NREL
NATIONAL RENEWABLE ENERGY LABORATORY

2016 NREL Photovoltaic Module Reliability Workshop

Technical Monitor: Sarah Kurtz

February 23 – February 25, 2016
Lakewood, Colorado

NREL/PR-5J00-68116

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

NREL's PHOTOVOLTAIC (PV) MODULE RELIABILITY WORKSHOP (PVMRW) brings together PV reliability experts to share information, leading to the improvement of PV module reliability. Such improvement reduces the cost of solar electricity and promotes investor confidence in the technology—both critical goals for moving PV technologies deeper into the electricity marketplace.

NREL's PVMRW is unique in its requirement that all participating organizations share at least one presentation (either oral or poster). This requirement greatly increases information sharing: If everyone shares a little information, everyone takes home a lot of information.

In 2016, the PVMRW was held in Golden, Colorado, February 23–25. Workshop participants shared more than 100 presentations and posters, covering topics such as PV reliability, standards, and performance in extreme climates.

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SunShot
U.S. Department of Energy

SunShot Initiative:
Accelerated Deployment via Proven PV Hardware Reliability

Geoffrey S. Kinsey
Technical Advisor
Solar Energy Technologies Office

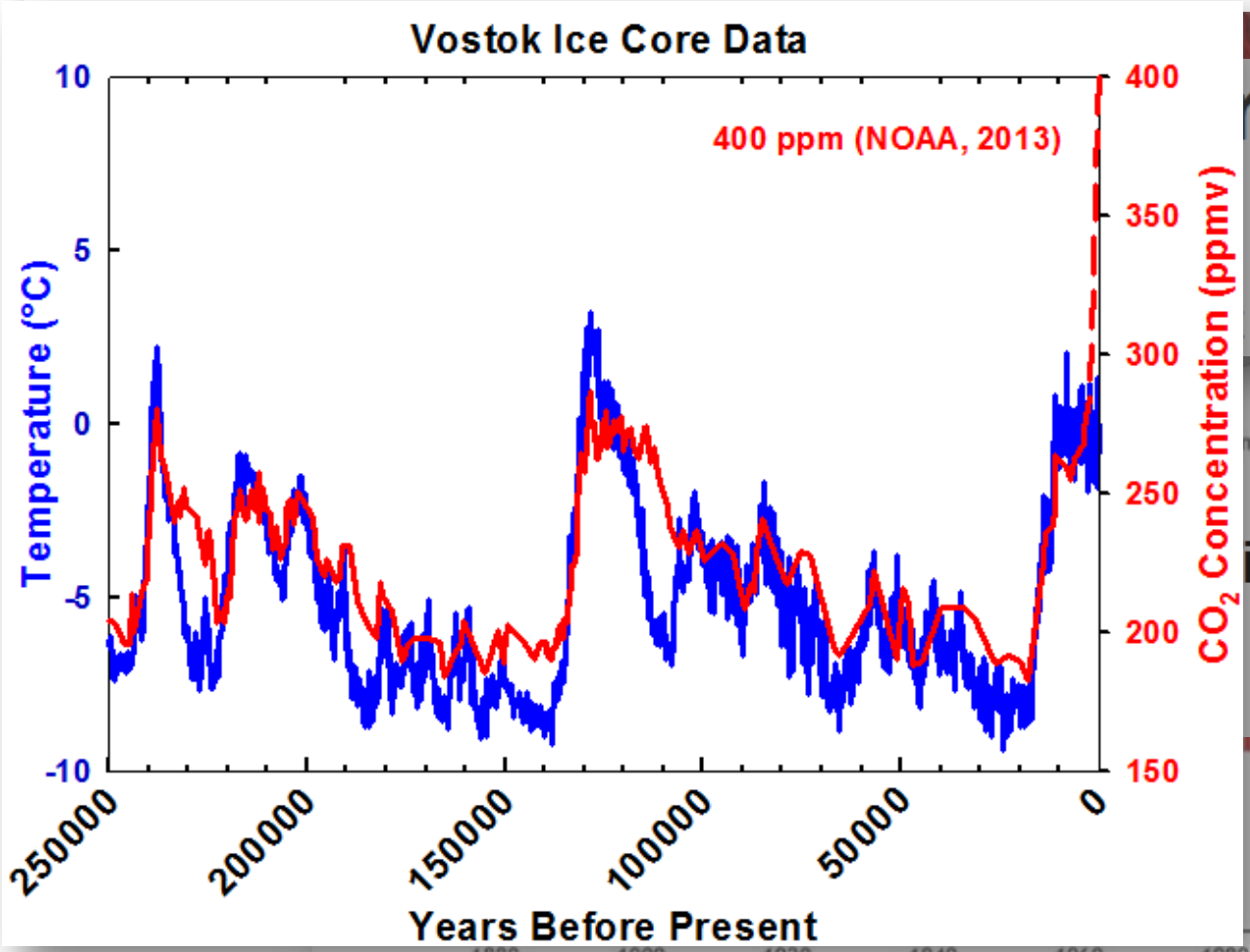
Solar year in review

Climate

January 2016 temperatures compared to historical record

Denver ties record low temperature two days after tying record high

POSTED 8:27 AM, AUGUST 18, 2015, BY WEB STAFF AND GREG DUTRA, *UPDATED AT 10:10AM, AUGUST 18, 2015*



r Heat Record

U.S. News & WORLD REPORT

monthly record.

NOAA NCEI

record warmest

ime Feb. Record Heat

CBS Denver

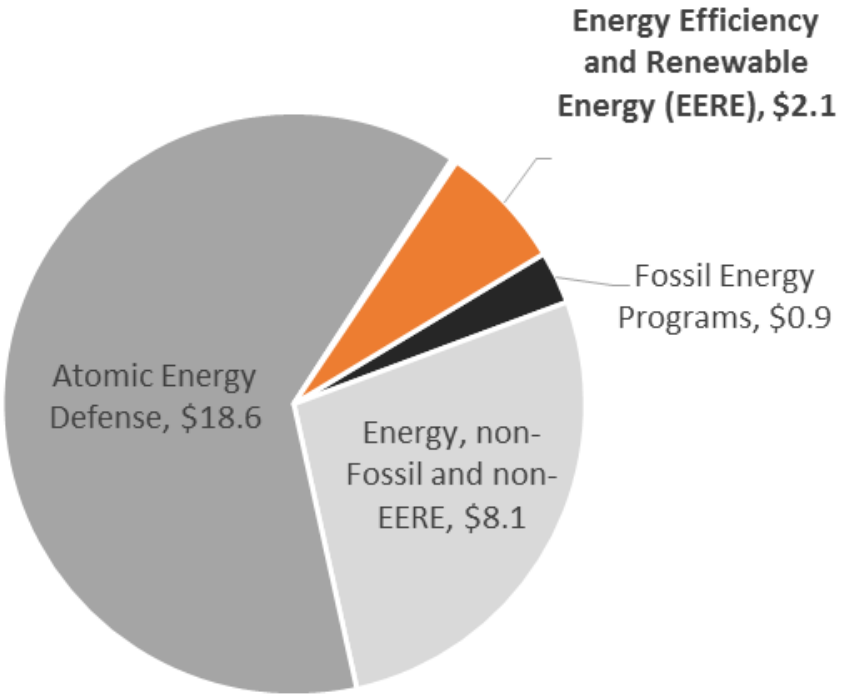
1880 1900 1920 1940 1960 1980 2000

DOE's 2016 budget… vs. Halloween costumes

SunShot
U.S. Department of Energy

Wait, Americans Spend How Much on Halloween?

