Sandia's Systems Approach to Photovoltaic Reliability

PV Systems Integrator 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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Presentation Outline

- Why System Reliability?
- Some of the basics
- Increase detail and complexity
- Summary

Diverse Users/Stakeholders Pose Challenges

Quality

RELIABILITY

Service Life

Performance

Availability

Warranty

How do you align these?

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Some Considerations

- Reliability is the probability of simultaneously satisfying:
  - The performance requirement
  - In a specified environment
  - At a particular time
- Reliability takes into account service life (expected lifetime)
- Quality is defined as creating a product suitable for the intended purpose, and doing it consistently.
- Failure definition can be inconsistent--user dependent--causing difficult to attain reliability objectives

Sandia's Systems Approach to PV System Reliability

- System: 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.
- Identify system reliability requirements; apply these to development of components as early as possible
- Comprehensive reliability plan requires:
  - Data
  - Methodologies
  - Tools
  - Models

Why is a Systems Approach Needed?

- Reliable components alone do not deliver reliable power
- Reliable systems can deliver reliable power in <u>well understood applications and environments</u>
- Supply chain is getting increasingly diverse; e.g. CEP
- Increasingly sophisticated components/systems; e.g. CPV
- Designs, materials, and technologies are getting increasingly diverse
- Increasingly numerous stake-holders making system reliability a much more complex target
  - Utilities
  - States
  - System owners
  - PPA brokers
  - Underwriters
  - Etc.

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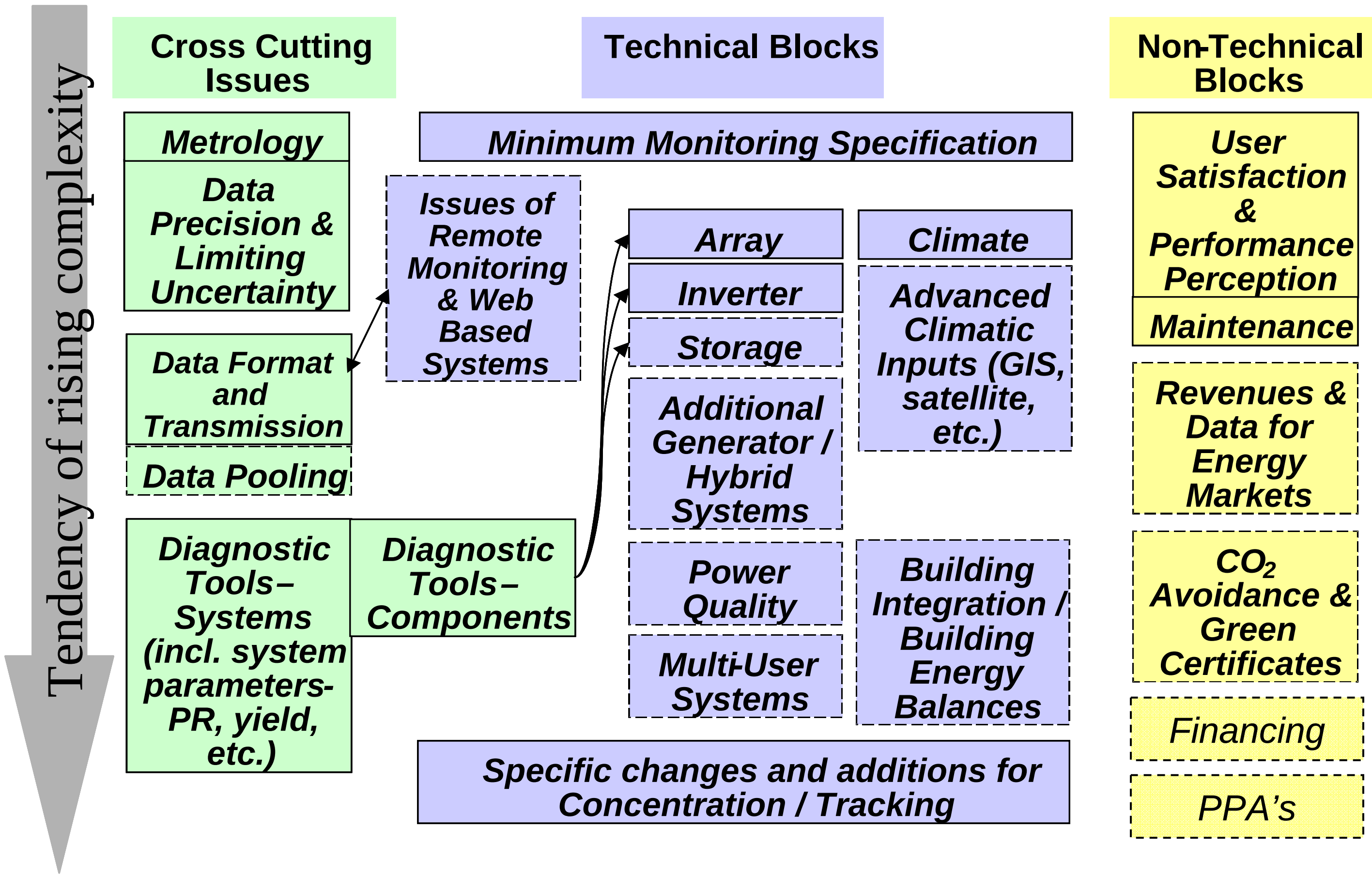
Complex PV Systems Deployed in Complex Markets



Sandia's PV Program Takes a Comprehensive Approach

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Sandia Program Elements

- Reliability
  - Predictive Modeling
  - Real-Time Studies
  - Accelerated Testing and Failure Modes Effects and Analysis
  - Technology Transfer and Codes & Standards
- System Modeling and Analysis
- System Grid Integration
- Test & Evaluation (System, Inverter, BOS, Modules)
- Market Transformation

Adapt Common Tools --Focus on Adoption--Minimize Cost

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Presentation Outline

- **Why System Reliability?**
- **Some of the basics**
  - ❖ Define system and its functional operation; define components and their functional operation
  - ❖ Define failure modes
- **Increase detail and complexity**

Boundary Diagrams
Codes & Standards
FMEA's
Baseline Performance
RBD's
Real-time Data
Long-term exposure
Failure Analysis
Mitigation
Accelerated Tests
Predictive Modeling

