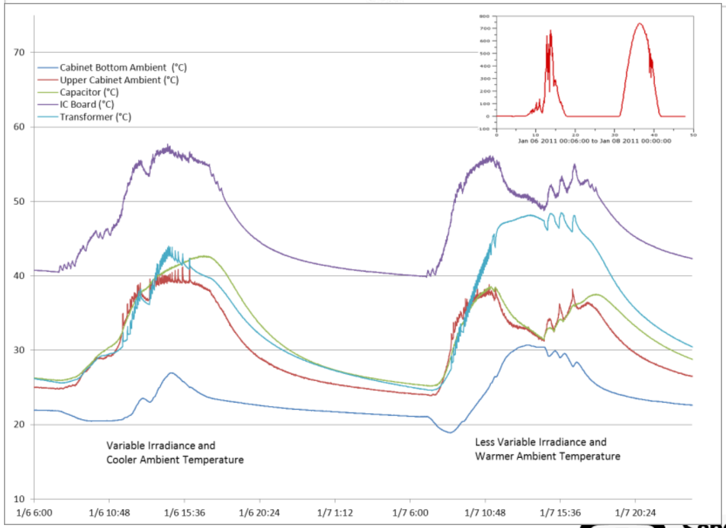
- **Long-term inverter exposure testing**
  - Quantify the effects of long term operation on residential utility interconnected PV inverters
  - Six 3kW-size inverters under test at Sandia and at NSMU (3 each location) since 2005
  - Re-characterize efficiency, power quality, maximum continuous power rating and utility compatibility operation every 2 years
  - To date, no appreciable degradation in performance has been discovered.
- **Temperature monitoring of inverters**
  - Began monitoring inverters in 2010
  - Four <10kW and one 75kW inverters instrumented with thermocouples
  - Inverter component temperature profiles are used to guide accelerated test protocols
- **Operations and Maintenance Database**
  - SNL developed a standard method for collecting O&M data into the PV Reliability O&M Database (PVROM)
  - Used to collect incident reporting information from which time to failure, time to repair, etc. statistics can be calculated
  - Statistics then used in the predictive model

Long-term inverter exposure



5-Year Maximum Continuous Power Rating Evaluation Results

Year	Initial Power level	Derate after 5 hrs of operation @ 40C
2005	2486	1962
2007	2413	1823
2010	2410	1854



Inverter component temperature profiles

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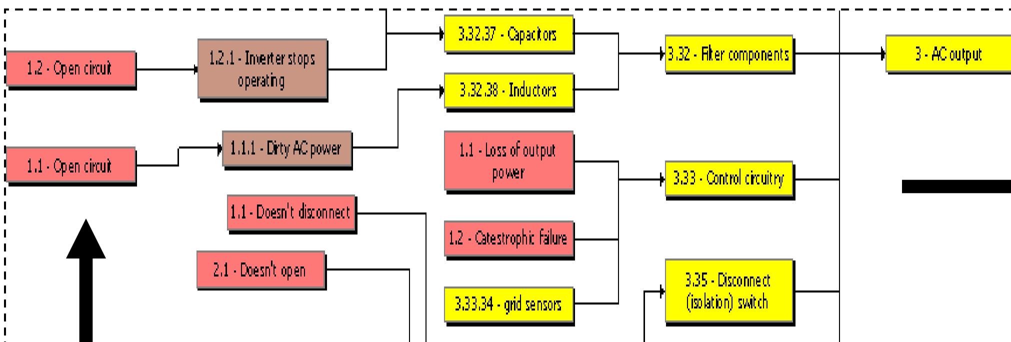
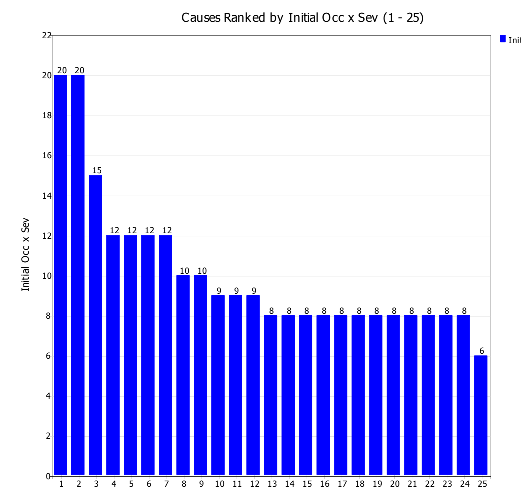
Building an understanding of critical failure modes from the ground up

