2024 Photovoltaic Inverter Reliability Workshop Summary Report & Proceedings

Daniel J. Friedman, Peter L. Hacke, Mowafak Al-Jassim, Silvana Ovaitt, and Susannah Shoemaker

National Renewable Energy Laboratory

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Office of Energy Efficiency & Renewable Energy
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List of Acronyms

AI	artificial intelligence
BESS	battery energy storage system
BOS	balance of systems
CMMS	computerized maintenance management system
COO	cost of ownership
CRADA	cooperative research and development agreement
DOE	U.S. Department of Energy
EMI/EMC	electromagnetic interference and compatibility
EPC	engineering, procurement, and construction
ESIF	Energy Systems Integration Facility
ESS	energy storage system
EV	electric vehicle
FMEA	failure mode and effects analysis
GFPI	ground-fault protection and interruption
HALT	highly accelerated life testing
IBR	inverter-based resource
IEC	International Electrotechnical Commission
IGBT	insulated gate bipolar transistor
IRA	Inflation Reduction Act
LCC	life cycle cost
LCOE	levelized cost of energy
MLPE	module-level power electronics
MOSFET	metal-oxide-semiconductor field-effect transistor
NDA	nondisclosure agreement
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
OEM	original equipment manufacturer
PCB	printed circuit board
PPA	power purchase agreement
PV	photovoltaic
PVROM	PV Reliability, Operations & Management
R&D	research and development
RBD	reliability block diagram
RETC	Renewable Energy Test Center
RSD	rapid shutdown system
SCADA	supervisory control and data acquisition
SETO	Solar Energy Technologies Office
SiC	silicon carbide
SOA	safe operating area
SSTDR	spread-spectrum time-domain reflectometry
TCO	total cost of ownership

Executive Summary

Photovoltaic (PV) deployment must scale up dramatically in the coming years to achieve a sustainable energy future. One key challenge to this scale-up is the reliability of PV inverters, which, along with relatively short (10–12-year) inverter lifetimes and shorter warrantees (typically 5 years), is one of the most common causes of PV system failures. To address these challenges, the National Renewable Energy Laboratory (NREL) organized the 2024 Photovoltaic Inverter Reliability Workshop, which was held April 11–12, 2024, at NREL's South Table Mountain campus in Golden, Colorado. The goal of the workshop was to bring together key stakeholders from industry, academia, national laboratories, and the U.S. Department of Energy to form working partnerships and develop priorities to address PV inverter reliability challenges over the next 5 years and beyond. This report summarizes the discussions that took place during the workshop and discusses the key conclusions and takeaways.

The workshop was organized around seven key topics, including the present state of inverter reliability; solutions for reliability challenges; life cycle cost and ownership issues; testing, standards, performance, and reliability metrics; data reporting, analytics, and sharing; and the future of PV inverter reliability research. Participants included inverter manufacturers, national laboratory researchers, academics, independent testing laboratories, and more. Over the course of the two-day workshop, attendees arrived at several key priorities and conclusions.

Participants agreed that the top priorities for addressing inverter reliability include breaking down barriers to inverter repair and maintenance (including pursuing "right to repair" regulations, open-source architecture, and possible support contracts), building a collective forum of knowledge for the PV inverter ecosystem (including a national inverter database cataloging failures), leveraging data to better understand inverters on multiple levels (from the reliability of components to the reliability of subsystems and the system as a whole), and advancing safety and standards.

Other key priorities that were highlighted in the workshop included developing more standardized reporting processes for failures, addressing manufacturing quality issues, investing in workforce development, understanding transformer failure modes and mechanisms, and focusing on predicting issues before they happen through better metrology, in addition to preventing them through qualification testing and quality of components and manufacturing. Some viewed moving to modularity as a priority, whereas others saw that as not cost-effective.

Data will play an increasingly important role moving forward. In the next 5 years, there will be much more inverter data available, in part from more artificial intelligence and intelligent controls inside inverters. Accordingly, there will be a need for good data analytics. Using this data to understand inverters on multiple levels will be key to the success of the inverter reliability effort.

Over the next 5 years, inverters will need to accommodate significant growth. Due to solar's low price point and the drive to decarbonize the energy system, solar installations have increased dramatically and will require the inverter industry to keep up with rapidly rising demand (see for example https://www.energy.gov/eere/solar/solar-futures-study). Secondly, more PV systems will be combined with energy storage, and this, combined with the transition from 1500V to

2000V inverters, means that inverter reliability will be increasingly challenged because of greater electrical loads. These developments highlight the importance of proactively addressing the inverter reliability challenges detailed above and continuing to work toward reliability through strong collaborations.

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1 Workshop Agenda

The agenda for the two-day workshop was as follows.

Table 1. Photovoltaic Inverter Reliability Workshop Agenda

Day 1: April 11, 2024	
8:00 – 8:30 AM	Registration
8:30 – 8:40 AM	Welcome – Bill Tumas, NREL
8:40 – 9:00 AM	Workshop Goals, Organization, and Logistics – Daniel Friedman and Peter Hacke, NREL
Session 1: Present State of Inverter Reliability	
9:00 – 9:20 AM	Keynote: Motivating Inverter Reliability – Allan Ward, U.S. Department of Energy Solar Energy Technologies Office
9:20 – 9:40 AM	Service in the Sun: The Reality of PV Inverter Reliability – Auston Taber, FranklinWH Energy Storage Inc.
9:40 – 10:00 AM	The Problem Today: The Impact of Inverter Reliability on Solar Growth – Charity Sotero, kWh Analytics
10:00 – 10:35 AM	**Q&A, Discussion**: What are the biggest impacts for plant operators in the inverter reliability space?
10:35 – 10:55 AM	Break
Session 2: Routes and Solutions for Reliability Challenges	
10:55 – 11:15 AM	Challenges and Solutions of Reliability Testing of Grid Relays for PV Applications – Wolfram Dege, SMA
11:15 – 11:35 AM	Condition Monitoring as a Methodology To Cope With MOSFET Unreliability – Johan Driesen, KU Leuven
11:35 – 11:55 AM	Long-Term Reliability Challenges and Solutions for Central Inverters – Bale Yang, Sungrow Power Supply Co.
11:55 – 12:30 PM	**Q&A, Discussion**: What are you seeing that could be helpful mitigating inverter challenges? What tools or resources would help?
12:30 – 1:35 PM	Working lunch with survey and discussion on the topic of R&D priorities from morning sessions, facilitated by Dan Friedman
Session 3: Lifecycle Cost and Ownership Issues	
1:35 – 1:55 PM	Developing NREL Analysis Around Inverter Supply Chains, Manufacturing Costs, and Lifecycle Cost of Ownership Issues – Michael Woodhouse, NREL
1:55 – 2:15 PM	Approaches Toward the Use of Total Cost of Ownership (TCO) Metrics for PV Inverters and Beyond – Sumanth Lokanath, VDC Americas
2:15 – 2:35 PM	Various Solutions for Servicing an Aging Inverter Fleet, George Kemper, DEPCOM Power
2:35 – 3:10 PM	**Q&A, Discussion**: What are the biggest expenses and highest priorities?
3:10 – 3:30 PM	Break
Session 4: Testing, Standards, Performance, and Reliability Metrics	
3:30 – 3:50 PM	Keynote: Ensuring Safety and Security—Implications for Reliability and Availability – Ken Boyce, UL Solutions
3:50 – 4:10 PM	Laboratory Testing To Assess Durability of Inverters and Field Experiences – Cherif Kedir, RETC
4:10 – 4:30 PM	Inverter Production Quality Assurance and Testing – Ignacio Carellan, Kiwa PI Berlin
4:30 – 5:05 PM	**Q&A, Discussion:** What testing or prequalification would you like to see to ensure reliability? Where are the gaps?
5:05 – 6:05 PM	NREL Energy Systems Integration Facility (ESIF) tours

Day 2: April 12, 2024	
8:00 – 8:30 AM	Registration
Session 5: Lifetime of Active and Passive Components	
8:30 – 8:50 AM	Leveraging Temperature Data To Maximize Inverter Performance and Reliability – Dylan Sontag, Silicon Ranch
8:50 – 9:10 AM	Lifetime Testing and Modeling of Cooling Fans in PV Inverters – Zheyu Zhang, Rensselaer Polytechnic Institute
9:10 – 9:30 AM	Screening Methodology for SiC MOSFETs – Anant Agarwal, The Ohio State University
9:30 – 9:50 AM	Live State of Health Monitoring of Inverter Subsystems – Faisal Khan, NREL
9:50 – 10:25 AM	**Q&A, Discussion**: What failure mechanisms are we not properly accounting for? How do we better accelerate the working environment of PV inverters to qualify components
10:25 – 10:45 AM	Break
Session 6: Data Reporting, Analytics, and Data Sharing	
10:45 – 11:05 AM	Characterization and Survivability Analysis of Inverter Faults Through an Analysis of O&M Records – Thushara Gunda, Sandia National Laboratories
10:05 – 11:25 AM	PV Inverter Availability From the U.S. PV Fleet – Chris Deline, NREL
11:25 – 11:35 AM	Open-Access Datasets From the Solar Data Bounty Prize and Their Potential in Reliability Analysis – Tassos Golnas, U.S. Department of Energy, Solar Energy Technologies Office
11:35 – 12:10 PM	**Q&A, Discussion**: How can we use data analytics to predict availability, reliability, and performance?
12:10 – 1:15 PM	Working lunch with survey and discussion on the topic of R&D priorities from workshop Day 1 afternoon and morning Day 2 sessions, facilitated by Dan Friedman
Session 7: Discussion-Centric Sessions on the Future of PV Inverter Reliability Research, Metrics For Success, and the State of the Industry 5 Years From Now	
1:15 – 1:45 PM	Breakout Sessions
1:45 – 2:15 PM	Report-Out From Breakout Sessions
2:15 – 3:00 PM	**Summary, Adjournment**
3:00 – 4:00 PM	NREL Energy Systems Integration Facility (ESIF) tours

2 Summary of Workshop Presentations, Discussions, and Takeaways

The workshop was divided into seven sessions:

1. Present state of inverter reliability
2. Routes and solutions for reliability challenges
3. Life cycle cost and ownership issues
4. Testing, standards, performance, and reliability metrics
5. Lifetime of active and passive components
6. Data reporting, analytics, and data sharing
7. The future of PV inverter reliability research, success metrics, and industry's state 5 years from now.

These sessions are covered in detail in Sections 2.1–2.7 below. The full Photovoltaic Inverter Reliability Workshop proceedings can be found in Section 4 of this report.

2.1 Present State of Inverter Reliability

The first three speakers discussed the present state of inverter reliability.

Solar Energy Technologies Office (SETO) PV Research and Development (Allan Ward, SETO)

In this presentation, Allan Ward from the U.S. Department of Energy's (DOE's) Solar Energy Technologies Office (SETO) discussed SETO's goals and motivations for PV inverter research and development (R&D).

One of SETO's key goals for PV is reducing the cost of PV electricity to less than 2 cents/kWh by 2030—a goal expected to accelerate PV adoption, as individuals and industry will naturally adopt the energy with the lowest cost. Inverters represent an important opportunity and priority for achieving this goal; over 60% of failures observed in PV power systems arise from inverters, and these failures drive up the cost of PV. Improving inverter reliability will help lower PV costs by ensuring PV systems' lifetimes and reducing operations and maintenance (O&M) costs.

To address inverter reliability challenges, SETO is interested in funding projects that allow inverters to withstand adverse conditions (climate, temperature, humidity, stresses from the grid, etc.) and adverse events (severe weather, O&M damage, installation damage, wildfires, etc.). Specific ideas to achieve these goals include exploring wide bandgap devices (expected to become less expensive over time), cooling systems (which tend to experience frequent failures), and passive devices.

SETO has also shifted its focus more toward resilience in recent years. Failures will occur, and it is crucial to address the response to those failures in addition to trying to minimize them in the first place. Two key focus areas are minimizing downtime and focusing on detection, response, and recovery. Specific ideas to achieve this include embedded sensors and self-diagnostics (detection), proactive maintenance (response), and hot-swap inverter legs and modular PV arrays (recovery)

SETO's desired outcomes from this workshop include establishing a stronger network of inverter experts that will drive PV inverter R&D and funding applications; understanding the technical challenges involved in improving inverter reliability and resilience and whether SETO funding is aligned with these challenges; learning how SETO can most effectively spend funds to improve current PV inverter reliability and resilience; and determining which emerging technologies SETO should accelerate.

Currently, only 15% of SETO's $236 million PV R&D budget is allocated to R&D in balance of systems (BOS) durability and system performance, but SETO is interested in dedicating more of its budget to addressing key challenges in this area.

Service in the Sun: The Reality of PV Inverter Reliability (Auston Taber, FranklinWH Energy Storage)

In this talk, Auston Taber from FranklinWH Energy Storage discussed several key challenges associated with inverter reliability and presented solutions to those challenges, focusing on the importance of qualified technicians and spare parts.

Taber cited a study (https://raptormaps.com/resources/2023-global-solar-report) that the solar industry loses $2.5 billion annually from equipment underperformance. These losses stem partly from insufficient qualified technicians to keep PV systems up and running; 44% of companies say that a lack of trained labor is the most significant barrier to solar company growth. This lack of trained labor heavily impacts inverters: 45% of inverter capacity are from manufacturers no longer in business, just 4 years after construction. There is also a general lack of documentation that leaves system owners without the support they need to keep their inverters running smoothly.

In addition to a lack of experienced labor and documentation, other issues that impact inverters include a lack of spare parts, limited third-party support, warranty gaps, service and training complexity, and design and compatibility. In terms of spare parts, fans often present an issue; in 2021, some fans had a 52-week lead time. Control boards are also a challenge; because the original equipment manufacturer (OEM) is the only supplier, if a system owner does not have spare parts or if the manufacturer is no longer in business, their system could be offline for a long time, with reengineering costs becoming prohibitive and replacement often becoming the only viable solution. Regarding design and compatibility, the wide range of AC voltages in utility-scale systems poses a challenge, as do communications.

Owners, OEMs, and technicians are key in mitigating these issues. Owners should think long-term about their sites and vet the OEM's products prior to installation. OEMs should consider giving more information to technicians to enable them to better troubleshoot equipment issues. OEMs should also continue to provide spare parts and/or provide schematics and specifications to others to permit the availability of such spare parts. Systems should be put in place by owners or the industry at large to facilitate technicians sharing information to empower themselves and the solar industry.

The Problem Today: The Impact of Inverter Reliability on Solar Growth (Charity Sotero, kWh Analytics)

In this presentation, Charity Sotero of kWh Analytics discussed how they, as insurers, use data to measure PV inverter reliability.

Even though operating and deployment costs for PV have decreased, insurance premiums have increased, becoming barriers for solar deployment in some instances. To lower costs and help accelerate PV deployment goals, kWh Analytics, unlike many other insurance companies, considers PV reliability when assessing risk.

To measure reliability, kWh relies on their claims data, O&M logs, and their PV database, which covers over 500 utility PV systems with an average age of 3.7 years and 11+ GW capacity. The claims data reveal what severity of events matters to the PV market. However, claims data may exclude low-loss events, i.e., those with a value below the deductible. By contrast, O&M records can provide insight into lower-loss events and those for which claims are not made—and, when combined with system data, O&M logs have the potential to show what factors make a difference in reliability.

Attrition claims varied between inverter types. Central and string inverters had a mean time from installation until insurance claim of 1.5 years and 2.2 years, respectively.

kWh used natural language processing to analyze O&M logs/tickets. They developed PV translation dictionaries with PV-specific terminology and acronyms and used a single-line diagram flow of energy to choose the most likely equipment type (most issues are caught at the inverter, but they do not always start there). The team found that inverters are the main driver of ticket frequency (51% of tickets), followed by DC distribution. Key terms that showed up frequently in these tickets included “controller,” “stack,” and “fan.” They found that inverter-driven resolutions are generally driven by repairs, which is important to insurance, as full inverter replacement is significantly more costly than inverter repair. In addition, the team found that inverter failures are the most frequent and expensive of all attritional claims, which consider all claims except natural catastrophes.

Discussion

The discussion portion of the first session was guided by the following question: “What are the biggest impacts for plant operators in the inverter reliability space?” Participants discussed various topics, focusing on balancing inverter cost targets and performance, combatting high equipment failure rates, leveraging insurance to facilitate the development of emerging technologies, and addressing workforce challenges.

Participants first discussed the competing demand between keeping costs low to meet DOE’s 2 cents/kWh levelized cost of energy (LCOE) target and selecting the right inverters to meet performance expectations. One reason that newer technologies fail more often may be that they are going after reducing costs to meet the 2 cents/kWh target, causing both manufacturers and system owners to take steps to lower costs over the short term. On the other hand, the reason the DOE goal focuses on LCOE is so that durability and reliability are factored in over the long term; it is not possible to meet the 2 cents/kWh LCOE goal with frequent, expensive failures. In addition, the industry is starting to see more willingness to spend more upfront for longer-term success. One participant pointed out that the data source used to assess this trade-off is key; in particular, owner costs need to be captured. The more asset owners and utilities provide data on owner costs and the costs' drivers, the faster the industry can evolve. For newly awarded projects, DOE assesses the trade-off between cost and durability/reliability by asking awardees to validate their predictions (otherwise, the only way to understand how that trade-off will play out is to wait 5–10 years to see field performance, which is not realistic).

The group also discussed how to make manufacturer-led failure analysis reports more accessible; these reports are crucial for academic research and national security. Some manufacturers are very participatory/open-book in terms of their field failure experiences, but those manufacturers are in the minority. Government regulations, such as "right to repair" laws, can set the right framework for more of this critical data to be shared by manufacturers. Agreements like cooperative research and development agreements (CRADAs) and nondisclosure agreements (NDAs) also provide intellectual property protections that can facilitate this information sharing, albeit in a more limited way. Another potential strategy is to incentivize manufacturers to provide failure mode data (insurance claims, warranty claims, etc.), which can be useful data sources for analysis.

Participants then discussed how to combat the high equipment failure rates in the inverter industry. OEM estimates of failure rates are not always accurate, and participants agreed that the industry needs to collaborate and share information to address this issue. The insurance industry typically addresses this issue by adding a weighting factor on top of the OEM rate to get a more accurate sense of the actual failure rate; this factor considers O&M quality, location, and so on. One potential solution is for stakeholders to develop a database that tracks purchasers' experiences with various equipment.

The group discussed the importance of providing incentives for solar reliability. In the broader energy market, if an energy provider trips offline, they have to buy energy on the open market, which can be very expensive and thus incentivizes day-to-day reliability. However, the solar industry participates in the energy market differently than other energy sources; for example, solar has many power purchase agreements (PPAs). This may set up improper incentives because engineering, procurement, and construction (EPC) companies are not taking as much of a financial hit when they run unreliable systems. On the other hand, there is a cost driver in that the system that fails must be repaired. In addition, the market is constantly changing and will likely react accordingly; for example, as batteries have gotten more popular, they have had fewer PPAs.

It is worthwhile to combine a variety of data sources relevant to inverter reliability —including weather data, O&M data, utility data, and so on—as each supplies a different piece of the big picture. There has been a push by government researchers to address standardization/ontology in PV performance data; one participant suggested that we should extend that to inverters. The language used in the inverter industry is different in different contexts (O&M tickets vs. manufacturing vs. academic journals), so some standardization could be very helpful.

Another key consideration that the group discussed is ensuring that there is a sufficient workforce to handle new technologies. A key issue the workforce is facing is the proprietary technology that inverter manufacturers have. This ties technicians to the business model of the OEM, which is very restrictive, and something the inverter industry needs to overcome. To address this issue, SETO wants to hear from a utility/asset owner (particularly as a partner on a project).

One participant also noted that there are competing demands for smaller-scale projects, which tend to be more visible near roads, and larger-scale projects (for example, the impact of safety considerations, like fires, depends on whether installations are on rooftops). However, DOE primarily focuses on utility-scale solar (>50-MW installations), which provides 85% of the solar on the grid.

2.2 Routes and Solutions for Reliability Challenges

In this session, speakers discussed a variety of methods for addressing inverter reliability challenges.

Challenges and Solutions of Reliability Testing of Grid Relays for PV (Wolfram Dege, SMA)

In this presentation, Wolfram Dege of SMA discussed reliability testing of grid relays.

In the last 5–10 years, SMA—a solar inverter manufacturer—has shifted its focus to conducting reliability testing on the component level. Reliability testing system level is still crucial, but is supplemented by an extensive test program for components. Component-level testing has several advantages: It can begin in very early stages, unlike system-level testing, so that failures are found earlier and bugs are fixed sooner. It is also much cheaper than doing the testing later on. It can use bigger inspection lots (i.e., bigger sample size inspections), yielding a better quality forecast and leading to better decisions. It also enables testing of components from several suppliers as well as targeted testing (higher stress levels, faster testing). Finally, it allows for a more detailed understanding of inverters—one of the most complex structures in the whole PV system.

Dege discussed SMA's reliability testing of grid relays, an inverter component that connects the inverter and the grid. Relays have a very harsh field mission profile, involving high currents and temperatures, power cycles, and mechanical switching. Because of the roughness of the contact surface, only small parts of the contact (about 5%–10% of the surface) conduct current. Oxide layers develop on the contacts over time, leading to increasing roughness, melting points, and resistance. The goal of the reliability testing was to figure out the field-relevant stressors (and the relation between them), an ageing model, and finally a field forecast.

Challenges with the testing included low acceleration, lack of information from suppliers, prevention of secondary damage, transfer of methods to larger relays, and difficulty with adjusting the working points due to thermal interdependencies. SMA is currently conducting their third iteration of testing, taking into account the lessons learned from the previous two iterations. Key insights from the testing are as follows: (1) It is important for relays (and indeed for all components) to conduct pretests to find the right stressors and suitable working temperatures. (2) Accelerated life tests for relays should involve cyclic current load under warm ambient conditions. (3) The main stressor causing the aging of relays is contact temperature.

Condition Monitoring as a Methodology To Cope With MOSFET Unreliability (Johan Driesen, KU Leuven)

In this talk, Johan Driesen of KU Leuven and EnergyVille—a Flemish joint research center by KU Leuven, VITO, imec, and UHasselt—discussed using condition monitoring to mitigate metal-oxide-semiconductor field-effect transistor (MOSFET) reliability challenges.

Common approaches to improving the reliability of power electronic components include examining reliability in the design phase (through lifetime estimation, selection of the best components, etc.) and conducting testing during the commissioning phase. However, condition monitoring during the comparatively long operational phase is often neglected. Driesen posited that the research community should rethink its culture around condition monitoring, as measurement-based condition monitoring can provide key insights into reliability.

Typically, condition monitoring is based on digital twins. This approach requires a significant amount of modeling, which poses key challenges. In addition, this approach still requires experimental data and an understanding of the physics of failure. Due to these issues, Driesen suggested that measurement-based condition monitoring is a better approach.

Condition-based monitoring can provide key insights into MOSFET reliability. The affected parameters on MOSFETs include die-level degradation and package-level degradation—both switching device failure modes. In theory, thermal measurements can enable estimation of whether the die is still well attached to the package. For lifetime estimation, new approaches are needed, as we now know that a constant failure rate is not an accurate assumption. We also need to define the mission profile, especially for the newer types of PV—e.g., for building-integrated PV systems.

Key takeaways from this work are as follows: (1) Switching devices are a reliability bottleneck. (2) Solder layer delamination and bond wire degradation form the main failure modes. (3) Changing temperatures is the leading cause of failure. (4) Current reliability handbooks are often not sufficient to accurately predict failure. (5) Condition monitoring is an alternative and can be done without a digital twin.

Long-Term Reliability Challenges and Solutions for Central Inverters (Bale Yang, Sungrow Power)

In this presentation, Bale Yang from Sungrow Power, a solar inverter manufacturer, discussed long-term reliability challenges and solutions for central inverters.

The long-term reliability of a PV system depends on the reliability of the inverter, which in turn depends on the maintenance and replacement convenience of the inverter. Inverter reliability challenges include complex operating conditions (humidity, salt spray, etc.), mass production and transportation challenges, and full life cycle operation and maintenance (troubleshooting the repair or replacement conveniently).

To address these challenges, Sungrow focuses on inverter reliability design, manufacturing and testing, and O&M. Key design considerations and how they are addressed are shown in Table 1.

Table 2. Key Considerations for Inverter Reliability Design

Key Design Considerations	Addressed by
Efficient heat dissipation	Power cavity direct ventilation and an electronic cavity heat exchanger
Wind and sand protection	Power cavity air duct smooth design, air inlet bend and quick release design, and electronic cavity self-cleaning design
Anti-corrosion design	Upgraded surface treatment technology; electrostatic spraying, passivation, and galvanization; and use of corrosion-resistant materials in structural components
High-altitude design	Use of a high-altitude simulation to ensure that the temperature rise of key components is within the acceptable range
Solar irradiation	Color of the inverter cabinet
Insulated gate bipolar transistor (IGBT) module design	Use of latest-generation wafers

Manufacturing and testing technology approaches include manufacturing process control (flexible manufacturing, digital factory, and reliable quality), environmental adaptability testing (sandstorm, snowfall, high altitude leading to higher temperature in the model, and low-pressure testing), and on-site reliability testing and verification. O&M approaches center on modular inverter design, which ensures that the faults of a single unit will not affect others. Modular inverter design also results in fast replacement with spare units and low energy yield loss.

Discussion

This discussion session focused on the question: “What are you seeing that could be helpful in mitigating inverter challenges? What tools or resources would help?” Participants discussed using field failure data to predict degradation, being proactive about reliability, making PV inverters modular, and bridging the gap between inverter manufacturers’ useful life models and actual field performance.

First, the group discussed SMA’s ability to collect field failure data. SMA collects field failures and forensics, but they are facing many of the same challenges discussed in the previous session—in particular, the same error codes can have many different root causes. In addition, for damaged inverters, the quality of the failure analysis depends on the inverter model and the resources and colleagues who are handling the failure analysis. However, their database is growing and improving. In addition, SMA has collaborations with national lab consortia and other partners to obtain better failure data and share it with the broader industry. The group also discussed that quantifying SMA’s degradation model based on component reliability is very challenging and requires significant resources. Still, it is the only feasible approach, given that information from the suppliers is lacking.

The group also discussed the feasibility of using temperatures inside the MOSFET junction to predict degradation. Some modules implicitly measure the junction temperatures, but usually, it is in a power package where the IGBT lies and temperature is indirectly measured. Combining those two measurements provides data that can be used to estimate how well the die is soldered. The group agreed that a cultural change with stakeholders involved is necessary. Currently, attitudes are very fatalistic: “These things just fail after ten years, so we just factor that in.” But the industry does not have to accept that. The reliability-related problems are sunk in the noise of the variability of renewables as a whole.

One participant argued that it is important to be more proactive when it comes to improving reliability. Partnering with inverter manufacturers on sensors to get better data and help predict failures is one potential avenue toward becoming more proactive. The group also discussed the importance of developing stronger requirements for testing components. The growing focus on circularity—including the European Commission’s plan to impose new rules related to servicing spare parts—as well as the move toward more service-oriented business models will provide a stronger incentive for data monitoring and reliability. It is in the interest of all inverter manufacturers to partner on these topics.

Testing and modeling at the device level can improve the reliability of the PV inverter, but the group also discussed another approach: making the PV inverter modular. One inverter manufacturer mentioned that they have a modular inverter design—and the key components of that modular inverter also have a modular design. In the future, that manufacturer plans to focus on more modularized inverters with smaller size to make replacement and repair more convenient. However, other manufacturers have found a modular approach too expensive and not integrated enough, resulting in lost money and reliability from the connectors between components.

Next, the group discussed bridging the gap between inverter manufacturers’ useful life models and actual field performance. Currently, there are no inverter manufacturers that make accelerated life tests appropriate for lifetimes of 25 years (to match the warranties of PV modules), but that is evolving. One key is to transfer knowledge from smaller parts to bigger parts. It is very difficult to include the right acceleration factors for inverters. One manufacturer present at the workshop mentioned that they do lifetime tests at the inverter level for each product, as well as several aging tests during the product development process.

2.3 Life Cycle Cost and Ownership Issues

In this session, presenters discussed life cycle cost and ownership issues.

Developing NREL Analysis Around Inverter Supply Chains, Manufacturing Costs, and Life Cycle Cost of Ownership Issues for Solar PV and Storage Projects (Michael Woodhouse, NREL)

Michael Woodhouse presented NREL’s solar-plus-storage techno-economic analysis portfolio, focusing on the portfolio’s analysis of inverter manufacturing costs, life cycle cost of ownership issues, and supply chains.

NREL’s solar-plus-storage techno-economic analysis portfolio covers financial and cost modeling, detailed manufacturing cost modeling (encompassing PV modules, inverters, and battery energy storage systems (BESS)), and system capital cost modeling. Key outcomes from this work include the U.S. Solar PV System and Energy Storage Cost Benchmarks and publicly available cost models. These financial analyses can be a useful means of evaluating technologies themselves.

In terms of inverter manufacturing cost modeling, the NREL team is focused on components and bottom-up cost modeling. The emphasis is also shifting from the direct cost of goods sold to the delivered minimum sustainable price. One of the challenges with this work is that inverters are very complex; it has been a challenge to add up the costs of all the different parts inside an inverter, so the team is working with industry to gather the relevant data. To achieve this, the NREL team is focused on data aggregation, both to protect industry data and to reduce the complexity of the problem. The team is aiming to track which technologies have the greatest market share in general. There are several data gaps that still need to be filled, including understanding bidirectional inverters and domestic vs. import costs.

In terms of inverter life cycle cost of ownership issues, the NREL team is focused on detailing and quantifying trade-offs between lower-cost inverters and longer lifetimes. The team is particularly focused on cash flow and putting a finer point on the total costs over the life cycle of the service. (For example, if you have a bad inverter, how does that affect your revenue?) The team is considering using field data and distributions for inverter maintenance issues and replacements to inform this analysis.

Finally, for inverter supply chains, the team is focused on identifying the largest sources of inverters in the United States, detailing the availability and costs of subcomponents in the United States and abroad, and projecting manufacturing tax credit claims. The principal components for utility and C&I standalone PV installations in the United States are central or string inverters from Europe, China, or Southeast Asia. The principal components for residential standalone PV installations in the U.S. are string inverters and module-level power electronics (MLPE) from China, Mexico, India, Israel, and there is some domestic production. AC-Coupled PV/BESS systems also have an additional bi-directional Inverter with domestic suppliers available. Tariffs could complicate this picture, as could the domestic content bonus, a 10% bonus adder for solar PV systems. The team is investigating how these considerations impact inverters, as well as focusing on filling data gaps in all three of the above areas.

Approaches Toward the Use of Total Cost of Ownership Metrics for PV Inverters and Beyond (Sumanth Lokanath, VDE Americas)

In this presentation, Sumanth Lokanath of VDE Americas discussed various “cost of ownership” metrics—including cost of ownership (COO), total cost of ownership (TCO), and life cycle cost (LCC)—that can shed light on how PV inverter reliability and availability impact profits. Lokanath focused on the TCO metric in particular.

The inverter is a “problem child” for PV systems, according to the available data. To accurately assess the true cost of a PV inverter system, it is critical to capture factors such as component failures, lost energy costs, and the impact of reliability on higher-order parameters like cost effectiveness.

The COO metric only captures O&M costs, neglecting EPC costs and loss of revenue. TCO, by contrast, takes these factors into account:

$$\text{TCO} = \text{EPC} + \text{O\&M} + \text{loss of revenue}$$

LCC builds on the TCO metric, also taking into account disposal and consequential costs; however, these are difficult to capture.

To capture the TCO, the first step is to build a reliability block diagram (RBD). Various parameters can be used as inputs to the RBD: current age, duty cycle, failure distribution, fixed costs, probabilistic costs (failed parts, logistics, labor, etc.), tasks, spare part pools, replacement strategy, state change conditions throughput allocation, backlog, and so on. The next step is to optimize the RBD model's inputs and assumptions. This approach allows users to track reliability/availability growth over time, which in turn allows users to develop more accurate benchmarks.

The TCO, as well as the COO and LCC, can be used in a variety of ways, including benchmarking suppliers, helping procurement organizations secure the most cost-effective inverters, and providing solar manufacturers with feedback on what is actually performing.

Solutions for Servicing an Aging Inverter Fleet (George Kemper, DEPCOM Power)

In this presentation, George Kemper of DEPCOM Power discussed several potential solutions for servicing an aging inverter fleet.

In DEPCOM's portfolio, inverters are the leading cause of loss of energy events. Today, there are approximately 12,000 out-of-warranty utility-scale inverters—and that number is likely to increase. Most cost models estimate that the end of life for an inverter is around 10 or 15 years, but in hot climates, this can happen a lot sooner. The cost to replace a single out-of-stock utility-scale inverter is around $300K–$500K.

One of the key challenges for asset owners is that traditional O&M service providers need expert technicians to identify and rectify complex central inverter issues. At DEPCOM, 82% of the inverter-related loss of energy events require a level 3 technician, i.e., someone who is trained on the specific platform in which the failure occurred.

A proactive post-warranty plan, including servicing and repowering, can help extend the life and mitigate the financial burden of the aging fleet. Key elements of a robust, proactive post-warranty plan include evaluating the spare part use rate, investing in the workforce, examining trend failures and applying analytics, and looking for new market incentives that favor reliability and easier repowering. Repowering can be an important strategy, particularly in cases where there is limited to no OEM support, access to spare parts, and/or access to trained technicians.

Kemper discussed two case studies, which illustrated the importance of proactive planning for new sites. In particular, for new sites, owners should consider installing vaults under the inverter pad to service cables and their conduits, which drastically reduces the cost of repowering and the associated labor; having service loops on all cables; considering string inverters (which are easier to replace and have a lower O&M cost), and buying lots of spare parts. That is because it is much cheaper to plan for replacements instead of reacting after a critical failure. If refurbishing an inverter is possible, a case study showed the return on investment to be 0.9 years, compared to 2.7–3.3 years for solutions involving new inverters.

Looking ahead, continuously increasing the DC voltage and deploying larger inverters will perpetually orphan our older systems. Standardization on AC output voltage would make future equipment replacement much easier.

Discussion

The Session 3 discussion was centered on the following question: "What are the biggest expenses and highest priorities?" The group discussed the relative merits and pitfalls of central inverters and string inverters at length and also touched on the Inflation Reduction Act, NREL's cost benchmarks, inverter payback periods, and the value of PV inverter service.

The group briefly discussed the impact of the Inflation Reduction Act (IRA), but one participant noted that it is too early to determine whether IRA has been effective in bringing inverter manufacturers to the United States.

The next topic of discussion was the place of central inverters versus string inverters in the market. The group agreed that central inverters do have a place in the market. Some owners are installing central inverters because they have a close relationship with a manufacturer who provides spare parts. In addition, central inverters are less expensive upfront and can result in lower LCOE. String inverters come with a higher capital expenditure cost to integrate, and more work needs to be done to bring the capital expenditure cost down. However, owners who are more sensitive to O&M costs are moving toward string inverters, and their European counterparts are also primarily installing string inverters. George Kemper's (DEPCOM) presentation cited a nearly 50% reduction in O&M costs with a string inverter. This was driven by higher availability and elimination of troubleshooting by technicians. (When something fails in a string inverter, a team of two technicians can swap that part out within a matter of hours. By comparison, central inverters require more personnel and more time and are more expensive to repair.) Replacement of a single central inverter can cost up to half a million dollars (including logistics, labor, etc.). Another benefit of string inverters is the standardization of the AC output.

Next, the group discussed the fact that NREL's cost benchmark does not currently factor in warranties and lead times. However, suppliers typically are not chosen based on their lead time, particularly for spares; instead, these decisions are driven by a performance or cost characteristics. Sandia may have looked more in depth at warranties and lead times.

The group also discussed inverter payback periods, which are very project-dependent. Better payback periods can be achieved by conducting a partial repower and salvaging some of the inverters that are on site. Selling existing equipment for spare parts can also help. However, each site has its own logistical issues, and it ultimately comes down to the cost of labor. There are not many options for older inverters, although there are a couple of manufacturers who still provide spare parts.

The group also discussed how to incorporate the value of providing high-quality service, as in a long-term service contract, into PV inverter cost analysis. Cash inflow is one important metric that is simple to capture, assuming that the service is monetized. To measure the cash outflow, it would be necessary to capture the impact of the service on the reliability.

2.4 Testing, Standards, Performance, and Reliability Metrics

In this session, presenters discussed testing, standards, performance, and reliability metrics.

Ensuring Safety and Security: Implications for Reliability and Availability (Ken Boyce, UL Solutions)

In this presentation, Ken Boyce of UL Solutions discussed the implications of safety and security measures for inverter reliability and availability.

As large-scale PV plants provide an increasing percentage of the renewable energy portfolio, the reliability, safety, and security of inverters will be key. In particular, inverter power control systems will play an increasingly important role in practically accomplishing the energy transition by maximizing the safe and extended use of existing infrastructure.

There are several key considerations when thinking about inverter safety and reliability. The first is data collection. Better collection of data within the inverter can help identify the sources of inverter issues, and better fault tolerance and recovery can help mitigate them. Another key consideration is optimal inverter strategies and how to future-proof sites. Historically, there has been more emphasis on lower installation costs, but this might be evolving. Another key consideration is cybersecurity. Continued increases in software updates and connectivity are expected—but this also provides new avenues for cyberattacks. Thus, robust cybersecurity measures are needed. Finally, the continued expansion of inverter applications (e.g., vehicle power export) is another important consideration.

Standards development will continue to play a critical role in achieving this safety and reliability. Importantly, standards codify our approach to risks—those we will accept, and those we agree to mitigate. Modeling and simulation approaches are also promising for optimizing performance, safety, and reliability. In particular, work on power conversion equipment modeling and simulation has been very positive.

Laboratory Testing To Assess Durability of Inverters and Field Experiences (Cherif Kedir, Saeed Arash Far, and Hung Pham, RETC)

In this presentation, Saeed Arash Far and Hung Pham from Renewable Energy Test Center (RETC), an independent testing lab, discussed RETC's testing cycle and the top reasons they have found for PV inverter failures.

RETC was established in 2009 to help companies navigate the certification process for renewable energy products. In 2019, RETC extended its capabilities to validate the solutions provided to consumers. Now, RETC provides a comprehensive accelerated test protocol that helps demonstrate bankability for energy storage system (ESS) components. The testing cycle includes a variety of standards that are bundled together to check safety, compliance, reliability, performance and efficiency, and compatibility.

Based on this testing, the RETC representatives provided a list of top reasons PV inverters fail. These include overheating (over time, the stress will cause sensitive components such as MOSFETs, capacitors, and IGBTs to fail), improper inverter installation (which can lead to premature failures), software issues (loss of communication can render the inverters inoperable, and troubleshooting can sometimes take a while), NEC code requirements, grid faults, and maximum power point tracking.

Inverter Production Quality Assurance and Testing (Ignacio Carellan, Kiwa PI Berlin)

In this presentation, Ignacio Carellan of Kiwa PI Berlin—a technical advisor and risk manager focused on quality assessment of PV and battery storage equipment—discussed Kiwa PI's approach to quality assurance testing, including the company's new IGBT testing procedure.

Most inverter manufacturers do not have a reliability testing program. This poses challenges for owners, as inverter reliability testing is very expensive, and which standards should be used for reliability inverter testing remains an open question.

In addition, when inverters fail, many manufacturers claim problems like dirt, poor maintenance, improperly tightened bolts, and so on. Kiwa PI Berlin offers clients a root cause analysis to determine the true cause of the inverter failure. Kiwa's root cause analysis starts with remote data analysis, including a PV plant design review, previous root cause analysis, O&M analysis, and a supervisory control and data acquisition (SCADA) data breakdown. Then, Kiwa goes into the field to conduct a forensic fire analysis. This involves analyzing the surrounding area for debris and signs of smoke, evaluating the inverter interior and exterior, and conducting witness interviews to determine the fire appearance, timing, colors, odors, and sounds.

Kiwa has also proposed new tests for IGBT reliability based on commutation analysis. They determined that is important not to affect electronics, as the spike in current can damage the inverter. In addition, unwanted intervals between the gate-emitter and collector-emitter voltages can result in the simultaneous opening of two IGBTs.

Based on the IGBT testing, Kiwa identified that one potential reason for failure could be the inverter's loss of control over IGBT commutations, resulting in incorrect commutation during cloudy days. To mitigate this issue, Kiwa recommends integrating measurements of IGBT switching behavior under simulated cloudy conditions and accounting for irradiance fluctuations at various operating temperatures.

In addition, quality assurance should begin at the production stage, as production oversight increases the reliability of inverters; verifying reliability only at the design stage can miss defective components.

Discussion

This discussion focused on the following question: "What testing or prequalification would you like to see to ensure reliability? Where are the gaps?" The participants first identified several key gaps, then discussed how extrinsic versus intrinsic factors contribute to reliability. The group also discussed safety, standards enforcement, the impact of cold weather on inverters, and software issues.

The group began by discussing the gaps. These include lifetime, warranties (inverter manufacturers typically provide 5-year warranties, compared to 25+ years for modules), solar plant field failure consequences, and lack of enforcement of certifications and standards like International Electrotechnical Commission (IEC) 62093, "Photovoltaic system power conversion equipment - Design qualification and type approval." Another key gap to be filled is learning from other industries that have successfully gone from a reactive to a proactive approach.

Next, the group discussed the extent to which reliability issues are driven by intrinsic factors versus extrinsic factors. On the one hand, intrinsic quality-related issues are responsible for inverter failures, and SETO is more focused on intrinsic reliability. However, one participant expressed concern that pouring resources exclusively into improving design and enforcing standards may not be substantially addressing the problem, given the impact of extrinsic factors like poor maintenance, supplier quality, and so on. Another participant contended that making standards mandatory (as well as clearer and more widespread) would be more effective, although standards typically address design, not manufacturing quality. For example, there are not many products that comply with IEC 62093, but there is a lot of interest in it, which is promising. Another participant agreed that while products should be installed directly and maintained the right way, there is real opportunity for benefits from those intrinsic properties.

The group also discussed the need to comprehensively address safety concerns. Inverters' unique functionality can lead to many safety consequences. For example, checking the equipment while it is installed on site introduces significant safety issues (e.g., exploding inverters). Fire hazards are also an issue. Rapid shutdown systems (RSDs) were introduced as safety mechanisms, but instead, they appear to be causing fires. The industry has adopted a tiered approach to mitigating fire hazards and minimizing the risk of exploding inverters, but if those problems persist, the industry will likely need to up the challenge conditions on that particular safety qualification. Cybersecurity will be another increasingly important safety consideration going forward.

The safety discussion resulted in a potential area for future study. One participant noted that the industry needs to develop a simple means of proving zero energy present, which is lacking on most inverters, because pulling the cover off puts people at risk. The industry also needs engineered solutions to achieve better compartmentalization between AC and DC components so there is no potential for any kind of contact.

The group then discussed inverter performance—in particular, the importance of designing tests to better understand inverter performance (and not just reliability). One participant discussed their organization's performance approach, which included using temperature cycling.

The next topic of discussion was the need for enforcement of standards to ensure reliability, as relying on the goodwill of manufacturers may not be sufficient in all cases. Similar to the existing standard for the interface between the inverter and the grid, perhaps the inverter community should develop standards for the interface between the inverter and the environment, as well as other factors, to help ensure reliability. For example, when an inverter is connected to the grid, that inverter is not the only thing being connected to the grid; how the inverter will behave in a multi-node system is a key consideration. IEC 62093 includes environmental conditions such as high humidity and elevated temperature; further customizing the standard for inverter reliability would take some thought, but 62093 would be the place to do it. There would also be an incentive to do the testing upfront, as following the standard could prolong the life of the inverter and circumvent a potentially expensive replacement. One participant recommended that every manufacturer should heavily instrument the first 5–10 units of every new component; this will cost more, but provides key insights.

The group also discussed the impact of cold weather on inverters. In general, inverters function well in the cold. Cold conditions are generally only an issue when combined with humidity, as condensation can cause failures and short-circuiting. Capacitors and fuses will drift during cold weather, and fans can fail in the cold, as the fan bearings tend to lose lubrication and seize. In addition, continuous temperature cycles can affect almost any component. Something to consider is that the North American Electric Reliability Corporation (NERC) requirement is to identify a single component for this potential failure. Cold-weather inverter testing can involve both active and passive testing. In addition, it is important to consider whether an inverter sees particular conditions, such as being in a cold climate overnight and shutting off when the sun comes up.

Next, the group discussed software issues (communications, etc.) Standard UL 5500 addresses software updates with safety implications; it is intended to be a horizontal standard that can be ingested and referenced in a particular product standard. In the next 9 months, UL will likely incorporate software updates for safety.

Finally, the group briefly discussed the fact that manufacturer specifications on performance cannot always be relied upon, such as derating curves.

2.5 Lifetime of Active and Passive Components

In Session 5, speakers discussed the lifetimes of active and passive components.

Enabling Proactive Ownership: Leveraging Temperature Data To Maximize Inverter Performance and Reliability (Dylan Sontag, Silicon Ranch)

In this presentation, Dylan Sontag from Silicon Ranch discussed moving from reactive to proactive maintenance of inverters through the use of predictive analytics.

Sontag's team at Silicon Ranch focuses on proactive maintenance of inverters to optimize performance, using anomaly detection to drive the best possible operations in the field. In addition to analyzing existing losses and tying them to specific components in the inverter, the team also uses predictive analytics to prevent losses from occurring in the first place (ideally, nighttime work can be scheduled to correct any issues that the predictive analytics identifies).

Data is a crucial piece of remote inverter management. Some inverters only generate a limited amount of data, but high-data inverters include individual temperatures from every IGBT junction within the inverter. This high level of data allows the Silicon Ranch team to be much more predictive and to partner with manufacturers early to proactively find solutions. However, even a simple cabinet temperature alone allows the team to spot outliers. The team was able to predict and proactively identify hundreds of failure points in a liquid-cooled inverter through trends in the water pressure, which led to the manufacturer doing a full inspection of the inverter *before* a trip event occurred. In another case, through proactive monitoring of IGBT health trends across a wide range of ambient conditions and inverter output, the team was able to detect and minimize a developing IGBT failure—a failure that otherwise would have likely resulted in >2 weeks of downtime. Despite these successes, data from the inverters, no matter how robust, will not capture all the possible temperature concerns on units, so thermal imaging of all connection points is also critical (at least annually).

In the future, the team will continue to work with partners to identify which sensors can be added to assess temperatures in different compartments or identify fan health remotely, as well as looking at the cost-effectiveness of those sensors.

Lifetime Testing and Modeling of Cooling Fans in PV Inverters (Zheyu Zhang, Rensselaer Polytechnic Institute)

In this presentation, Zheyu Zhang of Rensselaer Polytechnic Institute discussed his team's approach to cooling fan reliability testing and lifetime modeling.

To better understand the reliability of cooling fans in PV inverters, the team started with failure mode and effects analysis (FMEA) to identify the most critical failure modes, mechanisms, and stressors. By putting together the chance of occurrence, severity of occurrence, and chance of detection, the team developed a risk priority number. This helped the team establish a reliability testing platform with application-oriented design considerations and scalable sample sizes. The team then introduced a power supply to power multiple fan samples, with a current sensor to measure fan current, and then fed this data back to the computer. From there, the team derived a reliability model based on failure analysis, considering statistical variation.

Next, the team conducted cooling fan lifetime modeling, estimating the lifetime under a given mission profile through the conversion of dynamical stresses into effective static values. The team ran the tests for about 8 months, and the tests yielded adequate failures within this time frame. To verify the data, they sent the fans back to the vendor. Failure analysis indicated that the transistors in the fan printed circuit board (PCB) controller were consistently the failed part, which agreed with the team's assumption that temperature and relative humidity led to electrical failure of the fan. Because the operating conditions are far from the stress levels used in testing, the team calculated the acceleration factor. As a final step, because real-world stress levels are dynamic, rather than fixed, the team looked at a yearlong dynamic temperature profile and converted the dynamical stress to static stress. A similar process was applied to the relative humidity.

The team concluded that sample sizes and the number of stressors play a significant role in the lifetime model accuracy, resulting in a time-consuming and pricey testing process. In addition, coupling among stressors (electrical and mechanical) could worsen the lifetime, and a method to quantify the impact of coupling is needed, such as with combined-accelerated stress testing.

Screening Methodology for SiC MOSFETs (Anant Agarwal, The Ohio State University)

In this presentation, Anant Agarwal of The Ohio State University discussed the importance of screening silicon carbide (SiC) MOSFETs to reduce failure rates.

Although SiC has been around for over 40 years, its use in inverters suffers from reliability challenges. In particular, undetected extrinsic defects are causing early failure in the field. In this talk, Agarwal proposed aggressively screening incoming SiC power modules to make them more reliable, with the goal of reducing failure rates from 2%–3% to 2–3 ppm.

However, developing an adequate screening method is challenging. Screening by applying high gate voltage, increasing temperature, or increasing time (or all three) will reduce the lifetime of good devices. In addition, interface defects are very high and tend to increase near the conduction band edge as a result of screening which increases the on-resistance of the device.

Agarwal and his team have developed several innovative techniques to improve screening efficiency without reducing performance. The first technique relies on the fact that trench devices are less susceptible to surface defects and have a much higher intrinsic lifetime than planar MOSFETs. This makes it possible to apply much higher gate voltage to screen extrinsic defects. In the high gate voltage pulse screening method, the team measures the initial threshold voltage, heats up the device, applies a screening pulse, and then cools down the device and lets it recover over 48 hours. The team also developed a pulse burn-in method that is done for 10 hours. Every positive pulse, they shift the threshold, and every negative pulse, they bring it back. By applying a negative voltage, some of the threshold voltage shift can be recovered.

Developing specific screening methods for each vendor can help reduce the failure rates from 2%–3% toward the goal of 2–3 ppm.

Live State of Health Monitoring of Inverter Subsystems (Faisal Kahn, NREL)

In this talk, Faisal Kahn of NREL discussed state-of-health monitoring of inverter subsystems.

Monitoring the state of health of PV systems is essential. Many failures and power outages could be prevented with a workable technique to continuously monitor the state of health of PV systems, including PV panels and inverters. In other words, live state of health estimation can predict faults before they happen. NREL is currently conducting research on a state-of-health monitoring approach that could be integrated into the gate driver to get the information directly from the switching device.

As part of this work, the NREL team is looking at PV ground fault detection. PV fault ground detection using reflectometry is challenging because hundreds of interconnections and impedance mismatches exist inside a single PV string. In addition, the ground-fault protection and interruption (GFPI) may suffer from noise and provide a misleading fault indication.

The team came up with the idea to inject a high-frequency component across the terminals, which allowed them to identify the location and nature of the PV fault. They demonstrated the feasibility of using the spread-spectrum time-domain reflectometry (SSTDR) method with any variation in the number of strings, fault resistances, and number of faults, and showed that it was successful for detecting ground faults in PV arrays. This technique can test ground faults at night or in low illumination conditions—faults that may otherwise remain undetected by standard protection devices. The team also demonstrated that knowing the dynamic safe operating area (SOA) of a device or module is essential. Mean time to failure, which represents the expected life span of the device, cannot predict unusual circumstances and premature degradation, and it cannot answer why reliability of a power switching device drops abruptly beyond a certain time of aging—but the SOA can shed light on those issues.

Discussion

The questions guiding this discussion were "What failure mechanisms are we not properly accounting for?" and "How do we better accelerate the working environment of PV inverters to qualify components?" Participants discussed the price of wide bandgap devices, methods for tracing reliability issues back to inverters, early detection schemes and challenges related to SiC devices, the impact of cold temperatures on inverters, and new approaches to reliability.

The group began by discussing the price of wide bandgap devices. Electric vehicle (EV) adoption is bringing down wide bandgap devices' price, which is likely to benefit the solar industry. However, screening is critical to avoid failures, and that will increase the cost. This means that instead of 5 years, it may take 10 years to bring the cost of wide bandgap devices down to a sufficient level. Today, silicon IGBTs sell at 2 cents an amp in volume. Getting to 3 cents an amp in 5–10 years, including screening costs, would be a good outcome.

Next, the group discussed methods for tracing reliability problems back to inverters. Silicon Ranch has found that staying with the same site design has been helpful for understanding these issues, and having a standardized library of descriptors for labeling faults is also key. The industry as a whole would benefit from standardizing the way failures are described. Homogenizing data across different manufacturers has had a huge benefit, and it will be critical for industry as a whole to have conversations about how to improve on that front. Silicon Ranch is willing to share their data to move the industry forward, and SETO can be used as a pipeline for some of this information.

The group also touched on early detection schemes for SiC devices, discussing the underlying physics in the change in threshold voltage after an applied field as well as the excessive leakage current from the gate. Ideally, the vendors who are selling the SiC devices should do this testing, but they are not incentivized to do so, so the onus is on the user. The group also discussed the broader challenges related to SiC. SiC provides several advantages, including beneficial heat properties. However, embracing SiC may require updating design qualifications and looking at new tests.

The group then continued the discussion from Day One about how cold temperatures affect inverters, focusing on premature aging. Plastics tend to get more brittle in cold temperatures, and the moisture that plastics allow in will freeze at cold temperatures, which could crack the plastics. Moisture can also result in ice chunks inside the inverter at low temperatures. At cryogenic temperatures, serious solder problems may begin to appear. However, the biggest issues are the stresses caused by temperature cycling, as thermo-mechanical degradation depends on the temperature swing.

One participant suggested adopting a different approach to reliability, focusing on identifying solutions rather than uncovering the complexities of the problem (perhaps as the focus of another workshop). Several other participants chimed in with ideas. First, predictive analytics and reliability are both key. The community should also decide, however, how to balance the priorities of making inverters as reliable as possible and being able to respond to failures as quickly as possible. Exploring the fundamental design is another potential avenue. Adding more redundancy, resiliency, and/or self-healing properties could be worth the extra cost if it avoids expensive failures. However, self-healing components for power converters currently still have pronounced reliability issues. Another potential avenue is focusing more on engineering, as both engineering and design are critical for reliability.

Finally, one participant raised the question of what subsystem level (e.g., inverter, component, or subassemblies) should be the focus for monitoring and testing, given that it is impractical to monitor every single capacitor.

2.6 Data Reporting, Analytics, and Data Sharing

In this session, speakers discussed inverter-related data, including reporting, analytics, and sharing.

Characterization and Survivability Analysis of Inverter Faults Through an Analysis of O&M Records (Thushara Gunda, Sandia)

In this presentation, Thushara Gunda of Sandia National Laboratories discussed using O&M records to conduct a characterization and survivability analysis of inverter faults.

Inverter failures are responsible for a significant portion of overall failures, and the cost of repairs and replacement dominate O&M budgets; thus, understanding inverter failures is critical. To identify the most common failure modes within inverters as well as any patterns, Gunda's team analyzed text-based records, including maintenance logs, using a combination of machine learning and natural language processing techniques. They combined Sandia's PV Reliability, Operations & Management (PVROM) and EPRI's partner databases to obtain a total of 55,000 records covering 880 sites, 26 U.S. states, 13 climate zones, and 5.2 GW in DC capacity. The data set was dominated by utility-scale sites (80%) and central inverters. The team focused on inverter-specific corrective maintenance records (about a third of the total data set) and used natural language processing (latent Dirichlet allocation) to identify common failure modes. Supervised machine learning was used to fill in gaps in entries that did not have an asset label.

Upon analysis, the records showed several patterns. For example, temperate non-dry climates experienced a significant spike in tickets/records in the month of May. Communications tickets tended to peak in May, whereas heat management tickets peaked in November. Communication issues were dominant at the start, but as the sites aged, the heat management system became much more prominent. IGBT-related tickets spiked in February and November. There were many more tickets/records in the first year after installation, and they gradually decreased over time. While communication and IGBT tickets have held steady over time, ground fault-related tickets have greatly increased, though it is unclear whether they were actually more frequent, or whether the recording changed. For sites with mixed inverters (a mixture of central and string), the team saw a much higher prevalence of ground faults.

Future work will include updating datasets to consider more sites and technologies; implementing additional algorithms to extract more insights; and combining text-based insights with production and financial information.

PV Inverter Availability From the U.S. PV Fleet (Chris Deline, NREL)

In this talk, Chris Deline from NREL discussed quantifying PV inverter availability within the U.S. PV fleet.

Deline's team analyzed data collected as part of the PV Fleet Data Initiative with the goal of quantifying lost energy from inverter downtime. The PV Fleet Data Initiative, which is supported by SETO, provides free PV performance analysis in exchange for NDA-protected PV data. This data encompasses over 2,200 systems, 24,000 inverters, >8.5 GW capacity, and a range of climate locations.

Deline's team began by cleaning up the time series PV data using two separate open-source repositories: PVAnalytics (https://github.com/pvlib/pvanalytics) and rdtools (https://www.nrel.gov/pv/rdtools.html). The team then examined nearest-neighbor performance and looked at the times that inverters were offline and not recording production.

The start-up phase (the first 6 months after installation) showed lower availability (80%–90%), but after that, it is fairly steady (98% on average). The team also discovered two counterintuitive findings. First, system availability appeared to have a negative trend versus system size; the reason for this is unclear, but it could be explained by a lack of components or other issues related to larger inverters. Second, hotter climate zones exhibited better system availability.

The team also analyzed the Treasury 1603 dataset, which mostly consists of O&M records (for 100,000 systems) and annual observations, rather than the high-frequency time series data collected by the PV Fleet Data Initiative. The team computed the number of failure events and the lost production for each failure event.

They found that inverters had the highest failure rate occurrence, but meters were an issue as well; energy meters led to more loss production compared to any single event on the inverter side. Residential data had a much lower reported percentage of issues (in terms of number of events) for inverters. One key takeaway from this analysis is that shading inverters is key; in many cases, identical systems had different failure statistics due to the positioning of the inverters.

Open-Access Datasets From the Solar Data Bounty Prize and Their Potential in Reliability Analysis (Tassos Golnas, SETO)

In this presentation, Tassos Golnas from SETO discussed the availability of datasets from the Solar Data Bounty Prize and their potential to facilitate inverter availability analysis and reliability analysis.

The Solar Data Bounty Prize is a SETO-funded prize program designed to gather high-quality data that supports industry and academic research to develop, improve, evaluate, and validate models of real-world PV system performance. The idea behind the prize is that better PV models and system performance can be achieved through high-quality data.

All of the data gathered as part of the Solar Data Bounty Prize is available on the PVDAQ/PV Data Map (available on OpenEI.org). The data, which have 10-second to 15-minute time resolution, encompass five different systems across four U.S. states and more than 4 billion data points. System sizes range from 100 kWdc to 257,600 kWdc. Datasets contain the number of inverters and inverter channels as well.

This time series data lends itself well to inverter availability analysis (although communication outage effects may be a challenge to capture). The data can be used to examine the impact of temperature on availability; in many systems, temperature inside the inverter is provided. One challenge with this is that there is no verification of the failed component contained in the time series data. Another potential avenue for analysis is prognostics of failure, which can be achieved by finding signatures in the historical data. Again, the lack of verification of the failed component may be a challenge here. Reliability analysis, on the other hand, may be more difficult with only time series data, as O&M and fault logs are important for this type of analysis.

Discussion

The Session 6 discussion focused on the following question: “How can we use data analytics to predict availability, reliability, and performance?” The participants discussed collecting data on LCOE, improving the quality of data logs, considering the technician perspective, considering extreme weather data, and developing best practices for asset operators, among other topics.

The group began by discussing how to gather cost information that will shed light on whether inverter LCOE is improving. Understanding costs is tricky, as labor, spare parts, diagnostics, and lost production must all be factored in. Thus, there is no single metric that can communicate the observed cost versus the avoided cost. However, reasonable assumptions can be made about the cost of each of these components, and creating an epistemically accurate model seems feasible. A benchmark that depends on location and plant type could also be useful. One participant suggested plotting the availability as a function of O&M expenditure, and potentially relating that to the experience and quality of the team as well. Another good approach is to identify best practices, getting teams together to discuss common approaches. Warranty response time is another important factor to consider for availability, and would help the industry as a whole to have.

The group also discussed how to improve the quality of the data logs that are critical for data analysis. One idea, which the group agreed would be a significant value-add, was to implement a form with spell check, drop-down menus, etc. However, in the absence of regulatory requirements, this type of standardization is unlikely to happen. Grassroots support could move this effort forward, but would require getting and keeping people involved and convincing colleagues that the cost is worthwhile. NERC’s Generating Availability Data System (GADS) data, which is coming out this year, will create more requirements for owners, which could force reporting templates around the faults. To further this effort, the community should come up with common names. Silicon Ranch plans to provide data to Chris Deline at NREL to begin discussing how best to log things.

Next, the group discussed how the Sandia team processed O&M logs—in particular, how the team connected arc faults to wildfires based on the O&M logs. The team tried a few different approaches, the first of which was key term identification (done in the context of extreme weather analysis). However, there were several sites called things like “Solar Wind” or “Ridge Fire,” so that was a nonstarter. The team then narrowed their focus to inverters, and began to see a lot more coherence in the data. They also carefully considered the culture or environment under which the O&M logs were collected. For example, the team had no tickets related to wildfires, because people generally do not log O&M tickets while a wildfire is occurring.

The group also discussed the importance of considering the technician perspective when looking at data quality. Technicians are expected to work long days and then produce careful documentation, which can be challenging. Adopting standardized forms and putting as many items in a dropdown menu as possible could help produce better data without overburdening technicians. It is also important to take into account other factors that may impact technicians, such as making sure any apps they are using work offline. Data can also flow through different channels; for example, some technicians may use texts and emails instead of O&M logs. Using keyword libraries can also be helpful. One participant noted that in-house O&M activities tend to be a lot better structured than third-party O&M activities.

Next, the group discussed extreme weather data. Most extreme weather analysis has been done at the site level, but there is also data that looks at specific assets. The next step is to bring that data together. Although it is often a singular extreme weather event that greatly shortens the lifetime of an inverter (and extreme weather can cause ground faults), in many cases, the stressors are more routine. Another consideration is that some asset owners may preventatively take the system down if they anticipate that their site will be impacted by extreme weather.

The group briefly discussed the cause of the observed spike in ground fault events in the Month of May. Moisture ingress and storms played key roles, though many of the ground faults were nuisance triggers (i.e., there was no lightning at the site).

The group also emphasized the opportunity for collaboration in parsing O&M data and the importance of providing a standard or guidance. Most asset managers and O&M providers use some type of computerized maintenance management system (CMMS), and there is an opportunity for the inverter community to work with those vendors directly to build a library for solar for all CMMS systems (for example). Many CMMS systems come with the relevant options built in, but it is key to build awareness and develop best-practice guidance to incorporate the relevant information.

Finally, the group discussed best practices for asset operators when it comes to data collection. One participant noted the importance of collecting time-related data. Some records only include the date, but others include the hour and the minute, and that finer level of resolution is key. In addition, because the analytics available can work with diverse data, completion is much more important than consistency. Similarly, while spelling errors are not a major issue, behavioral notes are very important. There is a lot that likely does not make it into O&M logs because it seems obvious to the technician, but having that data would be helpful. Some records say things like, “the inverter was fixed,” and having more detail, like the downtime, how long the fix took, etc., would also be helpful. NREL, Sandia, and other labs have collaborated on putting together a best practices document for O&Ms and have helped develop standards.

2.7 The Future of PV Inverter Reliability Research, Metrics for Success, and the State of the Industry 5 Years From Now

The final session of the workshop had participants split into three breakout groups to discuss the following questions:

- How will the inverter industry look different in five years?
- What external factors must we prepare for?
- How will this industry change?
- What will we do to change the industry?

Breakout Group 1

The first breakout group agreed that one of the top priorities for inverter reliability is addressing the reliability of certain inverter components: IGBTs (and their eventual replacement with SiC MOSFETs), capacitors, fans, and fuses. In terms of the move from IGBTs to SiC devices specifically, the industry should build on what has been done in the EV industry to understand those devices' reliability. Manufacturing quality is another key priority. Implementing more fault-tolerant manufacturing processes—as well as potentially incorporating automative-grade components into inverters—may help provide the robustness that will be critical for the inverter industry going forward. Developing a manufacturing "round robin" to test different components and see how they behave and fail may also help.

The group agreed that in the next 5 years, there will be much more data available, in part from more artificial intelligence (AI) and intelligent controls inside the inverters—and accordingly, there will be a need for good data analytics. Using this data to understand inverters on multiple levels—from the reliability of components to the reliability of subsystems and the system as a whole—will be key. Growth will be another key feature of the next 5 years. The continued rapid growth of PV installations into the multi-TW scale will require the inverter industry to keep up with a growing level of demand. Inverter load is another key consideration. More storage will come online in the next 5 years, which will increase the number of hours per day that a given inverter is working, and the transition from 1500V to 2000V will mean that inverters are working at higher voltages as well. Inverters will need to be able to accommodate the greater load. Obsolescence will be another key consideration in the coming years. The aerospace industry may provide a good example for how to plan for obsolescence. Modularity to facilitate easy repair and replacement will also be important. Having two parallel paths for reliability testing, one for short-term feedback, and one for long-term feedback, could also prove useful.

Breakout Group 2

The second group discussed several key takeaways. The first is that, although inverters have been getting larger and operating at higher voltages for efficiency reasons, there has been a concurrent shift from monolithic to modular inverters. This shift is a positive development, and the industry should keep moving in that direction. The second takeaway is that the inverter business model poses barriers to repair and maintenance. To combat this issue, the inverter community could pursue “right to repair” regulations, open-source architecture, and more available documentation/training.

The group’s third takeaway is that the industry should continue trying to build toward a more collective forum of knowledge, perhaps seated at the national labs. It would be beneficial to have the national labs intercept failed components and study them, develop scorecards, and so on. On the subject of components, the group also discussed the possibility of developing some sort of centralized solar junkyard. Another takeaway was related to safety; the group discussed a 0V energy check as a best practice for safety purposes. Finally, the group recommended continuing to invest in workforce development. There are some sporadic training programs for technicians, but retention and expertise continue to be an issue. It would also be desirable to develop a common language within the PV inverter workforce.

Breakout Group 3

The third breakout group agreed that a top priority for the inverter industry is transformers. Transformers are a long-lead item, and new products and makers may be less reliable. Thus, understanding failure modes and mechanisms is key. To give appropriate guidance to the inverter industry, researchers can work to understand the interaction of these transformers with renewable energy sources versus legacy energy sources; this includes dealing with harmonics, high-frequency and other noise, and power cycles. Owners may also need to become more aware of failure modes, which may involve researchers publishing and raising awareness about these failure modes.

Other top priorities include supporting technicians and spare parts (the inverter community needs new recommendations on how to address these priorities), collecting the top inverter components that need attention/are failing and cataloging them, and focusing on inverter safety. Fires are a key issue when it comes to inverter safety; the number of fires is rising, and the industry needs a better mechanism to collect and gather information about fires. When one system has a fire, the responsible thing to do is to shut down all similar systems of that design and inspect them carefully with independent engineers (including visual inspection, insulation resistance, and thermography). It is still unclear why fires are more of a concern in the United States than in Europe, and the research community should follow up on this question.

Additional priorities include ensuring that people are following the commissioning protocols contained within standards; distinguishing between workmanship and equipment (a time-based approach is needed for this, as many equipment issues cannot be seen at time zero); and developing a root cause analysis reporting process. For the root cause analysis reporting, inverters need to self-report if there is an arc flash. Although fire marshals and UL will not disclose an issue, asset owners may, and when that happens, the focus should be on experience, not finger-pointing. A consumer protection agency is needed; like with cars and airplanes, safety should take precedence.

Other key priorities include predicting things before they trip (versus ensuring reliability); providing support for discontinued inverter models via “right to repair” laws or policy; considering providing support contracts for PV, similar to what is offered in the wind industry; and popularizing standards such as IEEE 2800, “IEEE Standard for Interconnection and

Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems," and IEC 62093, "Photovoltaic system power conversion equipment - Design qualification and type approval." Advertising successful applications of these standards was suggested. The group also recommended codifying where things are failing with data and developing a more standardized way of reporting (this may be an area where assets and OEM can self-organize to provide more standardization across the industry). To motivate standard reporting of O&M issues, NREL may be able to incentivize owners, similar to how the PV Fleet Data Initiative works. Another key priority is developing a national database of inverter failures that quantifies the actions taken and the time they were taken. Figuring out what causes the lower train current versus the drain source voltage over time and temperature will also be key.

The group predicted that in 5 years, grid-forming inverters will be more critical, leading some to wonder if we might expect new failure modes associated with them, and there will be more repowering as time goes on. In addition, more systems will be combined with storage and thus more stressed.

Final Thoughts

At the end of the workshop, participants noted that it would be helpful to include more asset managers and O&M vendors in the next workshop to hear their feedback, understand their needs, and analyze some of their data. It may also be worth considering including battery park installations in the workshop discussions in the coming years. Finally, taking a closer look at the statistics of safety would be helpful.

3 Summary and Topics for Future Workshops

The 2024 Photovoltaic Inverter Reliability Workshop brought together participants from across the PV inverter ecosystem—including inverter manufacturers, national laboratory researchers, academics, independent testing laboratories, and more—to form working partnerships and develop priorities to address key PV inverter reliability challenges. Presentations and discussions spanned a range of topics, including data reporting and analytics, testing and standards, and life cycle cost and ownership issues, and a variety of takeaways were discussed. However, at the end of the workshop, participants concluded that the top priorities for addressing inverter reliability challenges include prioritizing inverter repair and maintenance, developing a collective forum of knowledge, leveraging data to understand inverters on multiple levels, and focusing on safety and standards.

In the coming years, inverters will face new pressures: accommodating increasing demand, coping with higher loads, and making use of the abundance of data that is likely to arise from AI and intelligent controls. Accordingly, the majority of participants voted in a follow-up survey to hold the PV Inverter Reliability Workshop yearly, to keep abreast of these challenges.

In future iterations of the PV Inverter Reliability Workshop, participants requested that more O&M companies, inverter vendors/OEMs, field technicians, developers/EPCs, and asset owners be included to provide a broader range of data and insights. There was also a suggestion to invite attendees from other industries (e.g., aviation) that work in inverters.

In the follow-up survey, participants also provided several suggestions for topics to be discussed at future workshops. These included several **topics under the O&M umbrella**: health monitoring and proactive O&M, mean time to repair optimization strategies, and more on O&M best practices and how to collaborate. Participants also suggested several **topics related to standards and information sharing**: standards development (including communication standards), requirements for inverter manufacturers to perform reliability testing and comply with regulations/standards, market/owner standardization, common naming conventions for issues, a potential data sharing program from asset owners to support U.S. solar fleetwide insights, insights from field technicians, and more actionable information for asset owners and inverter manufacturers.

Participants also suggested a handful of **topics related to inverter technology**: intrinsic technology development; the impact of new inverter operational modes, including hybrid inverters with energy storage and grid-forming operation; electromagnetic interference and compatibility (EMI/EMC); perovskites; BOS research topics; and component reliability. A couple of **manufacturing topics** were also suggested: how to improve PV inverter manufacturing reliability and more details on inverter-level highly accelerated life testing (HALT) done by OEMs. **Root cause analysis** was another popular topic area suggested. Other topics included **workforce**, **safety**, **the impact of extreme weather**, **maturity updates**, **different scales of work/analysis**, and **online condition monitoring**.

4 Workshop Proceedings

The rest of this document contains speakers' presentations from the 2024 NREL Reliability of Photovoltaic Inverters Workshop. All presentations and materials are being distributed with permission from the authors.

2024 Reliability of PV Inverters Workshop Agenda

April 11 – 12, 2024
NREL South Table Mountain campus, 15013 Denver W Pkwy, Golden, Colorado
Conference Room: RSF Building, Room X320 'Beaver Creek'

Day 1: April 11, 2024	
8:00 – 8:30 AM	Registration
8:30 – 8:40 AM	Welcome – Bill Tumas, NREL
8:40 – 9:00 AM	Workshop goals, organization, and logistics – Daniel Friedman and Peter Hacke, NREL
Session 1: Present state of inverter reliability. Session Chairs: Akanksha Singh, Andy Walker	
9:00 – 9:20 AM	Keynote: SETO Photovoltaics Research and Development–Motivating Inverter Reliability – Allan Ward, US DOE Solar Energy Technologies Office
9:20 – 9:40 AM	Service in the sun: The reality of PV inverter reliability – Auston Taber, FranklinWH Energy Storage, Inc.
9:40 – 10:00 AM	The problem today: The impact of inverter reliability on solar growth – Charity Sotero, kWh Analytics
10:00 – 10:35 AM	**Q&A, Discussion**: What are the biggest impacts for plant operators in the inverter reliability space?
10:35 – 10:55 AM	Break
Session 2: Routes and solutions for reliability challenges. Session Chairs: Martin Hawron, Barry Mather	
10:55 – 11:15 AM	Challenges and solutions of reliability testing of grid relays for PV applications – Wolfram Dege, SMA
11:15 – 11:35 AM	Condition monitoring as a methodology to cope with MOSFET unreliability – Johan Driesen, KU Leuven
11:35 – 11:55 AM	Long-term reliability challenges and solutions for central inverters – Bale Yang, Sungrow Power Supply Co.
11:55 – 12:30 PM	**Q&A, Discussion**: What are you seeing that could be helpful mitigating inverter challenges? What tools or resources would help?
12:30 – 1:35 PM	Working lunch with survey and discussion on the topic of R&D priorities from morning sessions, facilitated by Dan Friedman
Session 3: Lifecycle cost and ownership issues. Session Chairs: Emma Cooper, Wayne Li	
1:35 – 1:55 PM	Developing NREL analysis around inverter supply chains, manufacturing costs, and lifecycle cost of ownership issues – Michael Woodhouse, NREL
1:55 – 2:15 PM	Approaches towards use of total cost of ownership (TCO) metrics for PV inverters and beyond – Sumanth Lokanath, VDC Americas
2:15 – 2:35 PM	Various solutions for servicing an aging inverters fleet, George Kemper, DEPCOM Power
2:35 – 3:10 PM	**Q&A, Discussion**: What are the biggest expenses and highest priorities?
3:10 – 3:30 PM	Break
Session 4: Testing, standards, performance, and reliability metrics. Session Chairs: Elsa Kam-Lum, Peter Hacke	
3:30 – 3:50 PM	Keynote: Ensuring safety and security--Implications for reliability and availability – Ken Boyce, UL Solutions
3:50 – 4:10 PM	Laboratory testing to assess durability of inverters and field experiences – Cherif Kedir, RETC
4:10 – 4:30 PM	Inverter production quality assurance and testing – Ignacio Carellan, Kiwa PI Berlin
4:30 – 5:05 PM	**Q&A, Discussion:** What testing or prequalification would you like to see to ensure reliability? Where are the gaps?
5:05 – 6:05 PM	NREL Energy System Integration Facility (ESIF) tours *

2024 Reliability of PV Inverters Workshop Agenda

April 11 – 12, 2024
NREL South Table Mountain campus, 15013 Denver W Pkwy, Golden, Colorado
Conference Room: RSF Building, Room X320 'Beaver Creek'

Day 2: April 12, 2024	
8:00 – 8:30 AM	Registration
Session 5: Lifetime of active and passive components. Session Chairs: Patrick McCluskey, Greg Horner	
8:30 – 8:50 AM	Enabling Proactive Ownership: Leveraging Temperature Data to Maximize Inverter Performance and Reliability – Dylan Sontag, Silicon Ranch
8:50 – 9:10 AM	Lifetime testing and modeling of cooling fans in PV inverters – Zheyu Zhang, Rensselaer Polytechnic Institute
9:10 – 9:30 AM	Screening methodology for SiC MOSFETs – Anant Agarwal, The Ohio State University
9:30 – 9:50 AM	Live state of health monitoring of inverter subsystems – Faisal Khan, NREL
9:50 – 10:25 AM	**Q&A, Discussion**: What failure mechanisms are we not properly accounting for? How do we better accelerate the working environment of PV inverters to qualify components
10:25 – 10:45 AM	Break
Session 6: Data reporting, analytics, and data sharing. Session Chairs: Sumanth Lokanath, Joe Karas	
10:45 – 11:05 AM	Characterization and survivability analysis of inverter faults through an analysis of O&M records – Thushara Gunda, Sandia National Laboratories
11:05 – 11:25 AM	PV inverter availability from the US PV fleet – Chris Deline, NREL
11:25 – 11:35 AM	Open-access datasets from the Solar Data Bounty Prize and their potential in reliability analysis – Tassos Golnas, U.S. Department of Energy (DOE), Solar Energy Technologies Office
11:35 – 12:10 PM	**Q&A, Discussion**: How can we use data analytics to predict availability, reliability, and performance?
12:10 – 1:15 PM	Working lunch with survey and discussion on the topic of R&D priorities from workshop Day 1 afternoon and morning Day 2 sessions, facilitated by Dan Friedman
Session 7: Discussion-centric sessions on future of PV inverter reliability research, metrics for success, state of industry five years from now	
1:15 – 1:45 PM	Breakout sessions
1:45 – 2:15 PM	Report-out from breakout sessions
2:15 – 3:00 PM	**Summary, adjournment**
3:00 – 4:00 PM	NREL Energy System Integration Facility (ESIF) tours *

Bus transportation information

Thursday, 11 April 2024:

- Bus from the Denver West Marriott to the RSF main doors, one at 7:30 AM and one at 7:45 AM.
- * Bus from the RSF main doors to ESIF at 5:00 PM for tour.
- Bus from ESIF main door to Denver West Marriott at 6:15 PM

Friday, 12 April 2024:

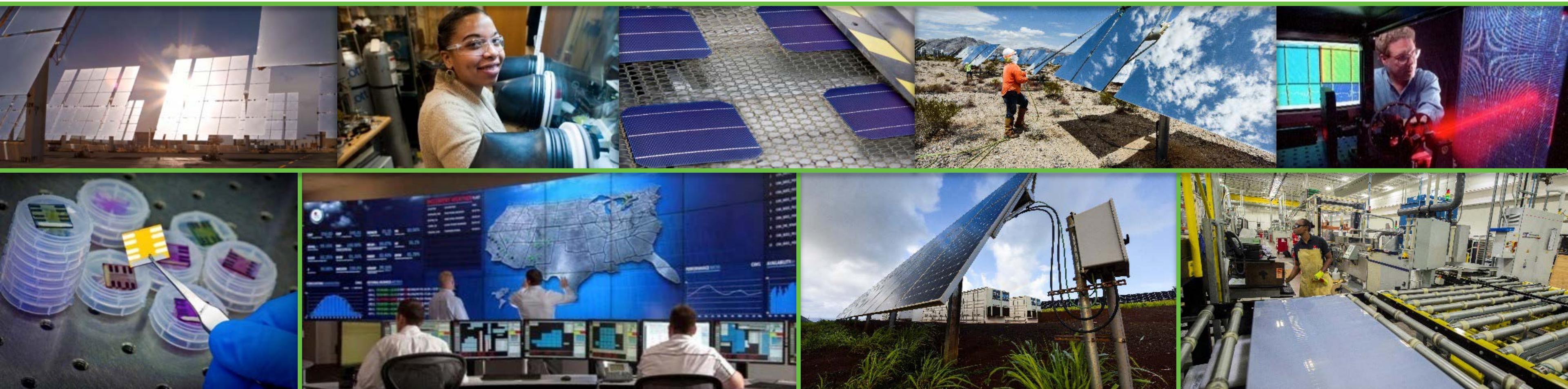
- Bus from the Denver West Marriott to the RSF main doors, one at 7:30 AM and one at 7:45 AM.
- * Bus from the RSF main doors to ESIF at 3:00 PM for tour.
- Bus from ESIF main door to Denver West Marriott at 4:15 PM.

U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

SETO Photovoltaics Research and Development Motivating Inverter Reliability

Allan Ward, PhD

Solar Energy Technologies Office



Decarbonizing the Electricity and Energy Sectors

The United States is targeting a **carbon-free electricity sector by 2035** and **100% clean energy economy with net-zero emissions by 2050**

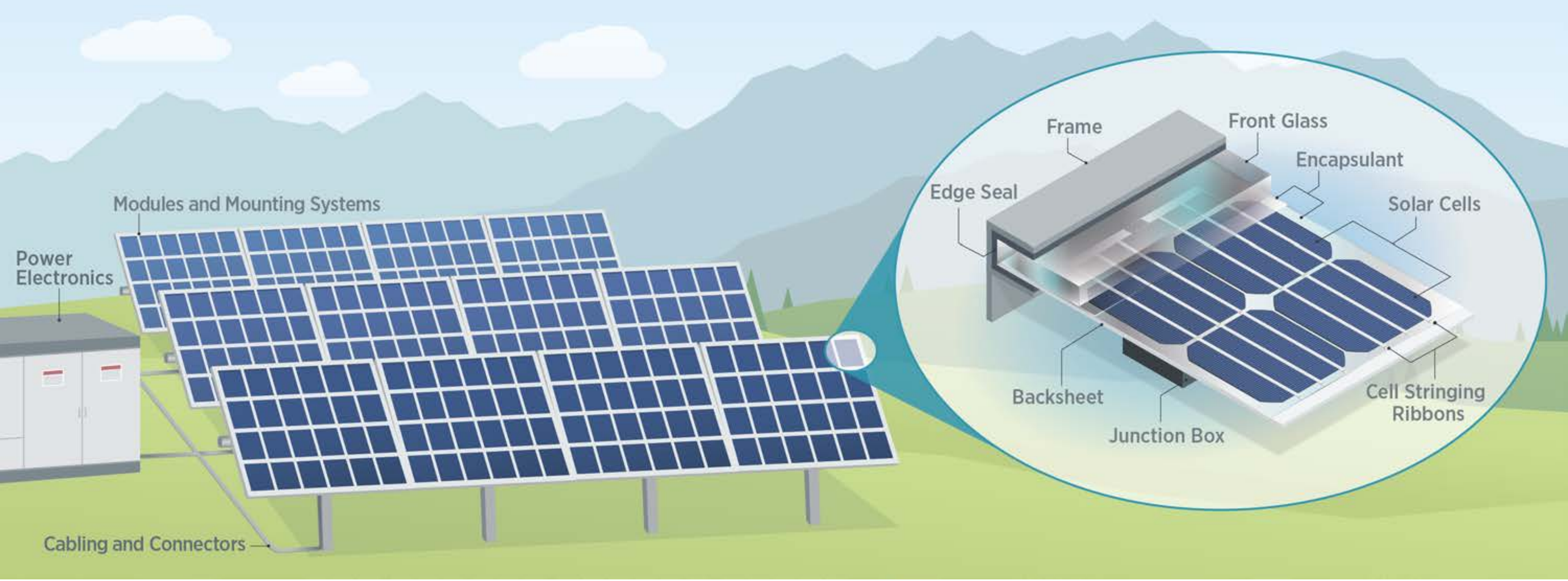
- In a fully decarbonized grid, predictions indicate that 30-50% of U.S. electricity generation would come from solar
- To meet the 2035 goal, we need to deploy solar at two to five times the current rate

2030 SETO Photovoltaic Goals

Photovoltaic (PV) electricity costs less than 2 cents/kWh

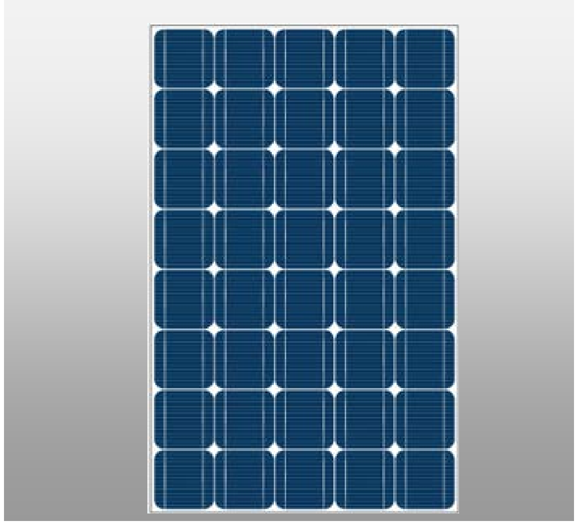
Seamless integration with other land uses

Reduced overall PV system life cycle impacts



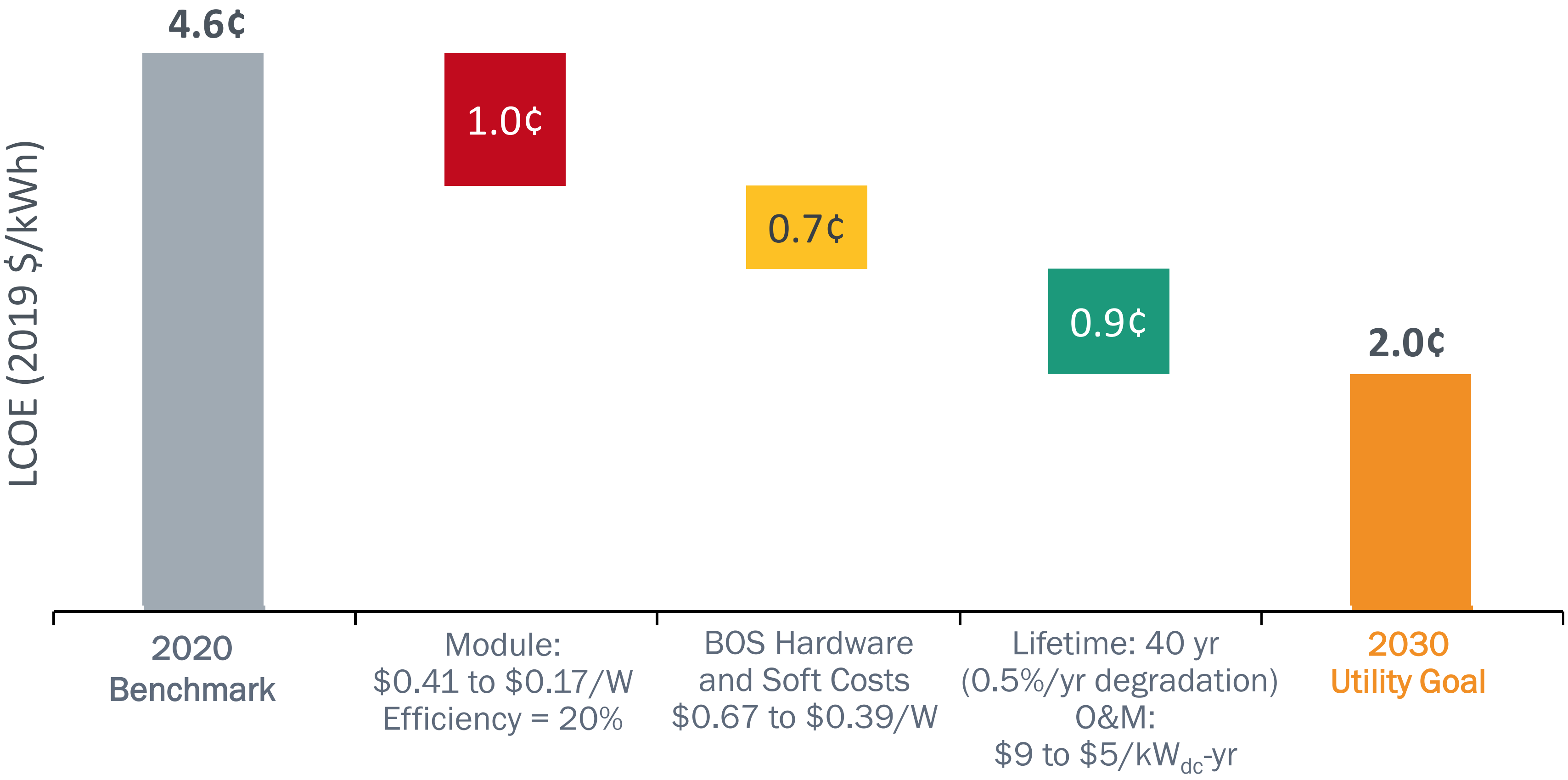
Photovoltaic System Elements

PV Modules	Electrical & Structural BOS	Inverter
32% of utility-scale system cost	**25%** of utility-scale system cost	**4%** of utility-scale system cost



Source: National Renewable Energy Laboratory. “U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks Q1 2023” https://www.nrel.gov/docs/fy23osti/87303.pdf

A Pathway to $0.02 per kWh for Utility-Scale PV



2024 PV R&D Portfolio ($236M)

Cell & Module R&D

($127M)

Optimizing environmental benefits along entire PV lifecycle (Re-X)

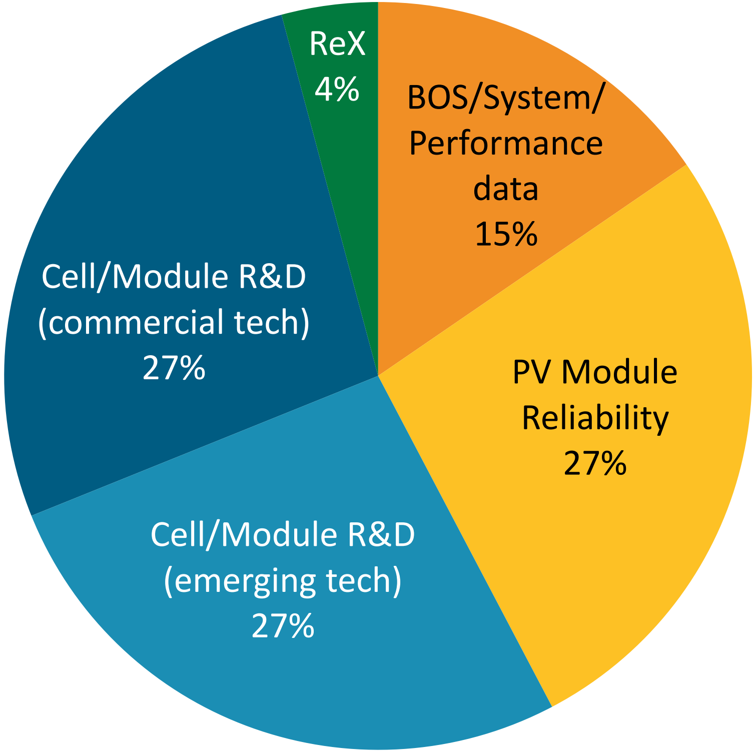
($10M active; $10M in planning)

Systems level, BOS, Data, and Extreme weather

($36M)

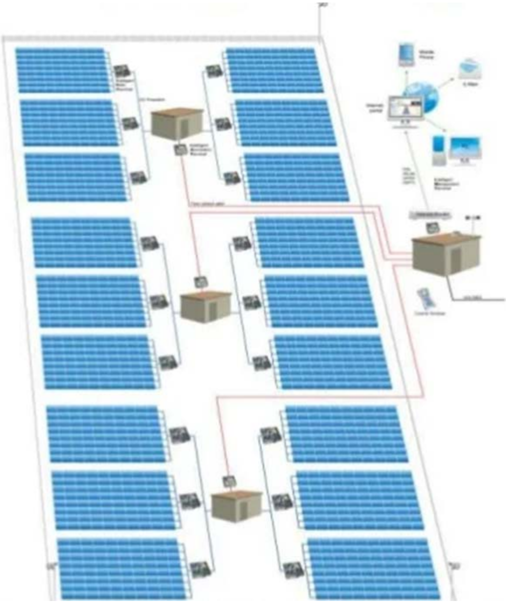
Module Reliability

($63M)

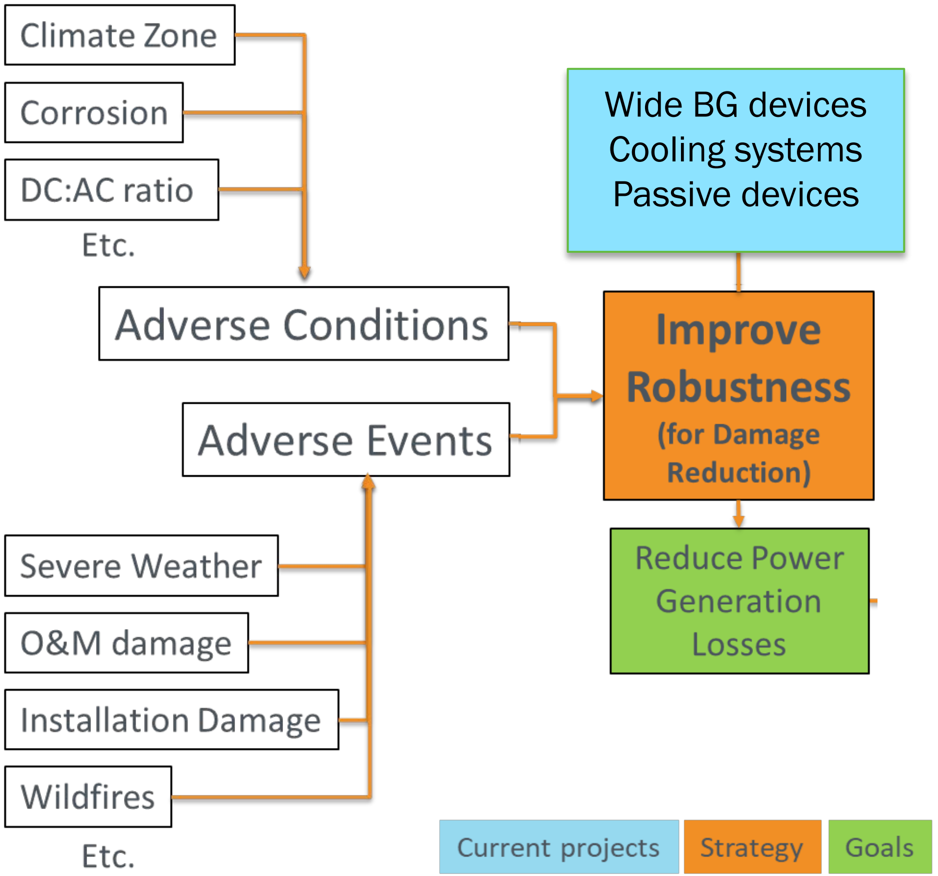


BOS Durability and System Performance

- $36M portfolio in FY2024
- R&D on BOS reliability and to improve system performance over entire lifetime
- Added inverter durability to PV R&D portfolio in FY23



Inverter Durability and System Performance



Climate Zone

Corrosion

DC:AC ratio

Etc.

Adverse Conditions

Adverse Events

Severe Weather

O&M damage

Installation Damage

Wildfires

Etc.

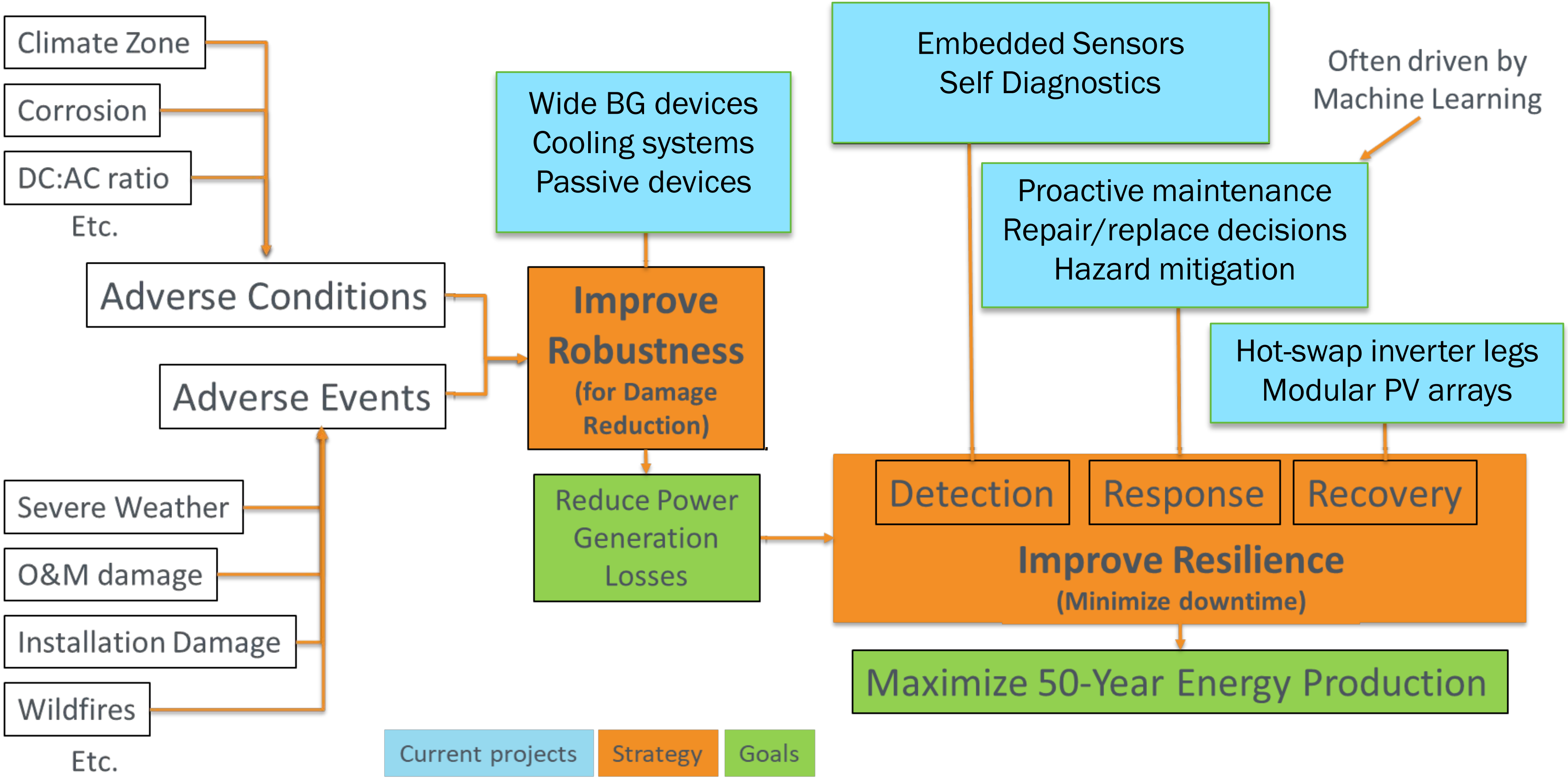
Wide BG devices
Cooling systems
Passive devices

Improve Robustness
(for Damage Reduction)

Reduce Power Generation Losses

Current projects | Strategy | Goals

Inverter Durability and System Performance



Climate Zone

Corrosion

DC:AC ratio

Etc.