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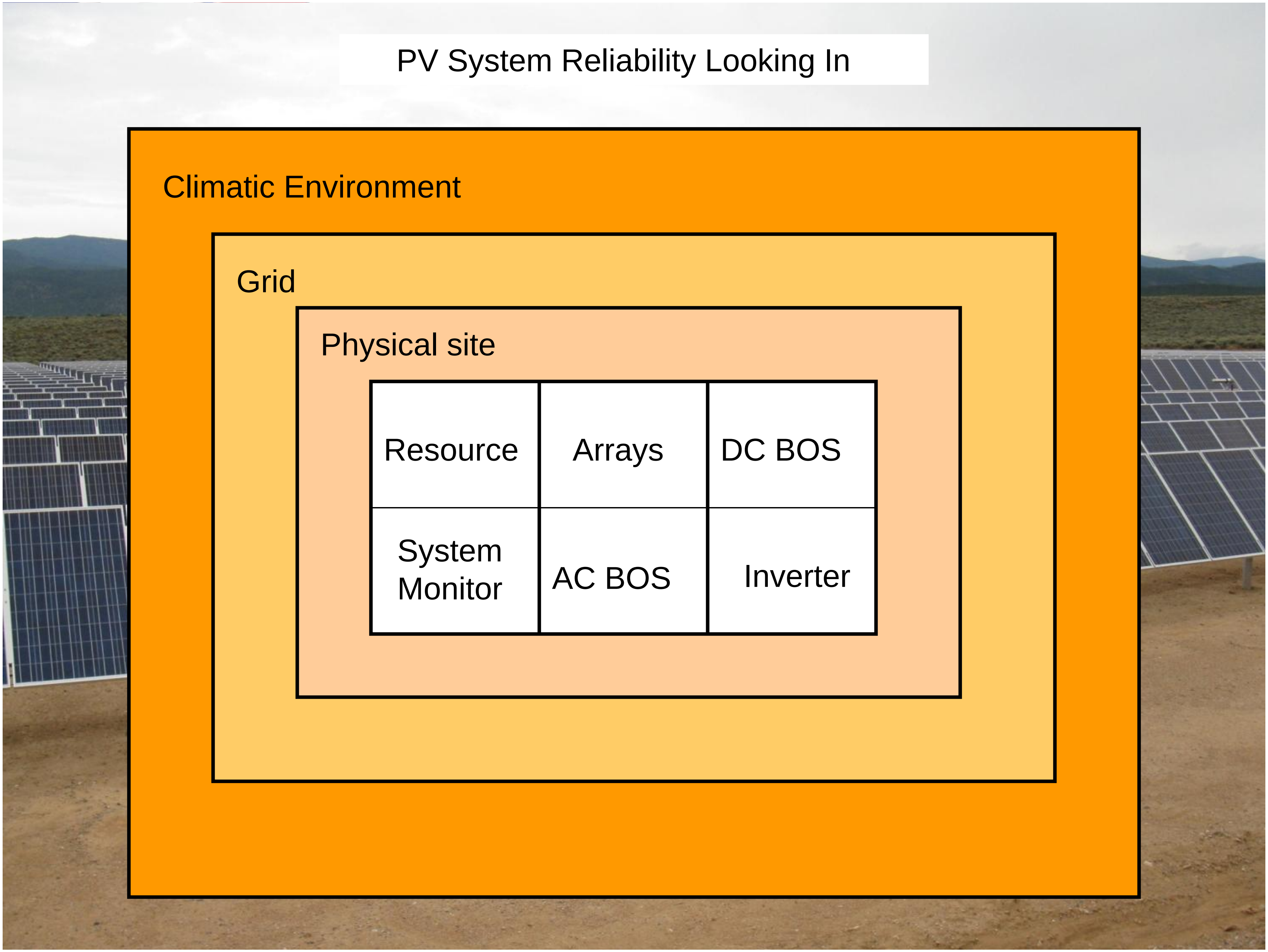

PV System Reliability Looking In
Climatic Environment
Grid
Physical site
Resource
Arrays
DC BOS
System Monitor
AC BOS
Inverter

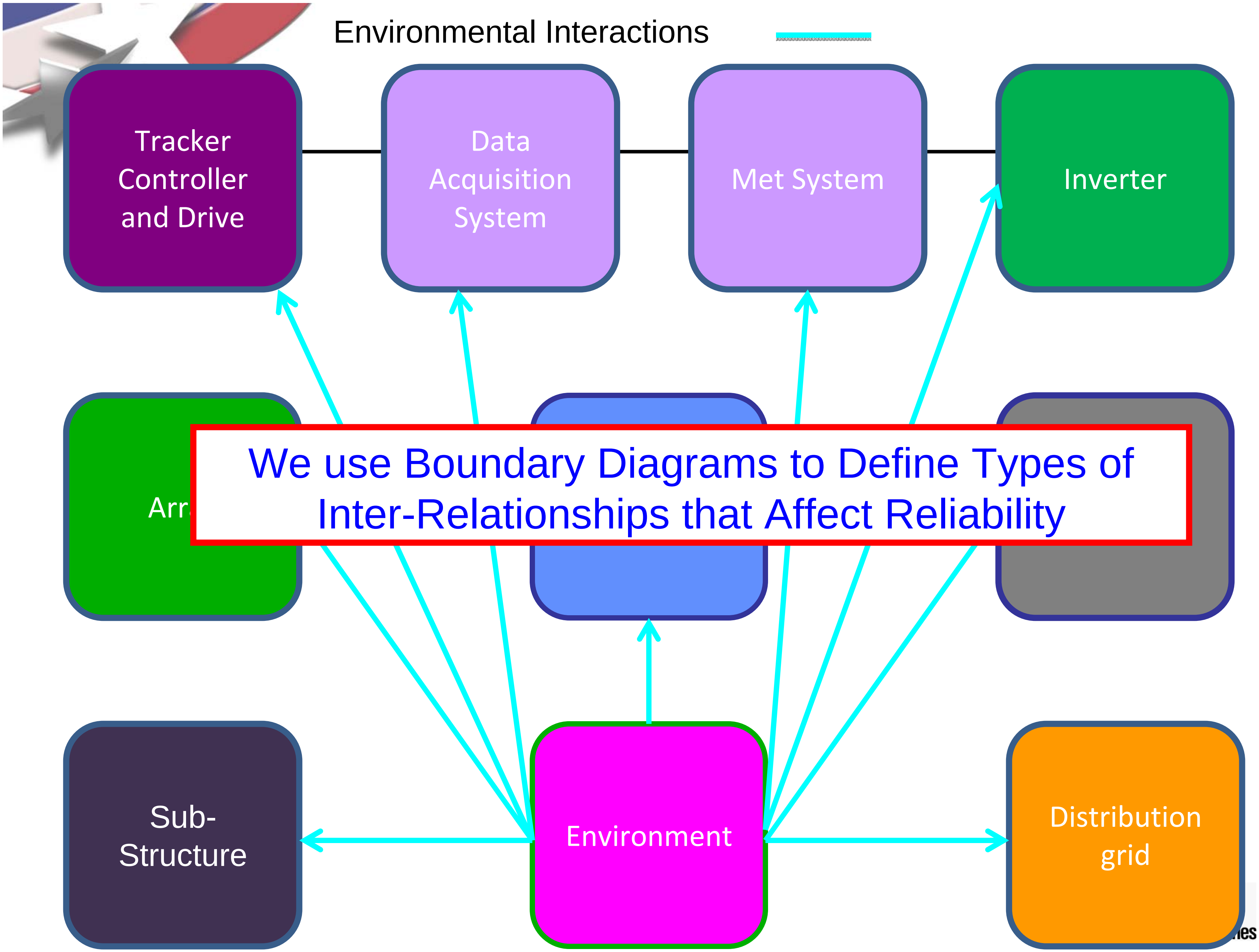
Factors that influence how reliability is addressed

We divide factors into three categories:

– Performance is the primary factor

– Economics enters the picture as we consider the cost of reliability measures vs. cost of unreliability