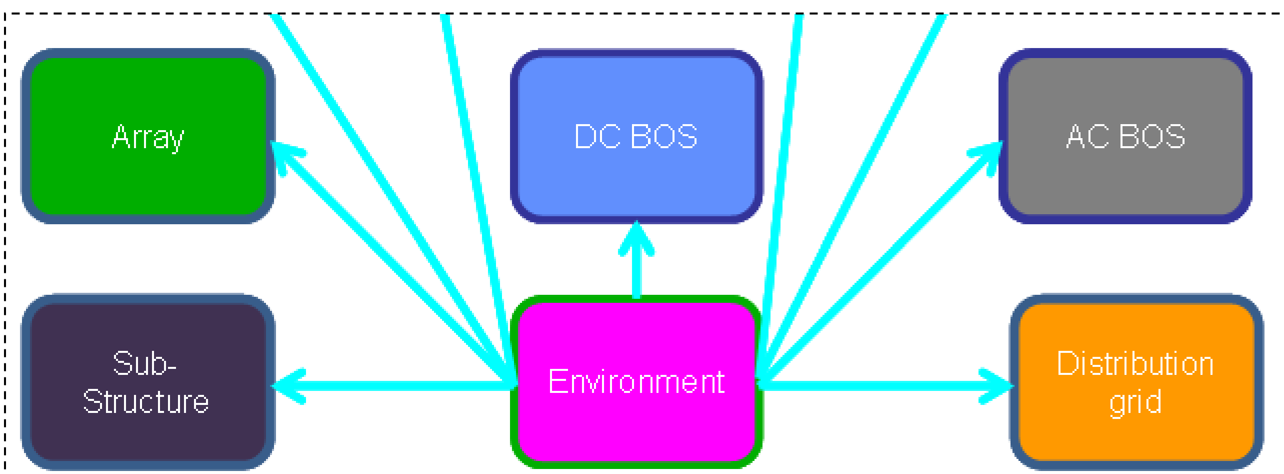
Boundary Diagram

FMEA

Pareto







High risk items:

Installation

Interconnects

Capacitors

Accelerated Testing

- Many labs and manufacturers are developing accelerated life tests (ALTs) for modules; fewer are developing ALTs for inverters
- Goal: Develop protocols and data for modeling
- Sandia focuses ALT development based on our specialties in materials, semiconductors, power electronic devices, corrosion
- Recent results have been published on ALTs for conductive tapes specific to thin-film modules
- In 2010, Sandia began developing an accelerated test for IGBTs used in many inverters
- Next steps:
  - Determine appropriate additional high-risk inverter components for accelerated testing
  - Publish results and protocols; incorporate into standards or guidelines as appropriate

Rob Sorensen will be addressing overall ALT development for inverters and Bob Kaplar will be addressing IGBT ALT results

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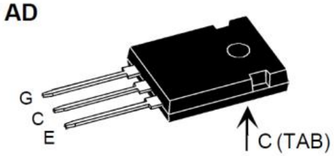
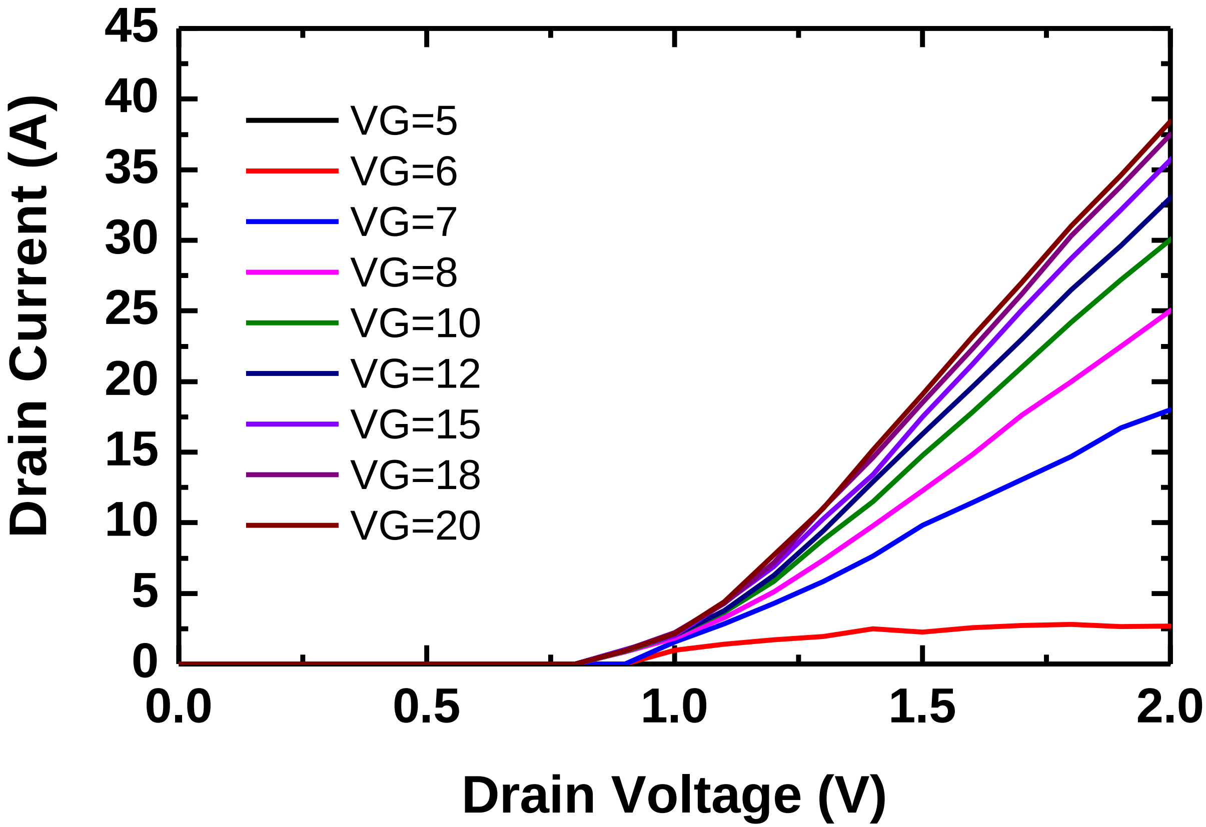
IGBT Accelerated Reliability Testing