Adverse Conditions

Adverse Events

Severe Weather

O&M damage

Installation Damage

Wildfires

Etc.

Wide BG devices
Cooling systems
Passive devices

Improve Robustness
(for Damage Reduction)

Reduce Power Generation Losses

Embedded Sensors
Self Diagnostics

Often driven by Machine Learning

Proactive maintenance
Repair/replace decisions
Hazard mitigation

Hot-swap inverter legs
Modular PV arrays

Detection

Response

Recovery

Improve Resilience
(Minimize downtime)

Maximize 50-Year Energy Production

Current projects | Strategy | Goals

SETO’s Desired Outcomes of this Workshop

- Establish a stronger network of inverter experts that will drive PV inverter R&D (and applications for funding)
- Understand the technical challenges to improve inverter reliability and resilience - is SETO funding aligned with these challenges?
- Learn how we can most effectively spend funds to improve current PV inverter reliability and resilience
- Determine which emerging technologies we should accelerate to meet 2035 and 2050 DOE goals

Thank you for your participation!

Allan.Ward@ee.doe.gov

Service in the Sun

The Reality of PV Inverter Reliability

Auston Taber – 4/11/24

DUNGEONS & DRAGONS®

STRENGTH
12

DEXTERITY
10

CONSTITUTION
16

INTELLIGENCE
14

WISDOM
13

CHARISMA
15

Auston Taber
CHARACTER NAME

VP of Service	Industry Veteran	Auston
CLASS & LEVEL	BACKGROUND	PLAYER NAME
White/Latino	Lawful Innovative	Level 16 (Years)
RACE	ALIGNMENT	EXPERIENCE POINTS

CHARACTER APPEARANCE

Visionary leader with a penchant for technology and strategy.
PERSONALITY TRAITS

Sustainability and innovative in energy, commitment to family and team success.
IDEALS

Passionate about advancing renewable energy, family, and nurturing a thriving workplace
BONDS

Can be too absorbed in the latest tech or project (but it's usually a bonus!)
FLAWS

FRANKLINWH

SOLAR SUPPORT

HUAWEI

SMA

GRID ALTERNATIVES

REC SOLAR

A.M. Sun
SOLAR + ROOFING

CURRENT LANDSCAPE

Solar industry losing $2.5B annually from equipment underperformance

Raptor Maps
Nikhil Vadhavkar, CEO and Eddie Obropta, CTO

The biggest barrier to growth for solar companies? 44% of companies say a lack of trained labor

EnergySage
Spencer Fields, Director of Insights

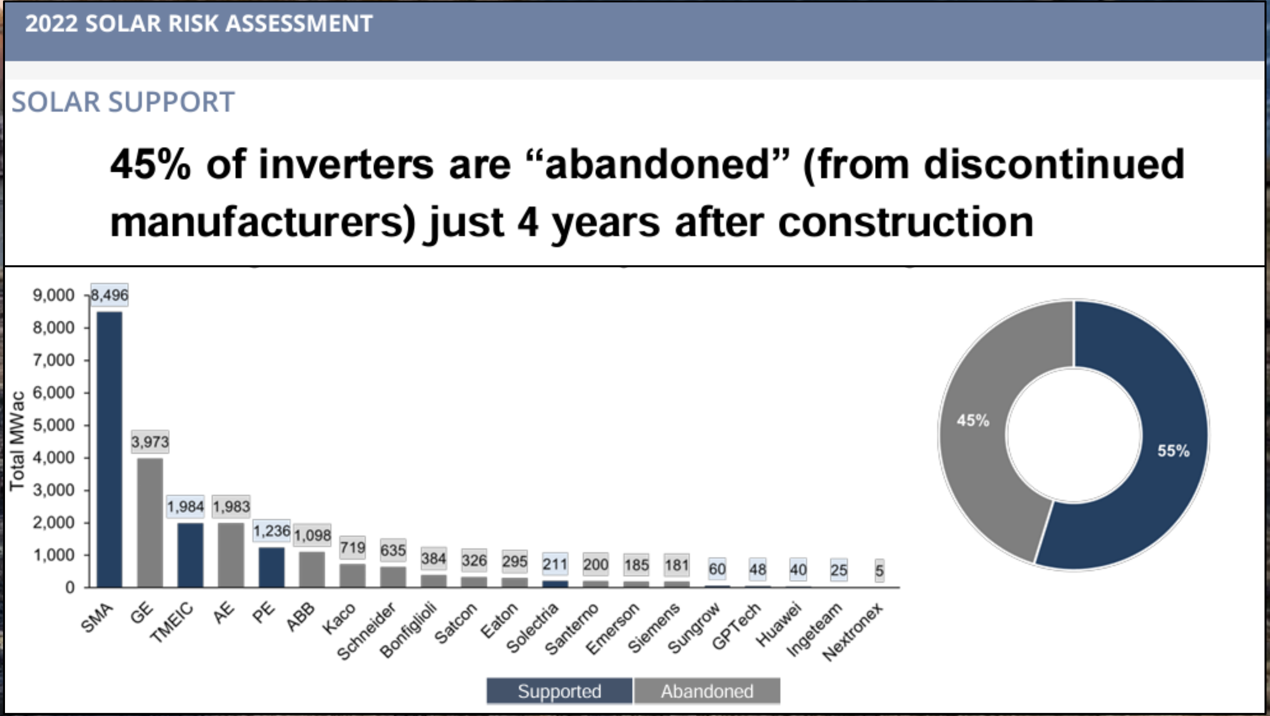
Operating and Maintaining Solar Farms | Josh Fraughton

SUNCAST media


kWh analytics

SOLAR
RISK
ASSESSMENT

2023


2022 SOLAR RISK ASSESSMENT

SOLAR SUPPORT

45% of inverters are "abandoned" (from discontinued manufacturers) just 4 years after construction

LIFECYCLE CHALLENGES

EXPERIENCED LABOR

SPARE PARTS

LIMITED 3RD PARTY SUPPORT

WARRANTY GAPS

SERVICE & TRAINING COMPLEXITY

DESIGN & COMPATIBILITY

DESIGN & COMPATIBILITY

RESI and C&I

600V vs 1000V vs 1500V

480v AC

240v AC

600v AC

WHAT ABOUT COMMUNICATIONS?!

RS485

ETHERNET

POWERLINE

Utility

600V vs 1000V vs 1500V

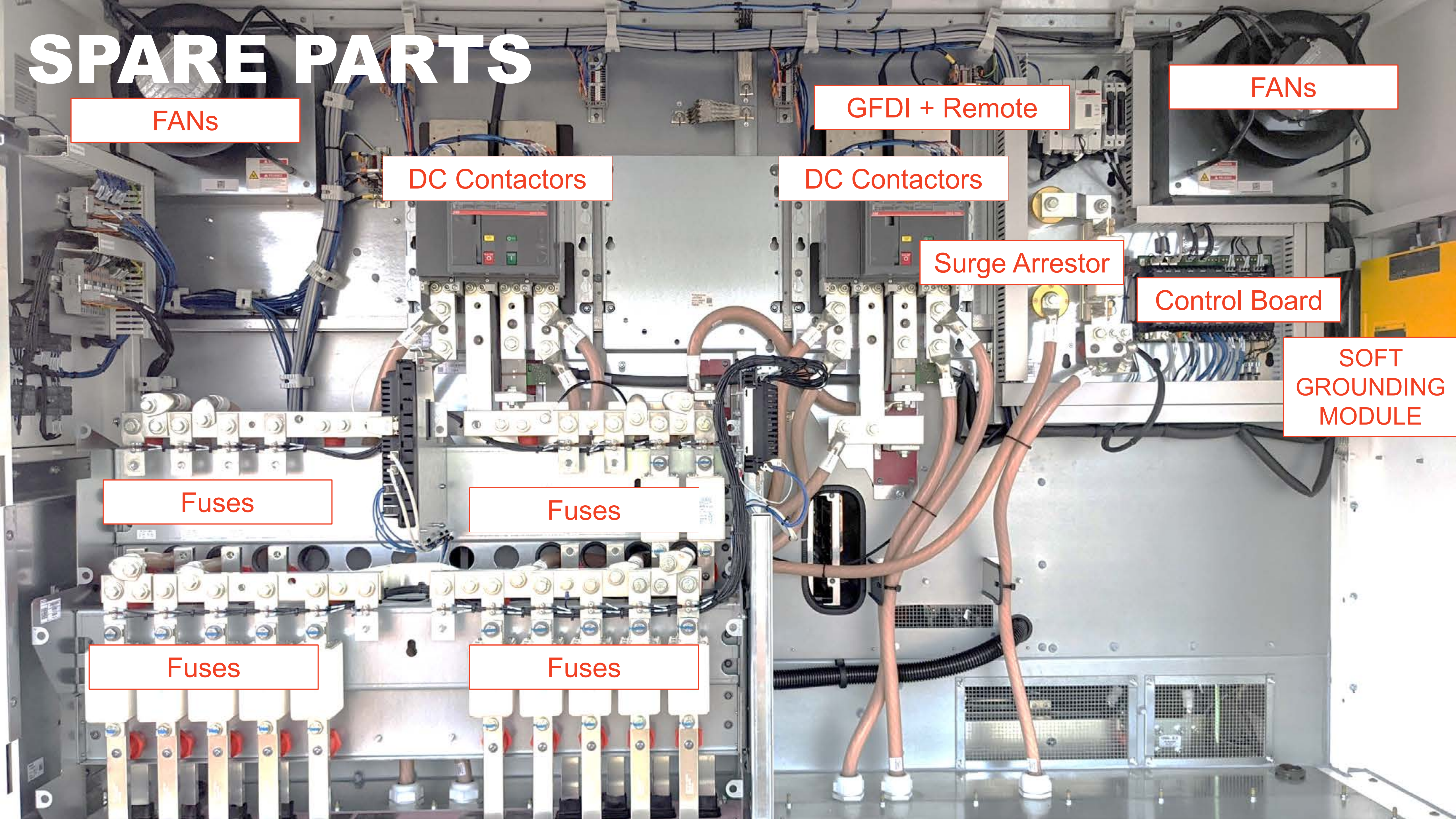
480v AC

600v AC

385v AC

345v AC

SPARE PARTS



FANs

GFDI + Remote

FANs

DC Contactors

DC Contactors

Surge Arrestor

Control Board

SOFT GROUNDING MODULE

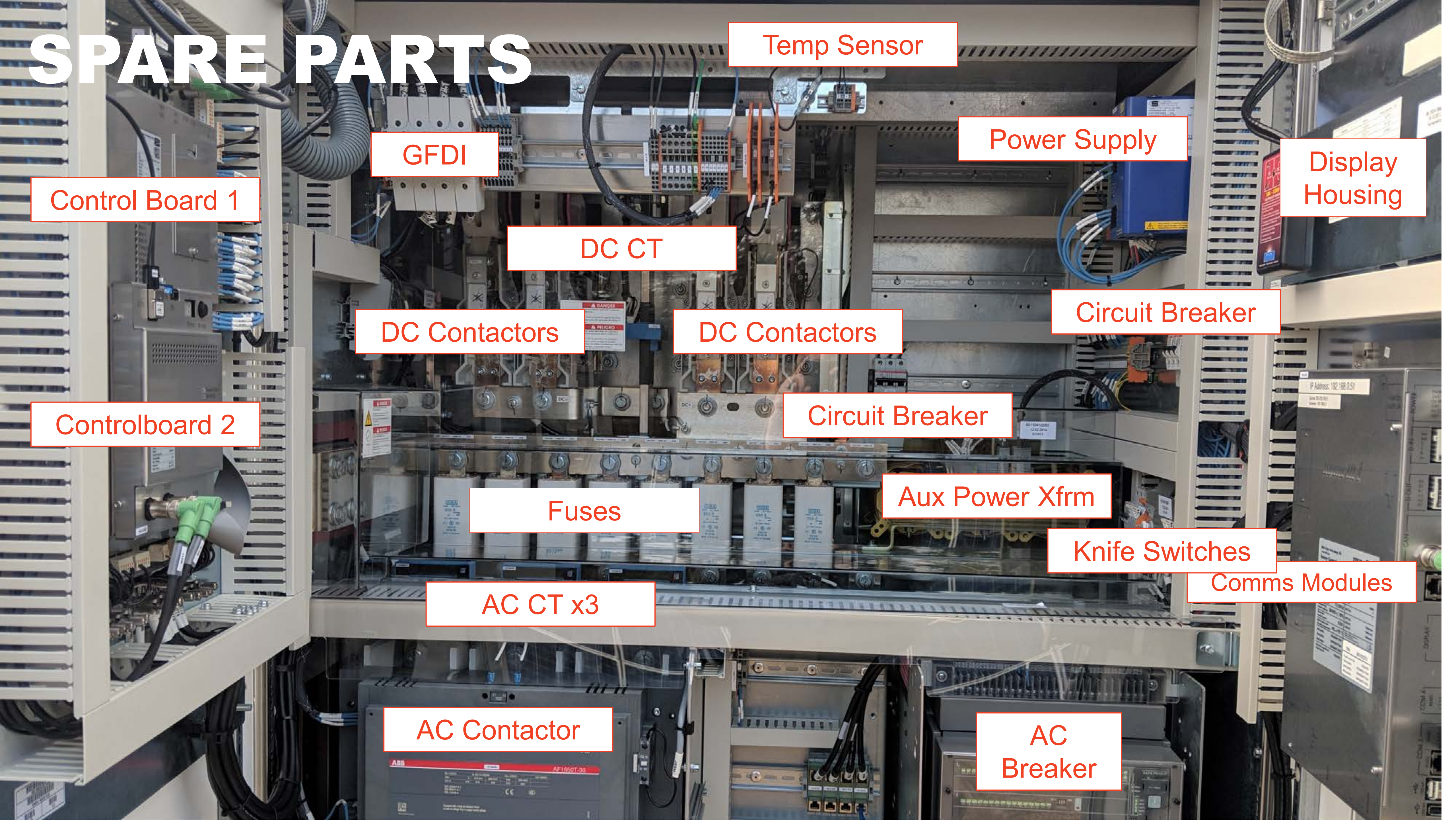
Fuses

Fuses

Fuses

Fuses

SPARE PARTS


Temp Sensor
GFDI
Power Supply
Display Housing
Control Board 1
DC CT
DC Contactors
DC Contactors
Circuit Breaker
Circuit Breaker
Controlboard 2
Fuses
Aux Power Xfrm
Knife Switches
Comms Modules
AC CT x3
AC Contactor
AC Breaker

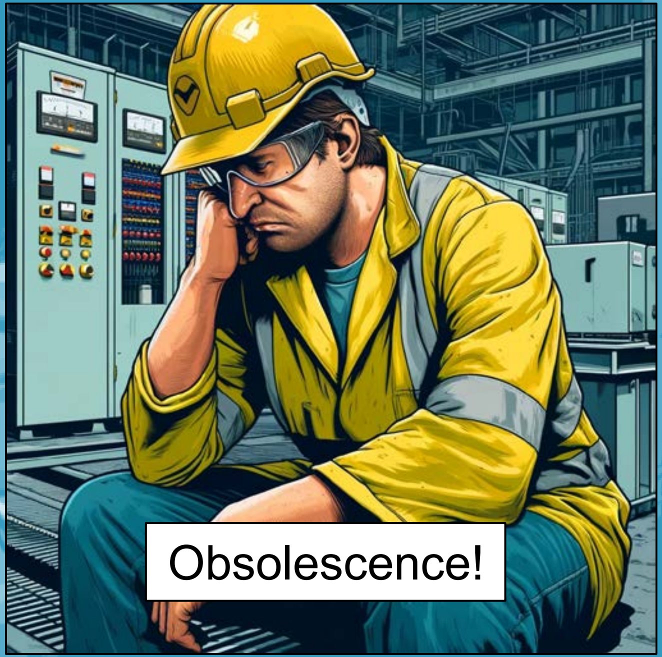
SPARE PARTS LOGISTICS

48 Hrs

0-72 Hrs

No Stock?

16 weeks+



Obsolescence!

SUCCESS!

UNTRAINED!

EXPERIENCED LABOR

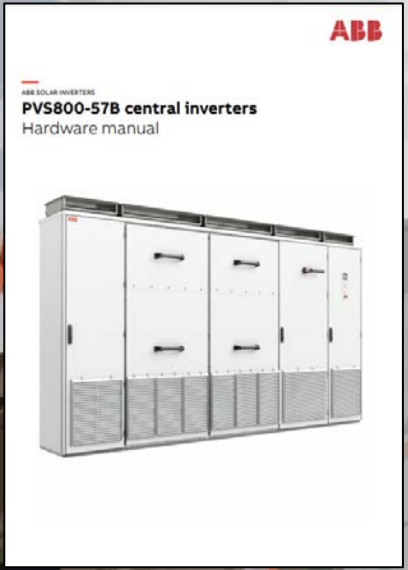
Requirements

- 5+ Years in Electrical/Renew
- Advanced troubleshooting
- Experience with 5+ Inverte
- Detail oriented (take note
- Read circuit diagrams fo
- Take apart and reassem
- Experience with Safety p
- NABCEP, NEC, IEEE, UL
- MVT switching experience
- Working knowledge of monitoring systems and data analysis
- Ability to lead and manage projects/teams
- Commissioning Experience

SERVICE & TRAINING COMPLEXITY

REQUIREMENTS

- Access to a knowledge base
- Trusted Resource
- Techs 1-2 years of experience
- CPR/First Aid
- Circuit Diagram Training
- Basic Troubleshooting
- Procedures

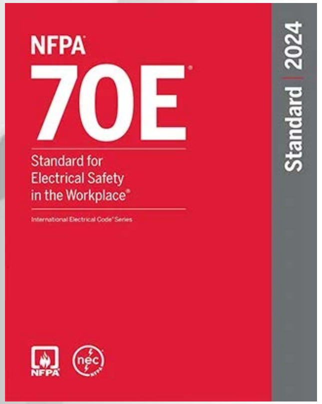


ABB

ABB SOLAR INVERTERS

PVS800-57B central inverters

Hardware manual

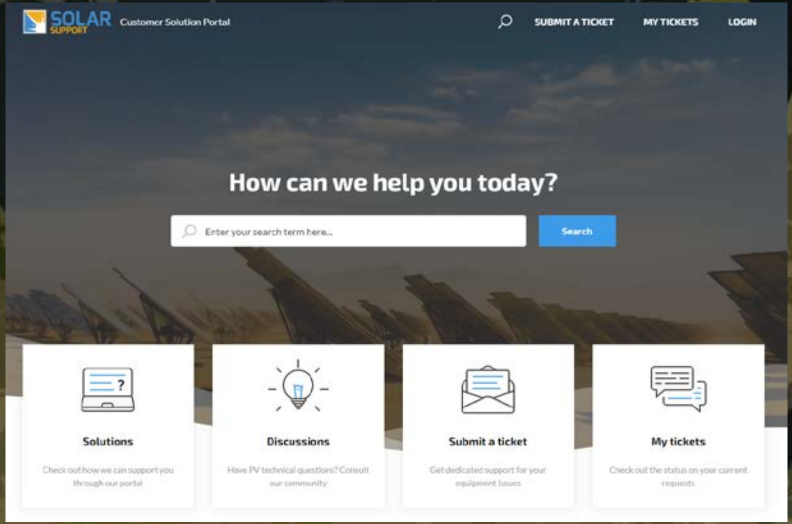

NFPA

70E®

Standard for Electrical Safety in the Workplace®

International Electrical Code® Series

Standard | 2024


SOLAR SUPPORT Customer Solution Portal

SUBMIT A TICKET

MY TICKETS

LOGIN

How can we help you today?

Enter your search term here...

Search

Solutions

Check out how we can support you through our portal

Discussions

Have PV technical questions? Consult our community

Submit a ticket

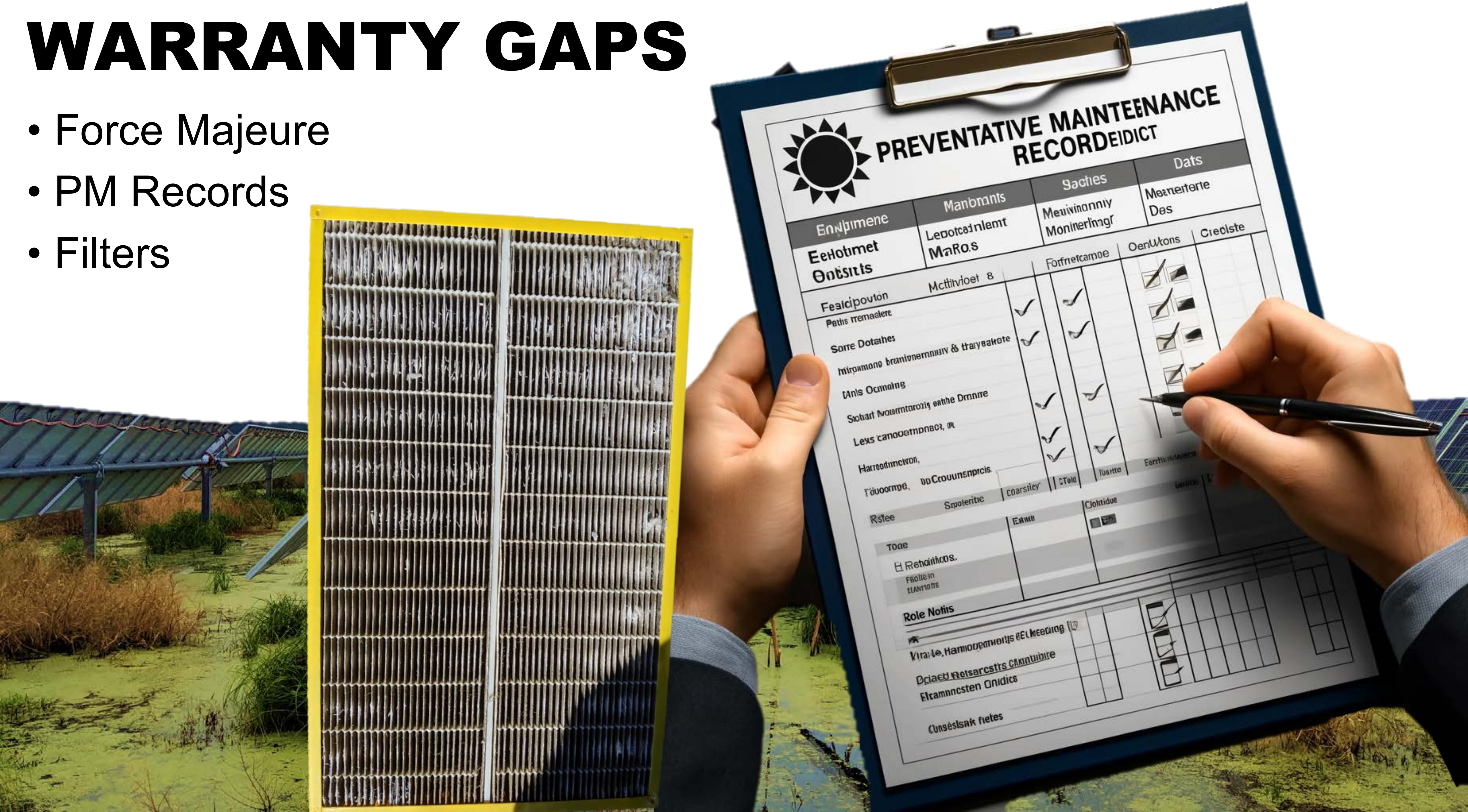
Get dedicated support for your equipment issues

My tickets

Check out the status on your current requests

WARRANTY GAPS

- Force Majeure
- PM Records
- Filters



LIMITED 3rd PARTY SUPPORT

Challenges

- Limited amount of providers
- Subcontractors prevalent (why?)
- Proficient in certain models
- No shared knowledge base
- Lack of Spares (again)

We don't have this, but we should!

OEM's

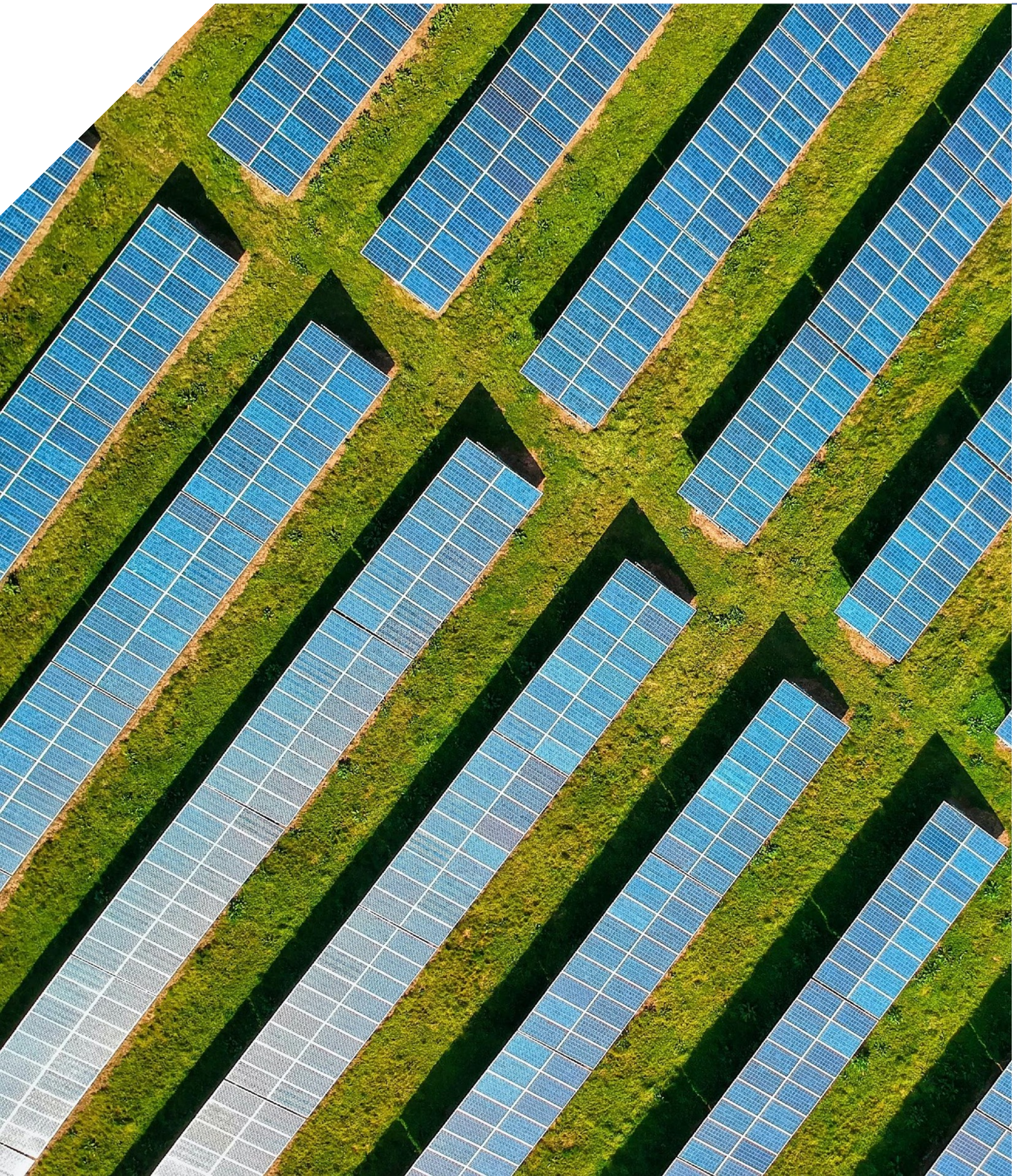
- Proprietary Info
- Training
- Documentation

Techs

- Talk to each other
- Share Information
- Empower our industry

OWNERS!

DON'T GO CHEAP ON INSTALL! Vet your OEMs products!
Ask for options and opinions!



THE INSURANCE POV: THE PRESENT STATE OF PV INVERTER RELIABILITY

Charity Faith Sotero
Adam Shinn, Nikky Venkataraman

And with support from SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy U.S. DEPARTMENT OF ENERGY

INTRODUCTION

INSURANCE IS INEVITABLE

Insurance is a block to building solar.

Building and operating costs have decreased → insurance premiums have *increased*.

Insurance does not typically take PV reliability when accounting for risk.

kWh Analytics' Mission:

- To instead *accelerate* the PV boom with insurance.

FIG 1. **PV SYSTEM COSTS OVER TIME** (UTILITY PV) RAMASAMY, 2021

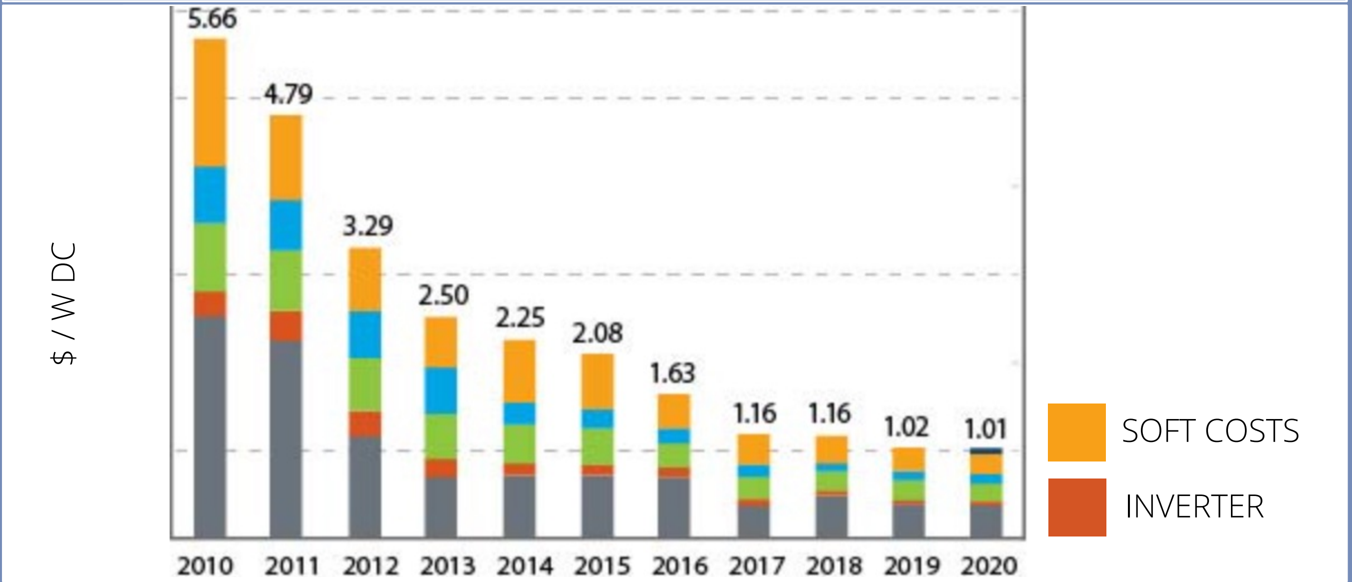
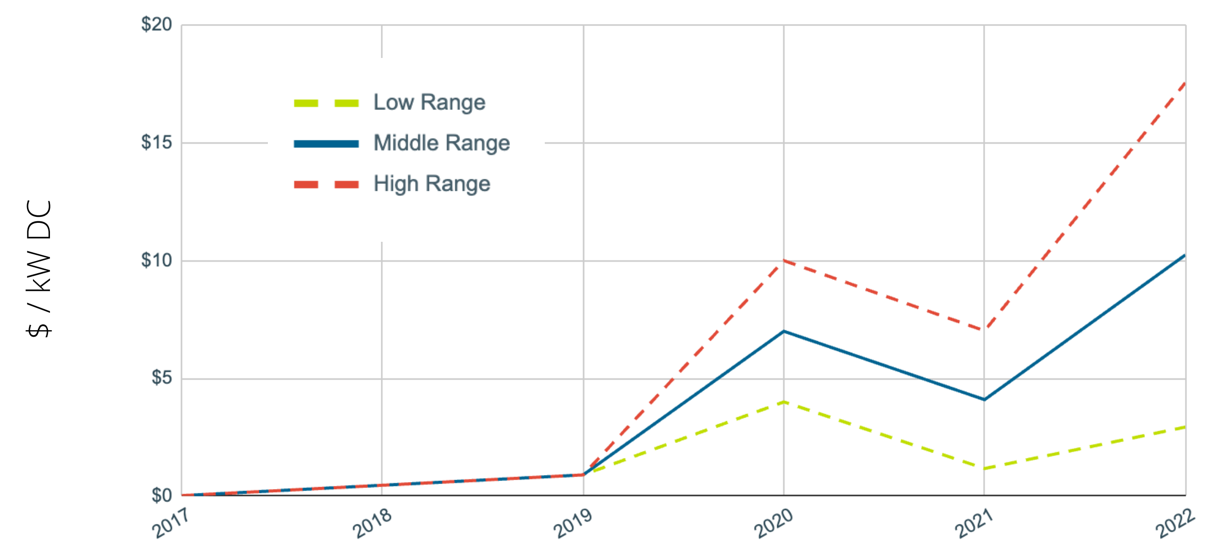


FIG 2. **PROPERTY INSURANCE PREMIUMS** (UTILITY PV) NREL, LBNL, NRF



FIGURES AND DATA COURTESY OF: NREL, LBNL, NRF

INTRODUCTION

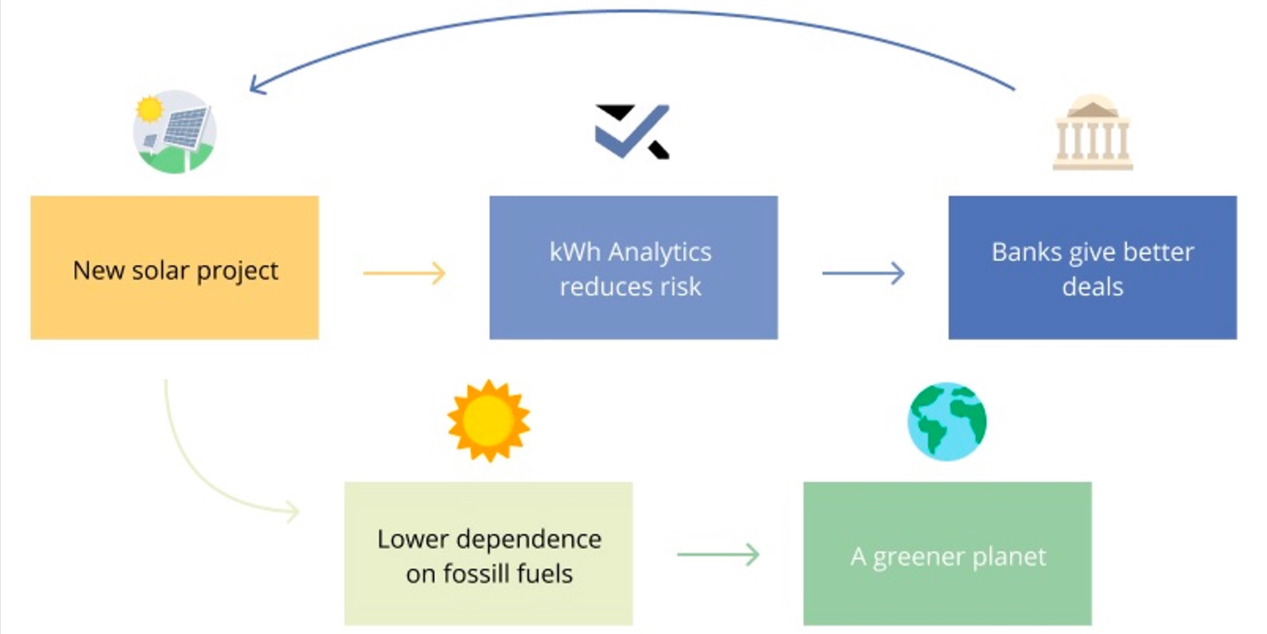
MARKET LEADER IN CLIMATE INSURANCE

Founded in 2012,

kWh Analytics is the leading provider of Climate Insurance, **leveraging the most comprehensive database of renewable assets.**

- Team with expansive industry-specific knowledge
- kWh Analytics database covers 30% of U.S. solar assets
- kWh Analytics protects $23B of renewable energy assets

FIG 3. **INSURANCE AS A TOOL TO BUILD MORE SOLAR**



New solar project

kWh Analytics reduces risk

Banks give better deals

Lower dependence on fossill fuels

A greener planet

INTRODUCTION

DOE 50-YEAR LIFESPAN PROJECT

Most systems in the U.S. were installed < 25 years ago

PV components have reached end-of-life earlier than the expected 30 to 35-year lifespan.

PV SYSTEMS THAT FOLLOW RELIABILITY "BEST PRACTICES"

- have an **increased lifespan,**
- and **get the best insurance rates.**

FIG 4. **PROJECT** LIFE **EXPECTATIONS** FOR UTILITY PV WISER, 2020

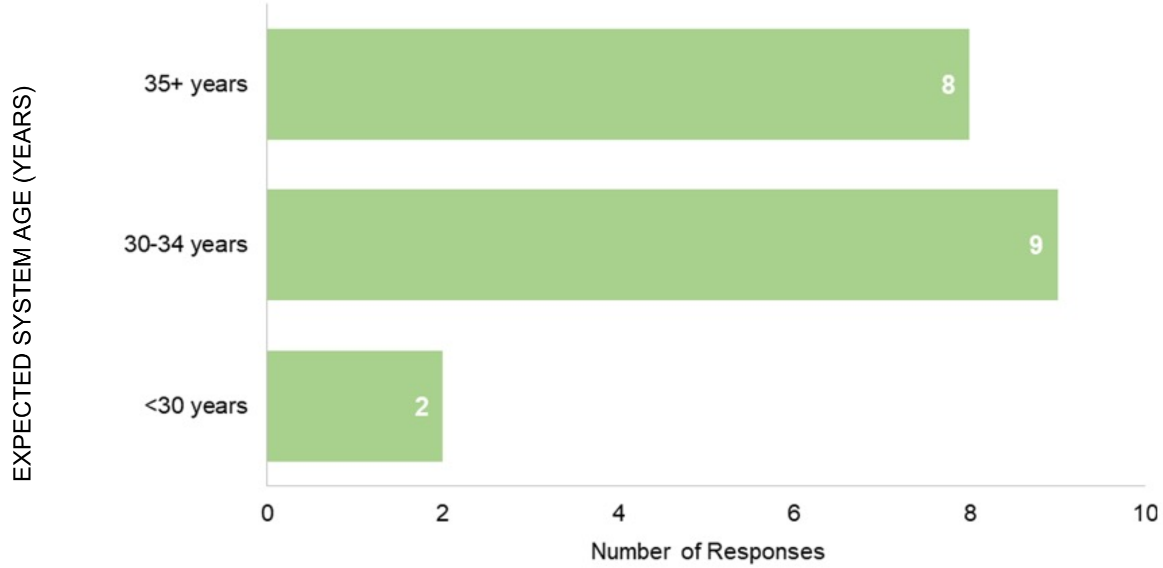


FIG 5. **PV COMPONENT FAILURES** GUNDA, 2020

ACTIVITY DESCRIPTION	MEAN TIME TO FAILURE (YEARS)
INVERTER - IGBT MATRIX*	1.9
INVERTER - FAN MOTOR	2.2
INVERTER – UNKNOWN REBOOT	1.6
BROKEN MODULES	2.3
DAMAGED RACKING	1.5
HYDRAULIC CYLINDER	1.0
TRACKER MOTOR CONTROLLER	1.1
TRACKER BEARING(S)	1.7

OBJECTIVES OUTLINE

THE INSURANCE POV

"HOW DOES INSURANCE USE **DATA** TO **MEASURE RELIABILITY**?"

1. WHY	2. DATA	3. PROCESSING	4. BIG PICTURE	5. DETAILED VIEW	6. IMPLICATIONS
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1. WHY

DOES INSURANCE CARE?

Insurance has a vested interest in equipment reliability

2. DATA

WHAT DATA DO WE HAVE?

Summary of the data available for analysis.

3. PROCESSING

HOW ARE DATA PROCESSED?

Pre-processing needed to use data.

4. BIG PICTURE

WHAT IS THE BIG-PICTURE PROBLEM?

Using claims data to understand the present state of inverter reliability

5. DETAILED VIEW

WHAT ARE THE DETAILED PROBLEMS?

Using O&M logs to get a more detailed view of the present state of inverter reliability

6. IMPLICATIONS

WHAT DOES INSURANCE CARE ABOUT?

Conclusions and takeaways for the insurance market and inverter reliability

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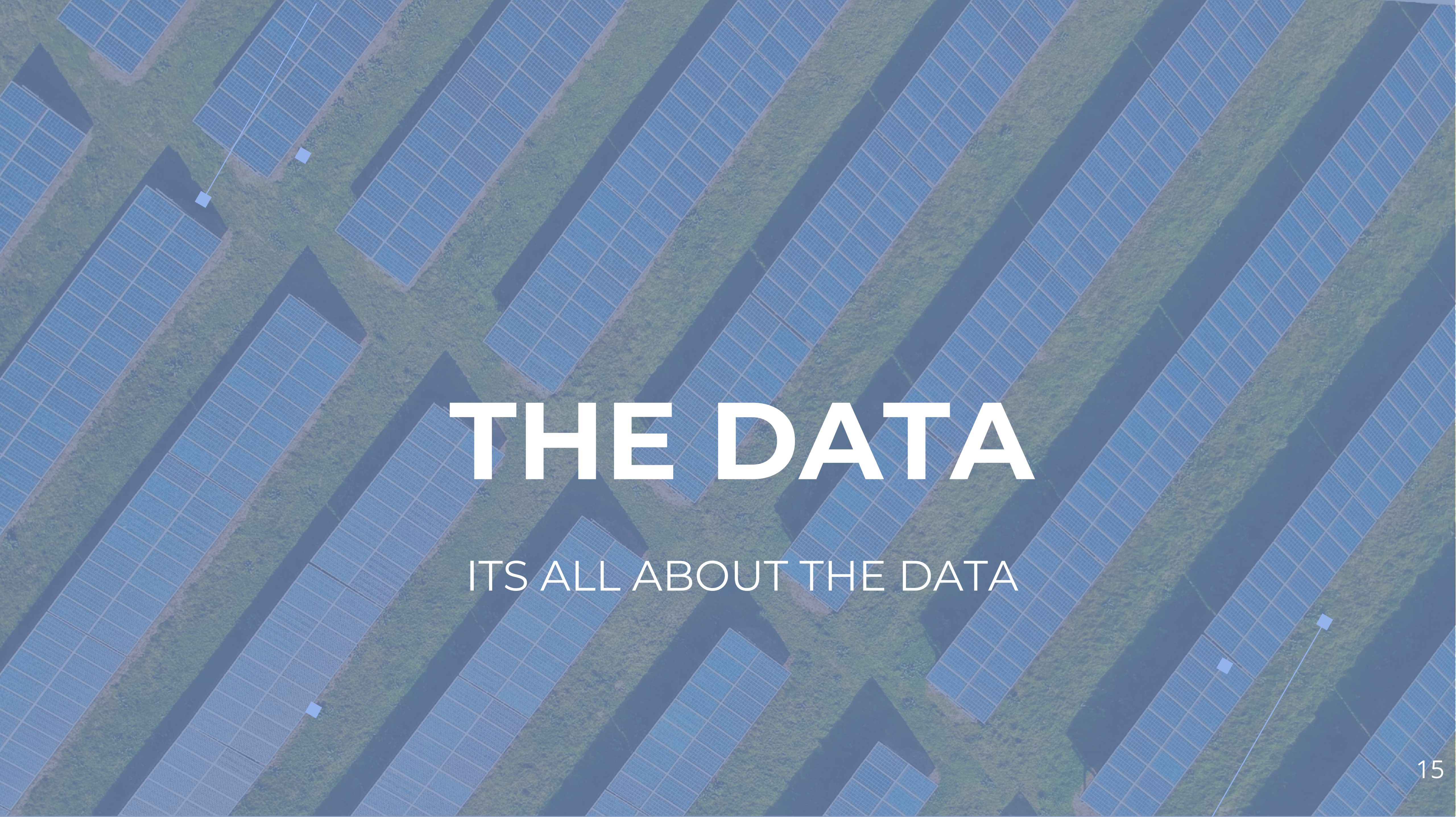
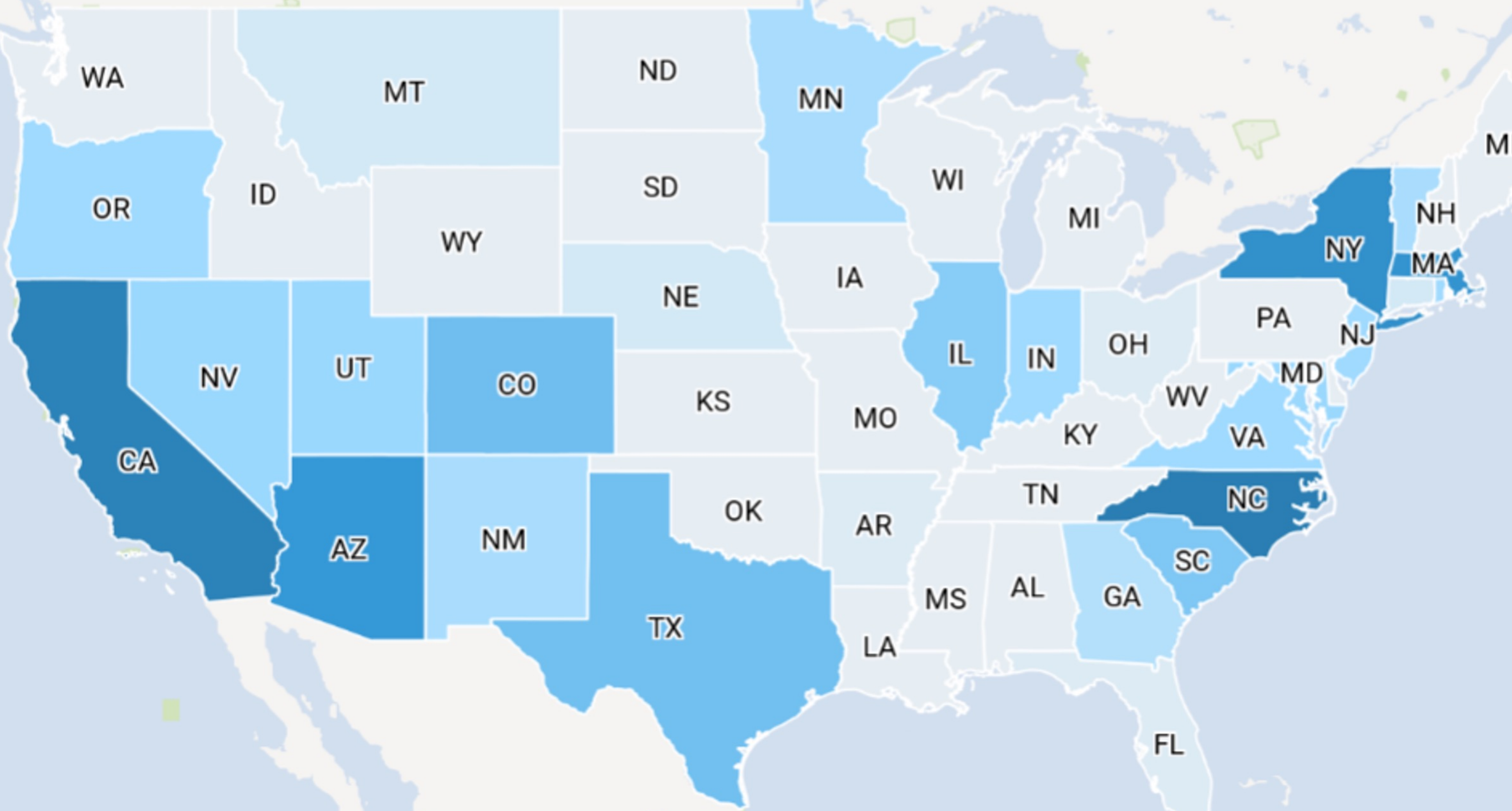


THE DATA

ITS ALL ABOUT THE DATA

FIG 6. **MAP OF DATA**

DATA SUMMARY



COLOR LEGEND
RECORDS, BY STATE

0%	1%	5%	15%	30%

11+
GW CAPACITY (DC)
2005-2024

500+
UTILITY PV SYSTEMS

3.7
AVG SYSTEM AGE

2,000+
SYSTEM-YEARS

DATA

INSURANCE CLAIMS DATA

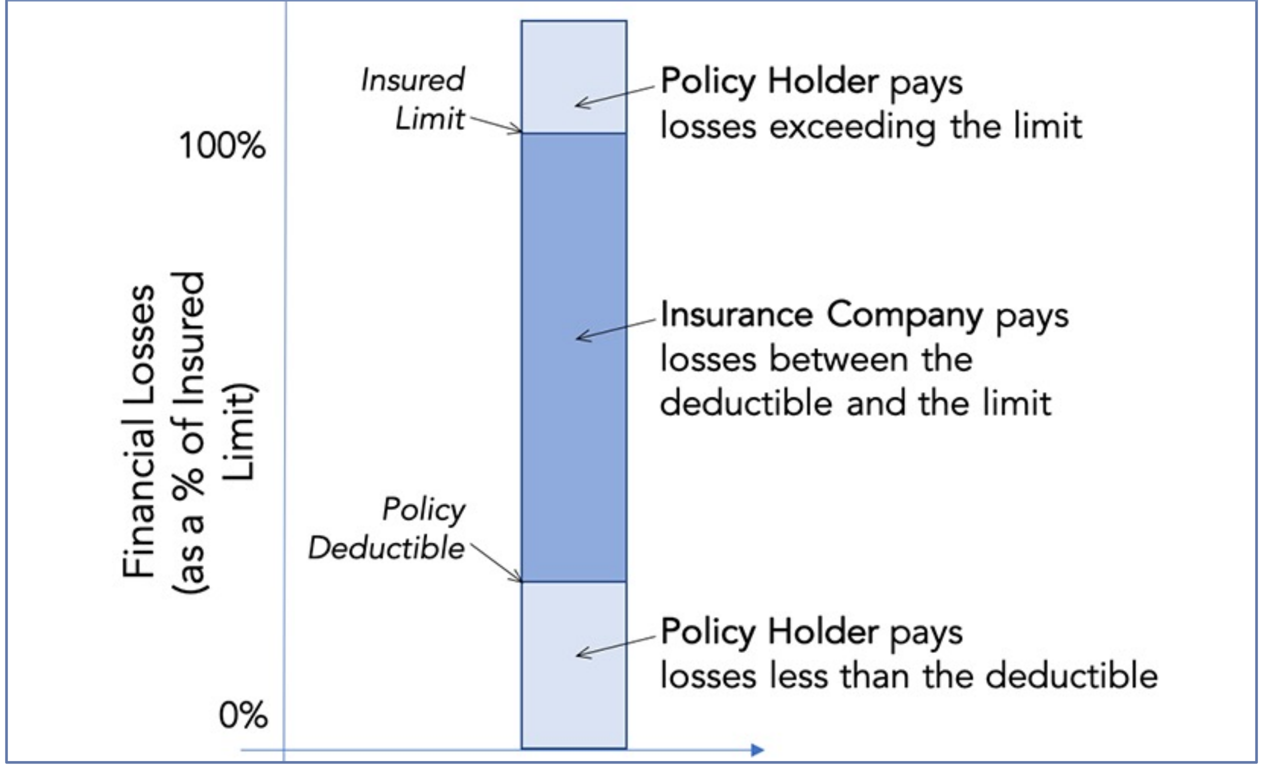
Insurance claims are a collection of significant loss events

- “What events really matter to insurance, to the market?”

Claims data is shaped by insurance policy design

- Subject to limits and deductibles

FIG 7. **CONVENTIONAL PROPERTY INSURANCE**



DATA

INSURANCE CLAIMS DATA: IS THERE MORE

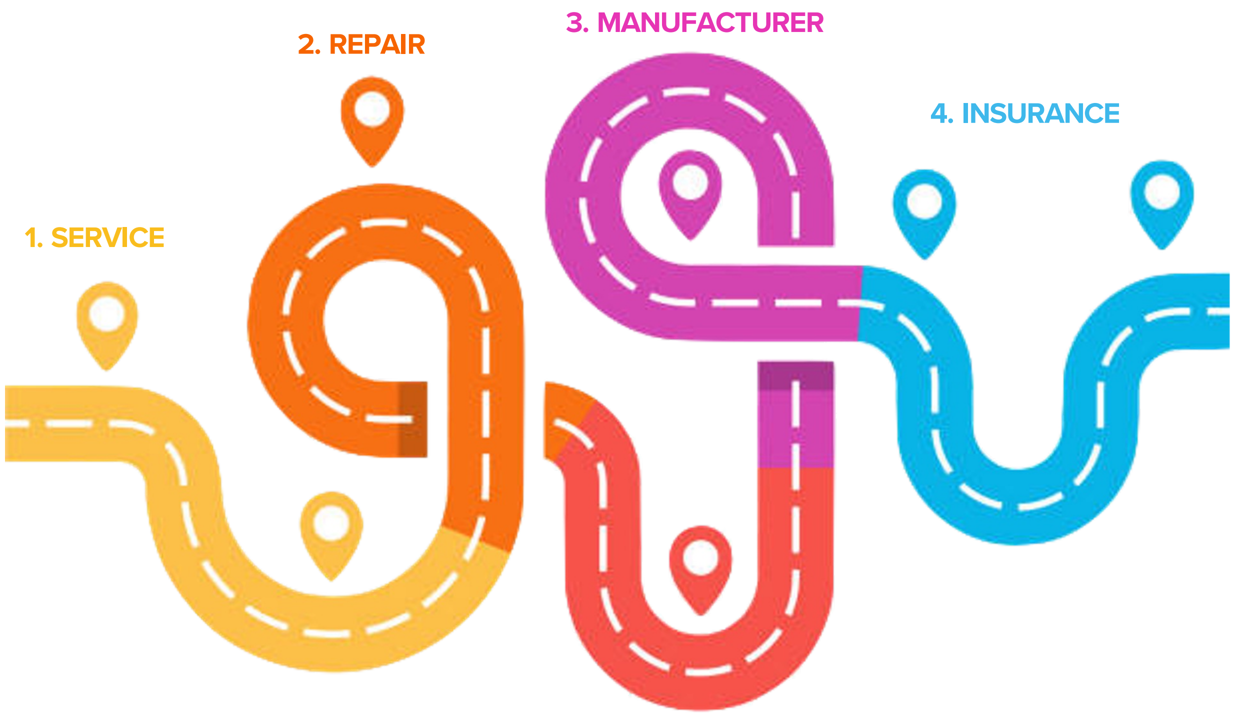
Insurance claims are only a part of the PV loss workflow

- What happened before the insurance claim?
- What happened if there wasn't an insurance claim filed?

Operations & Maintenance

- Technicians keep records

FIG 8. **RESOLUTIONS:** GENERAL WORKFLOW OF PV TROUBLESHOOTING



OPERATIONS & MAINTENCE LOGS

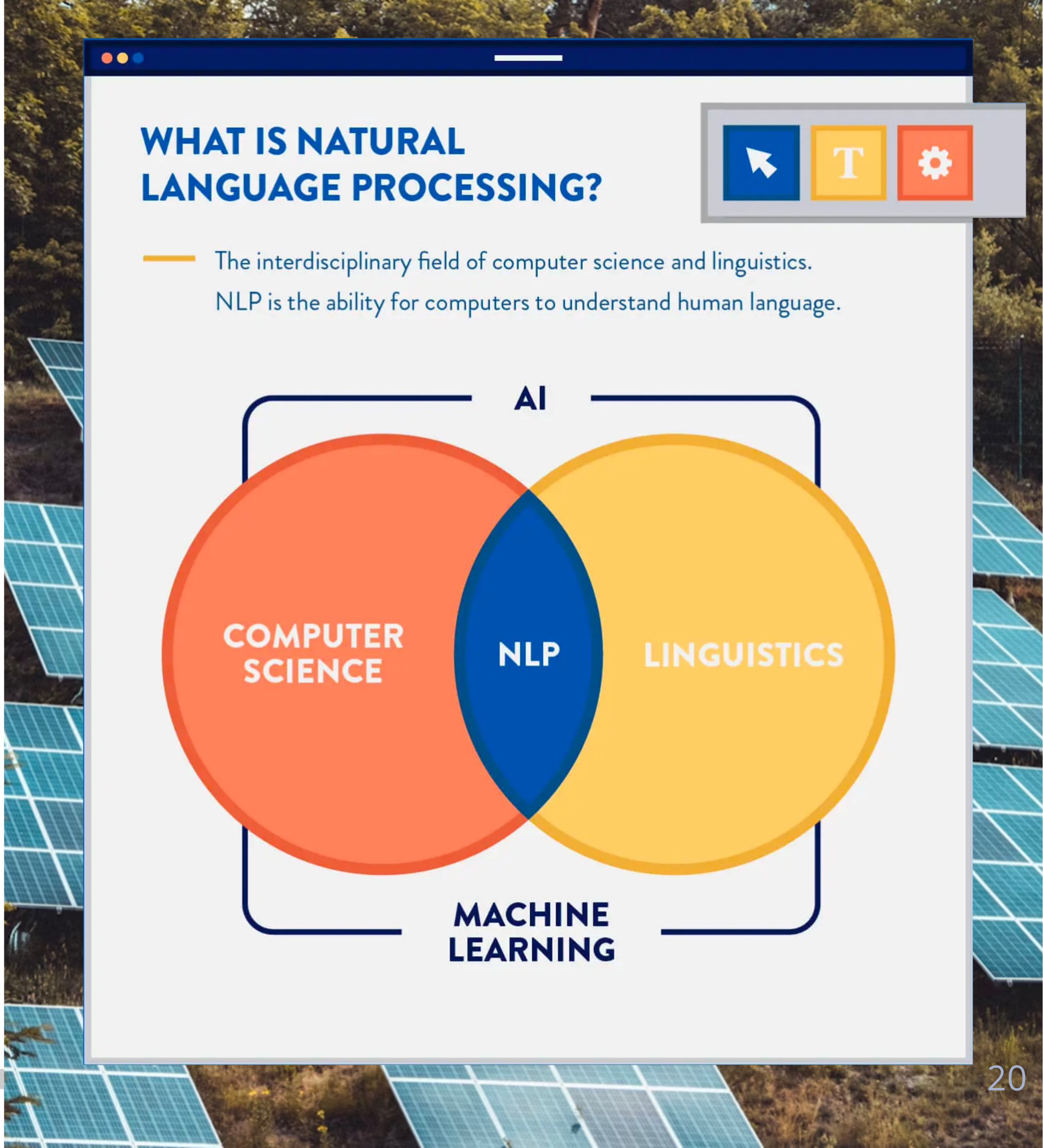
When combined with system data,
O&M logs have the potential to prove **what factors make a difference in reliability.**

START DATETIME	END DATETIME	ENERGY LOST	TECHNICIAN NOTES	EQUIPMENT TYPE	FAILURE MODE	RESOLUTION OUTCOME
04-01-21 10:01 AM	04-02-21 2:30 PM	1,980 kWh	CB 1.8 strings damaged due to fire incident from short circuit event	Combiner Box	Short Circuit Event	Replace Connectors
08-11-23 9:22 AM	08-11-23 11:22 AM	1,076 kWh	Panels stuck in wind stow, change tracker from 0 to 4, re-boot PLC's.	Tracker	Wind Stow	Remote Restart

DATA & METHODOLOGY

THE MYSTERY OF O&M LOGS

“4/1 During PM noted Inv 1 was down, further inspection revealed CB 1.8 strings damaged due to fire incident from short circuit event caused by unknown animal chewing on conductors. Opened WO-7879 for new trenching from arr to CB. PO-245 to insurance for wiring conduit fuses. 4/2 [mfg] rep on-site to inspect damage. 4/17 [mfg] subcontractor arrived. 4/25 [mfg] finished repairs, with the exception of 6 connectors which they did not have the parts for. 4/26 Completed and tested repairs.”



WHAT IS NATURAL LANGUAGE PROCESSING?

The interdisciplinary field of computer science and linguistics.

NLP is the ability for computers to understand human language.

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THE PRE-PROCESSING PROCESS

PV LANGUAGE + DOMAIN EXPERTISE

DATA PRE-PROCESSING

PV LANGUAGE + DOMAIN EXPERTISE

STEP 1

PV TRANSLATION DICTIONARIES

Collect PV-specific synonyms, terminology, acronyms. Built off the work of pvOps, and an open-source contribution to pvOps.

STEP 2

EXTRACT: EQUIPMENT TYPES

Use the single-line diagram flow of energy to choose most likely (earliest) equipment type.

STEP 3

EXTRACT: RESOLUTION OUTCOME

Use PV workflow hierarchy to choose most likely (last) resolution outcome.

DATA PRE-PROCESSING

PV LANGUAGE + DOMAIN EXPERTISE

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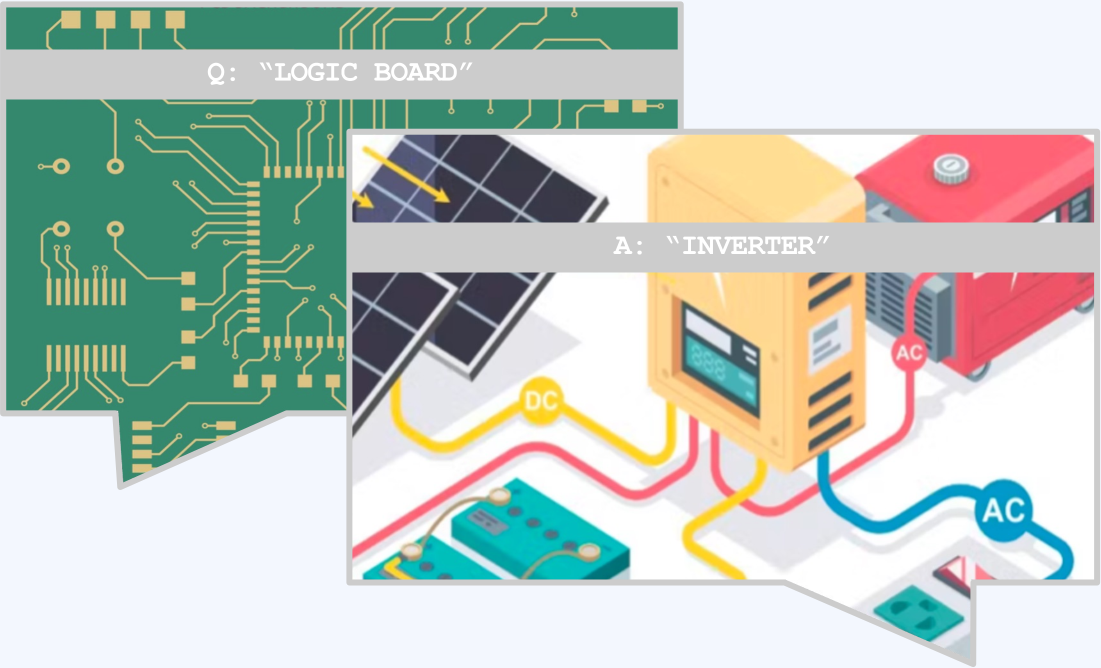
FIG 7. **DATA PRE PROCESSING:** CUSTOM PV TERMINOLOGY DICTIONARIES



DATA PRE-PROCESSING

PV LANGUAGE + DOMAIN EXPERTISE

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FIG 8. **EQUIPMENT TYPES:** SINGLE LINE PV ENERGY FLOW

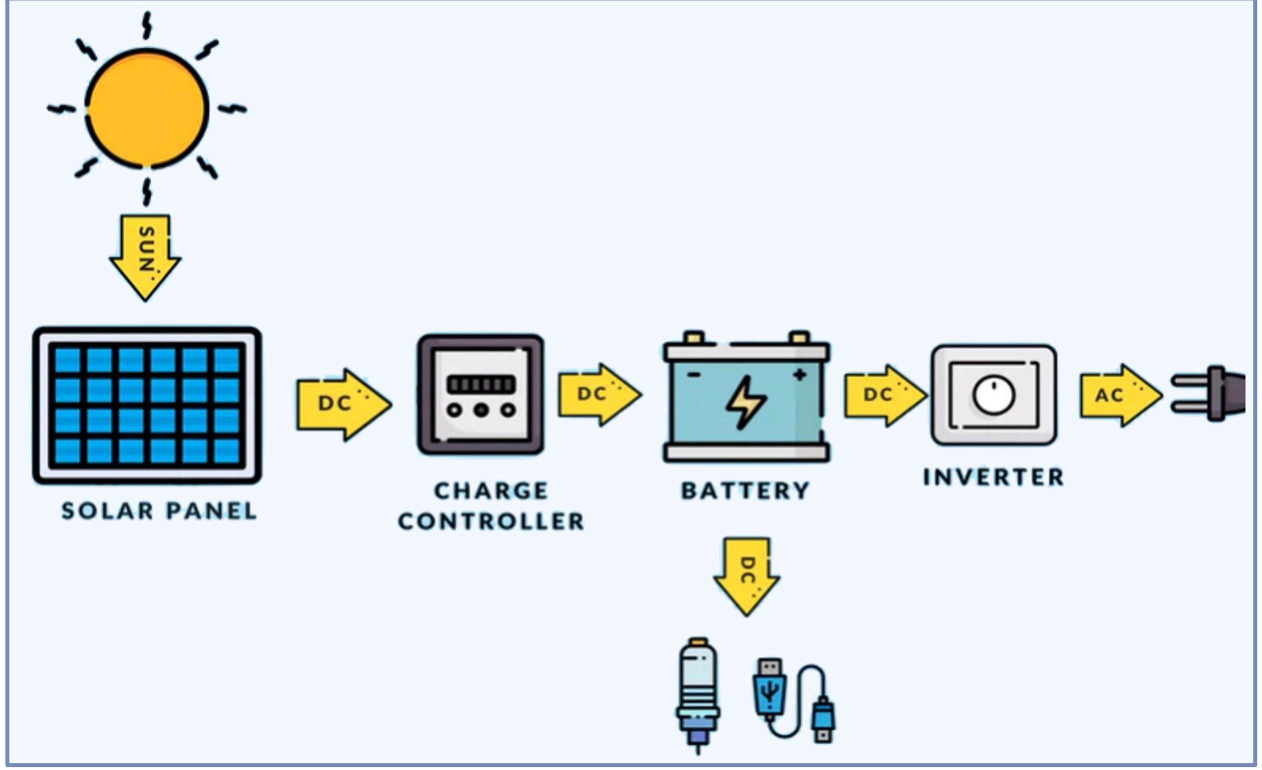

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FIG 9. **RESOLUTION OUTCOMES:** GENERAL WORKFLOW OF PV TROUBLESHOOTING

"FAILURE EVENTS"

"INSURANCE CLAIMS EVENTS"

- Failure events that cause significant property or revenue loss to the asset owner.

"OPERATIONS & MAINTENANCE EVENTS"

- Text records of any actions a technician had to perform on a system.
- These may include failure events that result in a loss, or even a claim
- But also include preventative maintenance events, work orders, purchase orders, etc.

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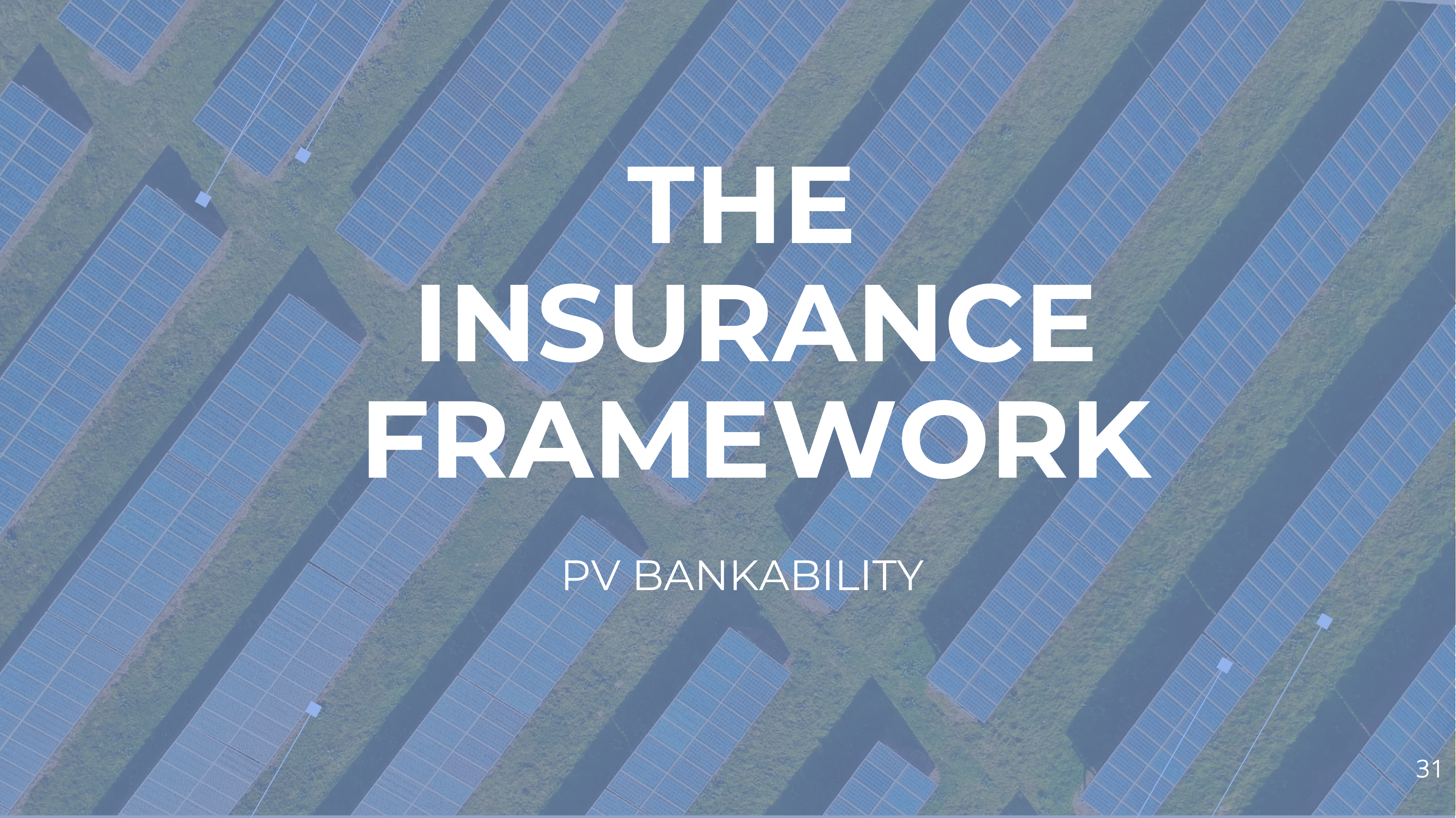


THE INSURANCE FRAMEWORK

PV BANKABILITY

PV BANKABILITY

THE BALANCING ACT

PERFORMANCE

“Energy production”

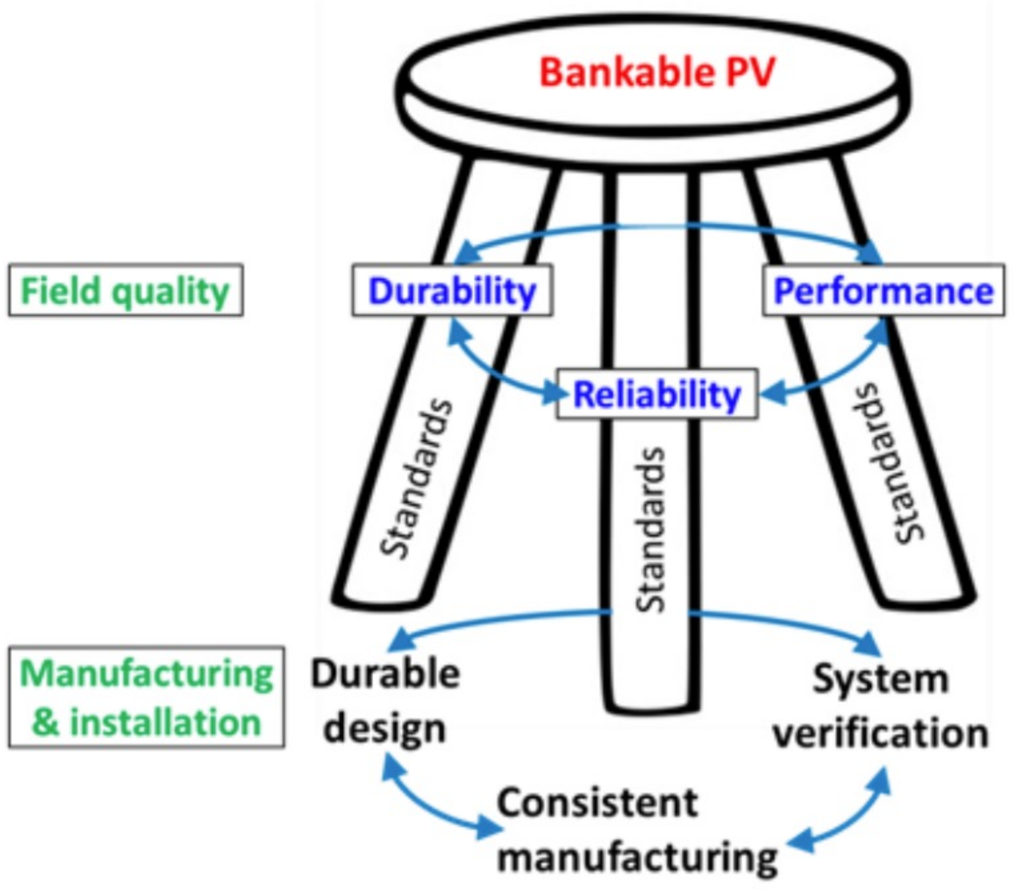
DURABILITY

“Gradual decline of performance”

RELIABILITY

“Occurrence of disruptive events”

FIG 10. **BANKABLE PV AS A 3-LEGGED STOOL** JORDAN, 2014



PV BANKABILITY

THE BALANCING ACT

PRODUCTION

PERFORMANCE

“Energy production”

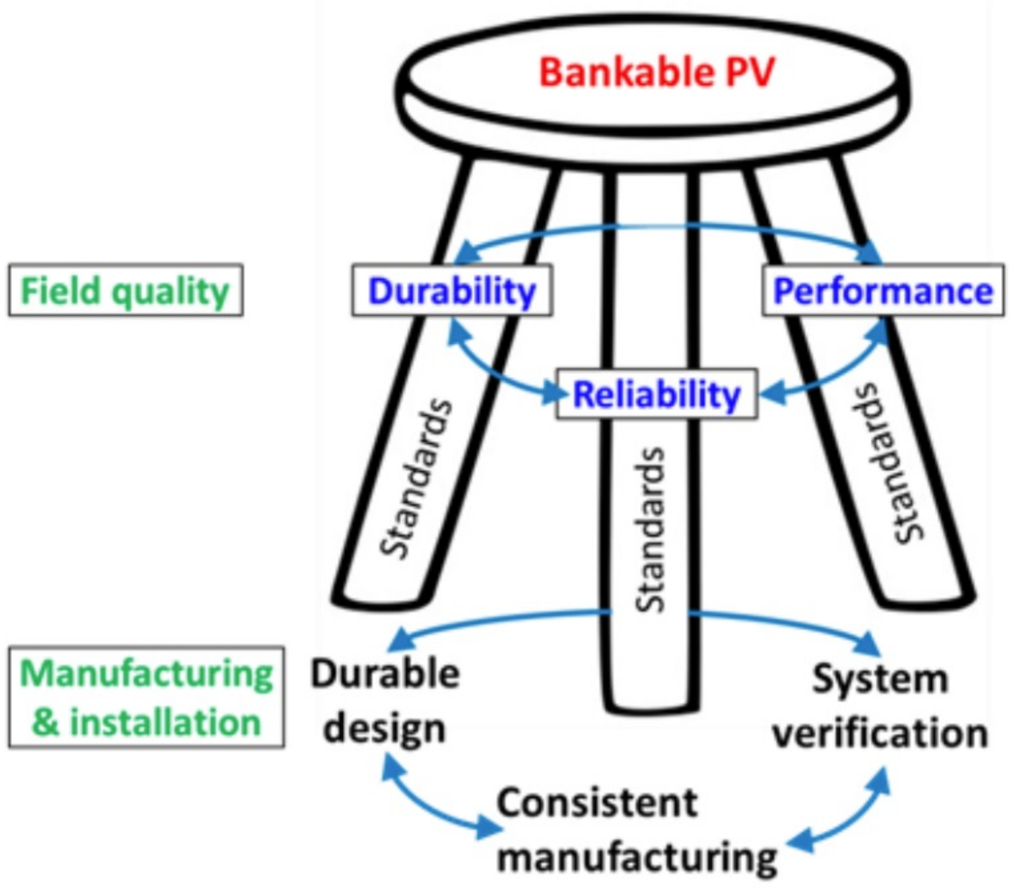
DURABILITY

“Gradual decline of performance”

RELIABILITY

“Occurrence of disruptive events”

FIG 10. **BANKABLE PV AS A 3-LEGGED STOOL** JORDAN, 2014



THE BALANCING ACT

PERFORMANCE

"Energy production"

DURABILITY

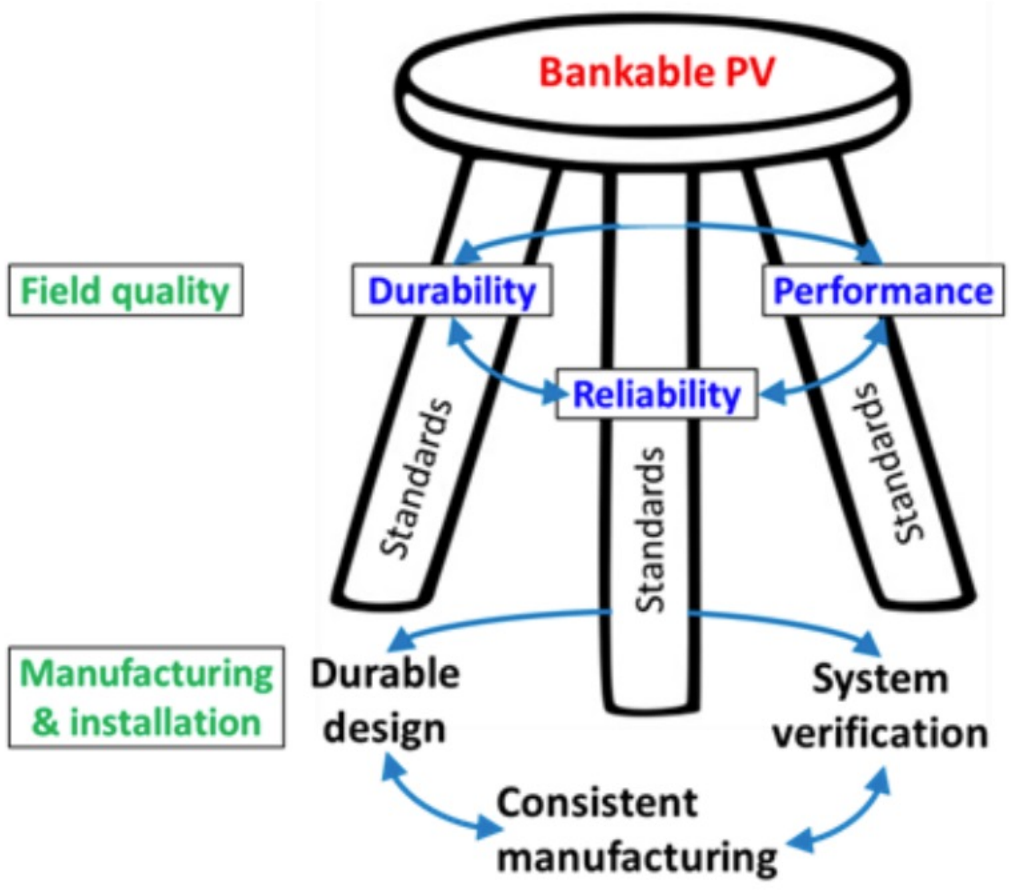
"Gradual decline of performance"

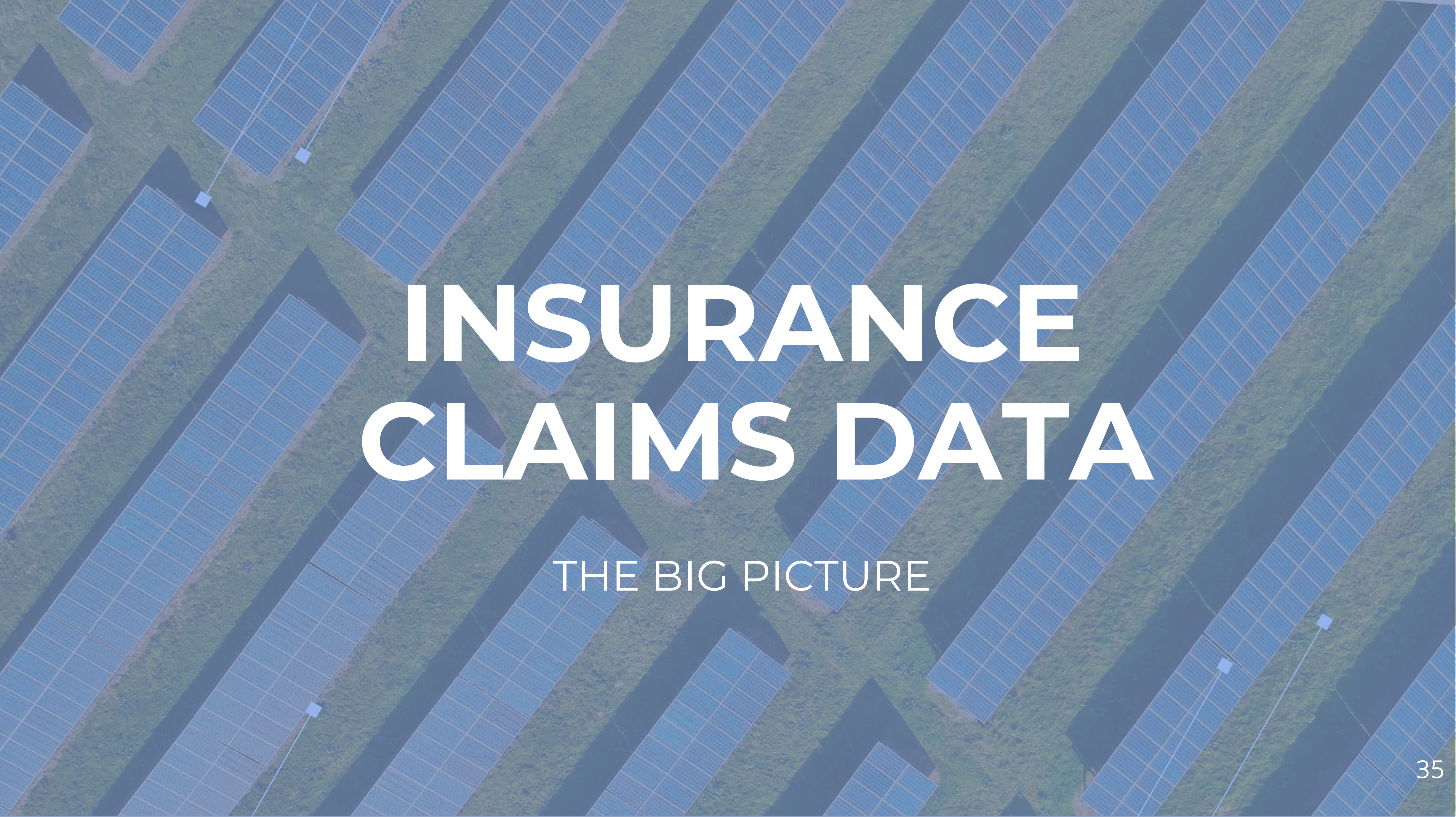
PROPERTY

RELIABILITY

"Occurrence of disruptive events"

FIG 10. **BANKABLE PV AS A 3-LEGGED STOOL** JORDAN, 2014





INSURANCE CLAIMS DATA

THE BIG PICTURE

INSURANCE CLAIMS

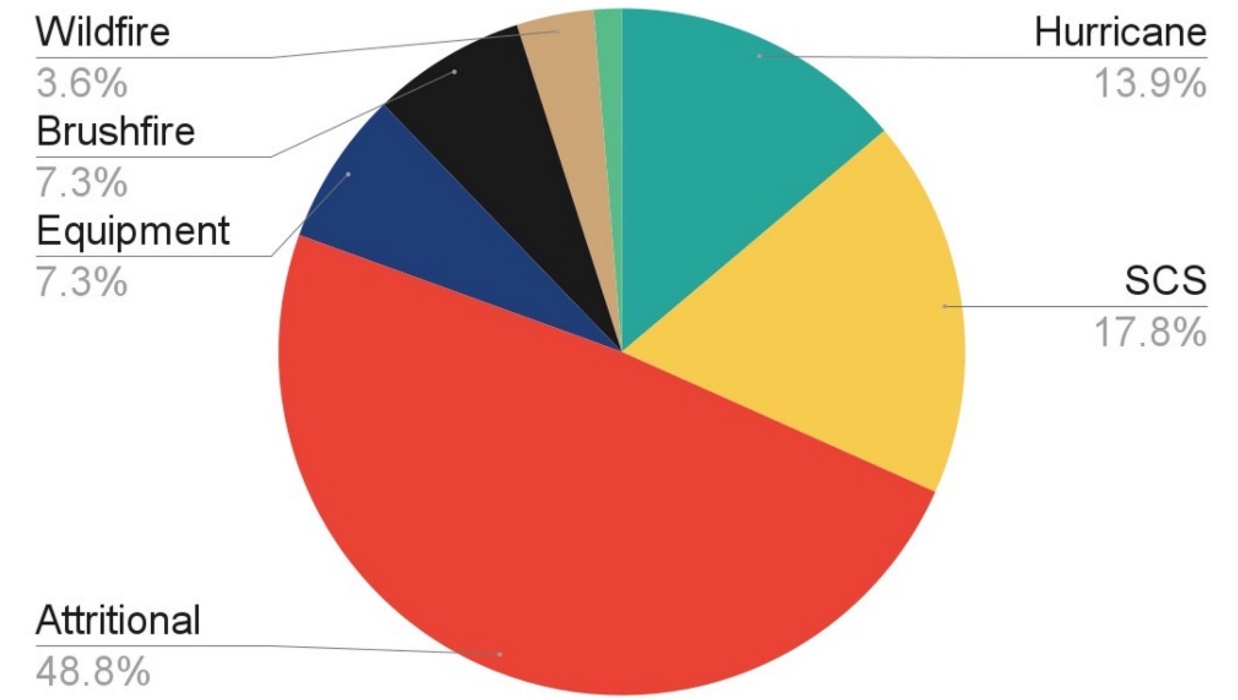
NATURAL CATASTROPHE PERIL

- The risk of loss due to some extreme weather event, such as hail or fire

ATTRITIONAL PERIL

- The risk of loss due to non-weather-related events (such as equipment failure, theft/vandalism, etc.)
- Attritional losses are the most common and expected events

FIG 13. **CLAIMS FREQUENCY, BY PERIL**



CLAIMS DATA

ATTRITIONAL CLAIMS

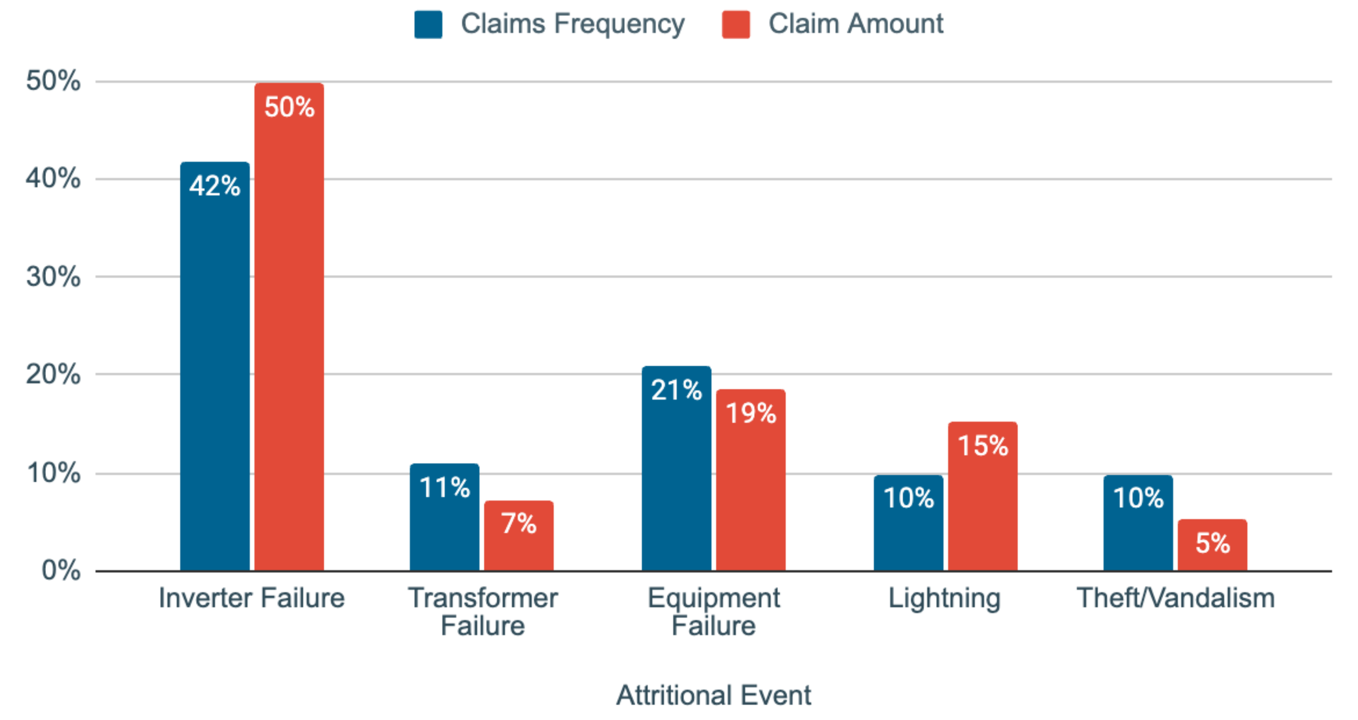
NATURAL CATASTROPHE PERIL

- The risk of loss due to some extreme weather event, such as hail or fire

ATTRITIONAL PERIL

- The risk of loss due to non-weather-related events (such as equipment failure, theft/vandalism, etc.)
- Attritional losses are the most common and expected events
- Of all attritional claims, **inverter failures** are by far the most frequent and costly

FIG 13. **CLAIMS IMPACT, FOR ATTRITIONAL SUB-PERILS**



OBJECTIVES OUTLINE

THE INSURANCE POV

"HOW DOES INSURANCE USE **DATA** TO **MEASURE RELIABILITY**?"

1. WHY	2. DATA	3. PROCESSING	4. BIG PICTURE	5. DETAILED VIEW	6. IMPLICATIONS
DOES INSURANCE CARE?	**WHAT DATA DO WE HAVE?**	**HOW ARE DATA PROCESSED?**	**WHAT IS THE BIG-PICTURE PROBLEM?**	**WHAT ARE THE DETAILED PROBLEMS?**	**WHAT DOES INSURANCE CARE ABOUT?**
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O&M TEXT LOGS

IT’S ALL IN THE DETAILS

INSIGHTS & IMPACTS

O&M CATEGORY

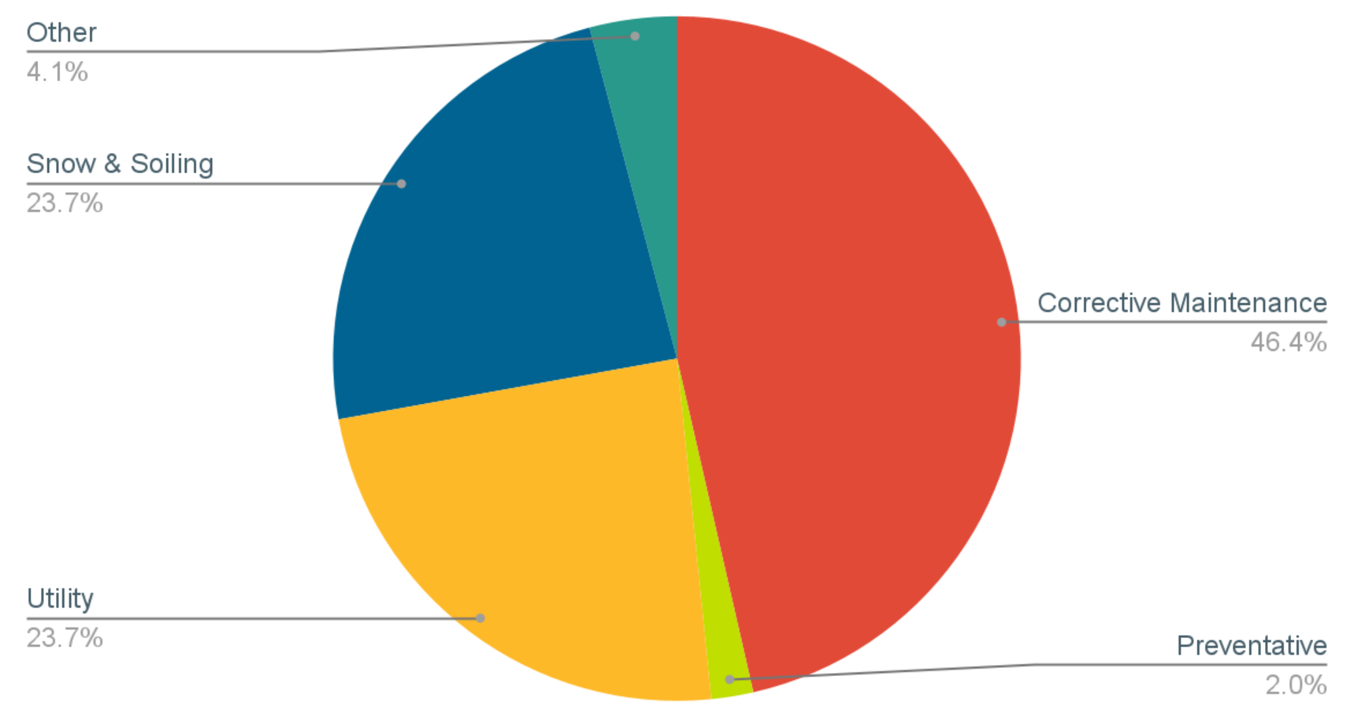
Notable frequency of tickets in response to snow/soiling and utility grid events.

Most tickets are opened due to "corrective maintenance" events.

CORRECTIVE MAINTENANCE PERFORMED IN *RESPONSE* TO A SIGNIFICANT LOSS EVENT.