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



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

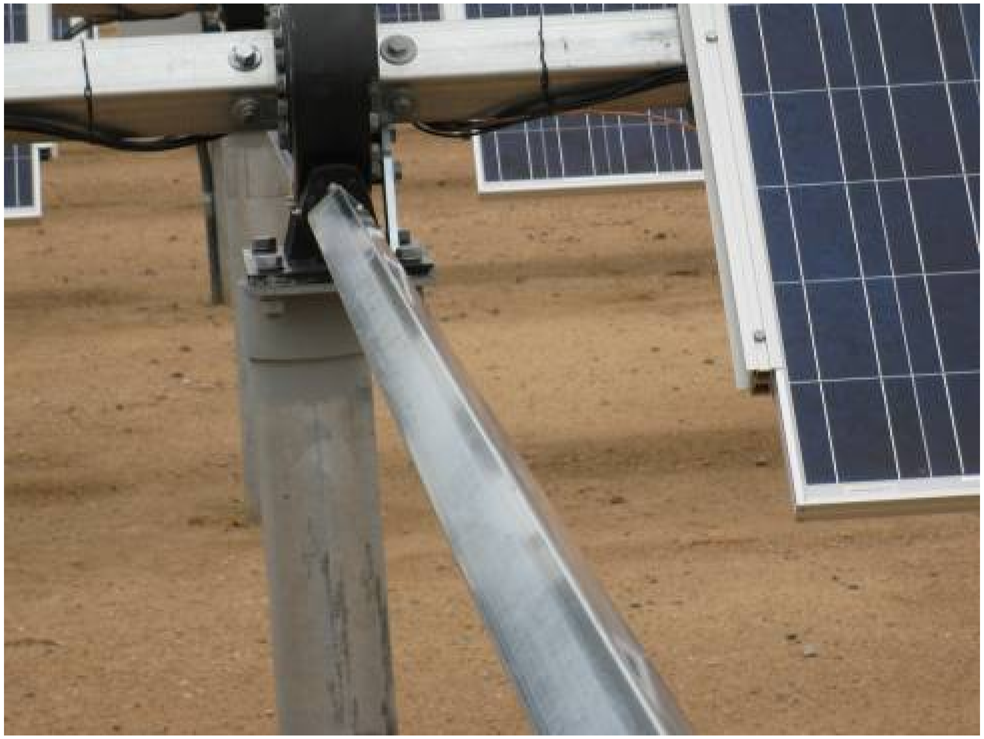
Physical/Mechanical Interactions

Tracker Controller and Drive

Array

Sub-Structure

Environment



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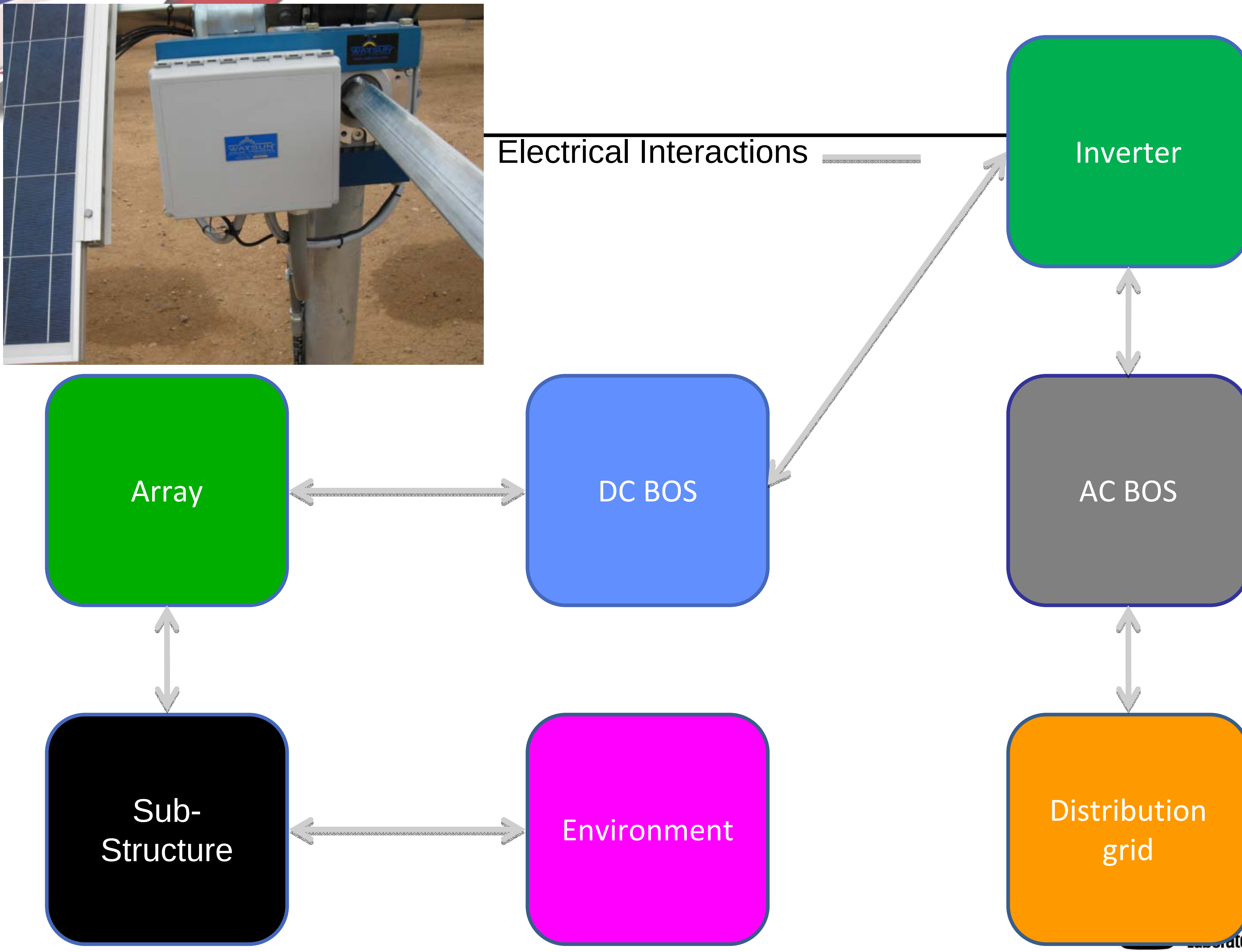
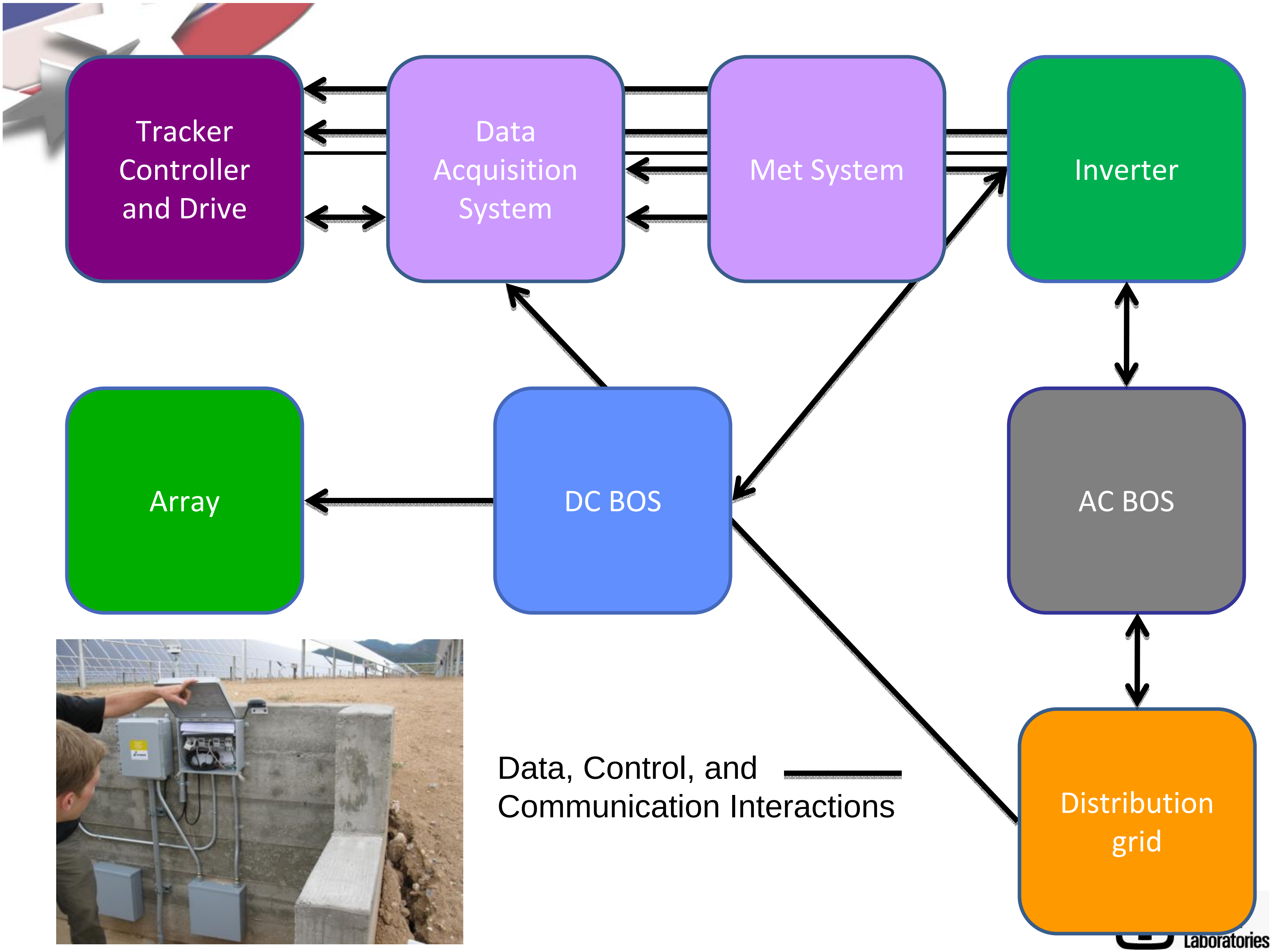
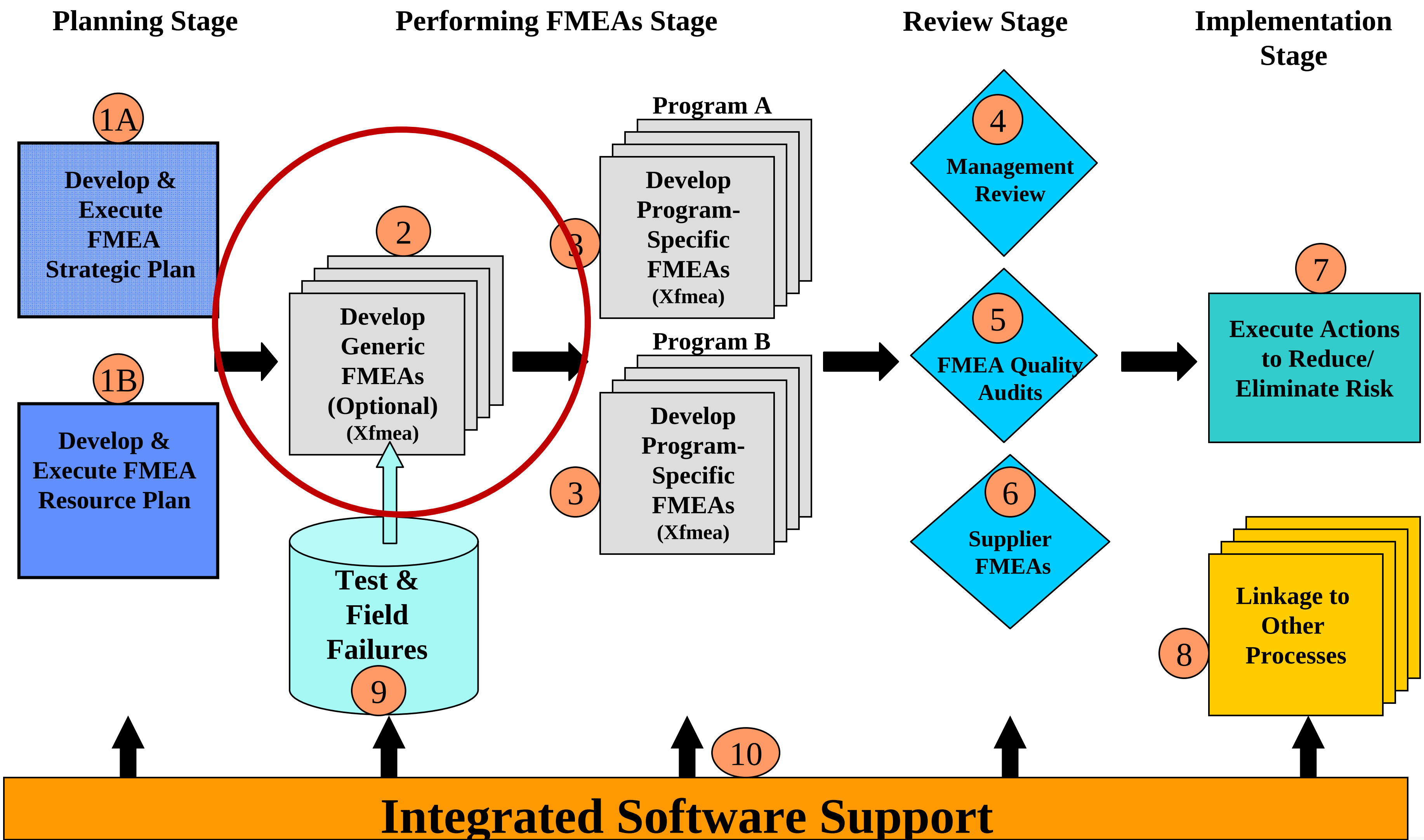