TO-247 AD
(IXGH)

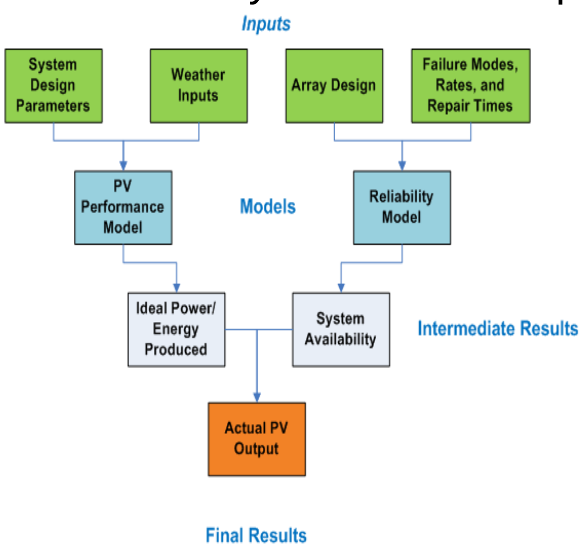


- **IGBT High Current Testing**
  - IXYS IXGH30N60BD1 IGBT (in the SMA 1800U Inverter)
  - Tested to 40A



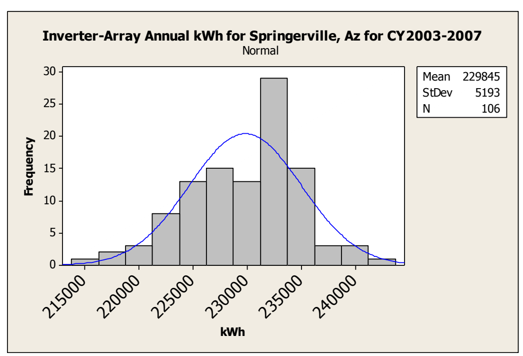
Predictive Model Development

- Sandia is developing and implementing a data-based model to predict kWh and cash flow of PV systems integrating reliability, weather, performance and cost using GoldSim
- PV Reliability and Availability Predictive Model (PVRAM) incorporates system design, degradation rates, ALT failure statistics and O&M incident rates
- Demonstrated PVRAM with 5 years of field data for the TEP Springerville system. Interfaced PVRAM with PVROM for rapid data analysis of field failures.
- Model can be used to predict kWh produced with uncertainty bands, can be used as a design tool, and to perform sensitivity studies
- Easy to include component-level reliability



Comparison of Model to Springerville, AZ, USA Performance Data

Field Data Variation in Annual kWh



Comparison of Model with Field Data

Percentile	Field Data (kWh)	Prediction (kWh)
5	221,300	229,900
50	229,800	247,700
95	238,400	263,600

The 90% confidence intervals for the prediction and the field data overlap with 8% difference between the medians