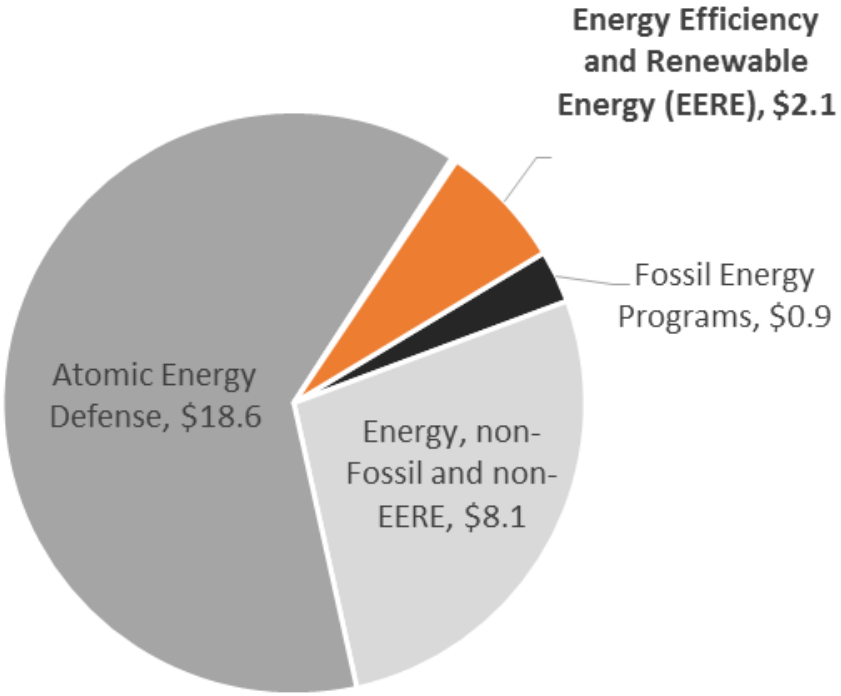
The Atlantic



in billions

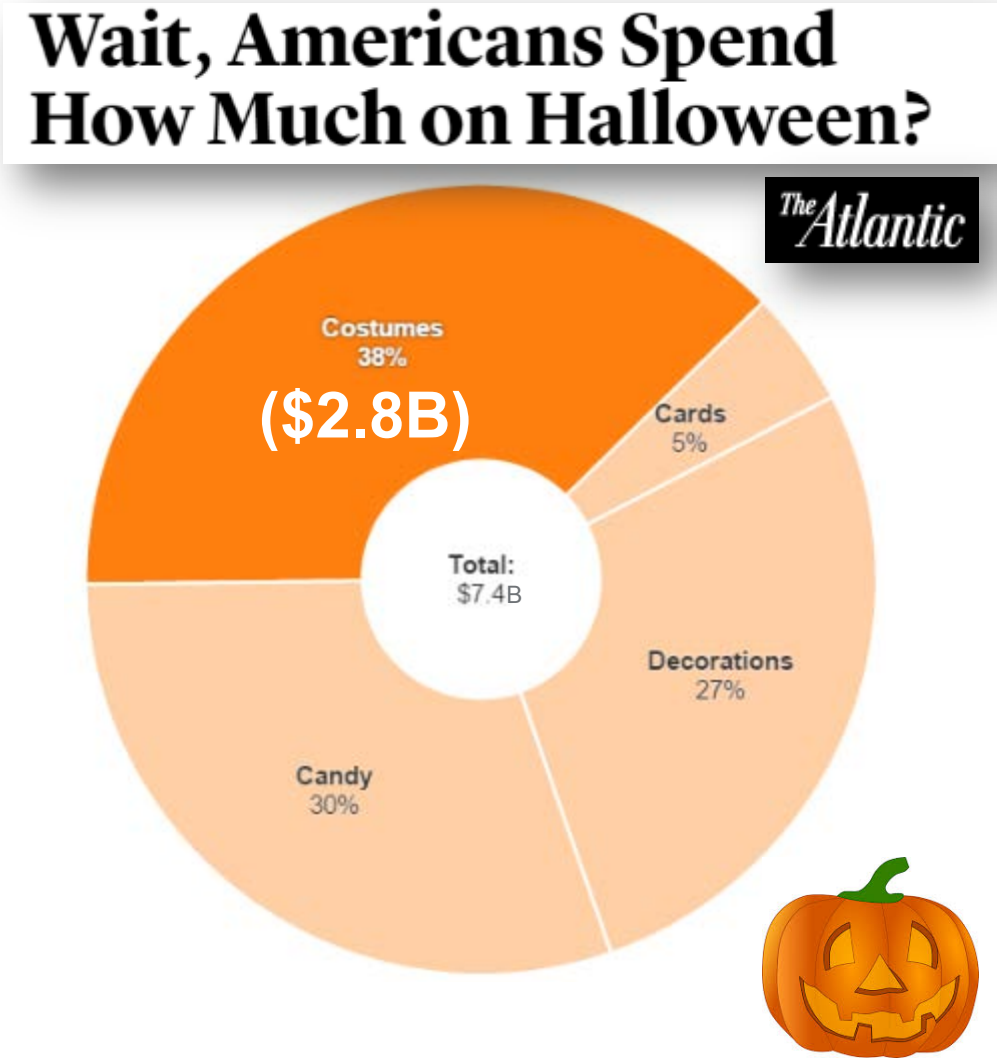
2016 total: $29.6 billion

DOE's 2016 budget… vs. Halloween costumes



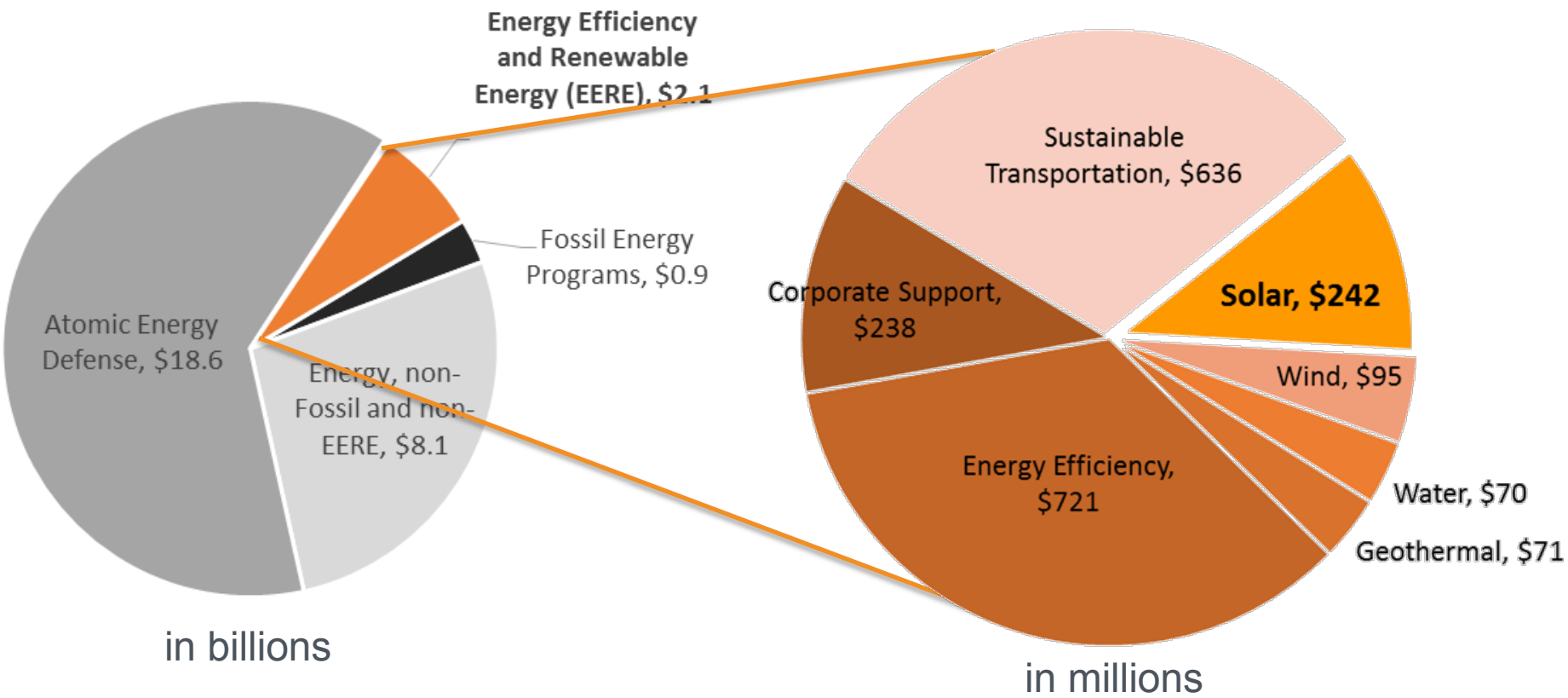
in billions

2016 total: $29.6 billion



2014 total: $7.4 billion

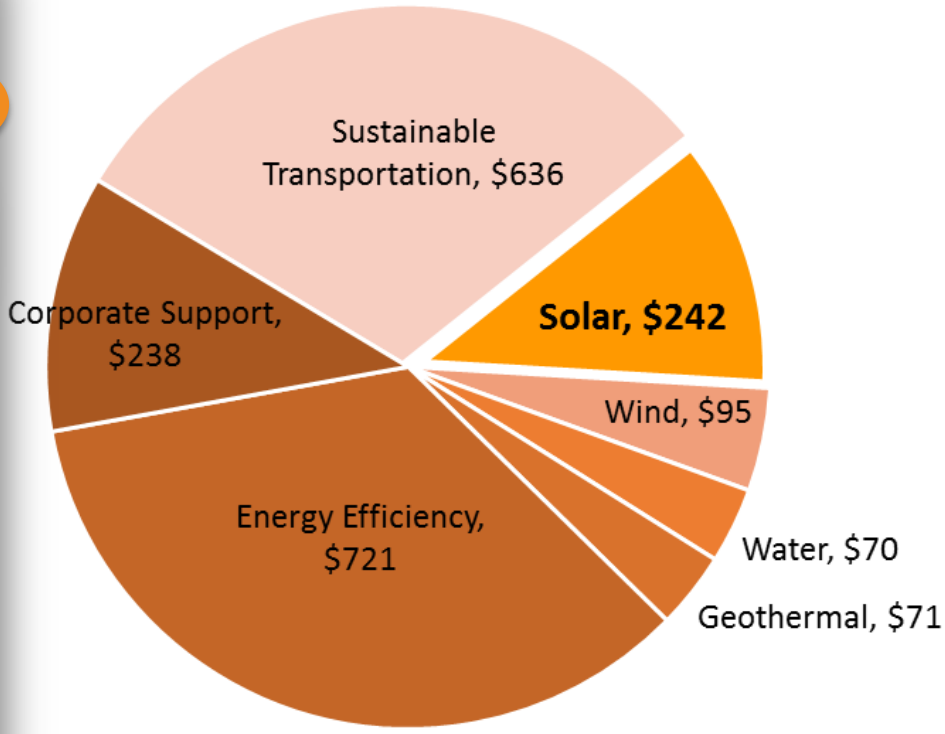
DOE's 2016 budget and EERE



2016 total: $29.6 billion

2016 total: $2.1 billion

DOE's 2016 solar budget… vs. Halloween costumes



in millions

Total: $2.1 billion

Reliability/durability/lifetime: 2016-2018

SunShot U.S. Department of Energy

Support of International PV Module Quality Assurance Task Force (PVQAT): $10.0M