PREVENTATIVE MAINTENANCE PERFORMED WITH NO CONNECTED LOSS EVENT *(WITH THE EXCEPTION OF POSSIBLE DOWNTIME DURING MAINTENANCE)*

FIG 10A. **TICKET COUNT, BY O&M CATEGORY**



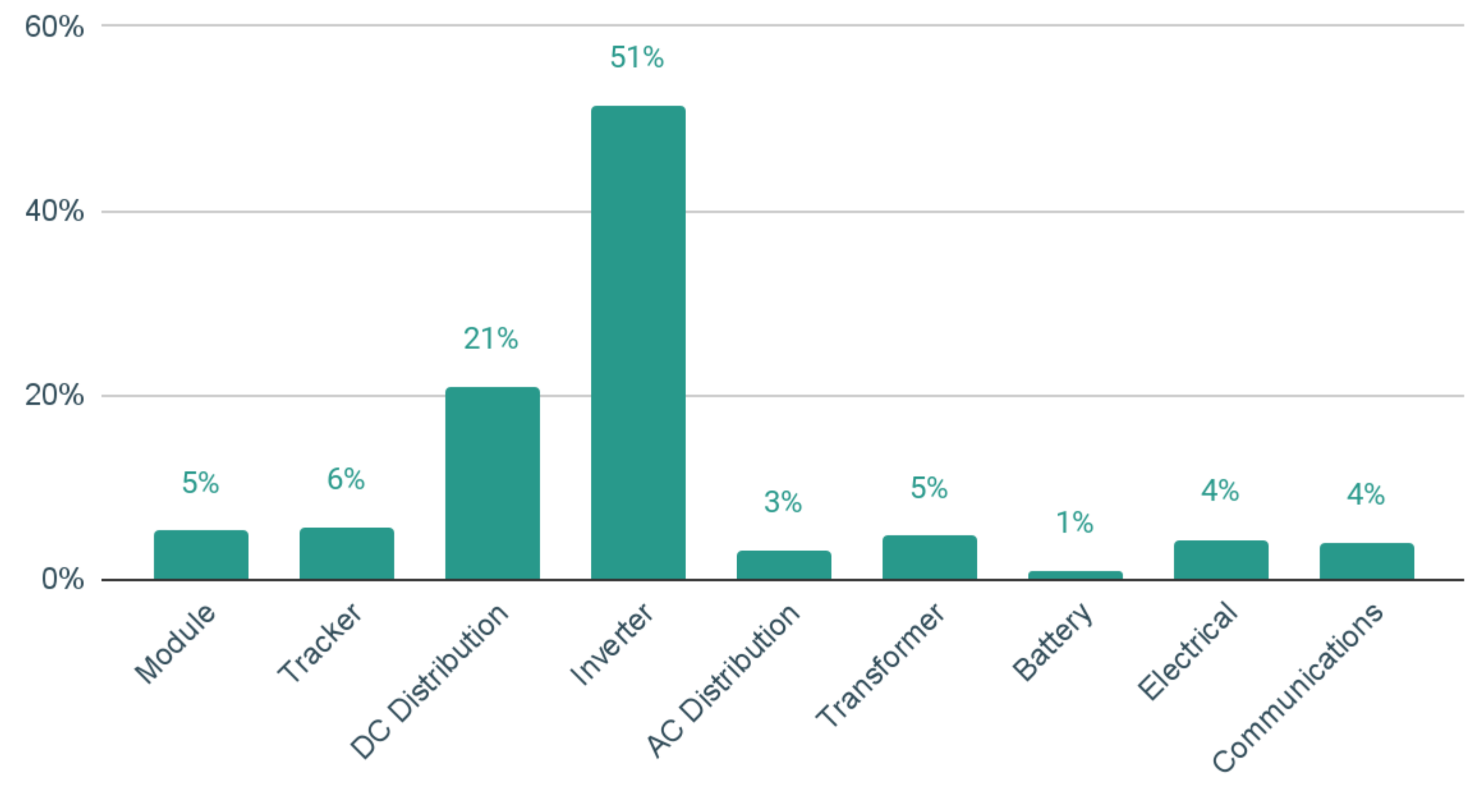
EQUIPMENT TYPE

We see that inverters are the main driver of ticket frequency

Followed by DC distribution.

Inverter technology and maintenance are key to PV system resiliency

FIG 10A. **TICKET COUNT, BY EQUIPMENT CATEGORY**



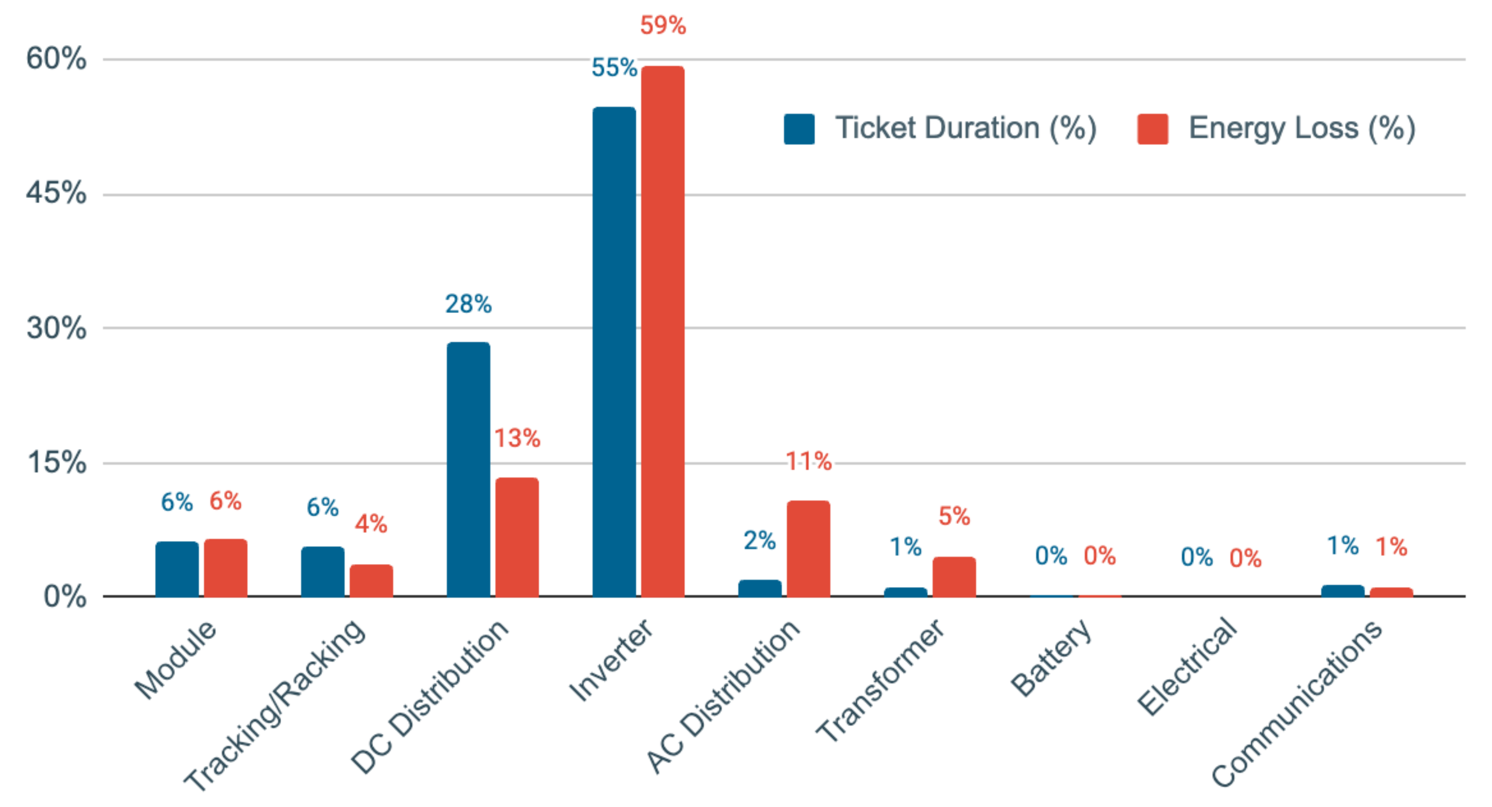
INSIGHTS & IMPACTS

EQUIPMENT TYPE

We see that inverters are the main driver of ticket duration and energy loss

Followed by DC and AC distribution.

FIG 10A. **TICKET COUNT, BY EQUIPMENT CATEGORY**



INSIGHTS & IMPACTS

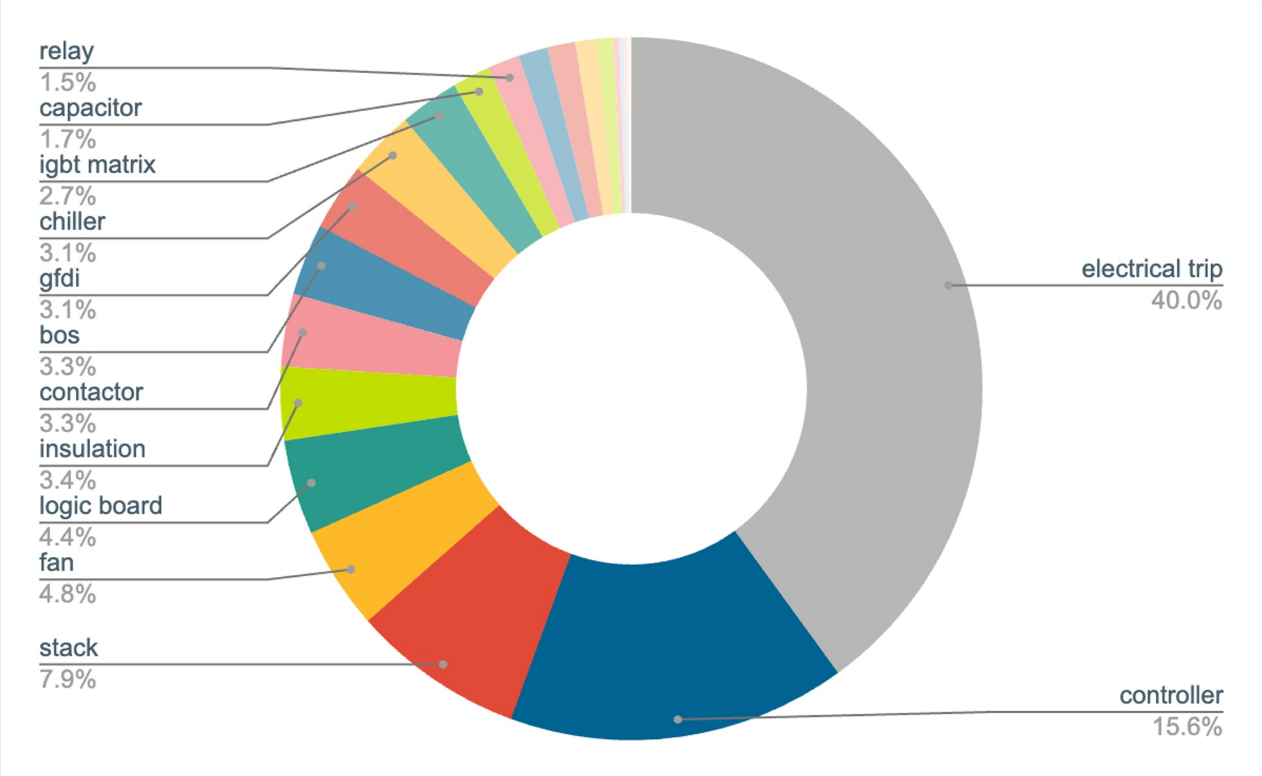
DEEP DIVE: INVERTERS

Inverter troubleshooting may include multiple key terms

Key terms that show up frequently in inverter-specific tickets give us insight into “high-touch” sub-components.

SPARE COMPONENTS AND PREVENATIVE MAINTENCE MAY REDUCE TICKET FREQUENCY

FIG 13. **KEYWORD FREQUENCY, INVERTER-RELATED ONLY**



INSIGHTS & IMPACTS

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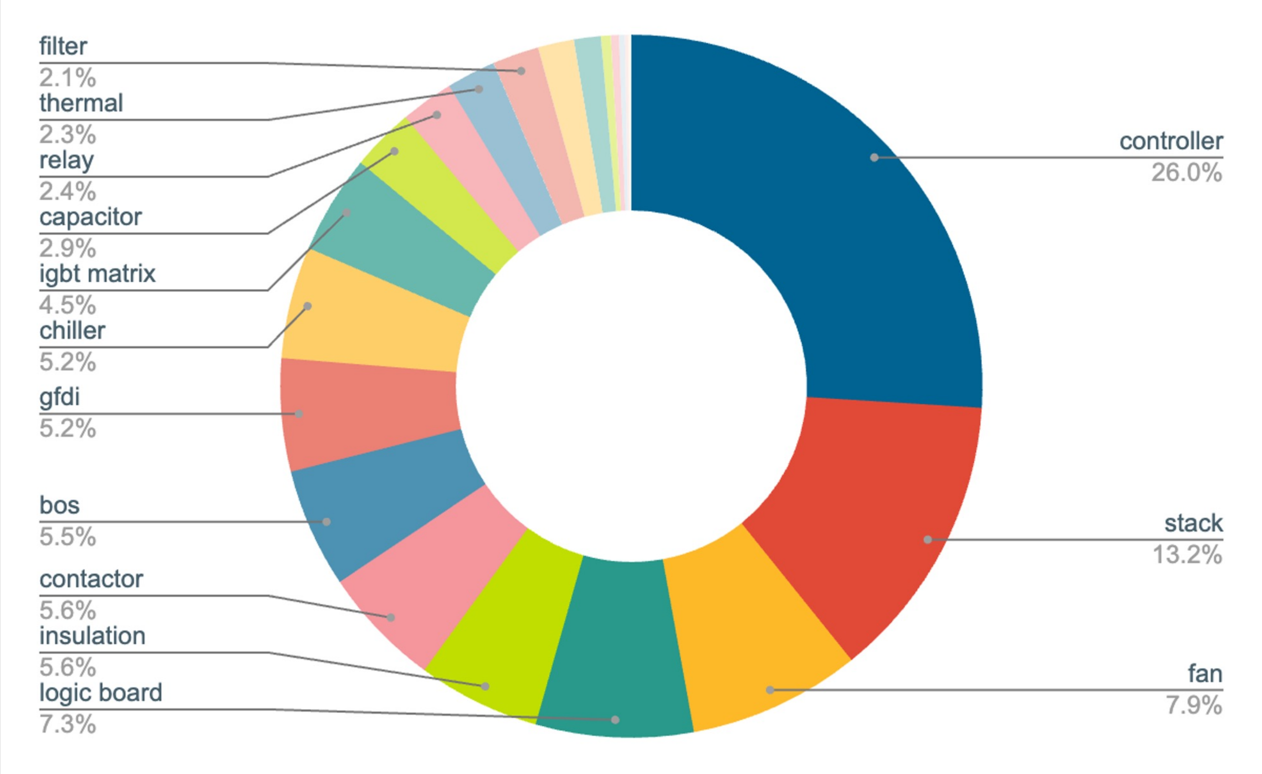
Key terms that show up frequently in inverter-specific tickets give us insight into "high-touch" sub-components.

SPARE COMPONENTS AND PREVENATIVE MAINTENCE MAY REDUCE TICKET FREQUENCY

FIG 13. **KEYWORD FREQUENCY, INVERTER-RELATED ONLY** ("TRIP" REMOVED)



INSIGHTS & IMPACTS

RESOLUTION OUTCOME

"Repair" and "Replace" as an outcome vary significantly between equipment types.

WHAT EQUIPMENT TYPES ARE DRIVEN BY REPLACEMENT VS. REPAIR?

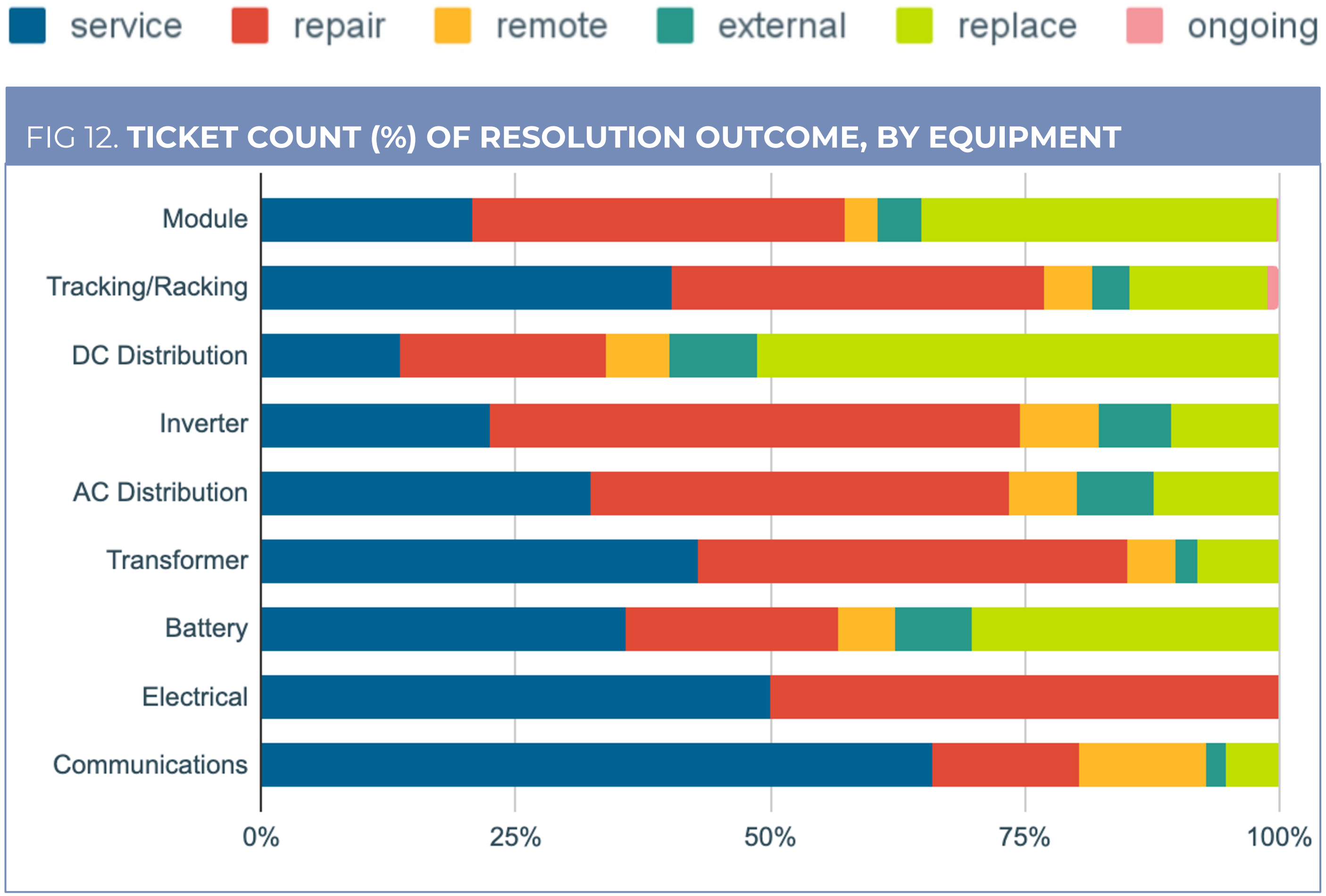


FIG 12. **TICKET COUNT (%) OF RESOLUTION OUTCOME, BY EQUIPMENT**

INSIGHTS & IMPACTS

RESOLUTION OUTCOME

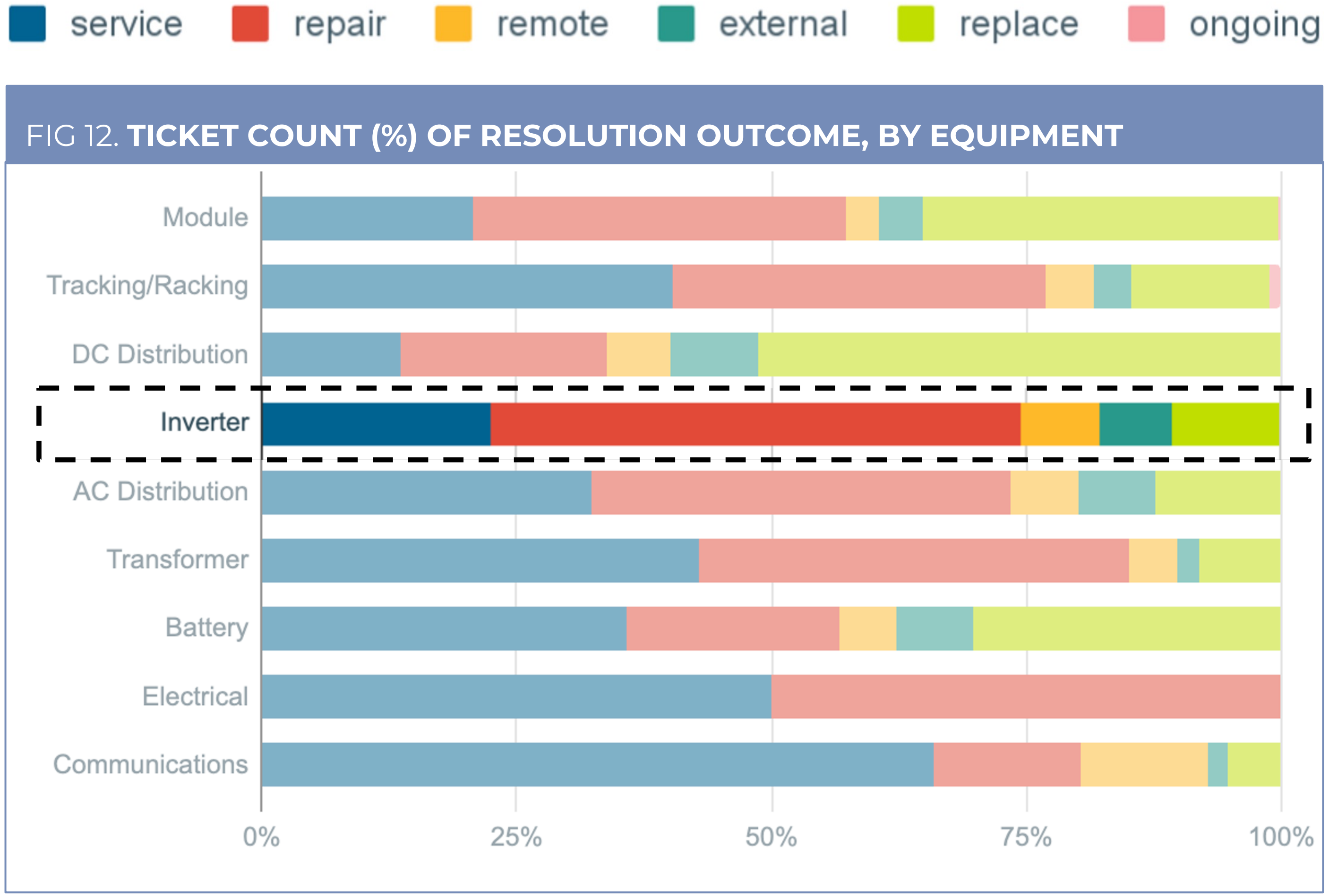
Inverter-driven resolutions are driven by repairs.

Inverters are made up of many sub-components, so there are many possible failure modes

This also means there is opportunity to repair issues

WHAT EQUIPMENT TYPES ARE DRIVEN BY REPLACEMENT VS. REPAIR?

FIG 12. **TICKET COUNT (%) OF RESOLUTION OUTCOME, BY EQUIPMENT**



OBJECTIVES OUTLINE

THE INSURANCE POV

"HOW DOES INSURANCE USE **DATA** TO **MEASURE RELIABILITY**?"

1. WHY

DOES INSURANCE CARE?

Insurance has a vested interest in equipment reliability

2. DATA

WHAT DATA DO WE HAVE?

Summary of the data available for analysis.

3. PROCESSING

HOW ARE DATA PROCESSED?

Pre-processing needed to use data.

4. BIG PICTURE

WHAT IS THE BIG-PICTURE PROBLEM?

Using claims data to understand the present state of inverter reliability

5. DETAILED VIEW

WHAT ARE THE DETAILED PROBLEMS?

Using O&M logs to get a more detailed view of the present state of inverter reliability

6. IMPLICATIONS

WHAT DOES INSURANCE CARE ABOUT?

Conclusions and takeaways for the insurance market and inverter reliability

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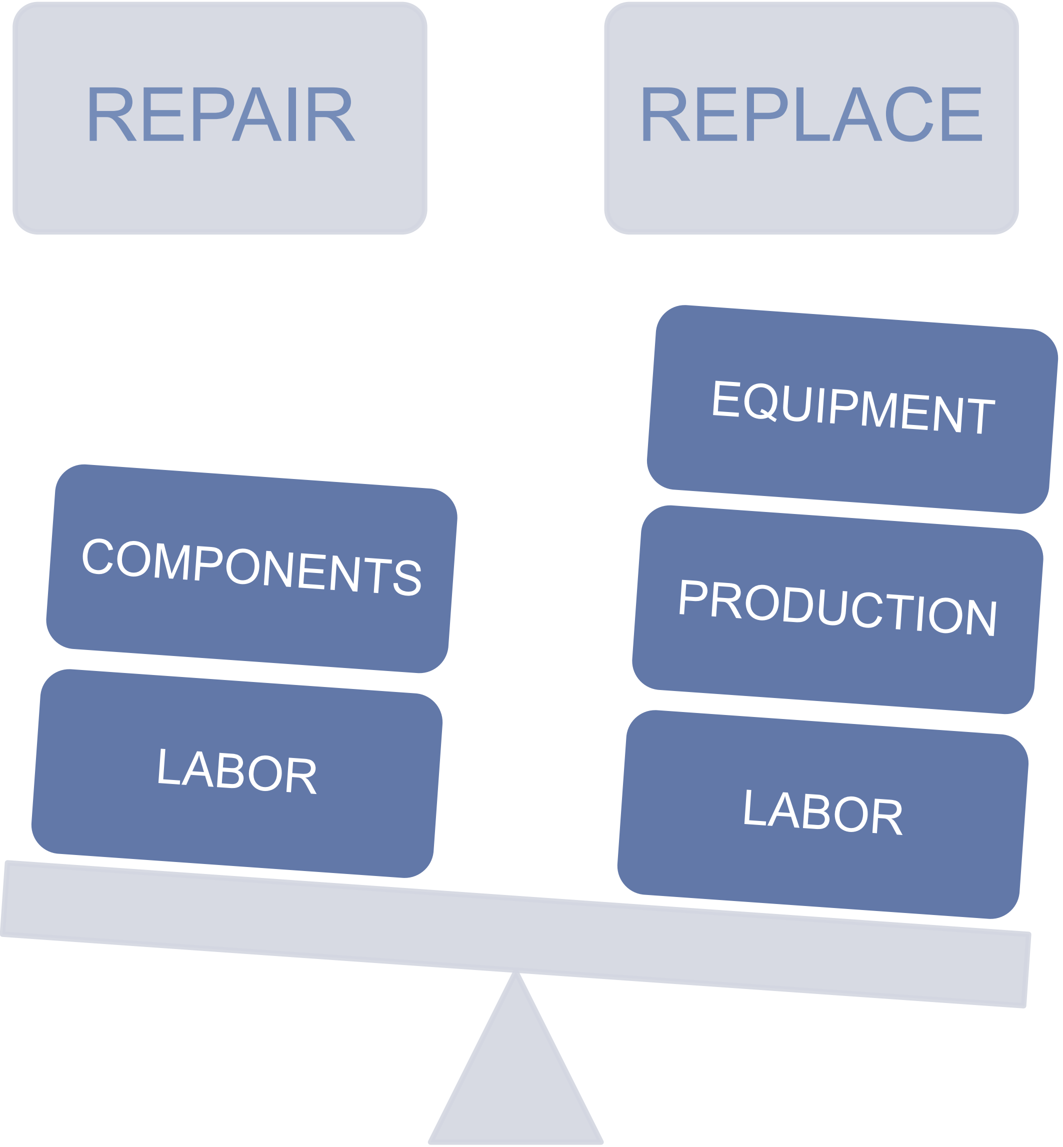
INSURANCE IMPLICATIONS

Full inverter replacement is significantly more costly than an inverter repair

- Insurance is looking to mitigate risk
- "Inverter failures will occur. Will the asset owner be able to repair?"



RELIABILITY: EXPANDED

Full inverter replacement is significantly more costly than an inverter repair

- Insurance is looking to mitigate risk
- "Inverter failures will occur. Will the asset owner be able to repair?"

CONSIDER: REPAIR

OPERATIONS & MAINTENANCE

- Technicians available to diagnose and repair?
- Sub-components available? Inventory on-hand? Special-order?

MAKE & MODEL

- PV technology moves fast, is this equipment still in production?
- Service support from manufacturers?

ENGINEERING DESIGN

- Modular sub-components?

INSURANCE IMPLICATIONS

RELIABILITY: EXPANDED

INSURANCE VIEWS RELIABILITY AS A BALANCING ACT

RELIABILITY INVOLVES EVERYONE IN THE PV VALUE CHAIN

CONSIDER: **REPAIR**

OPERATIONS & MAINTENANCE

- Technicians available to diagnose and repair?
- Sub-components available? Inventory on-hand? Special-order?

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ACKNOWLEDGEMENTS

SINCERE THANKS TO

To my predecessors in PV, who have created the existing body of work on PV resiliency, which I have had the honor learn from

To my colleagues who operate and maintain PV sites for us all

INTERESTED IN LEARNING MORE?

CONNECT TO THE PV FEEDBACK LOOP

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Nicole D. Jackson
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NREL

Andy Walker
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SETO

Tassos Golnas
Inna Kozinsky

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APPENDIX

Reliability in PV Applications

Accelerated life tests of relays

11.04.2024 Golden, Colorado

SMA Solar Technology AG, Wolfram Dege

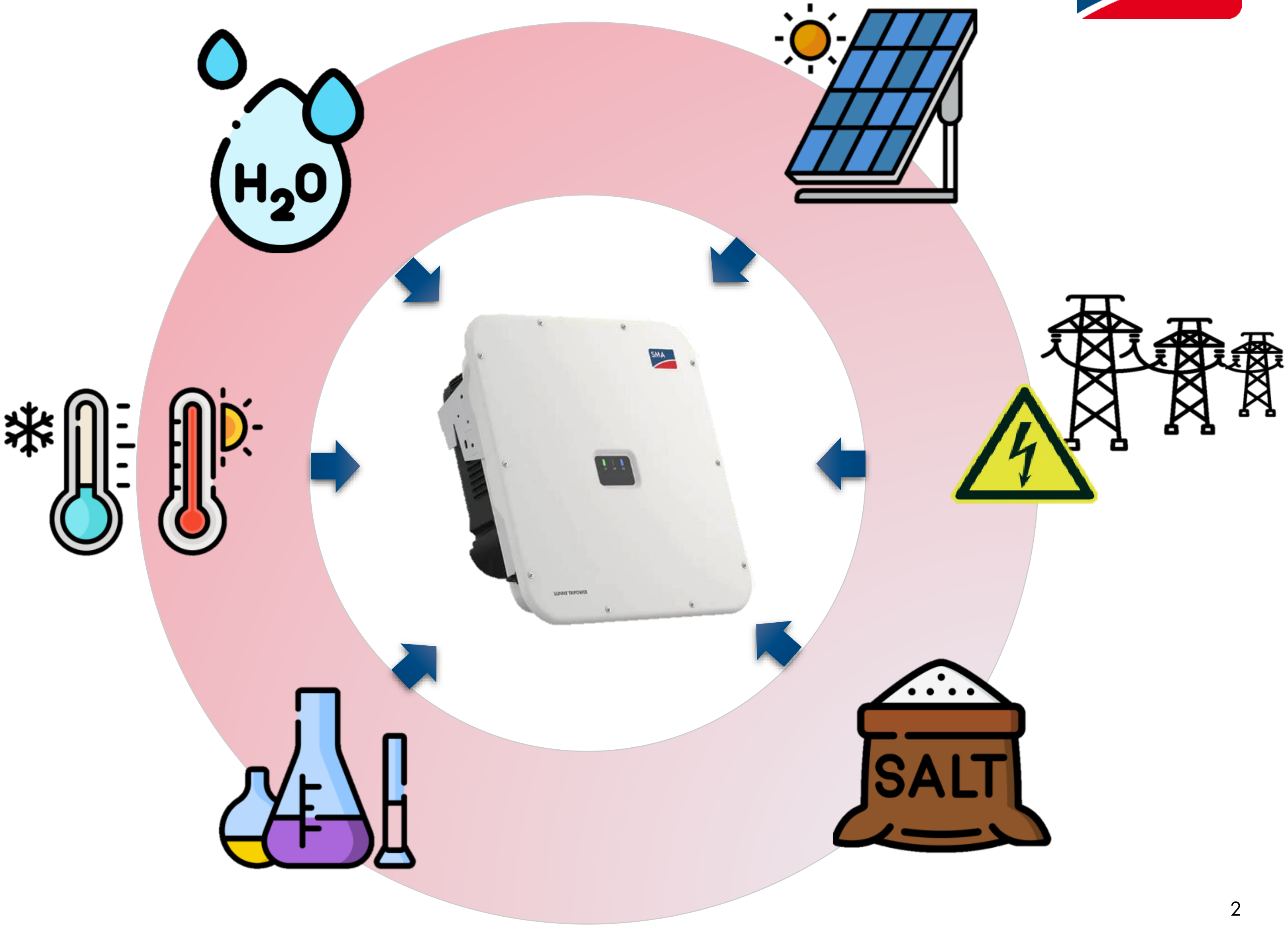
Environmental impacts on solar inverters

Environmental impacts

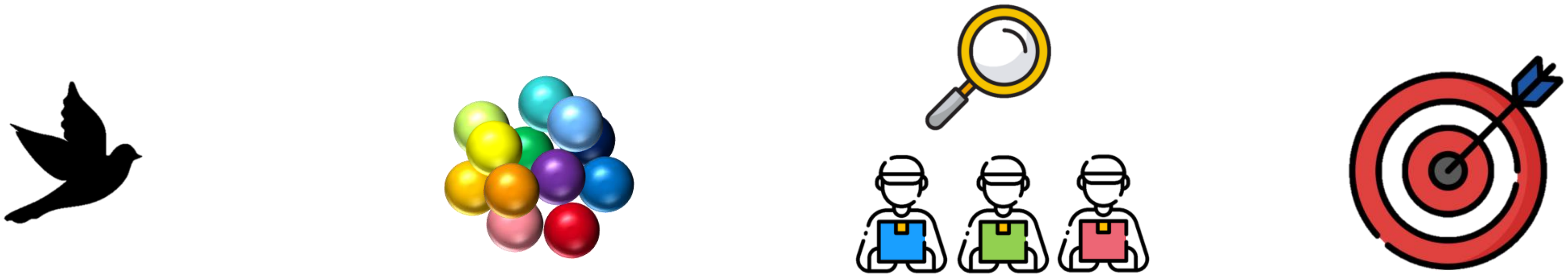
+

Operation

- Fatigue
  - Failures
    - End of life



Reliability testing on component level



Testing in early project stage

- Less failures in field
- Cheaper bug fixing

Bigger inspection lots

- Better quality of forecast
- Better decisions

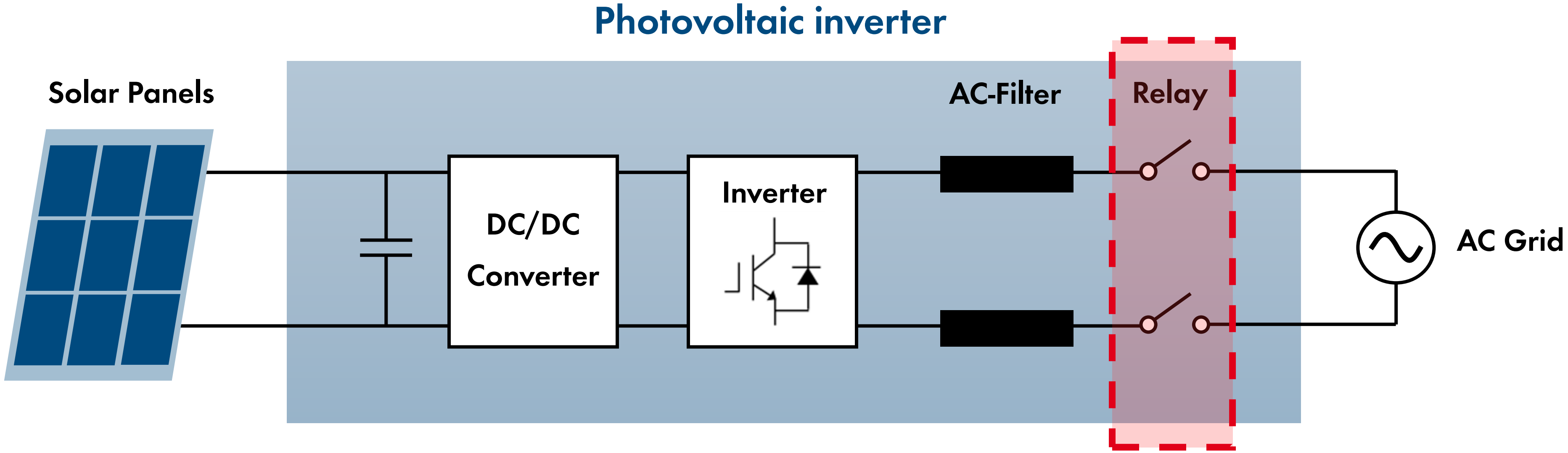
Testing of several suppliers

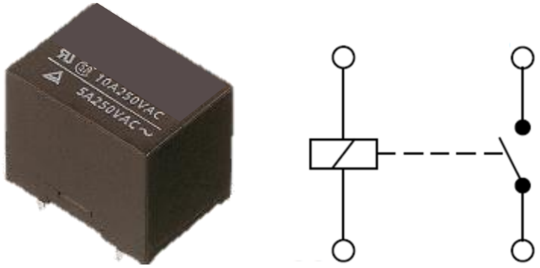
- Saving costs
- Increasing reliability

Targeted testing

- Higher stress levels
- Faster testing

Relay as interconnection between inverter and grid



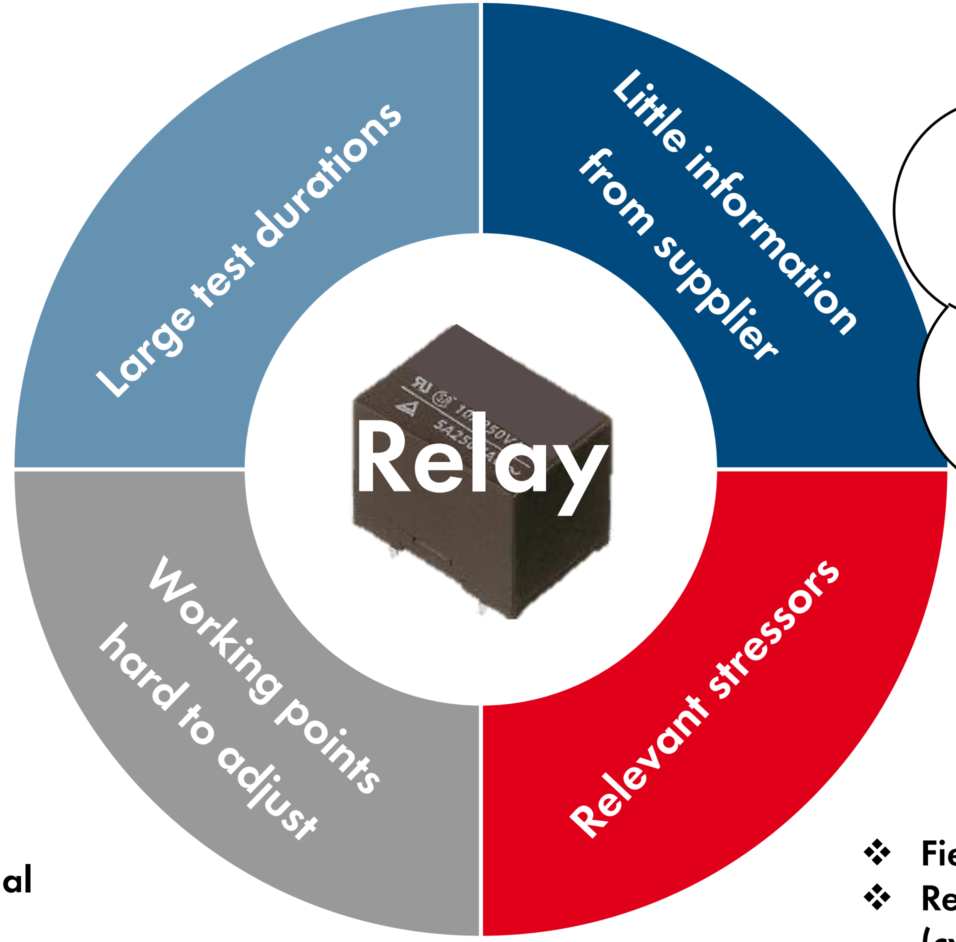


Field mission profile - Grid relays in PV application

- High currents + high temperatures
- Power cycles
- Switching

Life testing of relays - Challenges

- ❖ No failures in tests
  → no lifetime models
- ❖ No degradation model possible
- ❖ Extreme large test durations



Large test durations

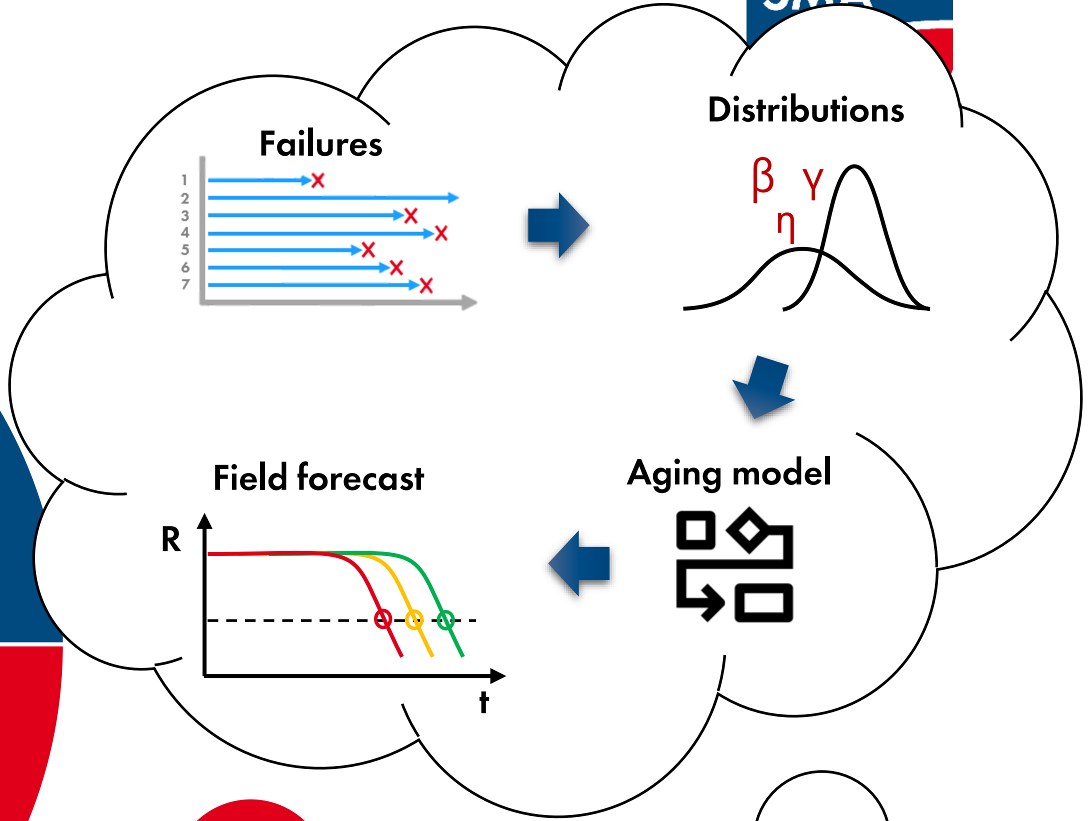
Little information from supplier

Relay

Working points hard to adjust

Relevant stressors

- ❖ Working points hard to adjust because of thermal interdependencies

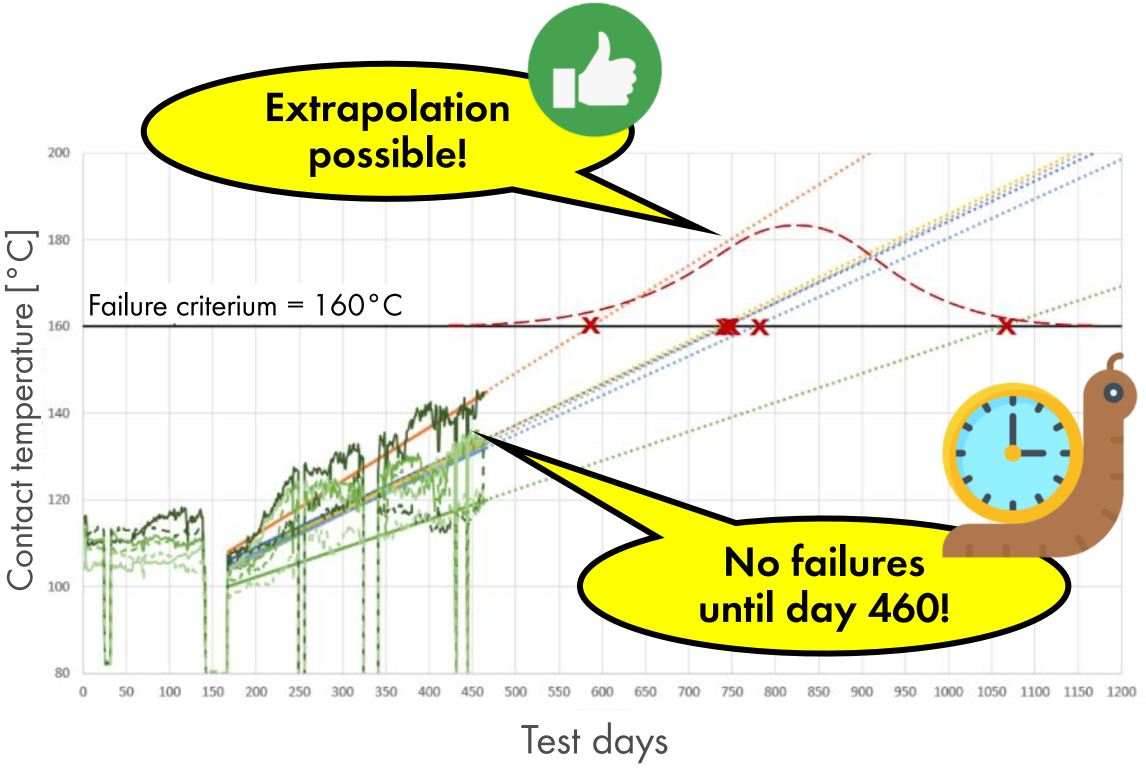


- ❖ Field relevant stressors unknown
- ❖ Relation of different stressors unknown (cycles, temperature...)

Challenges – Low acceleration

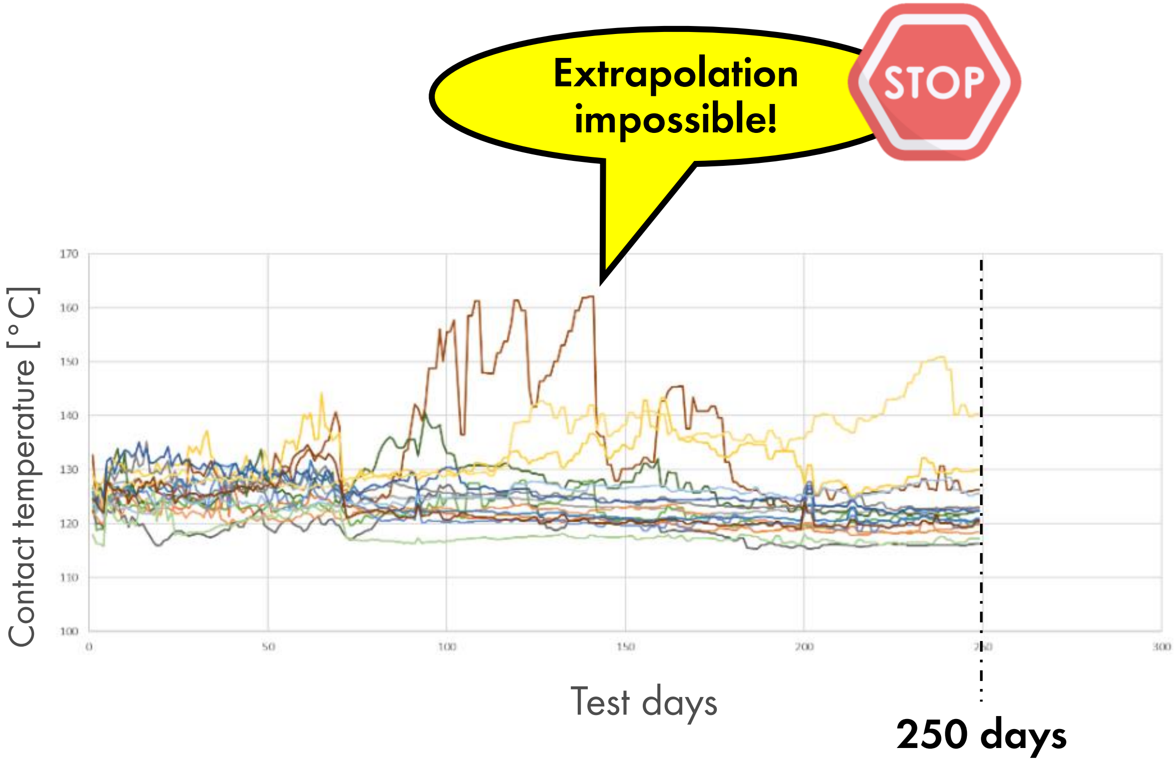
Current status

- Extreme large test durations (cyclic current test)
- No failures in tests → no aging models
- No degradation model → often no extrapolation possible



Extrapolation possible!

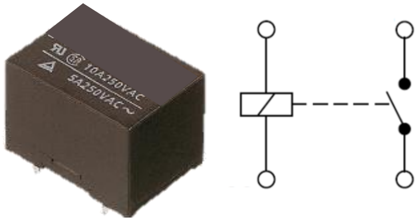
No failures until day 460!

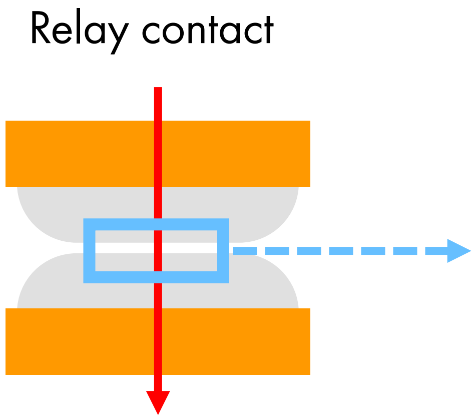


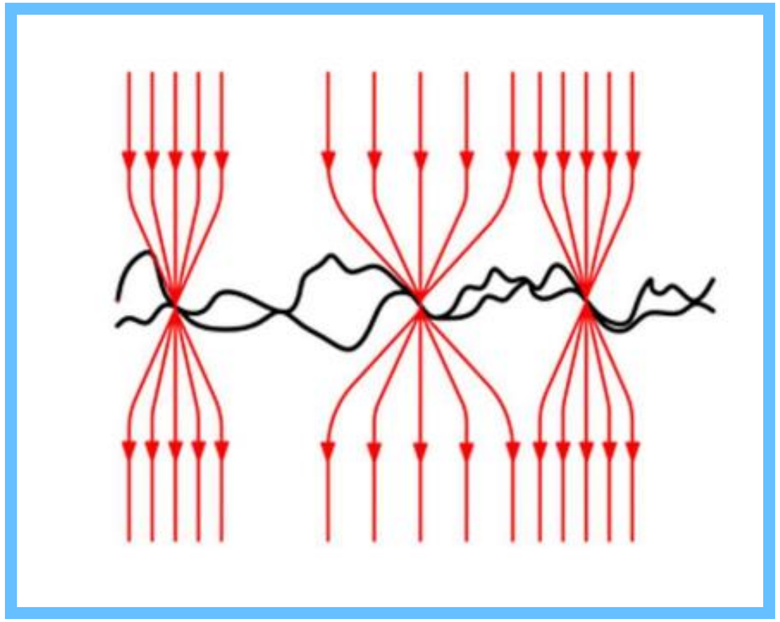
Extrapolation impossible!

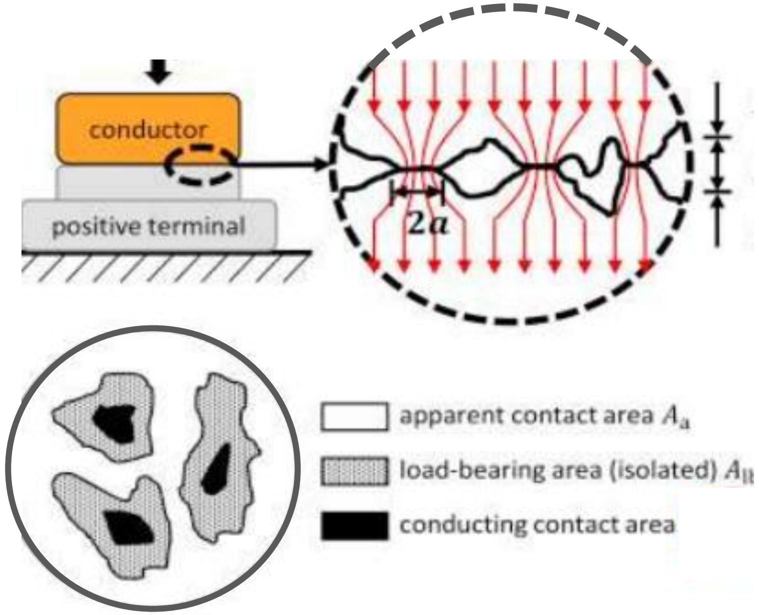
250 days

Physics of failure









Because of the roughness of the contact surface, only small parts of the contact are conducting current.

- Oxide layers occur on the contacts over time.
  - Closing the relay: The layers are destroyed by electric fields again and again.
    - Increasing roughness and melting points
      - Increasing resistance

Field analysis and pretests

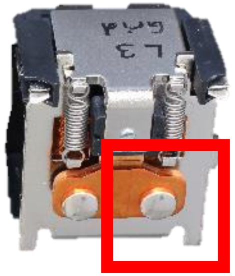
Field inverters

- About 9 years in operation
- Location is known
- Load profile is known
- No defect but aged relays

Pretests

- Humidity test
- Temperature shock test
- **Cyclic current test**

→ Failure mode from **cyclic current test** shows the most similarities to the field contacts

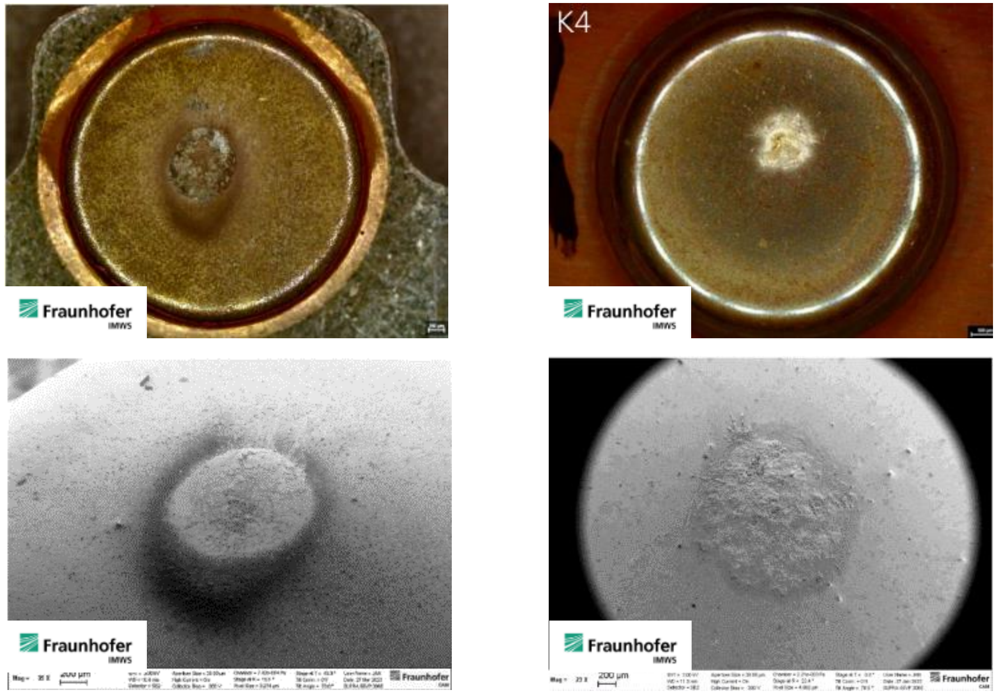


Relay contact

9 years in field

Relay contact

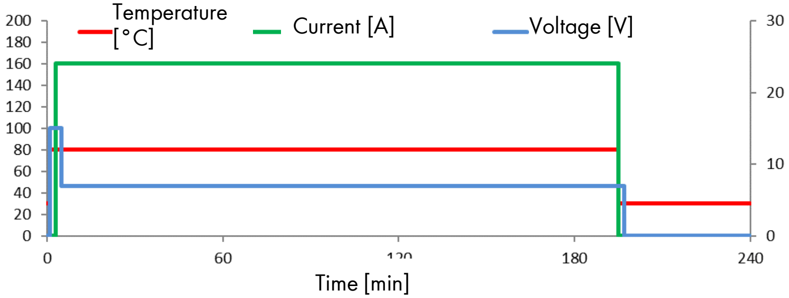
cyclic current test

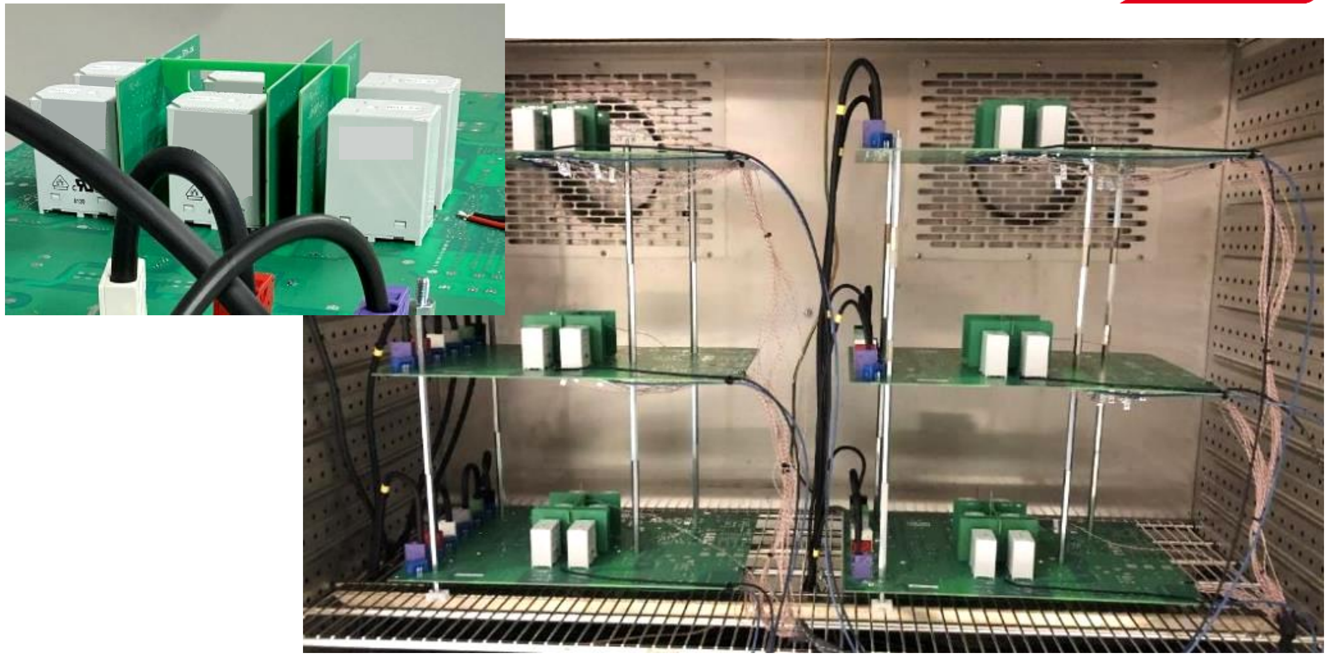


Iteration 1 – Test design – Accelerated life test

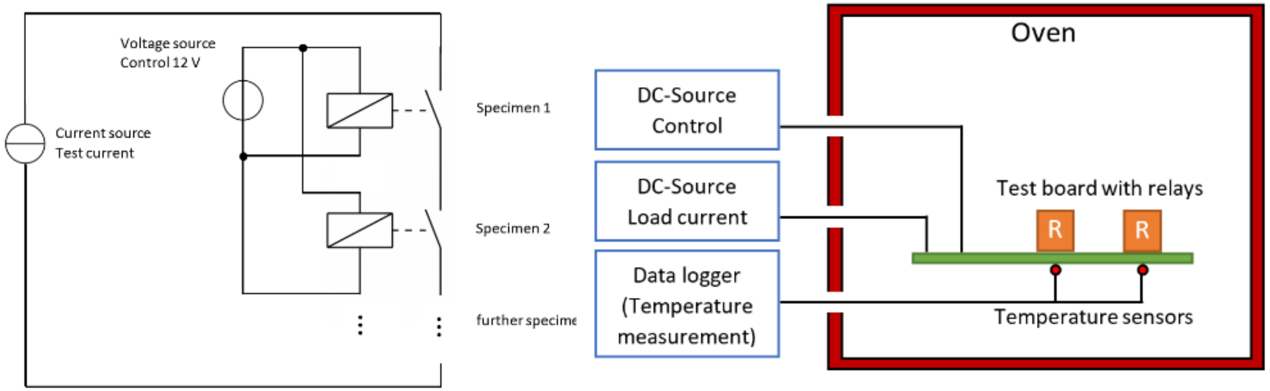
Cyclic current test

- Environment: Oven → 80°C
- Using boards from inverter with mounted relays
- Test profile: 3:15 h Current → 0:45 h No current



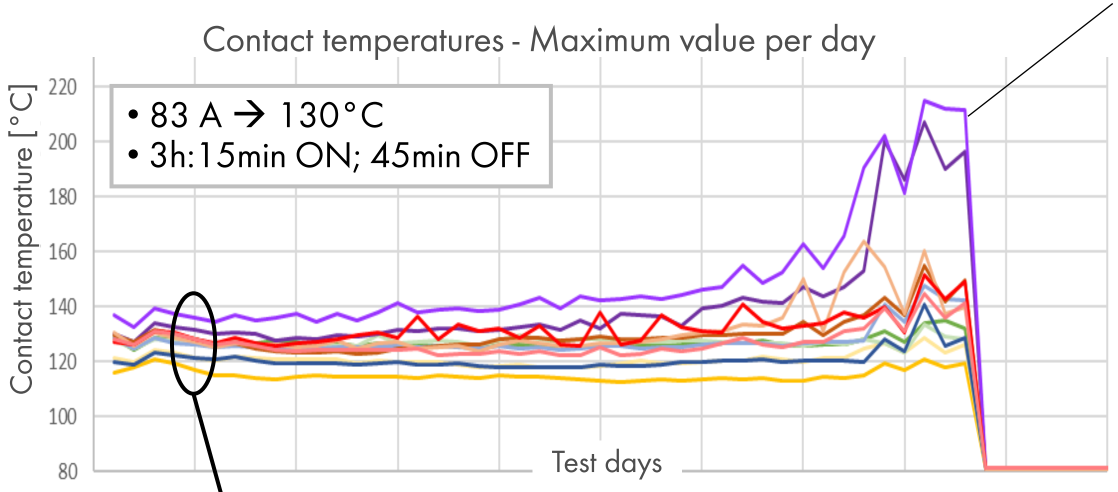


- 3 different working points:
  1. 60A (120°C)
  2. 80A (130°C)
  3. 100A (140°C)
- Permanent measuring temperatures of all contacts
- Failure criterium:
  Malfunction or contact temperature exceeds 210°C



Iteration 1 – Results

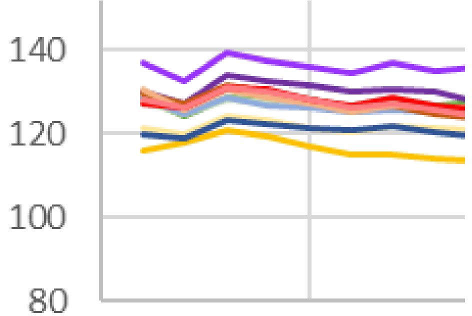
Relay 4



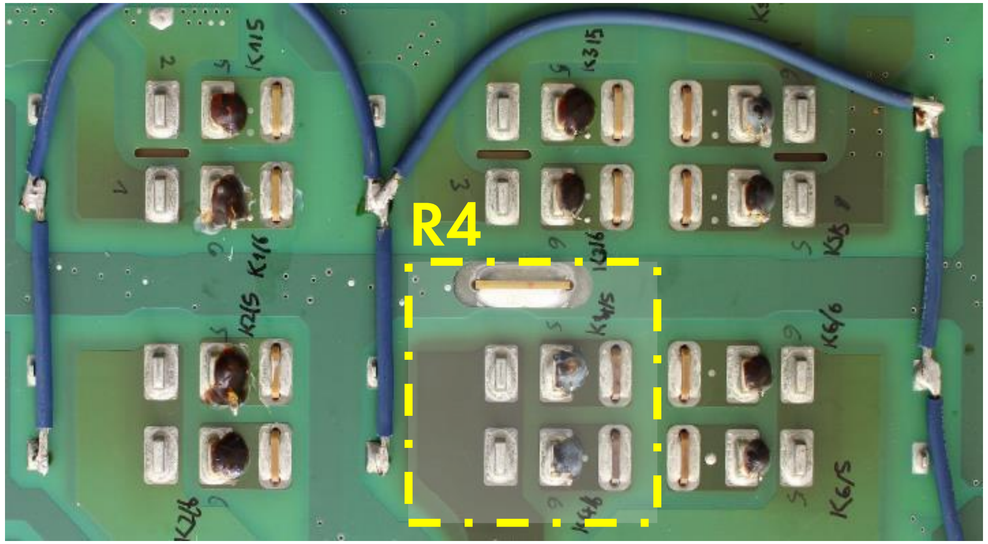
- 83 A → 130°C
- 3h:15min ON; 45min OFF

41 test days

Large dispersion



- 41 test days: Exceeding criterium 210°C
- 43 test days: Stopping test
- Hottest relay: R4



Solder side of pcb

Iteration 1 – Results

Test group	Number Specimen	Cycle time [h:min]	Contact temperature in steady state in current phase	Adjusted test current	Run time (1st failure)
1	6	4h (3:15 ON 45 Off)	**120 °C**	58 A	241 days (suspension)
2	6	4h (3:15 ON 45 Off)	**130 °C**	83 A	41 days
3	6	4h (3:15 ON 45 Off)	**140 °C**	97 A	7 days

Working points and their impact:

Deformation of plastic!

- **140°C** (~100 A): Too high for regular aging; danger of inappropriate failure mechanisms
- **130°C** (~80 A): Failures in the range of 40 test days
- **120°C** (~60 A): Ageing comparatively slowly; test time too long

Iteration 1 – Conclusion

Findings after the end of the test:

- The higher the **initial contact temperature**, the faster the temperature increase over time
- Range for sufficient **working point** around **130 °C**
- **Wide dispersion of contact temperatures**:

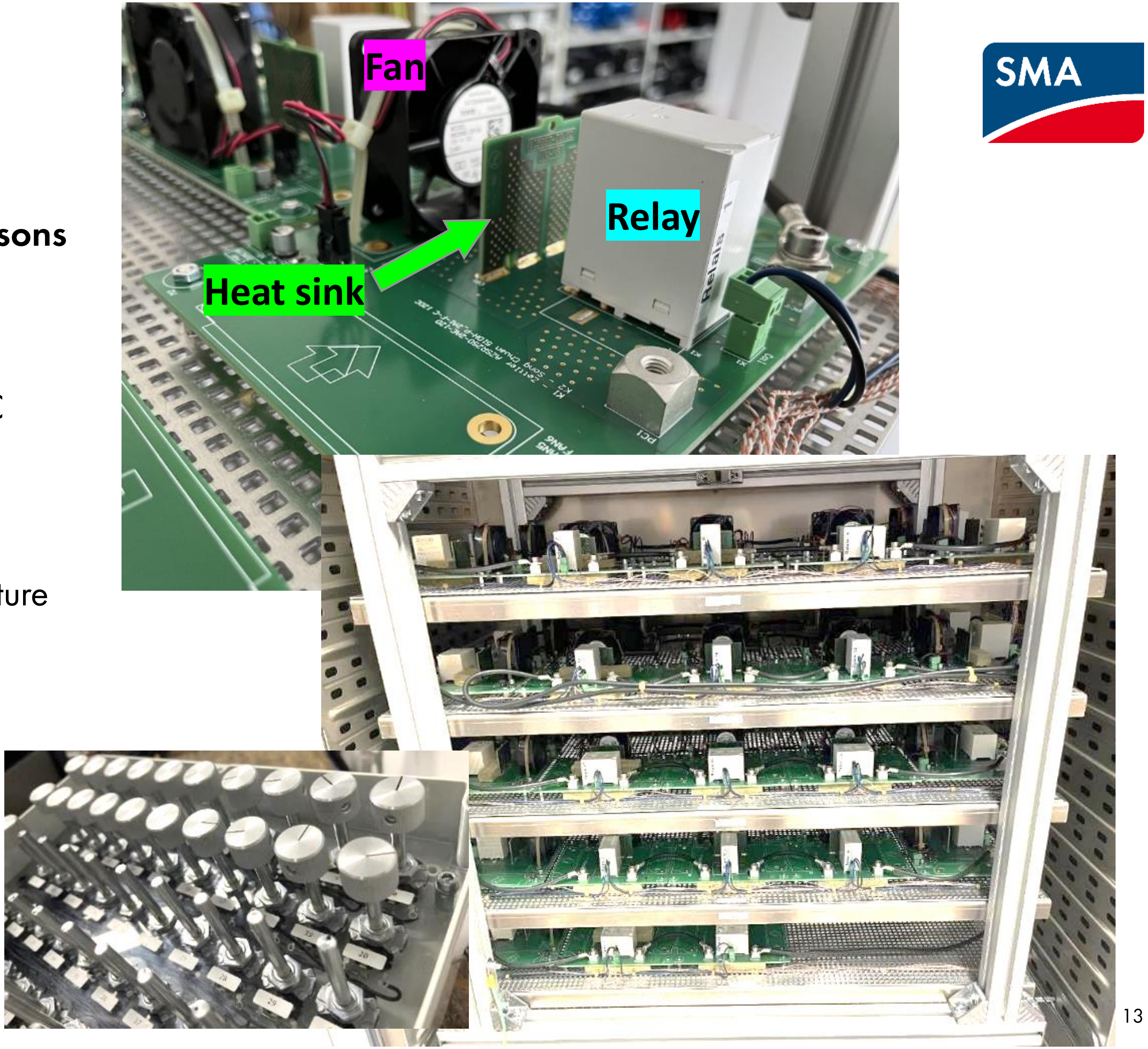
  → The contacts of the relays in the middle of the board are the hottest and are aging the fastest
- Not easy to replace or short circuit a failed device

  → only **1 failure per test group → No distributions or aging model**

Iteration 2 – Test design

New test taking into account the lessons learned

- Cyclic current test
- 3 test groups 125°C, 130°C, 135°C
- 8 specimen per test group
- 1 DUT → 1 test board
- Control of the working point temperature
- Heatsink + Fan
- Control via potentiometer per fan

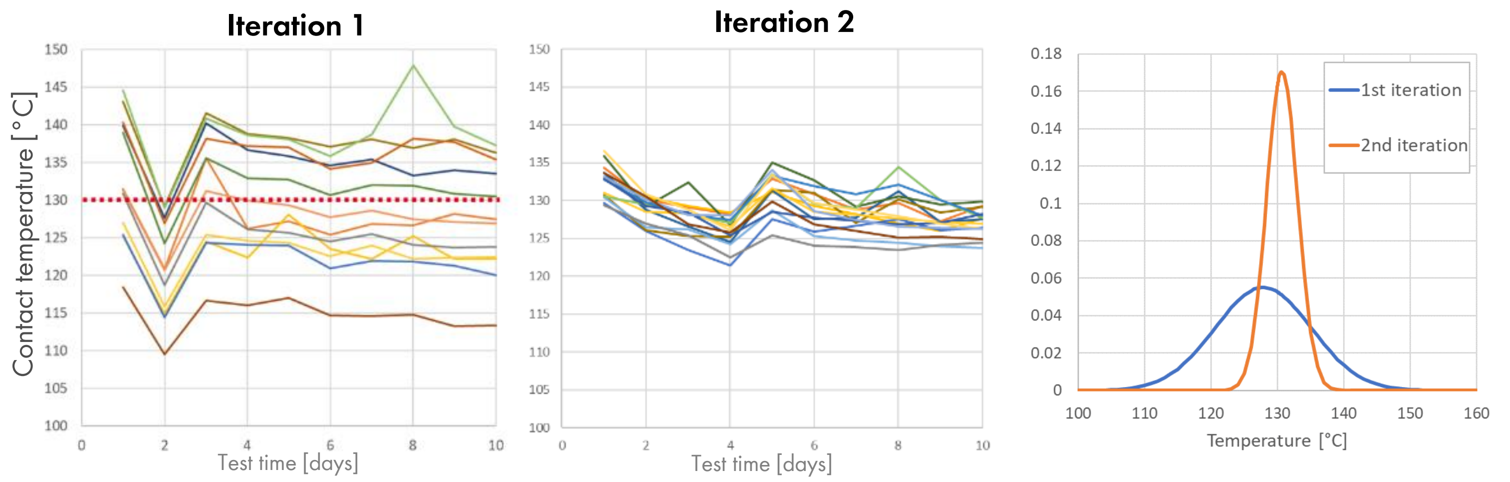


Iteration 2 – Results

Test group	Cycle time [h:min]	Adjusted test current	Contact temperature in steady state in current phase	Run time (1st failure)
1	3:30h (3:15 ON 0:15 Off)	71.5 A	**125 °C**	249 days
2	3:30h (3:15 ON 0:15 Off)	72.5 A	**130 °C**	249 days
3	3:30h (3:15 ON 0:15 Off)	75 A	**135 °C**	261 days (1 failure after 210 days)

Again, large test duration and only 1 failure!

- Better dispersion
  → no outliers, no temperatures above 135°C
- Even the hottest specimen of the 135°C test group is colder than the hottest specimen from iteration 1 @ 130°C

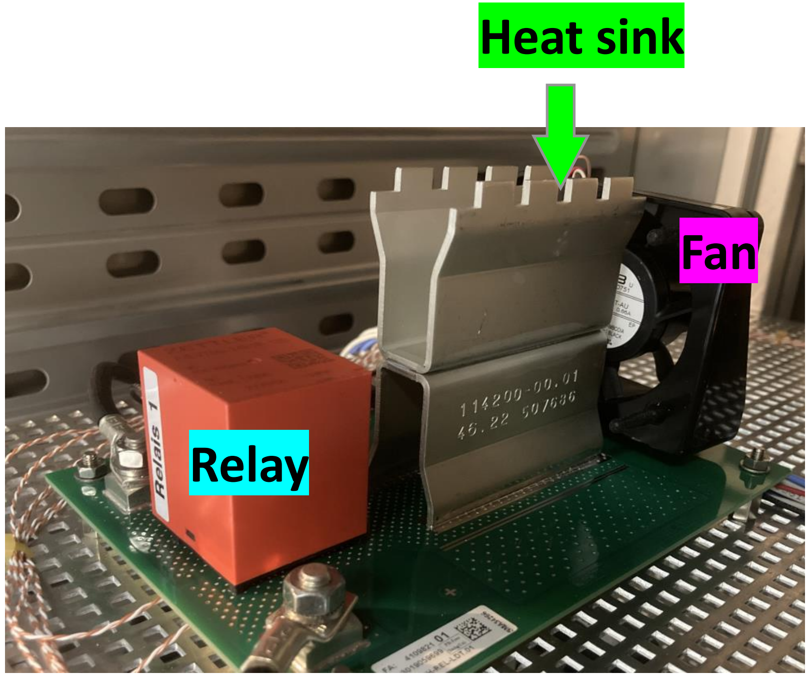


Dispersion of contact temperatures after stop of temperature control

Iteration 2 – Conclusion

Pro	Contra
➢ Test concept and test setup confirmed ➢ Comparatively narrow temperature corridor ➢ More exact results to be expected	➢ Long test duration ➢ More complex test setup ➢ Adjustable temperature range still too small ➢ Time-consuming support in the first weeks of testing (due to adjusting temperatures) ➢ Temperatures can still change significantly in the first few weeks

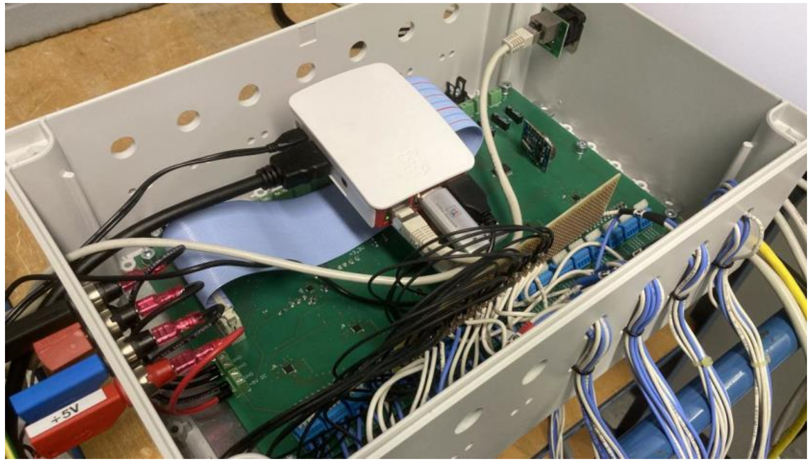
Iteration 3 – Test setup with loop-controlled fans



Test setup with PI-Controller

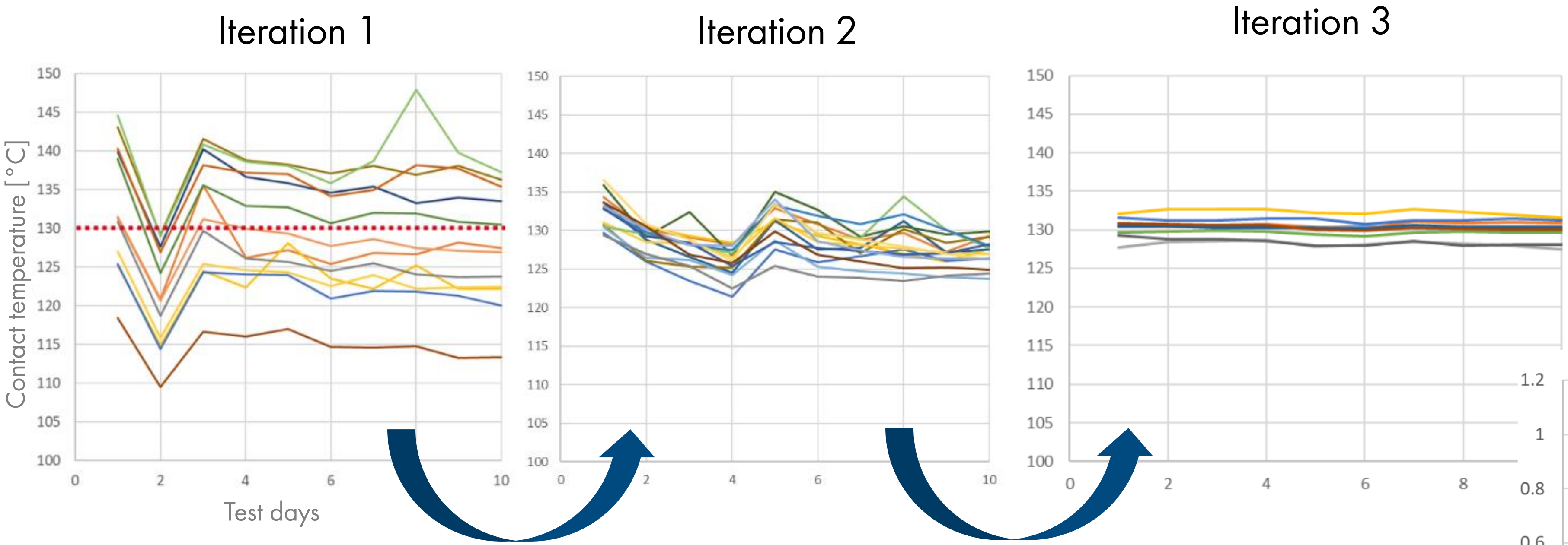
- Better temperature control
  - Enlargement of the heat sink
  - Fan with increased voltage / rotation rate range
- PWM driven loop control of each fan via RaspberryPi

Raspberry Pi®



Dispersion – Comparison of contact temperatures before aging

Dispersion of contact temperatures


Iteration 1

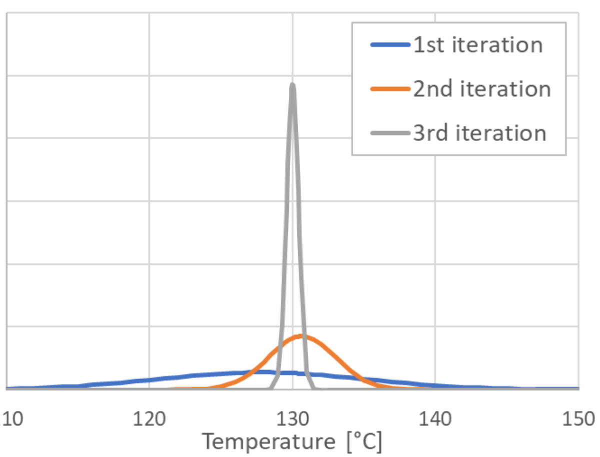
Iteration 2

Iteration 3

- Heatsinks
- Fans
- Temperature control by human

- Heatsinks → Larger
- Fans → More adjustable rotation rate range
- Machine controlled

Iteration	Standard deviation
1st	7.24
2nd	2.34
3rd	0.42

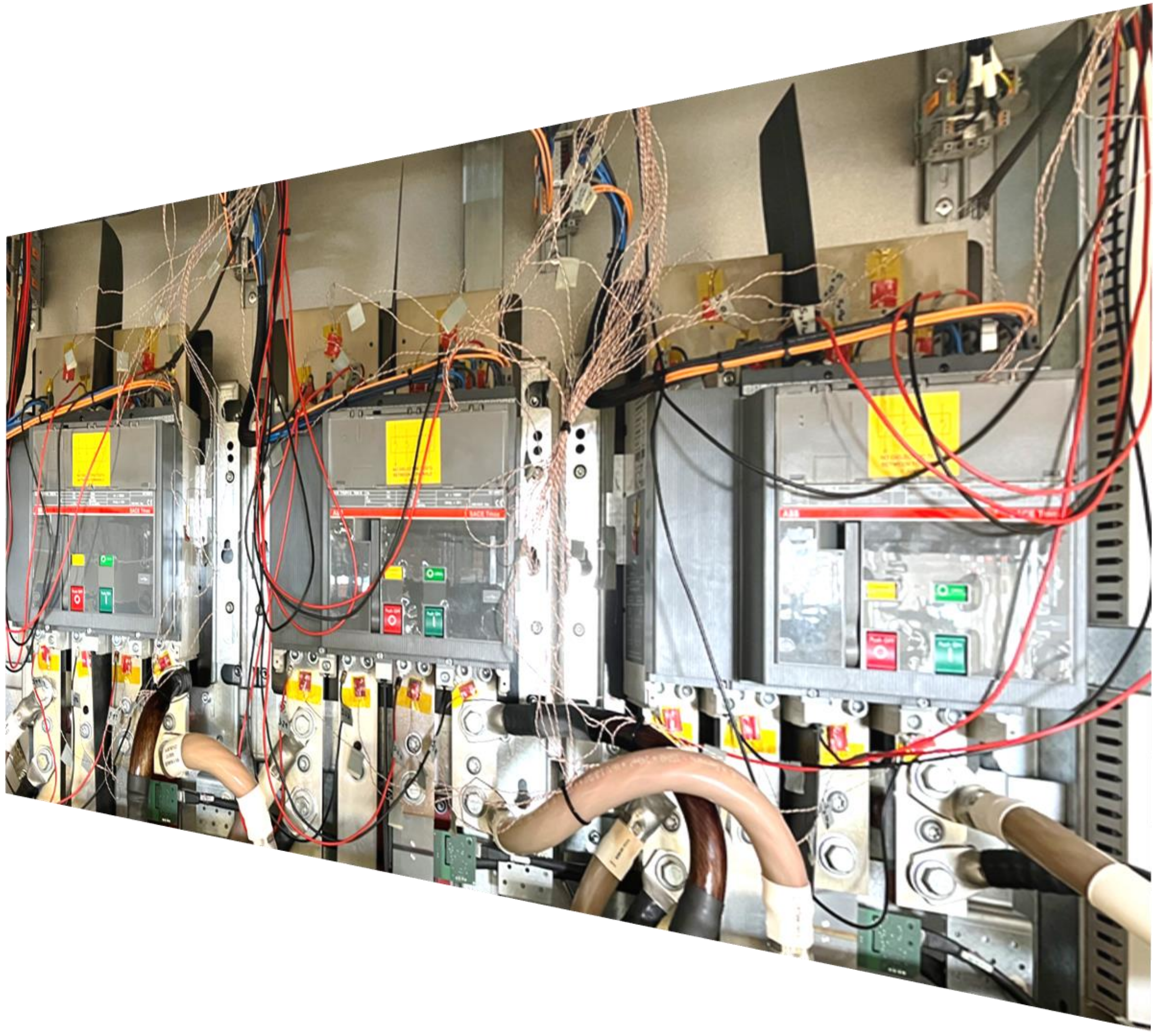


Insights for life testing of relays

- Pretests → Finding the right stressors and suitable working temperatures
- Accelerated life tests for relays → Cyclic current load under warm ambient conditions
- Main stressor for the aging of relays → Contact temperature (use for working point)
- Adjustment of the working point → Accuracy <1K
  → Fan driven control in the loop (PWM + PI-Controller)

Outlook → Central inverters, current > 1800A

- Challenges:
  - Transferring methods to large components
  - Working point adjustment
  - Preventing secondary damage
    (burning components, destroyed test system)



Thank you!

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Condition monitoring as a methodology to cope with MOSFET unreliability

Martijn Deckers, Johan Driesen
KU Leuven - EnergyVille

Content

- EnergyVille
- Introduction
- Failure modes of switching devices
- Lifetime estimation
- Condition monitoring
- Conclusion

Energy
Ville

ENERGY IN
TRANSITION

EnergyVille – A Flemish joint research center by KU Leuven, VITO, imec and UHasselt

- EnergyVille is a collaboration between 4 Belgian research partners, including KU Leuven, in the fields of sustainable energy and intelligent energy systems.

- EnergyVille develops technology and knowledge to support public and private stakeholders in the transition to an energy efficient, decarbonized and sustainable urban environment.

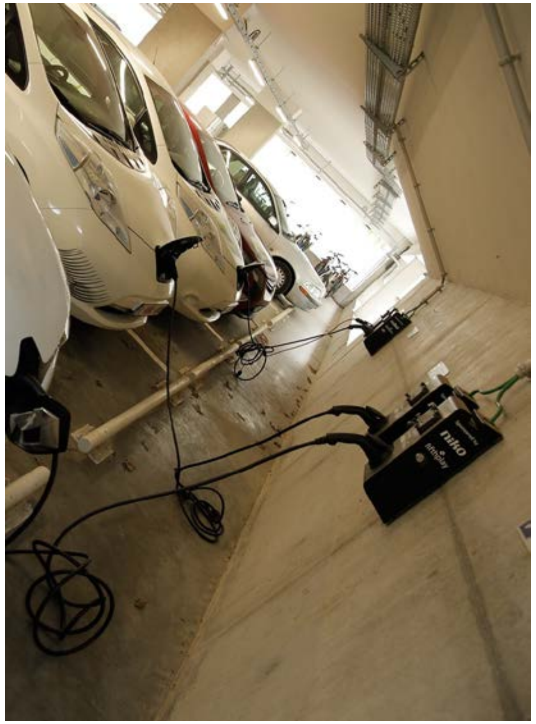
EnergyVille – Research

Power electronics

Low Voltage DC

PV applications

Battery charging



Introduction

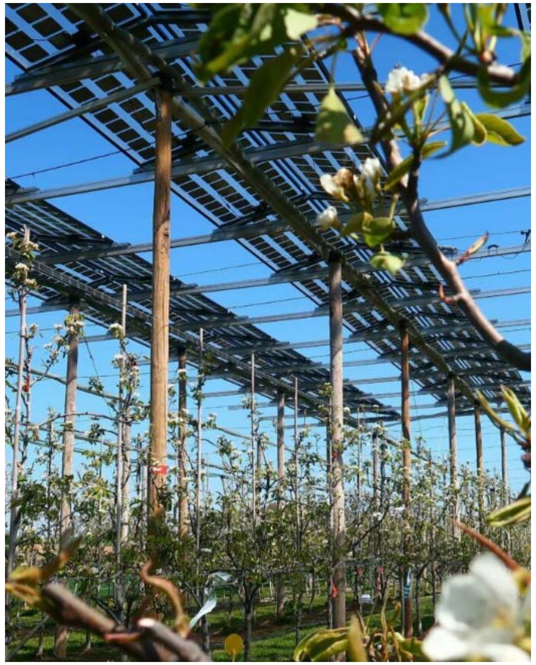
Going to a wide variety of PV system applications

Building integrated PV

Infrastructural PV

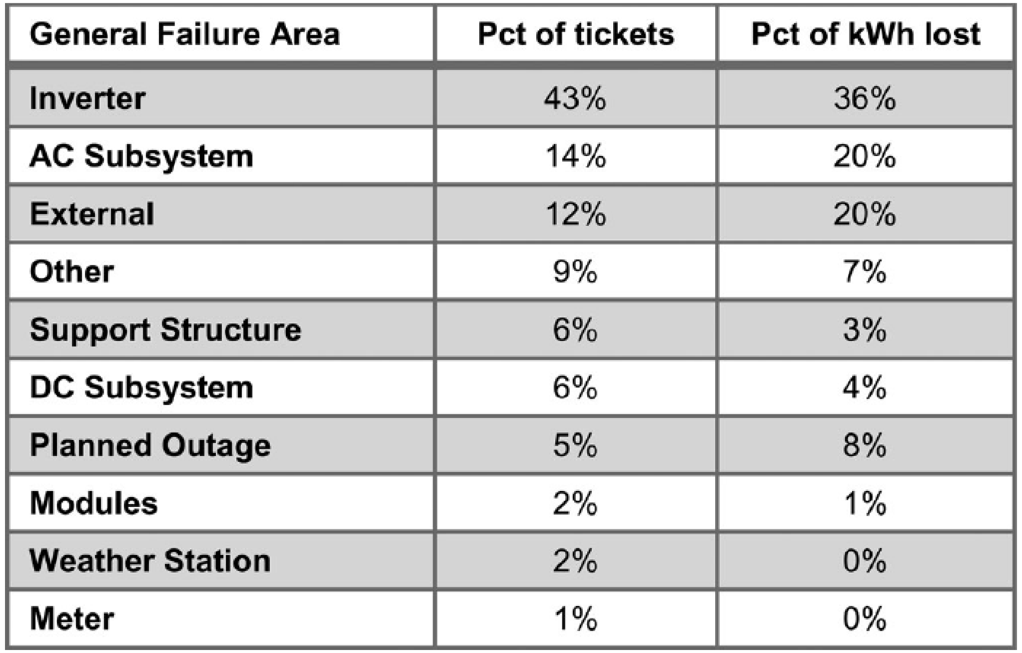
Floating PV

Agricultural PV



More extreme environments and difficult to perform maintenance

Converter as reliability limiting component

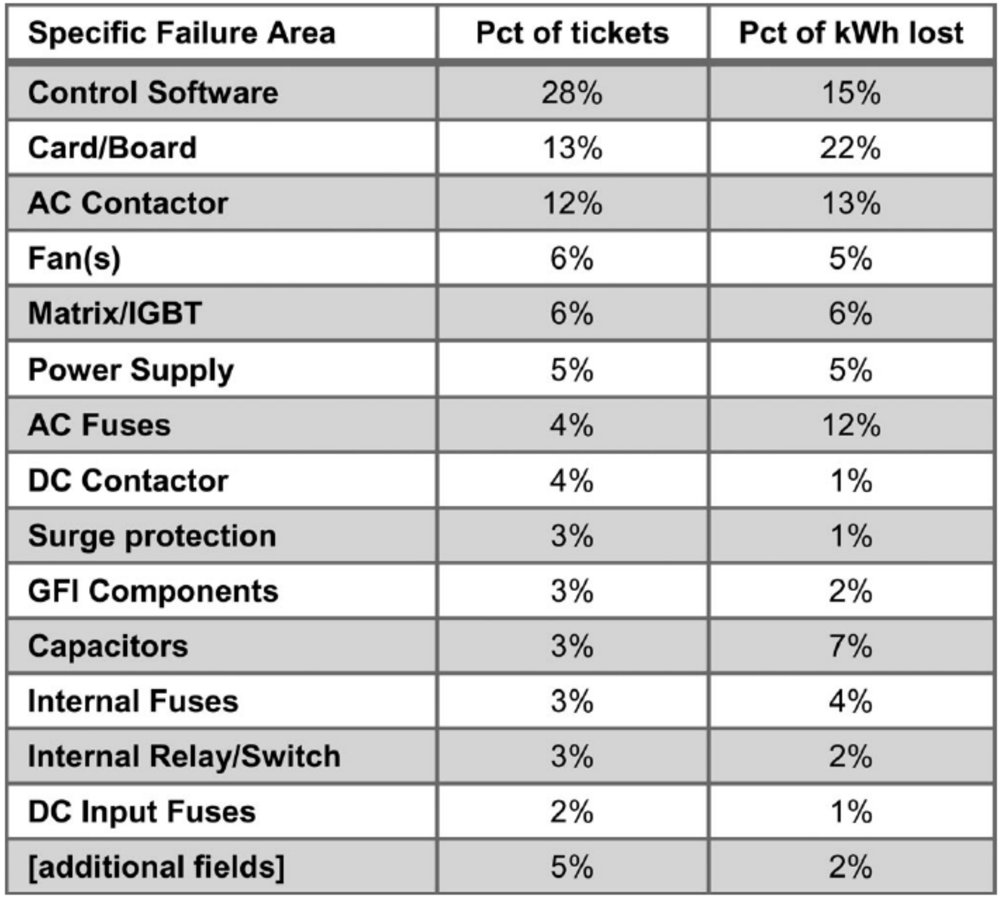


General Failure Area	Pct of tickets	Pct of kWh lost
Inverter	43%	36%
AC Subsystem	14%	20%
External	12%	20%
Other	9%	7%
Support Structure	6%	3%
DC Subsystem	6%	4%
Planned Outage	5%	8%
Modules	2%	1%
Weather Station	2%	0%
Meter	1%	0%

[1]

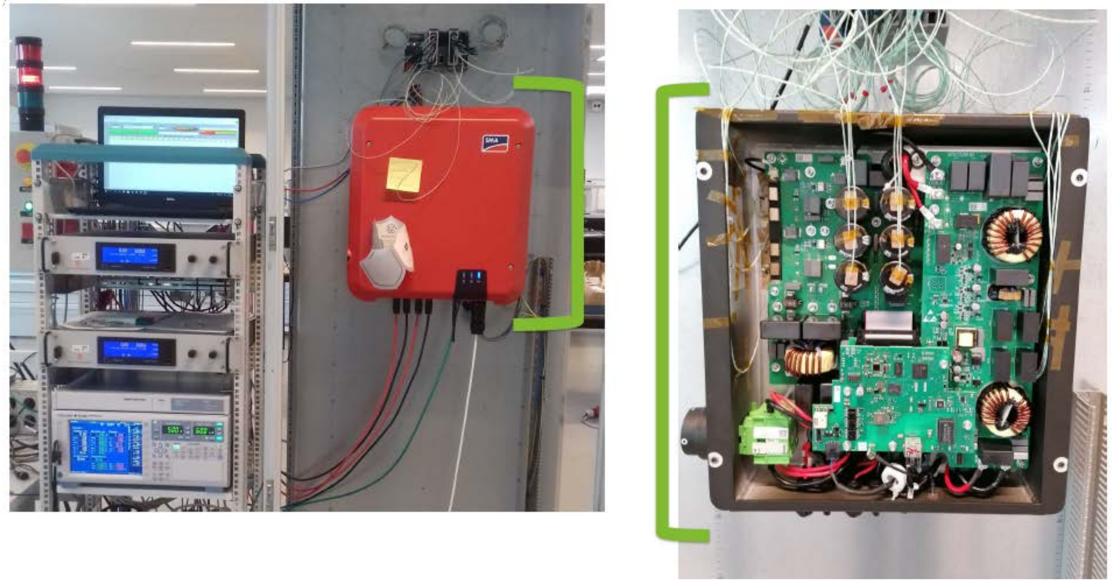
EnergyVille 1 PV test setup [2]

Switching devices are prone to failure



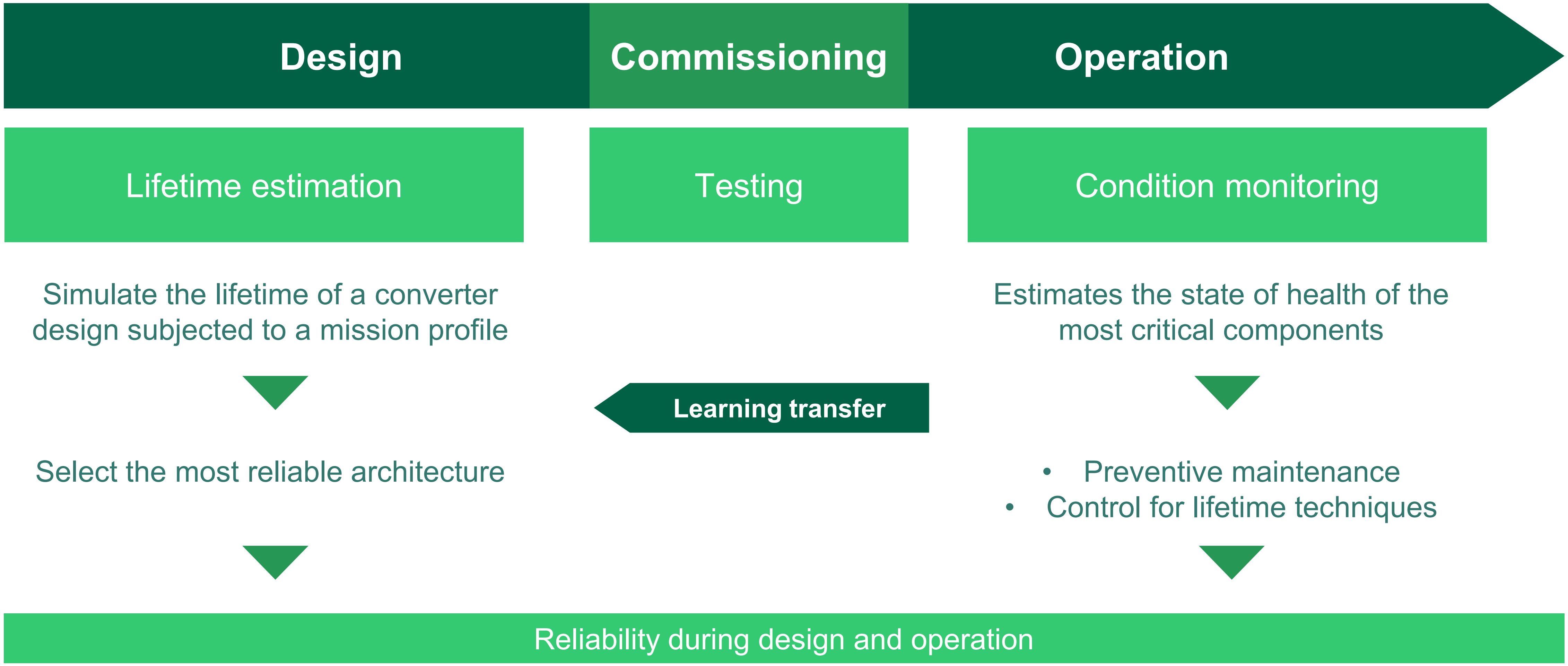
Specific Failure Area	Pct of tickets	Pct of kWh lost
Control Software	28%	15%
Card/Board	13%	22%
AC Contactor	12%	13%
Fan(s)	6%	5%
Matrix/IGBT	6%	6%
Power Supply	5%	5%
AC Fuses	4%	12%
DC Contactor	4%	1%
Surge protection	3%	1%
GFI Components	3%	2%
Capacitors	3%	7%
Internal Fuses	3%	4%
Internal Relay/Switch	3%	2%
DC Input Fuses	2%	1%
[additional fields]	5%	2%

[1]



Example of reliability tests done at EnergyVille [3]

Improving the reliability of power electronic components



Design | **Commissioning** | **Operation**

Lifetime estimation

Testing

Condition monitoring

Simulate the lifetime of a converter design subjected to a mission profile

Estimates the state of health of the most critical components

Learning transfer

Select the most reliable architecture

- Preventive maintenance
- Control for lifetime techniques

Reliability during design and operation

Failure modes of switching devices

Stressors

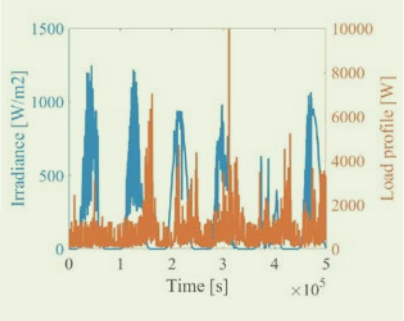
Voltage stress

- Causes stress in the dielectric layer and causes stacking faults.
- Mainly **avoidable** in PV converters by design

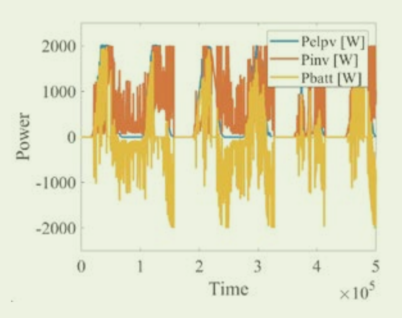
Temperature stress

- External high temperatures strengthen this effect.
- **Mismatch of expansion coefficient** and accumulation of **deformation energy**.