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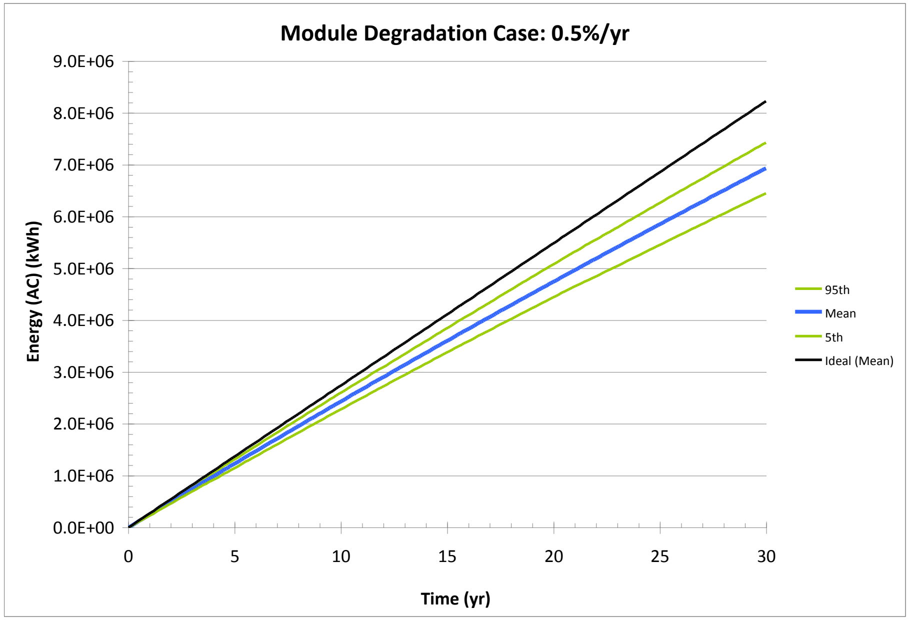
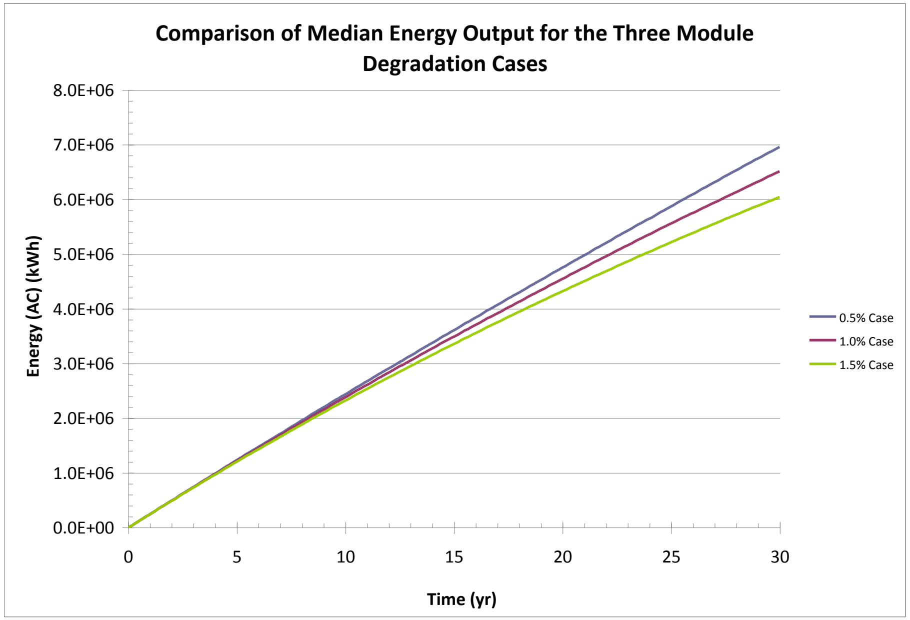
Integrated Predictive Model: Early Results

Model run: Energy produced by one 100 kW block using Si modules and one inverter



The 90% confidence interval for the 0.5% module degradation scenario is compared to the ideal case (perfect availability).