Electrical Interactions
Inverter
Array
DC BOS
AC BOS
Sub-Structure
Environment
Distribution grid



Tracker Controller and Drive
Data Acquisition System
Met System
Inverter
Array
DC BOS
AC BOS
Distribution grid
Data, Control, and Communication Interactions

EFFECTIVE FMEA PROCESS



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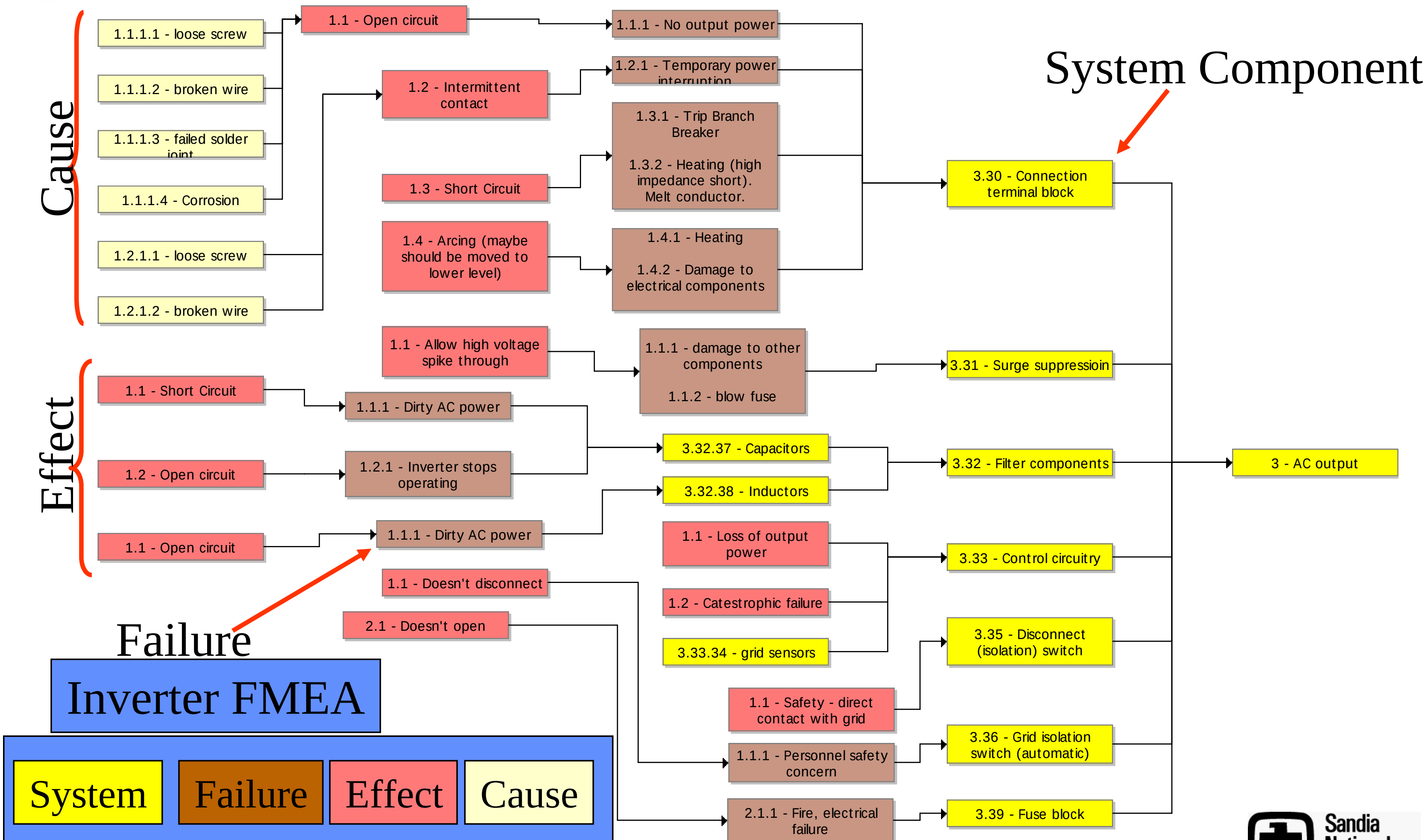
Cause-effect diagram shows possible failure modes