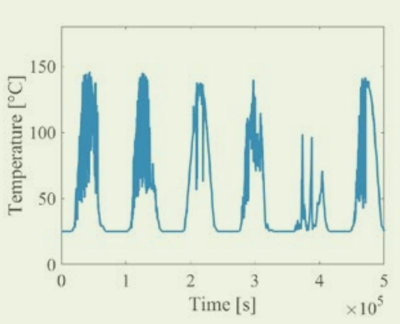
Fast weather changes



Fast changing power



Fast changing temperature

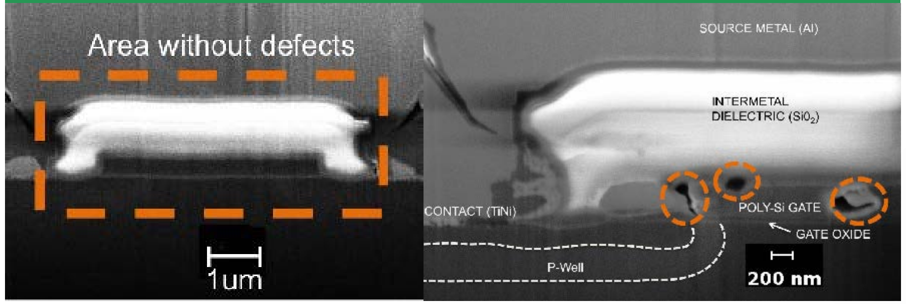


[4]

Switching device failure modes

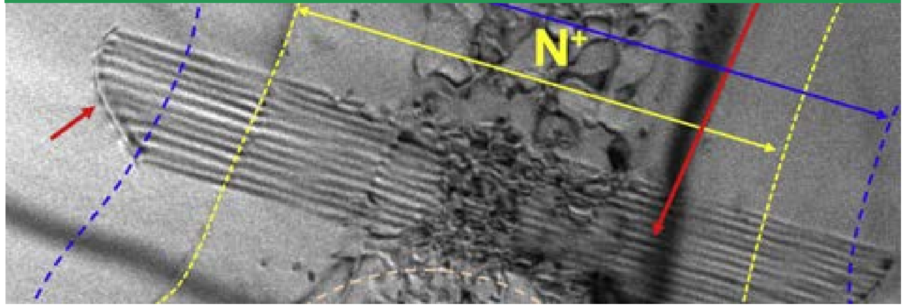
Die level degradation

Gate oxide degradation

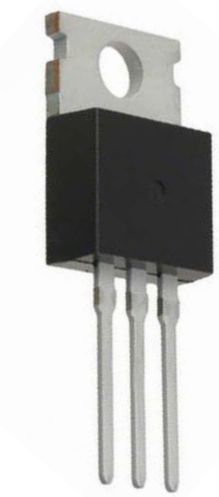


[5]

Body diode degradation

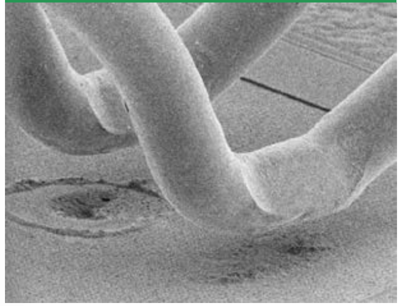


[6]



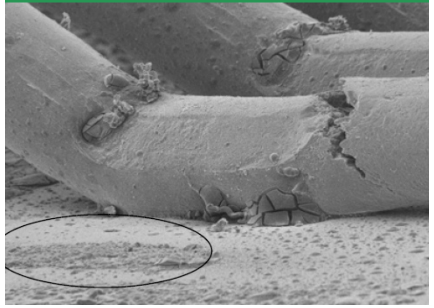
Package level degradation

Bond wire lift-off



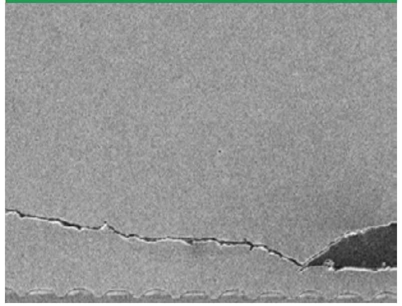
[7]

Bond wire creaking



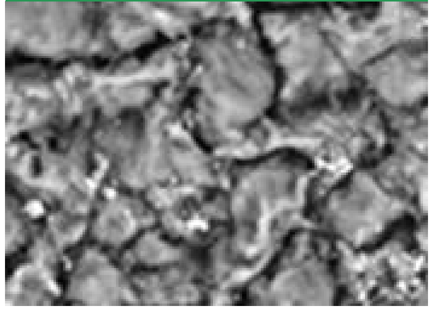
[7]

Solder layer delamination



[8]

Metallization deconstruction



[9]

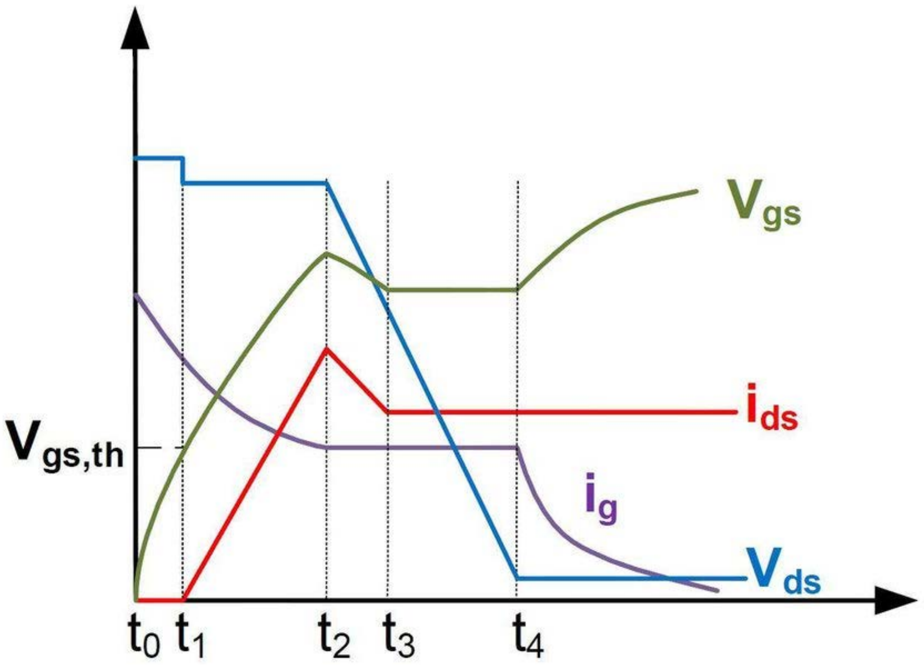
Affected parameters in MOSFETS

Die level degradation

- Miller plateau voltage
- Miller plateau duration time
- Drain leakage current
- Gate leakage current
- Threshold voltage
- Drain source on resistance

Package level degradation

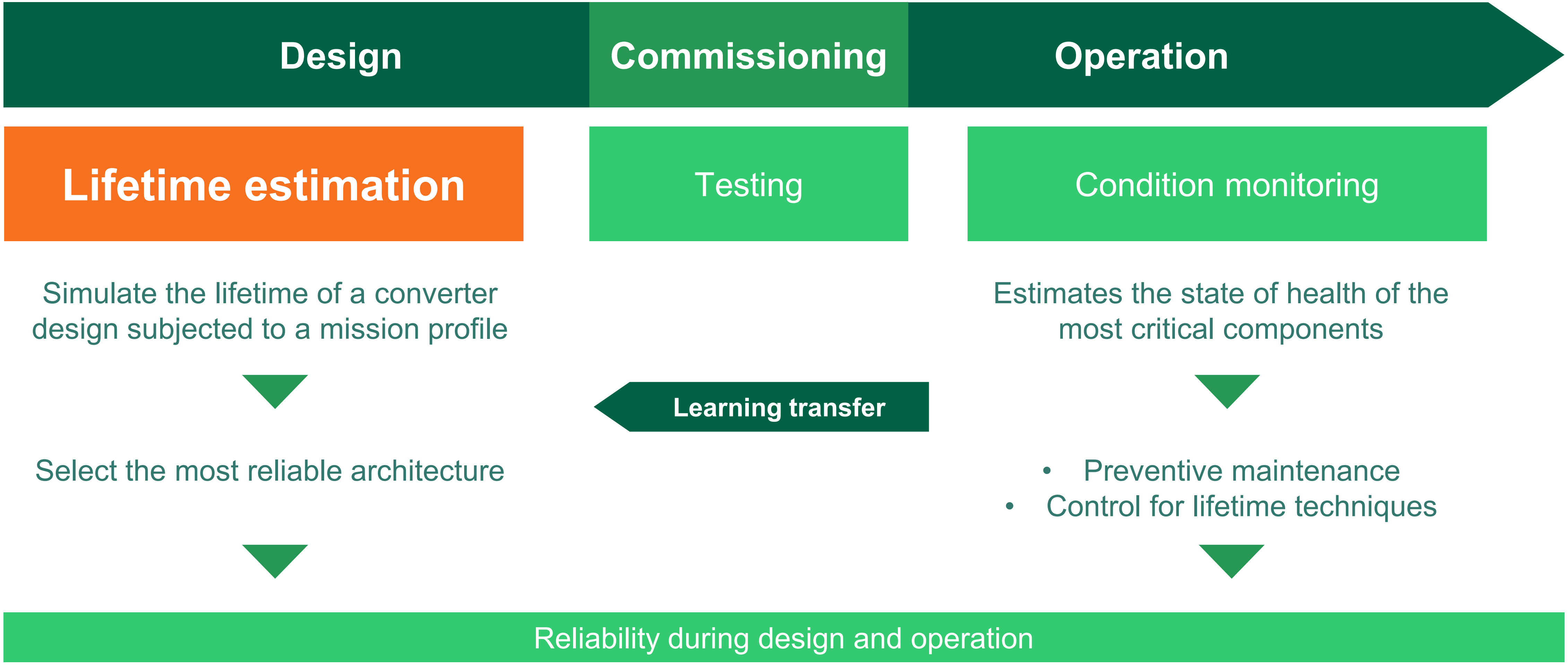
- Thermal resistance
- Drain source on resistance



[10]

Lifetime estimation

Improving the reliability of power electronic components



Design

Commissioning

Operation

Lifetime estimation

Testing

Condition monitoring

Simulate the lifetime of a converter design subjected to a mission profile

Select the most reliable architecture

Learning transfer

Estimates the state of health of the most critical components

- Preventive maintenance
- Control for lifetime techniques

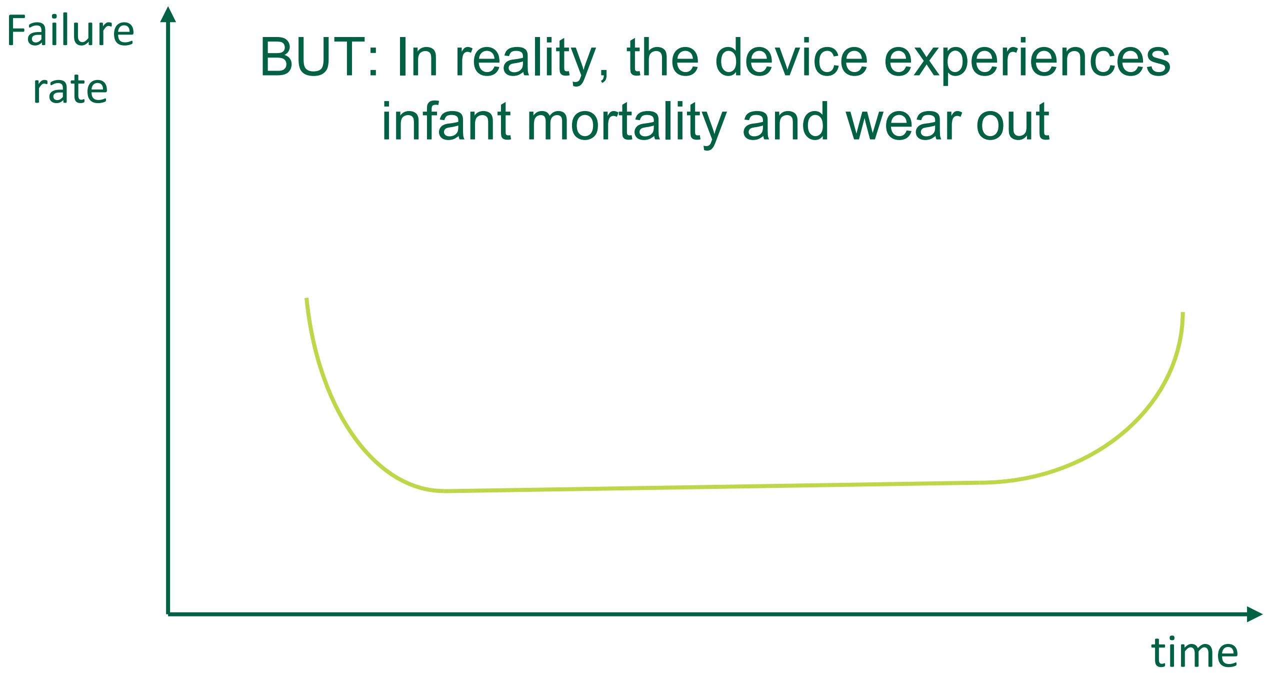
Reliability during design and operation

Lifetime estimation – Classical approaches

Reliability handbooks

- MIL-HDBK-217-F
- Telcordia SR-332
- IEC 62380
- IEC 61709
- RDF 2000
- FIDES

Based on the assumption of a constant failure rate



BUT: In reality, the device experiences infant mortality and wear out

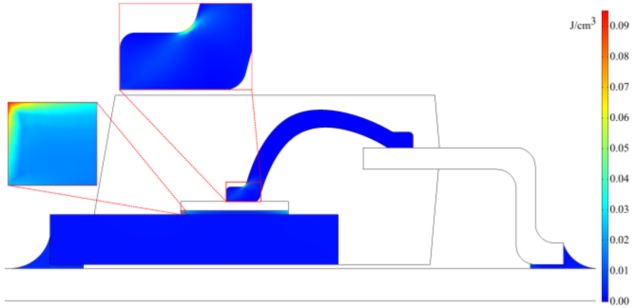
➢ **Other methods are needed to find the time dependent failure rate for accurate estimation.**

Lifetime estimation – Physics of failure

Using the actual stress levels

Stress → Degradation

The experienced stress can be simulated in FEM



[11]

The constants of the model still need to be determined empirically

Bond wire liftoff

$$N_f = C_2 \cdot (\Delta\varepsilon_p)^{-C_3}$$

Solder layer delamination

$$N_f = L_S / \left[a_5 \cdot (\Delta\varepsilon_p)^{n_4}\right]$$

Using the die temperature

Temperature swing → Expansion mismatch → Stress → Degradation

As the models are empirical, temperature cycles can also be used.

Coffin-Manson model

$$N_f = A\ (\Delta T_j)^{-\alpha}$$

Coffin-Manson-Arrhenius model (LESIT model)

$$N_f = A\ (\Delta T_j)^{-\alpha}\ e^{\frac{E_a}{k_b T_{jm}}}$$

Norris-Landzberg model

$$N_f = A\ f^{\beta}\ (\Delta T_j)^{-\alpha}\ e^{\frac{E_a}{k_b T_{jm}}}$$

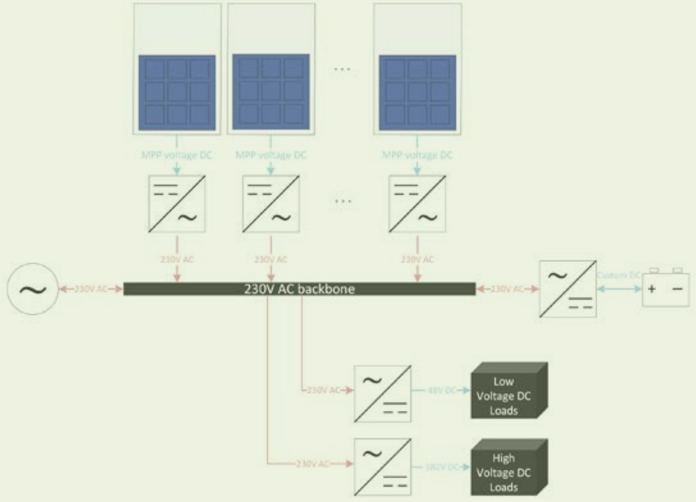
[12]

…

Lifetime estimation – Models

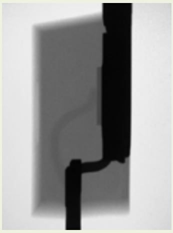
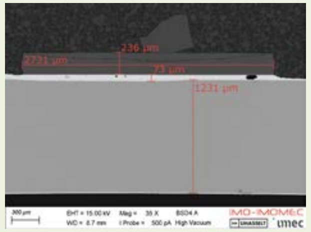
Electrical model

Is known from the system architecture

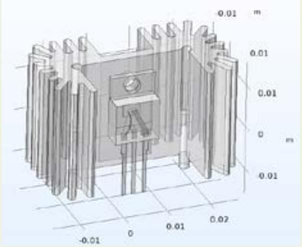


Thermal model

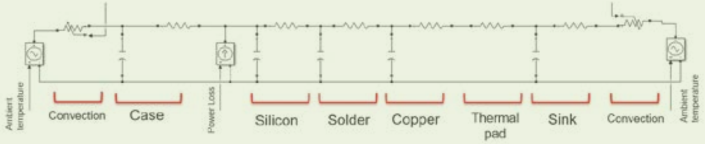
SEM images

Finite element models

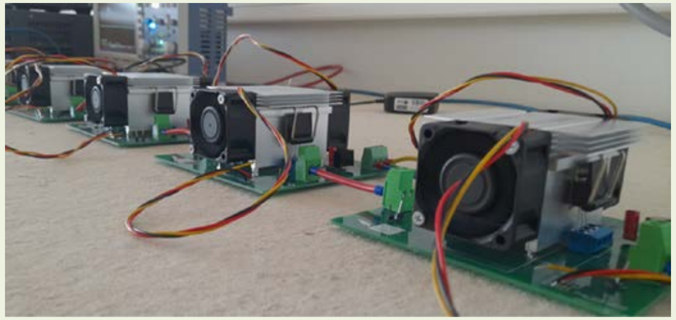


Lumped thermal networks

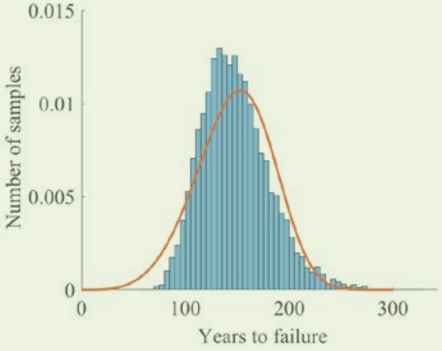


Reliability model

Accelerated power cycling tests



Failure distributions

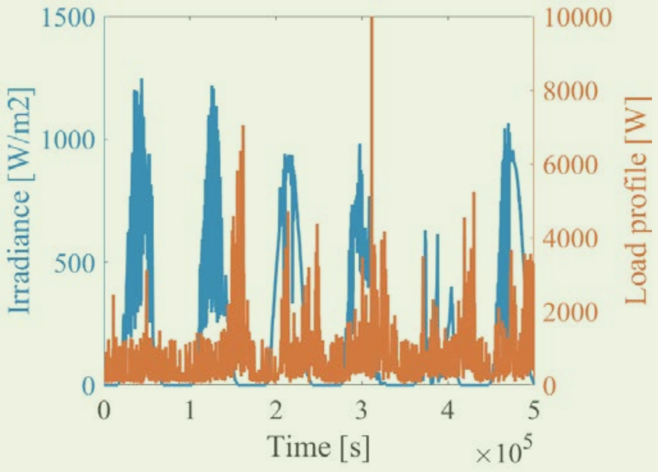


[13]

Lifetime estimation – Full process

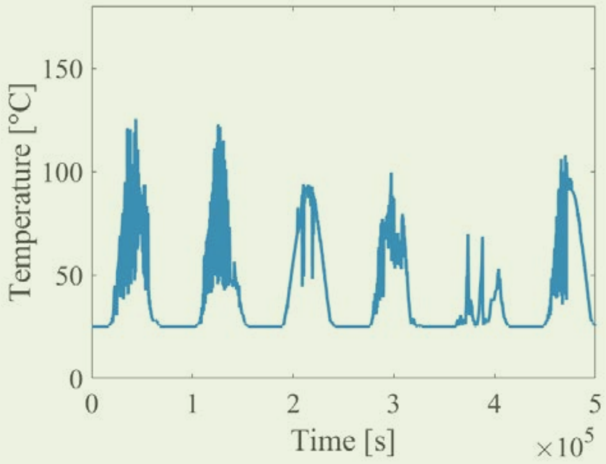
Mission profile

Input data is collected from the test setup such as temperature and irradiance profile



Component internal temperature

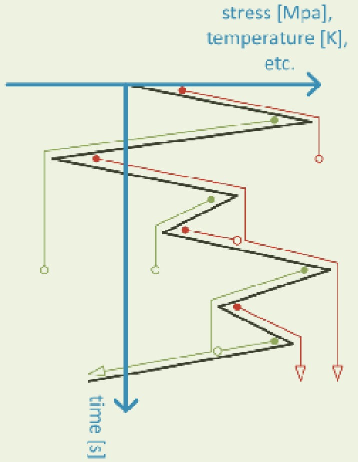
The thermal model is used to convert the input data to the component internal temperature for different cases



Lifetime estimation – Full process

Rainflow counting

Rainflow counting is used to convert the temperature profile into discrete cycles



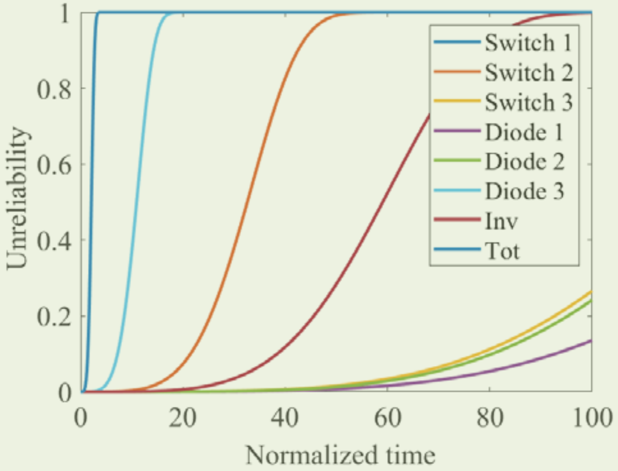
[14]

Monte Carlo simulation

Monte Carlo simulations is used to introduce uncertainty leading to a failure distribution

Unreliability function

By integrating this distribution, the unreliability function is found



Lifetime estimation – Take away

- Current handbook-based methods highly simplify the failure process by assuming a constant failure rate.

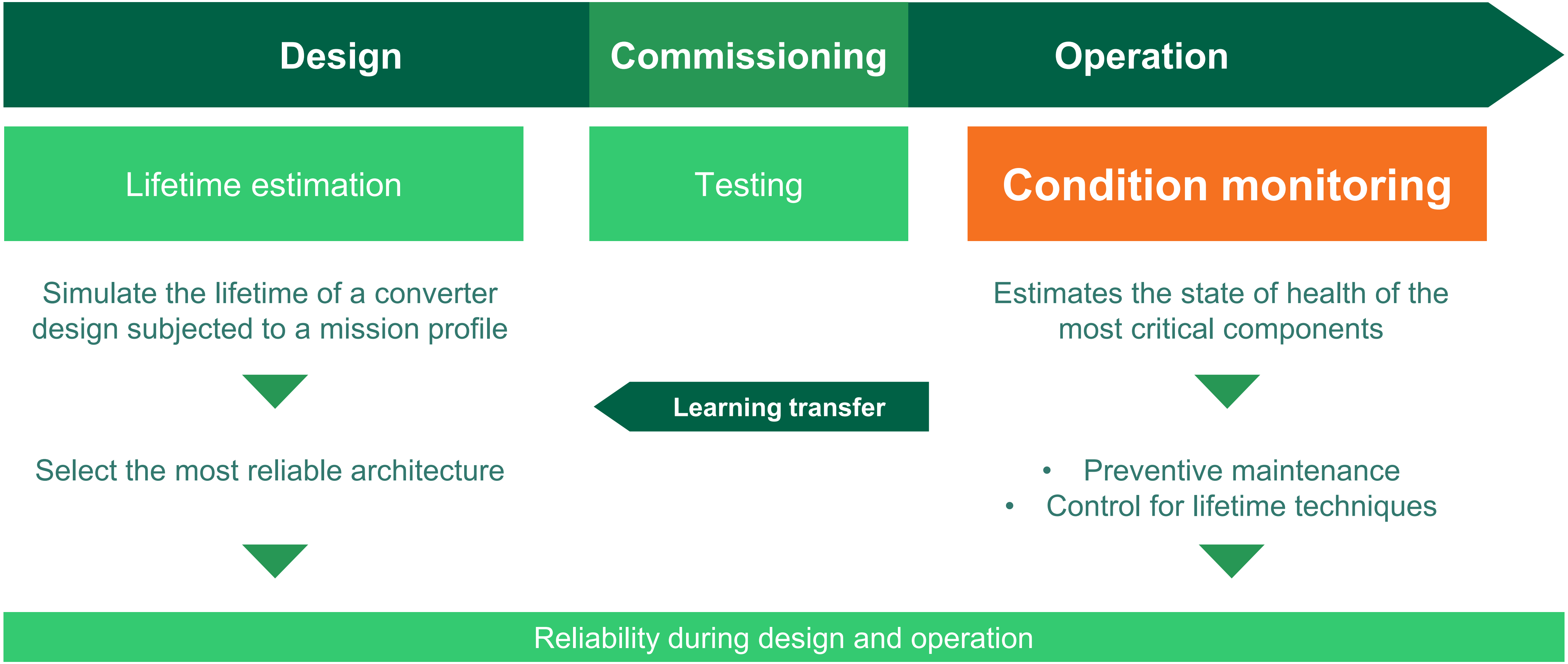
- Physics of failure-based methods solve this problem by introducing a mission profile and time dependent failure rate.

- It is not needed to model the exact stress but making temperature and failure modes is still tedious.

- Research toward practical but accurate methods for industry is needed.

Condition monitoring

Improving the reliability of power electronic components



Design

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Operation

Lifetime estimation

Simulate the lifetime of a converter design subjected to a mission profile

Select the most reliable architecture

Testing

Learning transfer

Condition monitoring

Estimates the state of health of the most critical components

- Preventive maintenance
- Control for lifetime techniques

Reliability during design and operation

Condition monitoring – What to measure

Degradation of the bond wire

- Drain source on resistance Rds(on) increases

➢ But also dependent on die temperature

➢ Difficult to see the degradation effect

Degradation of the solder layer

- Thermal resistance increase

➢ Die temperature is needed to calculate it

The Rds(on) can be measured but the die temperature is also needed.

Solutions:

1) Compare the measured results with a digital twin => difficult modeling
2) Implement an additional measurement only sensitive to temperature => More measurements but limited complexity

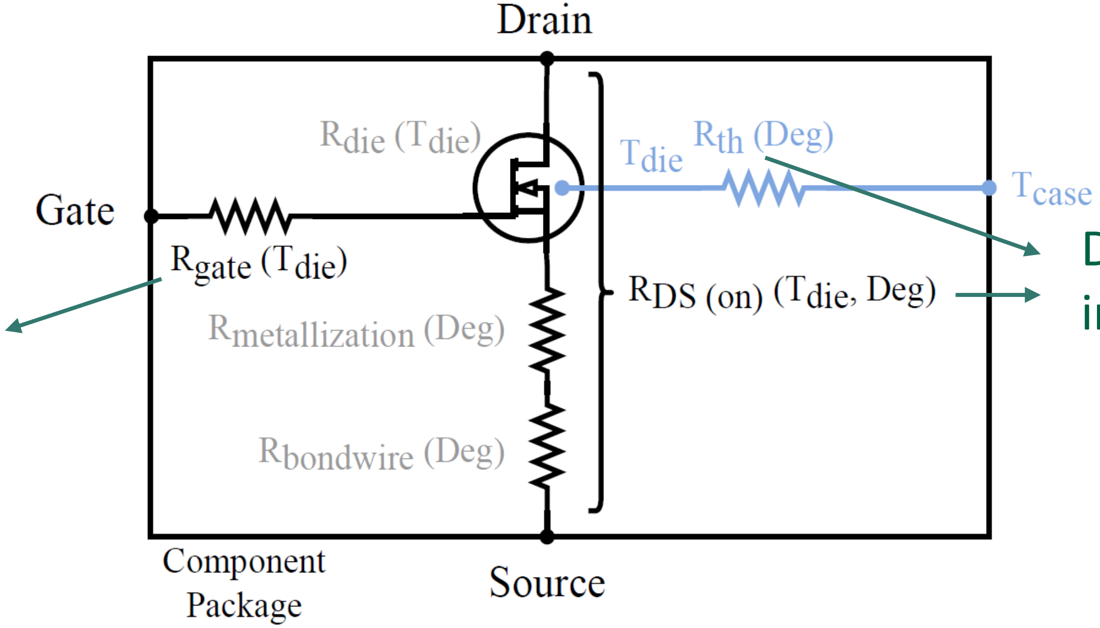
Condition monitoring – What to measure

Degradation of the bond wire

- Drain source on resistance Rds(on) increases
  - ➢ But also dependent on die temperature
  - ➢ Difficult to see the degradation effect

Degradation of the solder layer

- Thermal resistance increase
  - ➢ Die temperature is needed to calculate it

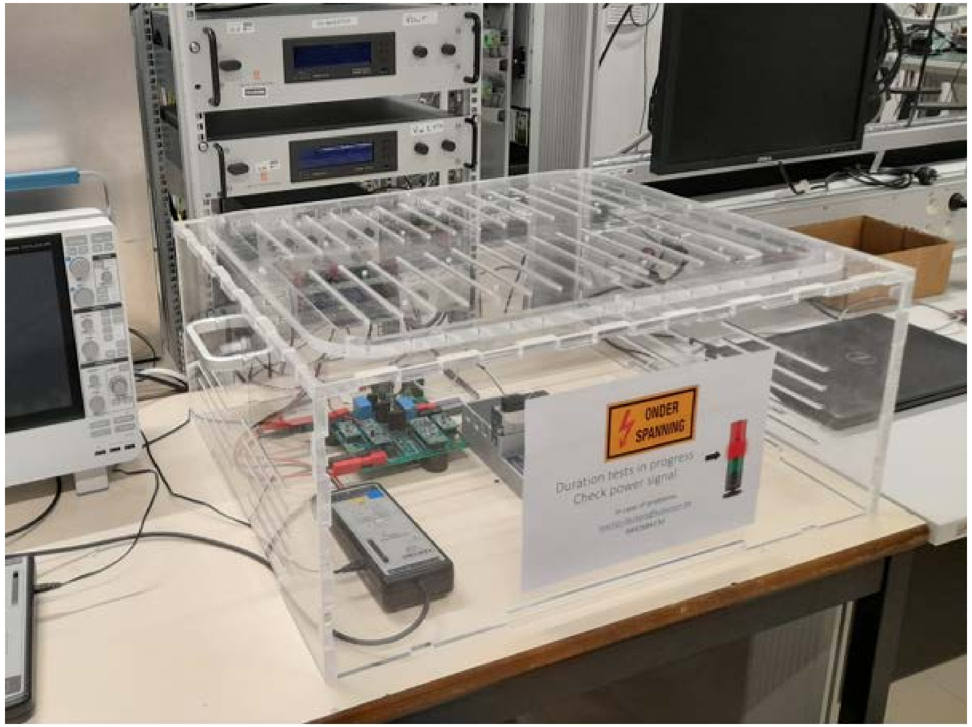


Rgate can be used as a temperature indicator

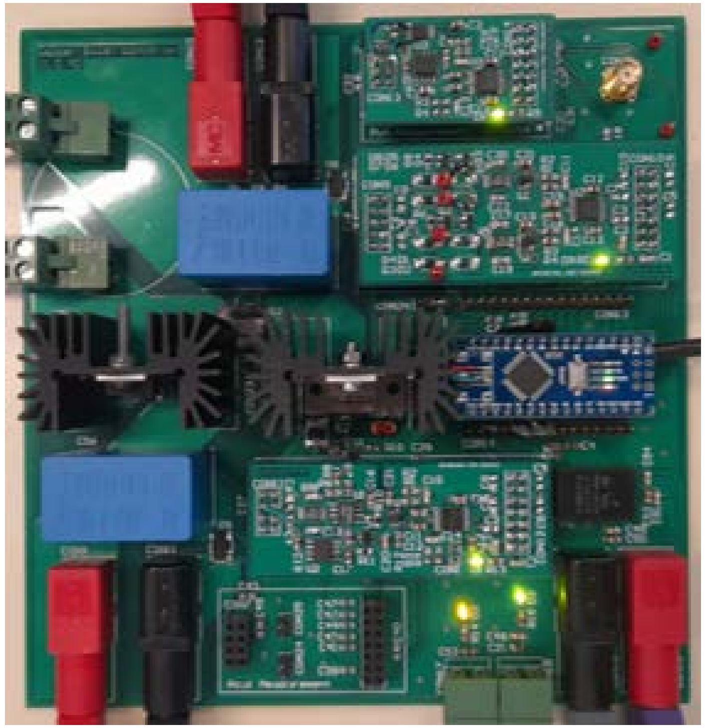
Degradation indicators

Condition monitoring – Test setup

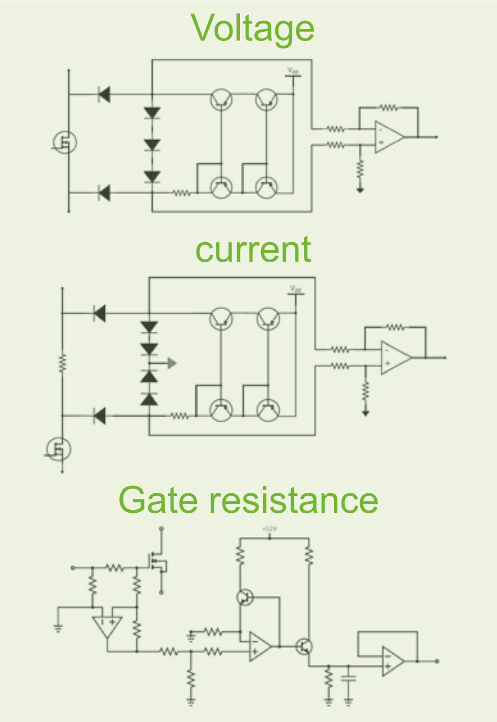
Experimental setup



Close-up PCB



Measurement circuits

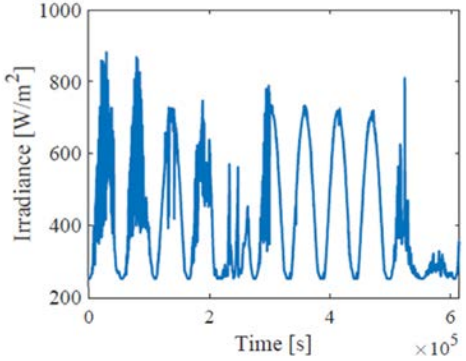

Voltage

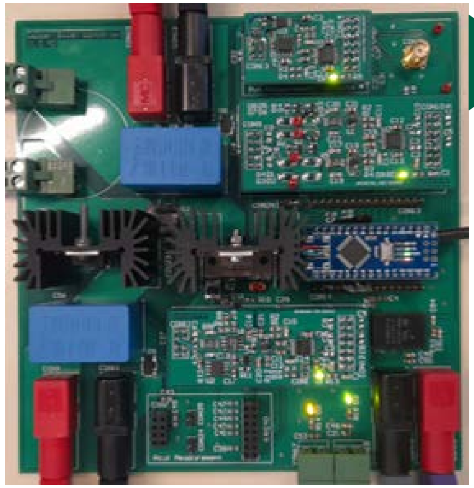
current

Gate resistance

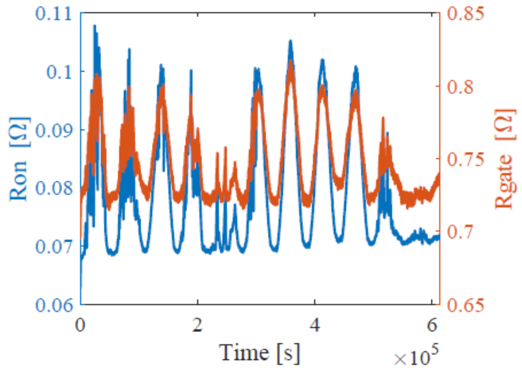
Condition monitoring – Test setup

Irradiance

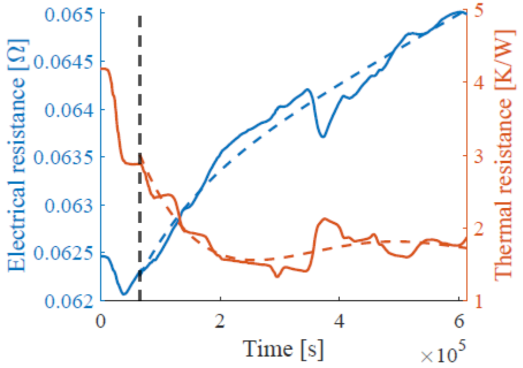




Measurements



Degradation



As degradation is a slow process, a lot of samples can be taken to decide upon the level of degradation.

Condition monitoring – Take away

- A lot of condition monitoring is based in digital twins
  - A lot of modeling is needed
  - Real time calculations can take up large amounts of processing power often requiring dedicated processors

- Full measurement-based condition monitoring
  - An additional measurement is needed
  - Implementation can be simple keeping the additional cost to a minimum

Conclusion

Conclusion

- Switching devices are reliability bottleneck
- Solder layer delamination and bond wire degradation form the main failure modes
- Changing temperatures is the main cause of failure
- Current reliability handbooks are often not sufficient to accurately predict failure
- Condition monitoring is an alternative and can be done without digital twin

Thank you

References

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SUNGROW

Long Term Reliability Challenges and Solutions for Central Inverter

Speaker: Bale Yang

Clean power for all

Long Term Reliability Challenges

- Complex operating conditions

- Mass production and transportation challenges

- Full lifecycle operation and maintenance

Contents

Efficient Heat Dissipation

Power Cavity
Direct Ventilation

- Front inlet and back outlet
- Core module components are at the cold air zone

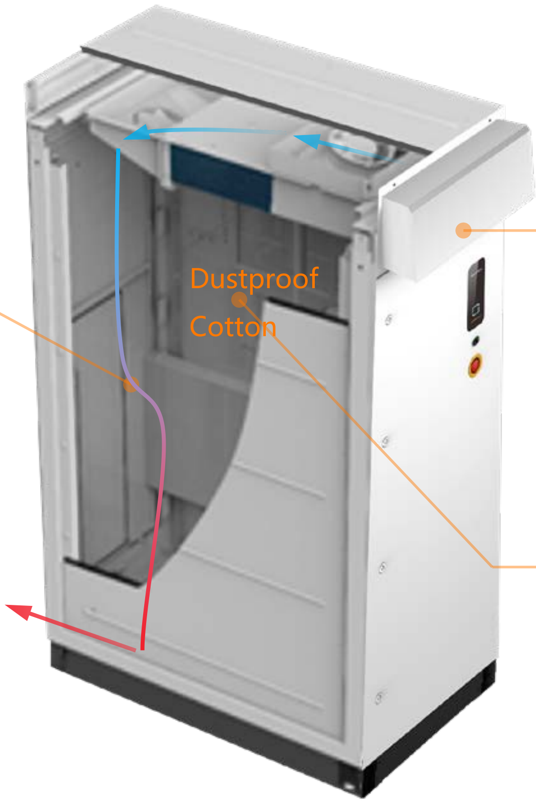
Electronic Cavity
Heat Exchanger

- Heat exchanger on the top
- Intelligent temperature control
- Independent internal and external heat dissipation cycle

Wind & Sand Protection

Power Cavity Air Duct Smooth Design

- Smooth air duct design from top to bottom against vortex and sand accumulation
- Special sand-proof design of power cavity fan and reactor



Air Inlet Bend and Quick Release Design

- Bend design resists direct wind and sand blowing
- The wire mesh uses a plug buckle design that can be quickly disassembled for cleaning sand and dust.

Electronic Cavity Self-cleaning Design

- Built-in dust-proof cotton to collect dust that enters during O&M.
- The dust-proof cotton is removable and easy to clean.

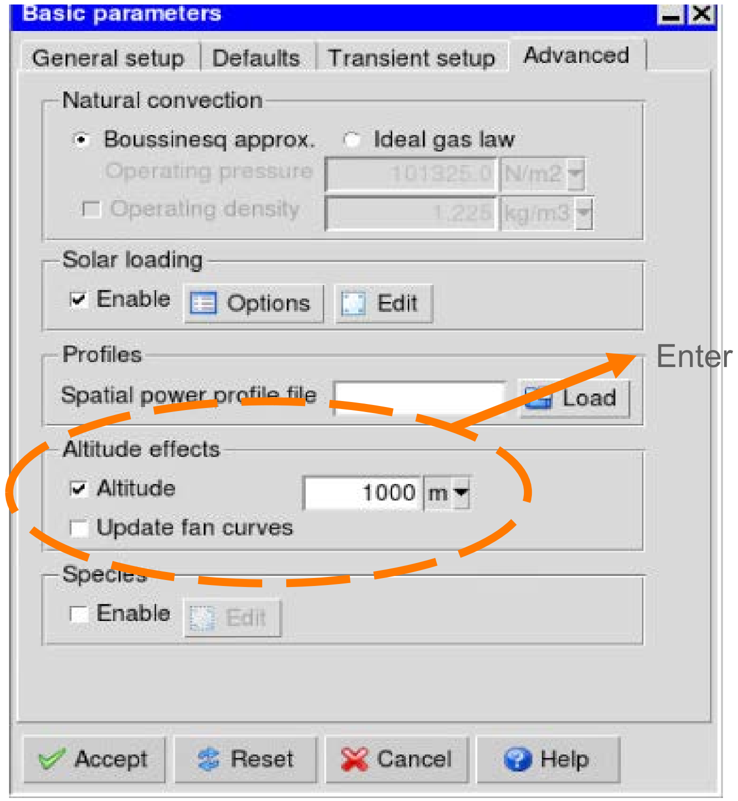
Anti-Corrosion Design

- Upgrade surface treatment technology to enhance anti-corrosion performance (such as spraying process).
- The inverter cabinet adopts anti-corrosion processes such as electrostatic spraying, passivation, and galvanization.
- Structural components use corrosion-resistant materials like hot-dip galvanized plates.

C5 Anti-Corrosion

High Altitude Design

Environmental suitability design--High altitude simulation



Basic parameters

General setup | Defaults | Transient setup | Advanced

Natural convection
● Boussinesq approx. ○ Ideal gas law
Operating pressure 101325.0 N/m2
☐ Operating density 1.225 kg/m3

Solar loading
☑ Enable Options Edit

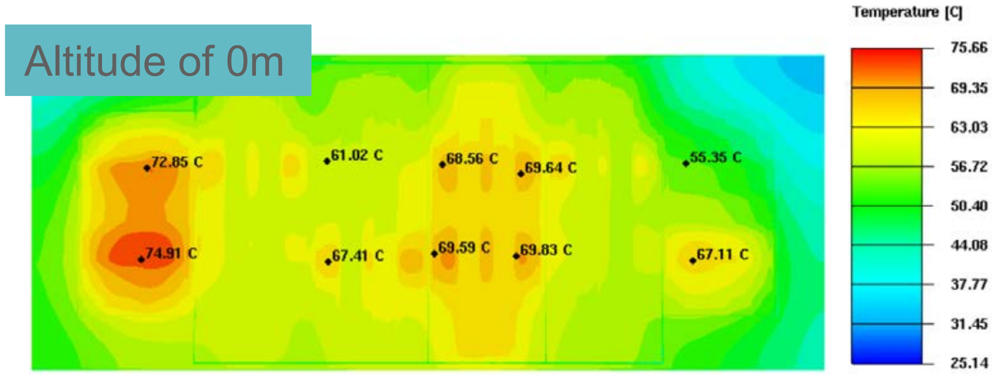
Profiles
Spatial power profile file Load

Altitude effects
☑ Altitude 1000 m
☐ Update fan curves

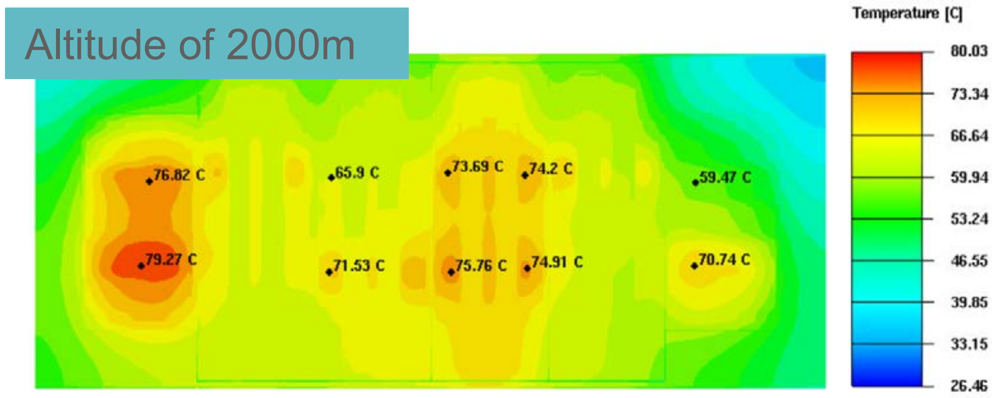
Species
☐ Enable Edit

Accept Reset Cancel Help

Enter actual altitude



Altitude of 0m



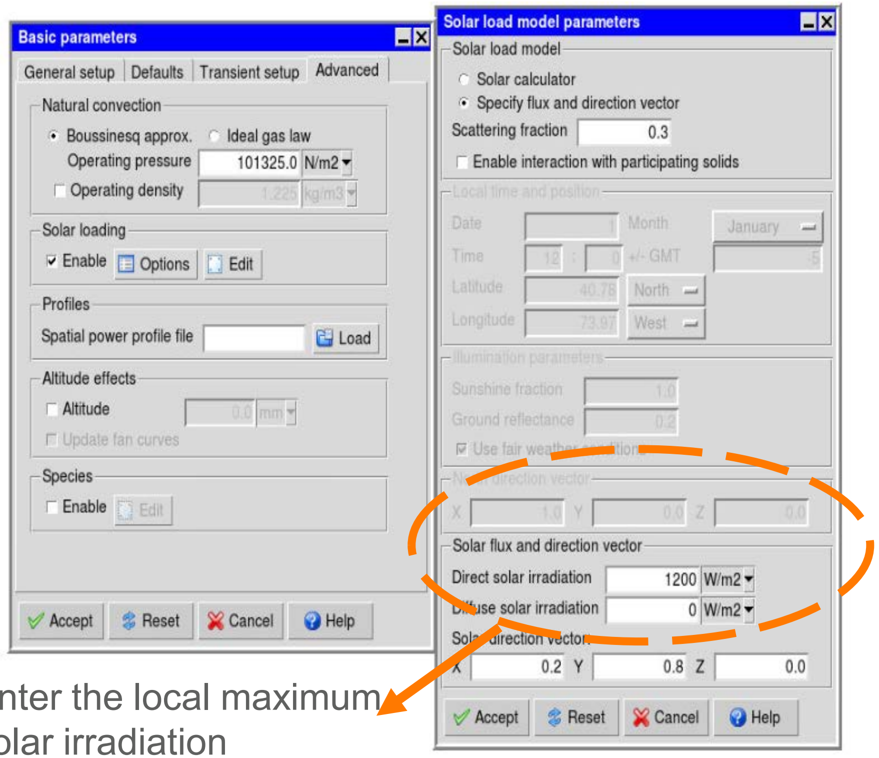
Altitude of 2000m

Solar Irradiation Consideration

① Material irradiation parameters comparison

Color	Solar reflectance	Solar absorption ratio	Hemispherical emissivity
RAL9003	0.79	0.21	0.91
RAL7035	0.51	0.49	0.91
RAL7004	0.29	0.71	0.91
RAL7033	0.21	0.79	0.91
RAL6005	0.09	0.91	0.91
RAL7016	0.08	0.92	0.91

② Solar irradiation simulation



Natural convection
● Boussinesq approx. ○ Ideal gas law
Operating pressure 101325.0 N/m2
☐ Operating density 1.225 kg/m3
Solar loading
☑ Enable Options Edit
Profiles
Spatial power profile file Load
Altitude effects
☐ Altitude 0.0 mm
☐ Update fan curves
Species
☐ Enable Edit

Solar load model
○ Solar calculator
● Specify flux and direction vector
Scattering fraction 0.3
☐ Enable interaction with participating solids
Local time and position
Date 1 Month January
Time 12 : 0 +/- GMT 5
Latitude 40.78 North
Longitude 73.97 West
Illumination parameters
Sunshine fraction 1.0
Ground reflectance 0.2
☑ Use fair weather conditions
North direction vector
X 1.0 Y 0.0 Z 0.0
Solar flux and direction vector
Direct solar irradiation 1200 W/m2
Diffuse solar irradiation 0 W/m2
Solar direction vector
X 0.2 Y 0.8 Z 0.0

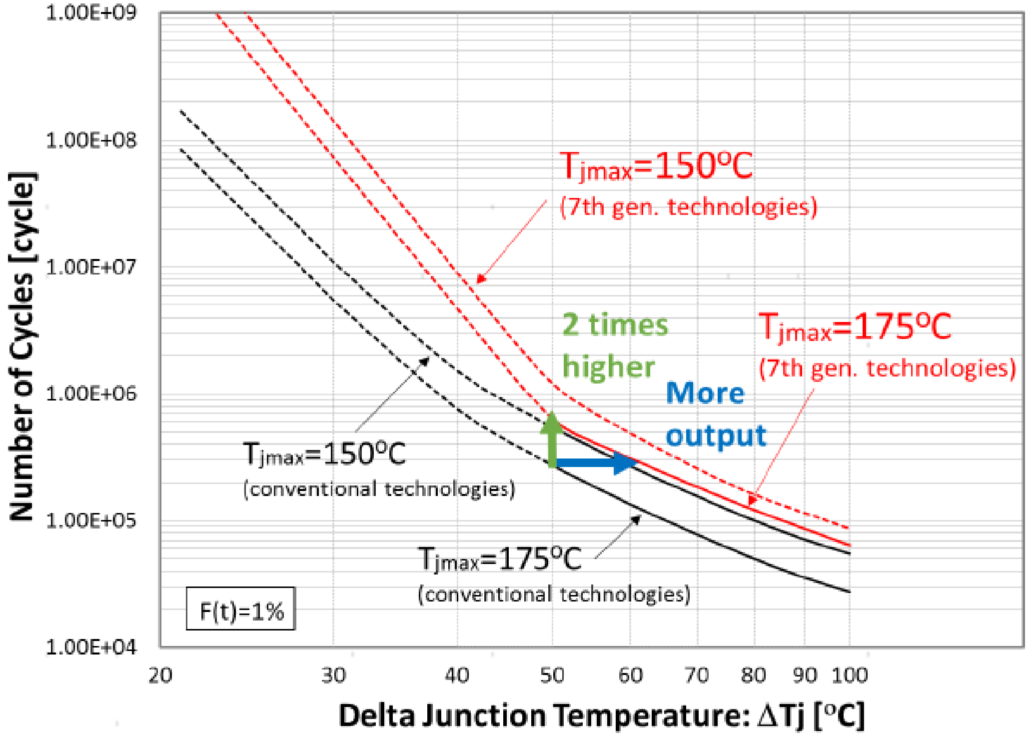
Enter the local maximum solar irradiation

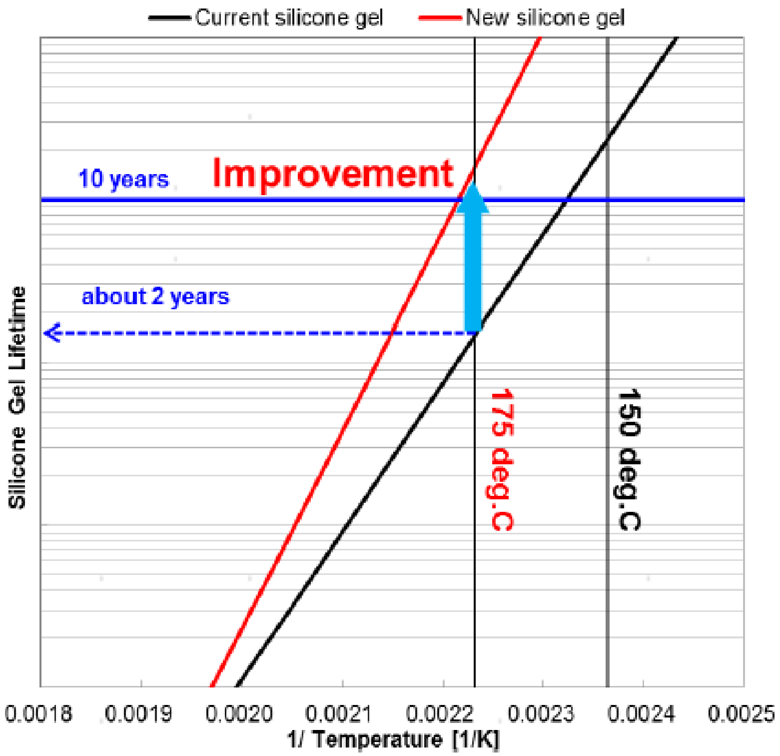
IGBT Module Design

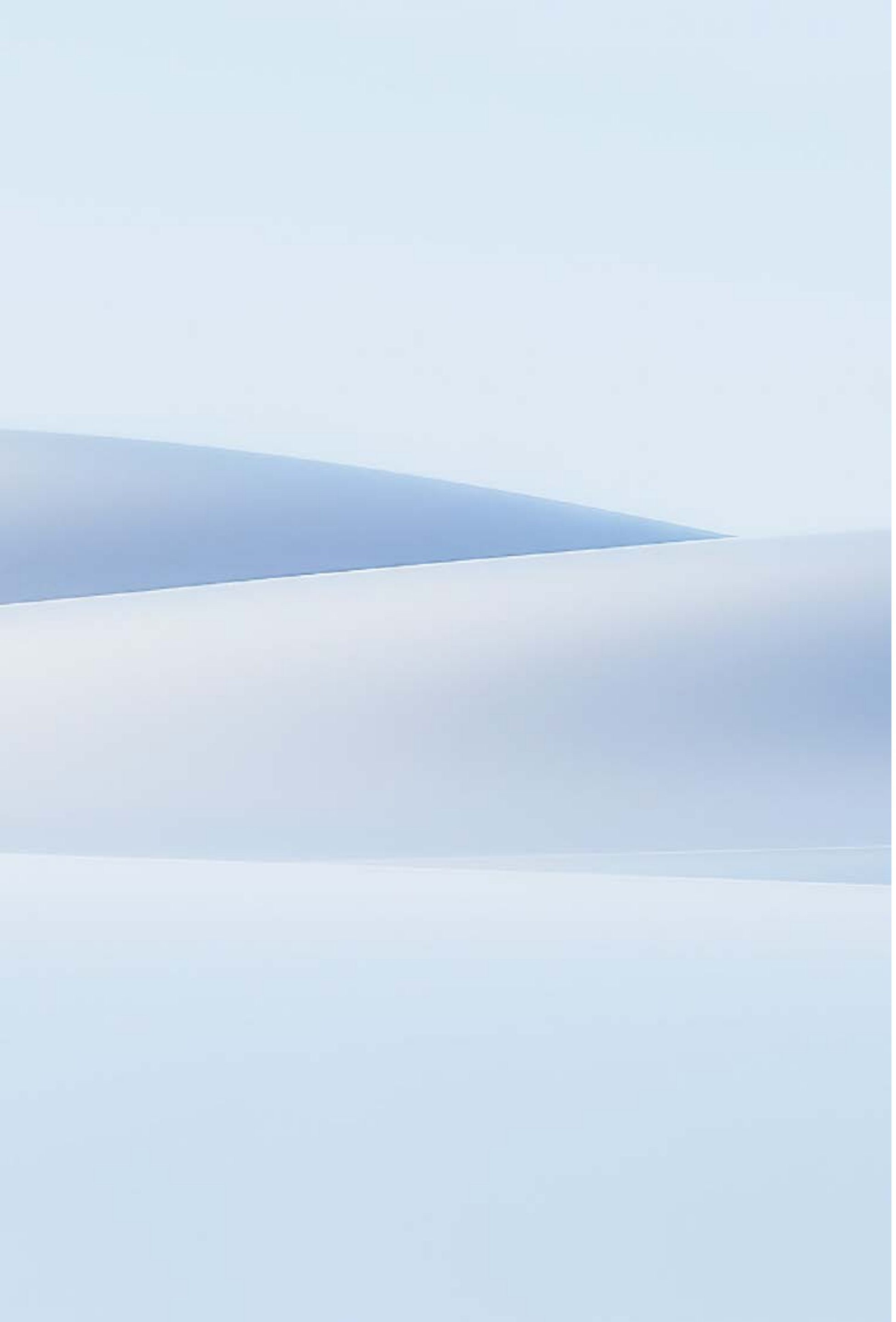
SUNGROW

Collaborating with manufacturers to develop 175°C IGBT using latest generation wafers.

- Using new soldering materials to improve heat withstand capability;
- Optimization of the wire diameter and length of the aluminum binding wire increases the power life cycles by 2 times;
- Use new silicone gel material to increase the service life at 175°C and improve the long-term insulation performance;







Contents

Manufacturing Process Control

Flexible Manufacturing

- Full-range and full-process production across multiple sites
- Modular production with a production line compatibility rate of 90%+

Digital Factory

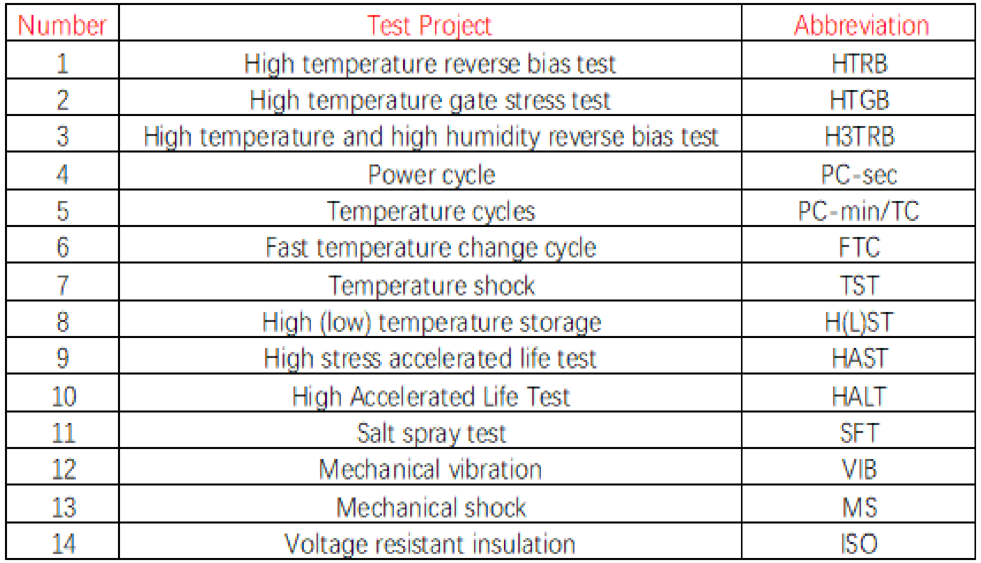
- Integrated SAP/MES/TMS/WMS/SCADA systems
- 80%+ information coverage
- 90%+ automation rate of key processes

Reliable Quality

- Integrated functional testing with 100% coverage
- MES/TMS fool proof alert, 100% traceable
- 99%+ pass rate in circulation

IGBT Reliability Verification

Strict testing of IGBT modules：HTRB、HTGB、H3TRB….



Number	Test Project	Abbreviation
1	High temperature reverse bias test	HTRB
2	High temperature gate stress test	HTGB
3	High temperature and high humidity reverse bias test	H3TRB
4	Power cycle	PC-sec
5	Temperature cycles	PC-min/TC
6	Fast temperature change cycle	FTC
7	Temperature shock	TST
8	High (low) temperature storage	H(L)ST
9	High stress accelerated life test	HAST
10	High Accelerated Life Test	HALT
11	Salt spray test	SFT
12	Mechanical vibration	VIB
13	Mechanical shock	MS
14	Voltage resistant insulation	ISO

Environmental Adaptability Testing

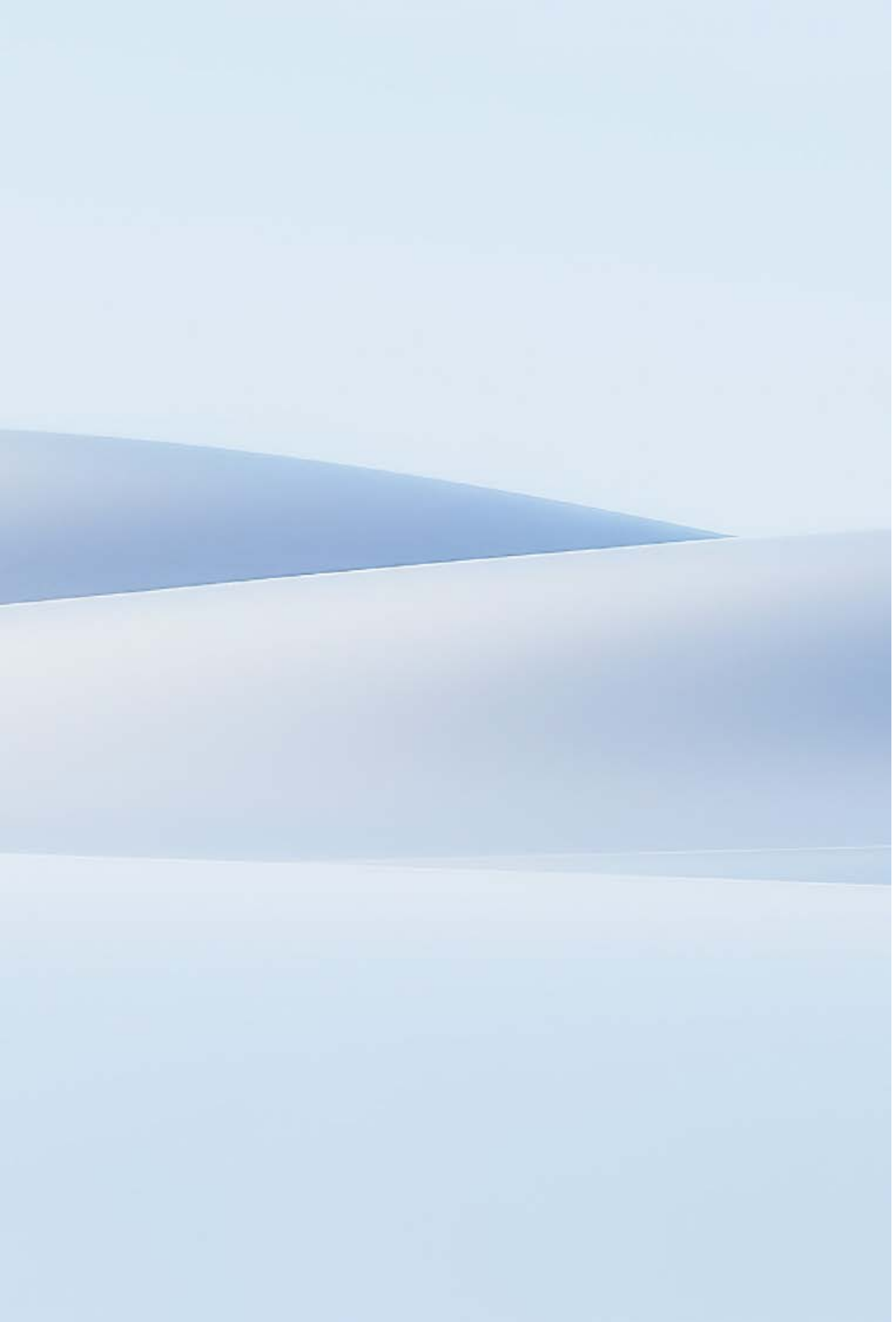
Sandstorm test: Sandstorm 32m/s, sand dust 75-135um

Snowfall test: snowfall thickness 10cm

High altitude and low pressure testing

On Site Reliability Testing and Verification

- Combiner box input short circuit test;
- Short circuit at the far and near ends of the inverter inputs;
- Inverter bus short circuit test;
- Inverter output short circuit test;
- Grid fault test;
- Inverter DC arc test;
- …

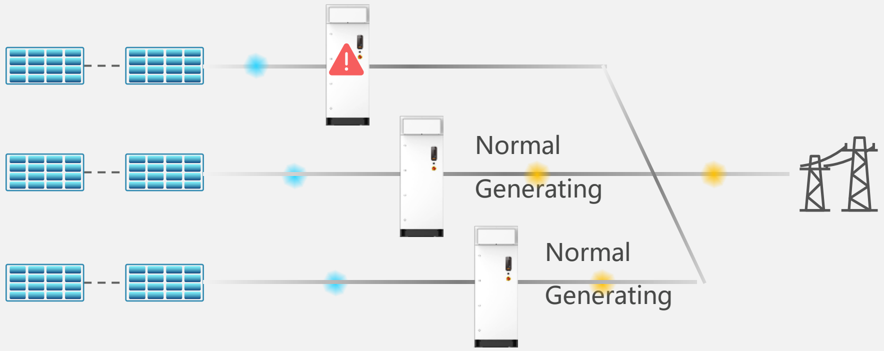


Contents

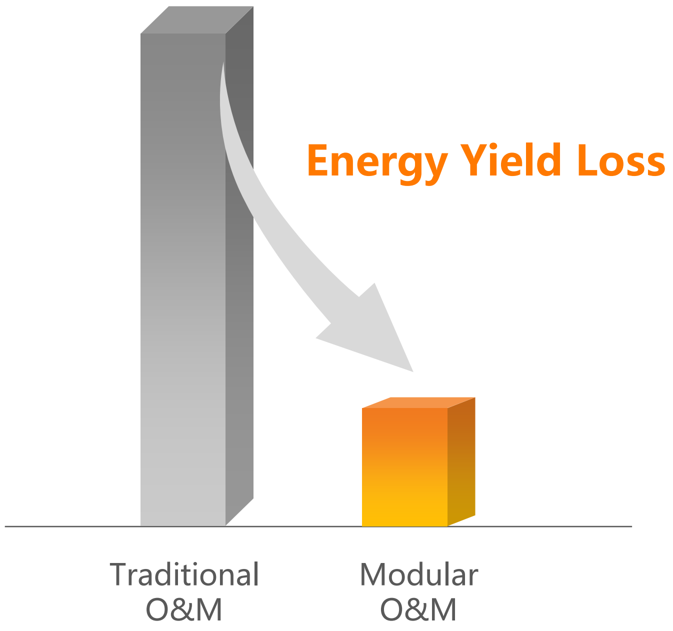
Modular Inverter Design

SUNGROW

1 **Faults of a single unit won't affect others**



2 **Fast replacement with spare units, low energy yield Loss**



Note: the replacement time for tradition O&M is regarded as 15 days

Modular Components Design

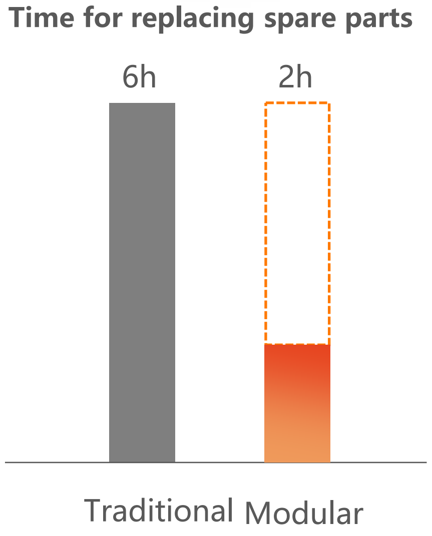
Modular Component Design： More Efficient O&M

Plug and Play

Less Time for Replacing

Replacing efficiency improved by

▲ 70%



Thanks

APPROACHES TOWARDS USE OF TOTAL COST OF OWNERSHIP (TCO) METRICS FOR PV INVERTERS & BEYOND

RELIABILITY OF PV INVERTERS WORKSHOP
NREL, DENVER.
APR 2023

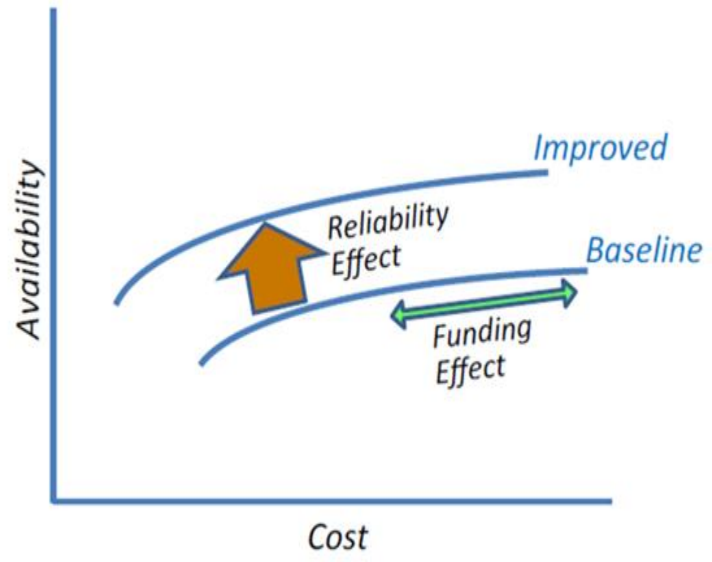
SUMANTH LOKANATH
RAY-ILLUMINATI LLC

APPROACHES TOWARDS USE OF TOTAL COST OF OWNERSHIP

- AGENDA:

1. Metrics Paradigm
    A. Getting to Pragmatic & Actionable Metrics
    B. Motivation
    C. TCO - Definition & Elements
2. Deep Dive into Cost of Ownership (COO)
    A. Introducing RBD’s to capture O&M costs
    B. Capturing Performance Impact – Performance/Capacity Loss (Availability Growth Curves & Benchmarks)
3. From COO to TCO.
4. Presenting an use case for TCO and introducing the TCO Benchmark

ORDER OF SYSTEM (FX) ABILITY EVALUATION PARAMETERS



Cost Effectiveness — 1st Order - Parameter

Life-Cycle Costs | **System Effectiveness** — 2nd Order - Parameter

3rd Order - Parameter

R & D Cost
Production/Construction Cost
Operation & Support Cost
Retirement & Disposal Cost

Performance
Availability
Dependability
Other

4th Order - Parameter

Functional Design
Reliability
Maintainability
Human Factors & Safety
Producibility
Others

Test & Support equipment
Supply support (Spares)
Personnel & Training facilities
Transportation & Handling
Computer Resources

5th Order - Parameter

1. Accessibility
2. Calibration
3. Diagnostic Aids
4. Displays Controls
5. Fasteners
6. Handling
7. Logistic pipeline
8. Mounting
9. Packaging
10. Personnel Skills
11. Safety
12. Selection of parts
13. Software reliability
14. Standardization
15. Storage
16. Transportability
17. Others

MOTIVATION

- An Illustrative Example

Asset Type - # Work orders

	First Solar	Sun Ed
Row Labels	**% of Wos**	**% of Wos**
INVERTER	47.0%	43%
DC Subsystem	22.8%	6%
Other	12.5%	28%
AC Subsystem	11.1%	14%
TRACKER	4.7%	6%
Weather Station	1.7%	2%
METERING	0.1%	1%

Energy Loss by Asset Type Issue

	First Solar	Sun Ed
Row Labels	**% of Lost Energy**	**% of Lost Energy**
External	36%	20%
INVERTER	22%	36%
DC Subsystem	3%	4%
Other	10%	7%
AC Subsystem	26%	20%
Planned Outage		8%
Support Structure	3%	3%
Modules		1%

Plant Systems

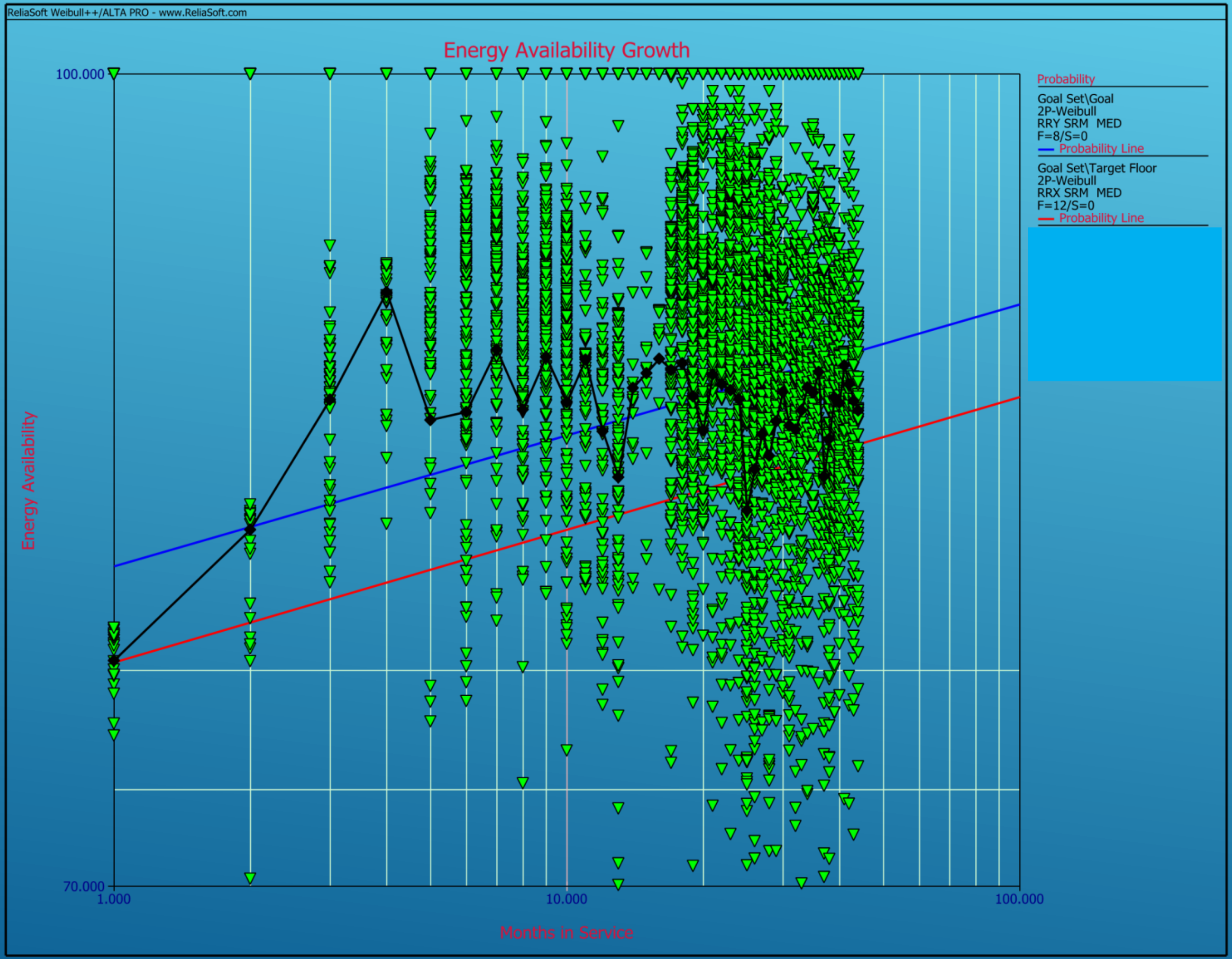
	First Solar	Sun Ed
Row Labels	**% of WO**	**% of WO**
Parts / Matl	63.3%	52.0%
Other	19.0%	9.0%
PM	10.2%	1.0%
Construction	5.7%	4.0%
S/W	1.8%	9.0%

First Solar	Sun Ed	
46	600	plants
2.85	??	GW
132*	2.25	years of operation

Sources: First Solar SRE Data- Nov 2015, SunEdison Data – PV Systems Reliability – An operators perspective, Anastasios Golnas, IEEE Journal Of PV, Jan 2013.

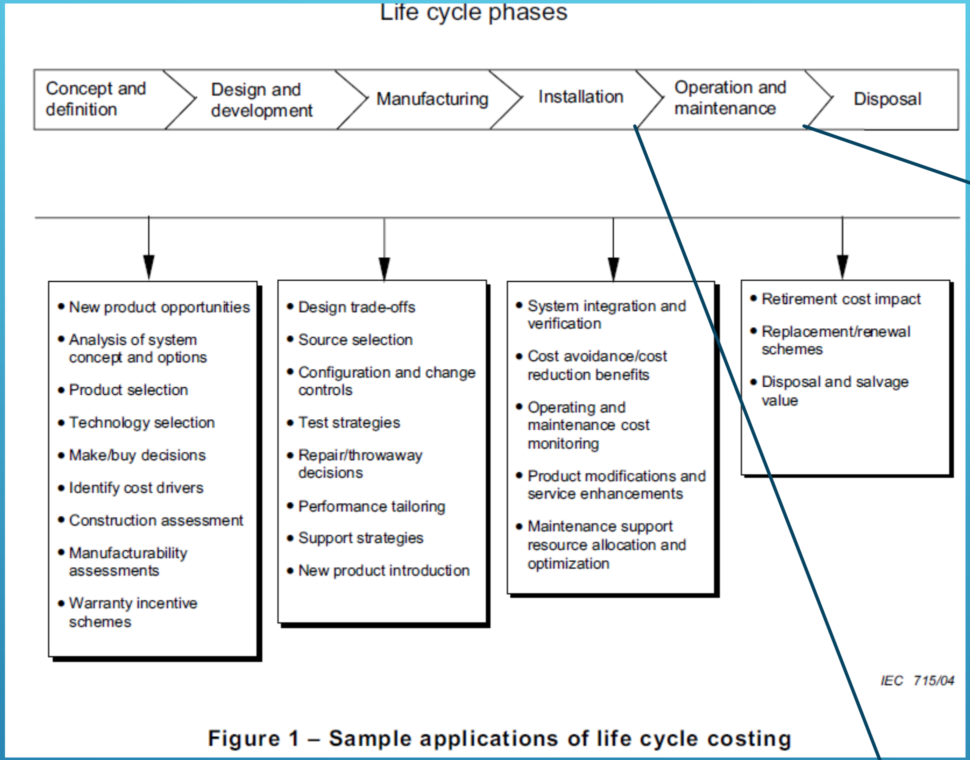
MOTIVATION

AVAILABILITY GROWTH CURVE – INVERTER MODEL A



Months in Production	Target Floor	% Below Floor	Cost of Lost Energy
2	93.10%	32.00%	$78,101
4	95.00%	0.00%	$16,571
6	96.00%	3.72%	$71,490
8	96.60%	21.38%	$64,158
10	97.00%	7.55%	$61,193
12	97.30%	34.73%	$53,350
14	97.45%	0.21%	$3,023
15	97.55%	0.50%	$2,575
16	97.70%	4.09%	$1,049
17	97.88%	12.39%	$36,769
18	97.90%	2.44%	$33,069
19	98.030	24.09%	$61,090
20	98.098	43.02%	$99,093
21	98.161	20.54%	$34,546
22	98.219	23.02%	$36,015
23	98.274	27.00%	$31,704
24	98.325	26.65%	$29,807
25	98.373	55.49%	$117,553
26	98.418	49.27%	$107,102
27	98.460	43.96%	$71,095
28	98.500	48.20%	$126,571
29	98.538	43.90%	$78,357
30	98.574	26.94%	$63,032
31	98.608	41.07%	$111,402
32	98.641	45.52%	$111,587
33	98.672	39.88%	$61,535
34	98.701	34.86%	$34,124
35	98.729	40.65%	$31,481
36	98.756	34.26%	$16,508
37	98.782	51.90%	$60,640
38	98.806	47.26%	$42,681
39	98.830	34.27%	$45,083
40	98.852	32.13%	$48,057
41	98.874	28.95%	$35,929
42	98.895	39.95%	$47,220
43	98.915	40.17%	$64,675
44	98.935	45.33%	$47,122

EMERGING PARADIGMS - (COO/ TCO/LCC COSTS)



Life cycle phases

Concept and definition → Design and development → Manufacturing → Installation → Operation and maintenance → Disposal

- New product opportunities
- Analysis of system concept and options
- Product selection
- Technology selection
- Make/buy decisions
- Identify cost drivers
- Construction assessment
- Manufacturability assessments
- Warranty incentive schemes

- Design trade-offs
- Source selection
- Configuration and change controls
- Test strategies
- Repair/throwaway decisions
- Performance tailoring
- Support strategies
- New product introduction

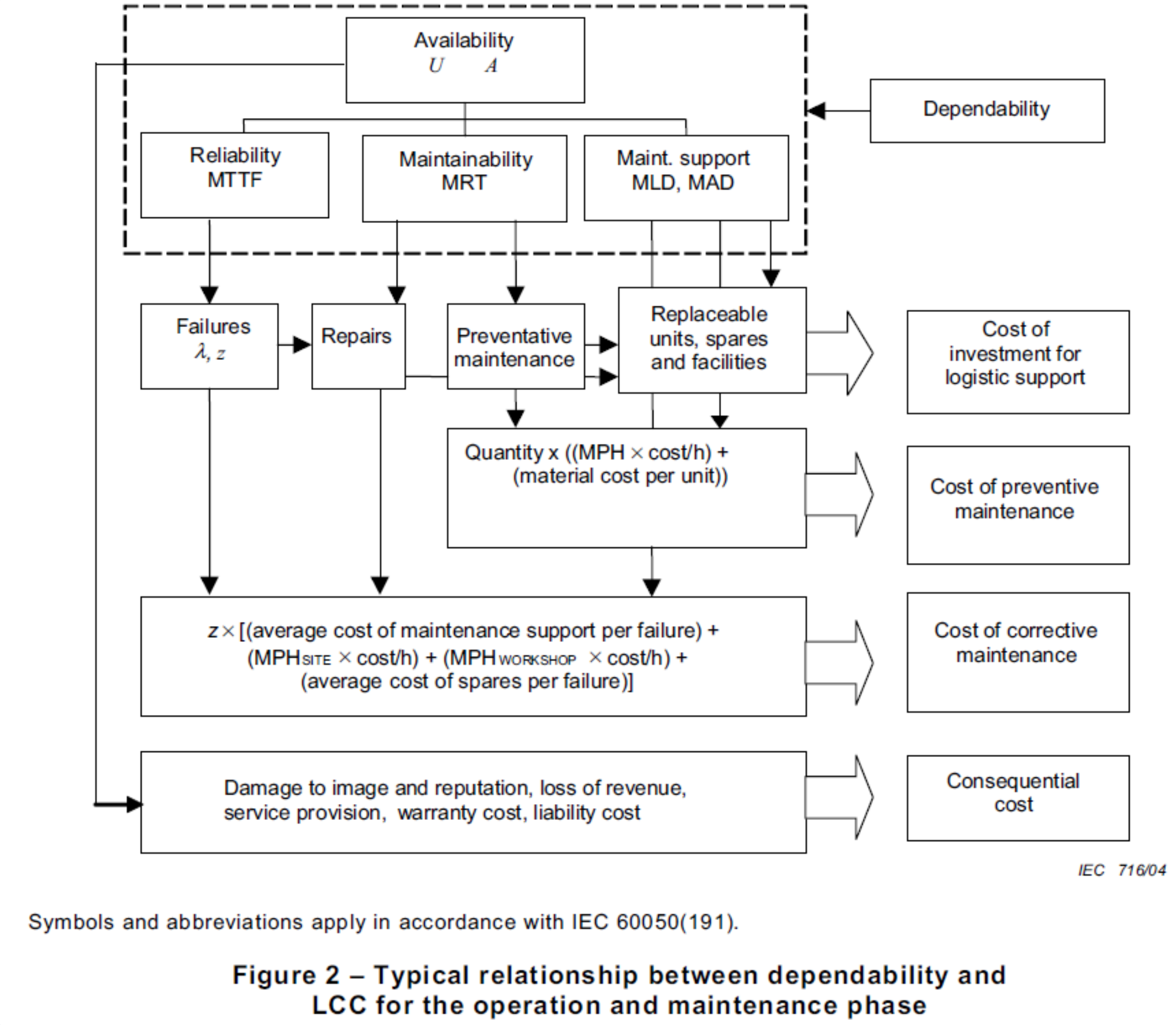
- System integration and verification
- Cost avoidance/cost reduction benefits
- Operating and maintenance cost monitoring
- Product modifications and service enhancements
- Maintenance support resource allocation and optimization

- Retirement cost impact
- Replacement/renewal schemes
- Disposal and salvage value

IEC 715/04

Figure 1 – Sample applications of life cycle costing

COO- Cost of Ownership (O&M only)
TCO – Total Cost of Ownership (EPC +O&M + Loss of revenue)
LCC – Life Cycle Cost (EPC +O&M +Disposal +consequential costs)



Symbols and abbreviations apply in accordance with IEC 60050(191).

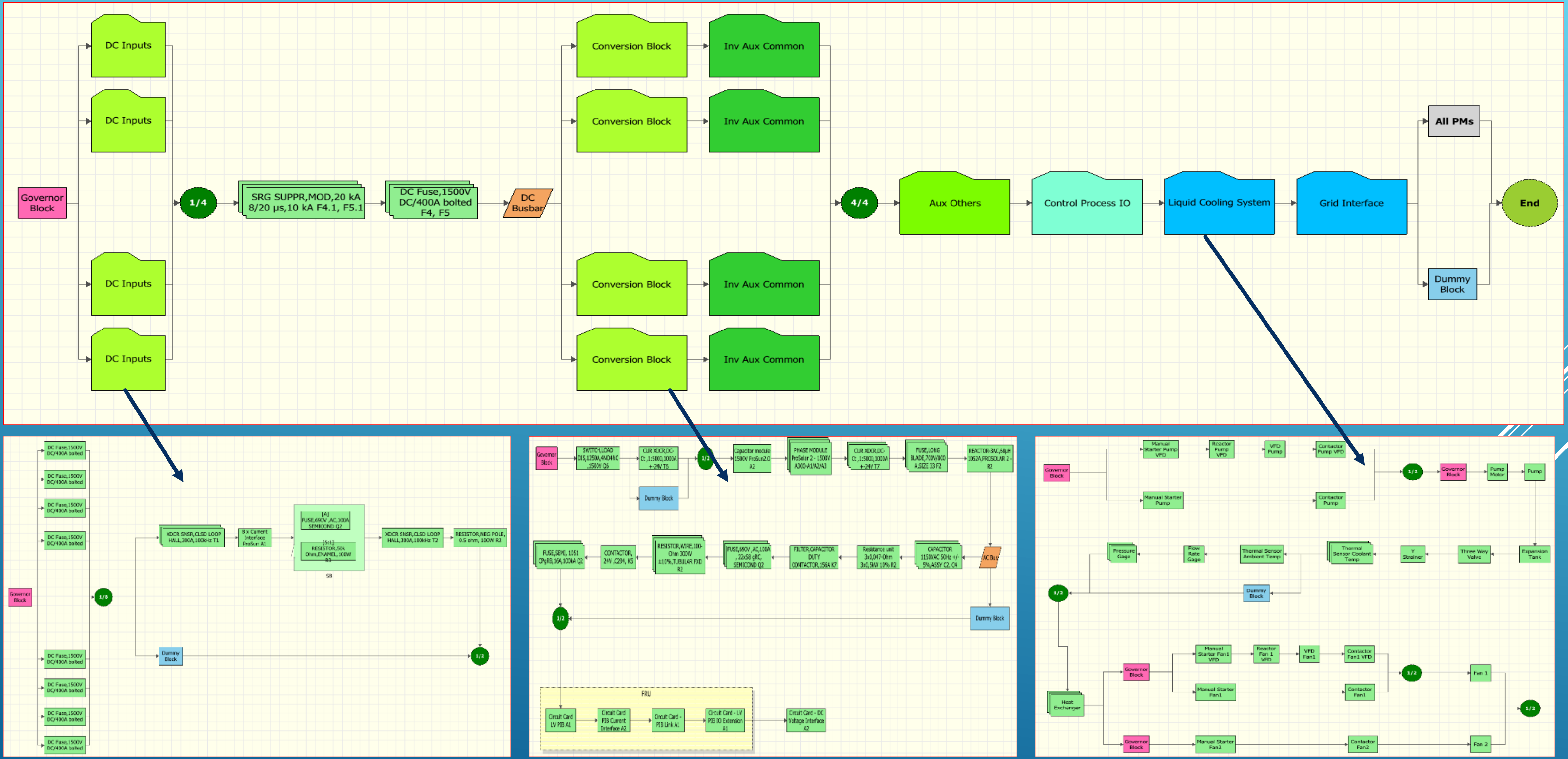
Figure 2 – Typical relationship between dependability and LCC for the operation and maintenance phase

Source: IEC 60300-3-3 2nd Edition – Dependability Management - Application Guide – Life Cycle Costing

COST OF OWNERSHIP MODELING (RBD'S)

- Create a Cost of Ownership (TCO) model for each of the systems in a power plant to provide **some measure of certainty regarding the cost of maintaining the asset**.
- This modeling also addresses the reasonable expectation that it will be capable of producing power at any given time in the form of **an availability estimate and an expended cost estimate**.
- Models of the systems that make up a power plant may then be used to model any particular configuration desired. **These start as Reliability Block Diagrams (RBDs).**
- The following is an example of an inverter product Reliability Block Diagram (RBD) and the resulting cost and availability information. (This information is an example only)
- **Quality of output is a function of the quality of inputs and assumptions used**.

INVERTER COO MODEL: USES RELIABILITY BLOCK DIAGRAMS (RBD) LEVERAGING RELIABILITY MODELS → ESTIMATE AV, OPERATING COSTS.