30 Year energy production is only 15% lower for the highest degradation rate for the Flagstaff location.

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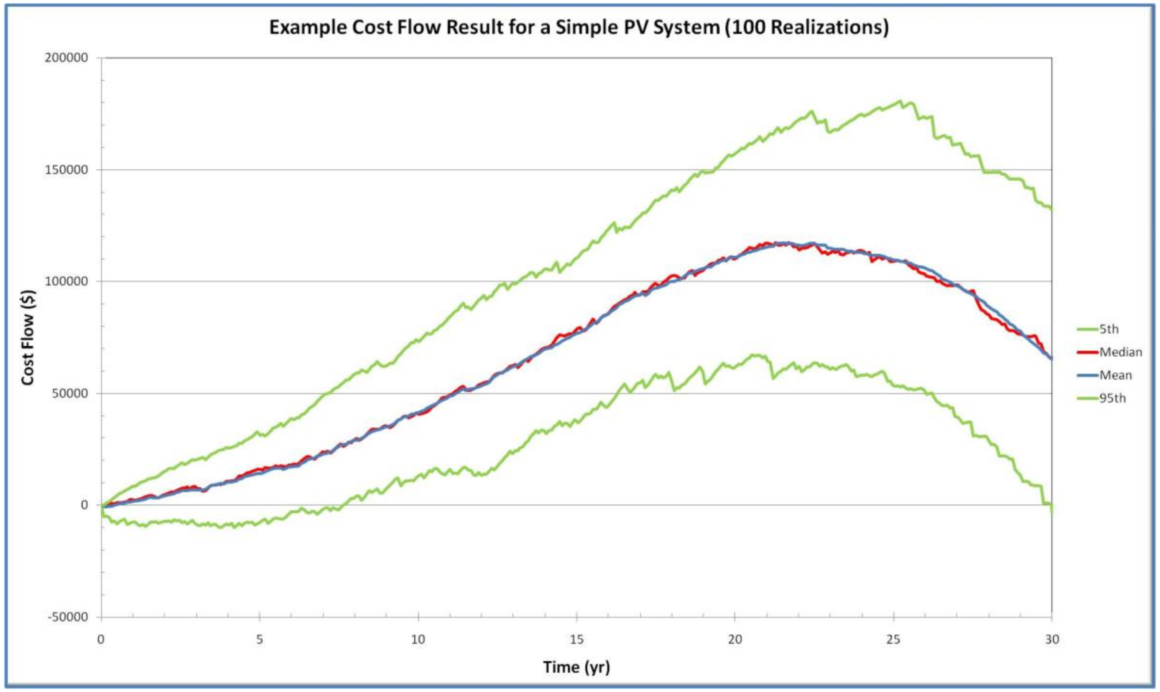
Integrated Predictive Model: Early Results

Cash flow model depends on location, system size, initial cost, reliability, performance, interest rates, loan term, local labor rates

- Example shown here is proof of concept based on 100 kW block using Si modules and one inverter



Next Steps:

- Sensitivity trade for inverter block size and inverter reliability
- Optimize cash flow model
- Create web-based interactive tool

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Standards

- Safety standards exist and are in use for PV inverters
  - UL 1741, IEC 62109-1, others
- Limited *performance* standards and guidelines exist and are in use for PV inverters
  - IEEE 1547, IEC 61683, Sandia Test Protocols
- One *qualification* standard exists for PV inverters and other BOS components, and is infrequently used
  - IEC 62093
- No *reliability* standards or guidelines exist
- Sandia is collaborating with the Power Electronics group at ASU to develop a matrix and Gap Analysis of existing standards and guidelines which are or could be applicable to inverters and power electronics for PV

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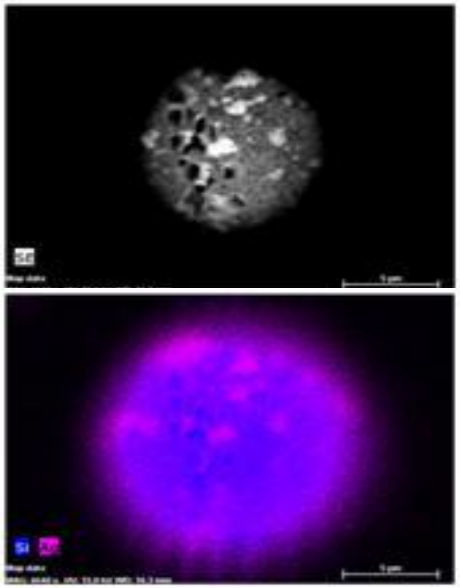
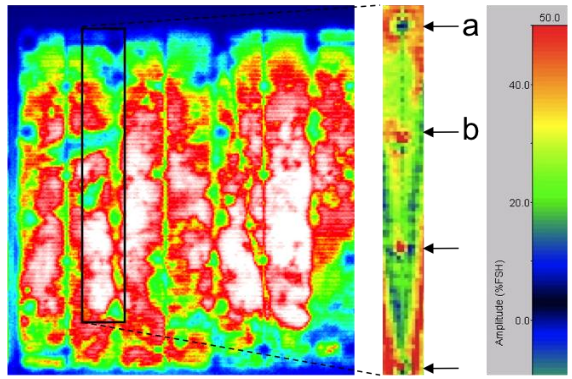
Diagnostics