Manufacturing and Reliability Science for CIGS Photovoltaics: $4M

Degradation Assessment of Fielded CIGS Photovoltaic Module Technologies: $3.0M

Scientific Approach to Reducing PV Module Material Costs While Increasing Durability: $2.5M

Improving PV performance estimates in the System Advisor Model with component and system reliability metrics: $0.6M

From Modules to Atoms: Increasing Reliability/Stability of Commercially-Relevant PV Technologies: $6M

PV Risk Reduction through Quantifying In-Field Energy: $4.5M

Sandia National Laboratories Regional Test Centers Program: $8.3M

Coupled Thermo-Mechanical and Photo-Chemical Degradation Mechanisms - CPV Technologies (PREDICTS, Stanford): $0.6M

Module-Level Exposure and Evaluation Test for PV Modules (PREDICTS2 CWRU): $1.4M

Novel Accelerated Aging Protocols for Photovoltaic Modules (EPRI): $1M

Unified Numerical Solver for Device Meta-stabilities in CdTe Thin-Film PV (PREDICTS, ASU): $0.7M

Generalizable Mechanistic Understanding of Module-level Light-, Moisture- and Thermal-Induced Instabilities in CIGS (PREDICTS2 UI): $1.4M

Non-destructive evaluation of water ingress in photovoltaic modules (PREDICTS2, LLNL): $0.6M

Backsheets: Correlation of Long-Term Field Reliability with Accelerated Laboratory Testing (PREDICTS2 UL): $1.3M