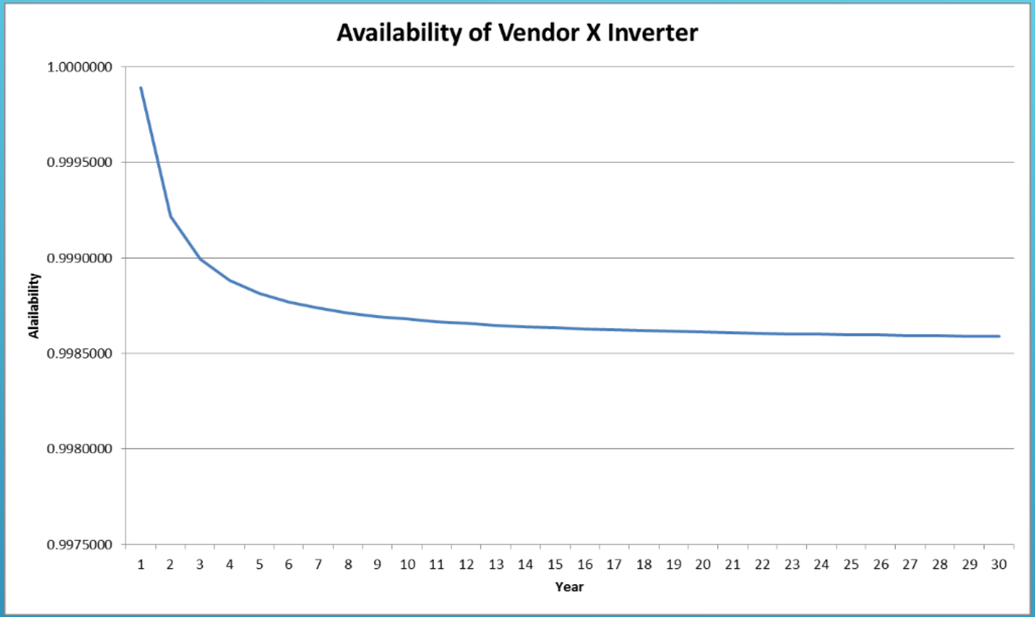


Reference: IEC 61078:2016 Reliability Block Diagrams (RBDs) in dependability analysis

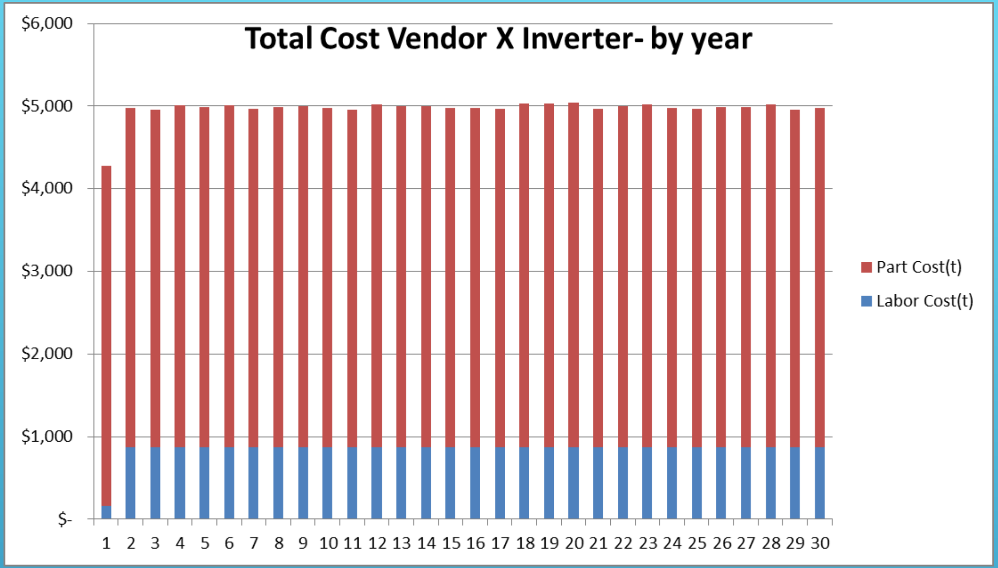
RBD MODELS: INPUTS -

- Current Age
- Duty Cycle
- Failure Distribution (Fixed, Exponential, Lognormal, Weibull etc.)
- Fixed Costs (Acquisition, disposal, Downtime/contract)
- Probabilistic Costs (failed part, logistics, labor, loss of production)
- Operates even if the system is down flag.
- Maintenance Group (Tasks, Crews, Spare part pools)
- Tasks – Corrective, Preventative, Inspection, conditional, scheduled, multiple, downing vs. non-downing, priority.
- Spare part pools (Restock as needed, Scheduled Restock, Emergency spares
- Replacement Strategy
- State Change Conditions
- Standby/Load Sharing Configuration
- Throughput allocation (Weighted/equal share)
- Backlog – send to failed block/ Process/ignore backlog/ limit backlog

RBD MODELS: OUTPUTS -



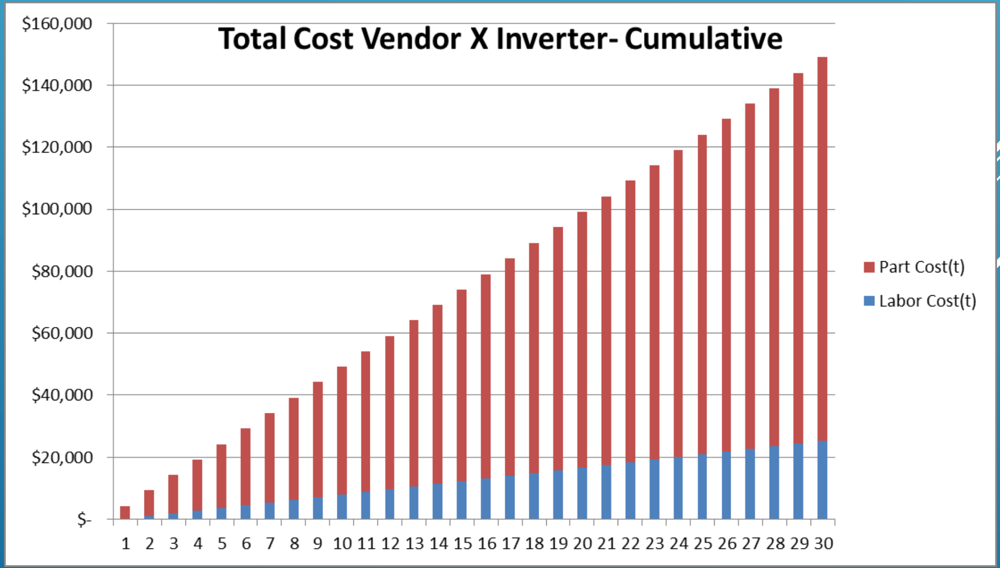
Inverter Throughput Availability



Repair Costs per Year (CM+PM)

Advanced:

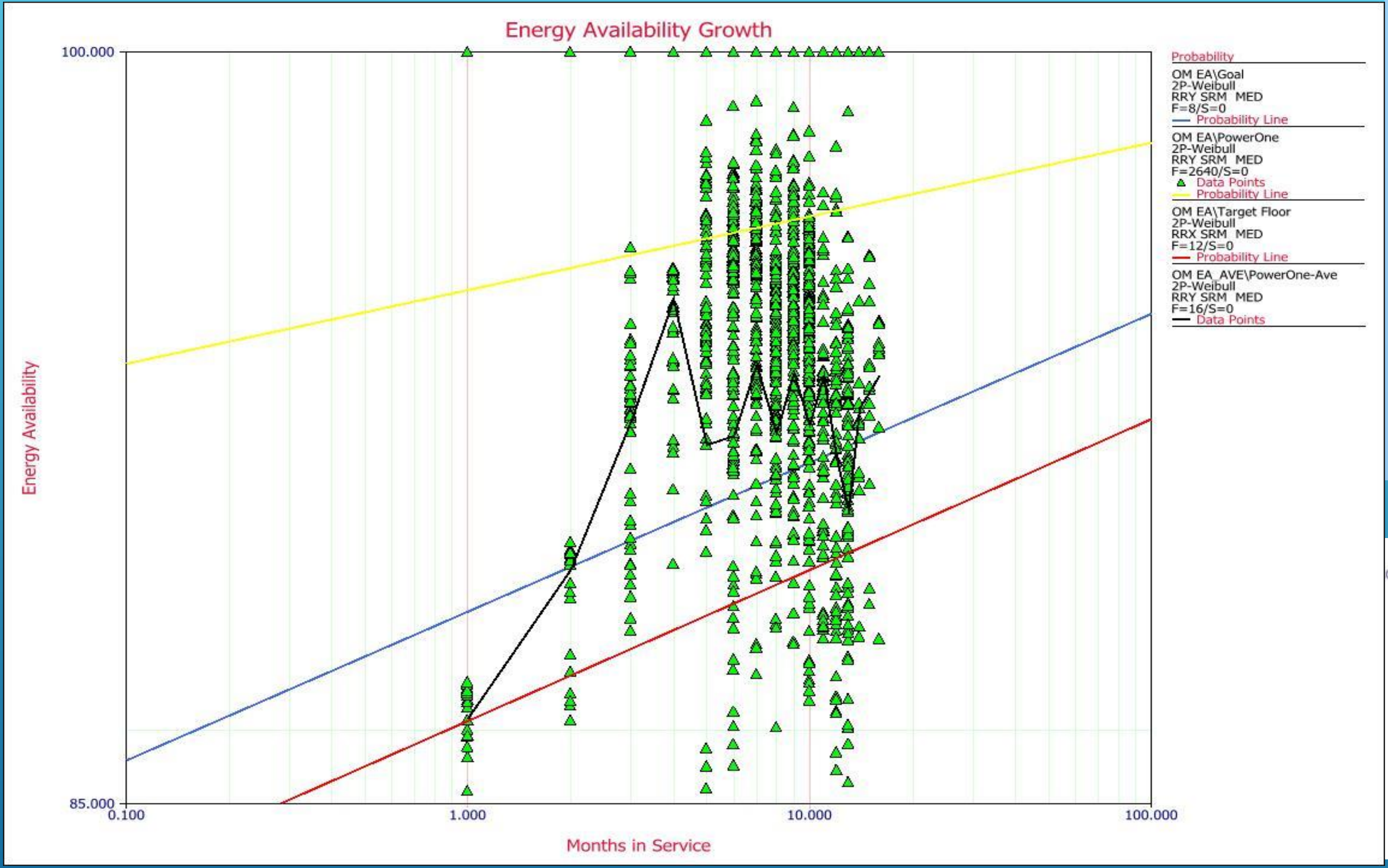
- Cost / System Downing Event
- System Downtime Rate
- Revenue per unit Uptime/Throughput
- Revenue per unit produced
- Cost of Crew/Spare part Pool/ part, holding, failure, downtime, opportunity
- Systems Revenue



Cumulative Costs by Year

Reference: Repairable Systems Analysis Through Simulation (reliasoft.com)

EMERGING PARADIGMS – SYSTEM EFFECTIVENESS (FIELDED GROWTH & COST OF LOST ENERGY CONCEPT)



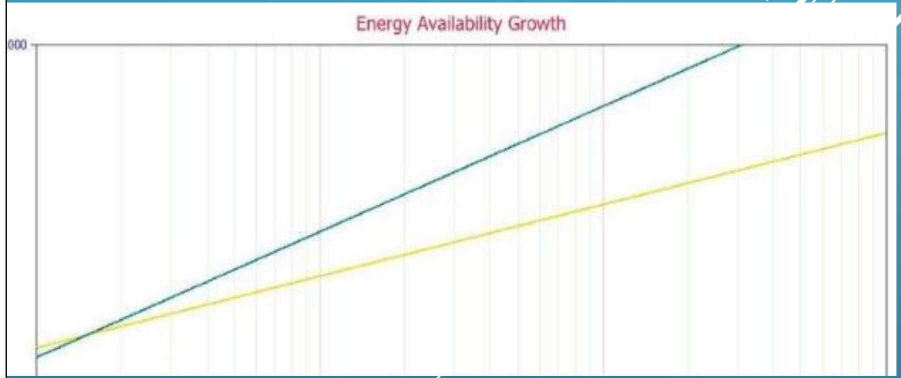
Blue line is Goal Line

Red line is the floor (lower 90 percentile)

Yellow Line is the growth line for this inverter since introduction in FS fleet

Black line is Average value of EA for this inverters

Slope of yellow line is lower than the blue line indicating slower reliability growth.



Months in Production	2	4	6	8	10	12	14	15	16	18	24	26	36	42	48
Target Floor	93.10%	95.00%	96.00%	96.60%	97.00%	97.30%	97.45%	97.55%	97.70%	97.90%	98.30%	98.60%	98.80%	98.90%	99.00%
% Below Floor	32.00%	0.00%	3.72%	21.38%	7.55%	34.73%	0.21%	0.50%	4.09%						
Cost of Lost Energy	$78,101	$16,571	$71,490	$64,158	$61,193	$53,350	$3,023	$2,575	$1,049						

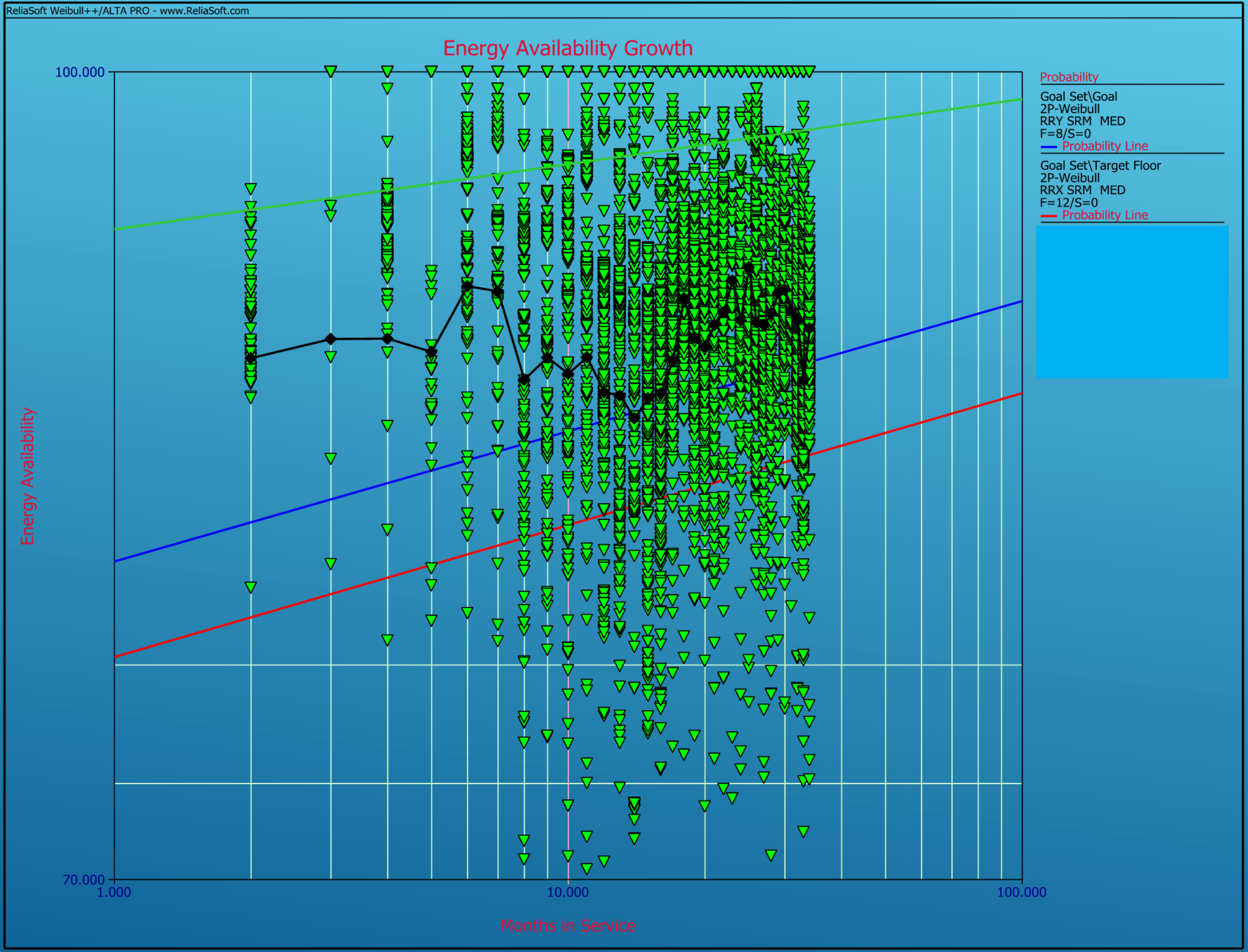
GUIDE TO THE CHARTS – AV GROWTH CURVES

- The “Effective Availability” compares Energy Generated / (Energy Generated + Lost Energy).
- Lost energy downtimes have been properly classified by Operations Center operators as forced outages with the correct inverter GADS code classification.
  - Obtain the lost energy for each inverter [Green triangles] by comparing the population on site. Only consider outages/derates labeled with the GADS code category “Inverter”. Only consider derates & “Forced” and “Maintenance*” outages.
    - An individual inverter downtime is created when irradiance > 85 W/m2 and the inverter is either derated or offline.
    - If other inverters are online, a lost energy calculation is performed to determine the expected energy from the offline inverter based on the performance of its peers.
- The % below the floor is a statistical calculation of the probability of falling below the floor value for that month, given the actual distribution of inverter availabilities.
- To determine the cost of lost energy – the above-lost energy estimate is used with the assumed value of $100 / MWh. The cost of lost energy is cumulative since the last reported date.

- Maintenance (Planned) typically is rare during daytime as all maintenance is typically completed at nighttime
- GADS - "Generating Availability Data System" is a NERC reporting requirement for conventional power plants. It is supposed to collect data about equipment performance.

COST OF LOST ENERGY (COLE)

AVAILABILITY GROWTH CURVE – INVERTER MODEL C

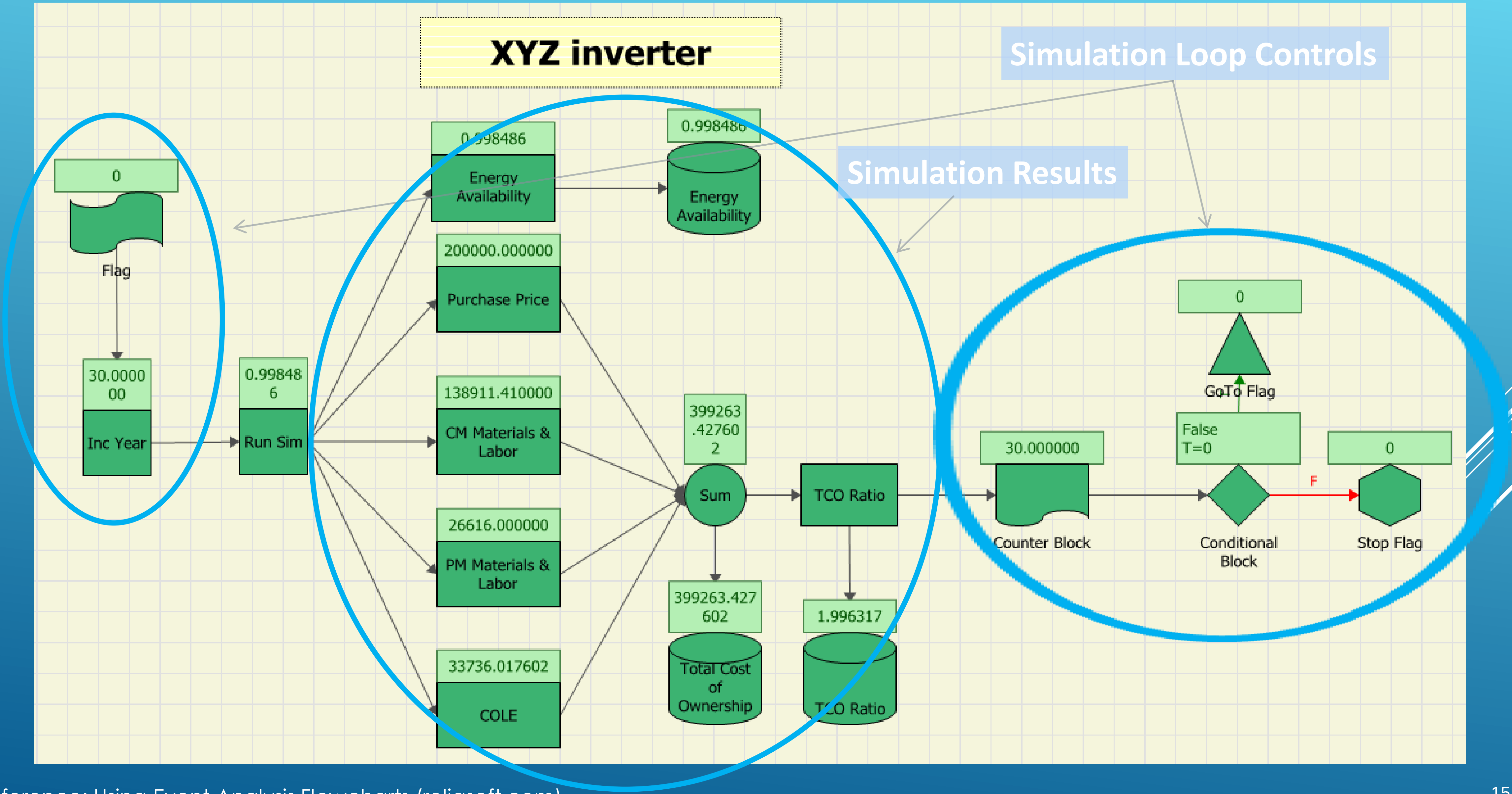


Months in Production	Target Floor	% Below Floor	Cost of Lost Energy
2	93.00%	0.00%	$1,379
3	94.23%	0.00%	$537
4	95.02%	0.00%	$2,895
5	95.57%	3.83%	$11,968
6	95.99%	0.00%	$6,498
7	96.33%	0.00%	$8,537
8	96.60%	8.79%	$43,509
9	96.83%	0.00%	$39,397
10	97.02%	0.00%	$53,589
11	97.19%	0.00%	$32,479
12	97.34%	0.00%	$52,362
13	97.472	17.62%	$61,007
14	97.589	33.50%	$57,895
15	97.694	17.56%	$51,654
16	97.790	17.55%	$69,728
17	97.877	25.24%	$43,111
18	97.957	0.60%	$15,845
19	98.030	21.66%	$38,369
20	98.098	16.54%	$50,631
21	98.161	4.64%	$29,245
22	98.219	4.43%	$19,853
23	98.274	3.30%	$10,680
24	98.325	17.92%	$24,477
25	98.373	0.30%	$6,822
26	98.418	11.94%	$18,682
27	98.460	8.60%	$17,981
28	98.500	11.07%	$16,839
29	98.538	16.06%	$16,902
30	98.574	1.38%	$17,407
31	98.608	30.25%	$17,946
32	98.641	6.68%	$29,025
33	98.672	33.53%	$100,483
34	98.701	20.68%	$23,833

THE SECOND MODEL: FROM COO TO TCO

- Total Cost of Ownership (TCO) models are built by first creating Reliability Block Diagram (RBD) for each of the systems in a power plant.
- The TCO simulation model (Event Analysis Model) calls the Reliability Block Diagram (RBD) for the equipment of interest then simulates the RBD extracting the resulting cost and availability information.
- The resulting information
  - Energy Availability – Ratio of the energy that was produced to the energy that could have been produced without failures
  - CM Materials and labor – The costs of Corrective Maintenance
  - PM Materials and labor – The costs of Preventative Maintenance
  - Cost of Lost Energy (COLE) – Lost energy based on downtime x the cost of energy
  - TCO – Total Cost of Ownership – Purchase price + CM + PM + COLE
  - TCO Ratio - TCO costs / Purchase Price - Metric for comparison to similar assets

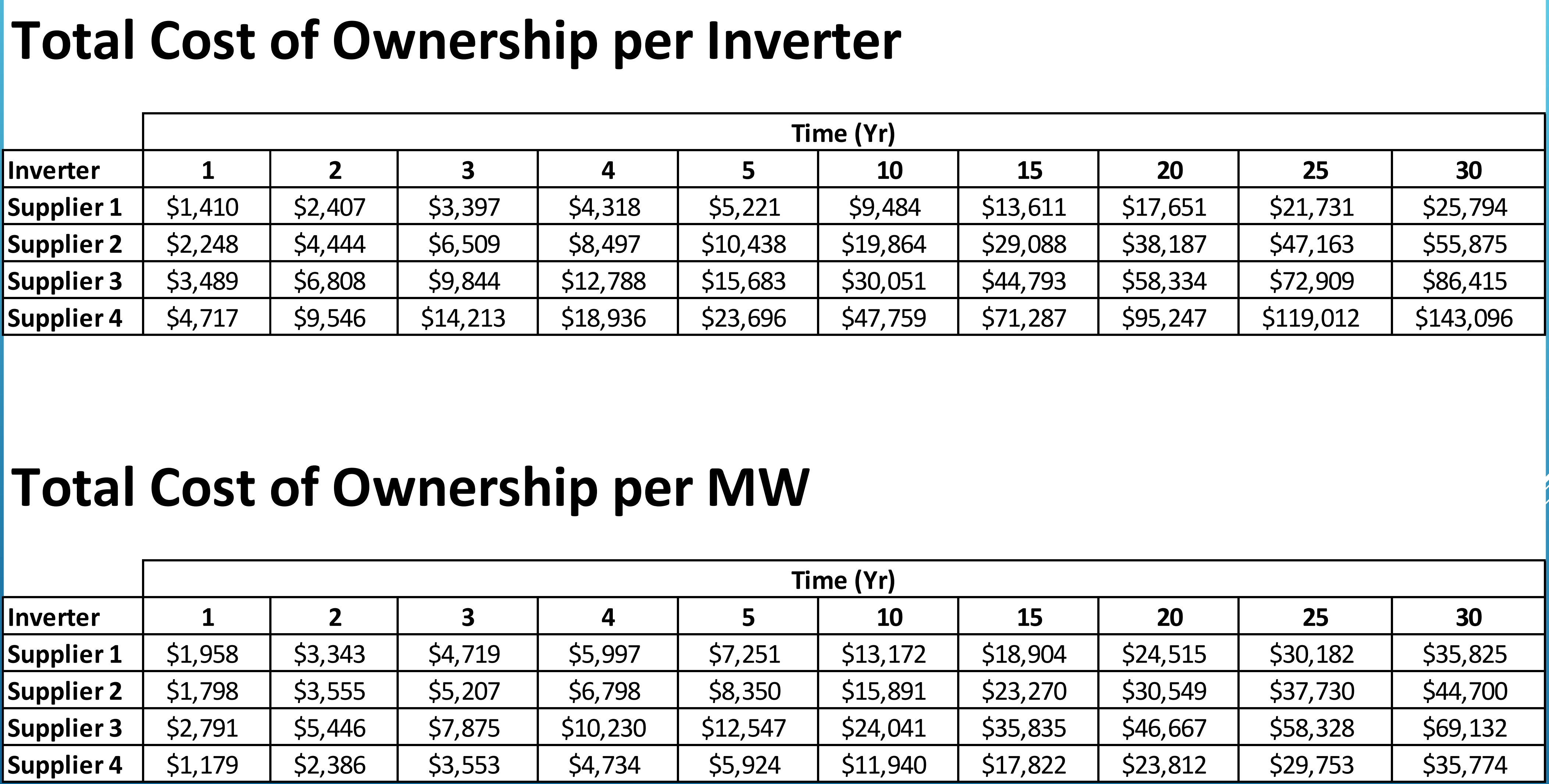
TOTAL COST OF OWNERSHIP (TCO) MODEL – EVENT ANALYSIS FLOWCHART



Reference: Using Event Analysis Flowcharts (reliasoft.com)

USE CASES - COST OF OWNERSHIP (COO) COMPARISON

Modeled COO – Based on Supplier Provided Models



Total Cost of Ownership per Inverter

	Time (Yr)									
Inverter	**1**	**2**	**3**	**4**	**5**	**10**	**15**	**20**	**25**	**30**
Supplier 1	$1,410	$2,407	$3,397	$4,318	$5,221	$9,484	$13,611	$17,651	$21,731	$25,794
Supplier 2	$2,248	$4,444	$6,509	$8,497	$10,438	$19,864	$29,088	$38,187	$47,163	$55,875
Supplier 3	$3,489	$6,808	$9,844	$12,788	$15,683	$30,051	$44,793	$58,334	$72,909	$86,415
Supplier 4	$4,717	$9,546	$14,213	$18,936	$23,696	$47,759	$71,287	$95,247	$119,012	$143,096

Total Cost of Ownership per MW

	Time (Yr)									
Inverter	**1**	**2**	**3**	**4**	**5**	**10**	**15**	**20**	**25**	**30**
Supplier 1	$1,958	$3,343	$4,719	$5,997	$7,251	$13,172	$18,904	$24,515	$30,182	$35,825
Supplier 2	$1,798	$3,555	$5,207	$6,798	$8,350	$15,891	$23,270	$30,549	$37,730	$44,700
Supplier 3	$2,791	$5,446	$7,875	$10,230	$12,547	$24,041	$35,835	$46,667	$58,328	$69,132
Supplier 4	$1,179	$2,386	$3,553	$4,734	$5,924	$11,940	$17,822	$23,812	$29,753	$35,774

Note: All costs are cumulative

USE CASES - COST OF OWNERSHIP (COO) BENCHMARKING

Modeled COO – Based on Actual Costs

Total Cost of Ownership per Inverter

	Time (Yr)					
Inverter	**1**	**2**	**3**	**4**	**5**	**6**
Supplier 1	$1,125	$1,458	$1,526	$1,527	$2,008	$2,884
Supplier 2	$15,637	$15,875	$19,238	$32,671		
Supplier 3	$3,841	$5,076	$5,088	$5,496	$6,243	
Supplier 4	$8,319	$12,763	$15,730			

Red → Actuals >50% from predicted

Orange → Actuals 20-50% higher from predicted

Yellow → Actuals 10-20% higher from predicted

Green → anything lower than predicted or <10% greater.

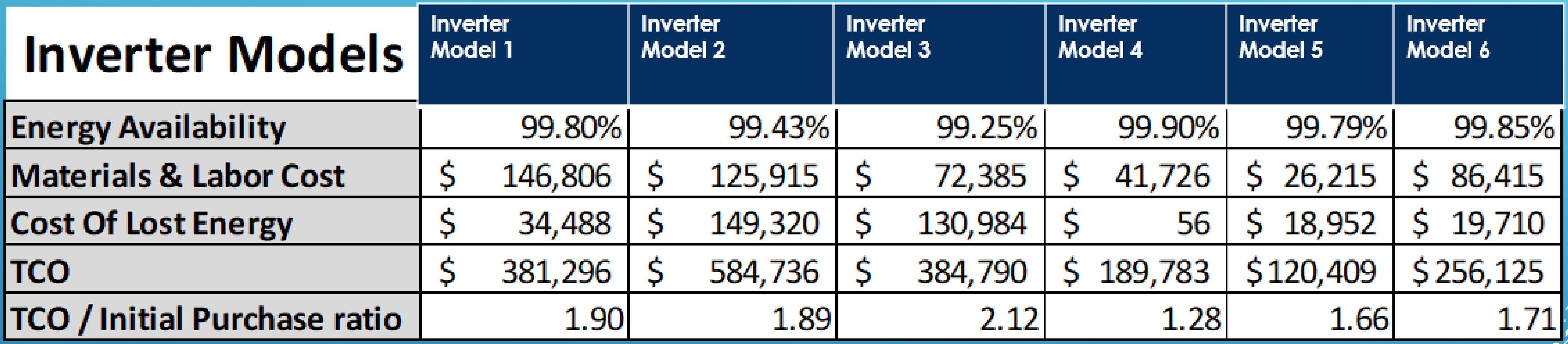
Total Cost of Ownership per MW

	Time (Yr)					
Inverter	**1**	**2**	**3**	**4**	**5**	**6**
Supplier 1	$1,562	$2,025	$2,119	$2,121	$2,789	$4,005
Supplier 2	$10,425	$10,583	$15,390	$26,137		
Supplier 3	$2,845	$3,760	$3,769	$4,397	$4,995	
Supplier 4	$2,080	$3,191	$3,932			

Note: All costs are cumulative

USE CASES - TOTAL COST OF OWNERSHIP (TCO) BENCHMARK

Modeled TCO – Based on Actual Costs



Inverter Models	Inverter Model 1	Inverter Model 2	Inverter Model 3	Inverter Model 4	Inverter Model 5	Inverter Model 6
Energy Availability	99.80%	99.43%	99.25%	99.90%	99.79%	99.85%
Materials & Labor Cost	$ 146,806	$ 125,915	$ 72,385	$ 41,726	$ 26,215	$ 86,415
Cost Of Lost Energy	$ 34,488	$ 149,320	$ 130,984	$ 56	$ 18,952	$ 19,710
TCO	$ 381,296	$ 584,736	$ 384,790	$ 189,783	$ 120,409	$ 256,125
TCO / Initial Purchase ratio	1.90	1.89	2.12	1.28	1.66	1.71

The Total Cost of Ownership over 30 years.

Assumptions:

- $100 per lost MWH
- $60 labor rate

Ray Illuminati
Reliable Quality

MANAGING RISK - "A FOREST FROM THE TREES PERSPECTIVE"

Sumanth Lokanath
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BACKUP

SUMANTH LOKANATH

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Risk Discovery
Reliability Management,
Quality Systems &
Product Management,
Standards, Testing,
Solar & Renewables.

EDUCATION

BANGALORE UNIVERSITY
Bachelor's Degree
Electronics Engineering
1995-1999

ARIZONA STATE UNIVERSITY
Masters Degree
Electronics Engineering
2000-2003

ABOUT ME

PROVEN PERFORMANCE
High Performer

PEOPLE LEADER
Global Teams
Remote Teams

STRATEGIC PLANNING
Master of Strategy

PRODUCT DEVELOPMENT
Global Teams
Remote Teams

GROWTH MINDSET
YoY Proven Results

RESULTS DRIVEN
Global Teams
Remote Teams

CAREER JOURNEY

ASU PTL Research Assistant 2000 - 2003

First Solar Test Engineer 2003 - 2006

Reliability Manager 2006 - 2012

Sr. Manager Systems Reliability 2012 - 2020

Director Product Reliability 2020 - 2023

ASU MSEE 2000 - 2003

IEC International Electrotechnical Commission — **TC82 Technical Contributor** 2010

Ray Illuminati Reliable Quality — **Founder & Principal** 2019

VDE AMERICAS — **Sr. Consultant** 2023

CAREER DEFINING MOMENTS


RELIABILITY SCIENCE


LINE QUALIFICATION


PEOPLE MANAGER


PLANT REPLICATION


LSS DESIGN & OPERATIONS


INVERTER QUALIFICATION


TRACKER QUALIFICATION

6 Number of Solar Module Models launched

4 Number of Solar Factories Replicated

6 Number of Solar Trackers launched

4 Product Launch Teams

AFFILIATIONS:

ASQ Excellence Through Quality™

ANSI

ARESCA American Renewable Energy Standards and Certification Association

IEEE Reliability Society

IEEE PES Power & Energy Society™

DEPCOM POWER®

A KOCH ENGINEERED SOLUTIONS COMPANY

Various Solutions for Servicing an Aging Inverter Fleet

George Kemper

ABOUT

DEPCOM POWER

About Me:

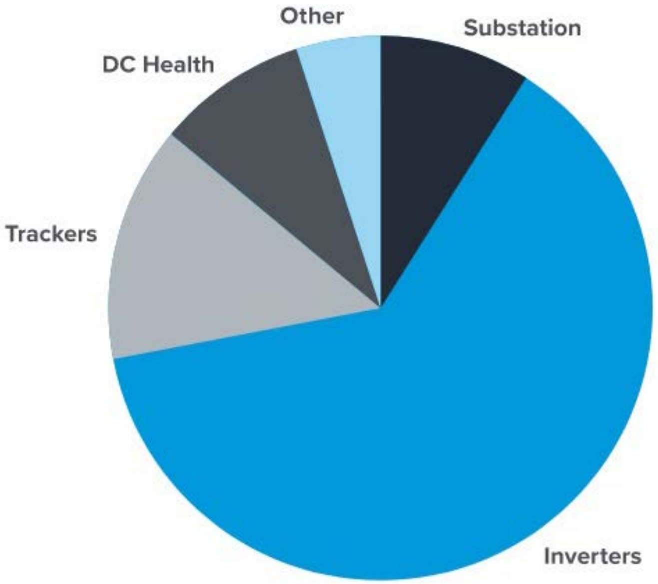
I began my journey on the solar coaster in 2016, working for an inverter manufacturer. Since then, I've worn multiple hats—IE, Developer, and EPC design engineer. However, my true passion lies in repower and retrofits. Each site's unique challenges fuel my enthusiasm for finding innovative solutions in the ever-evolving solar landscape.

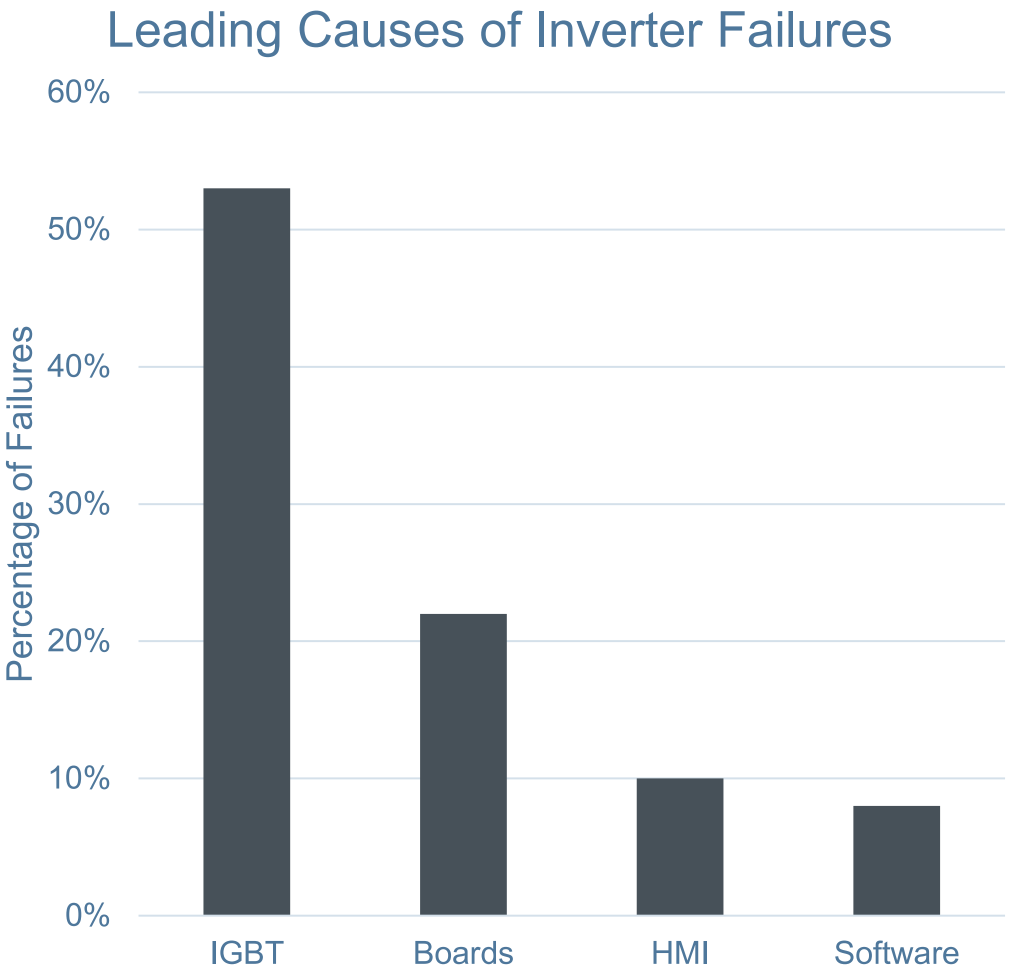
About DEPCOM Power:

DEPCOM Power, a Koch Engineered Solutions company, is a leading energy solutions partner for the utility solar and broader energy industries. Our comprehensive services include project development support, EPC, energy storage, repowering, and O&M.

Overview of Failures

- Inverters are the leading cause of loss of energy events
- Of the events shown, 82% will require a Level 3 Technician
- Most cost models estimate that the end-of-life for an inverter occurs around year 10 or 15, but in hot climates this may happen a lot sooner

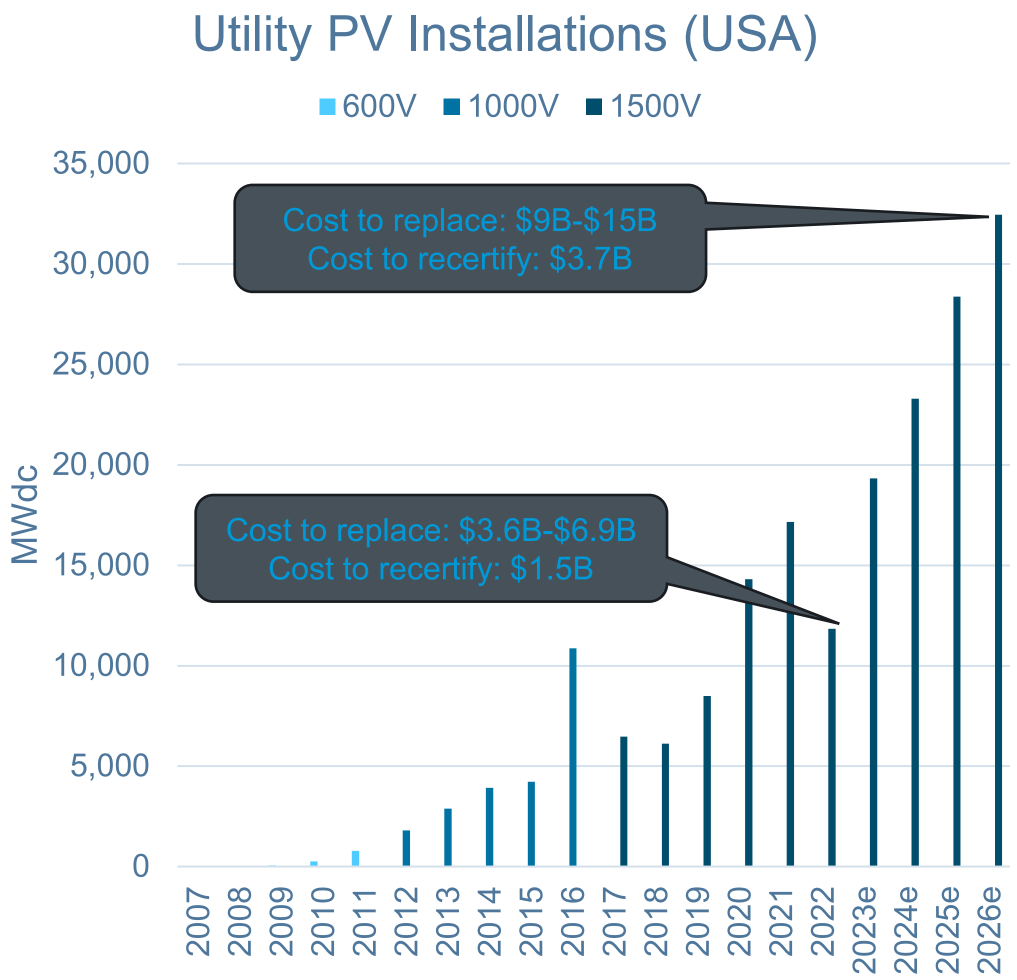




Financial Impact of Aging PV Equipment

DEPCOM POWER

- Today there is approximately 12,000 out of warranty utility scale inverters
- In the next 10-15 years this number will likely double
- In 2026 approximately 30,000 utility scale inverters will be out of warranty
- A proactive post-warranty plan can help extend the life and lessen the financial impact of the aging fleet
- The cost to replace a single inverter is $300k-$500k (National Average)



Utility PV Installations (USA)

Cost to replace: $9B-$15B
Cost to recertify: $3.7B

Cost to replace: $3.6B-$6.9B
Cost to recertify: $1.5B

Source: emp.lbl.gov/utility-scale-solar/

KOCH
ENGINEERED SOLUTIONS

Challenges for Asset Owners

Today:

- Traditional O&M service providers need expert technicians to identify and rectify complex central inverter issues

Common Issues:

- Increased failure of components
- Limited OEM technical support
- Lack of qualified third-party field technicians
- Spare part supply chain constraints and obsolescence
- Increased downtime and revenue loss

Proactive Service & Repower Plan

1. Evaluate spare part use rate, availability, and potential to secure long term supply
2. Ensure accessibility and availability of trained experienced technicians
3. Forecast the impact of catastrophic failures of major equipment and how it impacts PPA, insurance and revenue
4. Trend failures and apply analytics for enhanced preventive maintenance and proactive replacement
5. Analyze the impact of different equipment replacement options
6. Assess new market incentives and technologies
7. Generate an accurate life cycle cost model for the plant that schedules repairs and repowering at the proper time intervals

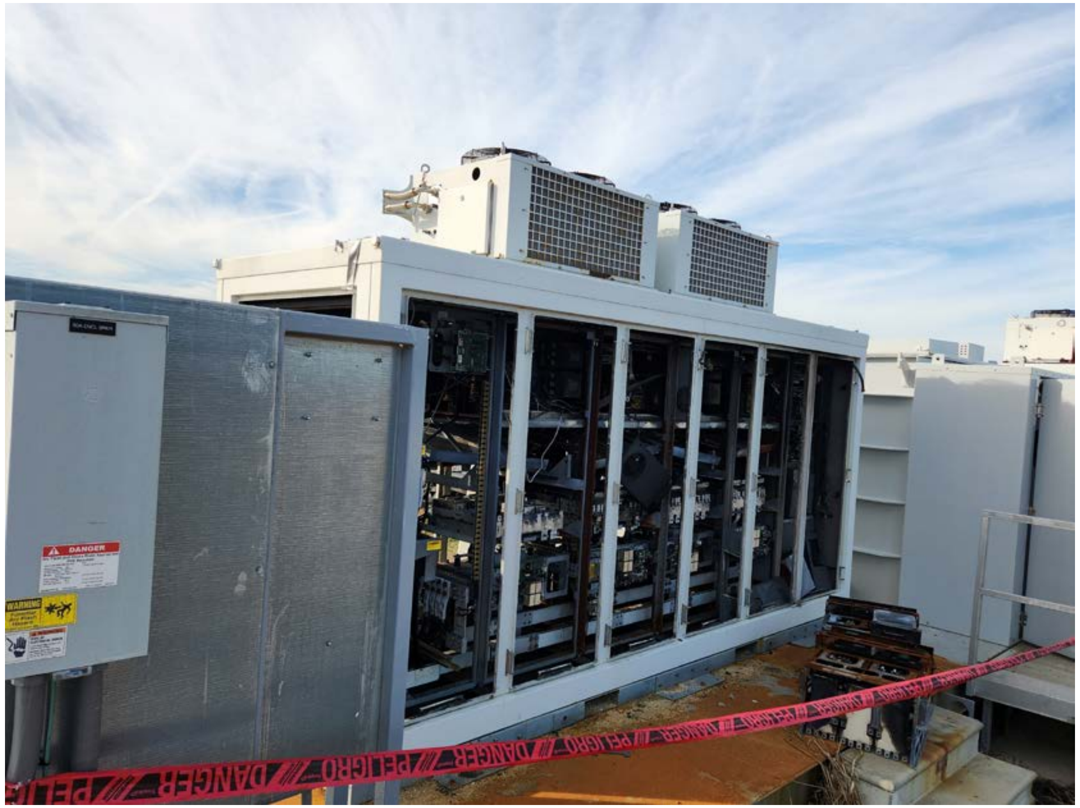
Why Repower

- Inverter no longer supported by OEM or manufacturer has left the market
- Limited or no access to spare parts
- Limited access to trained technicians
- Expanding Capacity or adding energy storage
- Leveraging market incentives
- Restoration + Re-power

Case Study 1

Problem Description

- Site Description:
    - Remote location in the Southwest
    - 3.12 MVA transformers with two 1.56MVA inverters per skid
    - Commercial Operation Date of 2015
- Problem:
    - Multiple inverters have experienced a catastrophic failure
    - OEM has limited support in the market

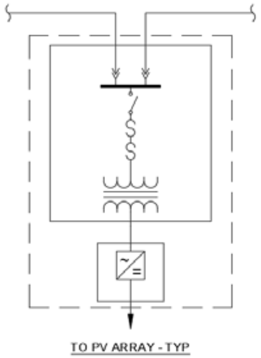


Case Study 1

Overview of Solutions

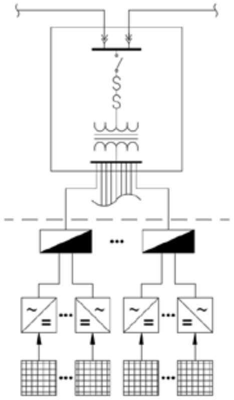
New 1500V Monolithic Central

Install 1 PCS skid that includes custom derated inverter and new transformer. The MPPT Voltage is near the bottom of the window and will operate in single voltage mode when arrays voltage falls outside the inverters window. Reuse DC BOS and splice existing conductors as needed.



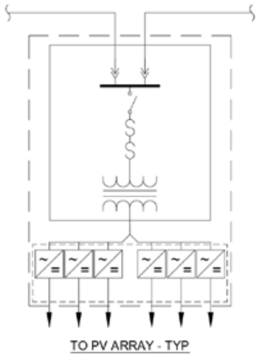
New 1500V String Inverter

Replace combiner boxes with custom derated string inverters that match the existing transformer's secondary voltage, utilize the existing parallel 4/0 for AC output conductors, and reuse the original transformer.



New Modular Central Inverter

Install new skidded modular central inverter with a new transformer. Array Voltage is within the inverters MPPT window. Reuse DC BOS and splice existing conductors as needed.



Refurbish Unit

Have a trained inverter technician diagnose and repair the inverter in the field if spare parts are available.

Case Study 1

DEPCOM POWER.

Production and Solution Cost Per PCS (2 Inverters)

	Refurbish Existing Inverter	New 1500V Monolithic Inverter	New 1500V Modular Central Inverter	New 1500V String Inverters
Inverter Qty.	1	1	6	28
Output Power	1560kVA	3000kVA (Curtailed)	520kVA (Curtailed)	111.4kVA (Curtailed)
Output Voltage	690Vac	450Vac	395Vac	690Vac
MPPT Min	585Vdc	637Vdc	576Vdc	570Vdc
Production Yr. 10	8065 MWh	8006 MWh	8233 MWh	7821 MWh
Production Yr. 15	7788 MWh	7429 MWh	7909 MWh	7644 MWh
Production Yr. 20	7529 MWh	7031 MWh	7662 MWh	7517 MWh
Repower Cost	$250,000	$500,000	$650,000	$1,000,000
Lead Times	?	30+ Weeks	30+ Weeks	15 Weeks
ROI	.9 Years	2.7 Years	3.04 Years	3.32 Years
Net Repowered Profit (10 Yr.)	$2,821,000	$2,368,000	$2,402,000	$2,492,000

Notes:
1) Prices are project specific and vary depending on region
2) ROI and NET Profit consider lost production and O&M cost

Case Study 2

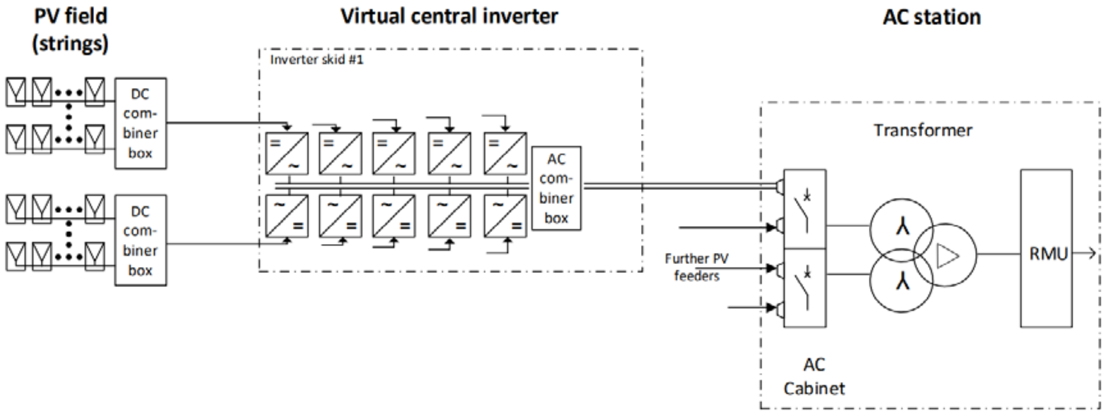
Problem Description

- OEM has left the US market and is no longer supplying spare parts for their inverters
- Commercial Operation Date of 2017
- The site is experiencing critical failures at an alarming rate
- The site is in a very remote location
- PPA has an energy guarantee

Case Study 2

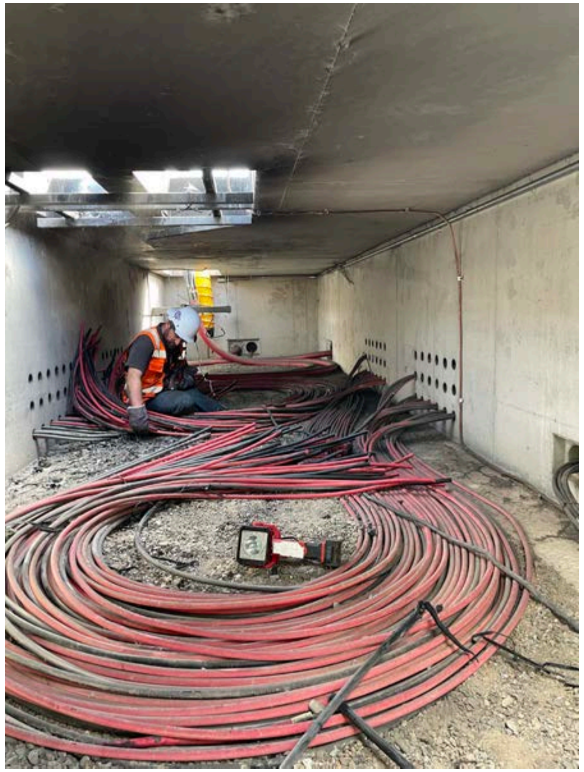
Solution

- Site utilized a virtual central solution, the inverters were derated so that the existing DC BOS and transformer could be reused
- Mobilize faster due to the shorter lead times associated with string inverters and AC BOS
- Cost to repower one PCS is ~$950k
- Advantages of string inverters:
  - ~50% reduction in O&M cost
  - Simplified spare parts strategy



Proactive Considerations for New Sites

- Install vaults underneath the inverter pad
- Have service loops on all cables
- Consider string inverters
  - Easier to replace
  - Lower O&M Cost



Conclusion

- It is cheaper to plan for replacements instead of reacting after a critical failure.
- Buy lots of spare parts and multiple spare PCS for large sites.
- Continuously increasing the DC voltage and deploying larger inverters will perpetually orphan our older systems, leading to challenges in terms of product reliability and availability.
- Standardization on AC output voltage on the larger central inverters would make future equipment replacements a lot easier.

Thank You

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DEPCOM POWER®

A KOCH ENGINEERED SOLUTIONS COMPANY

Inverter Quality Assurance

Pre-Production, Production, & Operations Field RCA

NREL Inverter Reliability Conference | Dr. Ignacio Carellan | April 11-12, 2024

Summary and agenda

1. Several inverters manufacturers do not have a reliability testing program. ISO 62093 NOT in use

2. Reliability starts from contracting stage

3. Kiwa PI Berlin proposes a new tests for IGBTs reliability

- Kiwa PI Berlin Introduction

- Manufacturing Quality Assurance

- Root cause analysis (RCA), a case study. Tests proposed

Kiwa PI Berlin Introduction

Trusted Solar and Storage Advisors

NREL Inverter Reliability Conference

Kiwa PI Berlin – Trusted Solar and Storage Advisors

15+

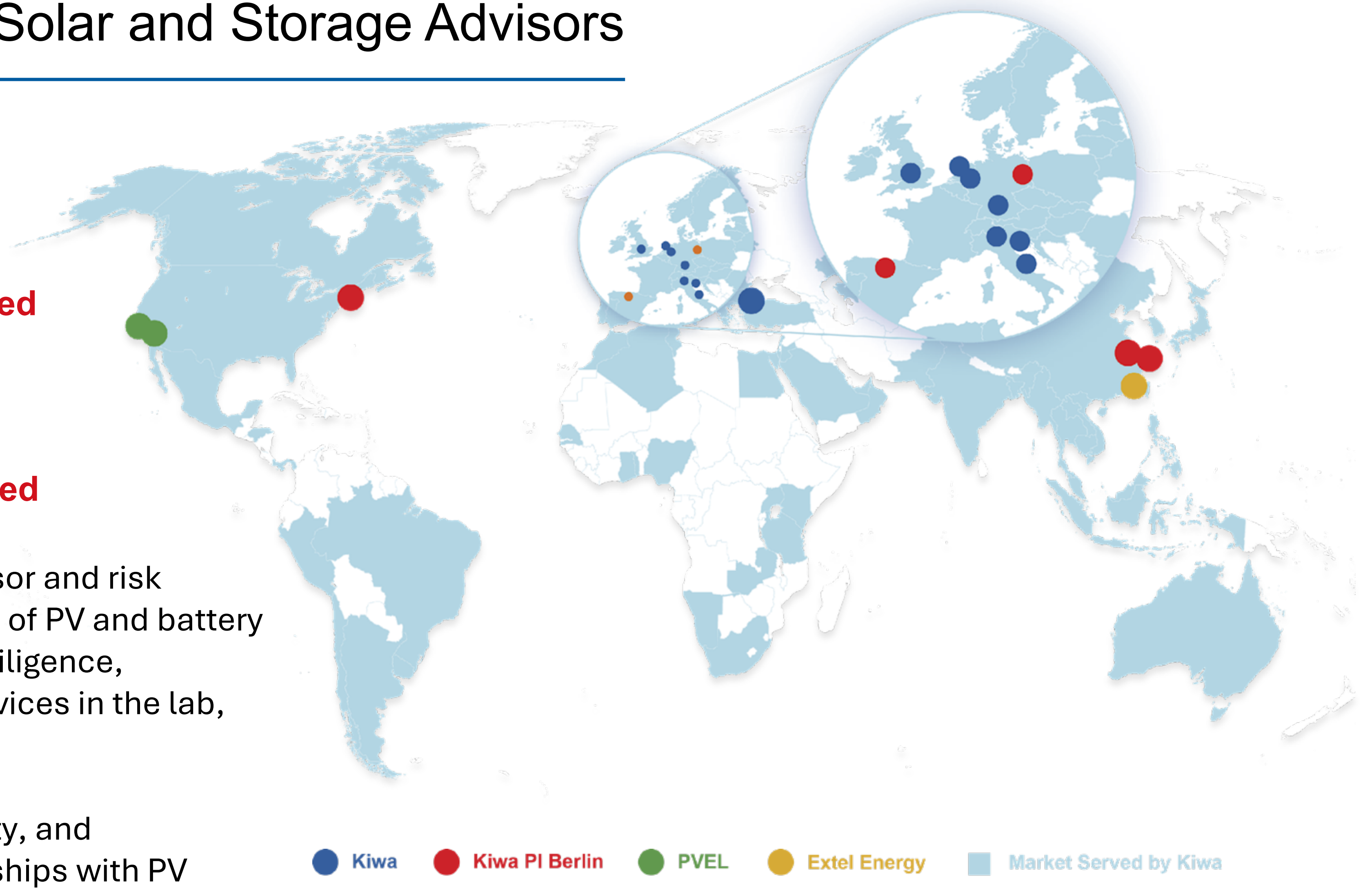
All TR1 Inverter Manufacturers Audited

25+ GW

Inverter Production Capacity Inspected

Kiwa PI Berlin is a leading technical advisor and risk manager focused on quality assessment of PV and battery storage equipment providing technical diligence, procurement, and quality assurance services in the lab, factory, and field.

We independently verify quality, reliability, and performance through our direct relationships with PV module, inverter and battery manufacturers



Manufacturing Quality Assurance

Contracting, Factory Inspections, Testing

NREL Inverter Reliability Conference

Quality Assurance: Pre-Production Stage Diligence

Industry Standards for Pre-Production Quality Assurance & Diligence Includes:

- **Supply Contract**
    - **-** Technical Specifications
    - \- Quality Assurance Requirements
    - \- Reliability testing. **NO IEC 62093: 2022***
- **Factory Audit**
    - **-** Manufacturing Quality Assessment
- **Supply Chain Traceability & ESG**
    - **-** Key Component Traceability & ESG compliance

kiwa
PI Berlin

PV Inverter Factory Audit Report

LOCATION: #######, ######

Quality Rating	Critical Findings	Major Findings	Minor Findings	Risk Management Recommended
Inverters line Above Average	0	2	3	Corrective action and verification Production supervision FAT Witness

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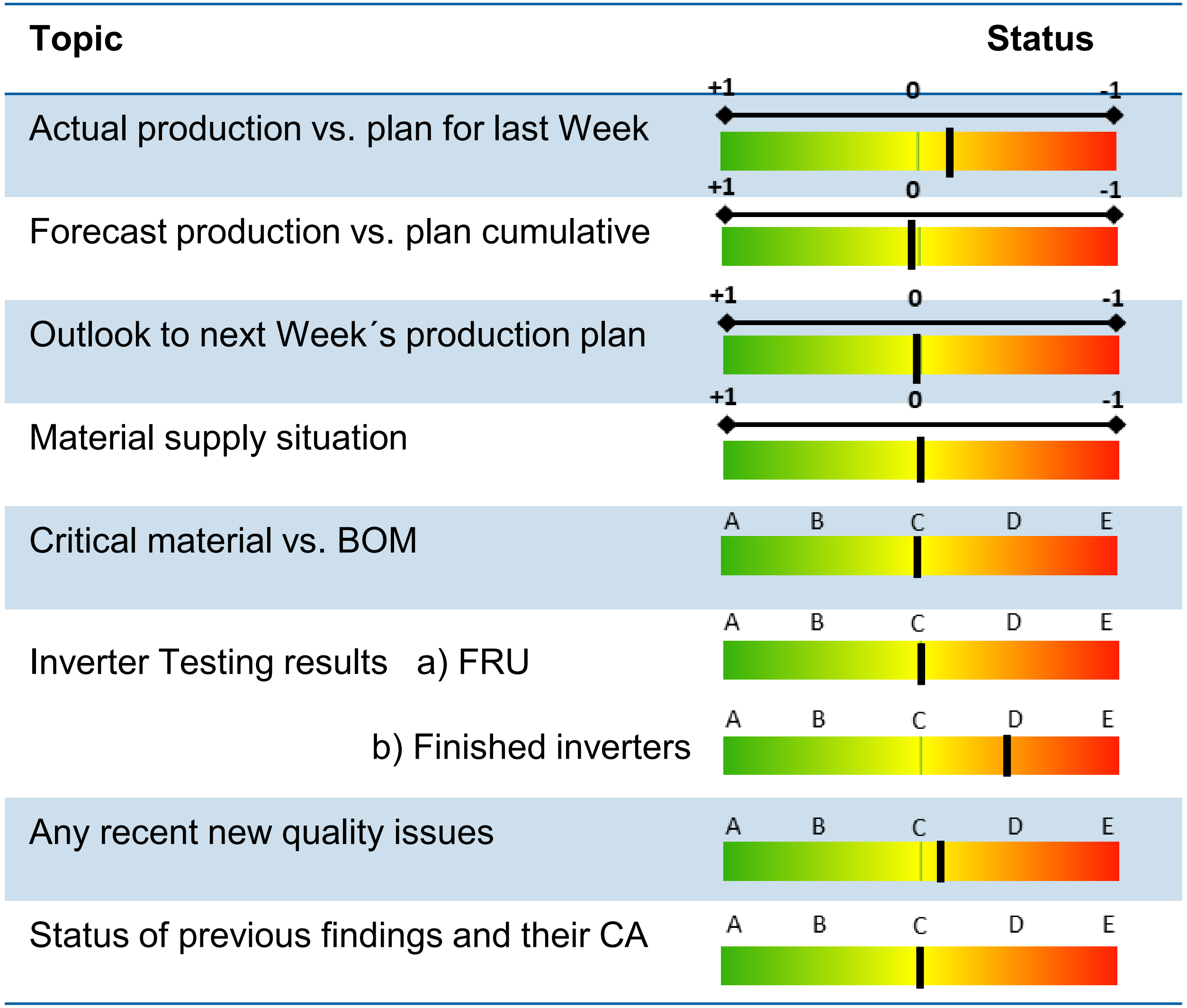
**IEC 62093: 2022 Photovoltaic system power conversion equipment - Design qualification and type approval*

Quality Assurance: Production Stage

Industry Standards for In-Production Quality Assurance Includes:

- **Production Oversight-** incoming quality inspections, materials management, quality controls, bill of materials, good practices.
- **FAT Witness-** Ensuring testing according to international standard and customer agreements.
- **Reliability testing –** Recommended tests to be performed to manufactured equipment
- **Packaging and shipment –** Internal controls of finalize goods and packaging procedures
- **Container loading check –** Visual inspection of loading procedures



Topic	Status
Actual production vs. plan for last Week	+1 0 -1
Forecast production vs. plan cumulative	+1 0 -1
Outlook to next Week´s production plan	+1 0 -1
Material supply situation	+1 0 -1
Critical material vs. BOM	A B C D E
Inverter Testing results a) FRU	A B C D E
b) Finished inverters	A B C D E
Any recent new quality issues	A B C D E
Status of previous findings and their CA	A B C D E

Operations Quality Assurance

RCA, Case Study, Field Testing

NREL Inverter Reliability Conference

Quality Assurance: Root Cause Analysis- 70 MW PV Plant

Case Study: IGBTs explosions

Root Cause Analysis Response from Manufacturer:

The alleged causes from the manufacturer in the 8D report can be summarized as follow:

- Different levels of dirt inside the FRU.
- Some bolts were not properly tightened.
- Defective fans poorly maintenance.
- And other measurements taken after the failures such as the diodes voltages or capacitors capacitance.

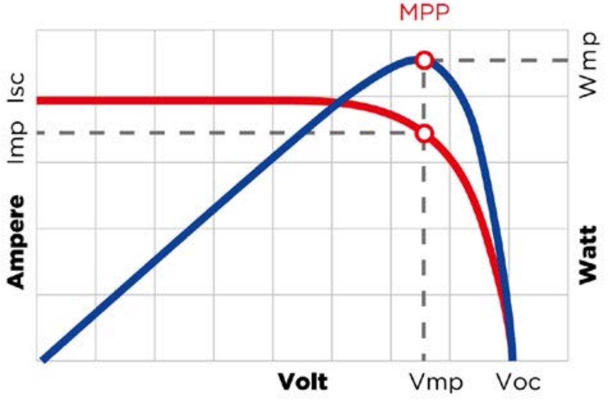
Reason To Verify RCA

The manufacturer makes design changes and replaces FRUs in most of the inverters at the PV Plant. However, the inverters continue to fail under the same circumstances.

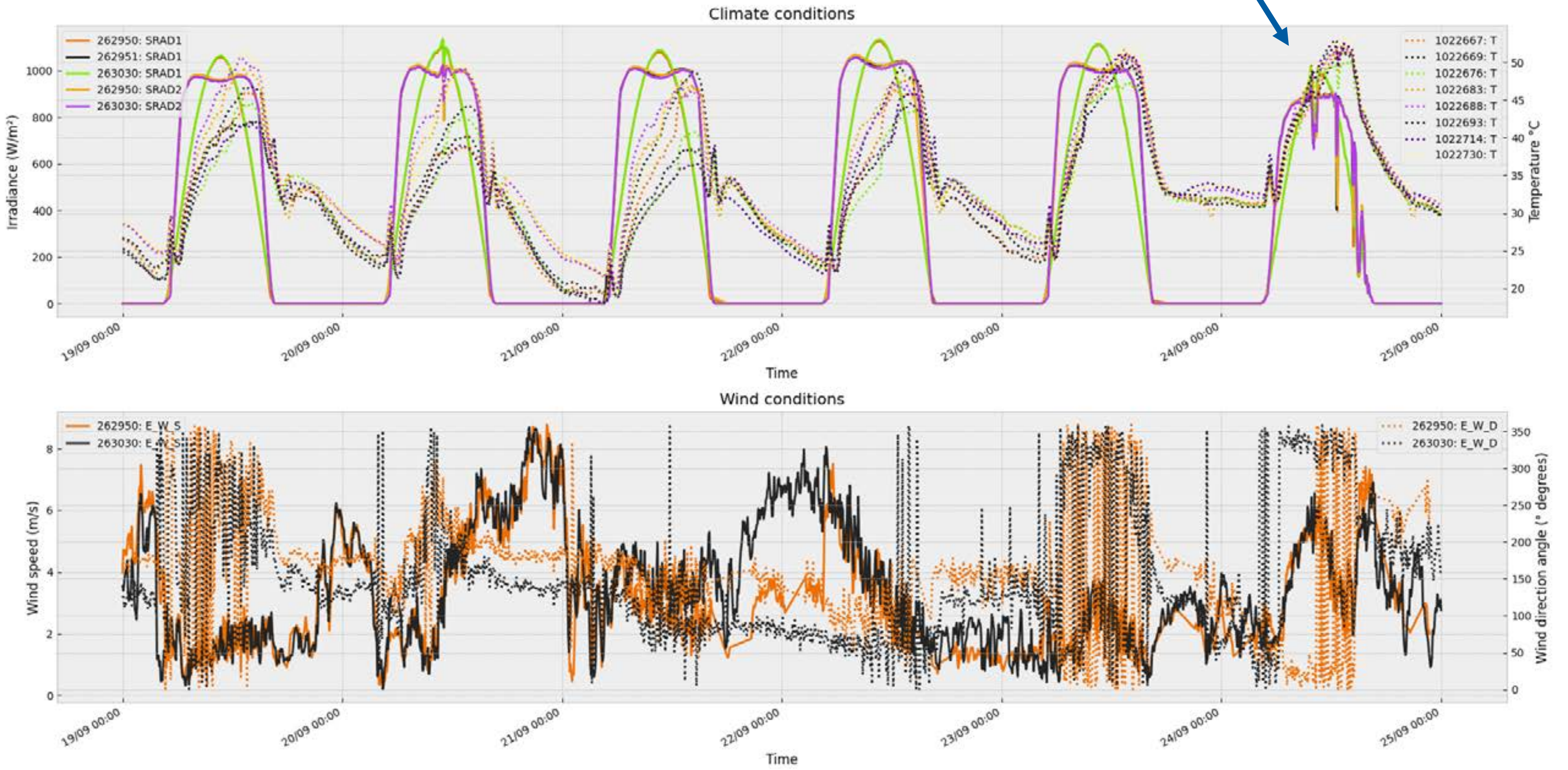
Manufacturer Claim Rejection *Example: It was determined that Converters SN. ###### and SN. ##### failed for causes that are not directly imputable to materials supplied by the Supplier under the Contract and included under Exhibit #####. Any replacement cost and/or repair costs, including the costs already incurred by the Supplier for shipping such products to the accredited facility of the Supplier in ####, shall be paid and sustained by the Client;"*

RCA: Remote Data Analysis

- PV Plant design review
- Previous RCA analysis
- Operation and maintenance analysis
- SCADA data breakdown



MPP and IV curve



Climate conditions: Irradiance, temperature and wind speed

RCA: Field Inspection – Forensic Fire Analysis

- **Surrounding area –** analysis of derbies from explosions or signs of smoke or finer in surrounding equipment.
- **Inverter exterior –** Remaining structure state of conservation. Sings of explosions, locations of signs, fire signs, smoke signs.
- **Inverter interior –** Location of the fire ignition, remaining components state of conservation. Type of material degradation (temperature, smoke, fire, arc).
- **Witnesses interview –** Description of the fire appearance. Timing, colors, odors, sounds

RCA : Field Testing of IGBTs. Commutation analysis

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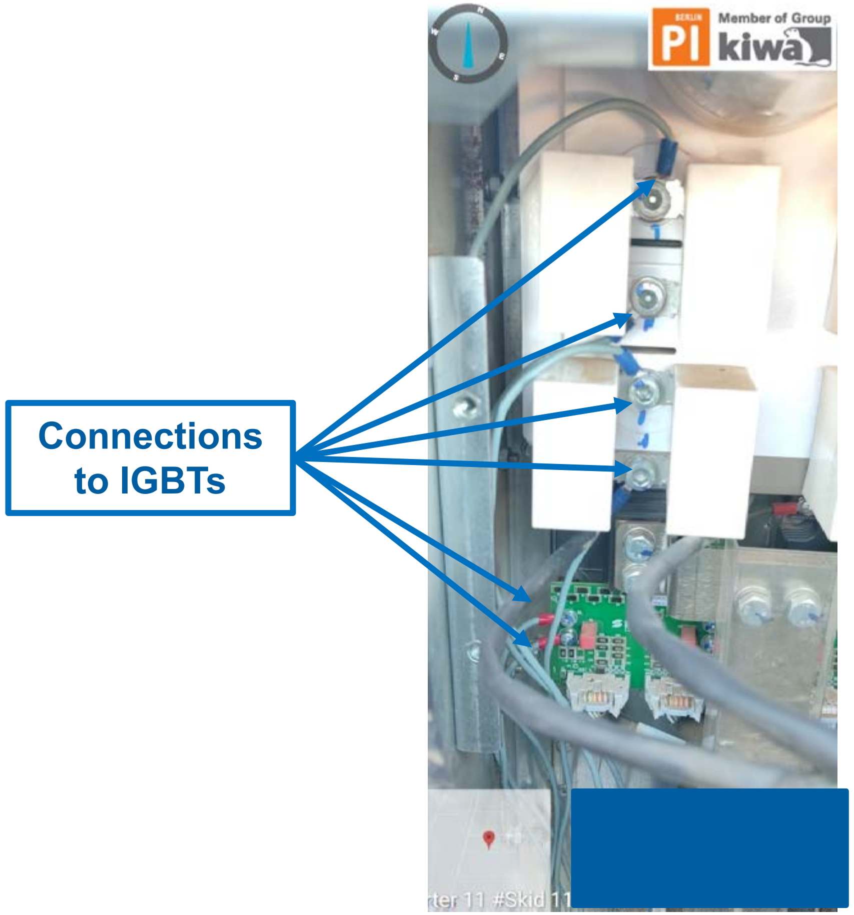


[redacted]

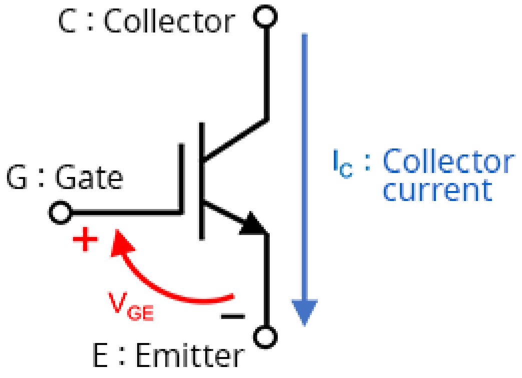
Connections to IGBTs

Testing Equipment:

- Portables oscilloscope
- Secondary oscilloscope
- Three differential proves
- Cabling

RCA: IGBT Commutation Voltages

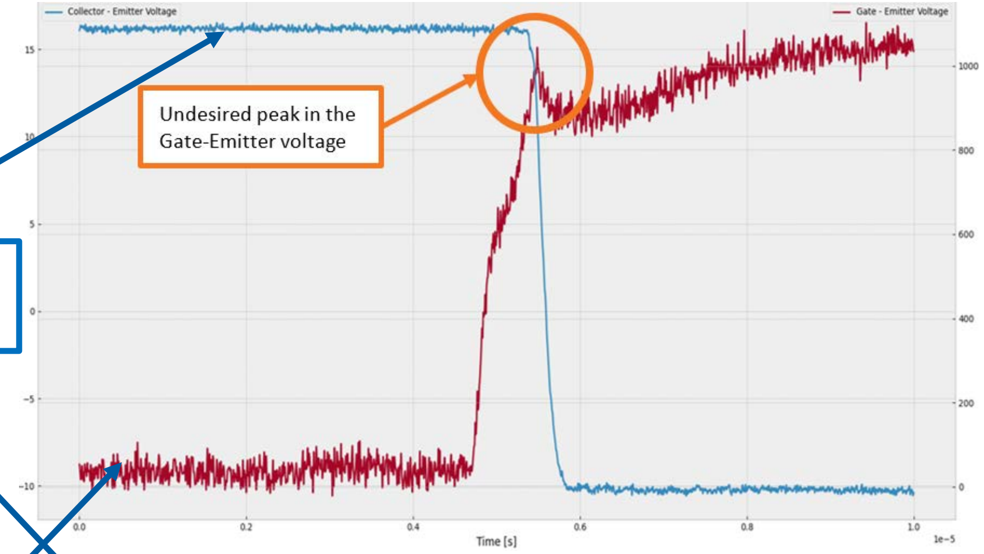
- Unintended spikes in the Collector-Emitter voltage lead to peaks in the current being driven.
- Unwanted intervals between the Gate-Emitter and Collector-Emitter voltages may result in the simultaneous opening of two IGBTs



IGBT equivalent circuit

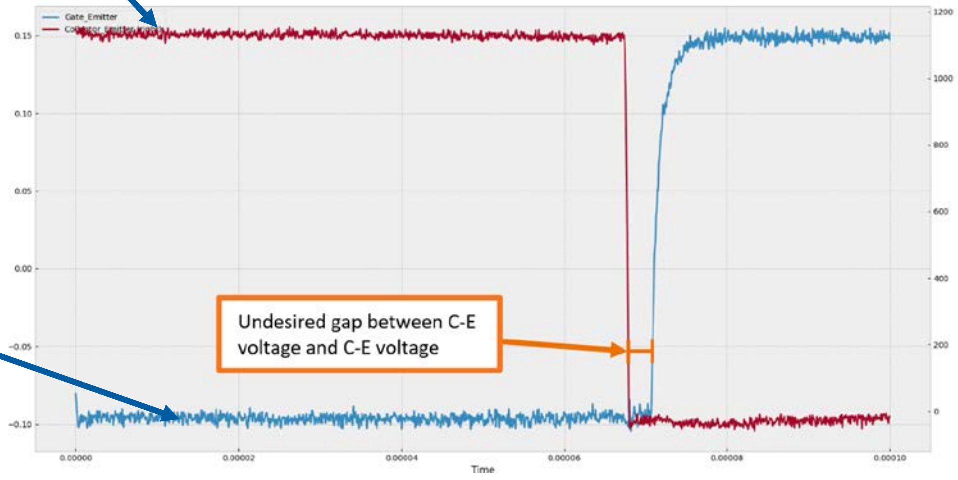
Collector-Emitter Voltage

Gate-Emitter Voltage



Undesired peak in the Gate-Emitter voltage

First set-up commutation voltages

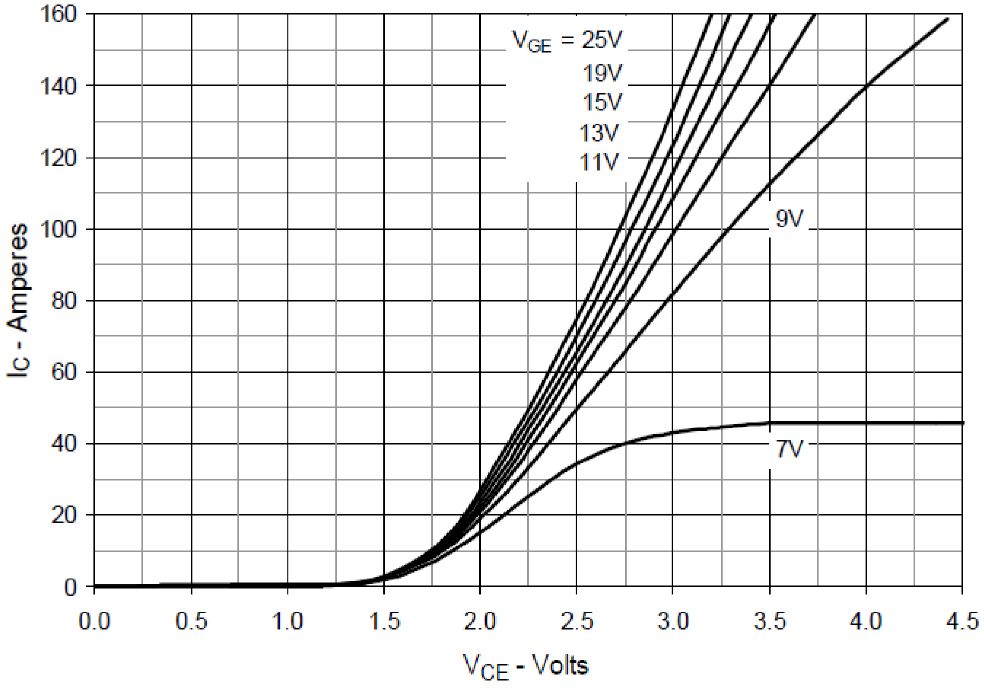


Undesired gap between C-E voltage and C-E voltage

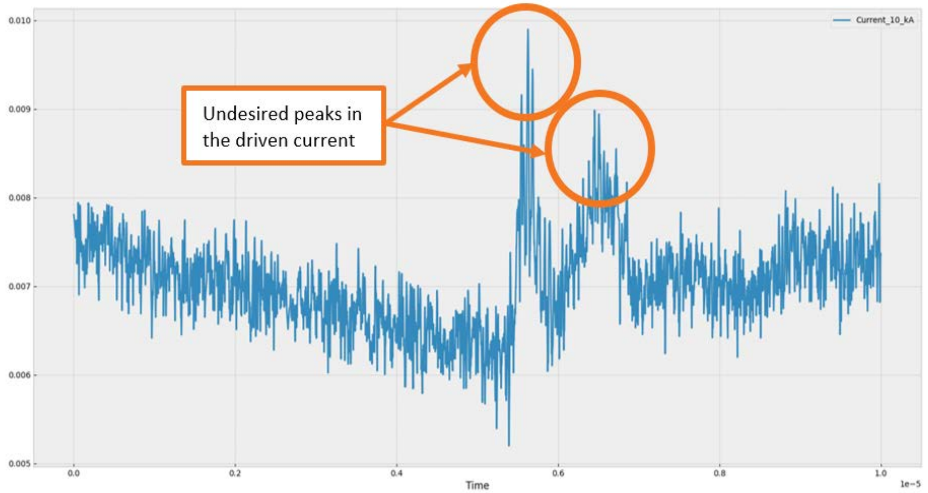
Second set-up commutation voltages

RCA: IGBT Commutation Currents

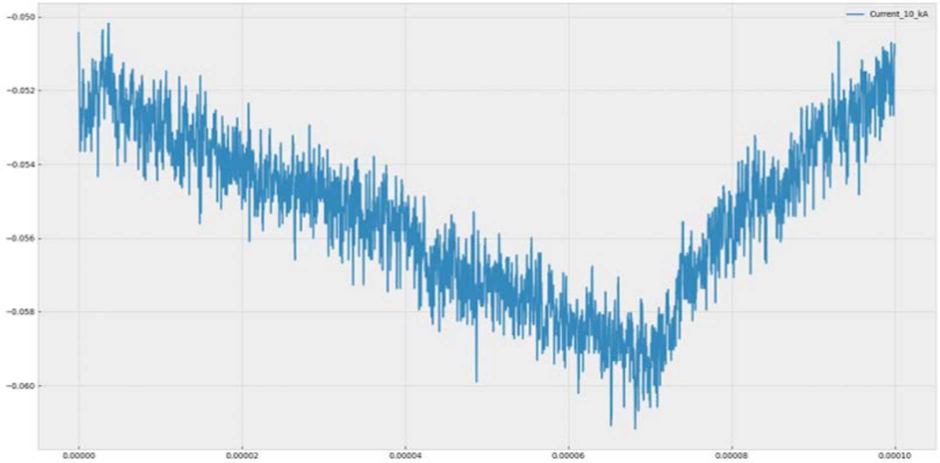
- Peaks in the gate-emitter voltage generate uncontrolled spikes in the generated currents.



Collector-Emitter voltage and current


Undesired peaks in the driven current

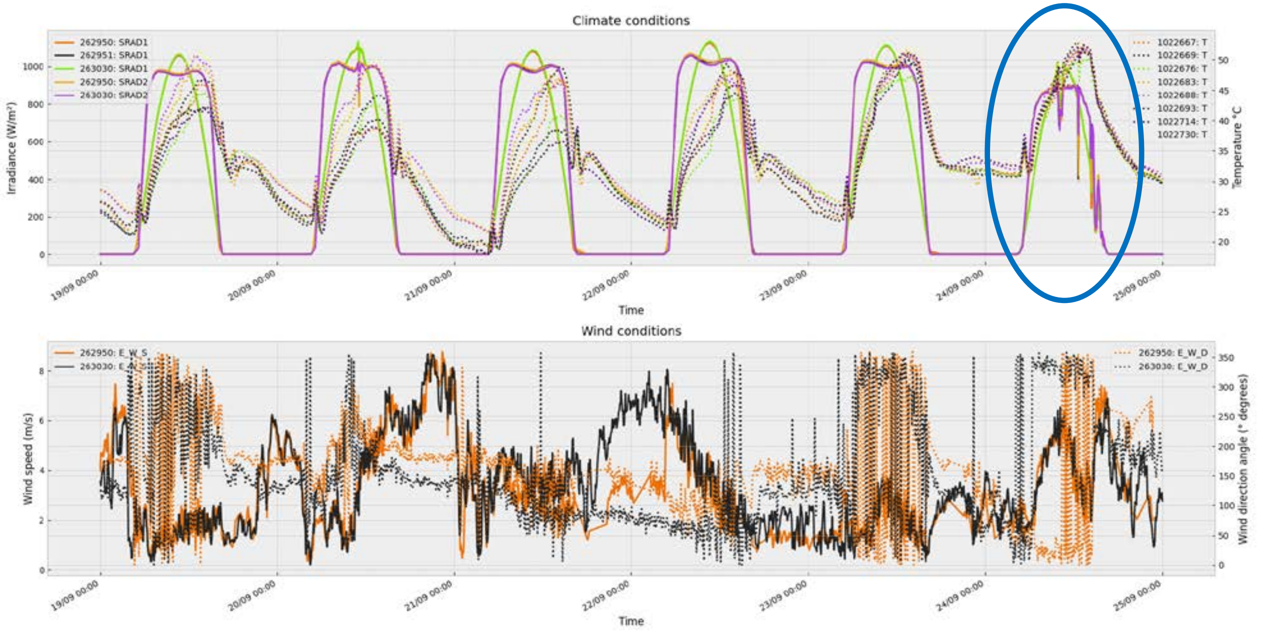
First set-up commutation current



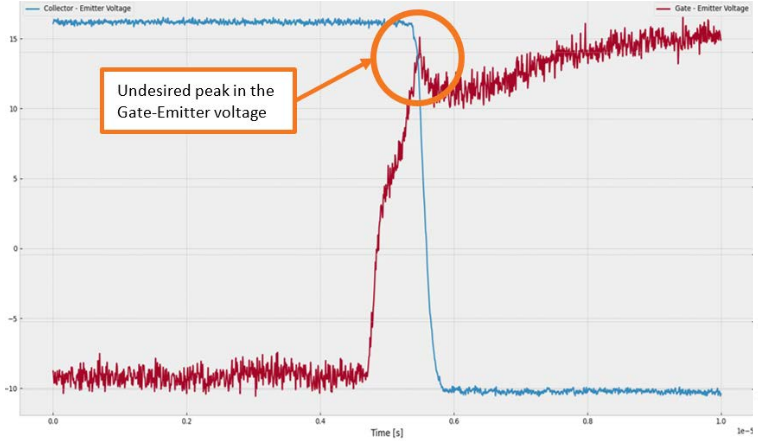
Second set-up commutation current

RCA: Conclusion

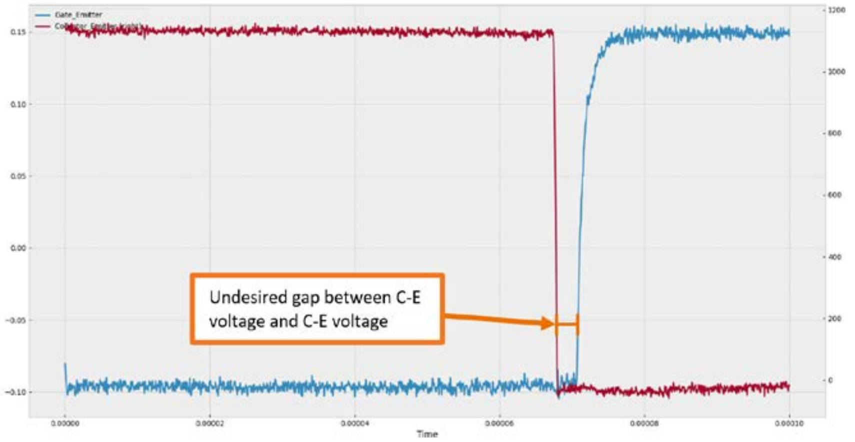
- Synthons of uncontrolled commutation of IGBTs
- Failures occurring during cloudy days
- **One potential reason for failure could be the inverter's loss of control over IGBT commutations due to rapid changes in MPPTs, resulting in incorrect commutation during cloudy days.**



First set-up commutation voltages



First set-up commutation voltages



Second set-up commutation voltages

Recommended tests

Kiwa PI Berlin recommends integrating measurements of IGBT switching behavior under simulated cloudy conditions, accounting for irradiance fluctuations at various operating temperatures. This approach allows for a more accurate evaluation of the IGBTs' performance and readability during operation.

Summary

1. Most inverters manufacturers do not have a reliability testing program. ISO 62093 NOT in use
2. Reliability starts from contracting stage
3. Kiwa PI Berlin proposes a new tests for IGBTs reliability

Thank you for listening

Questions?

Enabling Proactive Ownership:

Leveraging Temperature Data to Maximize Inverter Performance and Reliability

siliconranch.com

Optimizing Performance: Data and Analytics Capabilities

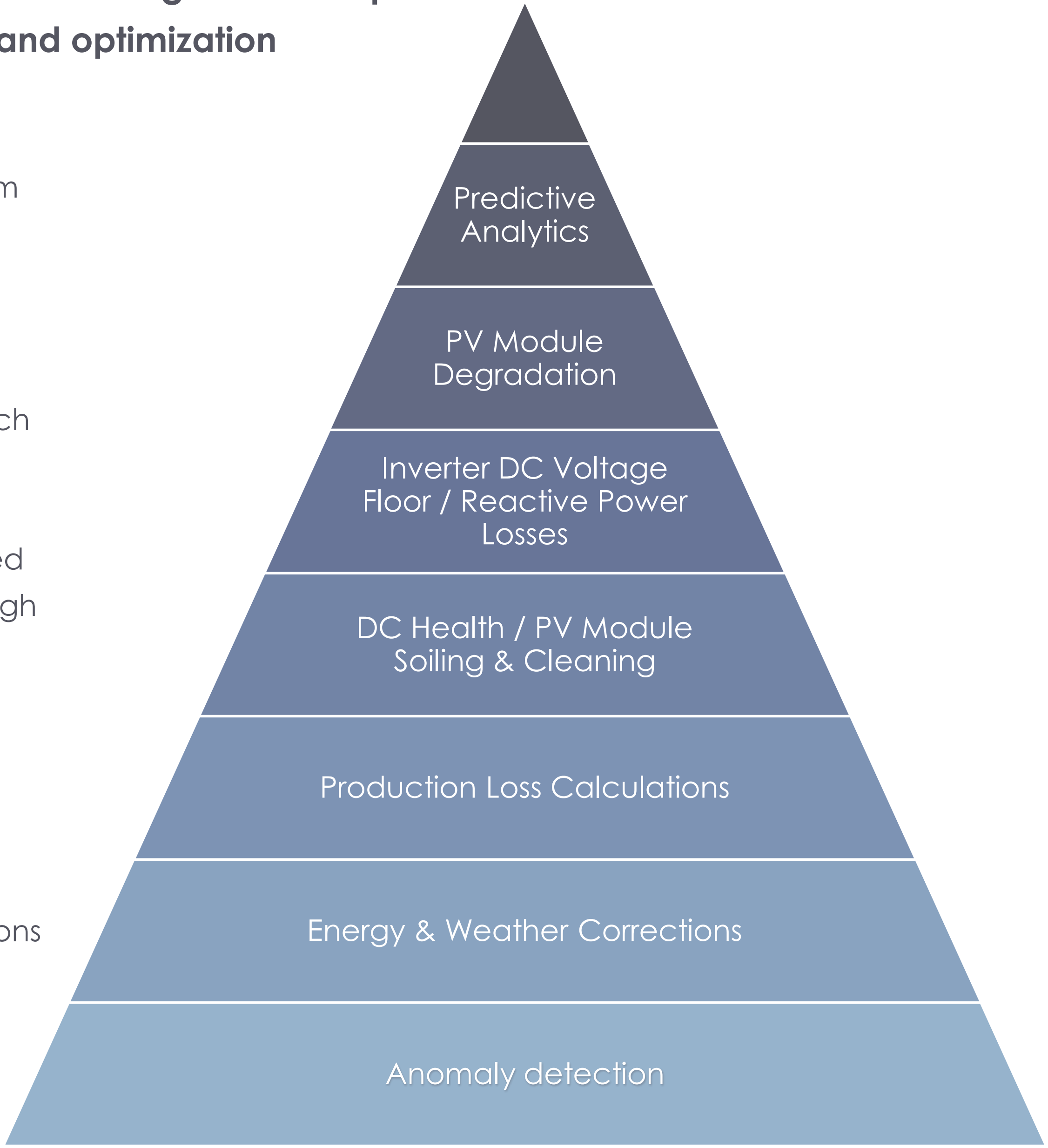
SR EPC streams plant sensor data to a modern cloud storage and computation platform to enable continuous plant monitoring and optimization

Data: Streaming sensor data is normalized and archived with short-term retention of 1 second data and long-term retention of 5-minute data. Data is cleaned to ensure accurate site estimates.

Alarm handling: Our SCADA and monitoring platform generates and prioritizes equipment anomaly alerts which are reviewed and responded to 7 days per week

Analytics: Plant operating data is cleaned and corrected for weather conditions. Results are compared against high fidelity performance models and site energy budgets. Losses are evaluated for economic impact enabling optimized maintenance activities including PV module washing and transformer tap settings, among others.

Predictive Analytics: Plant operating data and calculations are analyzed to detect the earliest indications of equipment degradation. Action is taken to prevent equipment failure and minimize the impact to plant operations and performance



Predictive Analytics

PV Module Degradation

Inverter DC Voltage Floor / Reactive Power Losses

DC Health / PV Module Soiling & Cleaning

Production Loss Calculations

Energy & Weather Corrections

Anomaly detection

Optimizing Performance: Reactive to Proactive Action

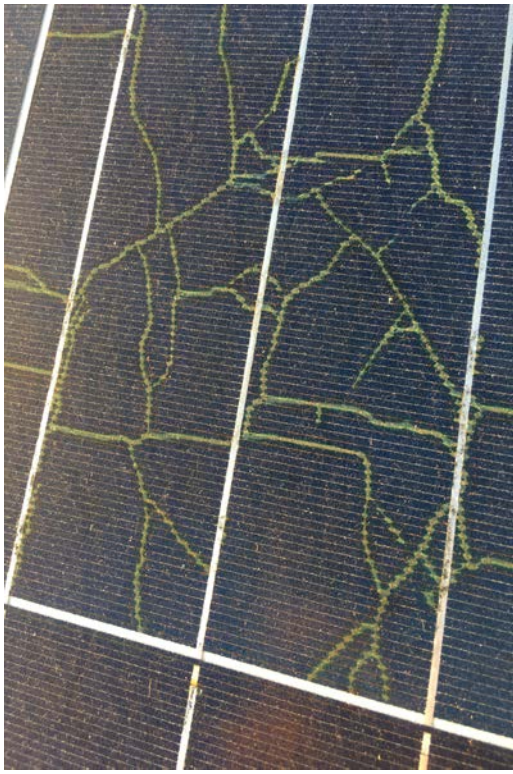
Beyond the focus on quickly addressing issues after they're discovered, we are continuing to strive to be proactive.

Serial Defect and Major Issue Management: Whenever major production-impacting issues or serial defects occur, do not stop managing the issue at repair. Progressing to identifying how to prevent that issue from occurring again or proactively addressing issues on similar units across our fleet.

Preventative Maintenance: Beyond performing standard preventive maintenance based on manuals or industry practices, progress to identifying additional checks to perform to identify failures before they occur.

Predictive Analytics: Developing and deploying in-house predictive signals based on actual plant data. Operating plant data is continuously monitored to identify and correct issues before they impact plant reliability and performance.

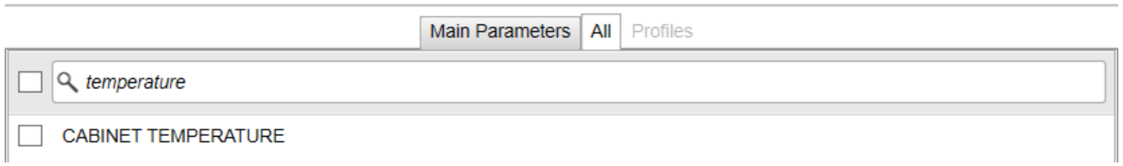
Revitalization: Moving to revitalizing plant performance through major equipment replacement or site expansion versus allowing underperforming equipment to continue to drag down performance for a site.