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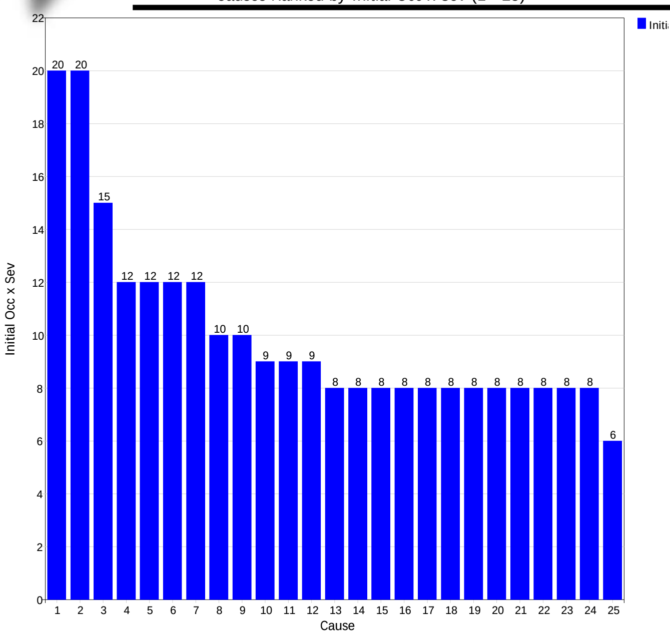
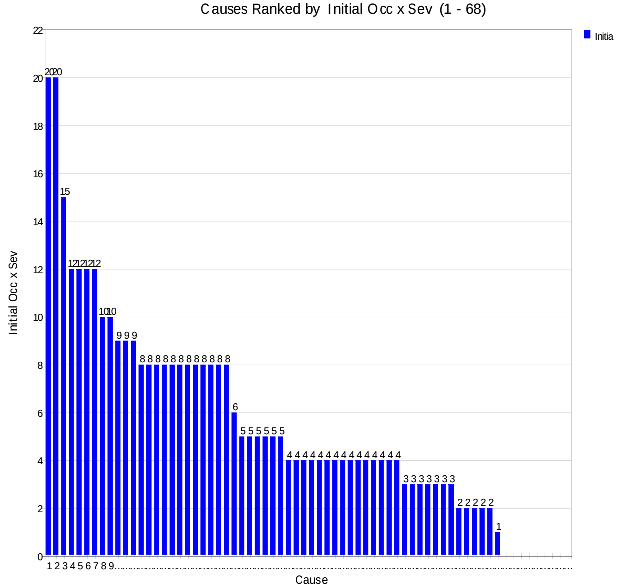
OxS (occurrence X severity) plots (pareto) help to focus attention on critical aspects of the system





Project: Crystalline Silicon Device

Causes Ranked by Initial Occ x Sev (1 - 25)

1: Oi x Si = 20 (4 x 5) - corrosion (Item: 14 - Frame)
2: Oi x Si = 20 (4 x 5) - improper installation (wrong metals, poor processes) (Item: 14 - Frame)
3: Oi x Si = 15 (5 x 3) - One or more cracked cells (Item: 3 - Cell Strings)
4: Oi x Si = 12 (4 x 3) - Increased series resistance due to solder joint degradation & or failure at gridline interface (Item: 3 - Cell Strings)
5: Oi x Si = 12 (4 x 3) - Fatigue due to thermal cycling (Item: 3 - Cell Strings)
6: Oi x Si = 12 (3 x 4) - improper use / installation (Item: 9 - Junction Box)
7: Oi x Si = 12 (3 x 4) - improper installation (Item: 14 - Frame)
8: Oi x Si = 10 (2 x 5) - Cracked cell (Item: 3.7 - Solar Cell)
9: Oi x Si = 10 (2 x 5) - Solder bond failure (Item: 3 - Cell Strings)
10: Oi x Si = 9 (3 x 3) - Decreased power in a single cell (Item: 3 - Cell Strings)
11: Oi x Si = 9 (3 x 3) - open circuit (Item: 9.10 - Bypass Diodes)
12: Oi x Si = 9 (3 x 3) - Delamination from glass (loss of optical coupling) (Item: 2 - EVA (Front))
13: Oi x Si = 8 (2 x 4) - moisture uptake by EVA (Item: 2 - EVA (Front))

c-Si FMEA

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Presentation Outline

- **Why System Reliability?**
- **Some of the basics**
- **Increase detail and complexity**
  - ❖ **Develop data resources**
  - ❖ **Develop methodologies**
  - ❖ **Share information/data, tools and processes**
- **Summary**

Codes & Standards

FMEA's

Baseline Performance

RBD's

Real-time Data

Long-term exposure

Failure Analysis

Mitigation

Accelerated Tests

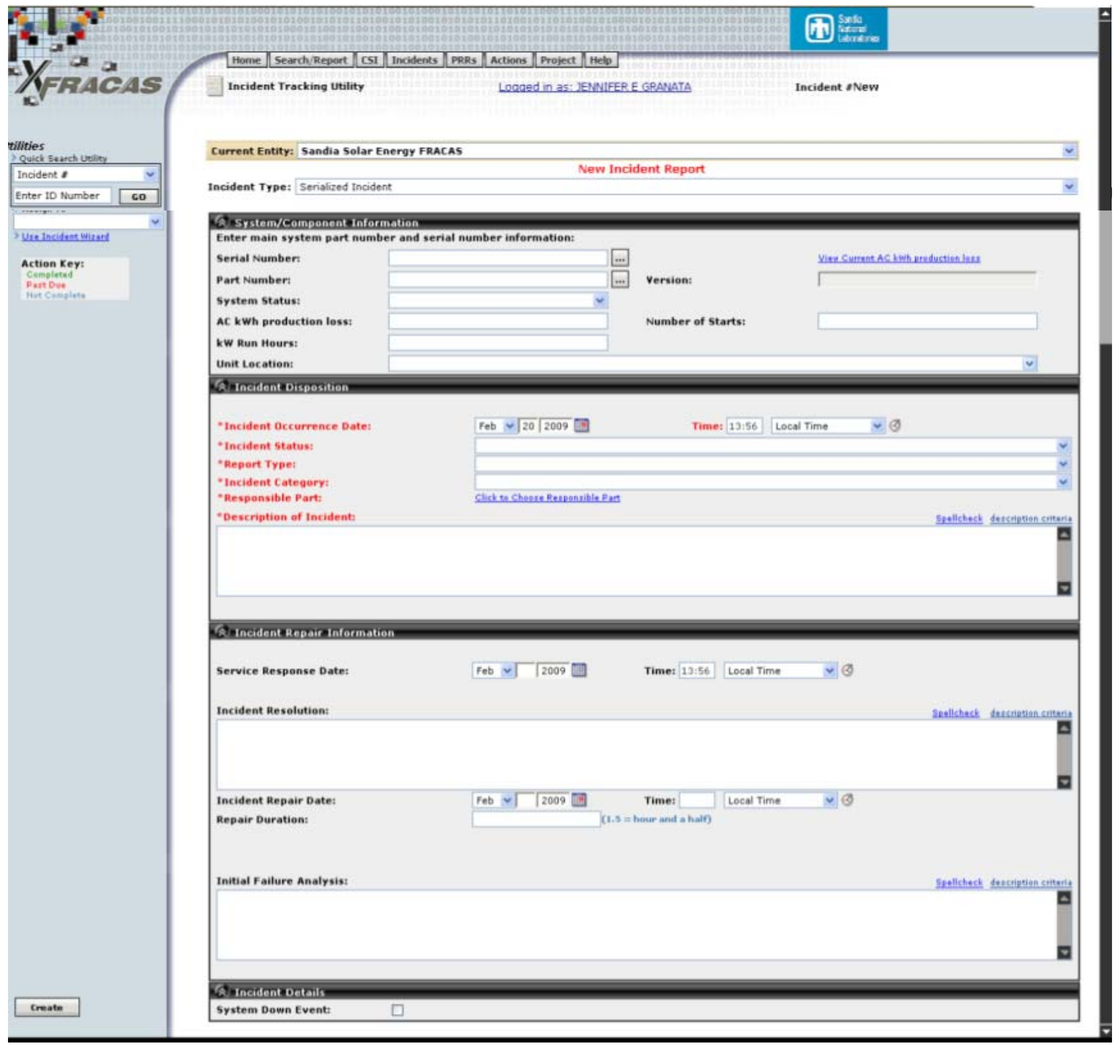
Predictive Modeling

Some Current Activities/Recommendations

1. Develop a reliability model of the system
2. Use reliability block diagrams (RBD's) to describe relationships (series, parallel, etc)
3. Collect component and subsystem field data
4. Collect component and subsystem lab based (ALT) data
5. Adjust data to fit environmental/operational constraints and conditions (natural and man-made environment)
6. Use stochastic and deterministic methodologies to predict reliability
7. Verify and/or adjust prediction through field data