Materials



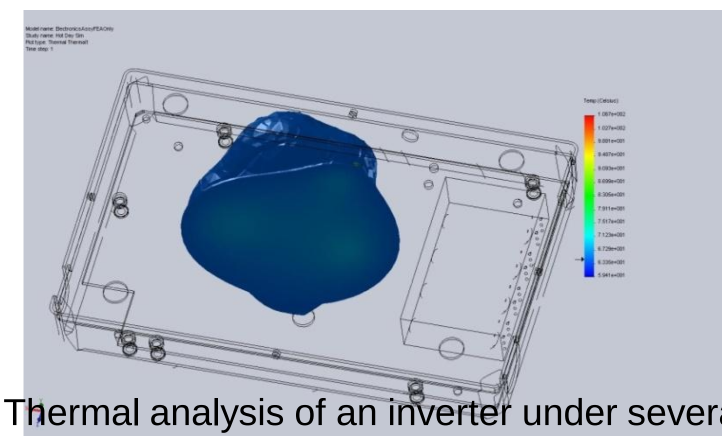
Characterization of conductive tape particles using SEM and elemental mapping provided foundation for development of accelerated life test.

Components



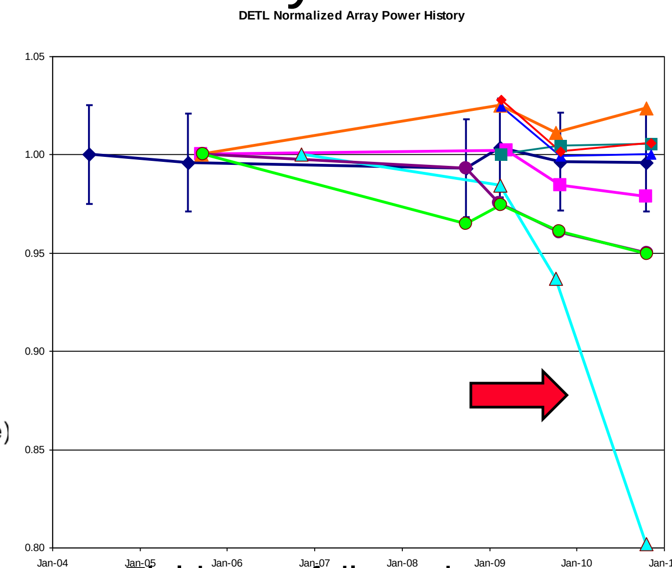
EL   Ultrasonic C-scan (scale)

Combined Electroluminescence and ultrasound provided key information for conductive adhesive bonding

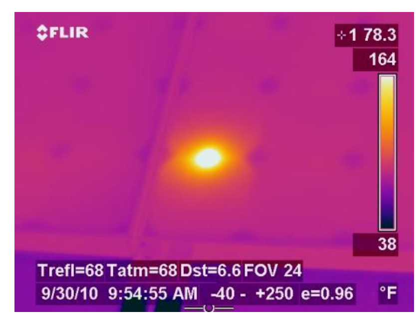


Thermal analysis of an inverter under several ambient temperature profiles

Systems



Field array failure triggers module diagnostic study and failure mode identification.