Remote Inverter Management: The Importance of Data

Inverter Manufacturer A Data

Low Data inverter

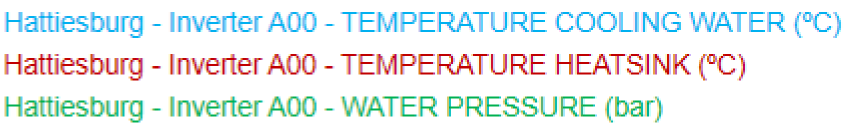


☐ *temperature*

☐ CABINET TEMPERATURE

Inverter Manufacturer B Data

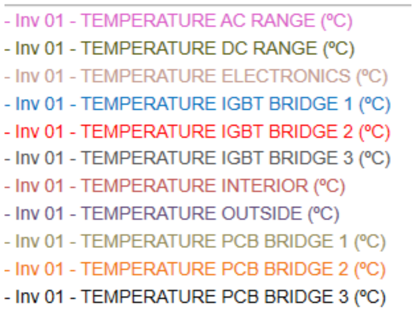
Liquid-cooled inverter



Hattiesburg - Inverter A00 - TEMPERATURE COOLING WATER (ºC)
Hattiesburg - Inverter A00 - TEMPERATURE HEATSINK (ºC)
Hattiesburg - Inverter A00 - WATER PRESSURE (bar)

Inverter Manufacturer C Data

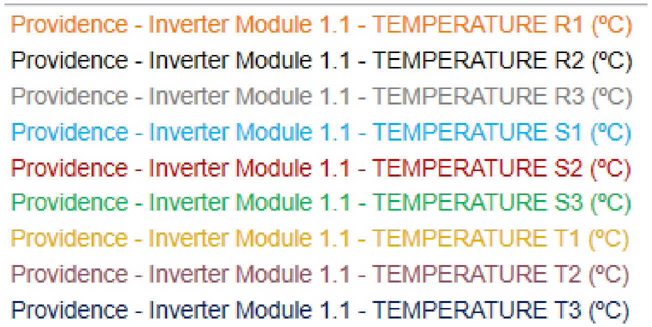
Mid Data inverter



- Inv 01 - TEMPERATURE AC RANGE (ºC)
- Inv 01 - TEMPERATURE DC RANGE (ºC)
- Inv 01 - TEMPERATURE ELECTRONICS (ºC)
- Inv 01 - TEMPERATURE IGBT BRIDGE 1 (ºC)
- Inv 01 - TEMPERATURE IGBT BRIDGE 2 (ºC)
- Inv 01 - TEMPERATURE IGBT BRIDGE 3 (ºC)
- Inv 01 - TEMPERATURE INTERIOR (ºC)
- Inv 01 - TEMPERATURE OUTSIDE (ºC)
- Inv 01 - TEMPERATURE PCB BRIDGE 1 (ºC)
- Inv 01 - TEMPERATURE PCB BRIDGE 2 (ºC)
- Inv 01 - TEMPERATURE PCB BRIDGE 3 (ºC)

Inverter Manufacturer D Data

High Data inverter

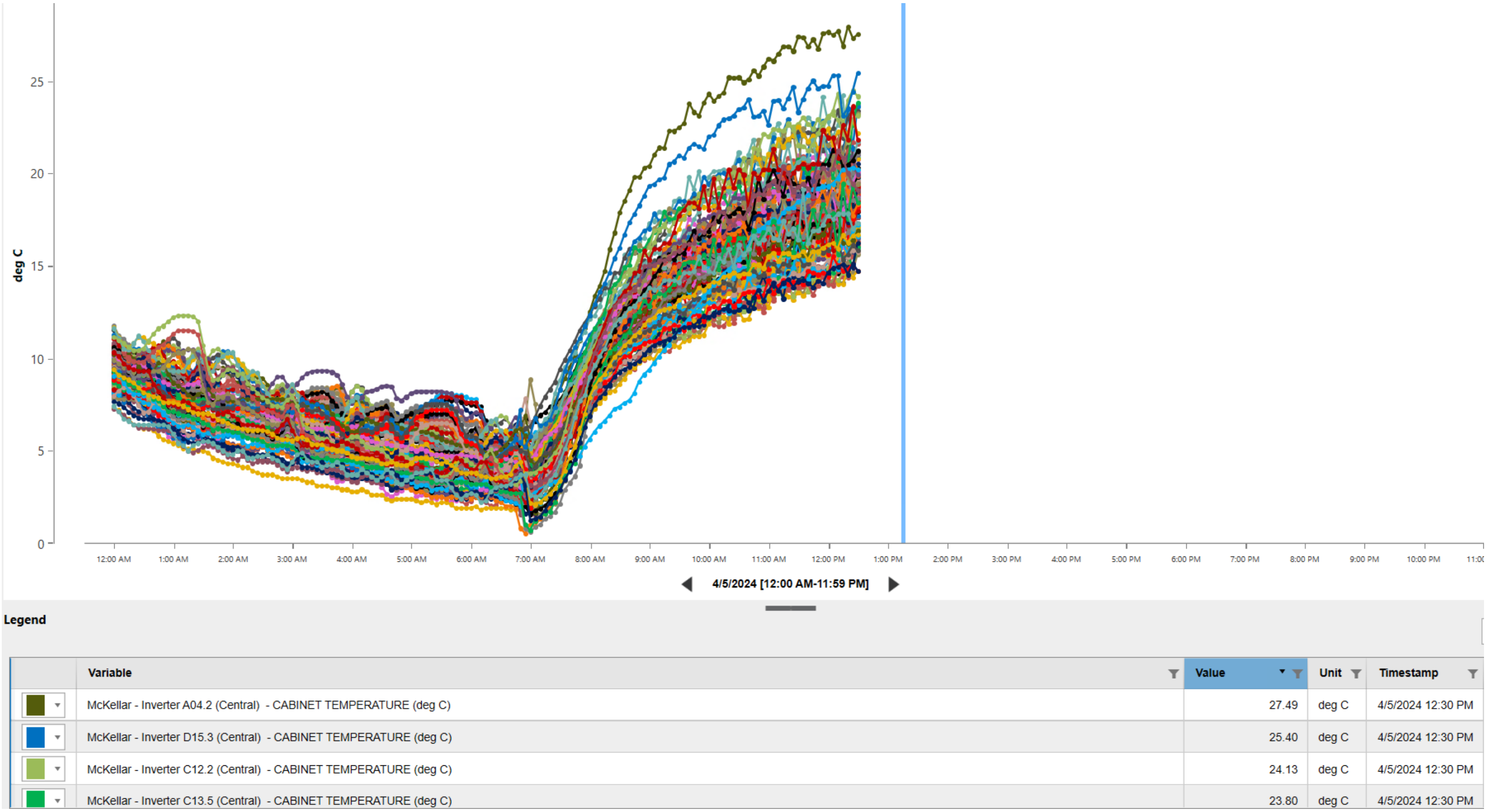


Providence - Inverter Module 1.1 - TEMPERATURE R1 (ºC)
Providence - Inverter Module 1.1 - TEMPERATURE R2 (ºC)
Providence - Inverter Module 1.1 - TEMPERATURE R3 (ºC)
Providence - Inverter Module 1.1 - TEMPERATURE S1 (ºC)
Providence - Inverter Module 1.1 - TEMPERATURE S2 (ºC)
Providence - Inverter Module 1.1 - TEMPERATURE S3 (ºC)
Providence - Inverter Module 1.1 - TEMPERATURE T1 (ºC)
Providence - Inverter Module 1.1 - TEMPERATURE T2 (ºC)
Providence - Inverter Module 1.1 - TEMPERATURE T3 (ºC)

Remote Inverter Management: Trending Data

Charting Temperature Data to Observe Temperature Outliers

If there are concerns about the thermal performance of inverters on-site, trend data to spot any clear outliers.



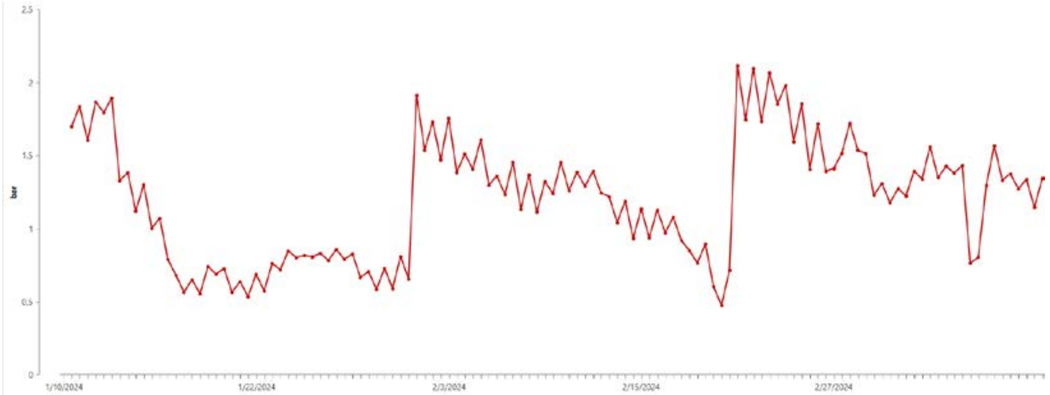
Legend

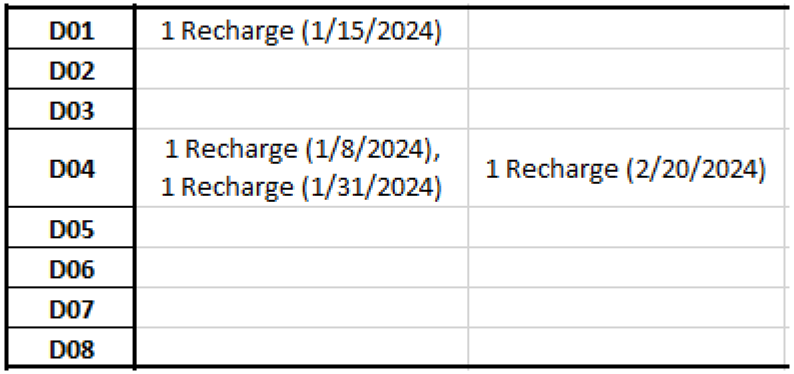
	Variable	Value	Unit	Timestamp
🟫	McKellar - Inverter A04.2 (Central) - CABINET TEMPERATURE (deg C)	27.49	deg C	4/5/2024 12:30 PM
🟦	McKellar - Inverter D15.3 (Central) - CABINET TEMPERATURE (deg C)	25.40	deg C	4/5/2024 12:30 PM
🟩	McKellar - Inverter C12.2 (Central) - CABINET TEMPERATURE (deg C)	24.13	deg C	4/5/2024 12:30 PM
🟩	McKellar - Inverter C13.5 (Central) - CABINET TEMPERATURE (deg C)	23.80	deg C	4/5/2024 12:30 PM

Remote Inverter Management : Predictive Analytics for Liquid Cooled Inverters

Inverter Coolant Pressure Trending

Proactive monitoring of cooling system performance to identify issues prior to outage events.





D01	1 Recharge (1/15/2024)	
D02		
D03		
D04	1 Recharge (1/8/2024), 1 Recharge (1/31/2024)	1 Recharge (2/20/2024)
D05		
D06		
D07		
D08		

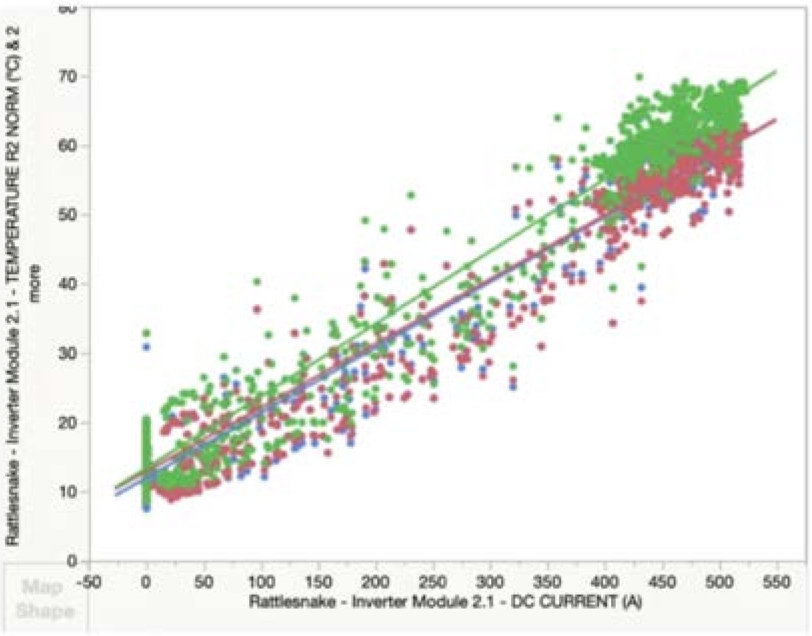
Early detection of sudden pressure drops and pressure drops below the threshold (0.6 bar) established with manufacturer to proactively refill coolant. If the pressure drops below 0.4 bar, the inverter will trip offline resulting in > 1 week of with significant lost power generation and much higher equipment repair costs.

The inverter manual states recharge should only be needed annually, so we track recharge dates so the manufacturer is clear these are warrantable refills within 1 year of the prior. This allows for the identification of units that require remediation to meet the expected recharge intervals.

Remote Inverter Management : Predictive Analytics for Preventative Maintenance

Inverter IGBT Failure Detection

Proactive monitoring of IGBT health trends across a wide range of ambient conditions and inverter output enabled detection and minimization of the impact of a developing IGBT failure.



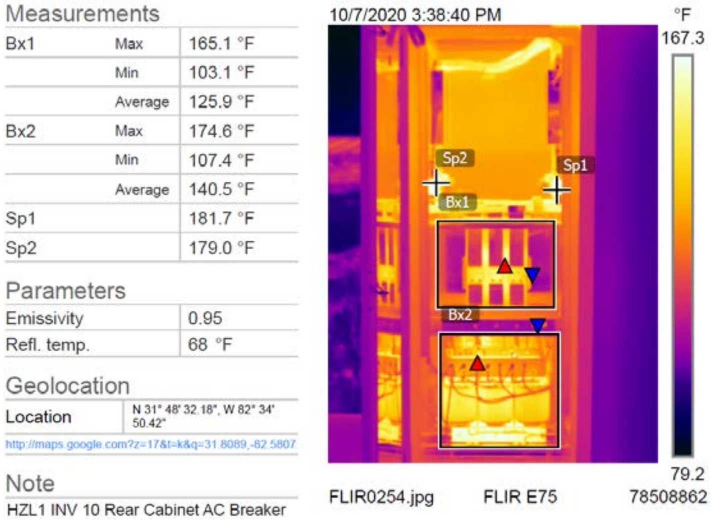
Early detection of the IGBT issue resulted in ~2 hours of downtime to implement repair.

Historically this type of failure would result in > 2 weeks of equipment downtime with significant lost power generation and much higher equipment repair costs.

Field Thermal Management:
Preventative Maintenance Thermal Scans

Hot Spot Detection

Data from the inverters, no matter how robust, will not capture all the possible temperature concerns on units, so thermal imaging of all connection points is critical to do at least annually



Measurements

Bx1	Max	165.1 °F
	Min	103.1 °F
	Average	125.9 °F
Bx2	Max	174.6 °F
	Min	107.4 °F
	Average	140.5 °F
Sp1		181.7 °F
Sp2		179.0 °F

Parameters

Emissivity	0.95
Refl. temp.	68 °F

Geolocation

Location	N 31° 48' 32.18", W 82° 34' 50.42"

http://maps.google.com?z=17&t=k&q=31.8089,-82.5807

Note

HZL1 INV 10 Rear Cabinet AC Breaker

10/7/2020 3:38:40 PM

FLIR0254.jpg FLIR E75 78508862

Measurements

Bx1	Max	190.3 °F
	Min	97.9 °F
	Average	128.5 °F

Parameters

Emissivity	0.95
Refl. temp.	68 °F

Geolocation

Location	N 31° 48' 32.37", W 82° 34' 50.70"

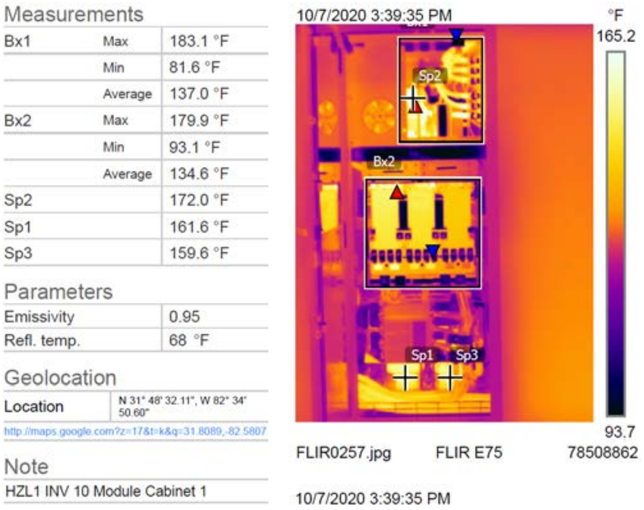
http://maps.google.com?z=17&t=k&q=31.8090,-82.5807

Note

HZL1 INV 10 Recombiner

10/7/2020 3:39:00 PM

FLIR0255.jpg FLIR E75 78508862



Measurements

Bx1	Max	183.1 °F
	Min	81.6 °F
	Average	137.0 °F
Bx2	Max	179.9 °F
	Min	93.1 °F
	Average	134.6 °F
Sp2		172.0 °F
Sp1		161.6 °F
Sp3		159.6 °F

Parameters

Emissivity	0.95
Refl. temp.	68 °F

Geolocation

Location	N 31° 48' 32.11", W 82° 34' 50.60"

http://maps.google.com?z=17&t=k&q=31.8089,-82.5807

Note

HZL1 INV 10 Module Cabinet 1

10/7/2020 3:39:35 PM

FLIR0257.jpg FLIR E75 78508862

10/7/2020 3:39:35 PM

Future Improvements: Incorporating More Data Points with Partners

- With our Partners, we have worked to identify further improvements in temperature monitoring that can be done to continue to improve our ability to identify issues prior to failures.

- We are continuing to work to identify what sensors can be added to assess temperatures in different compartments or identify fan health remotely.

- We review everything through an LCOE lens to ensure the CapEx investment is worth the Operational improvement.

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Lifetime Testing and Modeling of Cooling Fan in PV Inverter

Zheyu Zhang, zhangz49@rpi.edu

2024 Reliability of PV Inverters Workshop

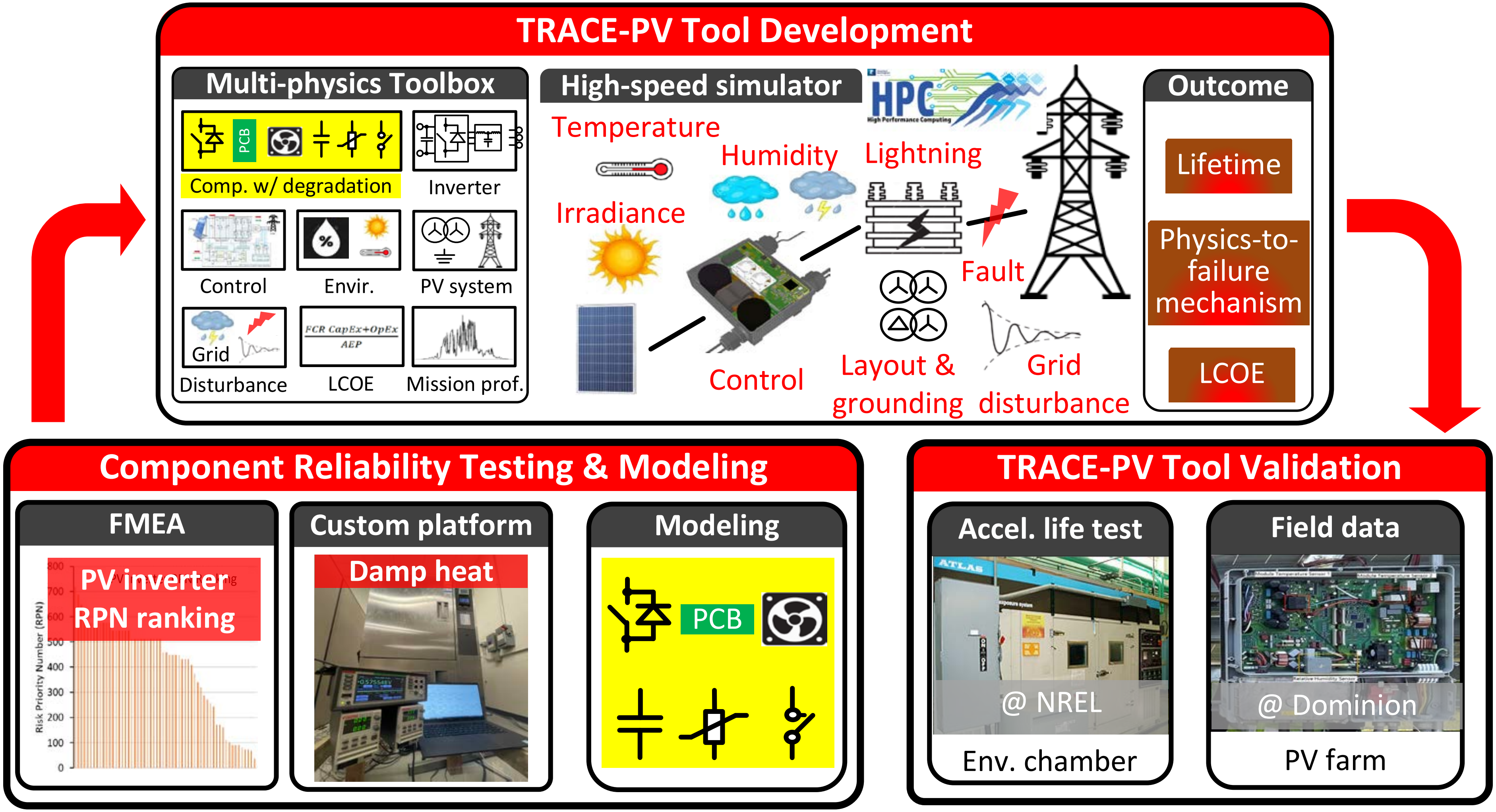
April 12, 2024

Outline

- **Introduction**
- **Cooling Fan Reliability Testing**
- **Cooling Fan Lifetime Modeling**
- **Summary**

Tool for Reliability Assessment of Critical Electronics in PV (TRACE-PV)

- **Creating an open-source tool to quantify PV inverter reliability**



TRACE-PV Tool Development

Multi-physics Toolbox

- Comp. w/ degradation
- Inverter
- Control
- Envir.
- PV system
- Grid Disturbance
- LCOE
- Mission prof.

High-speed simulator

Temperature

Humidity

Lightning

Irradiance

Fault

Control

Layout & grounding

Grid disturbance

Outcome

- Lifetime
- Physics-to-failure mechanism
- LCOE

Component Reliability Testing & Modeling

FMEA

PV inverter RPN ranking

Custom platform

Damp heat

Modeling

TRACE-PV Tool Validation

Accel. life test

@ NREL

Env. chamber

Field data

@ Dominion

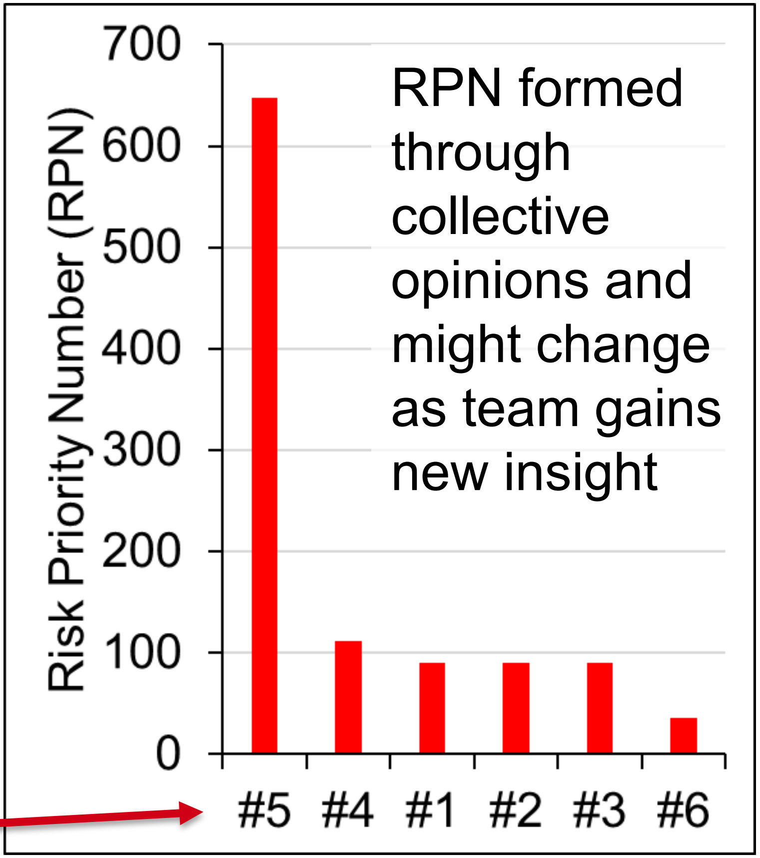
PV farm

Outline

- Introduction
- **Cooling Fan Reliability Testing**
- Cooling Fan Lifetime Modeling
- Summary

Failure Mode and Effects Analysis (FMEA) for Cooling Fan

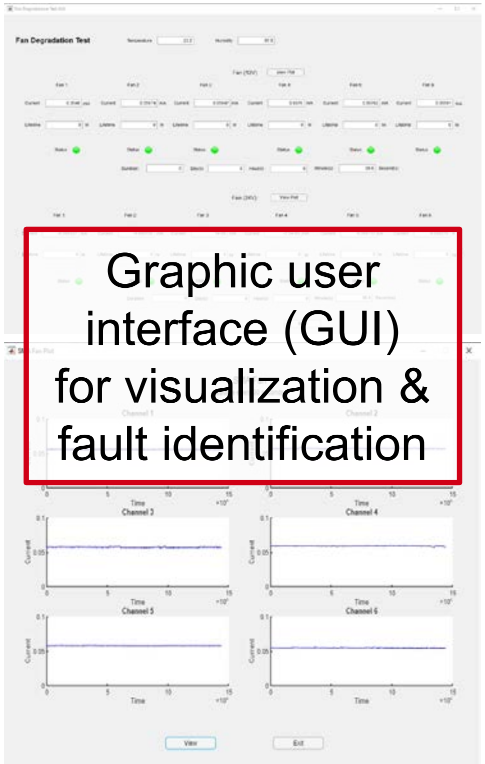
Failure Modes & Mechanisms		#	Critical stressors	O	S	D
Mechanical	Cage damage	1	Vibration	3	4	8
	Bearing failure	2	Lack of lubrication	3	4	8
	Lubrication deterioration	3	Wear out	3	4	8
Electrical	Cracks in fan's PCB	4	Excessive vibration, T, RH	2	7	8
	Envir. stressors	5	Ingress Protection (IP), T, RH	9	9	8
	Wiring errors	6	Manufacturing/human errors	1	8	5



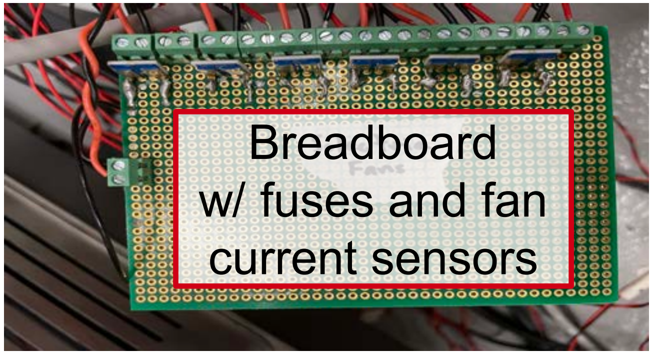
RPN formed through collective opinions and might change as team gains new insight

Temperature (T) & relative humidity (RH) identified as critical stressors

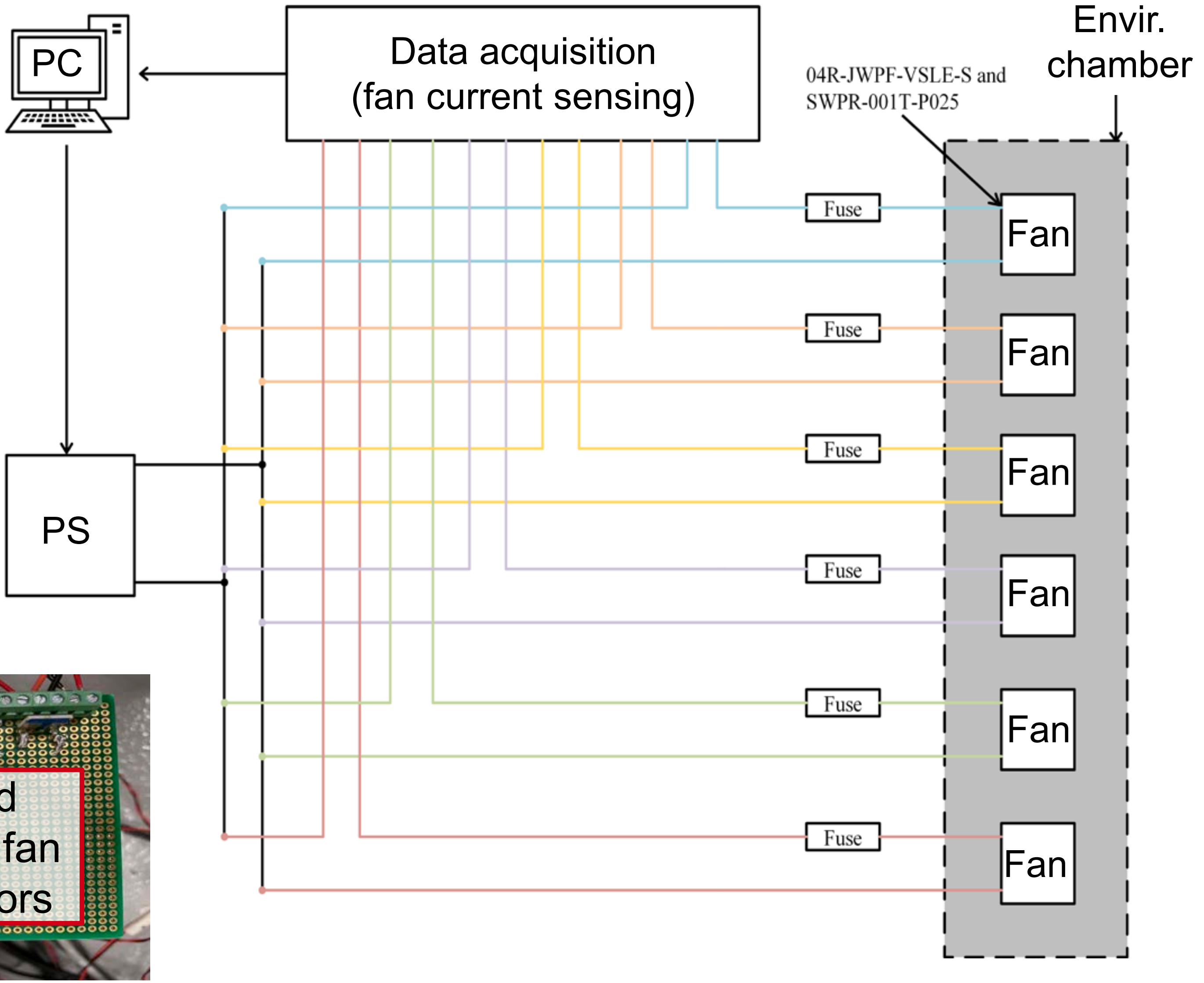
Reliability Testing Platform – Electrical Design (1)



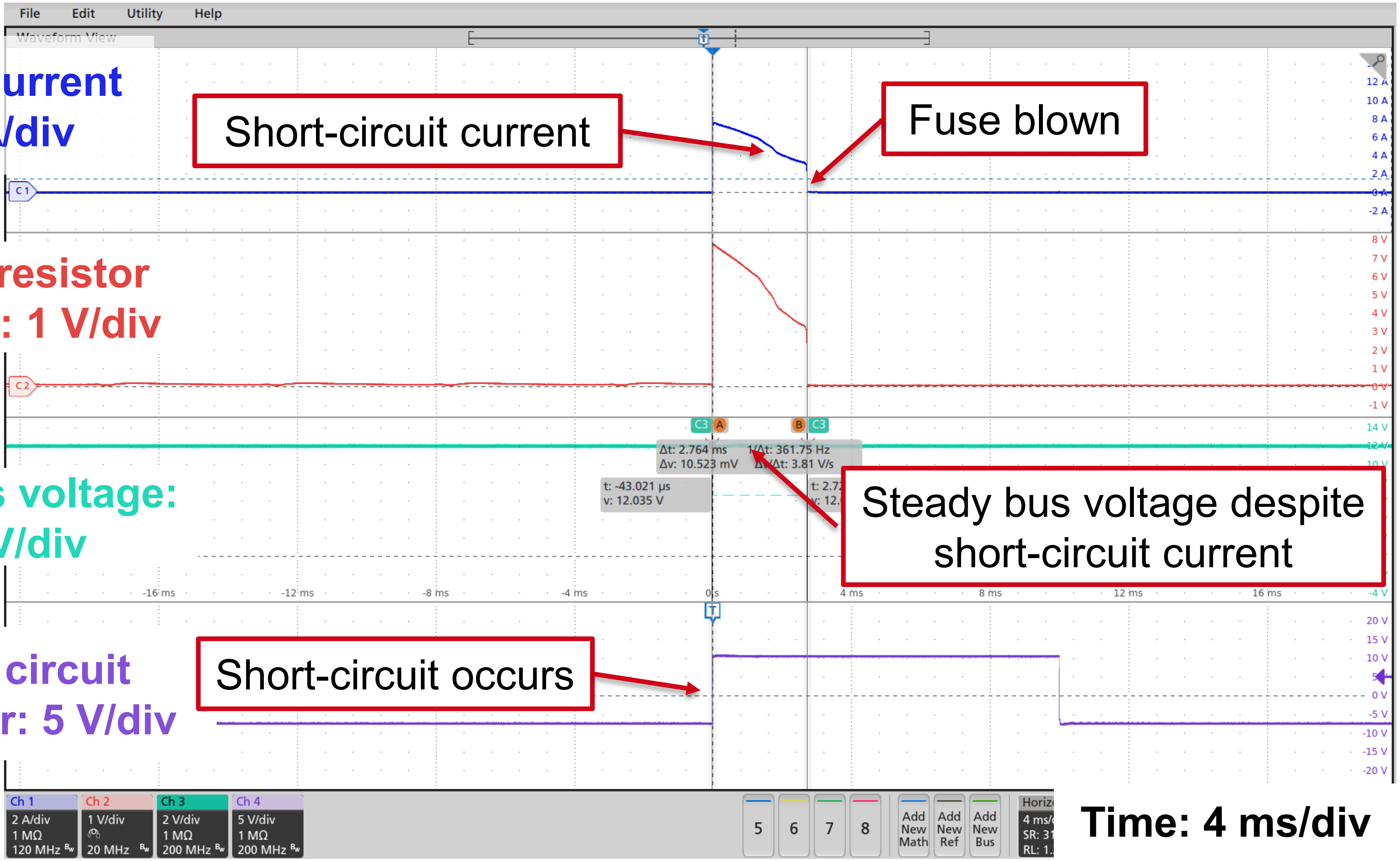
Graphic user interface (GUI) for visualization & fault identification



Breadboard w/ fuses and fan current sensors



Reliability Testing Platform – Electrical Design (2)



Δt: 2.764 ms 1/Δt: 361.75 Hz
Δv: 10.523 mV Δv/Δt: 3.81 V/s

t: -43.021 µs
v: 12.035 V

t: 2.72
v: 12.

Ch 1
2 A/div
1 MΩ
120 MHz

Ch 2
1 V/div
20 MHz

Ch 3
2 V/div
1 MΩ
200 MHz

Ch 4
5 V/div
1 MΩ
200 MHz

4 ms/
SR: 31
RL: 1.

Fan current
2 A/div

Short-circuit current

Fuse blown

Shunt resistor voltage: 1 V/div

DC bus voltage: 2 V/div

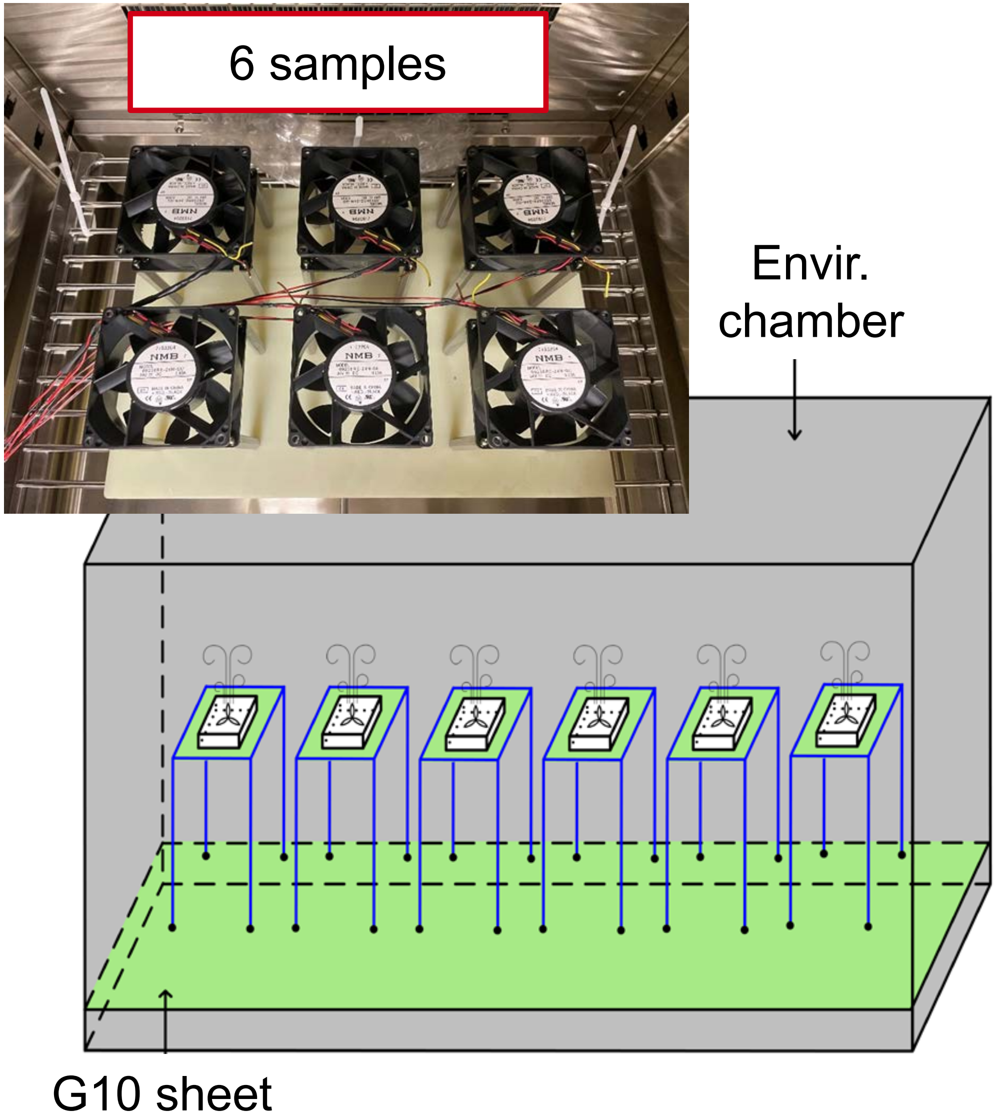
Steady bus voltage despite short-circuit current

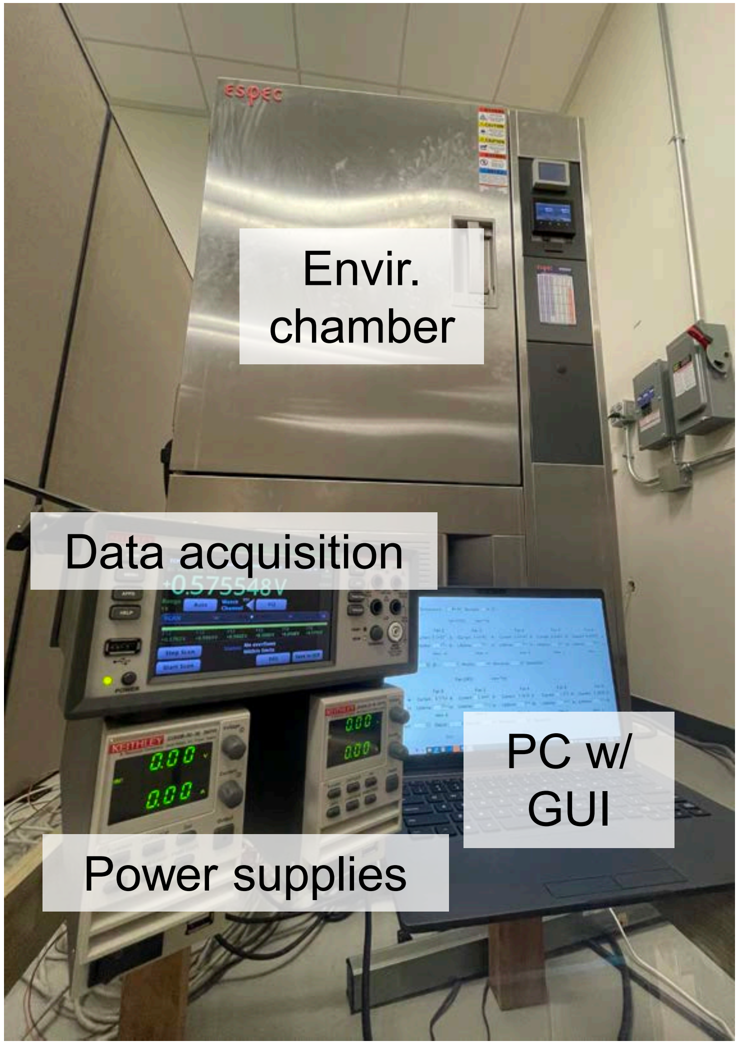
Short circuit emulator: 5 V/div

Short-circuit occurs

Time: 4 ms/div

Reliability Platform – Mechanical Design

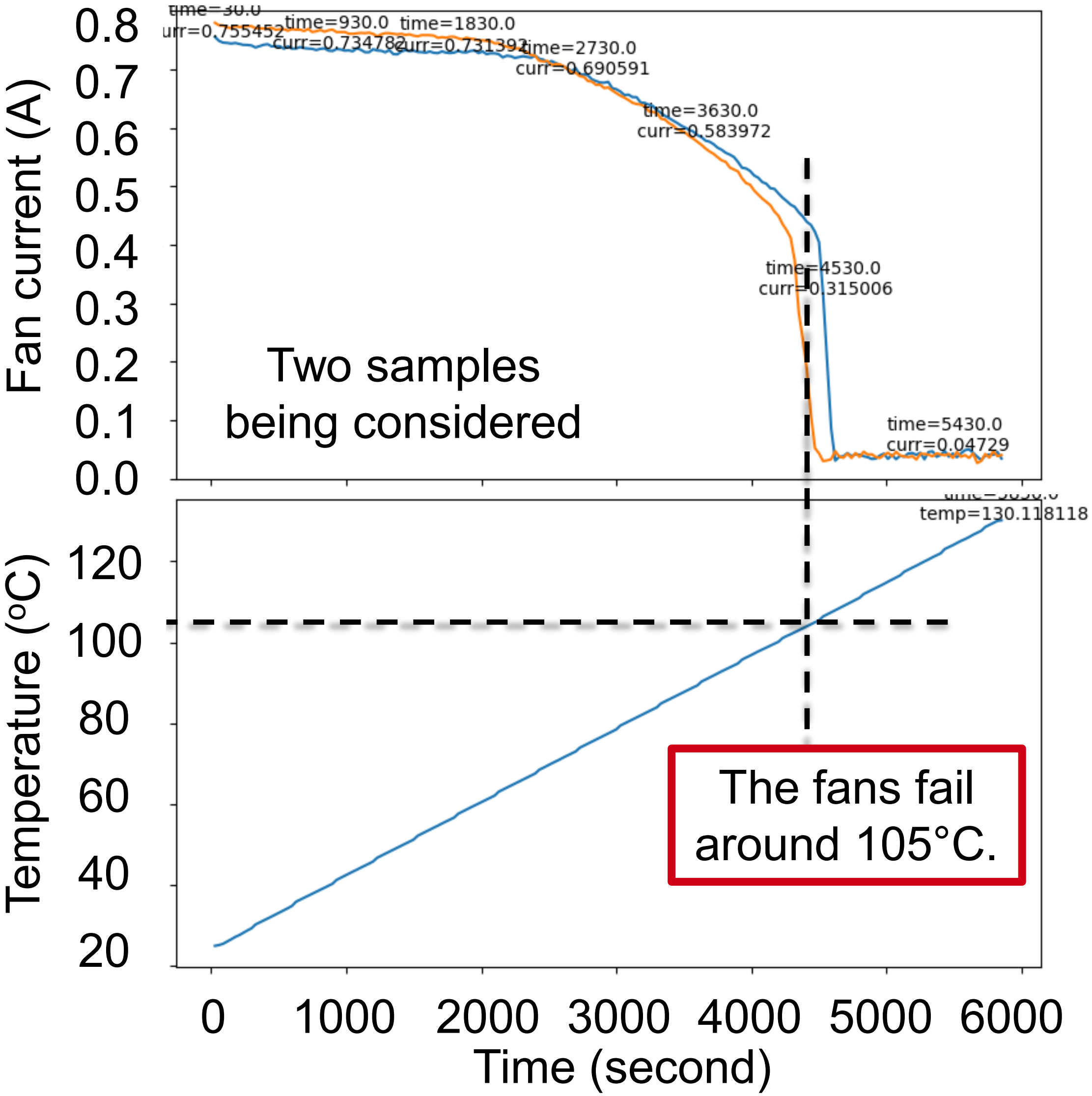




Reliability Platform – Stress Levels

- A time-efficient ramp-to-failure test performed to determine the reasonable stress level
- Consultation with vendors
- Considering resources

Phase	Temp. (°C)	RH (%)
I	85	95
II	85	85
III	95	95

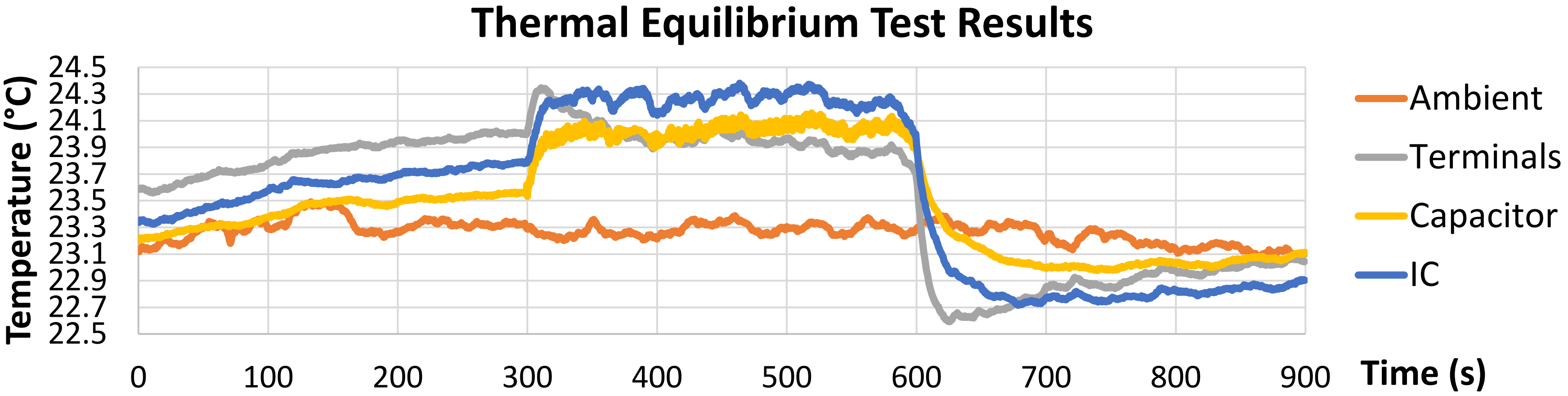


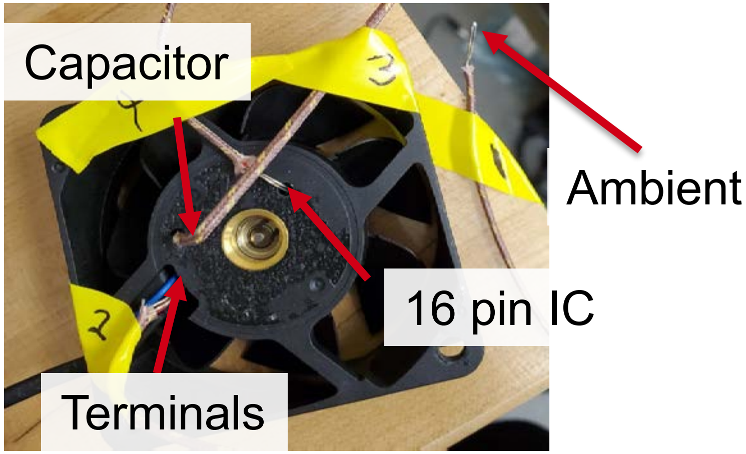
Two samples being considered

The fans fail around 105°C.

Reliability Platform — Operating Conditions

- In addition to Temp. & RH, cooling fan controlled on and off periodically to mimic the actual operating conditions in the field
  - On & off duration longer than the time allowing fan in the thermal equilibrium





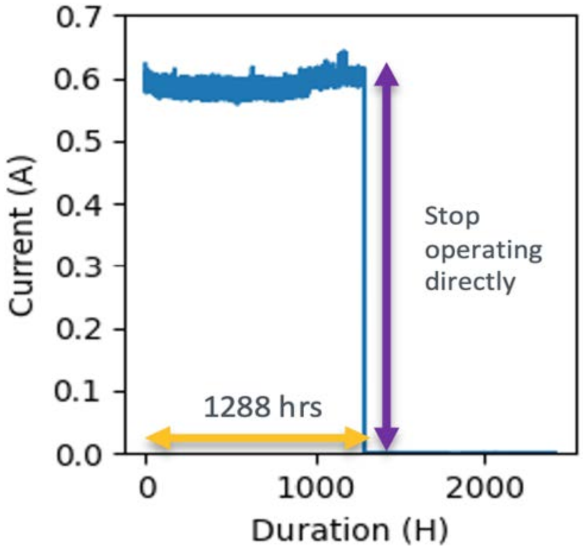
Position	Estimated thermal time constant (5τ)
Terminals	25 s
Capacitor	101 s
IC	72 s

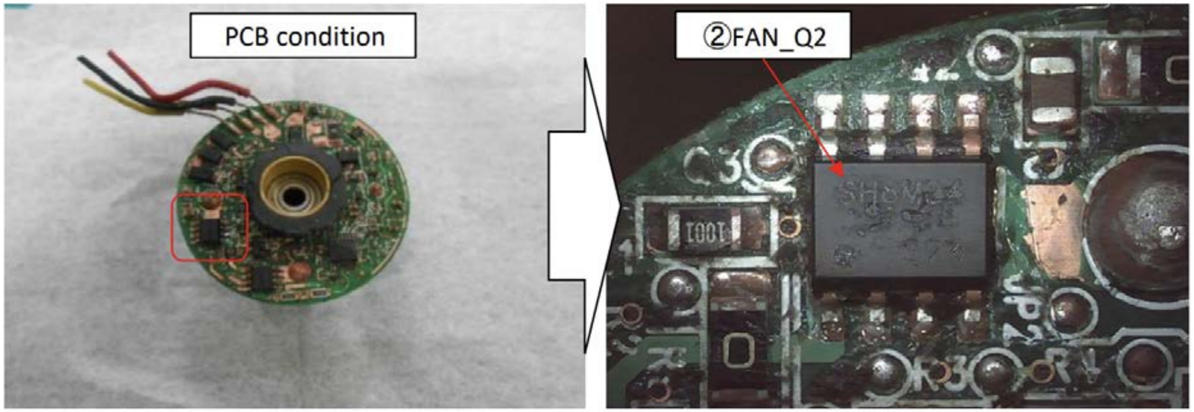
Outline

- Introduction
- Cooling Fan Reliability Testing
- **Cooling Fan Lifetime Modeling**
- Summary

Test Data and Failure Analysis

	85°C/95% RH	85°C/85% RH	95°C/85% RH
Sample number	**Phase I lifetime (hrs)**	**Phase II lifetime (hrs)**	**Phase III lifetime (hrs)**
1	1,025	1,250	745
2	1,288	1,813	742
3	1,273	2,232	796
4	953	1,847	639
5	1,177	1,924	813
6	N/A	1,846	N/A

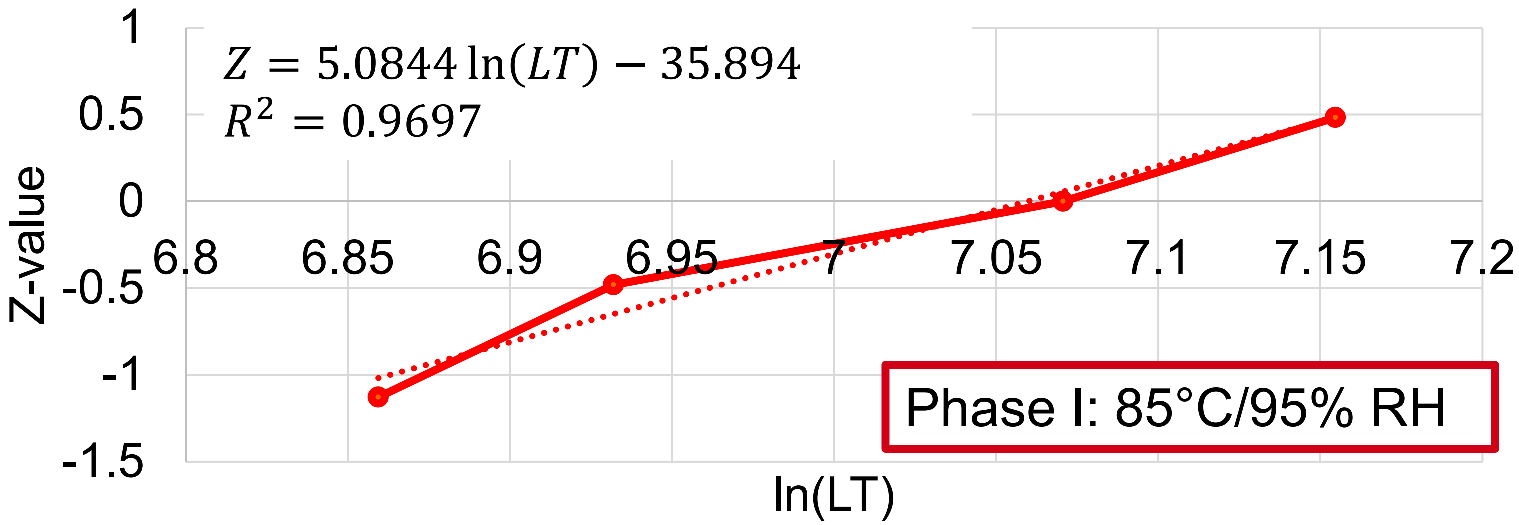




- Failure analysis indicated consistency of the failed part – transistors in the fan PCB controller

Lifetime Modeling – Given Stress Level

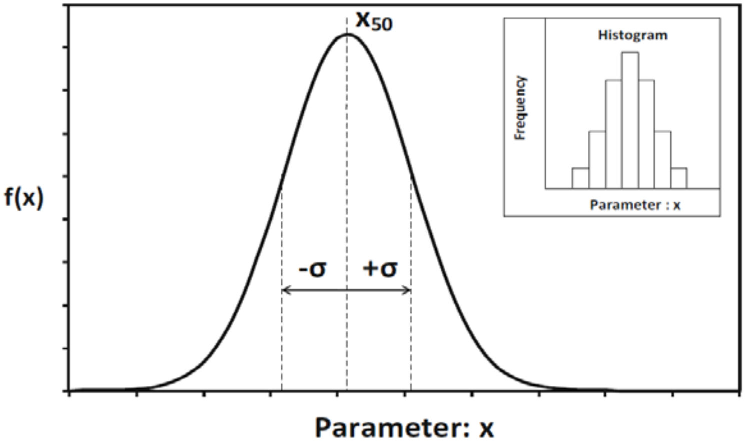
- **Lifetime (LT) follows lognormal distribution**



$$Z = 0 \ \rightarrow t_{50} = \exp\left(\frac{35.894}{5.0844}\right) = 1{,}164\ \mathrm{h}$$

$$Z = -1 \ \rightarrow t_{16} = \exp\left(\frac{35.894 - 1}{5.0844}\right) = 956\ \mathrm{h}$$

$$\sigma = \ln\left(\frac{t_{50}}{t_{16}}\right) = 0.197$$



Lifetime Modeling – Acceleration Factor (AF)

$$(t_{50})_{op} = AF \cdot (t_{50})_{stress}$$

$$AF = \left(\frac{RH_{stress}}{RH_{op}}\right)^{n} \cdot \exp\left[\frac{Q}{k_B} \cdot \left(\frac{1}{T_{op}} - \frac{1}{T_{stress}}\right)\right]$$

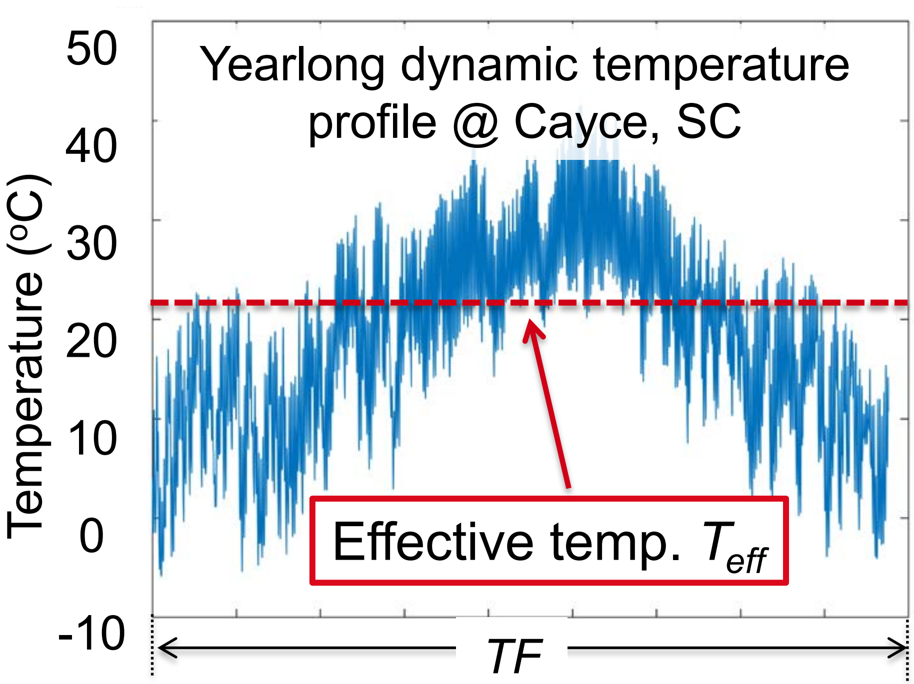
$$Q = k_B \cdot \left[\frac{\partial \ln(TF)}{\partial(1/T)}\right]_{RH} \qquad n = -\left[\frac{\partial \ln(TF)}{\partial \ln(RH)}\right]_{T}$$

Phase	Stress level	t_{50} (hrs)
I	85°C/95% RH	1,164
II	85°C/85% RH	1,788
III	95°C/85% RH	766

$$Q = k_B \cdot \left[\frac{\partial \ln(TF)}{\partial(1/T)}\right]_{85\%} = 0.96\ eV$$

$$n = -\left[\frac{\partial \ln(TF)}{\partial \ln(\xi)}\right]_{85°C} = 3.86$$

Lifetime Estimates – Effective Stressor



Location	Effective Temp. (°C)	Effective RH (%)
Cayce, SC	20.97	79.25
Phoenix, AZ	26.70	41.75
Miami, FL	25.85	78.68
Fort Peck, MT	13.70	67.30
Riyadh, Saudia Arabia	29.67	34.92

$$AF_{T(t),T_{eff}} = \exp\left[\frac{Q}{k_B}\cdot\left(\frac{1}{T_{eff}}-\frac{1}{T(t)}\right)\right]$$

$$T_{eff} = \frac{-(Q/k_B)}{ln\left[\frac{1}{TF}\int_0^{TF}\exp\left(-\frac{Q}{k_B T(t)}\right)dt\right]}$$

Outline

- Introduction
- Cooling Fan Reliability Testing
- Cooling Fan Lifetime Modeling
- **Summary**

Summary

- A method was proposed and implemented.
  - Starting from FMEA to identify the most critical failure mode(s), mechanism(s), and stressors
  - Establishing the reliability testing platform with application-oriented design considerations and scalable sample sizes
  - Deriving a reliability model based on failure analysis, considering statistical variation
  - Estimating the lifetime under the given mission profile through conversion of dynamical stresses into effective static values
- Takeaways
  - Sample sizes and number of stress levels play significant roles on the lifetime model accuracy, resulting in a time-consuming and pricy test.
  - Coupling among stressors (electrical and mechanical) could worsen the lifetime; the method to quantify the impact of coupling is needed.

Acknowledgement

- The team sincerely appreciates the support from the Department of Energy (DOE) Solar Energy Technologies Office (SETO) under Award Number DE-EE0009348.

U.S. DEPARTMENT OF ENERGY

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

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Screening Methodolgy for SiC MOSFETs

Dr. Anant Agarwal
Agarwal.334@osu.edu

April 11-12, Reliability of PV Inverters Workshop, NREL

Current Challenges in SiC for EVs

Four main challenges for SiC in EV and PV converters

1. SiC surface defects result in 2%-3% failure of devices in EV inverters.
2. Two main failure mechanisms:
   a. Gate oxide failures.
   b. Drain source failures under high drain voltage.
      1.2kV devices should not be used for 900V bus, 1.5kV devices should be used instead.
3. Shoot through is another failure mechanism in EV inverters due to short (2-4 microsecond) Short Circuit Withstand Time.
4. **Aggressive screening of incoming power modules in needed to reduce failure rates from 2%-3% to 2-3 ppm.**

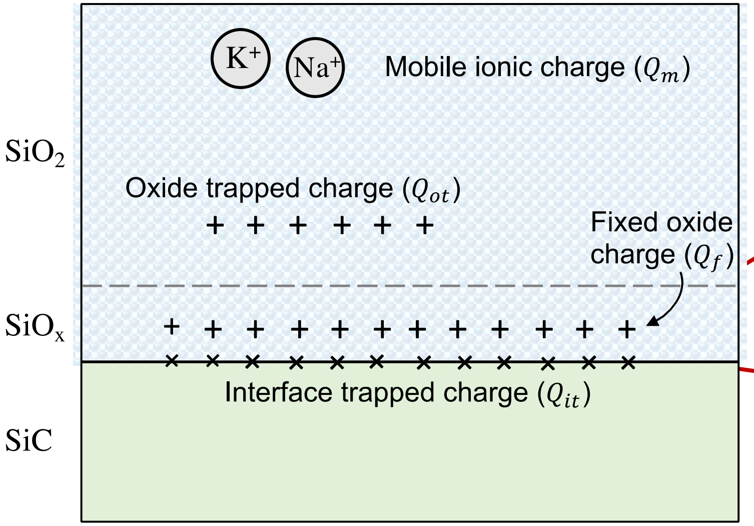
Oxide Reliability

Good News

Commercial SiC chips (600 – 1.7 kV) pass JDEC and automotive reliability test over 1000 hours

Is that Enough?

Two major defect issues with the oxide and interface:



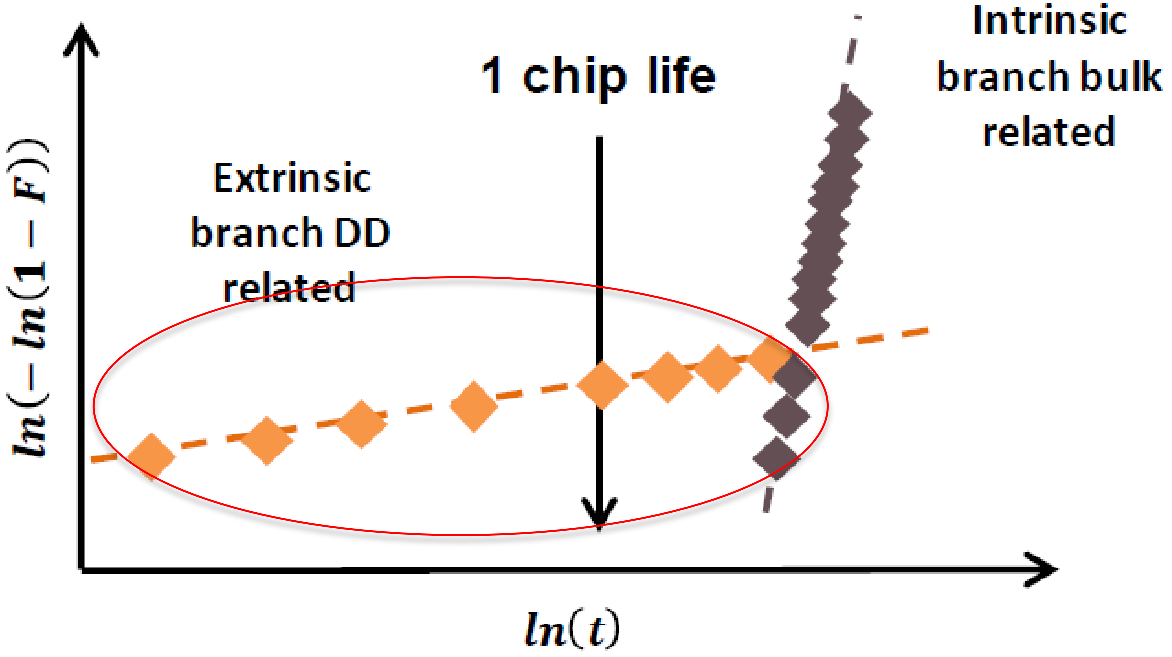
i) <u>Fixed oxide charges</u>
⇒ Threshold voltage variation

ii) <u>Interface defects</u>
⇒ Low inversion layer mobility
Si ~ 400 $cm^2/V \cdot s$
SiC ~ 20 $cm^2/V \cdot s$

Oxide Reliability

Undetected **Extrinsic** defects are causing early failure in the field.

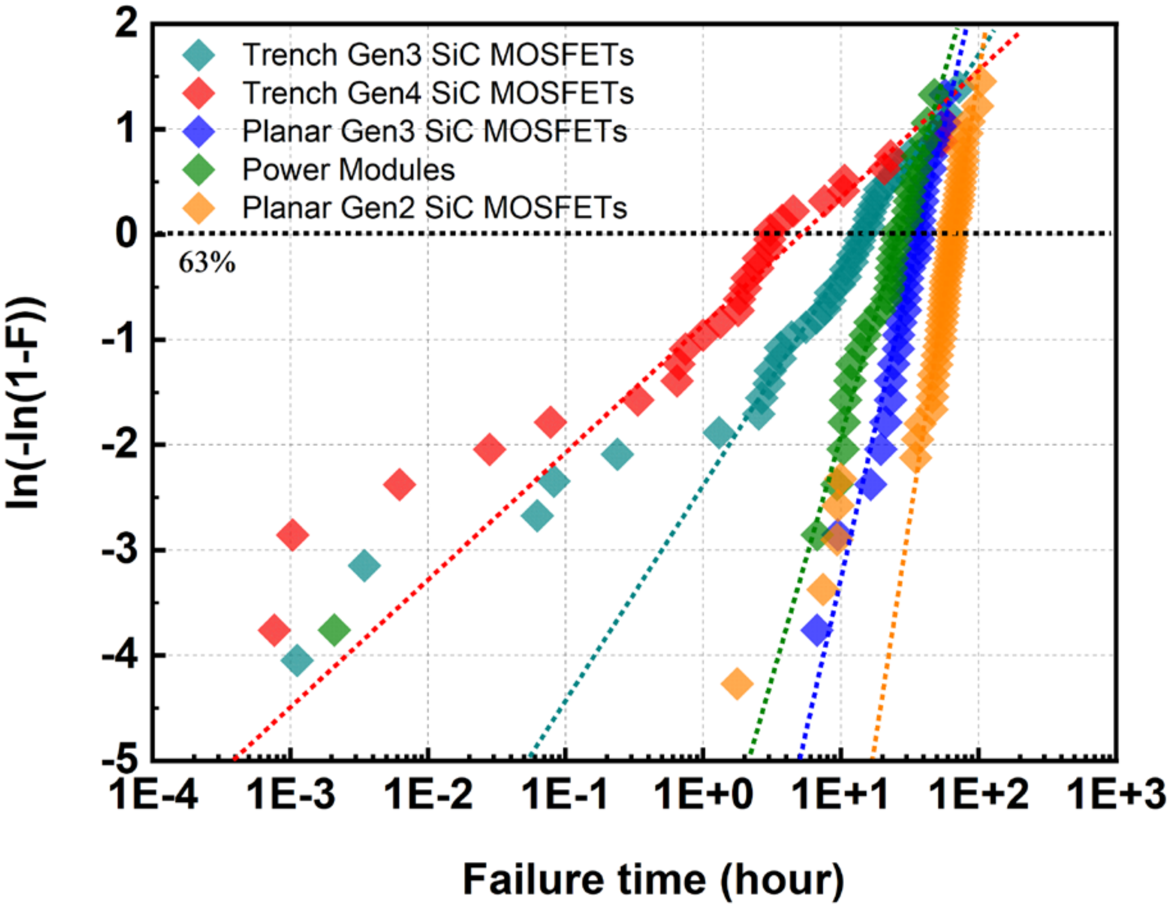
Imagine: You are receiving tens of thousands of devices every day, how do you catch all the bad guys without significantly damaging the good ones?



Peter Friedrichs, Robustness and reliability aspects of SiC power devices. 2021

Major Challenge of SiC MOSFETs in EV/PV

- **Gate oxide failure: Higher risk for early GOX breakdown**
- **EV requirement: Gate oxide lifetime >> 20 years at 150℃**



These devices were already
Screened by the Vendor

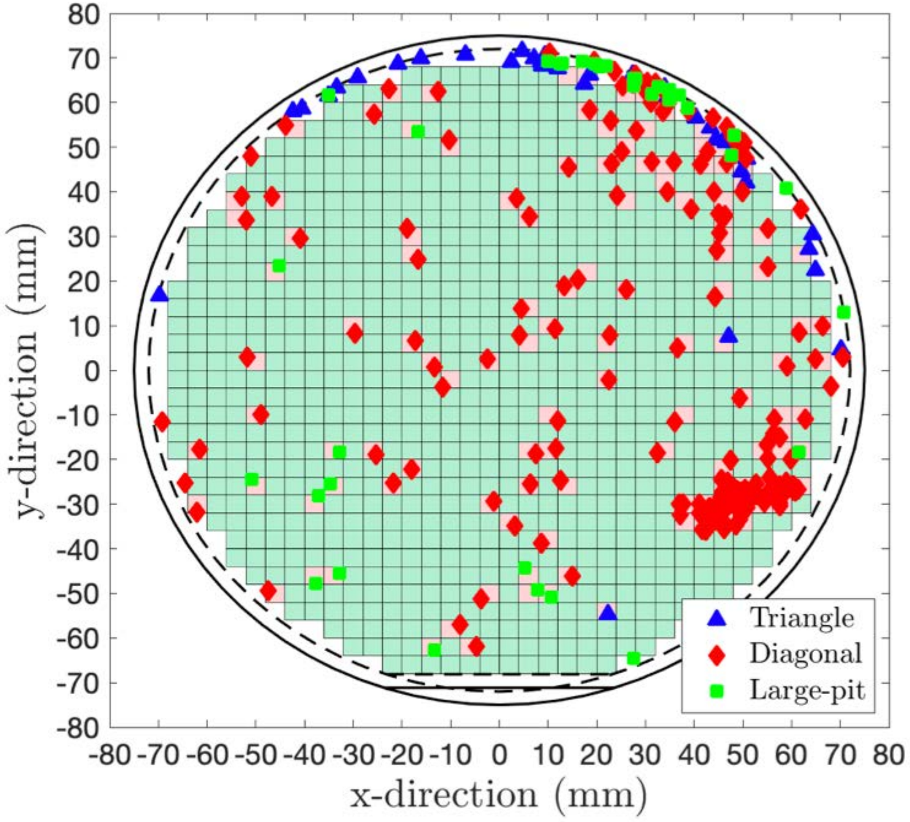
Oxide Reliability

Surface defects reduce yield for larger area devices

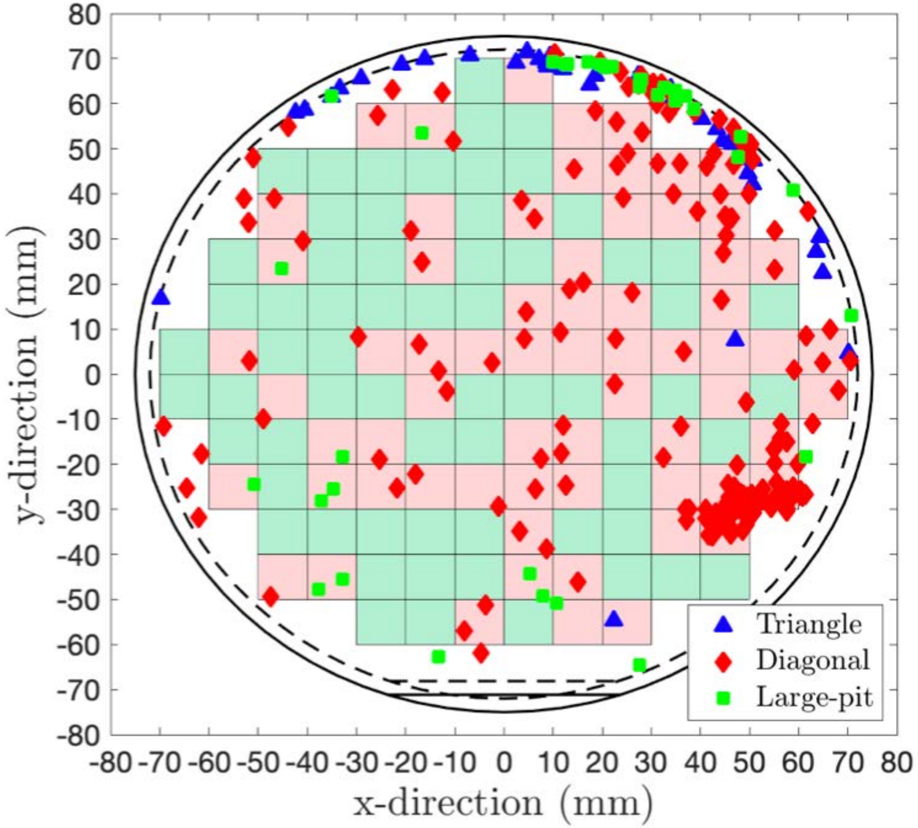
$< 0.2cm^{-2}$ defect density needed for > 80% yield of 500 A SiC power MOSFETs

Worst wafer
Defect density = 1.69/cm^2
Die size: 4mm x 4mm (65 A)
Yield: 92%

🟩 Good die 🟥 Defective die



Worst wafer
Defect density = 1.69/cm^2
Die size: 10mm x 10mm (500 A)
Yield: **49%**



Oxide Reliability

Solution:

Screening of devices coming into your warehouse.

Goal:

1. Remove potentially defective and unreliable devices.
2. Reduce failure probability of remaining devices.

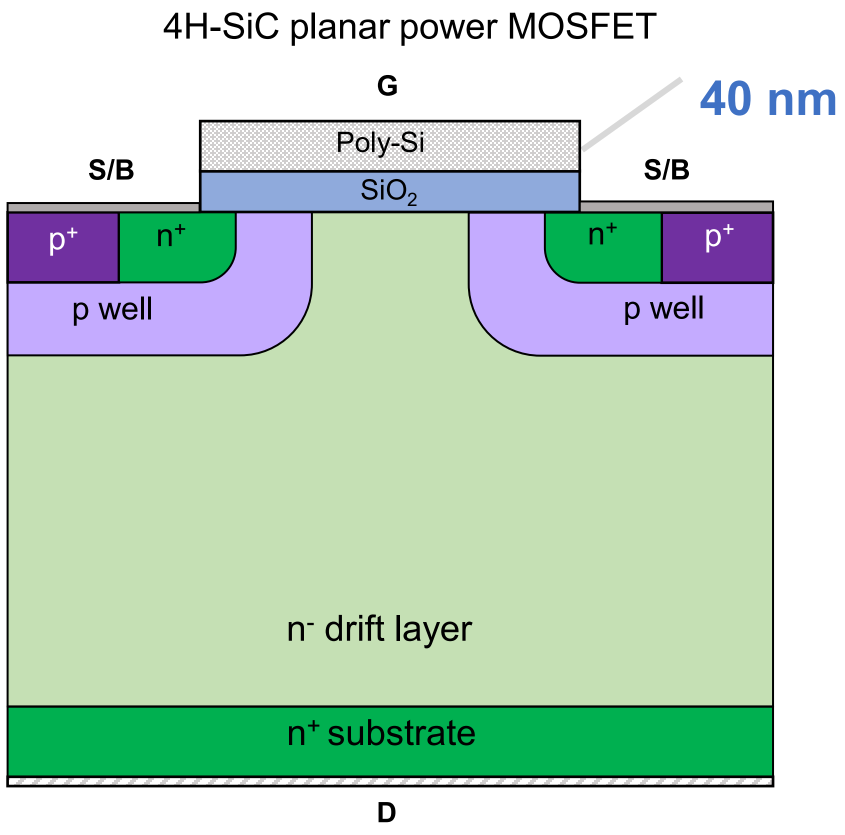
Current screening methods employed by device manufacturers are insufficient to catch all the killer defects causing extrinsic failures.

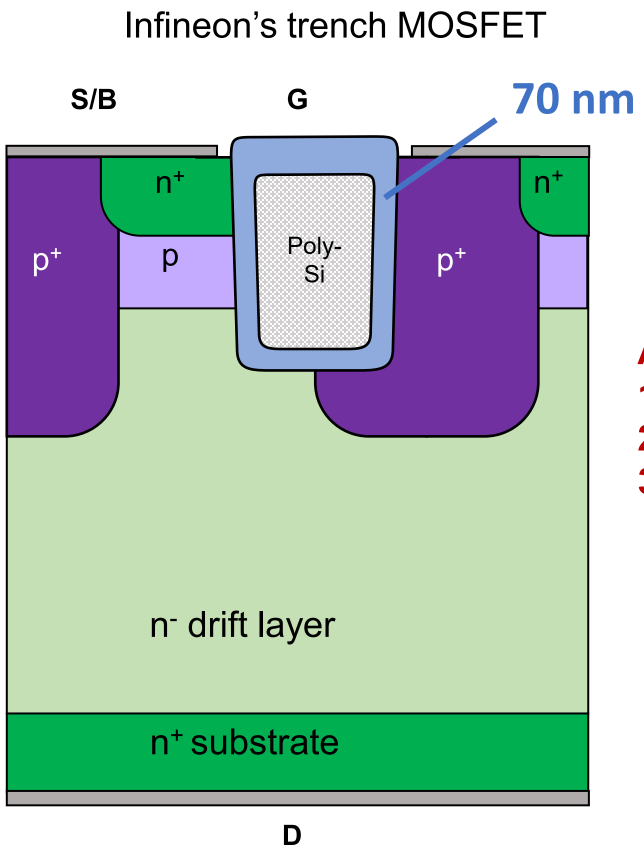
Our Job: Develop ways to improve screening efficiency without degrading device performance

Oxide Reliability

Trench Devices are less susceptible to surface defects.

These defects can result in 2-3% failure of devices in EVs in the field.





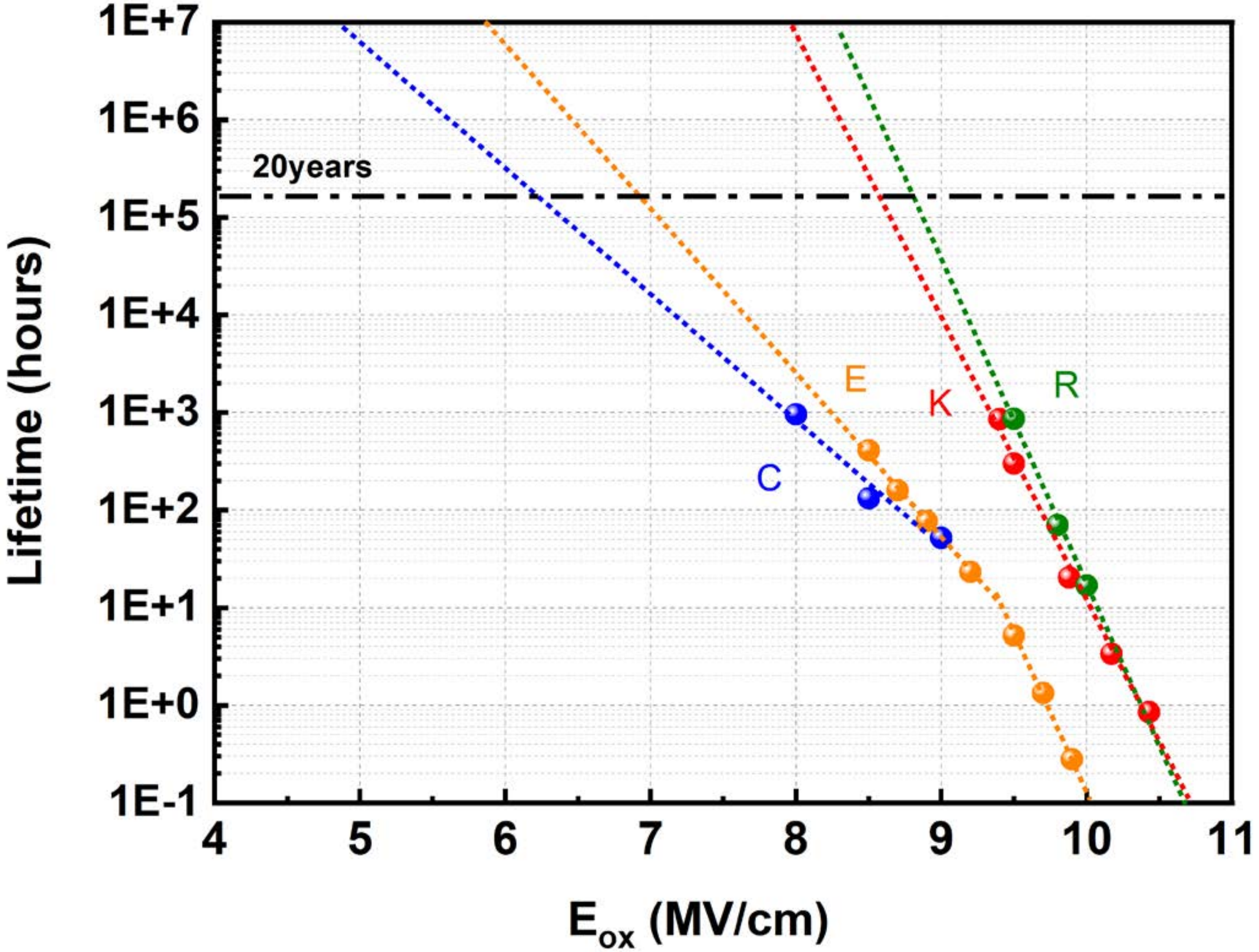
Advantages of trench MOSFETs:

1) **Smaller cell pitch**
2) **Smaller exposed oxide**
3) **Higher mobility => Thicker oxide**
   - **Higher oxide lifetime**
   - **More effective screening**

Oxide Reliability

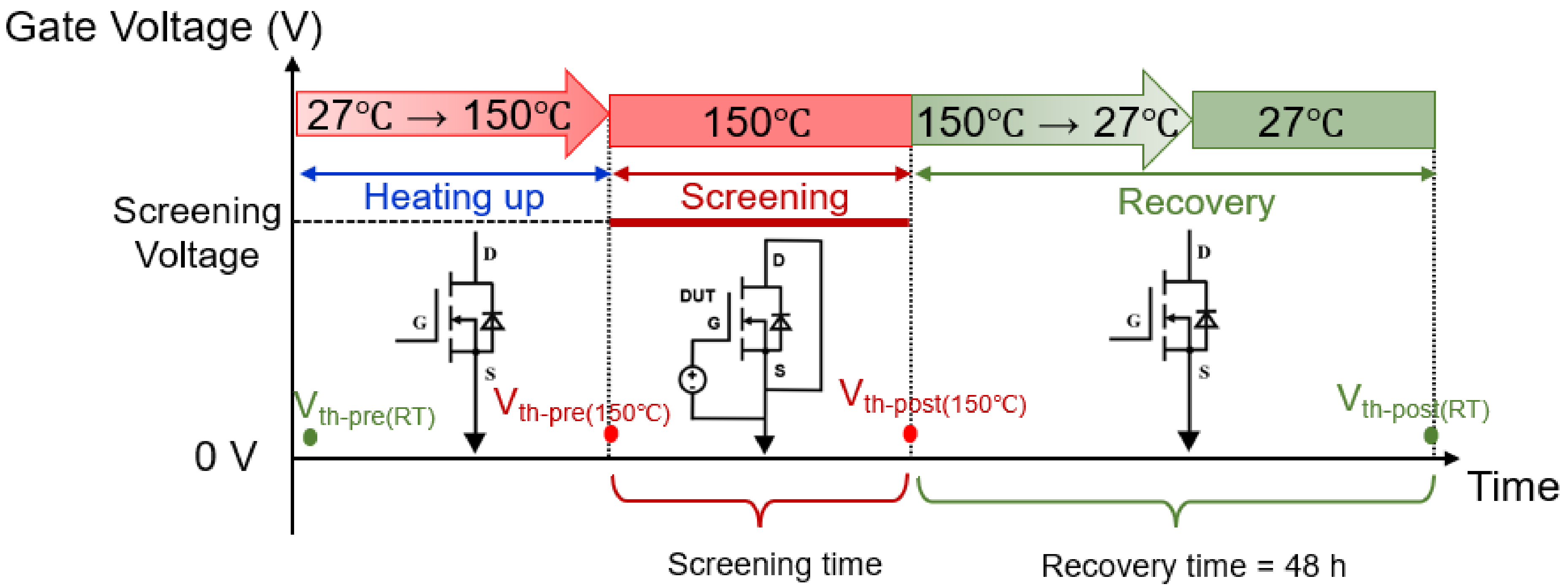
The Ohio State University

Intrinsic lifetime is much higher for trench devices (R, K) compared to Planar MOSFETs (C, E)



High Gate Voltage Pulse Screening Method

Threshold voltage is monitored during the test to check for device degradation.

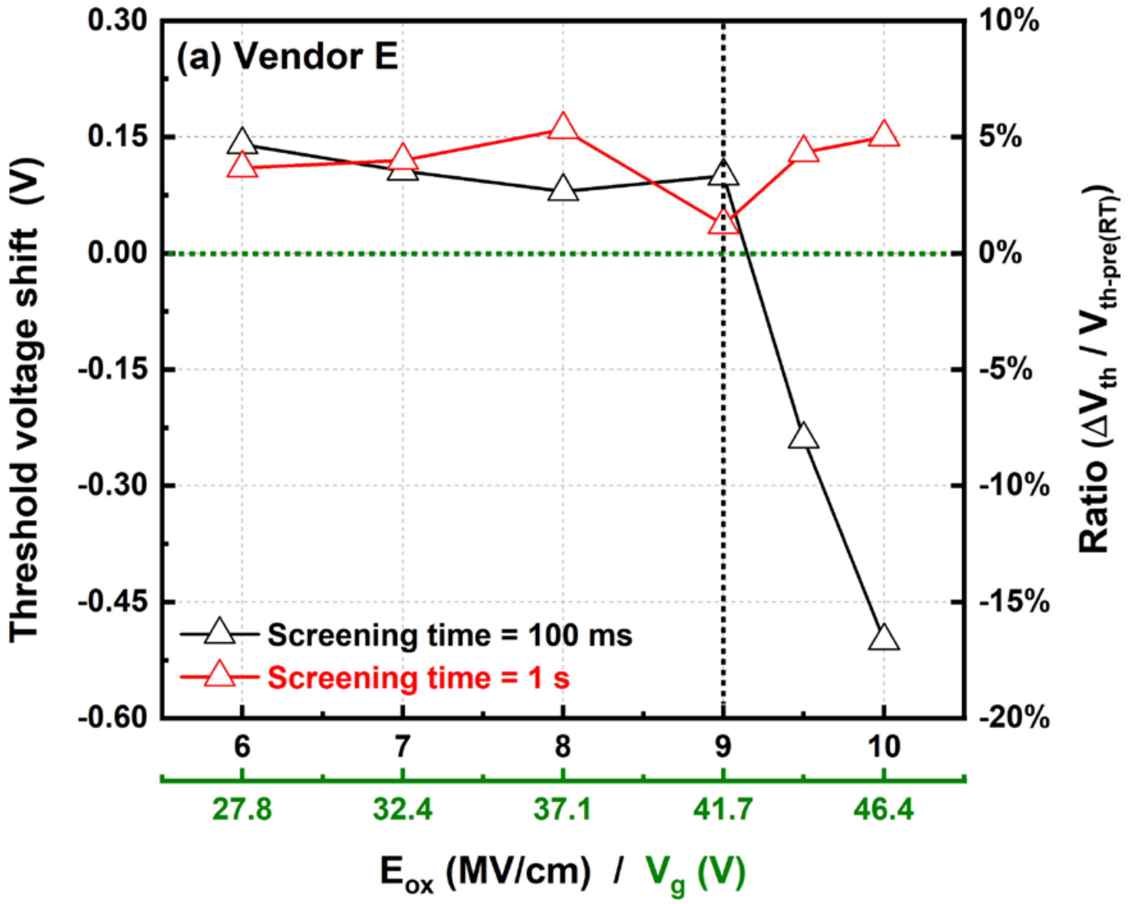


$$\Delta V_{th} = V_{th\text{-}post(RT)} - V_{th\text{-}pre(RT)}$$

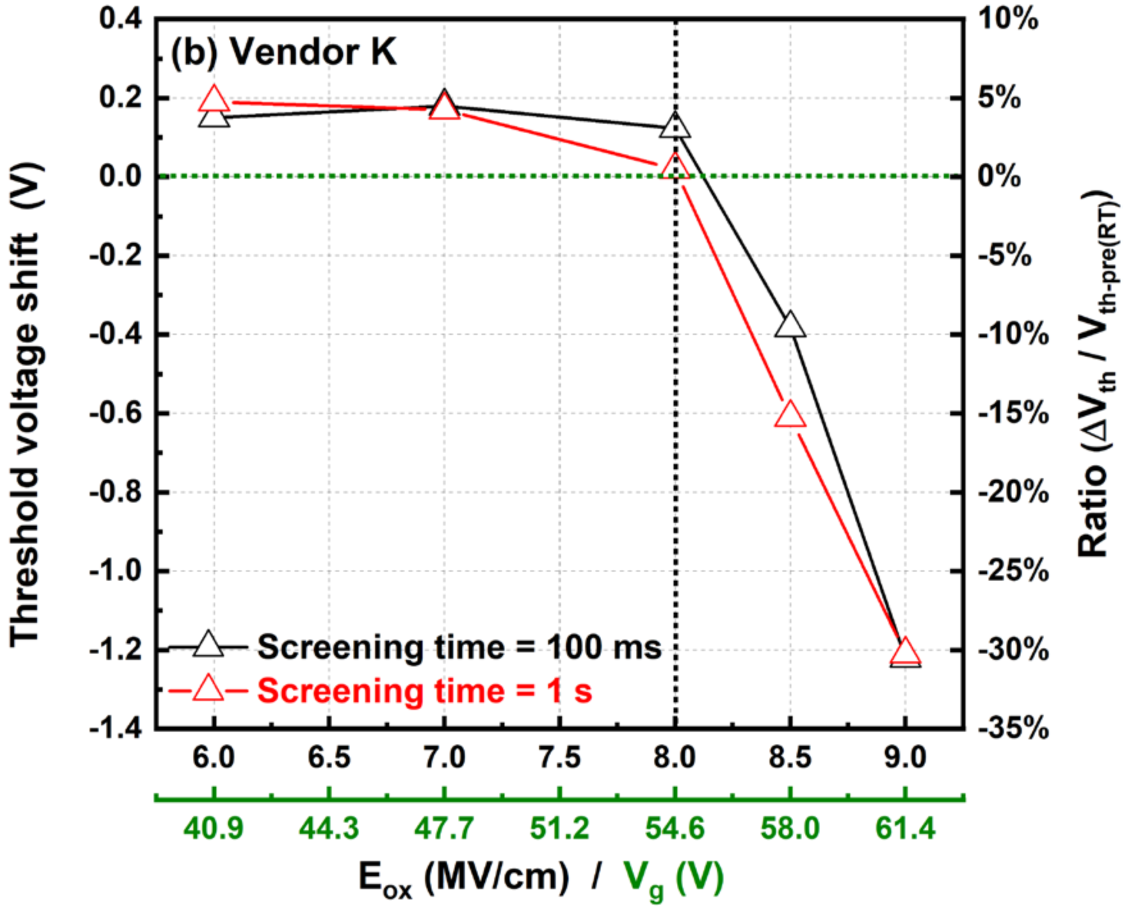
Oxide Reliability

V_{th} shift stays within 5% of the initial value after the recovery process at lower oxide electric fields.

SiC Planar MOSFET



SiC Trench MOSFET

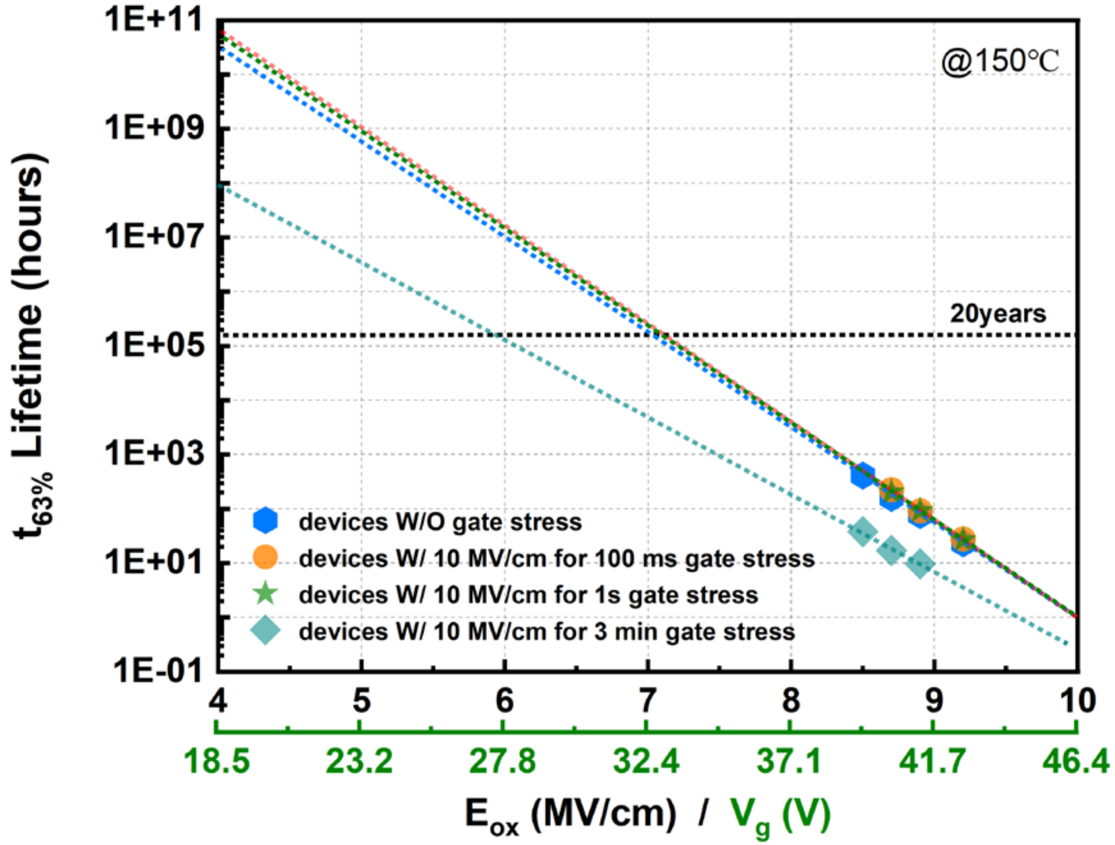


Oxide Reliability

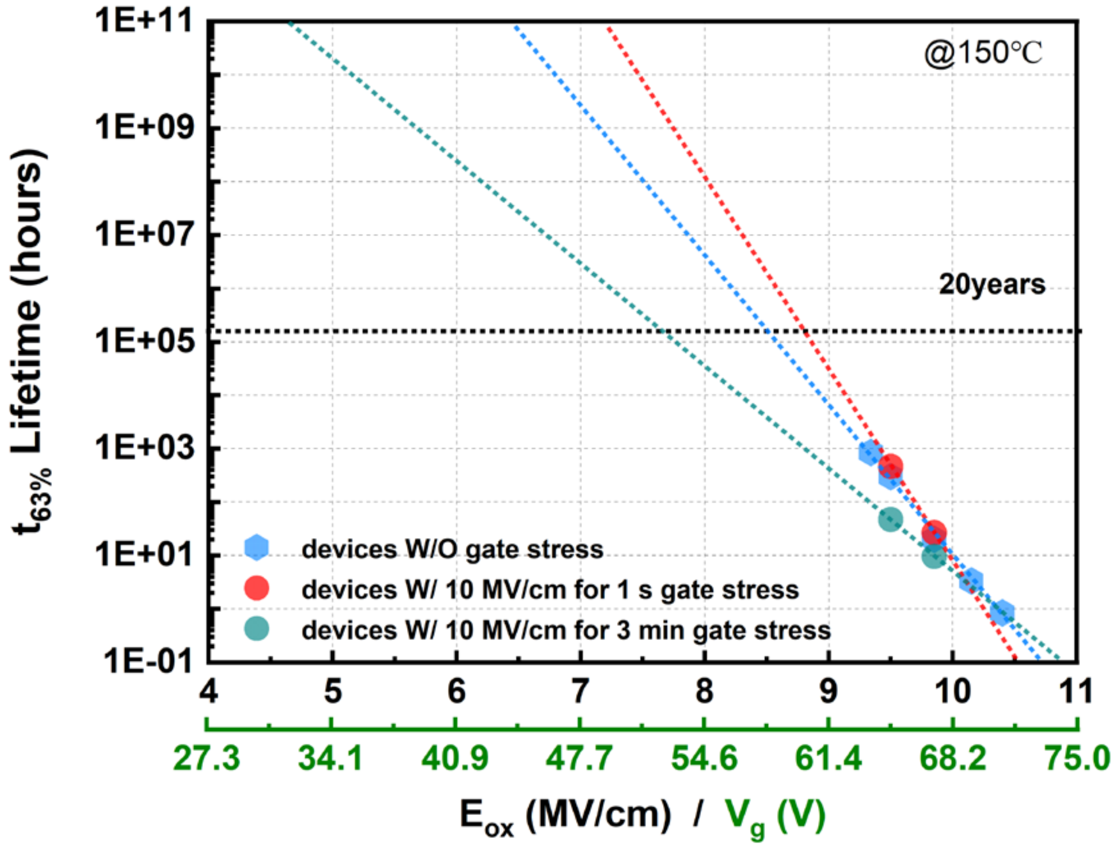
Effects of high gate voltage stress on intrinsic lifetime

Trench devices with thicker oxide can support higher screening voltages, allowing for higher screening efficiency.