PV Reliability O&M Database

- **Database used as a repository for field data:** PVROM
- **Standardized method for collecting and maintaining O&M data**
- **Web-based: user friendly**
- **Secure/Proprietary**
- **Data directly exported to predictive model tools**
- **Initially populated with legacy TEP data; others are adopting**
- **More partners are being sought**



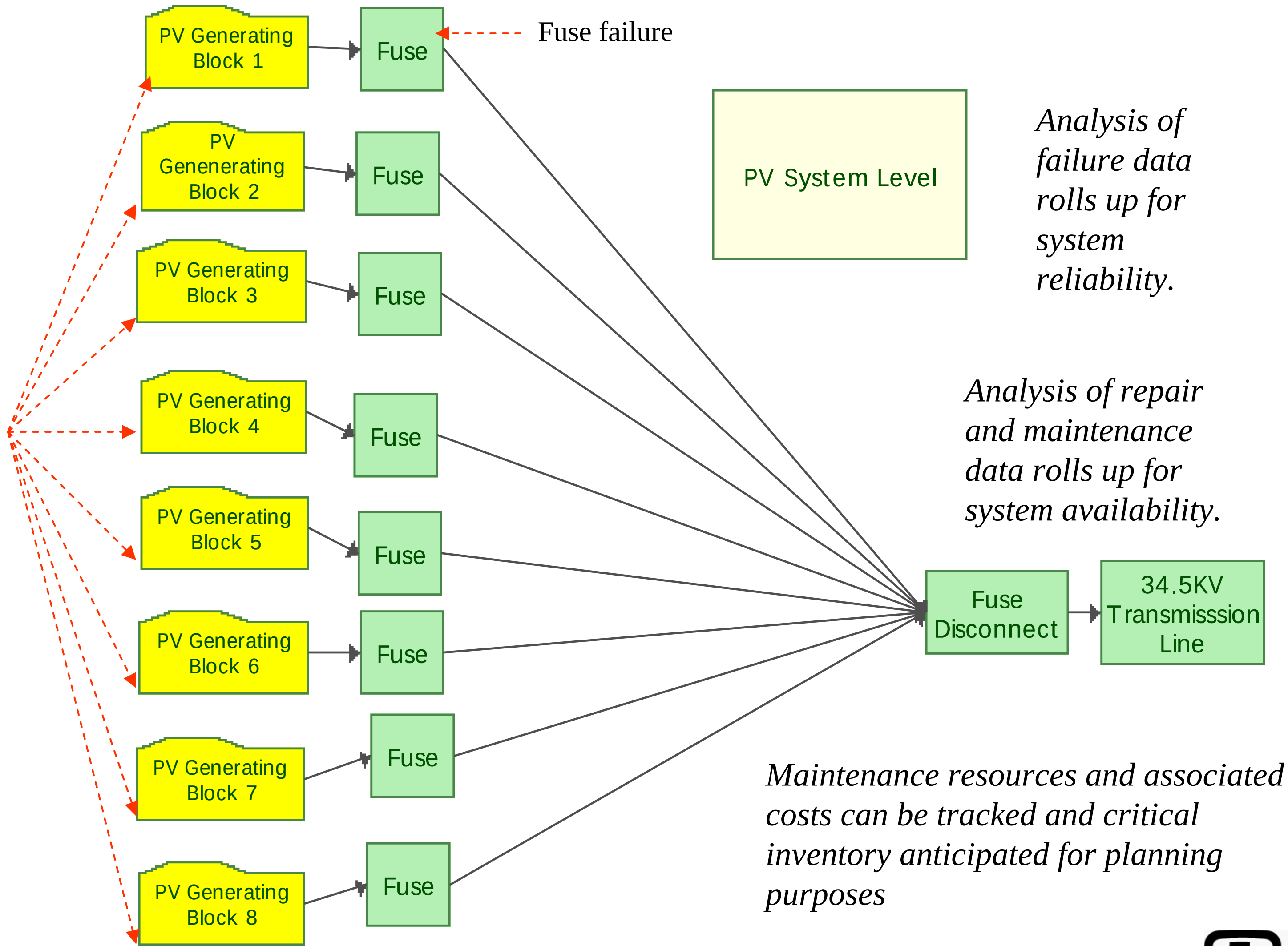
System Long Term Exposure Tests

Objective: Determine system degradation rates through controlled exposure tests in varied environments

- System configurations assure real life effects
- Tests being initiated in hot/dry, hot/humid, and cold climates
- Subset of modules subjected to lab level baseline tests
- Exposure tests subjected to quarterly inspections and semi-annual performance tests
- Maintain control modules indoors
- Minimize measurement errors

System Level Model/RBD

Blocks have lower level reliability models

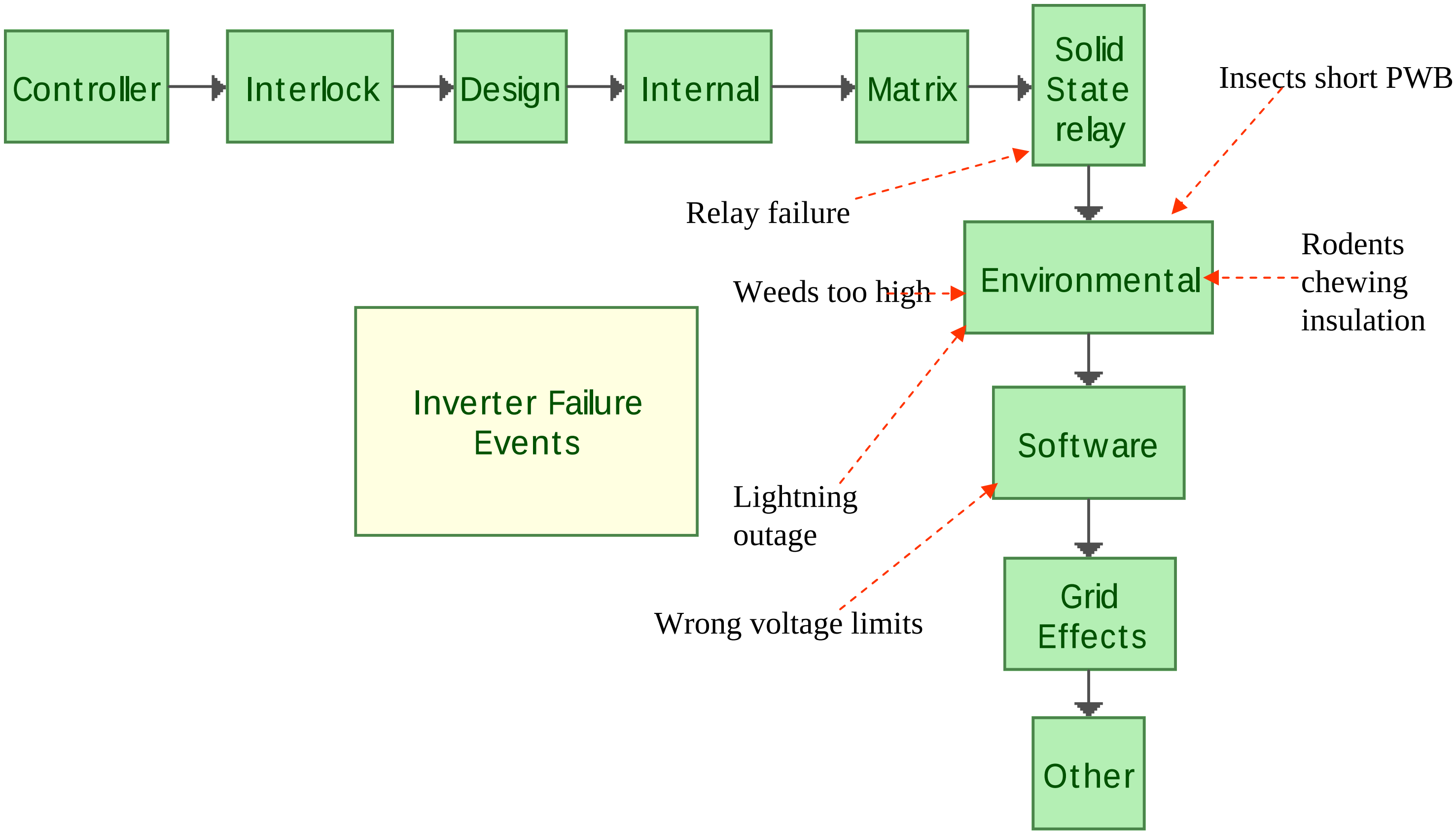


Analysis of failure data rolls up for system reliability.