Lab → **Field**

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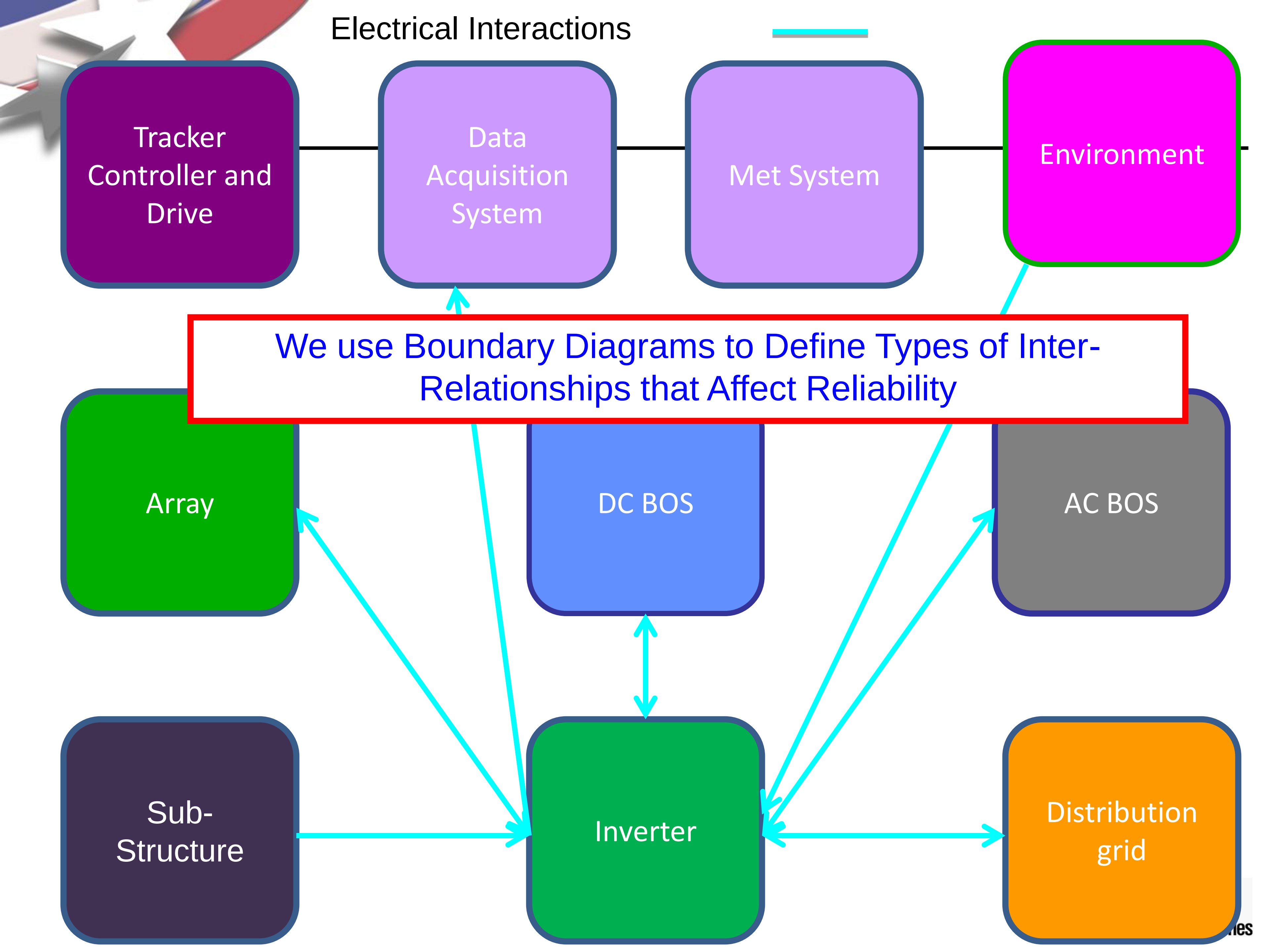
How You Can Contribute

- **What we need: PARTNERS!**
  - Data on failure modes and mechanisms
  - Stress testing results on inverters
  - O&M data
  - Partners for instrumenting more inverters
  - Vetting FMEAs
  - Suggestions on sensitive components for additional ALT development
  - Suggestions for model sensitivity studies
  - Input on inverter/PE standards Gap Analysis
- **Share your ideas!**