SiC Planar MOSFET



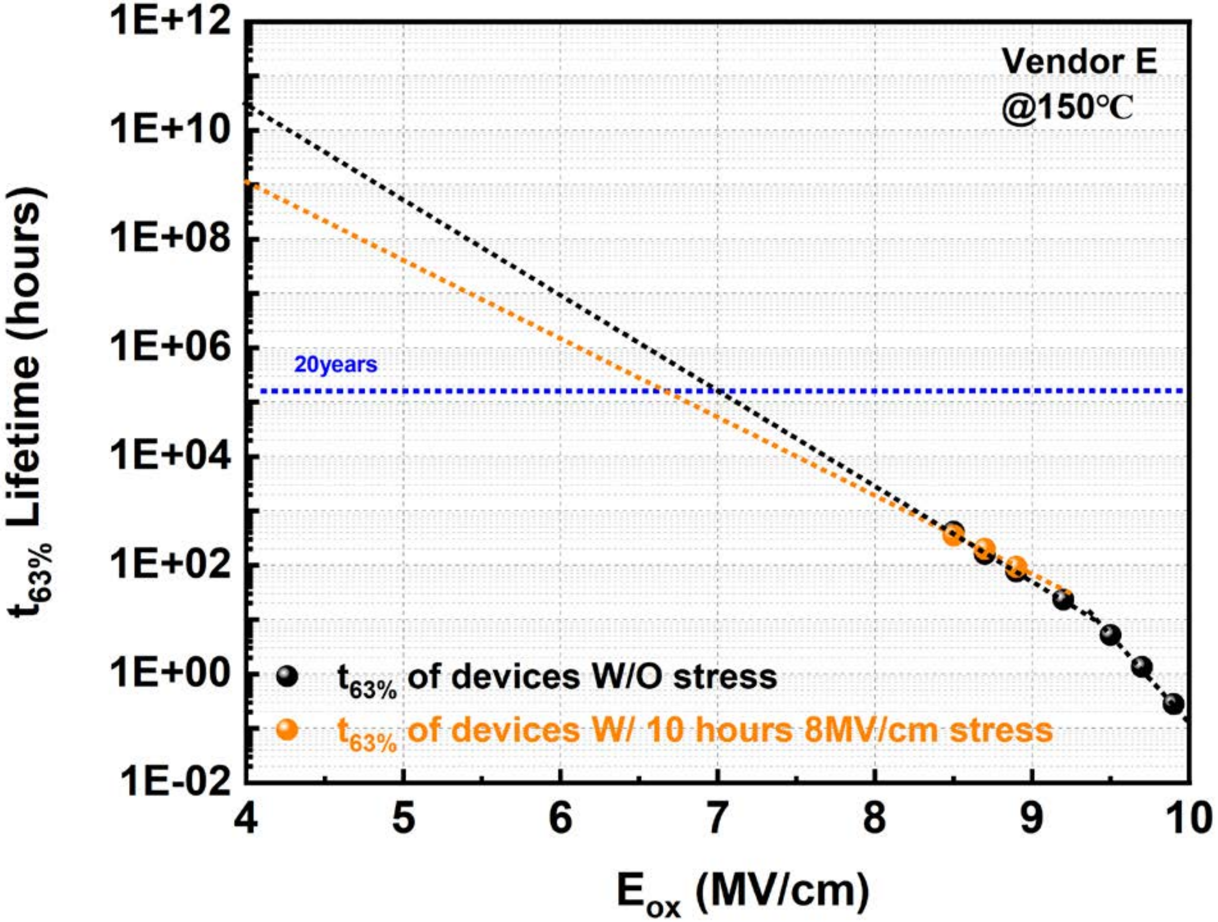
SiC Trench MOSFET



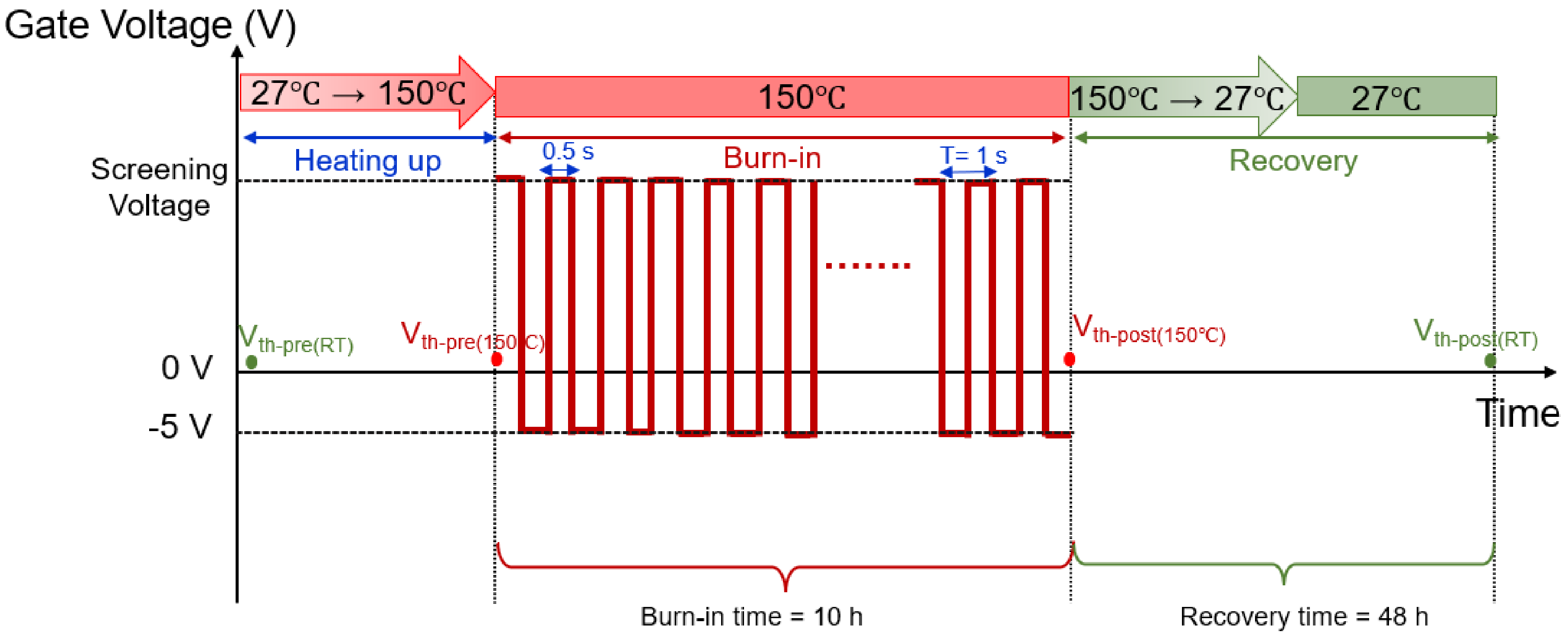
Oxide Reliability

In this case, 10 hours at $E_{ox} \leq 8$ MV/cm does not degrade the oxide intrinsic lifetime significantly.

SiC Planar MOSFET



Pulsed Burn-in Method



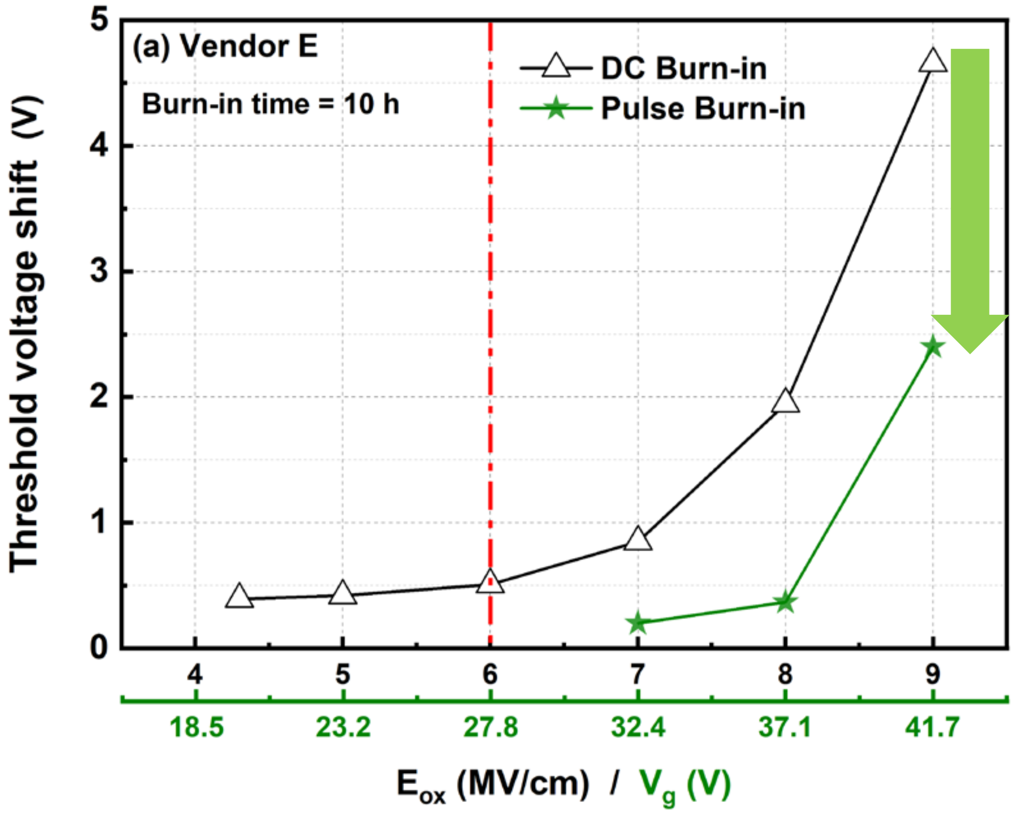
Pulse period T = 1 s
Pulse width = 0.5 m
Duty ratio = 50 %

$\Delta V_{th} = V_{th\text{-}post(RT)} - V_{th\text{-}pre(RT)}$

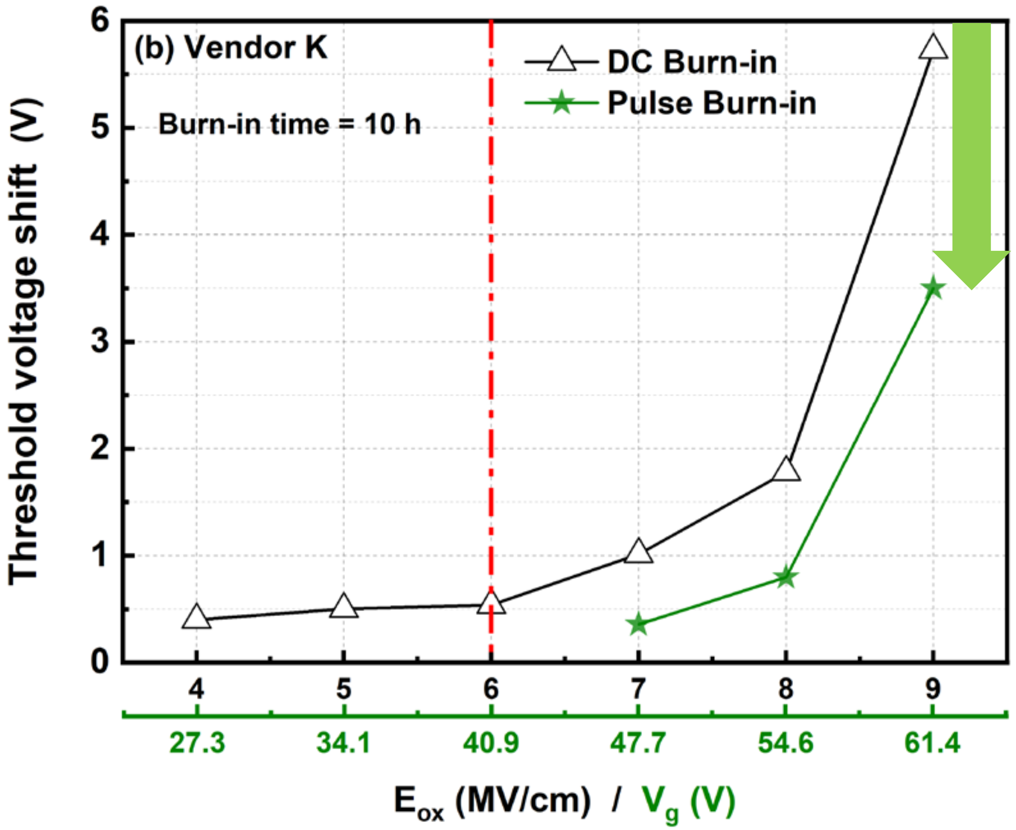
Oxide Reliability

By applying a negative voltage, some of the threshold voltage shift can be recovered.

SiC Planar MOSFET



SiC Trench MOSFET

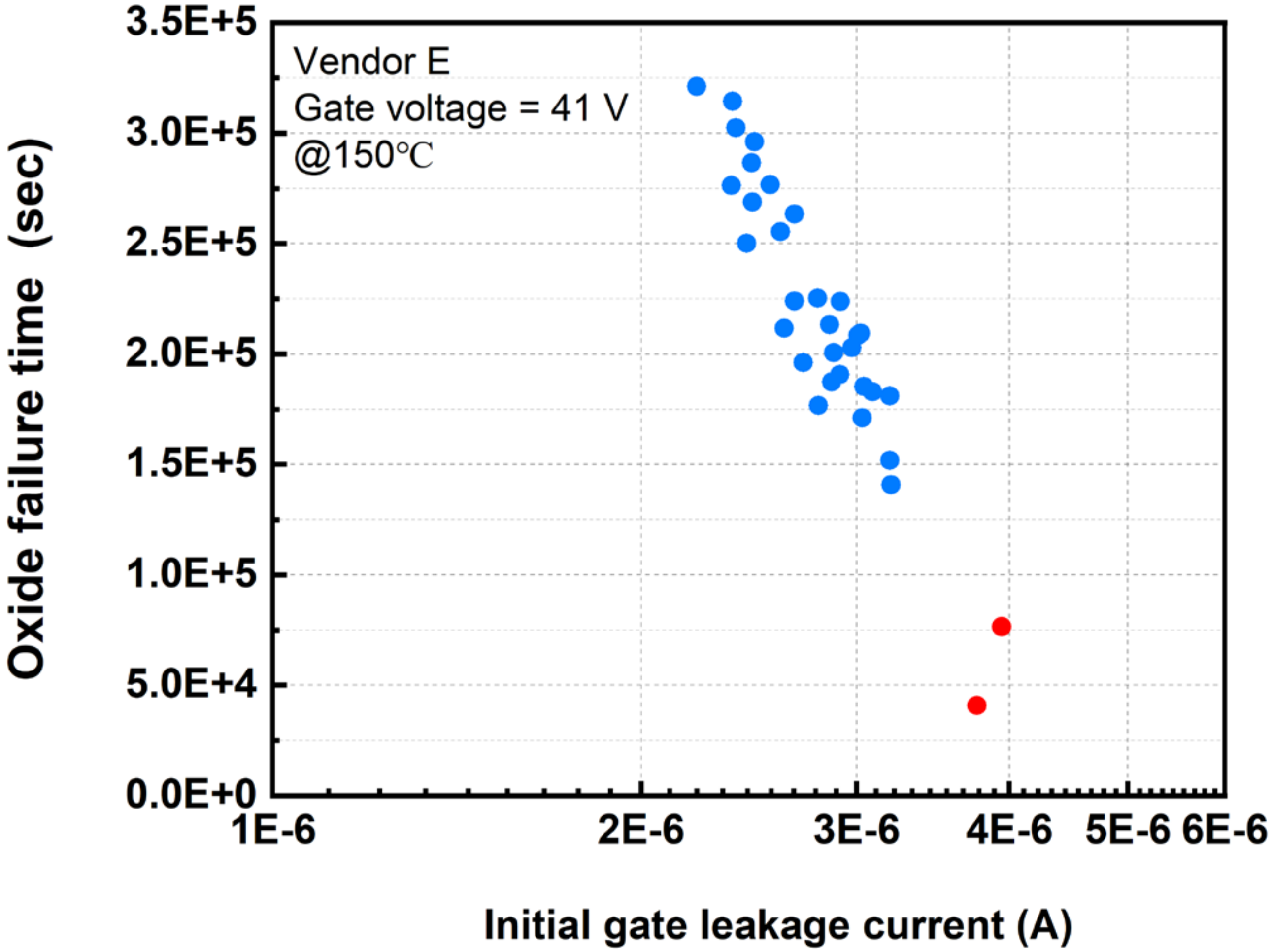


Oxide Reliability

THE OHIO STATE UNIVERSITY

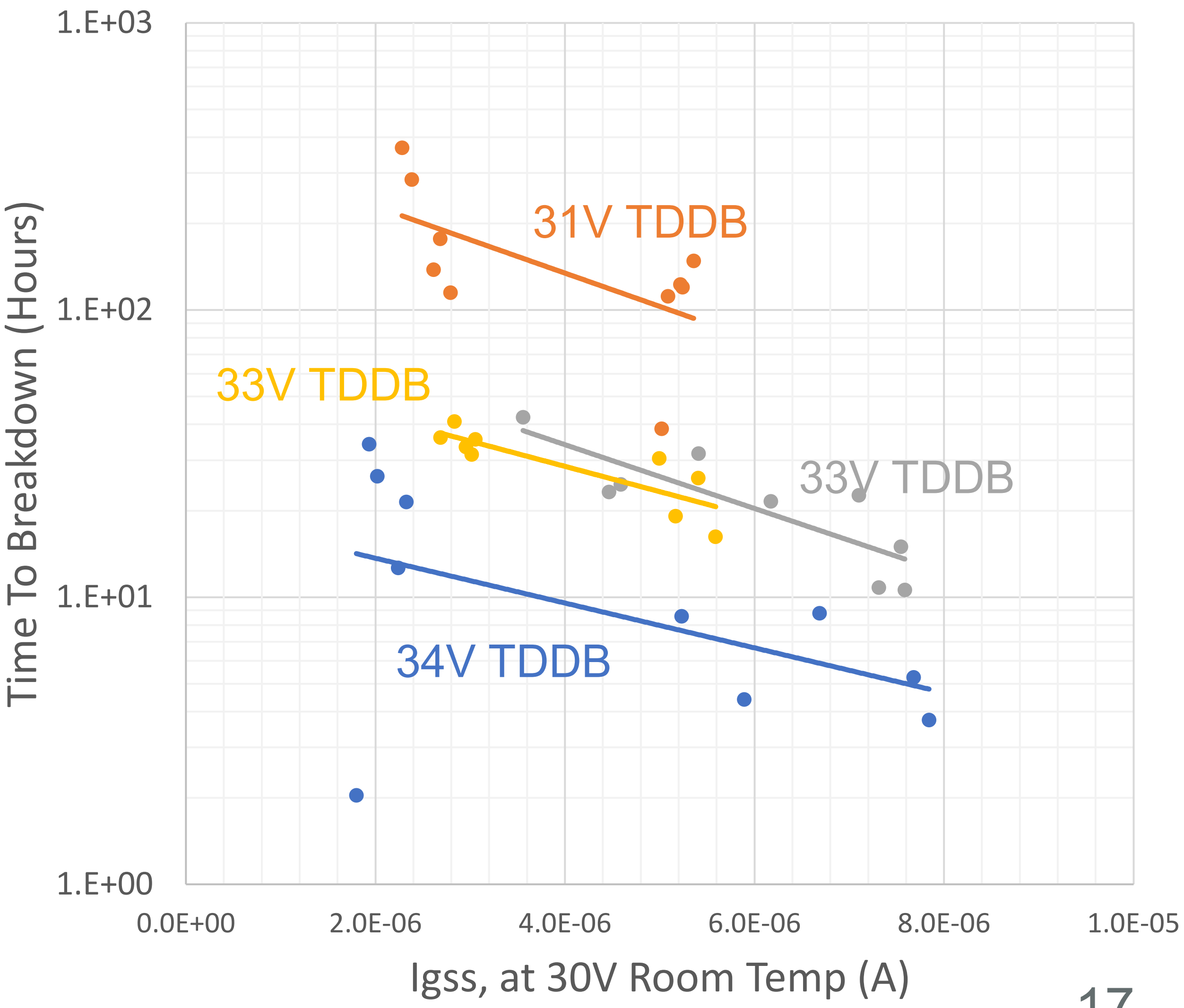
I_{gss} screening for oxide lifetime:

Higher initial gate leakage → Shorter oxide lifetime



Oxide Reliability

Multiple power modules were screened for I_{gss}, and then broken down during TDDB.



Summary

- ❑ It is absolutely necessary to screen incoming SiC power modules against gate oxide defects to reduce the failure rate from 2-3% to 2-3 ppm.
- ❑ We are developing screening techniques suitable for all the vendors of SiC power modules.

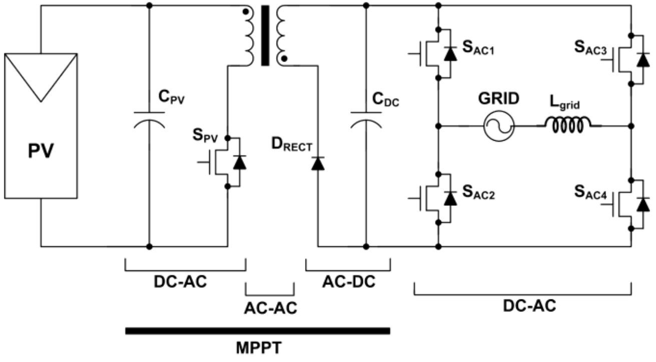
Thank you!

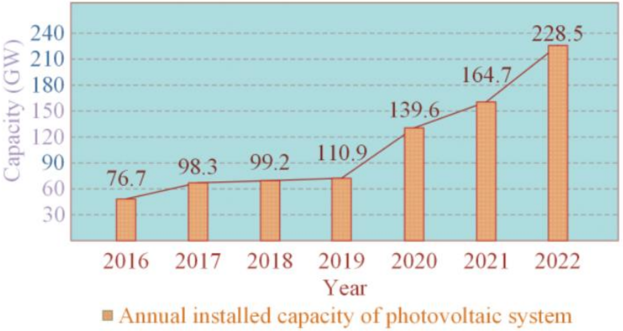
Live state of health monitoring of inverter subsystems

Faisal Khan

April 12, 2024
NREL

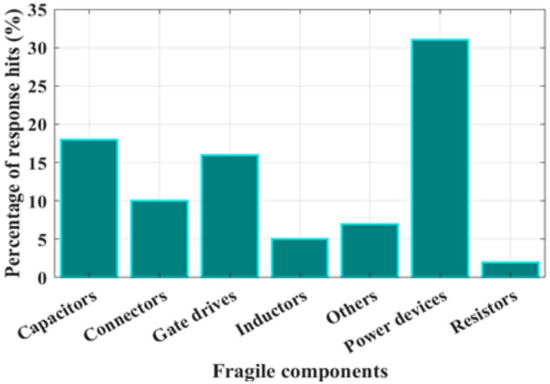
Components of a PV Subsystem and Reliability Issues

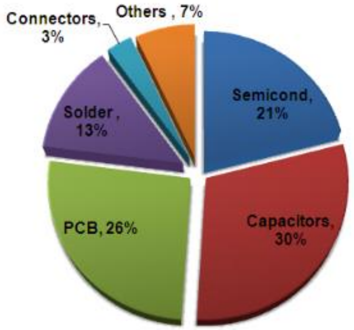




Power electronic converter circuit for PV power harvesting

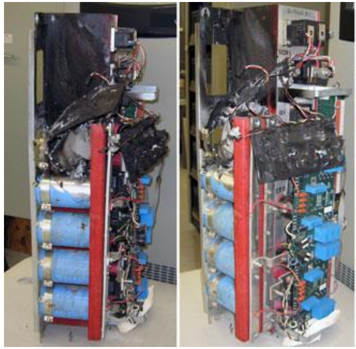
- PV panel degradation and cable faults
- Inverter degradation and converter failures
- Interconnect and protection system failures





YANG et al.: RECENT ADVANCES IN FAULT DIAGNOSIS TECHNIQUES FOR PHOTOVOLTAIC SYSTEMS: A CRITICAL REVIEW

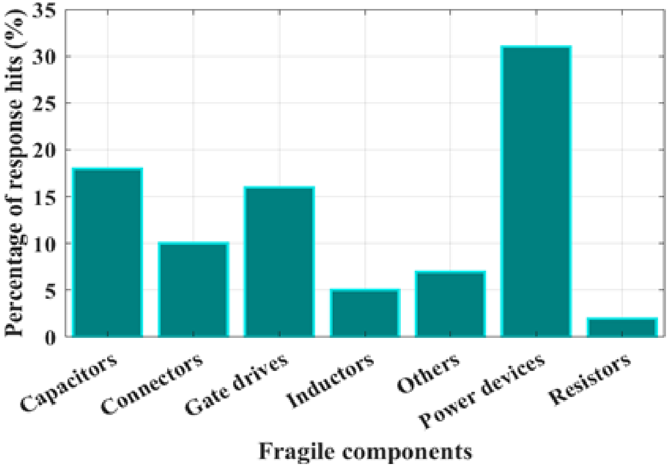
Energy Conversion Systems and Reliability

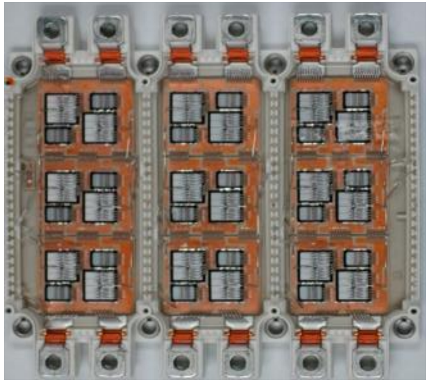


UPS Inverter Assembly

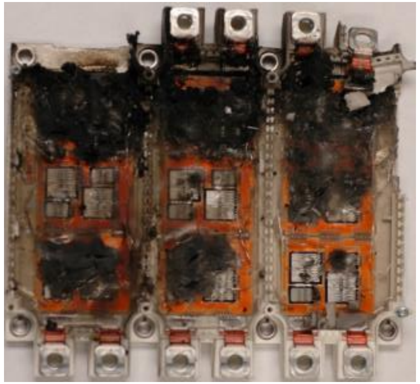
- A modern power conversion system may have components including high-power dc-ac inverters, electric machines such as motors and transformers, renewable energy sources such as wind generators or solar cells and energy storage units in the form of battery banks.
- Most of these power processing units are subjected to electrical and thermal stress resulting in performance degradation.
- In order to ensure a failure free operation, components in a power system employed in critical applications are being operated with redundancy and are needed to go through periodic replacements.
- This periodic maintenance is time and cost intensive, thus shows promise for optimization.

Degradation in Power Electronic Components and Systems





Healthy IGBT[1]



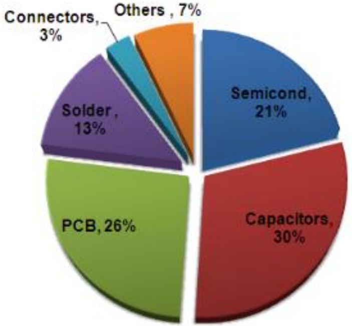
Failed IGBT due to thermal runaway[1]

- Power semiconductor devices (MOSFETs and IGBTs) are the most fragile components in power electronic systems.
- When they fail, results can be catastrophic.
- Failure prediction can reduce maintenance costs and potentially save human lives.

Wind turbine at fire due to failed IGBT module[1]

[1] *https://www.nrel.gov/pv/assets/pdfs/2015_pvmrw_131_das.pdf*

Power Converter Failure: Facts

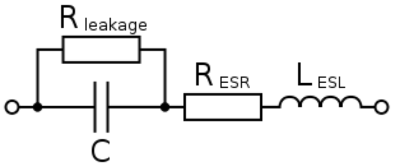


- Electrolytic capacitors and semiconductor switches are two of the most affected components due to aging in power converters.[1]
- Capacitor equivalent series resistance (ESR) increases and capacitance decreases due to aging.
- Accidental high voltage applied at the gate terminal increases the threshold voltage.
- MOSFET ON–state resistance (R_{DS}) changes due to thermal aging.
- Degradation at the contact area of bonding wire, such as metallization, and at the die solder layer occur due to thermal aging, which are reflected in the change in MOSFET R_{DS}.
- Threshold voltage, transconductance, and collector-emitter ON voltage change due to aging of IGBTs.

[1] U.S. Dept. of Defense. 1995. *Reliability Prediction of Electronic Equipment, Military Handbook 217F.*

Electrolytic Capacitor Failure

Aging



- **High voltage:** Capacitance value decreases and R_{ESR} value increases.
- **Transients:** Leakage current increases and internal short circuit may occur.
- **Reverse bias:** Leakage current becomes high with loss of capacitance and increase in R_{ESR}.
- **Vibrations:** The effects are internal short circuit, capacitance losses, high leakage currents, increase in R_{ESR}, and open circuits.
- **High ripple current:** Internal heating occurs and increase in core temperature results in gradual aging of capacitors.

PV Ground Fault and Corresponding Casualties

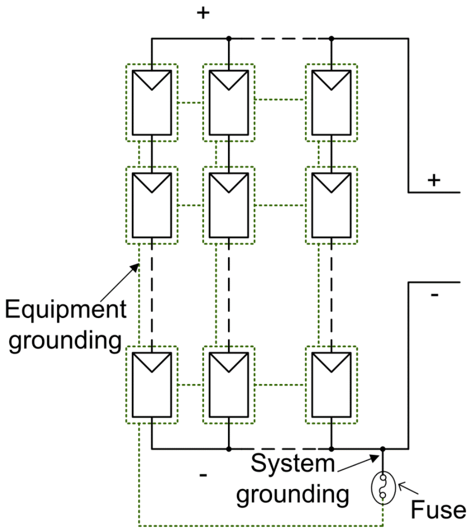
- According to the US National Electrical Code (NEC), PV systems with system voltage more than 50V require both equipment grounding and system grounding .
- A ground-fault protection and interruption (GFPI) device is installed in a PV system to detect the ground-fault, interrupt it and provide a fault indication to protect the system from potential fire hazards.
- Usually ground-fault is detected if the fault current exceeds some predetermines values set by the GFPI device.

Roof fire caused by ground fault

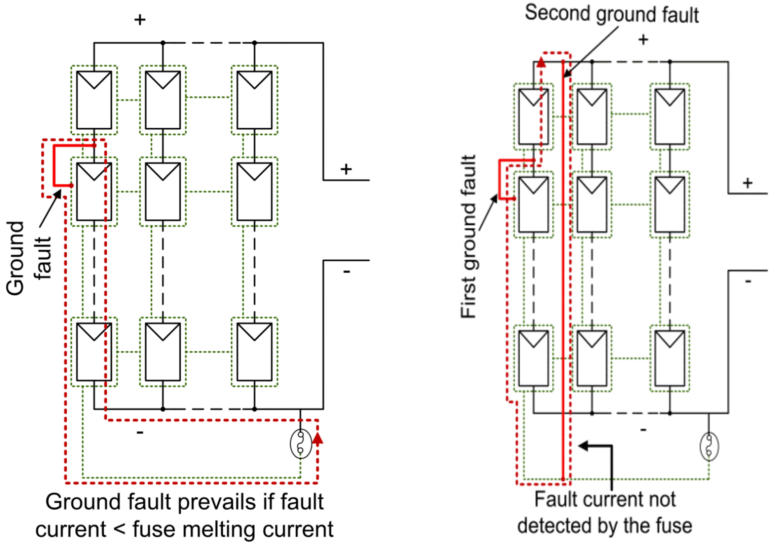
Possible Ground Faults in PV Systems and the Limitations of Existing Systems

Limitations of an existing ground fault protection and interruption (GFPI) system

- A ground-fault may occur in the absence of the solar irradiation. (i.e., during night) and remain undetected
- Ground-fault current may be smaller than the GFPI threshold current limit However, the current level may be enough to cause cell damage.
- GFPI may suffer from noise and provide misleading fault indication.
- An undetected ground-fault may pose as a “normal condition” and render to another ground-fault (double ground-fault). This may establish a fault current path without being interrupted by GFPI devices.



A healthy PV system

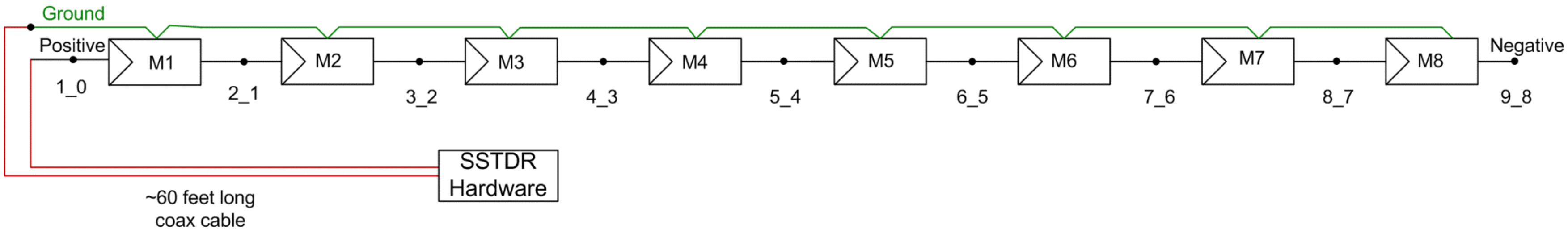


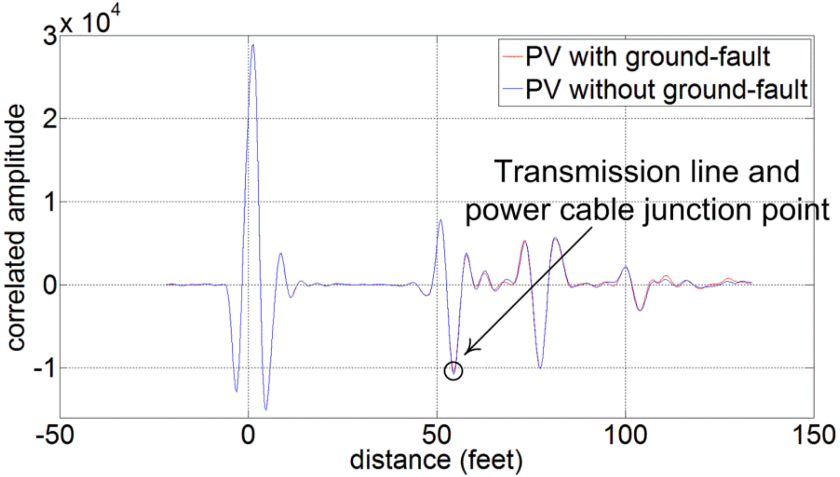
Ground fault prevails if fault current < fuse melting current

Fault current not detected by the fuse

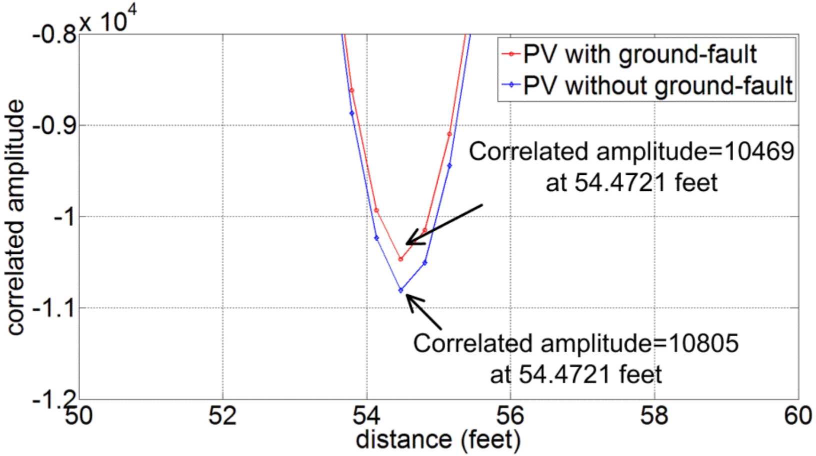
A faulty PV system

Experimental Results Showing PV Fault Detection Scheme: 1





Correlated amplitude vs. distance curve for a PV panel with and without ground-fault



Zoomed-in view of the correlated amplitude vs. distance curve

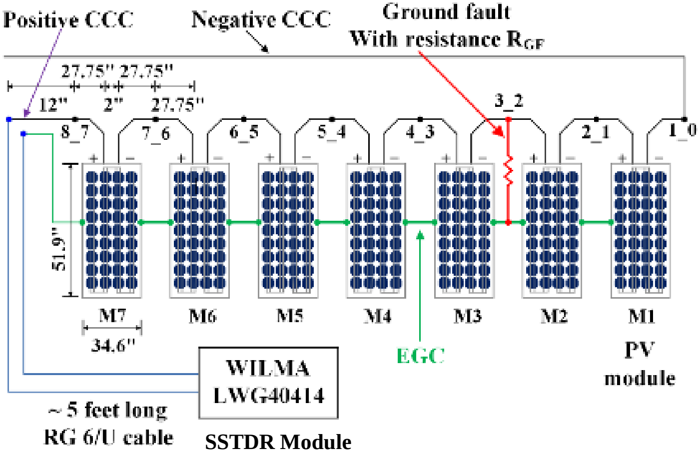
Experimental Setup

Test set-up used at DETL of SNL

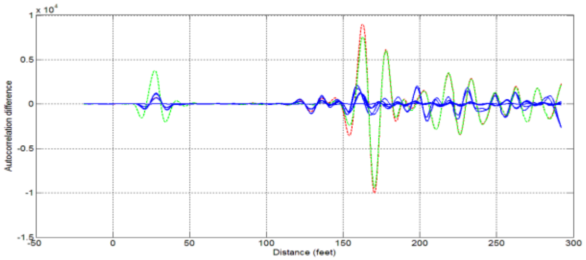
Maximum power (P_{max})	200 W
Short circuit current (I_{sc})	3.83 A
Open circuit voltage (V_{OC})	68.7 V
Maximum power current (I_{pmax})	3.59 A
Maximum power voltage (V_{pmax})	55.8 V

Challenges:

- Hundreds of interconnections and impedance mismatches exist inside a single PV string.
- Multiple reflections occur at different mismatches
- Interpretation of the SSTDR reflection is extremely difficult to detect the fault in PV array.



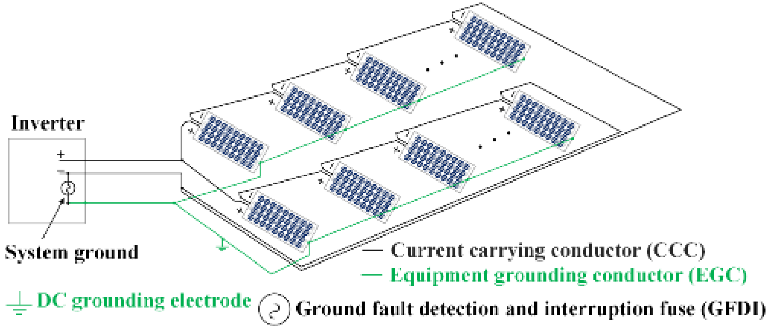
Experimental Results Showing PV Fault Detection Scheme : 2

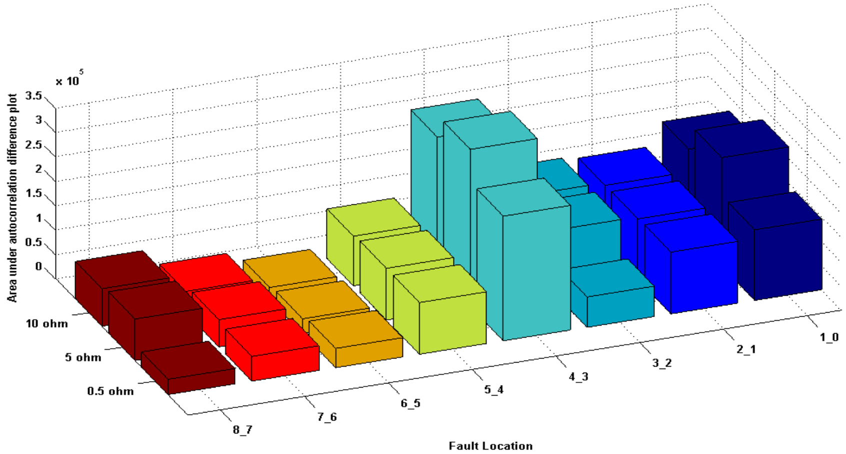


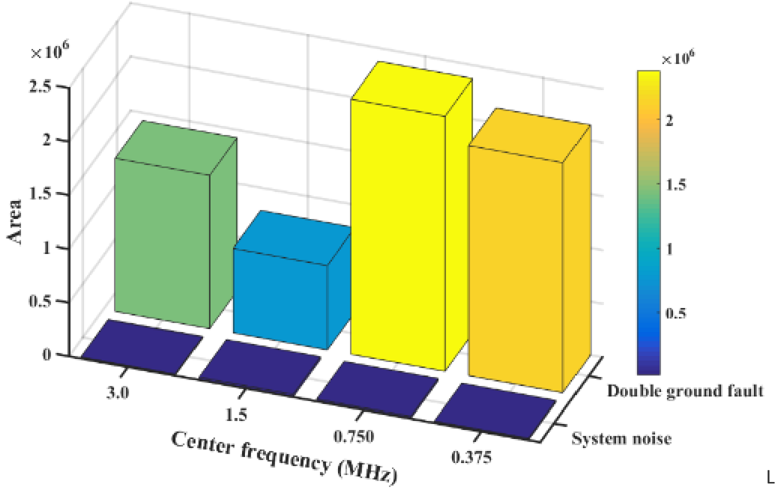
Differential autocorrelation data for faults at different locations

Limitations of GFDI:

- Depends on fault current magnitude
- Therefore, suffers from blind spot detection error and can not detect fault at night or low irradiance level

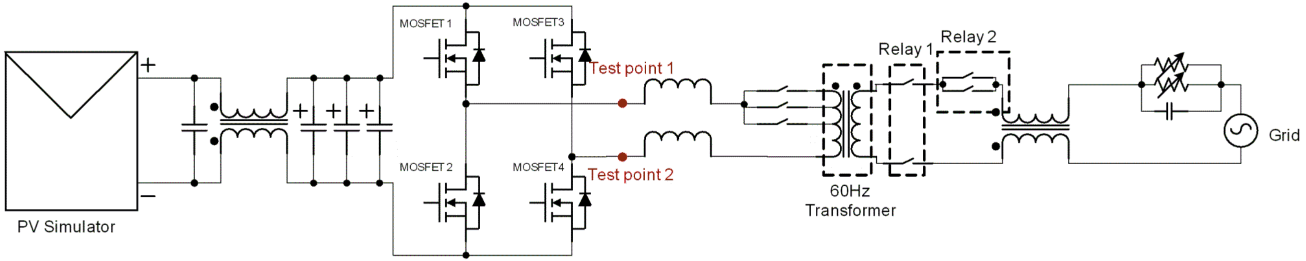


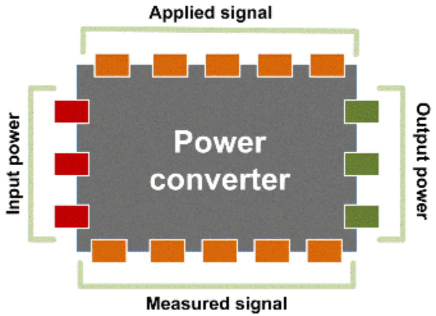




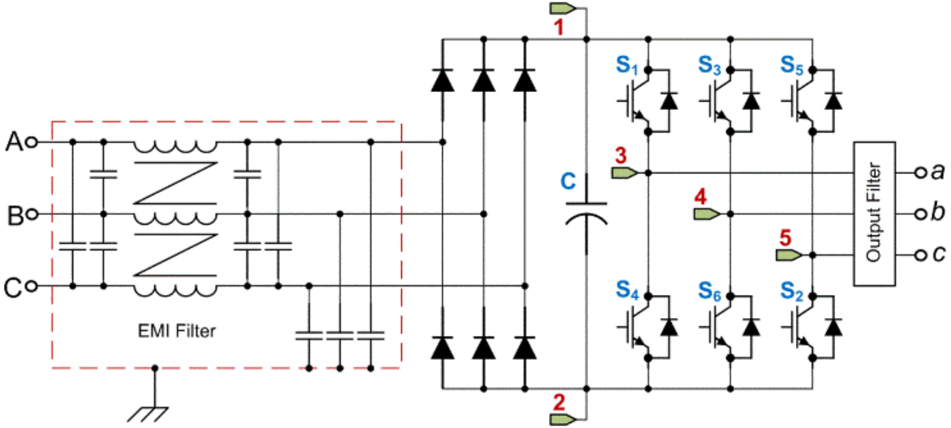
Area under the autocorrelation plot for different fault impedance

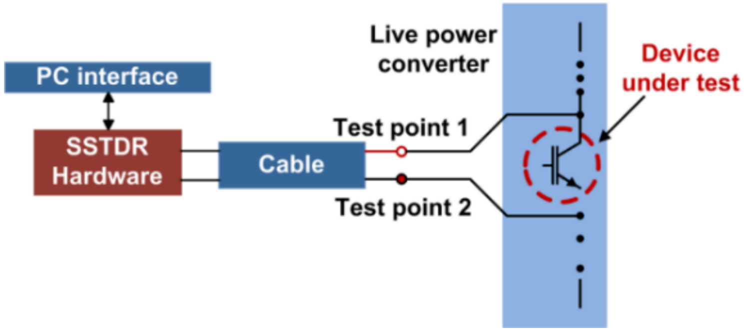
Converter’s Built-In SOH Estimator





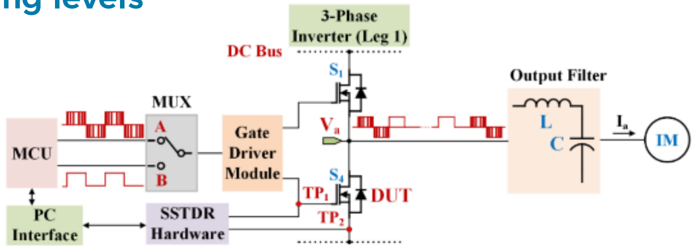
🟥 Input power nodes
🟩 Output power nodes
🟧 Intermediate nodes

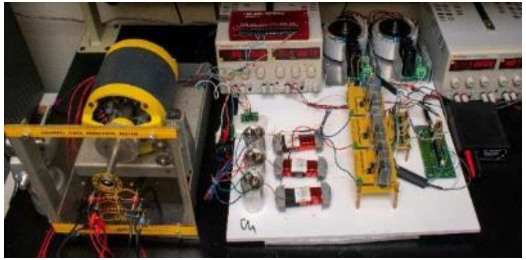


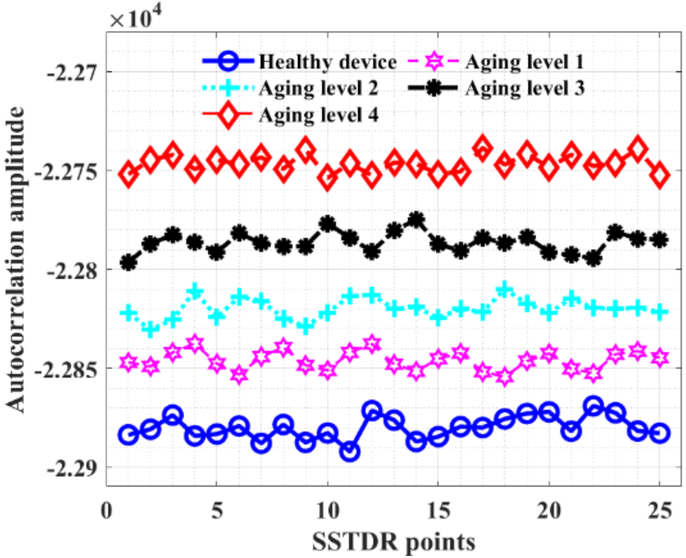


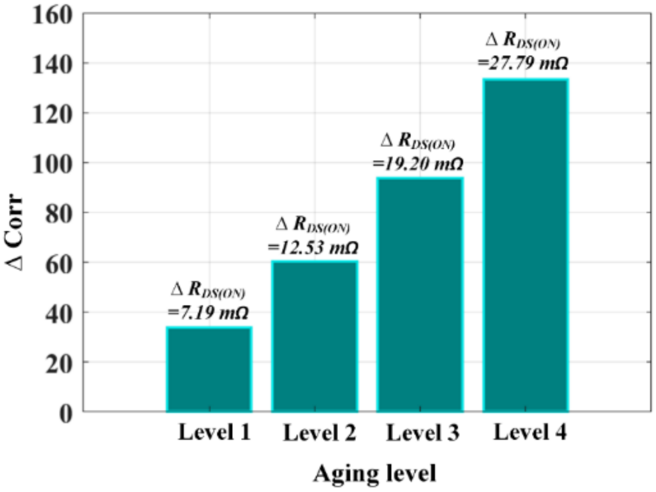
Live Condition Monitoring in a Three-Phase Inverter: 2019

Single device under test (DUT) with multiple aging levels



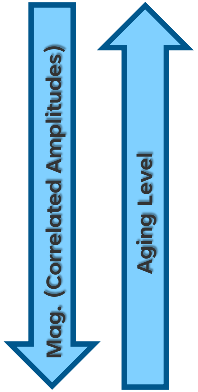




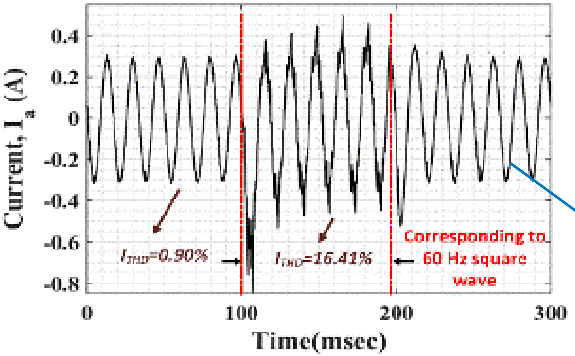


ΔCorr = auto-correlated amplitude − baseline

Aging level 3 > aging level 2 > aging level 1 > healthy device/baseline



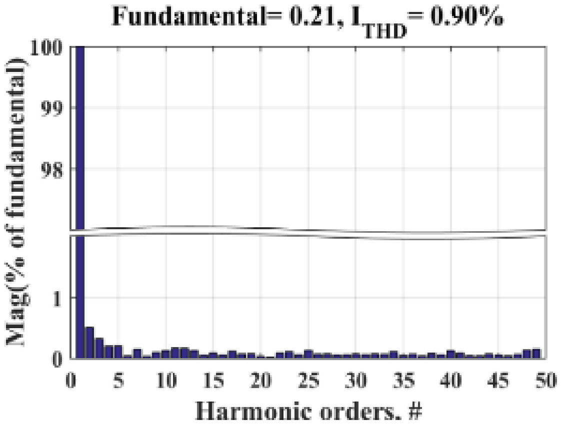
Live Condition Monitoring

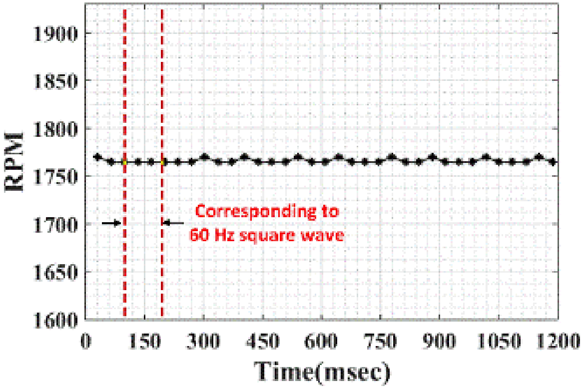


A-phase current

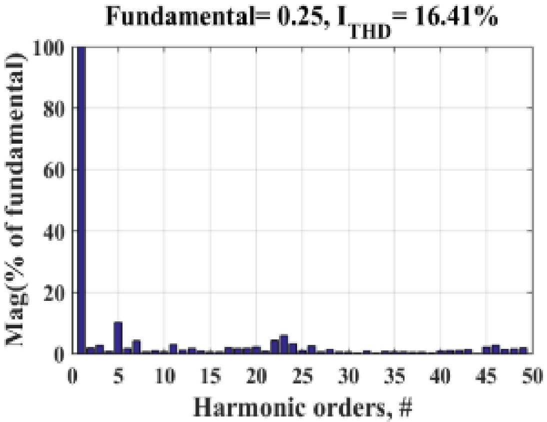
Harmonic Spectra

60 Hz Square Wave Mode





RPM of the Motor

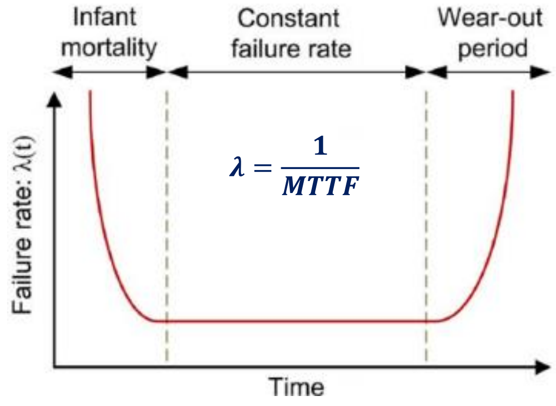


- Current magnitude is high at 60Hz square wave mode, but less than motor start-up current
- Motor Start-up time is way larger than 100 ms time.

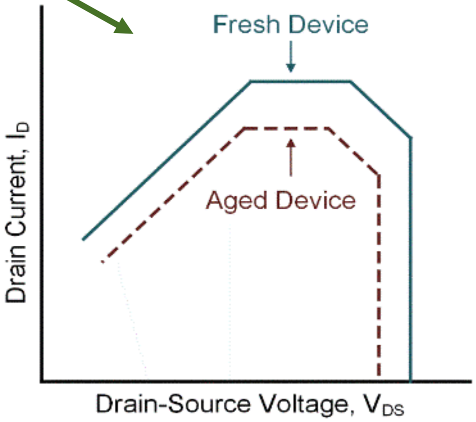
Device Degradation: Dynamic SOA

- Mean time to failure represents the expected life span of the device.
- **Mean time to failure** cannot:
  - Predict unusual circumstances and premature degradation.
  - Answer why reliability of a power switching device drops abruptly beyond a certain time and aging.

The answer lies in the fact that SOA is an age-dependent parameter rather than a constant value.



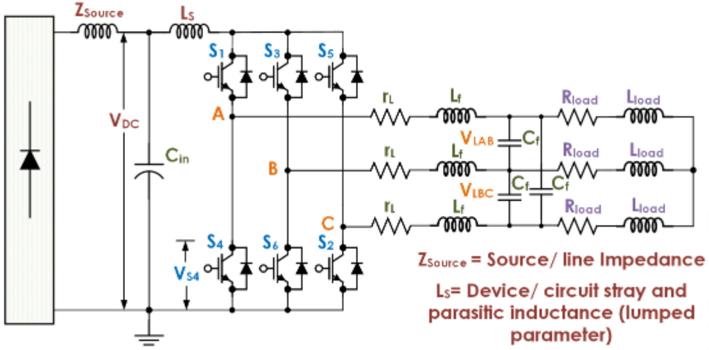
Bathtub curve



25 years old

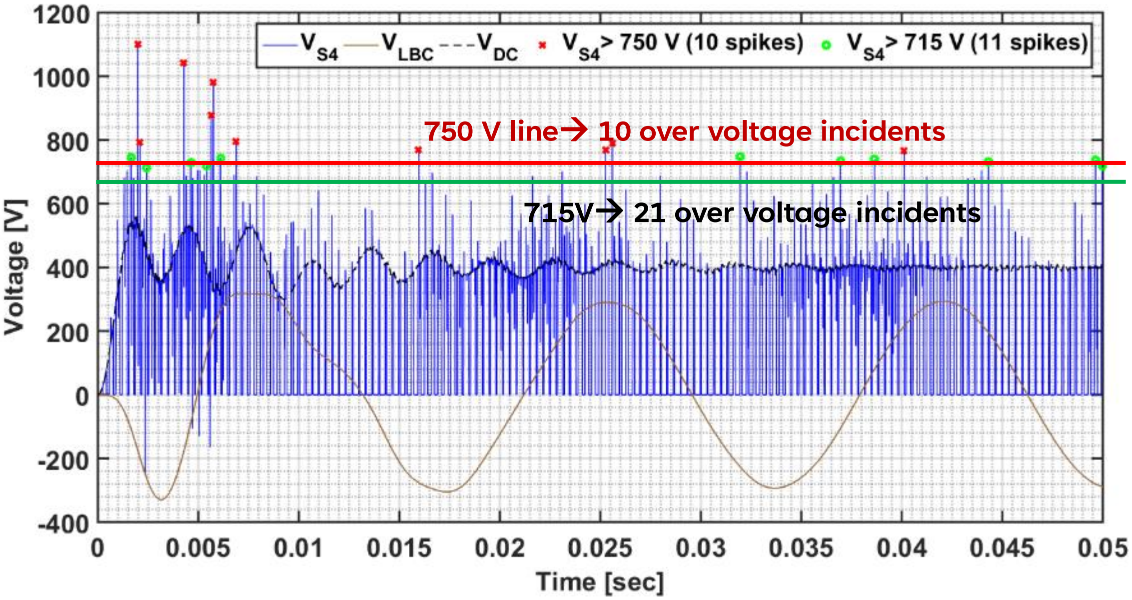
65 years old

A Case Study: SOA to Availability



Z_{Source} = Source/ line Impedance

L_S= Device/ circuit stray and parasitic inductance (lumped parameter)



750 V line→ 10 over voltage incidents

715V→ 21 over voltage incidents

S_4 is fresh, $V_{\text{breakdown, fresh}}$ = 750 V

S_4 is aged, $V_{\text{breakdown, aged}}$ = 715 V

- Fresh S_4 experiences 10 overvoltage situations
- Aged S_4 experiences 21 overvoltage situations

The supply line impedance, along with the circuit/device stray and parasitic inductances, cause considerable voltage spike at the DC bus during inverter operation.

Summary

- PV ground fault detection using reflectometry is challenging because hundreds of interconnections and impedance mismatches exist inside a single PV string.
- The SSTDR algorithm has been successfully used for detecting ground faults in PV arrays.
- We demonstrated the feasibility of using the SSTDR-based algorithm with any variation in the number of strings, fault resistances and number of faults.
- This technique can test ground faults at night or at low illumination that may remain undetected by standard protection device.
- Various online SOH measurement techniques have been presented with experimental results. The industry is yet to adopt a low-cost solution.
- Each technique has own strengths and limitations.
- Live state of health estimation can predict faults before it happens.
- Knowing the dynamic SOA of a device/module is pivotal.

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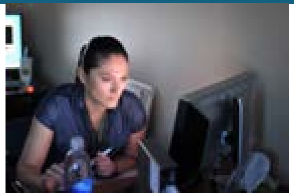
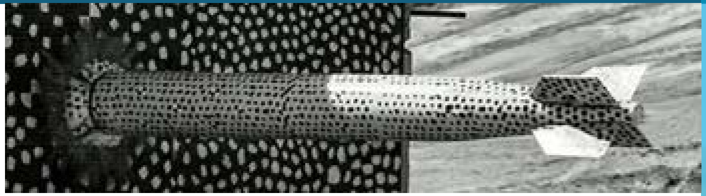
Characterization and survivability analysis of inverter faults through an analysis of O&M records





Thushara Gunda

Photovoltaics Inverter Reliability Workshop

April 2024

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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Chris McNalley (CMS Energy)
David Petrie (CMS Energy)
Yang Hu (GE Renewable Energy)

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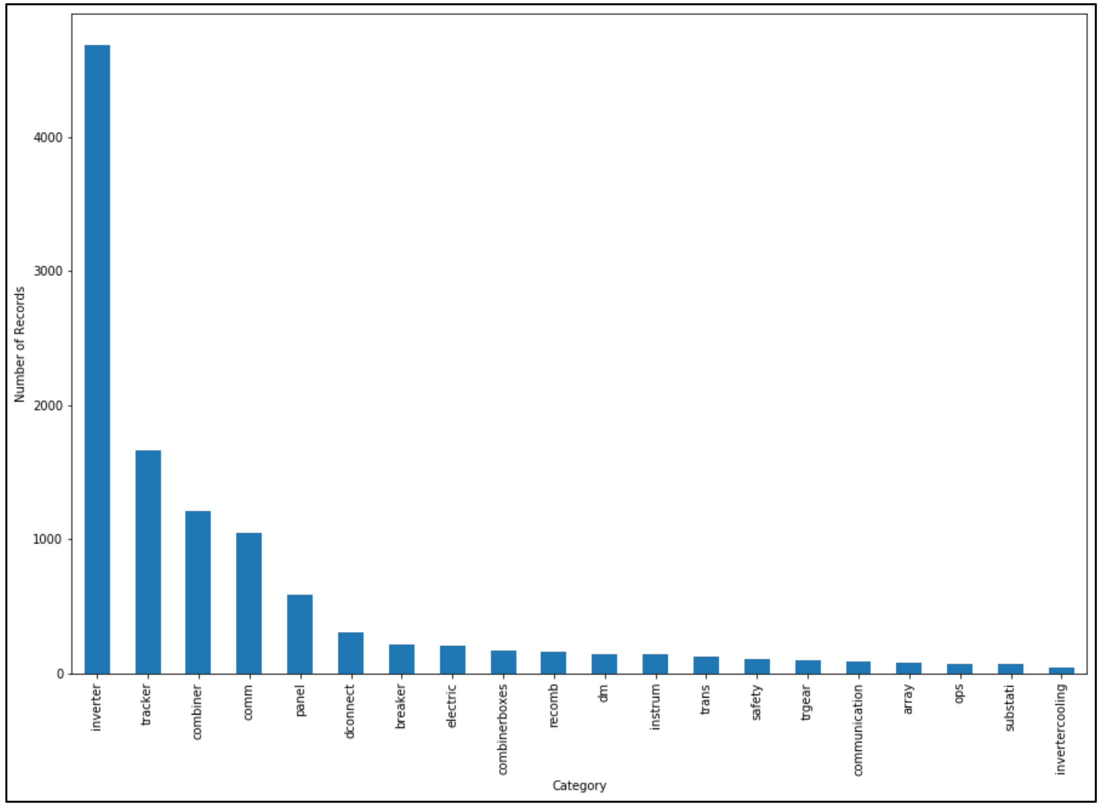
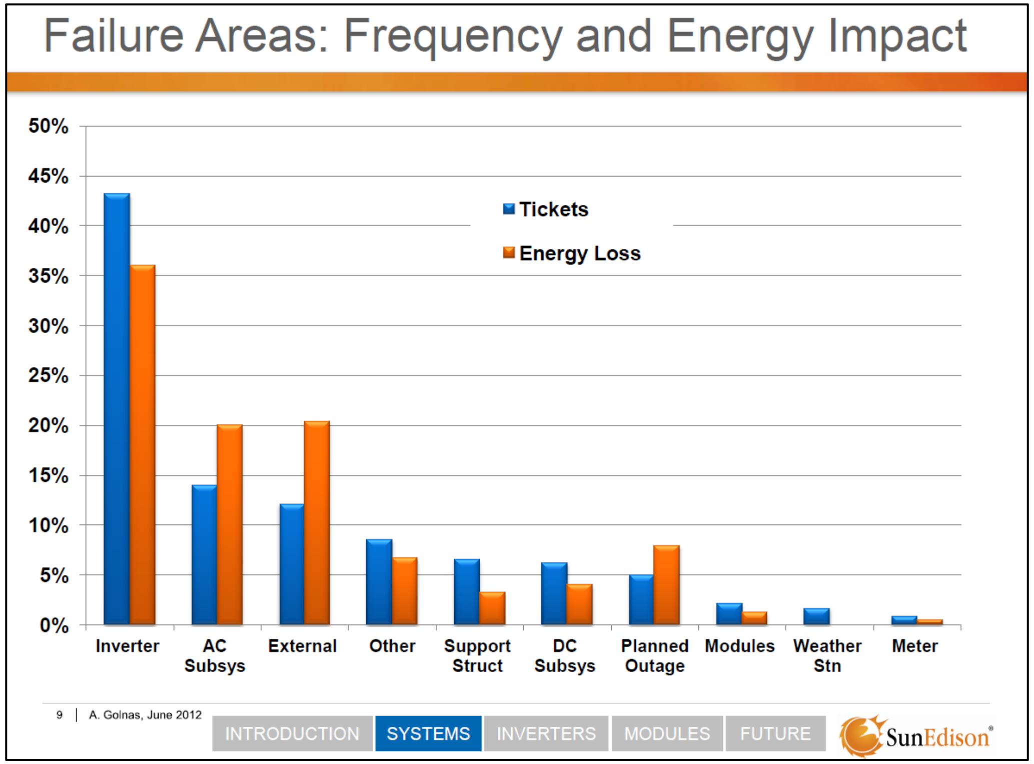
Inverters dominate failures

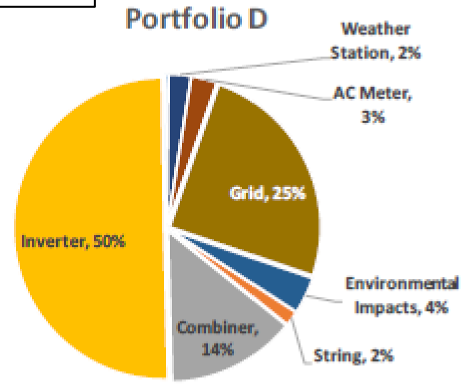


EPRI (2019)


Failure Areas: Frequency and Energy Impact

Golnas (2012)

- Multiple research studies have highlighted the prevalence of inverter failures
- Costs of inverter repairs and replacement also dominate O&M budgets (SEPA, 2019))



Component event percentages for Portfolio D

Freeman et al (2018)

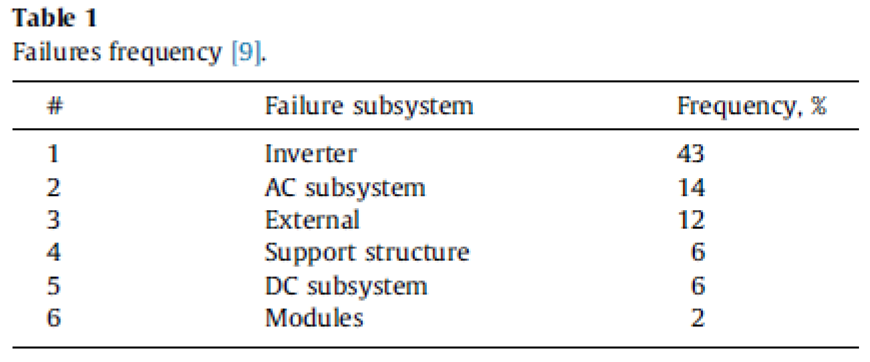


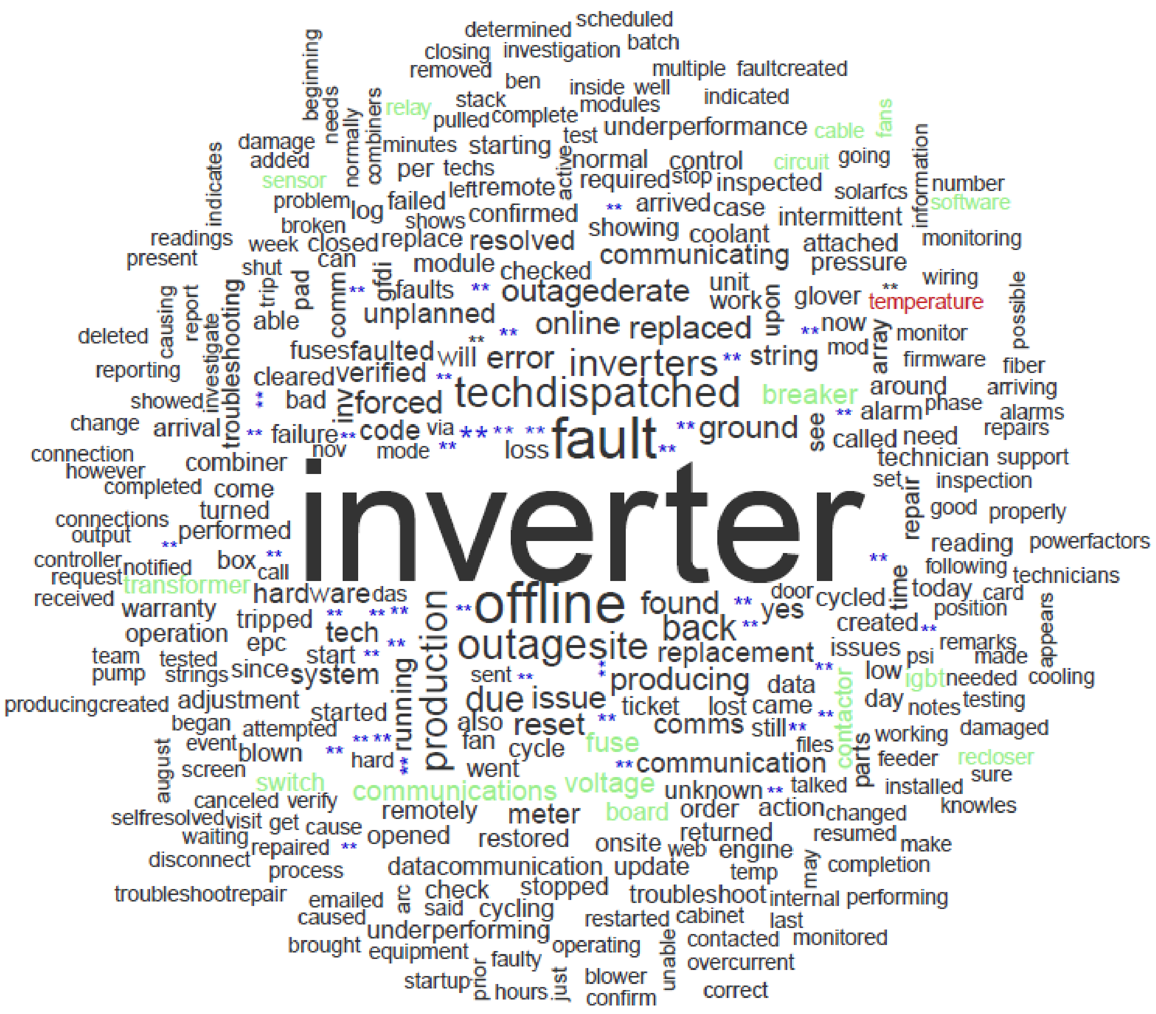
Table 1
Failures frequency [9].

#	Failure subsystem	Frequency, %
1	Inverter	43
2	AC subsystem	14
3	External	12
4	Support structure	6
5	DC subsystem	6
6	Modules	2

Cristaldi et al (2015)

Text-based records

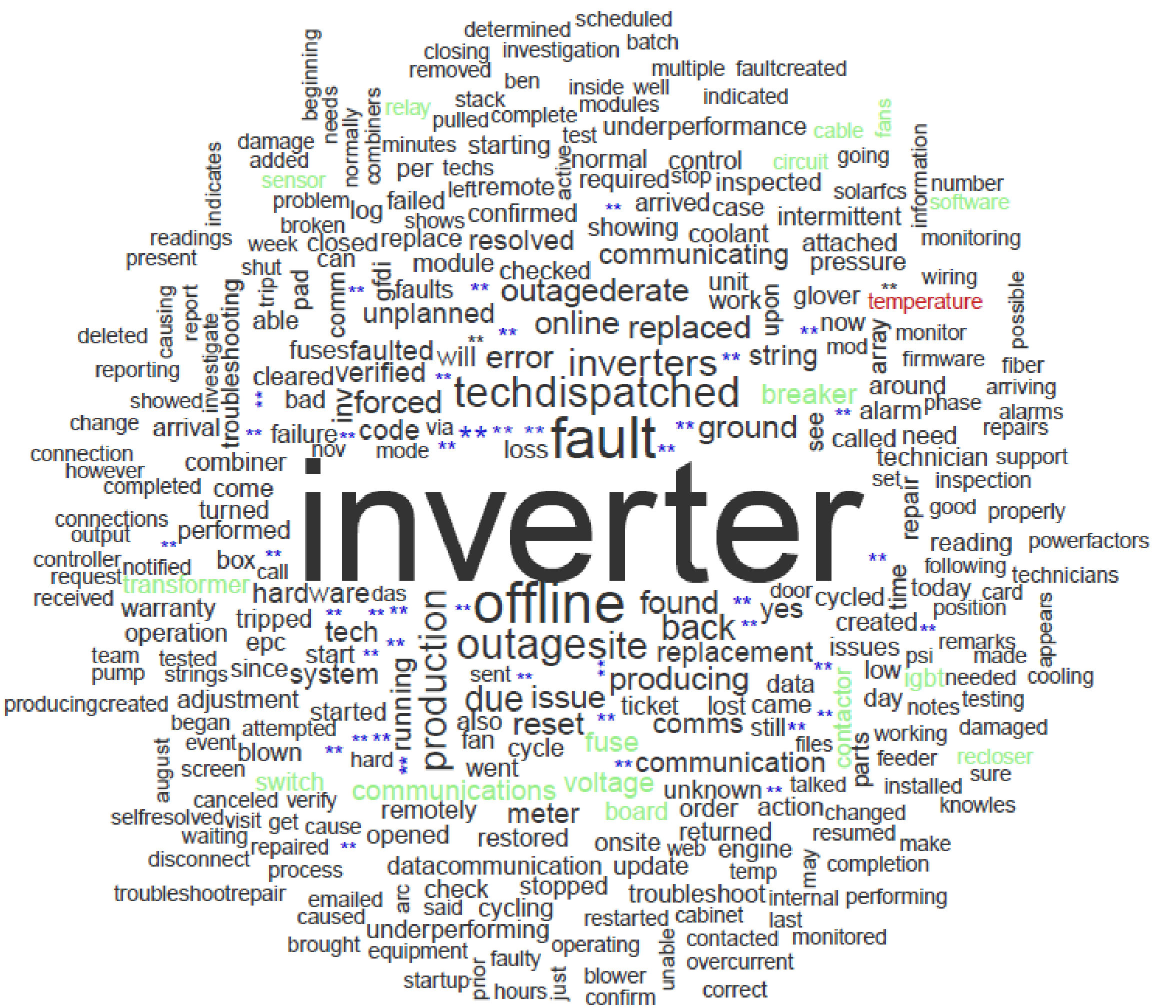
- Understanding of inverter failures is most commonly sourced from text-based records
  - Computer maintenance management systems (CMMS)
  - Annual performance reports
- These text records often have:
  - Common elements (e.g., site location, time, and description)
  - Varying levels of detail
- Often restricted to individual plants or individual company's fleet
- Systematic evaluation of content can be facilitated by machine learning (ML) and natural language processing (NLP) techniques



Common terms in tickets
Component/subsystems
Weather terms
proprietary terms

Study Objectives

- Analysis of maintenance logs to identify most common failures modes within inverters
- Identification of patterns and differences across climate, equipment, and other factors

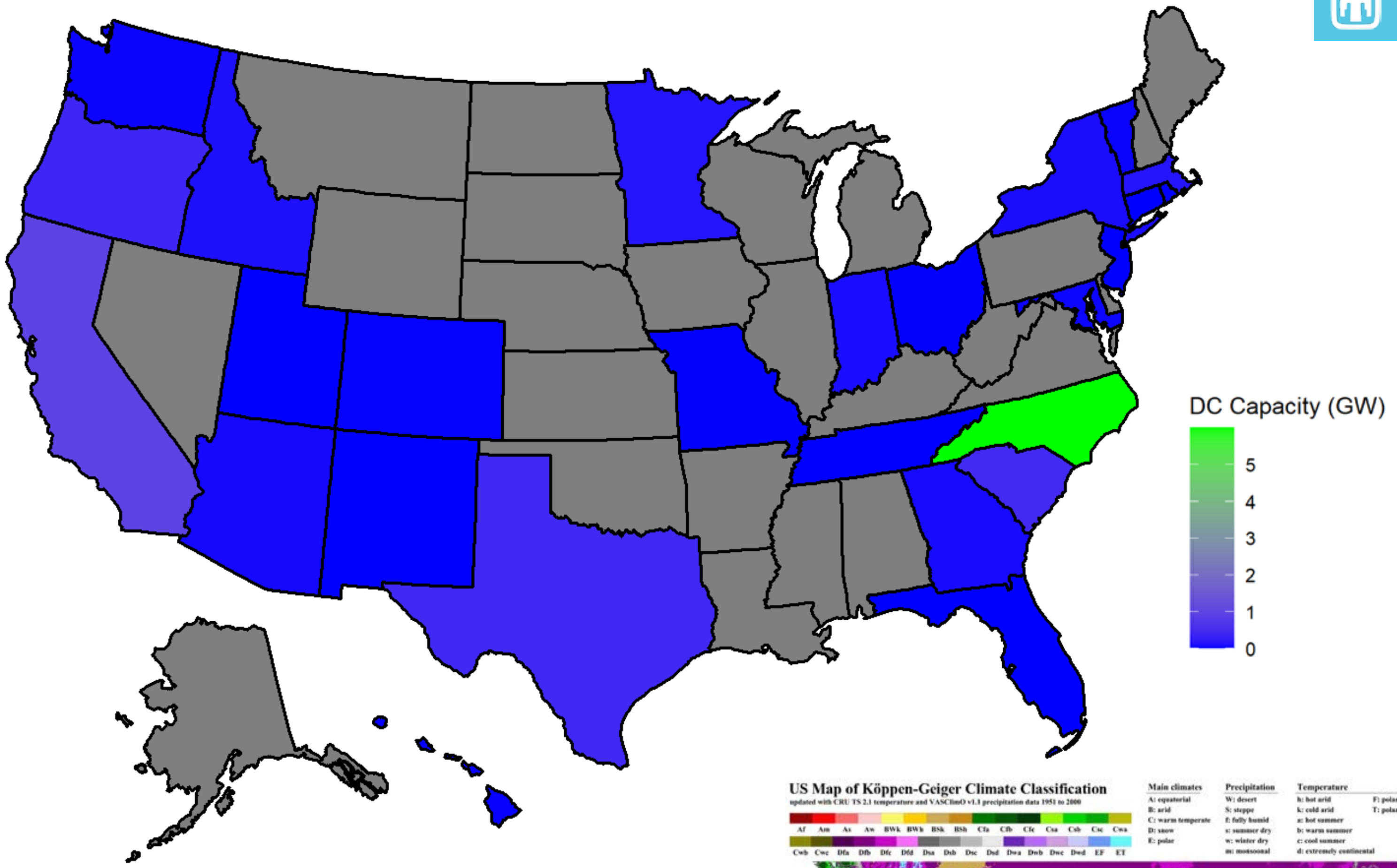


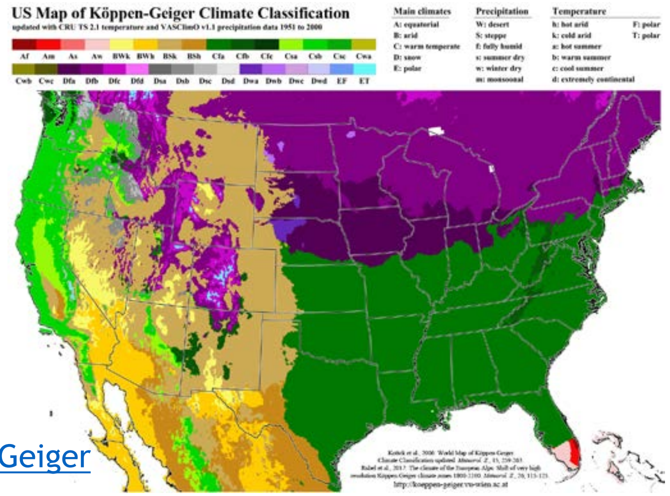
Dataset

Leveraged Sandia's PVROM and EPRI's partner databases

55K records (97% Corrective)

- 6 industry partners
- 880 sites (2008-2019 COD)
- 80% utility-scale
- 5.2 GW in DC Capacity (4.0 AC
- 26 U.S. states
- 13 climate zones
- Central inverter-type dominated





Koppen-Geiger

Analysis Methodology

- Analysis leveraged ML, NLP, and statistical techniques
- ML (support vector machines) was used to identify relevant inverter records
- NLP (Latent Dirichlet Allocation) was used to identify common failure modes
- Statistical technique (survival analysis) was used to characterize failure frequencies

Collection of O&M Records

SVM

Inverter-related Records

LDA

hardware
replacement
offline
…

ground
fault
wiring
…

power
cycle
supply
…

Identify Topics: Clusters of Words

Inverter cycling due to hardware malfunction. Power cycle.

hardware

power cycle

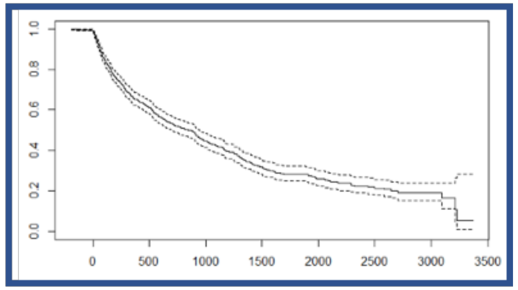
Inverter #4 down. AC fuse replaced. 24 volt power supply replaced.

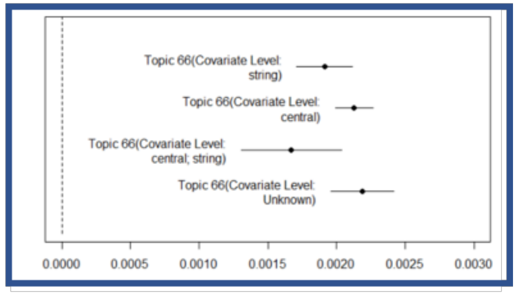
fuse

power supply

Identify Distribution of Topics in Inverter-related Records

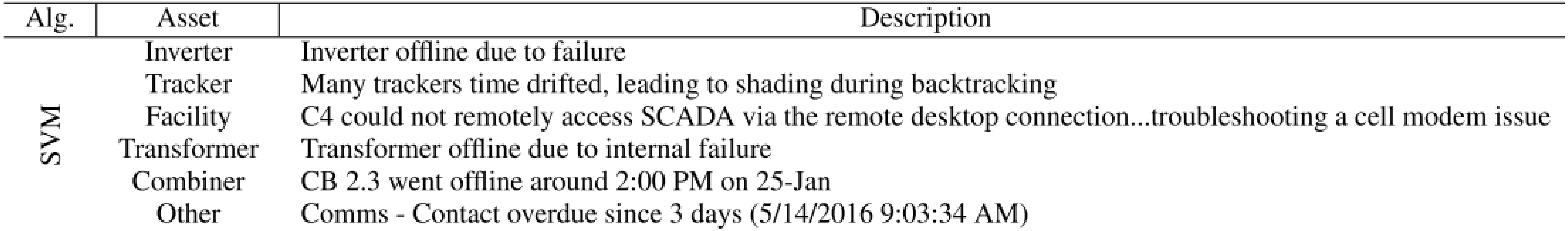
Data Analysis





Inverter Records

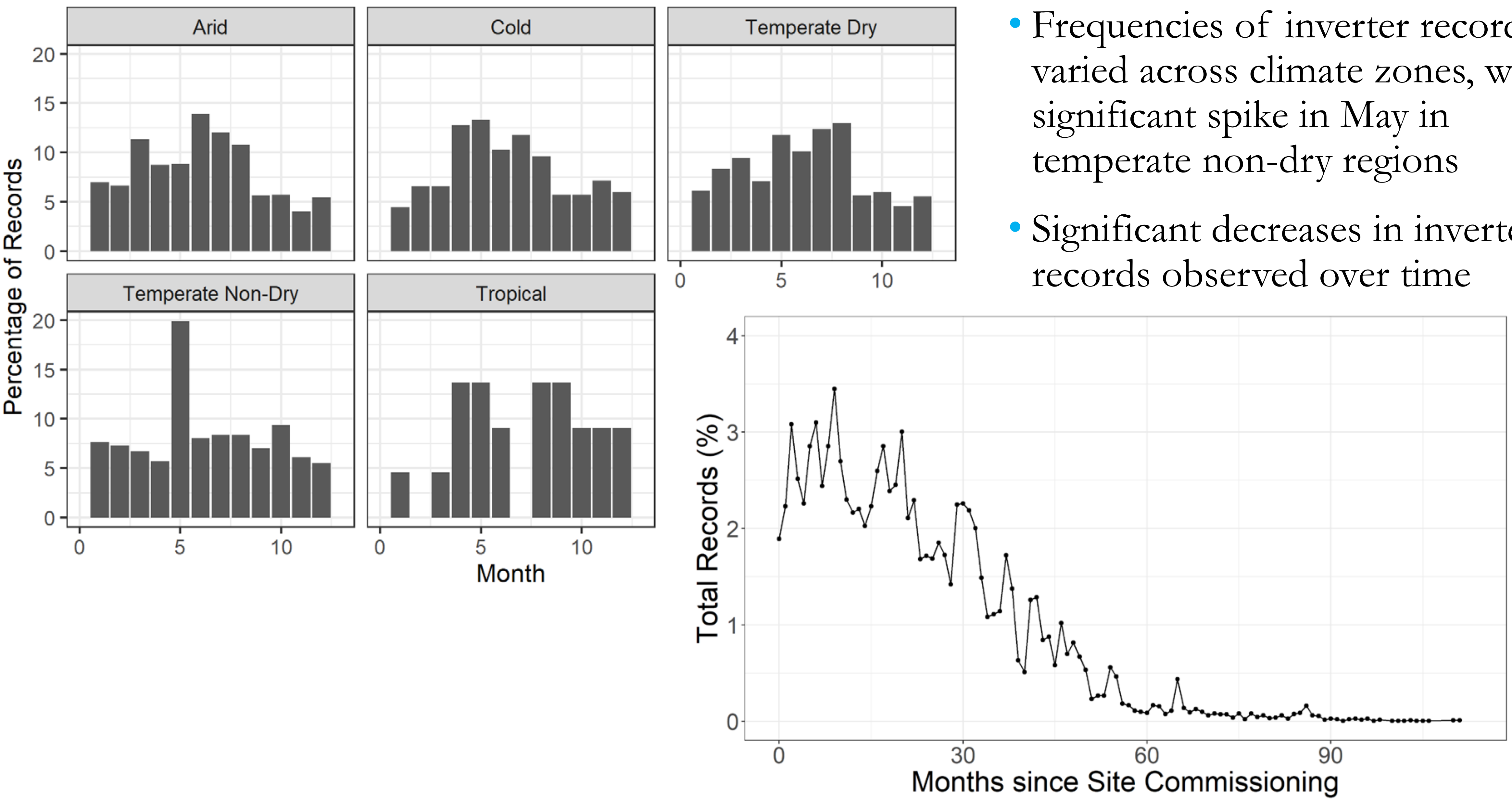
- Multiple records (~8K, 15%) lacked an asset label
- Supervised ML was used to gap-fill these entries
  - Converted text to term frequency-inverse document frequency representations
  - Implemented support vector machine algorithm to generate missing entries
  - 80-20 train-test split
- Post-implementation, approximately 1/3 of the total records were related to inverters (~18K)



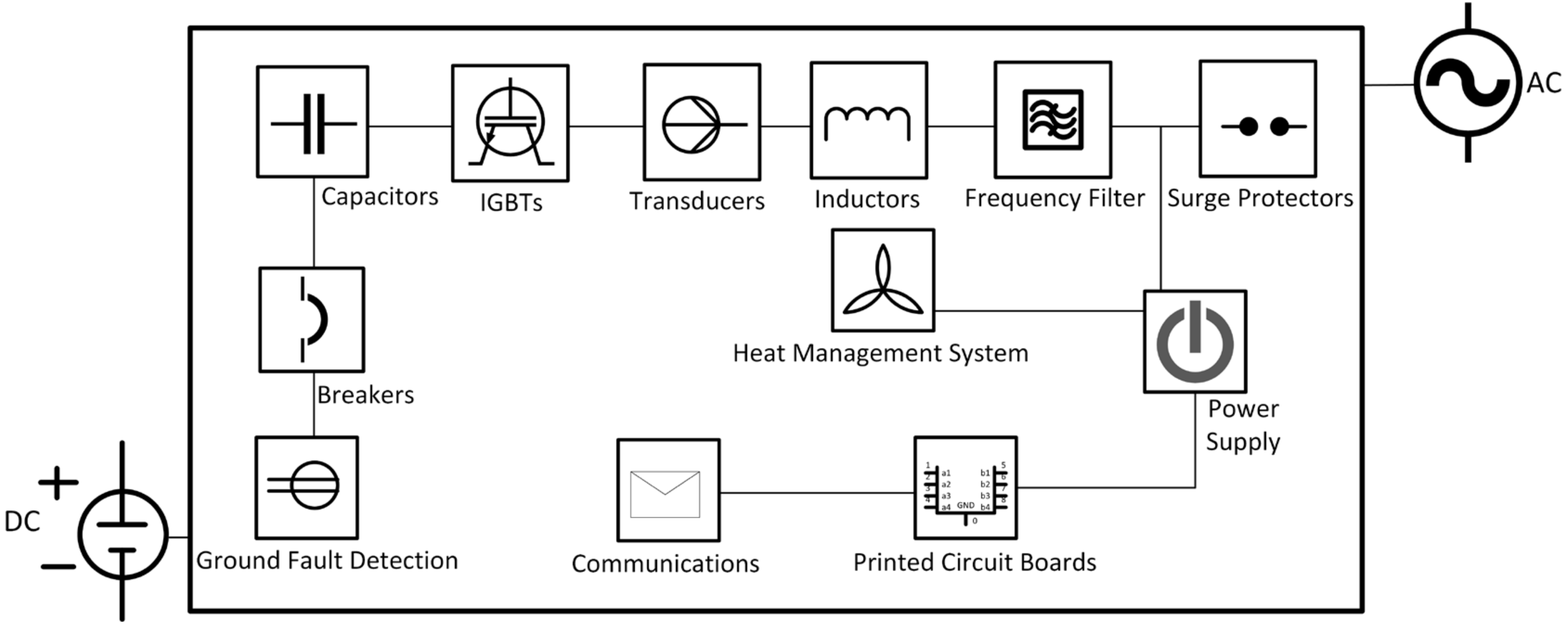
Alg.	Asset	Description
SVM	Inverter	Inverter offline due to failure
	Tracker	Many trackers time drifted, leading to shading during backtracking
	Facility	C4 could not remotely access SCADA via the remote desktop connection...troubleshooting a cell modem issue
	Transformer	Transformer offline due to internal failure
	Combiner	CB 2.3 went offline around 2:00 PM on 25-Jan
	Other	Comms - Contact overdue since 3 days (5/14/2016 9:03:34 AM)

Inverter Record Patterns

- Frequencies of inverter records varied across climate zones, with significant spike in May in temperate non-dry regions
- Significant decreases in inverter records observed over time



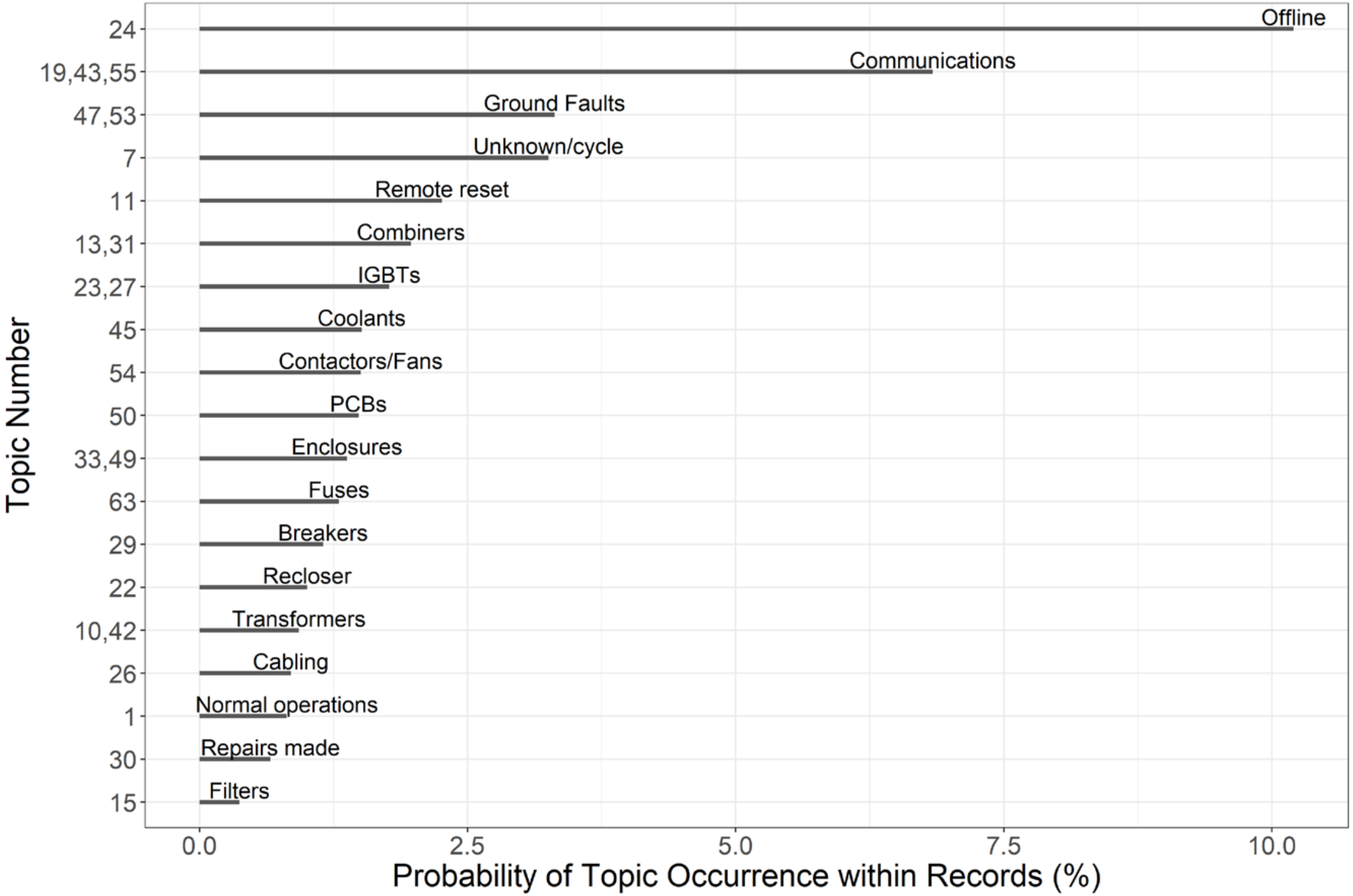
Inverter Components



- Multiple interconnected components make up an inverter
- Additional components may be external to inverter (cabling, recloser) or systems-level (software, communications)

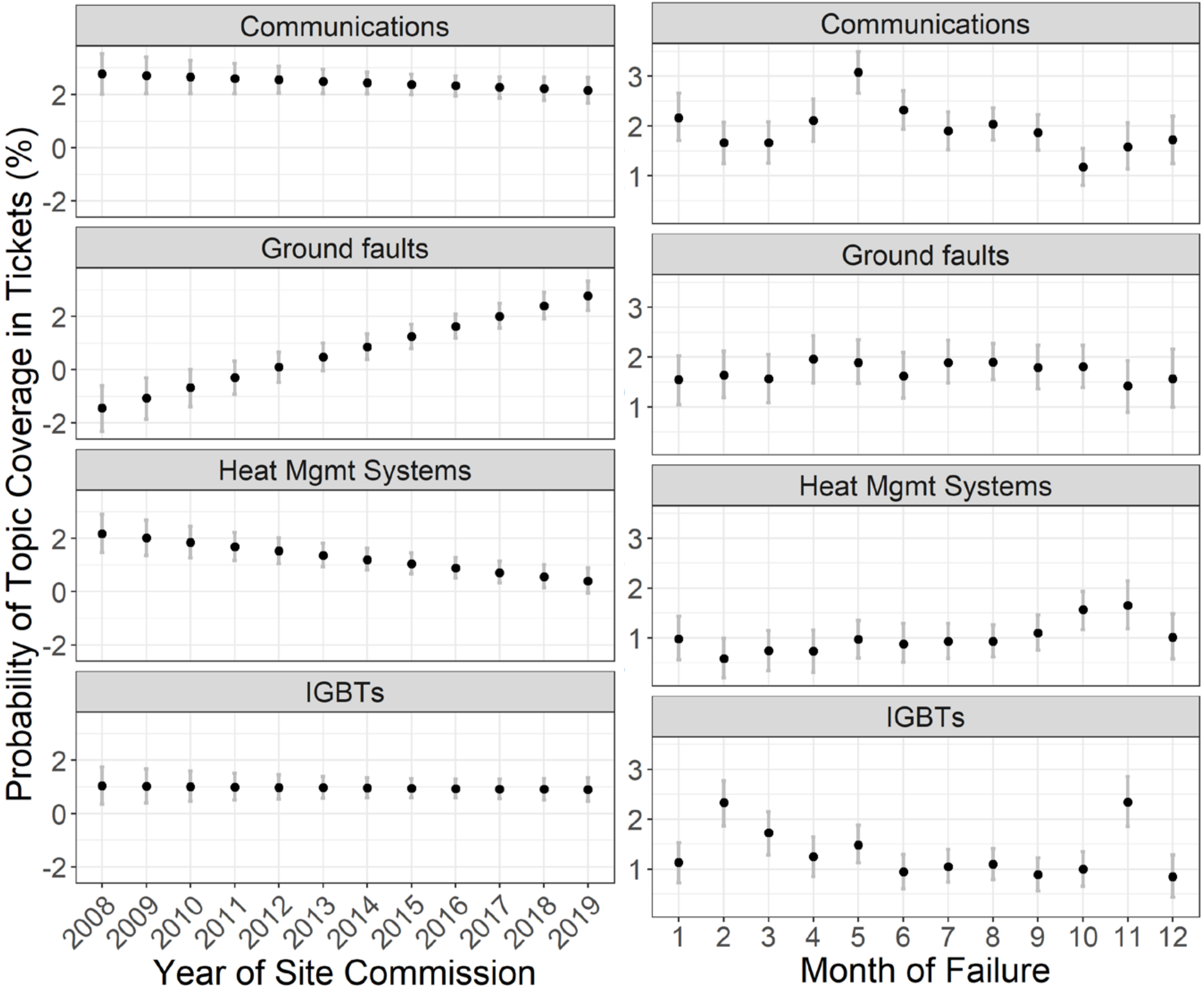
Common Failure Modes

- Latent Dirichlet Allocation (~unsupervised ML) can be used to group similar entries into "topics"
- Topics were manually reviewed and assigned labels
- Some topics captured general description of issues (e.g., offline) or resolutions (e.g., unknown/cycle)
- A number of topics pertained to specific inverter components (e.g., communications, ground faults)