Analysis of repair and maintenance data rolls up for system availability.

Maintenance resources and associated costs can be tracked and critical inventory anticipated for planning purposes

PV150 Inverter



This type of field experience is impetus for conducting Inverter level FMEA's

Photovoltaic Reliability and Availability Model (PVRAM)

- Model predicts for any component and any level of the system:
  degradation vs time--***reliability*** vs time--***availability*** vs time

Component	Actual Number of Failures 5 yr Cum	Expected Number of Failures 5 yr Cum	Expected Number of Failures 10 yr Cum	Expected Number of Failures 20 yr Cum
PV 150 Inverter (26 cSi arrays)	125	132	231*	429*
PV Module	29	26	31	38
AC Disconnect	22	17	23	31
Lightning	16	10	20	41
208/480 Transformer	5	3	3	3
Row Box	34	25	35	50
Marshalling Box	2	4	7	11
480VAC/34.5KV Xformer	5	4	5	9

- Model prediction is accurate at 5 years
- Predictions for 10 and 20 years need additional data
- Model is being exercised by running sensitivity analyses

Model Results for our initial run of PVRAM

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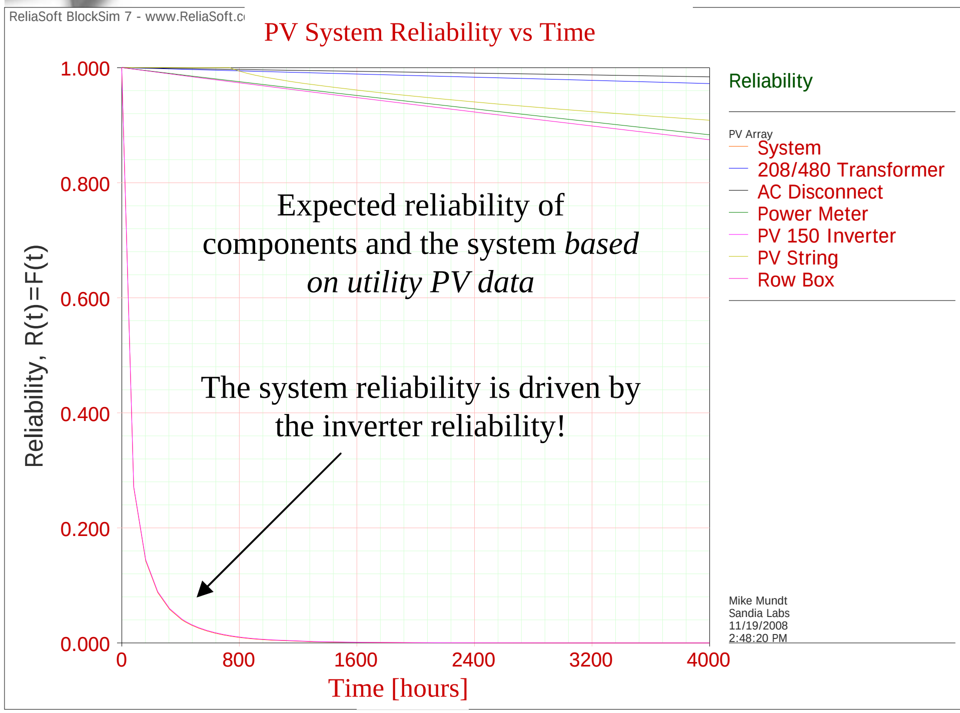
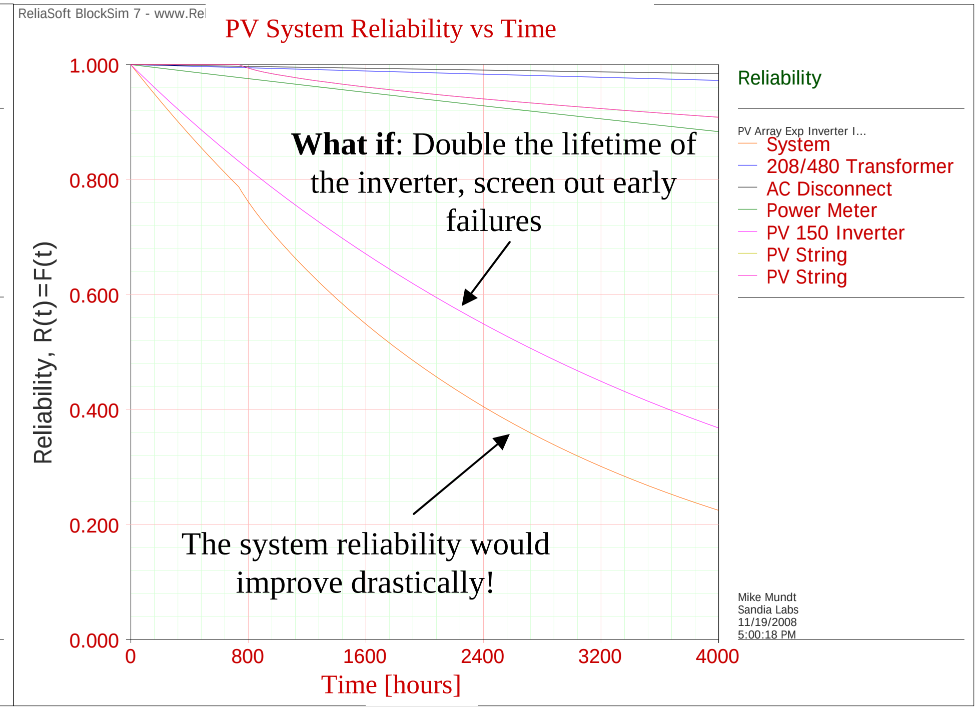
How would system reliability change by doubling inverter lifetime?





- *Real* field data (limited amounts,always more data needed)
- Viewing reliability of each component within a system shows "weakest links" – *opportunities for improvements and R&D efforts*
- Model the changes in availability or cost if improvements are made to one of the weak links – *how LCOE is affected? Do changes produce ROI?*
- Allows for trade-offs: Accept O&M costs for replacing less reliable inverter vs. cost of more reliable inverter and reduced O&M