Recent Publications/Presentations

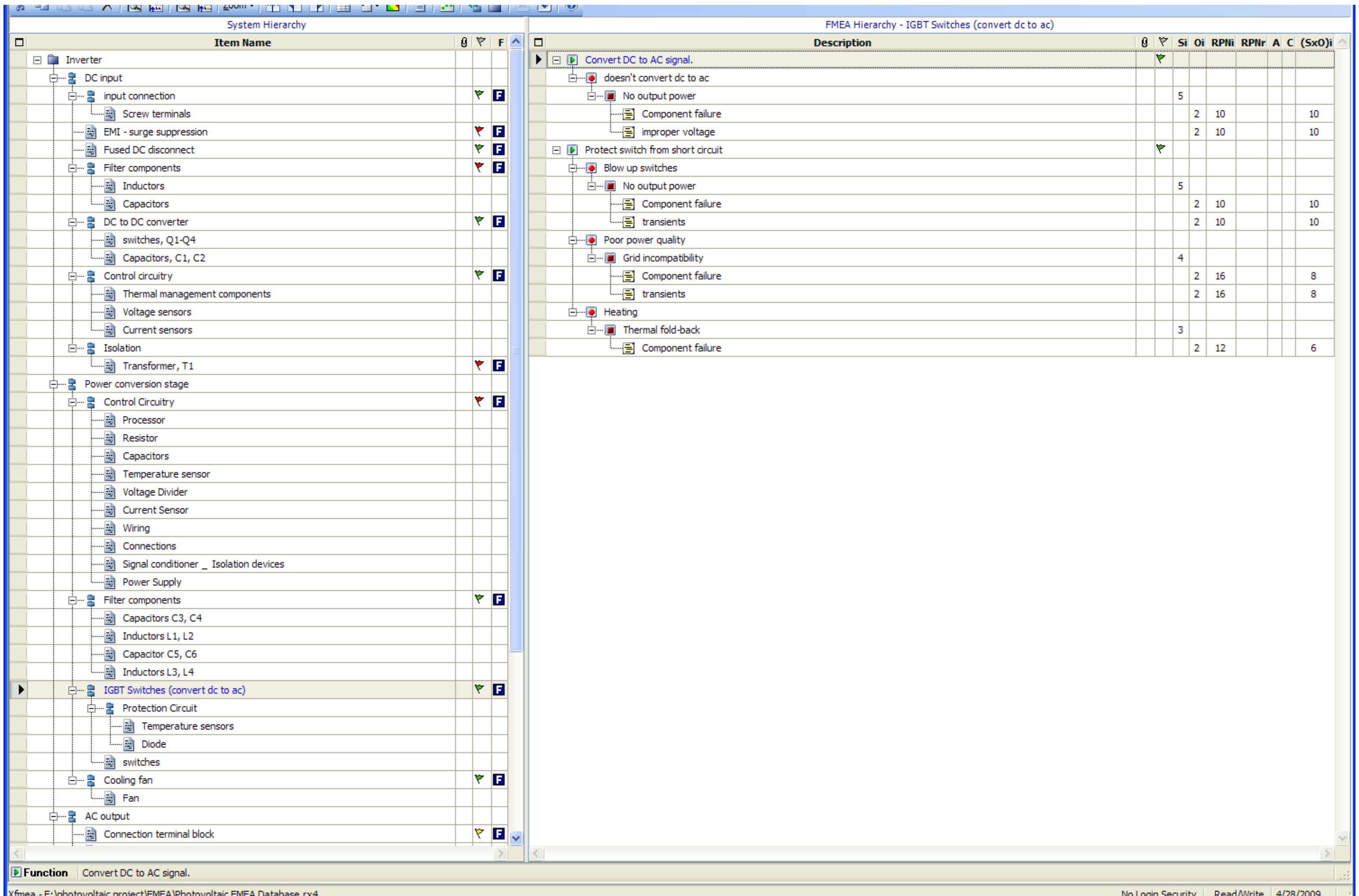
- E. Collins, et al, “A Reliability and Availability Sensitivity Study of a Large Photovoltaic System,” EU PVSEC, Valencia, Spain, September 2010
- N. Sorensen, et al, “Accelerated Testing of Metal Foil Tape Joints and Their Effect of Photovoltaic Module Reliability,” EU PVSEC, Valencia, Spain, September 2010
- M. Mundt, et al, “Photovoltaic System Reliability & Maintainability Data Collection and Analysis Using a FRACAS Tool,” presented at June 2010 International Applied Reliability Symposium
- E. Collins, et al, “Photovoltaic System Reliability & Maintainability Data Collection and Analysis Using a FRACAS Tool,” 35th IEEE PVSC, Honolulu, June 2010
- M. Yaklin, et al, “Impacts of Humidity and Temperature on the Performance of Transparent Conducting Zinc Oxide”, 35th IEEE PVSC, Honolulu, June 2010
- J. Granata, et al, “Approaches to Photovoltaic Systems Reliability,” ISTFA, November 2009
- J. Granata et al., “Long-Term Performance and Reliability Assessment of 8 PV Arrays at Sandia National Laboratories”, 34th IEEE PV Specialists Conference, Philadelphia, PA, June 2009.
- M. Mundt et al., “Reliability and Availability Analysis of a Fielded Photovoltaic System”, presented at June 2009 International Applied Reliability Symposium
- E. Collins et al., “Reliability and Availability Analysis of a Fielded Photovoltaic System”, 34th IEEE PVSC, Philadelphia, June 2009.
- N. Sorensen et al., “The Effect of Metal Foil Tape Degradation on the Long Term Reliability of PV Modules”, 34th IEEE PVSC, Philadelphia, June 2009.
- E. Quintana et al., “Exploring Diagnostic Capabilities for Applications to New Photovoltaic Technologies”, 34th IEEE PVSC, Philadelphia, June 2009.
- J. Granata and M. Quintana, “Reliability of PV Systems – How Long Can We Expect Them to Last?”, SEPA Webinar, June 2009
- J. Granata and M. Quintana, “System Level Reliability Methodologies”, APP International Reliability Workshop, July 2009

Additional Detail


Electrical Interactions
Tracker Controller and Drive
Data Acquisition System
Met System
Environment
We use Boundary Diagrams to Define Types of Inter-Relationships that Affect Reliability
Array
DC BOS
AC BOS
Sub-Structure
Inverter
Distribution grid

Failure Modes and Effects Analyses

- Excerpt shown for details of IGBT failure in residential inverter
- Baseline FMEAs available in XFMEA and in Excel format



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