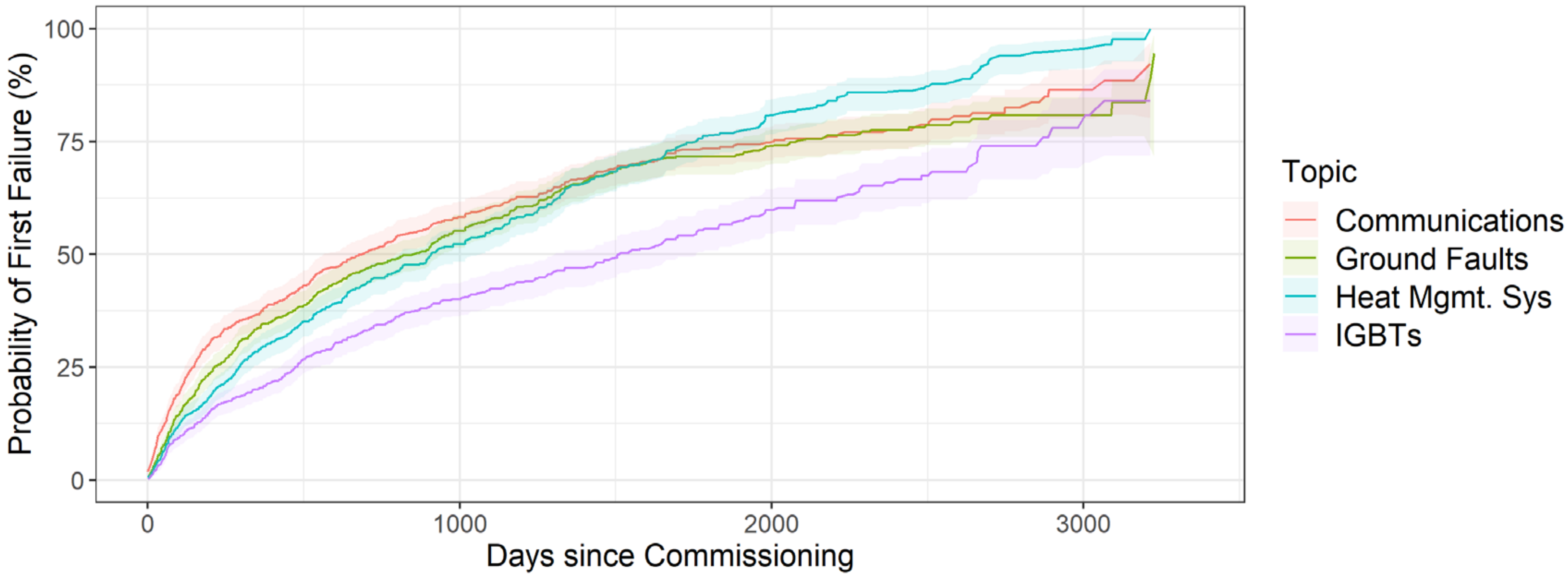


Topic Patterns

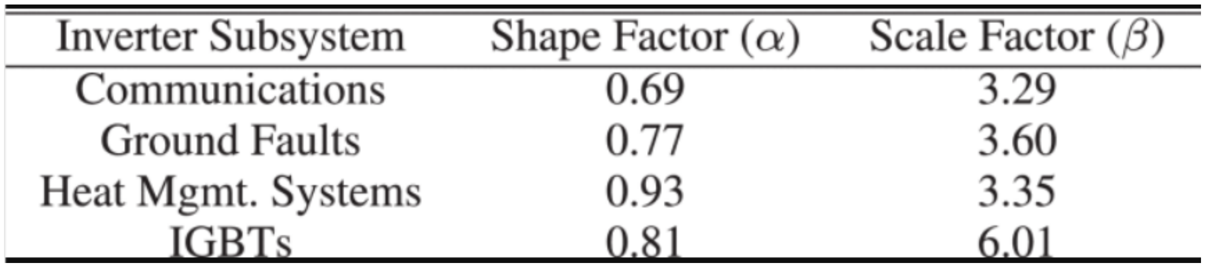
- Evaluated topic prevalence over time
- Across years:
    - Ground fault-related tickets have greatly increased
    - Communications-related tickets and insulated gate bipolar transistors (IGBTs) have held steady
    - Heat management systems-related tickets (i.e., coolants, fans, filters) have decreased
- Different seasonal patterns also emerged (e.g., communications tickets peak in May while heat management tickets peak in November)



Survival Analysis: Likelihood of First Failure

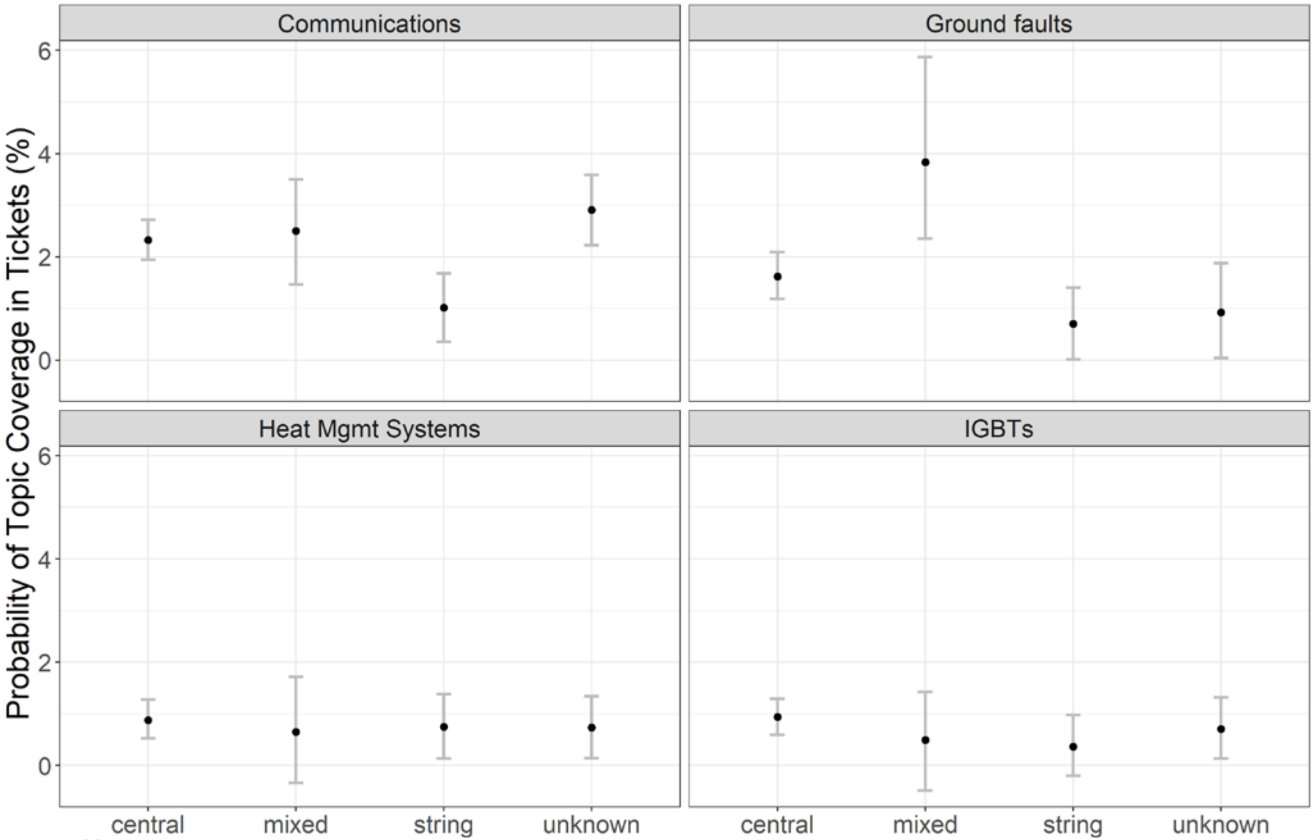


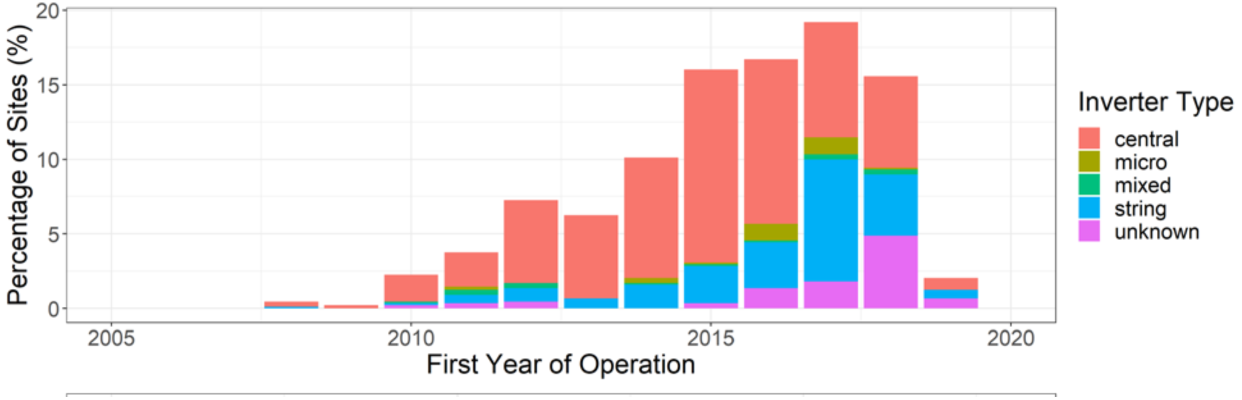
- Kaplan-Meier estimator (non-parametric) and Weibull (parametric) methods were used to characterize first occurrence of component failures
- Communication systems are most common for first two years, but after 9 years, heat management systems are most prevalent



Inverter Subsystem	Shape Factor (α)	Scale Factor (β)
Communications	0.69	3.29
Ground Faults	0.77	3.60
Heat Mgmt. Systems	0.93	3.35
IGBTs	0.81	6.01

Variations across Inverter Types



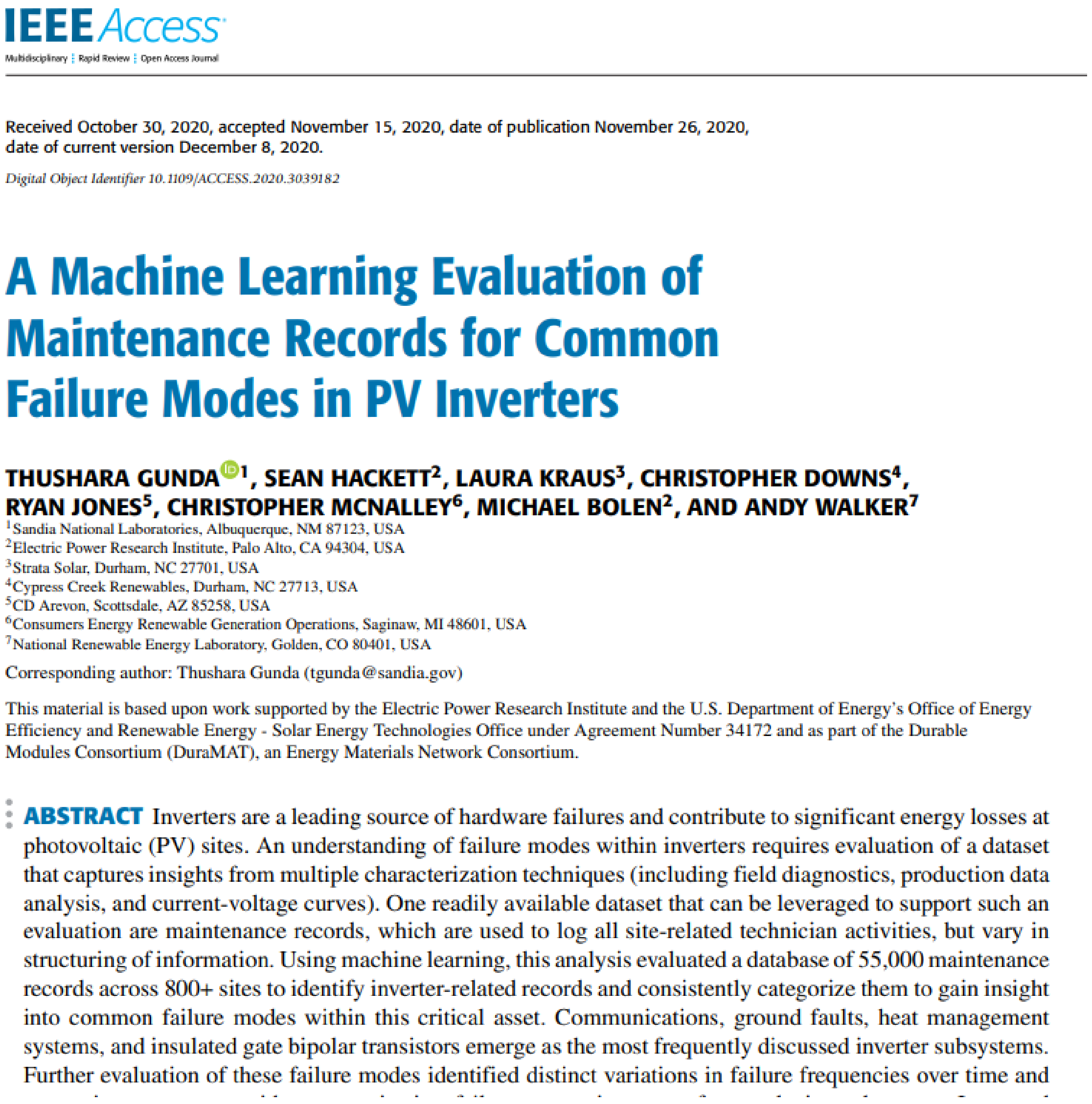


- Variations in ticket frequencies across inverter types (e.g., ground faults are most common in mixed inverter sites)
- Hard to ascertain representative nature of patterns, given the:
  - Dominance of central inverters
  - Changing patterns in inverter installations over time
  - Confounding factors: installation quality, changing technologies, differences in geographies, ….

Future Work

- Update datasets analyzed to consider more sites and technologies
- Implement additional algorithms to extract more insights
  - Relationship extraction
  - Sentence sequences
  - Foundational models
- Expand pattern analysis across production and financial information
  - Continued development of open-source software supporting text-to-time series fusion, [pvOps]
  - Develop benchmarks for data collection and performance

Open-Access Publication



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A Machine Learning Evaluation of Maintenance Records for Common Failure Modes in PV Inverters

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ABSTRACT Inverters are a leading source of hardware failures and contribute to significant energy losses at photovoltaic (PV) sites. An understanding of failure modes within inverters requires evaluation of a dataset that captures insights from multiple characterization techniques (including field diagnostics, production data analysis, and current-voltage curves). One readily available dataset that can be leveraged to support such an evaluation are maintenance records, which are used to log all site-related technician activities, but vary in structuring of information. Using machine learning, this analysis evaluated a database of 55,000 maintenance records across 800+ sites to identify inverter-related records and consistently categorize them to gain insight into common failure modes within this critical asset. Communications, ground faults, heat management systems, and insulated gate bipolar transistors emerge as the most frequently discussed inverter subsystems. Further evaluation of these failure modes identified distinct variations in failure frequencies over time and

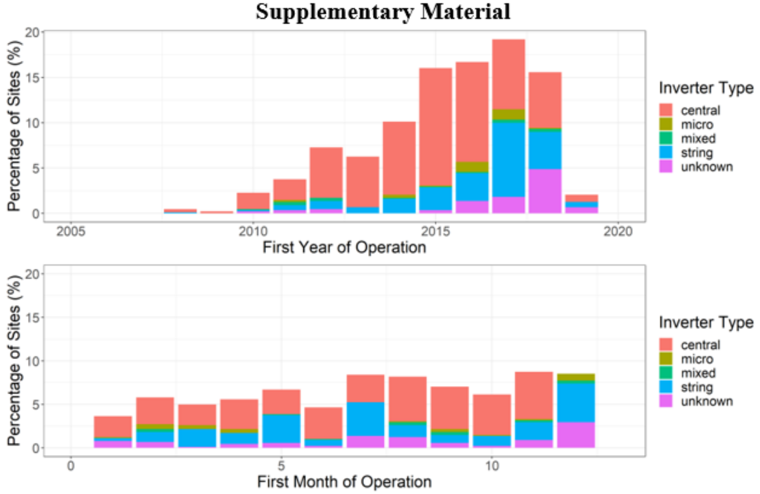

Figure A1. Commissioning dates of sites within database by year (A) and by month (B). Most of the sites have come online in the last 5 years. Sites with string inverters have been more frequent in recent years and concentrated in December.

Gunda, T., Hackett, S., Kraus, L., Downs, C., Jones, R., McNalley, C., ... & Walker, A. (2020). A machine learning evaluation of maintenance records for common failure modes in PV inverters. *IEEE Access*, 8, 211610-211620. DOI: 10.1109/ACCESS.2020.3039182

Thank you for your time!

Thushara Gunda

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PV Inverter Availability from the US PV fleet

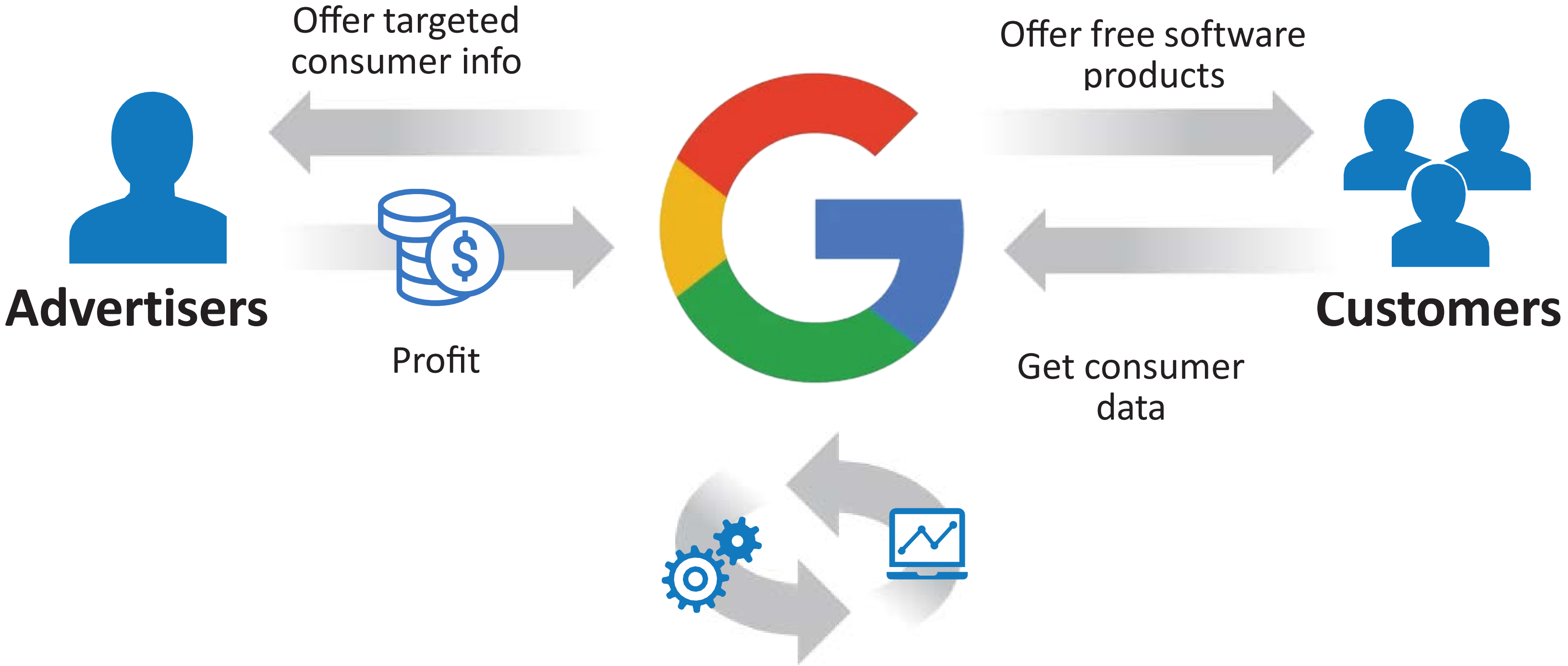
Reliability of PV Inverters Workshop, April 12, 2024

Chris Deline with content from Dirk Jordan, Kirsten Perry, Michael Deceglie, Robert White & Kevin Anderson (Sandia)

Agenda

- PV Fleet Data Initiative
  - Introduction
  - Methodology
  - System / inverter availability trends
- Treasury 1603 Dataset (2009-2016)
  - Pareto of logged issues and lost energy

Business Plan - Analogy



Offer targeted consumer info

Offer free software products

Advertisers

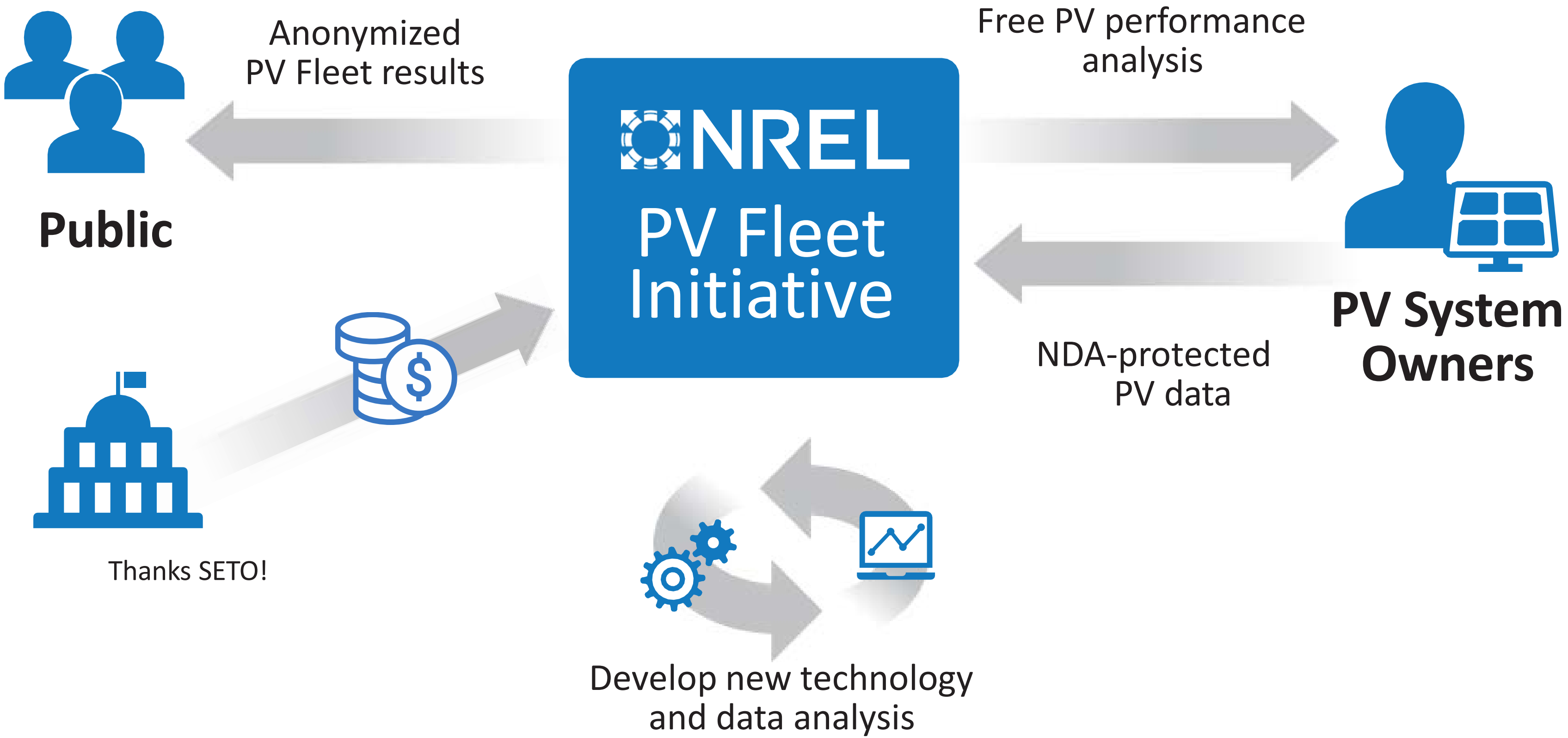
Customers

Profit

Get consumer data

Develop new technology and data analysis

Business Plan - Analogy



Public

Anonymized
PV Fleet results

NREL
PV Fleet Initiative

Free PV performance
analysis

NDA-protected
PV data

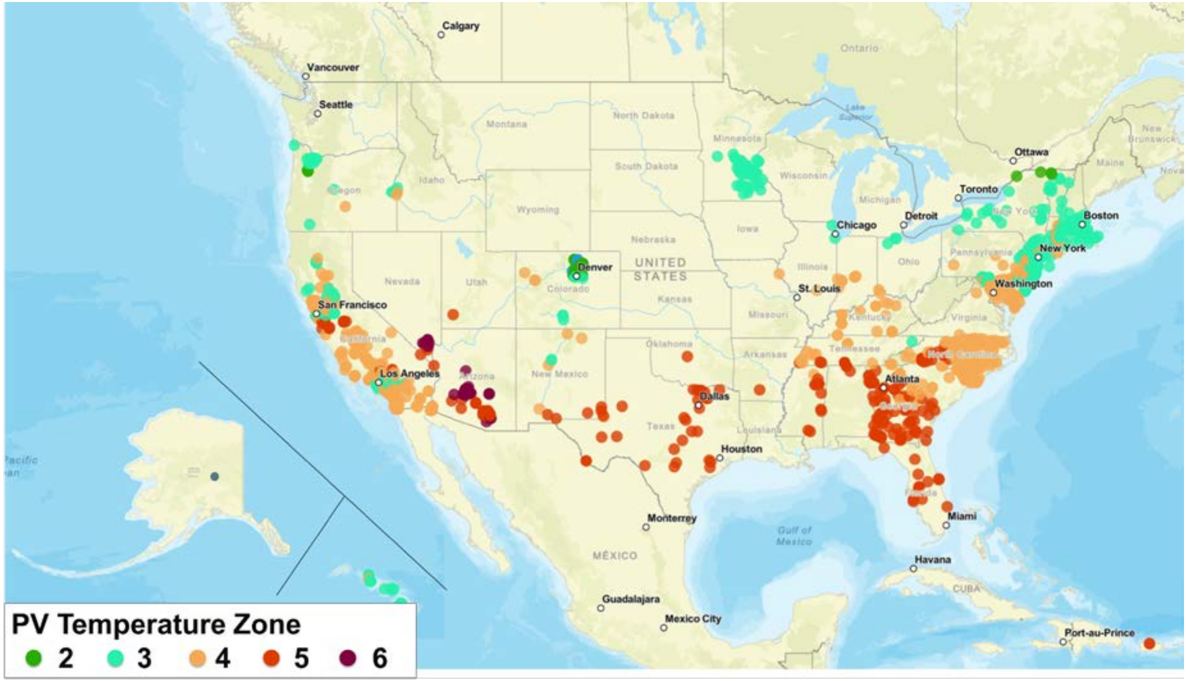
PV System Owners

Thanks SETO!

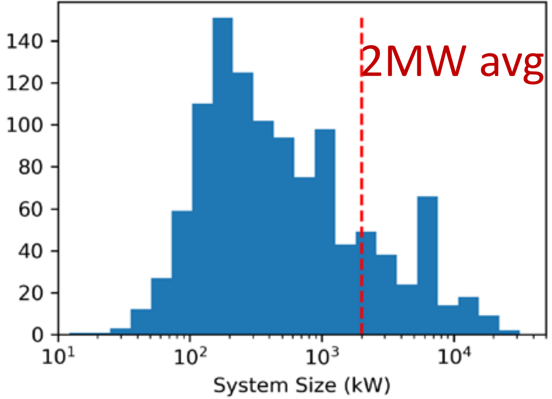
Develop new technology
and data analysis

PV Fleet Performance Data Initiative

>2200 systems, > 24,000 Inverters, >8.5 GW capacity



System power distribution



Mean system age: ~4.6 yrs

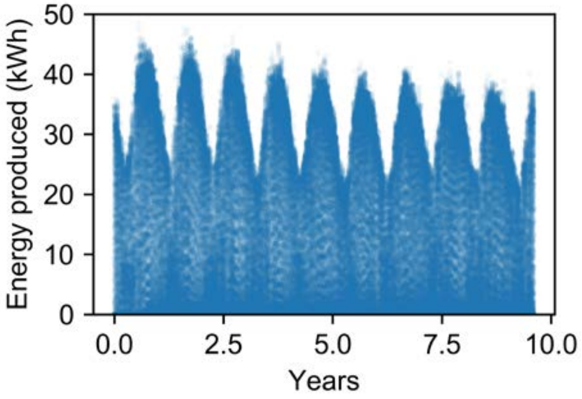
Deline et al., PVSC 2021

Temperature zones: Karin 2019

PV Field Performance

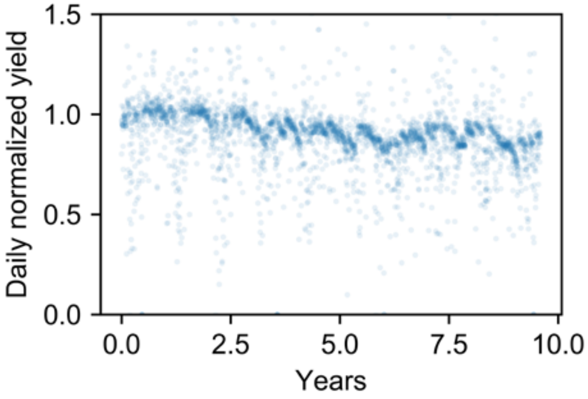
- PV power is a factor of irradiance & temperature
- Real data is messy (outages, instrumentation errors)
- Many systems -> automated analysis & data filtering

Raw energy time series



0. Data quality check
1. Normalize to model
2. Filter
3. Aggregate

Daily normalized energy yield

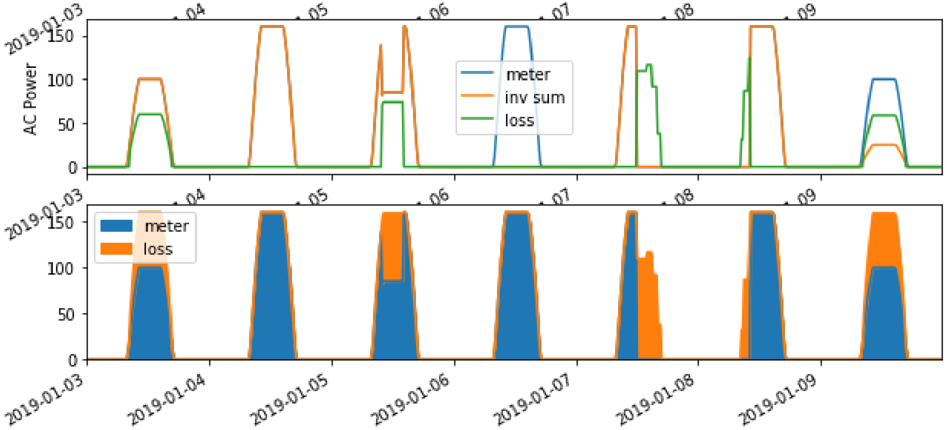


github.com/pvlib/pvanalytics

www.nrel.gov/pv/rdtools.html

Inverter availability analysis in RdTools

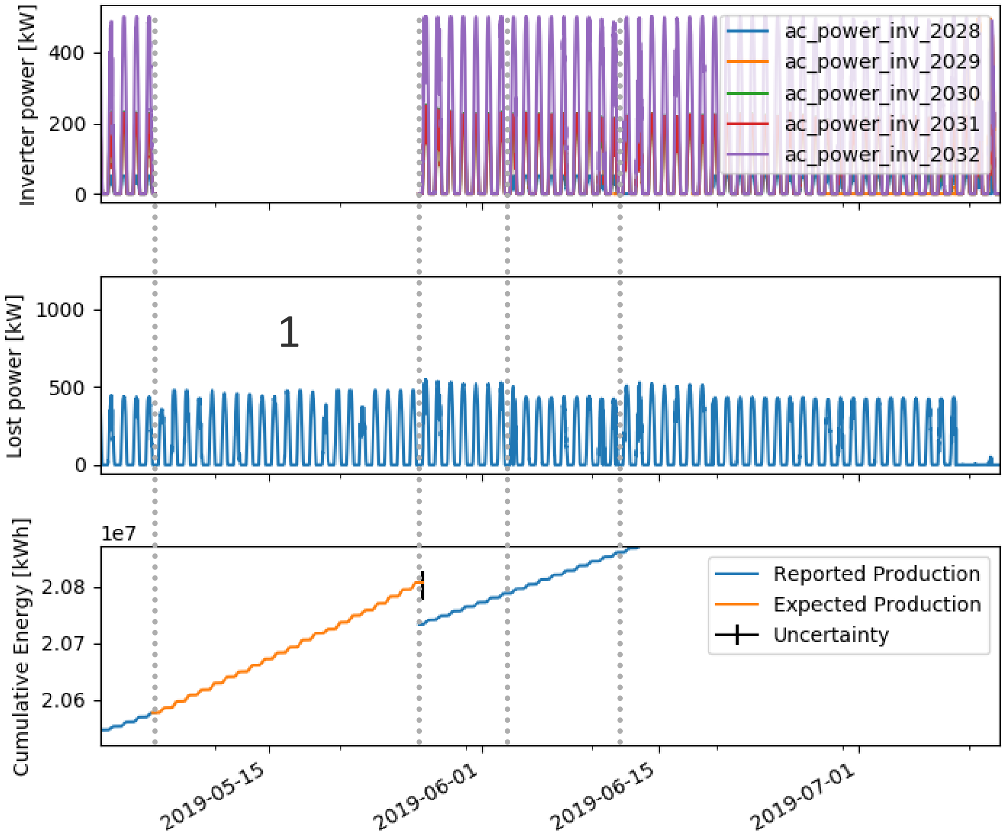
- Availability analysis conducted using RdTools.availability
- Goal: Autonomous quantification of lost energy from inverter downtime
- Compare inverters vs nearest neighbors and identify times of zero production at the subsystem-level
- Availability calculated as an energy-weighted (not time-weighted) value and rolled up monthly per system



- K. Anderson, R Blumenthal "Overcoming Communications Outages in Inverter Downtime Analysis", 47th IEEE PVSC, 2020
- nrel.gov/pv/rdtools.html

Inverter availability analysis – comms outage

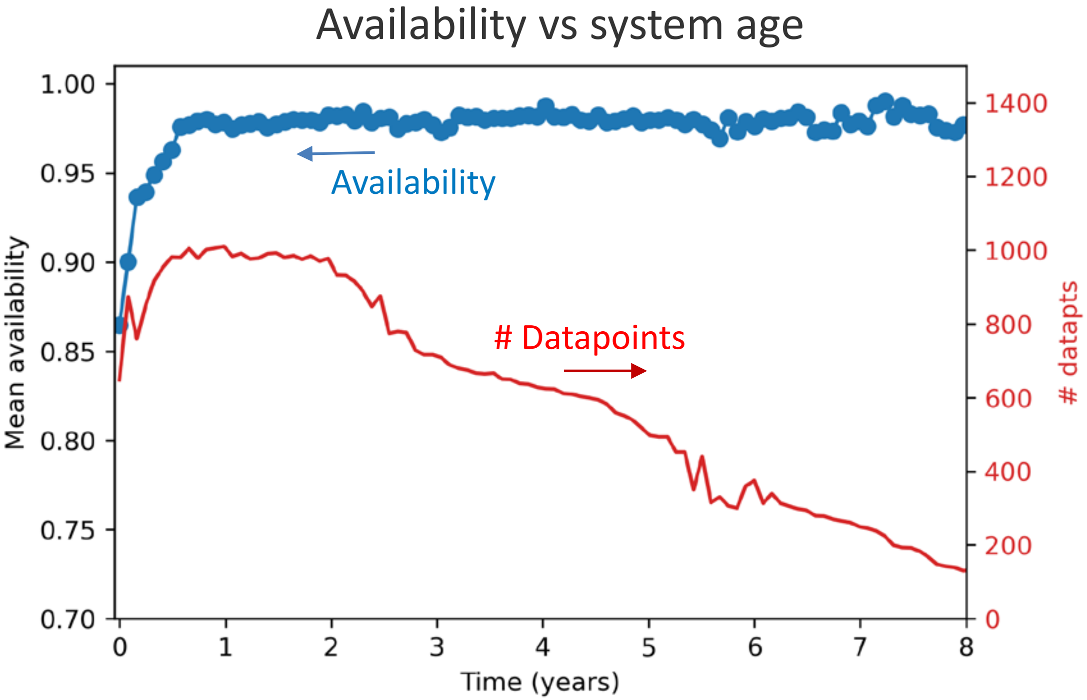
- Algorithm must be robust to communication outages/missing data to not bias lost energy estimates.
- Communication outage (period 1): compare cumulative meter energy with expected.
- A difference in actual vs expected energy during this period can be attributed to availability loss



K. Anderson, R Blumenthal "Overcoming Communications Outages in Inverter Downtime Analysis", 47th IEEE PVSC, 2020

Availability over System Lifespan

- Availability assessed for 1128 high-quality systems, grouped by time since t0
- Steady-state reached after first year, 97.9% avg availability
- Start-up phase in first 6 months shows lower availability (80%-90%)

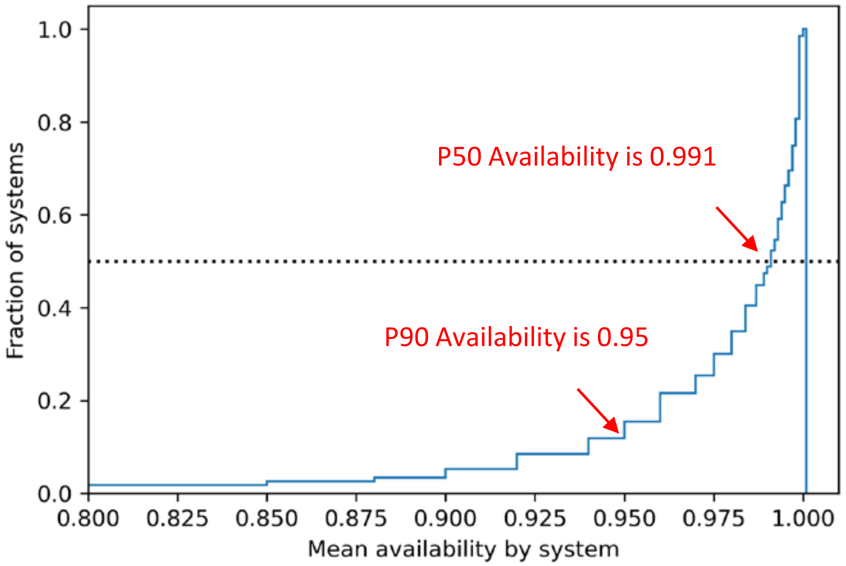


C. Deline et al. Availability and performance loss factors for US PV Fleet systems, NREL technical report 2024

System-level availability

- Grouping by system, we find the 97.9% overall avg is impacted by a **long tail of low availability systems**.
- Median P50 and P90 values can be calculated from the CDF of mean system availability.
- P90 system availability: **0.95**
- P50 system availability: **0.991**

CDF of mean system availability

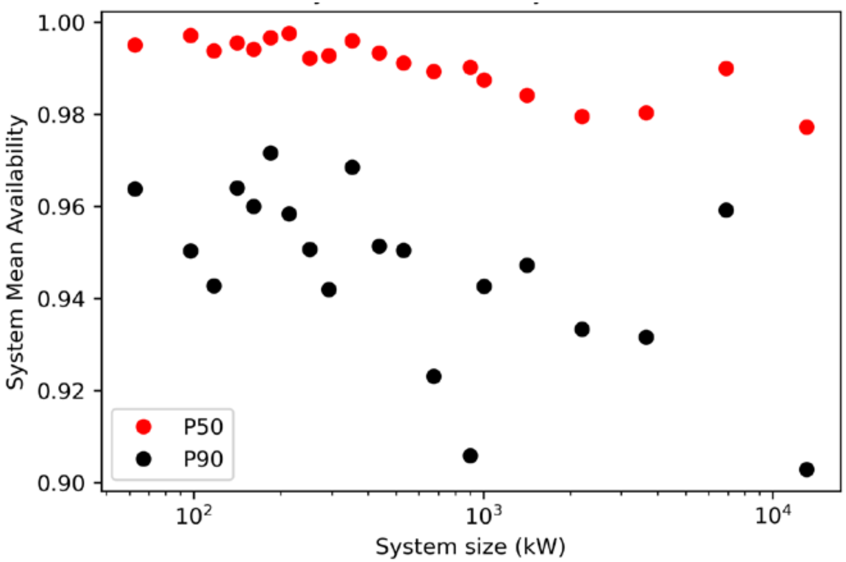


C. Deline et al. Availability and performance loss factors for US PV Fleet systems, NREL technical report 2024

System-level availability vs system size

- At both the P50 and P90 level, system availability appears to have a negative trend vs system size.
- P50 for systems <1 MW is 0.994. For larger systems 1MW – 30MW, median system availability is 0.984

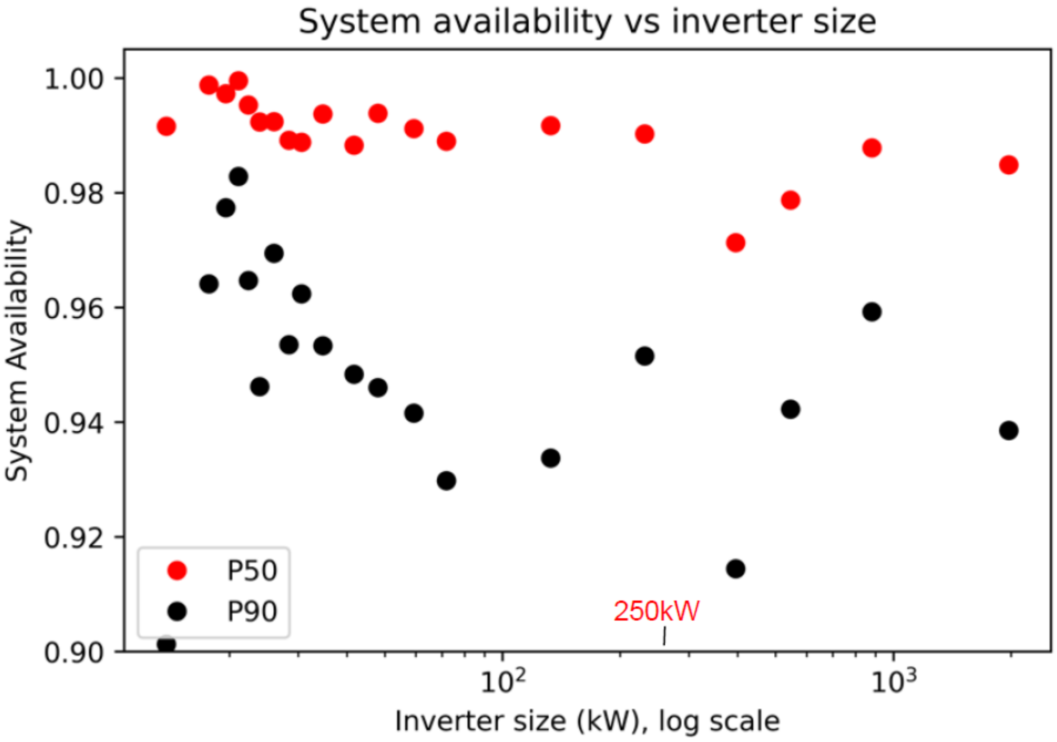
System availability vs System DC capacity



C. Deline et al. Availability and performance loss factors for US PV Fleet systems, NREL technical report 2024

System-level availability vs Inverter size

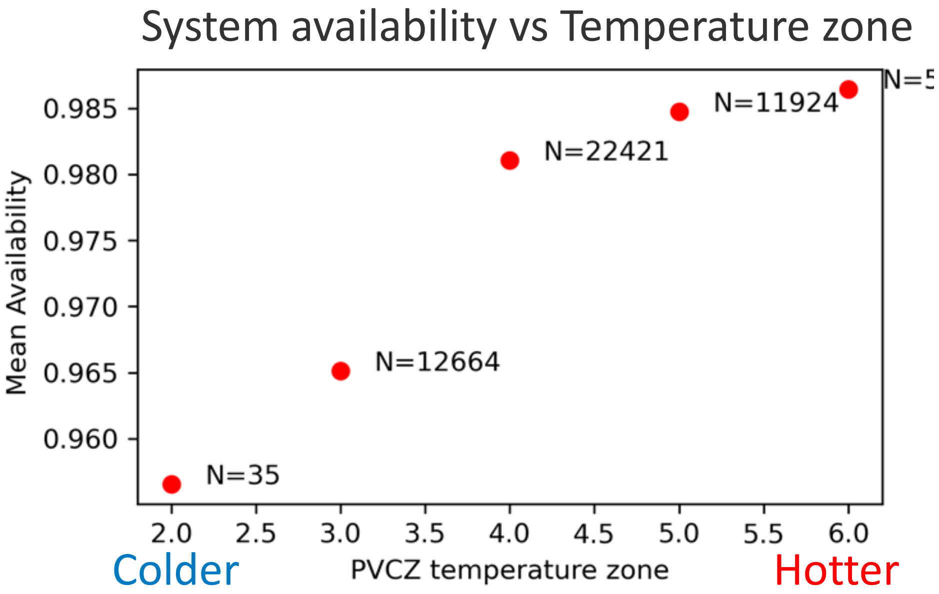
- Some of the availability trend may be due to inverter size: smaller inverters < 250kW tend to have better availability.
- This is the old string inverter vs central inverter debate!

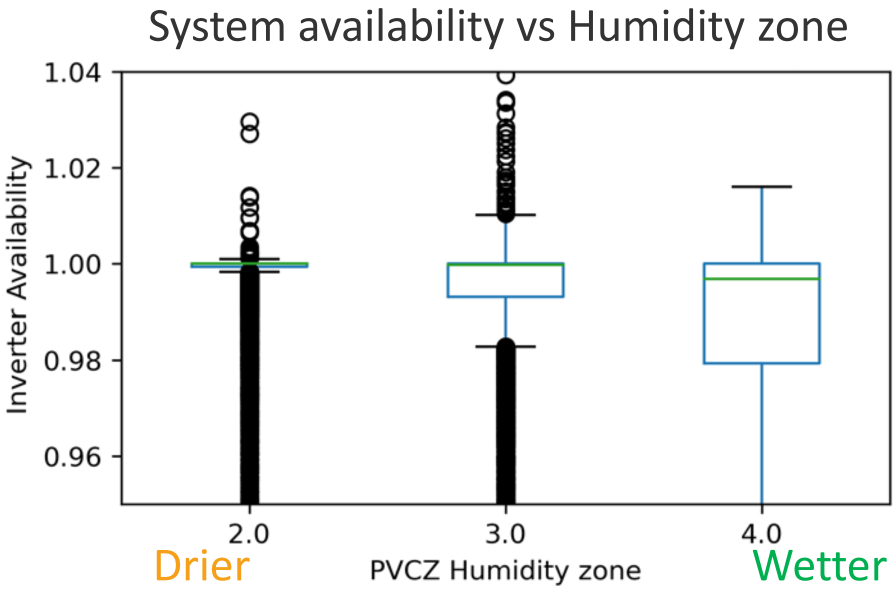


C. Deline et al. Availability and performance loss factors for US PV Fleet systems, NREL technical report 2024

System-level availability vs Climate

- Using Karin 2019 PV climate zones, we find lower availability for snowy climates or higher humidity climates.

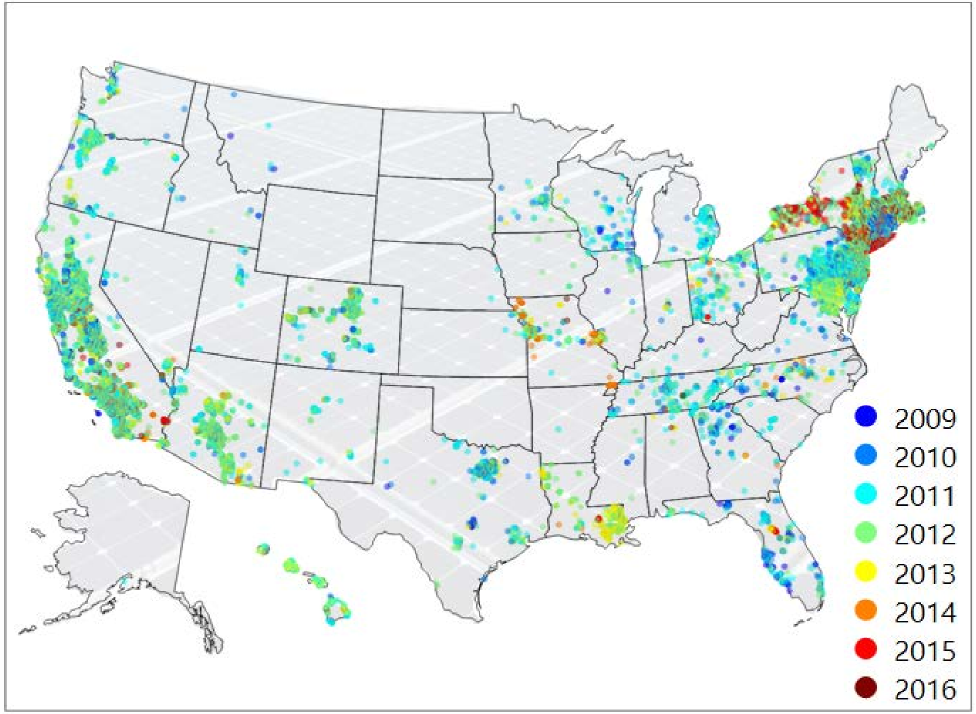




Agenda

- PV Fleet Data Initiative
  - Introduction
  - Methodology
  - System / inverter availability trends
- Treasury 1603 Dataset (2009-2016)
  - Pareto of logged issues and lost energy

1603 data ≈ 100,000 PV systems



>7GW capacity, ca. 7% of all systems in the US

> 60,000 systems 5 years of data

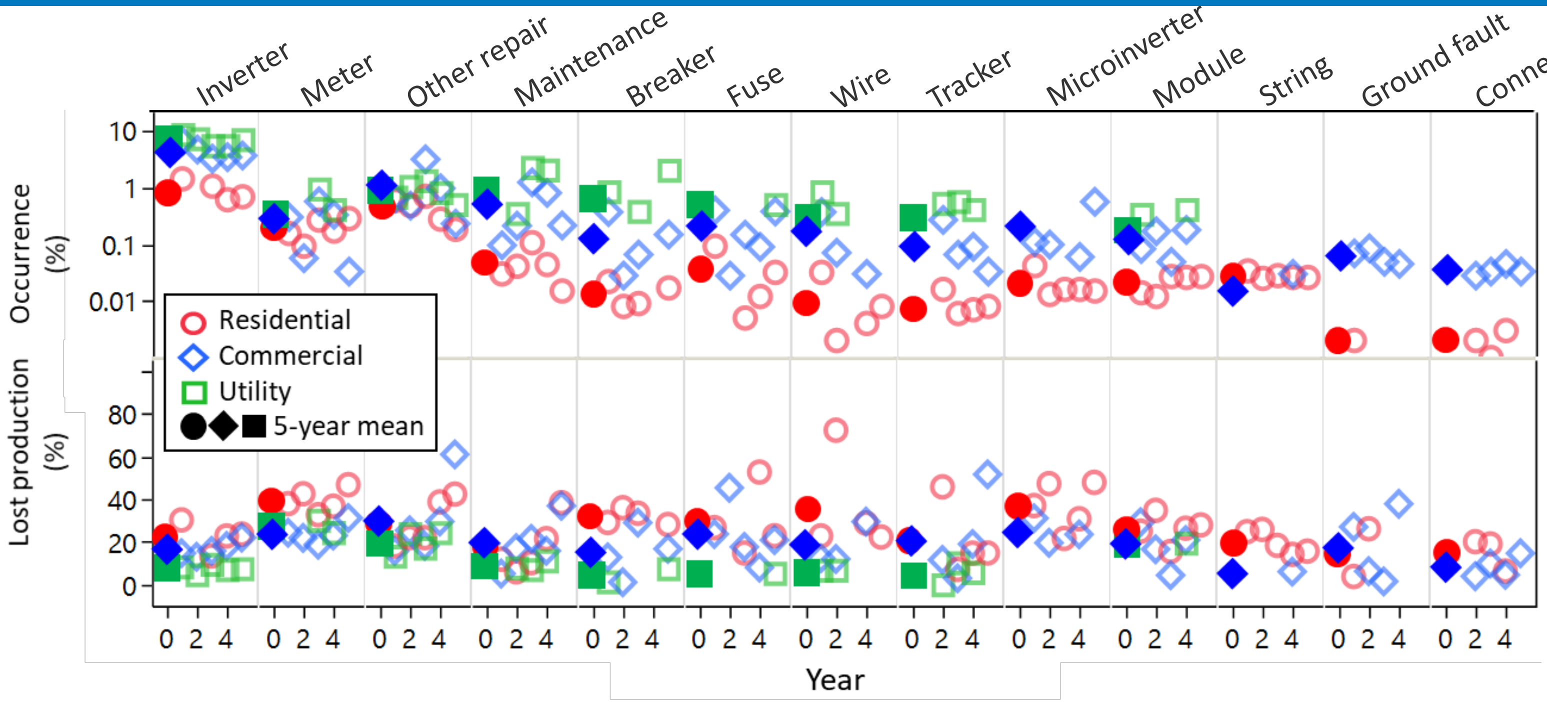
400-500 utility-scale systems

Annual production data, location, predicted production, size, no mounting configuration

Comments regarding the performance

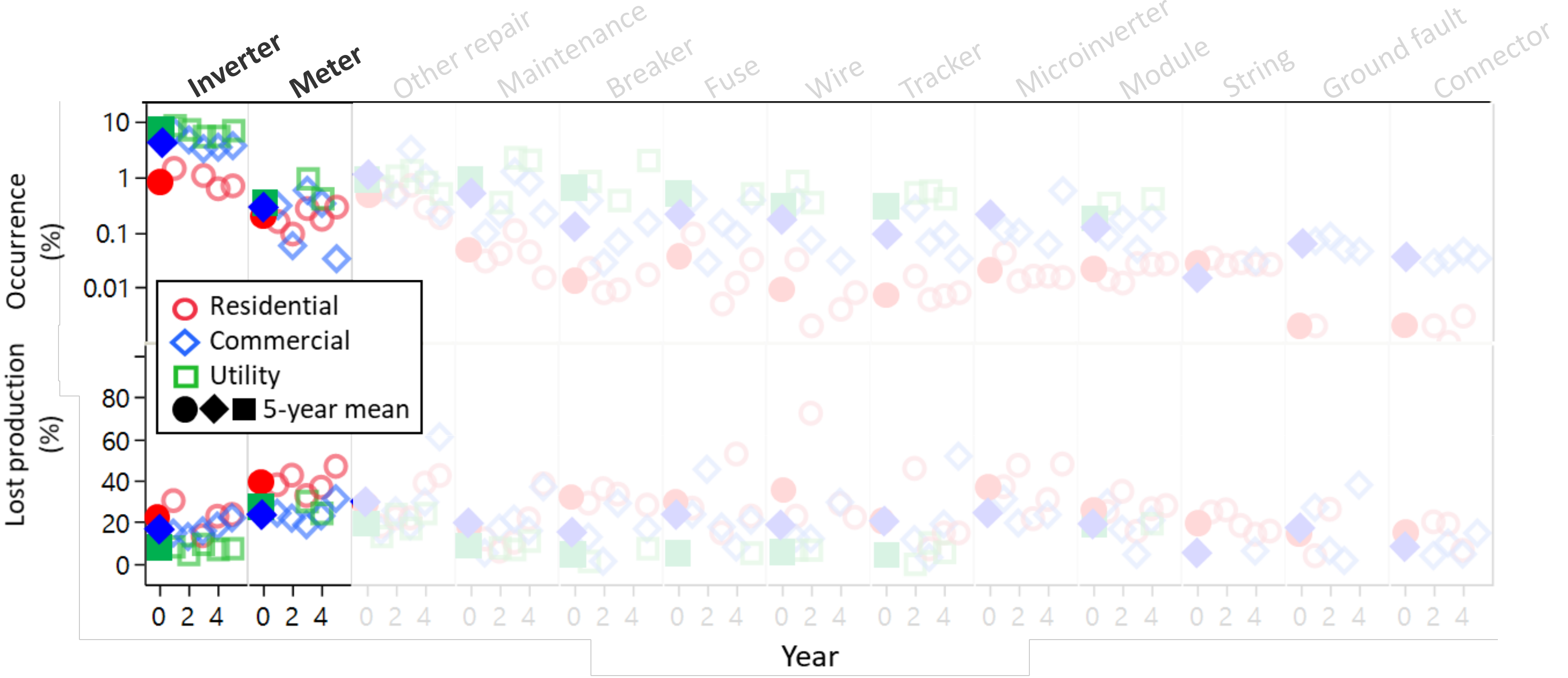
Jordan et al., “PV field reliability status—Analysis of 100 000 solar systems” Progress in PV, 2020.

Hardware failures



Jordan et al., “PV field reliability status—Analysis of 100 000 solar systems” Progress in PV, 2020.

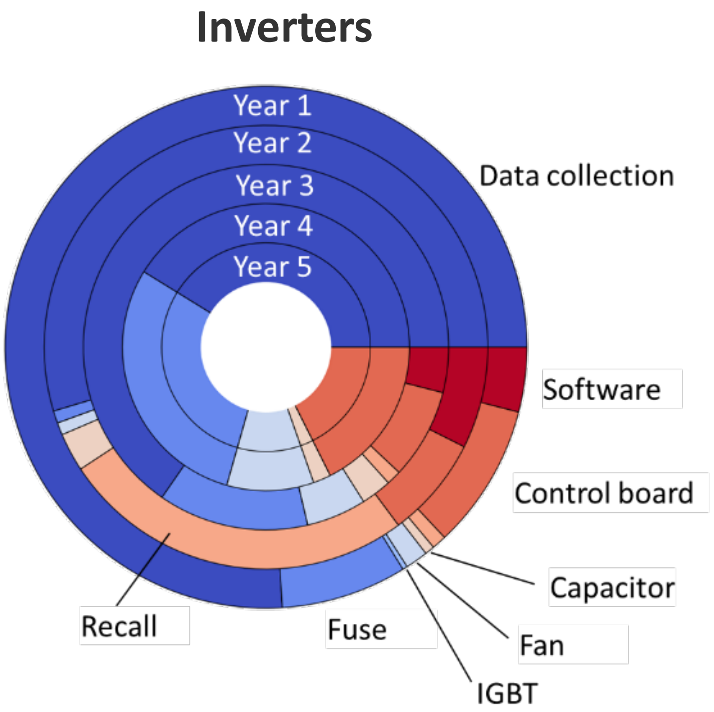
Hardware failures

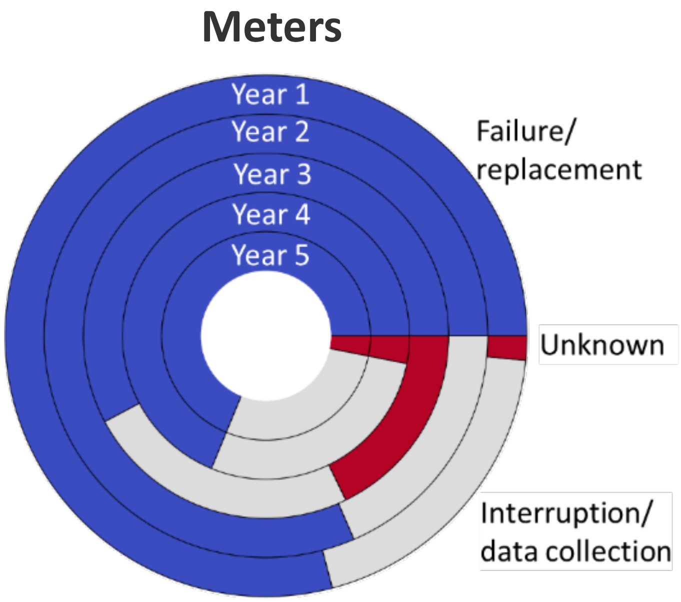


Inverters fairly high (no surprise) but meters are an issue too.

Jordan et al., “PV field reliability status—Analysis of 100 000 solar systems” Progress in PV, 2020.

Itemization of inverter & meter issues





In most cases we don’t know what failed
Data collection are most frequently mentioned when we do know
Control board and fuses are the next most common issues

¾ are replacements
Year1 & 2 higher → start-up issues

Inverter issues & climate

Utility-scale

Inverters are exposed & easily visible

Residential

Same inverter manufacturer, same location (PA),

Arrow points out inverter location

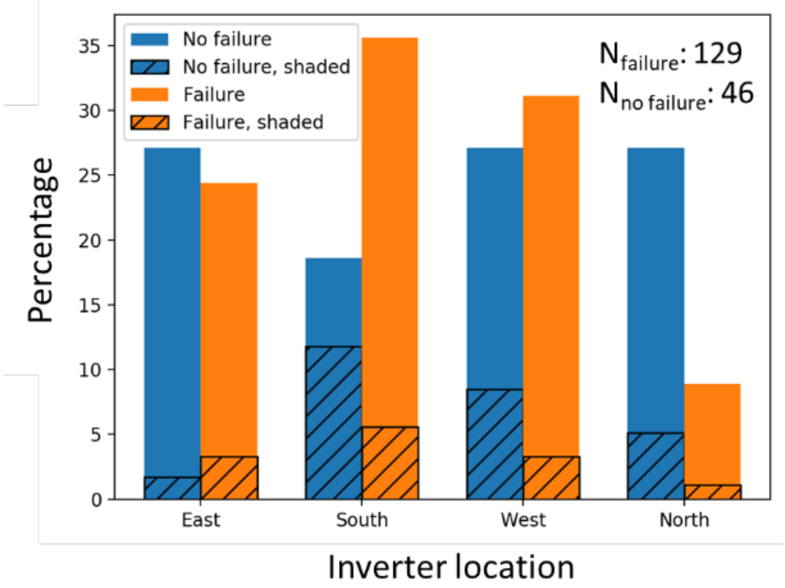
Inverter location: residential systems often depends on the building’s orientation

Preference for inverters: More shade the better

Jordan et al, PV System Failures – Temperature & Installation Effects. PVSC 2020

More inverter failures on South side

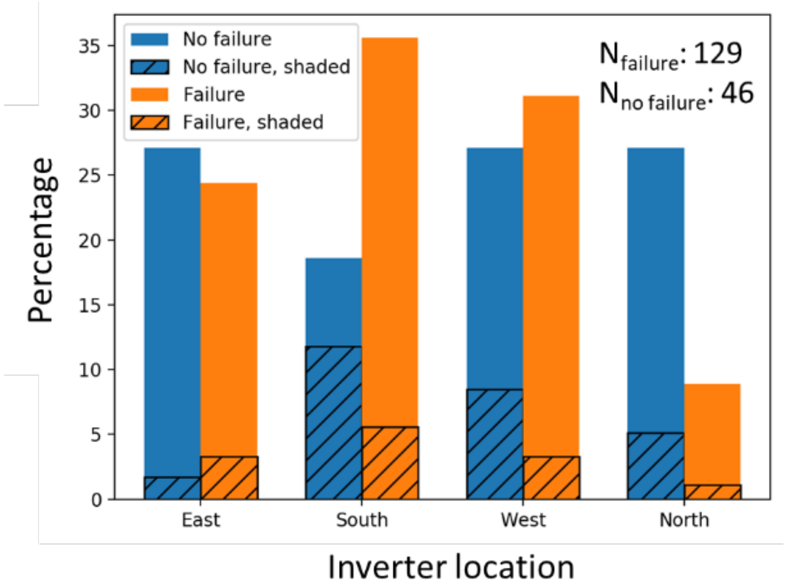
Random sample from systems with & without inverter failures



Jordan et al, PV System Failures – Temperature & Installation Effects. PVSC 2020

More inverter failures on South side

Random sample from systems with & without inverter failures



Inverter on South side but shaded

Inverters shouldn't be in sun all day, if no other choice → shade them!

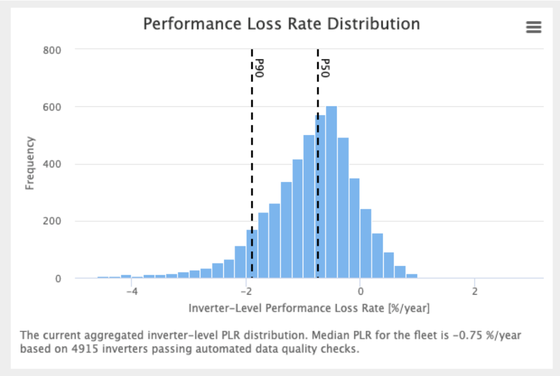
Jordan et al, PV System Failures – Temperature & Installation Effects. PVSC 2020

Conclusion

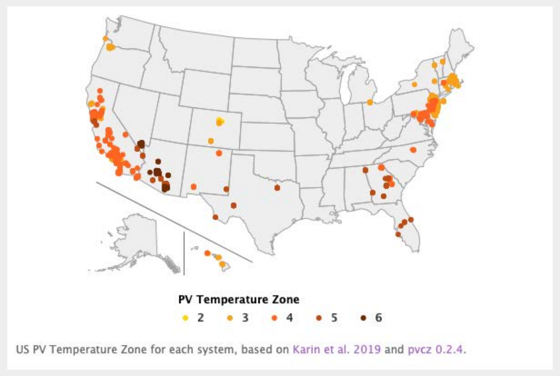
- Lower availability in the first 6 months before reaching steady-state
- System-level data shows a median (P50) system availability of 0.99, and a lower P90 value of 0.95.
- A dependence on system and inverter size is identified, with better availability for smaller PV systems and inverters <250kW vs 300kW-5MW.
- A separate study of 100,000 systems found inverters & meters to drive O&M issues .
- Shade your inverters!

Conclusion

- Reports, visualizations, raw data at nrel.gov/pv/fleet-performance-data-initiative.html



The current aggregated inverter−level PLR distribution. Median PLR for the fleet is −0.75 %/year based on 4915 inverters passing automated data quality checks.



US PV Temperature Zone for each system, based on Karin et al. 2019 and pvcz 0.2.4.

Thank you

chris.deline@nrel.gov

nrel.gov/pv/fleet-performance-data-initiative.html

Funding provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement Number 38258.
Thank You to DOE and our PV Fleet Partners!

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

PV Fleet Project Overview

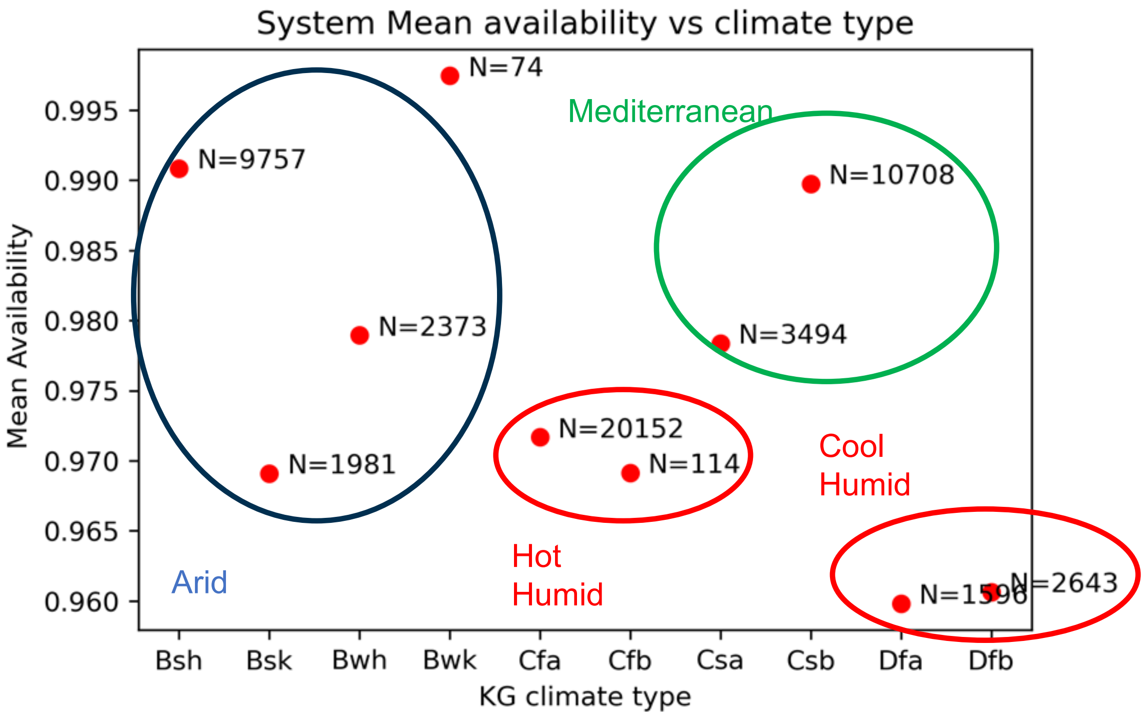
In the **PV Fleet Performance Data Initiative**, high-frequency data from commercial and utility-scale PV systems have been collected to examine performance trends at a fleet scale.

- Owners provide NDA-protected data to NREL
- Fleet-scale analysis provided in return
    - Annual degradation rate (Rd)
    - Loss factors (availability, soiling, etc)
    - Under-performing systems flagged
- Results are anonymized and aggregated for public dissemination
    - Validate pro-forma model assumptions
    - Identify performance trends by climate, technology, etc.

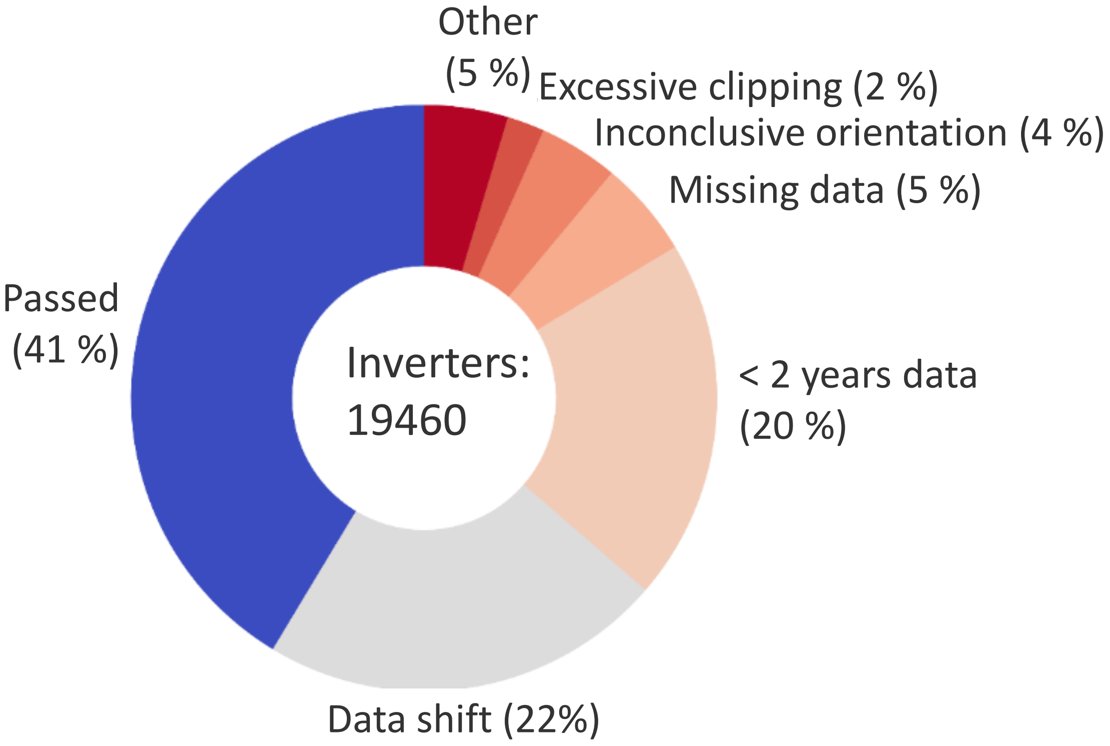
For more details or for partner opportunities, email chris.deline@nrel.gov

System-level availability vs Climate

- Similar trend when comparing vs Koppen-Geiger climate zones

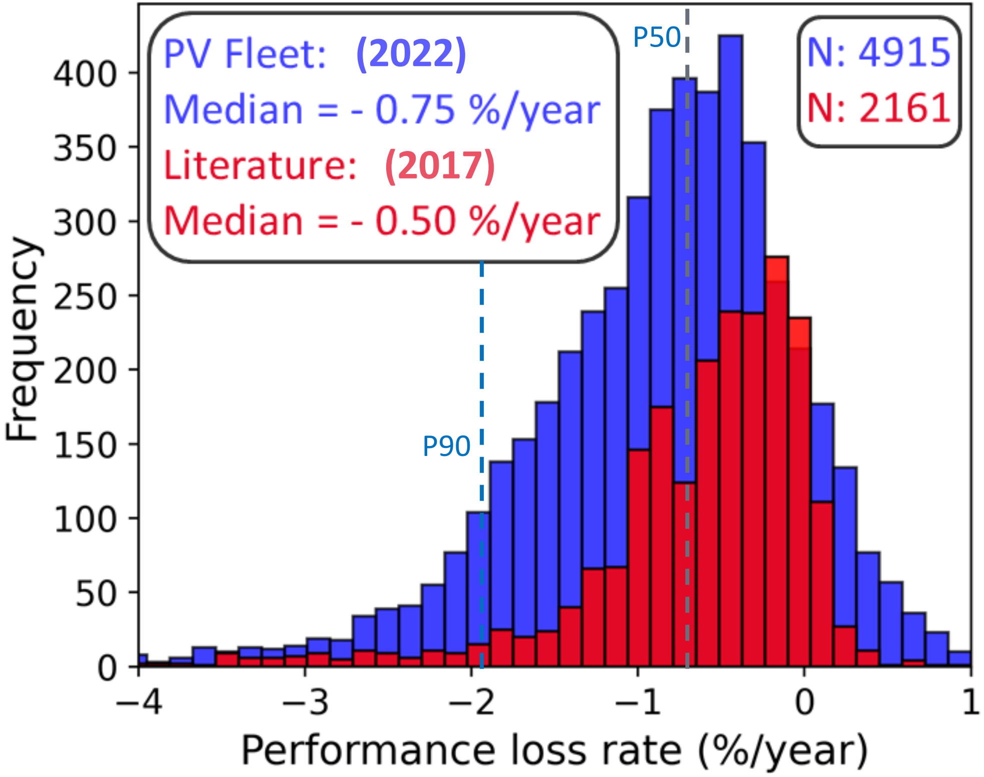


Breakdown of quality issues – PV Fleet



Jordan et al., Progress in PV, 2022

Degradation Rate Distribution 2017 - 2022



Each inverter in the fleet gets one 'vote'

Median system degradation: -0.75 %/year.

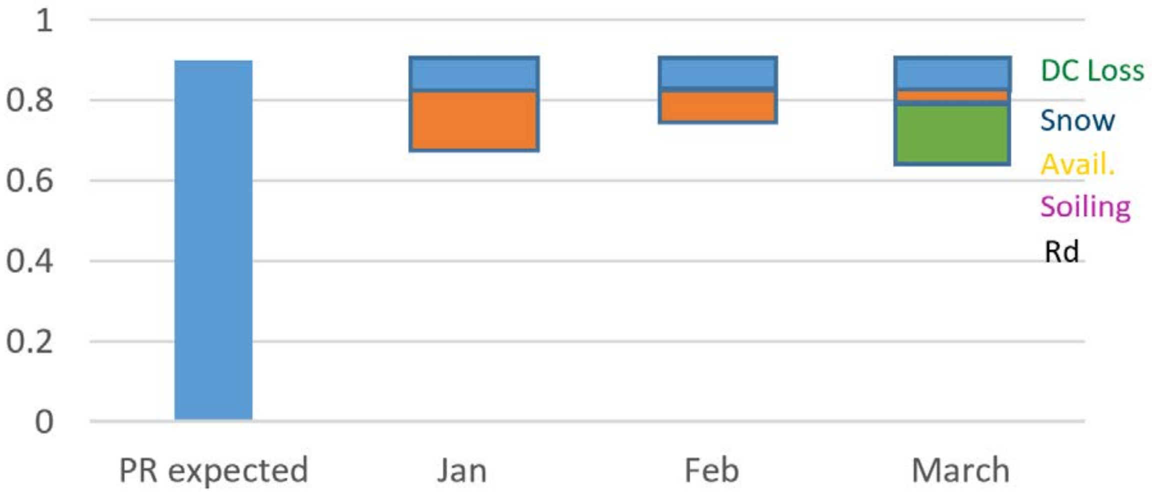
This is slightly higher than historical (module-based) values

2022 PV Fleet: Systems
2017 Literature: Mostly modules

Jordan et al., Progress in PV, 2017, 2022

Performance index analysis

Measured vs expected monthly roll-up with loss factors identified

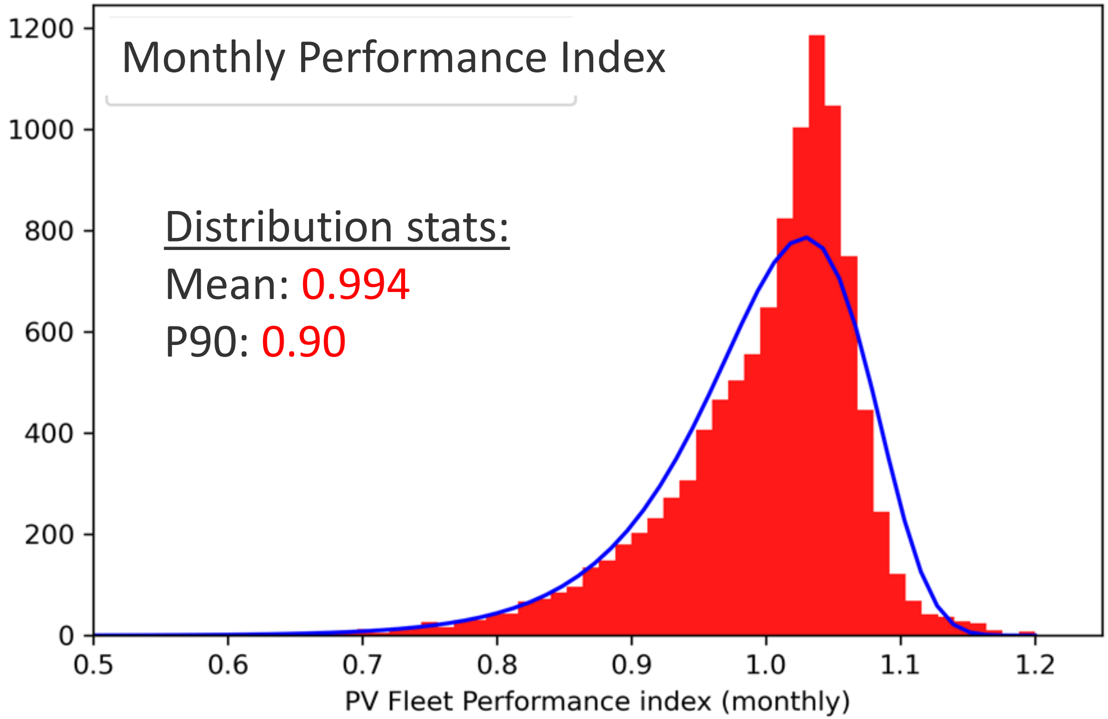


$$\text{Performance Index} = \frac{\text{Actual Production}}{\text{Expected Production}}$$

Expected Production estimated with PVWatts model and NSRDB weather

C. Deline et al., NREL/TP-5K00-78720, December 2020

Monthly Performance Index distribution



Distribution stats:

Mean: 0.994

P90: 0.90

- Adjusted for availability
- Removed 6-month startup and snow months
- Best fit extreme-value distribution shows decent agreement:

$$P(x) = \frac{1}{\beta} \exp\left[\frac{x-\mu}{\beta} - \exp\left(\frac{x-\mu}{\beta}\right)\right]$$

C. Deline, K. Anderson et al., PV Fleet Performance Data Initiative: Performance Index–Based Analysis, NREL/TP-5K00-78720, 2020

Quantitative Findings – pro forma loss factors

Energy Loss Term	PVWatts Default	PV Fleet Loss
Soiling	2%	2%
Shading	3%	
Snow	0%	0% - 10%
Mismatch	2%	
Wiring	2%	
Connections	0.5%	
LID	1.5%	0%
Nameplate	1%	
Age	0%	0.7%/yr
Availability	3%	1%
Total	**14.1%**	**11.8% + 0.7%/yr**

* In high-soiling areas

* Climate dependent

* Excluding initial startup

U.S. DEPARTMENT OF
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Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Open-access datasets and reliability analysis

Tassos Golnas

April 12, 2024

Data: A Means to an End

Better photovoltaic (PV) models and system performance through high-quality data.

PV models are important in:

- Project development and valuation
- Power plant operation and maintenance.

Better system performance means
lower cost of solar electricity.

Solar Data Bounty Prize Purpose

Support industry and academic research efforts to **develop**, **improve**, **evaluate**, and **validate** models of real-world PV system performance in diverse locations.

Solar Data Bounty Prize Recap

Goal: Incentivize system owners to share information-rich datasets from their assets

Phases and Prize Pools

- Two-stage, two-track program
- Up to $1,415,000 in cash prizes

Stage 1 Submission Materials

  - System metadata
  - One month or more of irradiance time series data

Stage 2 Submission Materials

  - Complete time series data

Results

The winners' data sets are shared publicly via a dedicated platform:

PVDAQ/PVData Map | Open Energy Information (openei.org)

By the numbers (1/2)

Solar Data Bounty Prize datasets:

- 5 different systems across 4 US states
- 110 kW_{dc} to 257,600 kW_{dc} system sizes
- 417 GB of data
- > 4 billion data points
- > 9,500 sensor channels
- 6.6 years average
- 10 sec. to 15 minutes time resolution

Data available on OEDI and through PVDAQ:

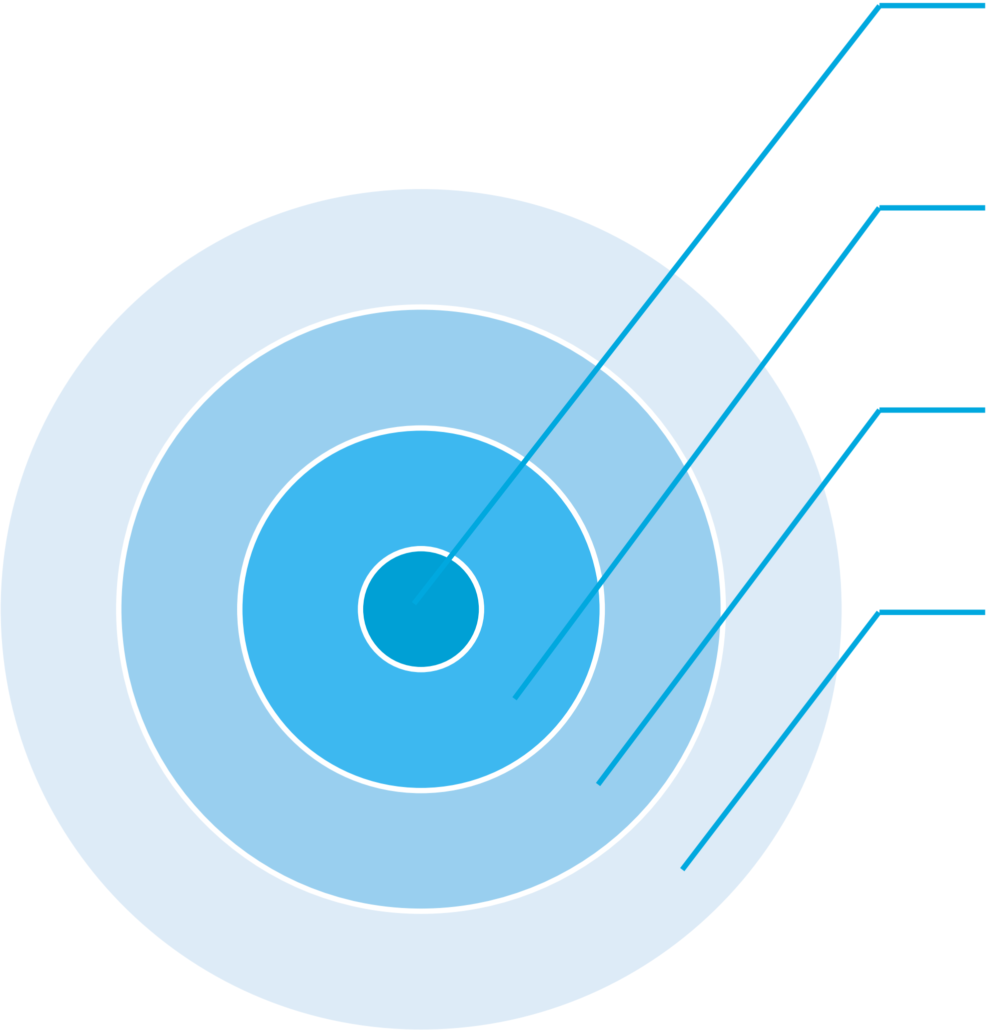
PVDAQ/PVData Map | Open Energy Information (openei.org)

Get the Data!

By the numbers (2/2)

System (State)	Shine On Solar (CA)	SR_GA	SR_CO	Farm Solar Array (CA)	Maui Ocean Center (HI)
Size (kW_{dc})	257,600	38,687	4,738	893	110
PV Technology	multi-Si	multi-Si	CdTe	mono-Si	mono-Si
Mounting	Single-axis tracking	Fixed Ground	Single-axis tracking	Fixed Ground	Fixed Roof
Years of data	7.0	7.8	6.2	6.9	4.9
Temporal resolution	10 second	5 min.	5 min.	5-15 min.	5-15 min.
Channels	4086	4798	438	124	58
Inverters	112	40	2 (x4 modules)	24	11
Inverter Channels	1120	920	136	119	44
Dataset Size (GB)	392.3	23.3	1.53	0.45	0.20

Reliability analysis based on macro-data



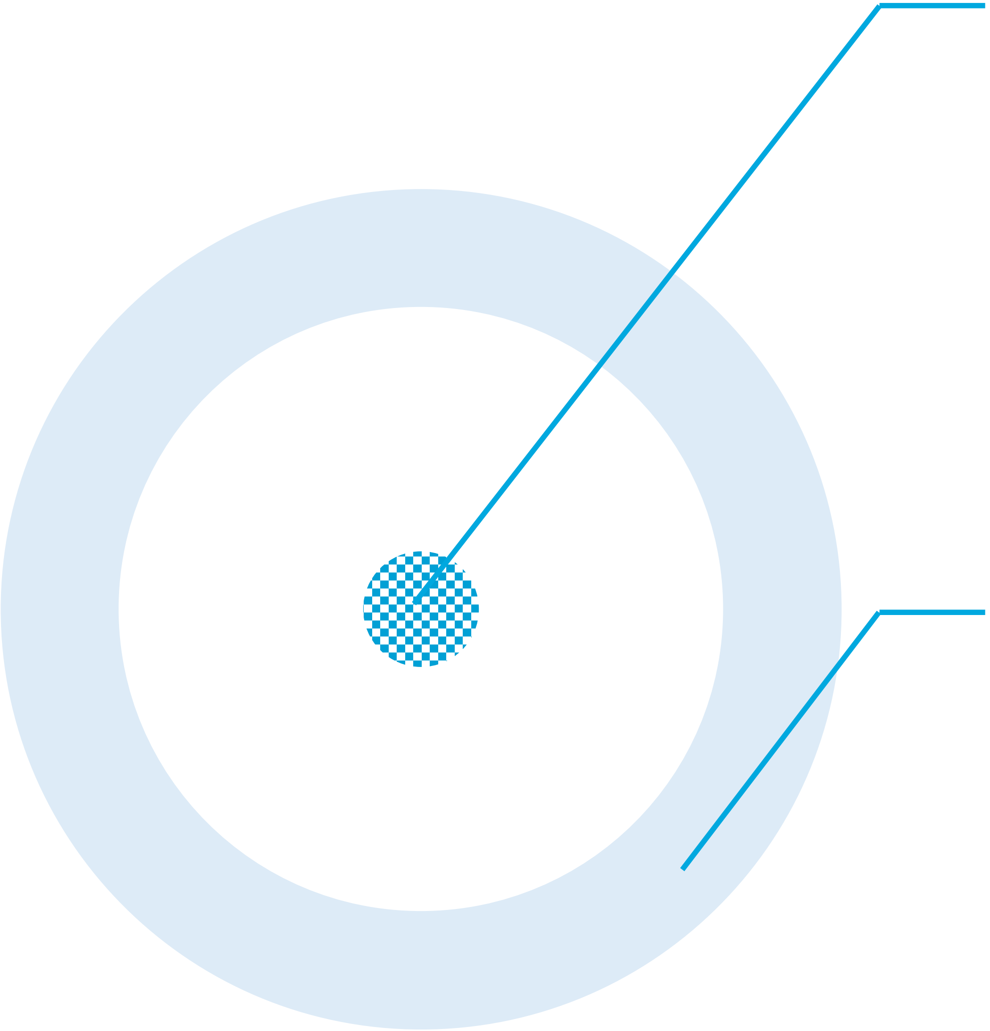
System specification and topology

Technician logs

Component fault logs

Timeseries data

Reliability analysis based on macro-data



System specification and topology

Timeseries data

What can one do with just timeseries data

Inverter availability analysis

- Challenge: communication outage effects

Impact of temperature on availability

- Challenge: no verification of failed component

Prognostics of failure

- Challenge: no verification of failed component

Conclusions

Solar Data Bounty Prize dataset available at PVDAQ/OEDI

- 5 systems, >6.5 years of timeseries data
- ~200 inverters, ~2300 inverter channels

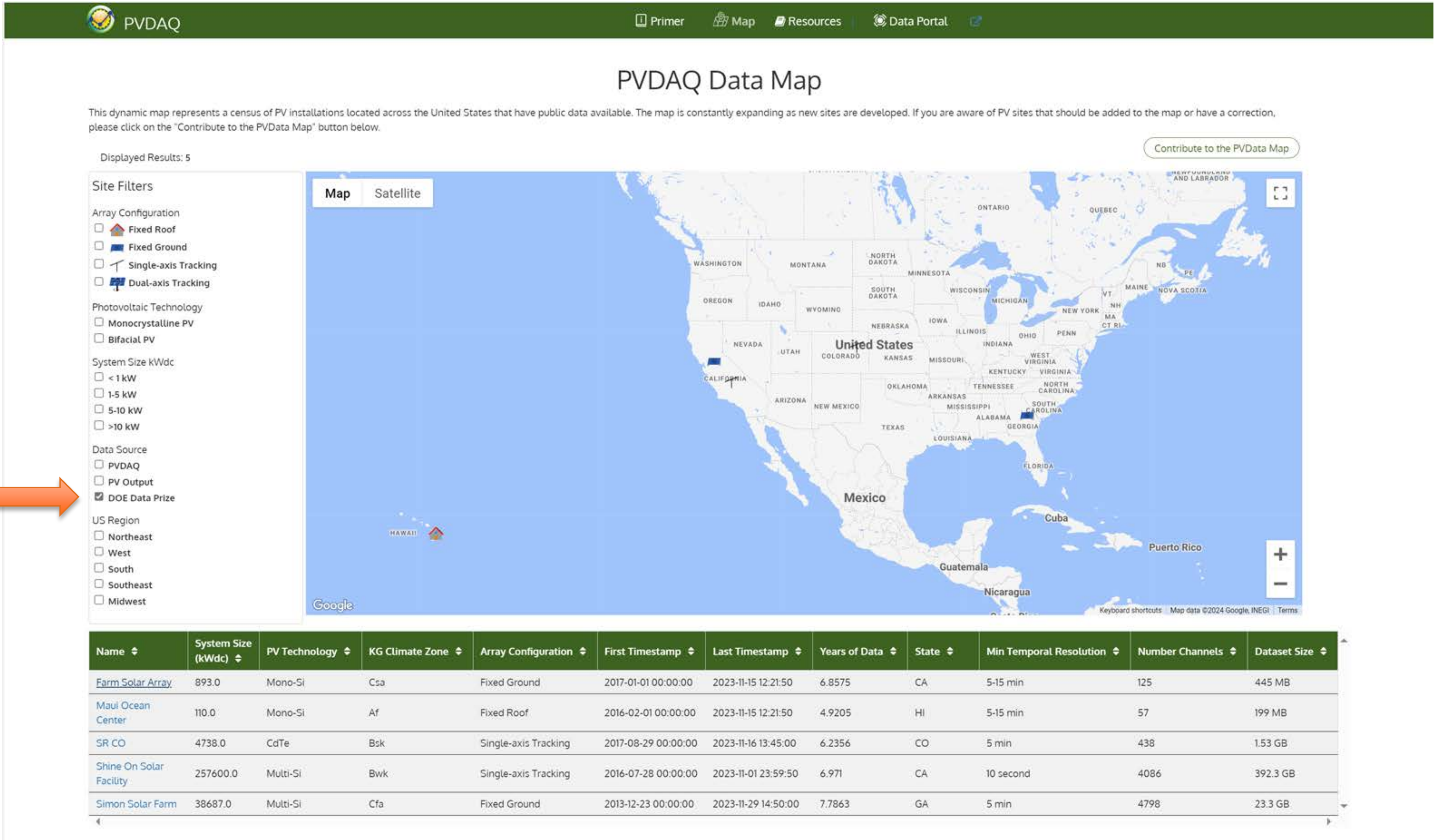
Availability analysis is eminently feasible

Reliability analysis challenged by lack of O&M and fault logs

Some level of prognostics probably feasible

Get the Data!

PVDAQ Data Map



PVDAQ Data Map

This dynamic map represents a census of PV installations located across the United States that have public data available. The map is constantly expanding as new sites are developed. If you are aware of PV sites that should be added to the map or have a correction, please click on the "Contribute to the PVData Map" button below.

Contribute to the PVData Map

Displayed Results: 5

Site Filters

Array Configuration
- ☐ Fixed Roof
- ☐ Fixed Ground
- ☐ Single-axis Tracking
- ☐ Dual-axis Tracking

Photovoltaic Technology
- ☐ Monocrystalline PV
- ☐ Bifacial PV

System Size kWdc
- ☐ < 1 kW
- ☐ 1-5 kW
- ☐ 5-10 kW
- ☐ >10 kW

Data Source
- ☐ PVDAQ
- ☐ PV Output
- ☑ DOE Data Prize

US Region
- ☐ Northeast
- ☐ West
- ☐ South
- ☐ Southeast
- ☐ Midwest

Name	System Size (kWdc)	PV Technology	KG Climate Zone	Array Configuration	First Timestamp	Last Timestamp	Years of Data	State	Min Temporal Resolution	Number Channels	Dataset Size
Farm Solar Array	893.0	Mono-Si	Csa	Fixed Ground	2017-01-01 00:00:00	2023-11-15 12:21:50	6.8575	CA	5-15 min	125	445 MB
Maui Ocean Center	110.0	Mono-Si	Af	Fixed Roof	2016-02-01 00:00:00	2023-11-15 12:21:50	4.9205	HI	5-15 min	57	199 MB
SR CO	4738.0	CdTe	Bsk	Single-axis Tracking	2017-08-29 00:00:00	2023-11-16 13:45:00	6.2356	CO	5 min	438	1.53 GB
Shine On Solar Facility	257600.0	Multi-Si	Bwk	Single-axis Tracking	2016-07-28 00:00:00	2023-11-01 23:59:50	6.971	CA	10 second	4086	392.3 GB
Simon Solar Farm	38687.0	Multi-Si	Cfa	Fixed Ground	2013-12-23 00:00:00	2023-11-29 14:50:00	7.7863	GA	5 min	4798	23.3 GB