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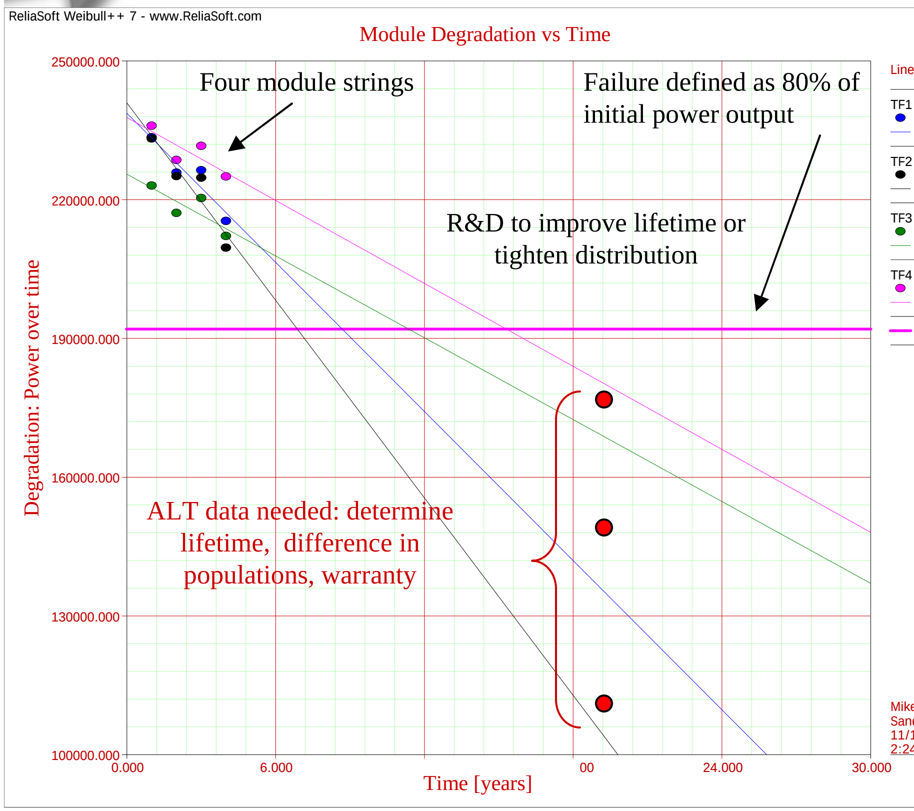
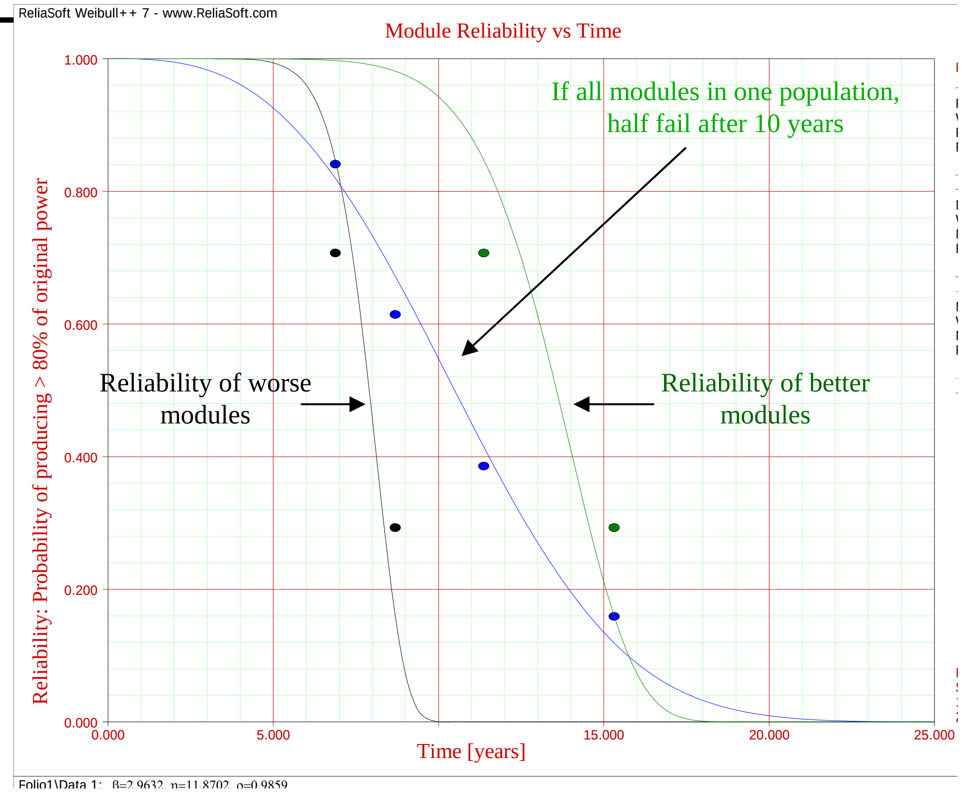
How do I improve my module design?





- Design of Experiment methods drive Accelerated Lifetime Testing
- ALT allows lifetime determination; reduces uncertainty
- *R&D or process improvement* opportunities identified
- Module manufacturers benefit from *module improvement, warranty predictions*
- More data needed!

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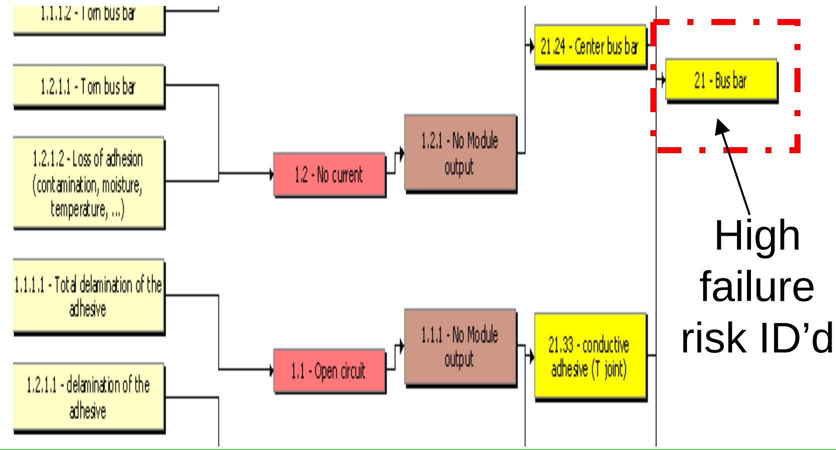
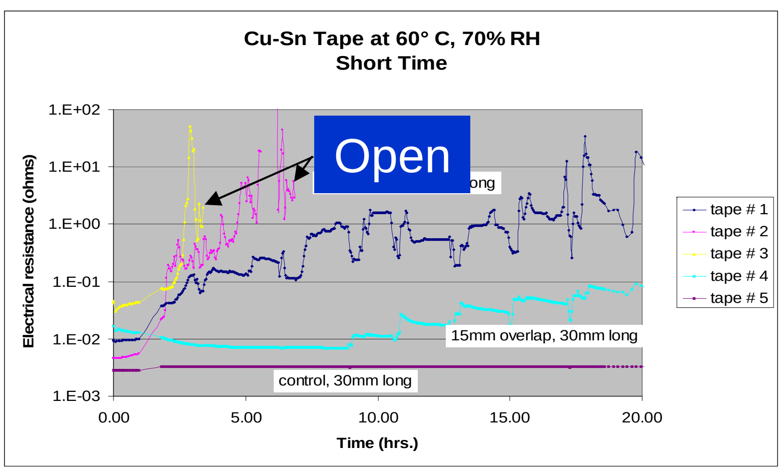
Reliability Methodologies With Industry Partner—A Success Story

- Teamed with module manufacturer to demonstrate Sandia's reliability tools
- Created FMEA in a team environment; specific issues to manufacturer's process identified

Failure Modes and Effects Analysis



Accelerated tests developed to quantify failure risk



Sorensen et al., *The Effect of Metal Foil Tape Degradation on the Long Term Reliability of PV Modules*, 34th IEEE PVSC

Next steps :

- Long term exposure tests at array level
- Baseline performance; degradation
- Modules/coupons for ALT validation
- Apply diagnostics as needed
- Reliability model
- Incorporate ALT results into RBD model

Summary: Major Themes in Sandia's Program

- Define reliability needs; some needs vary with application and customer (residential, commercial, utility), industry segment (integrators, manufacturers, financiers, etc.), technology, and stakeholder.
- Reliability database of fielded system failure modes, failure rates, degradation rates and O&M costs to be used to create predictive model(s)
  - data needs to be protected from disclosure and potential misuse
- Fielded system reliability and accelerated aging evaluation needed
  - for predictive models and correlations between lab and field tests
- Safety-related failures are high priority; risk of injury and industry liability/reputation
- Improve existing tests, increase use of best practices/methodologies for reliability and accelerated aging tests, and expanded applications of the information derived from lab and field evaluations

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