Predictive Models and Novel Accelerated Tests for the Reliability of Cell Metallization and Solder Joints in Photovoltaic Modules (PREDICTS2, SunPower): $1.3M

PV Lifetime Project: $XXX M

funding total (FY16-FY18): $48M

Reliability/durability/lifetime: 2016-2018

SunShot U.S. Department of Energy

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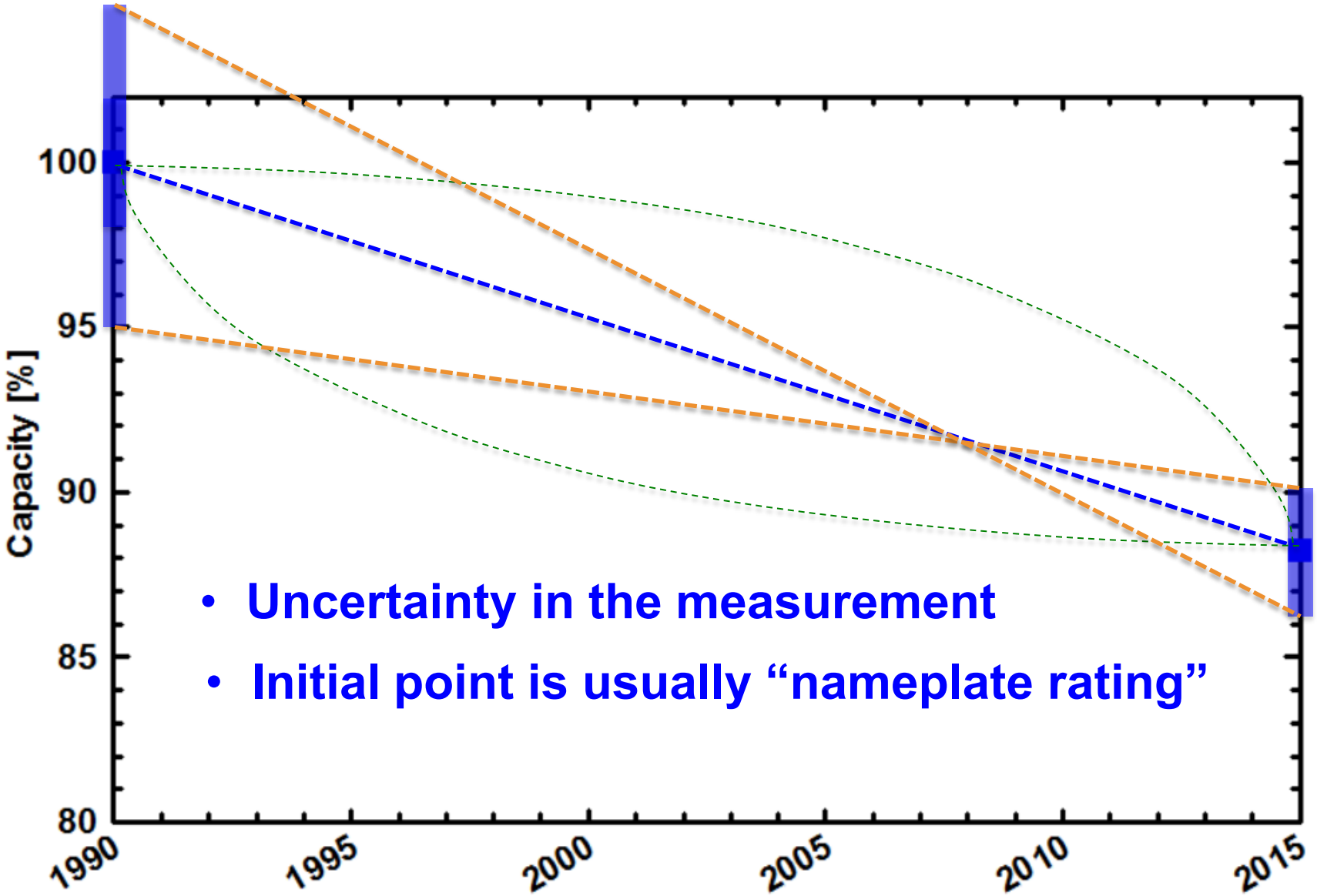
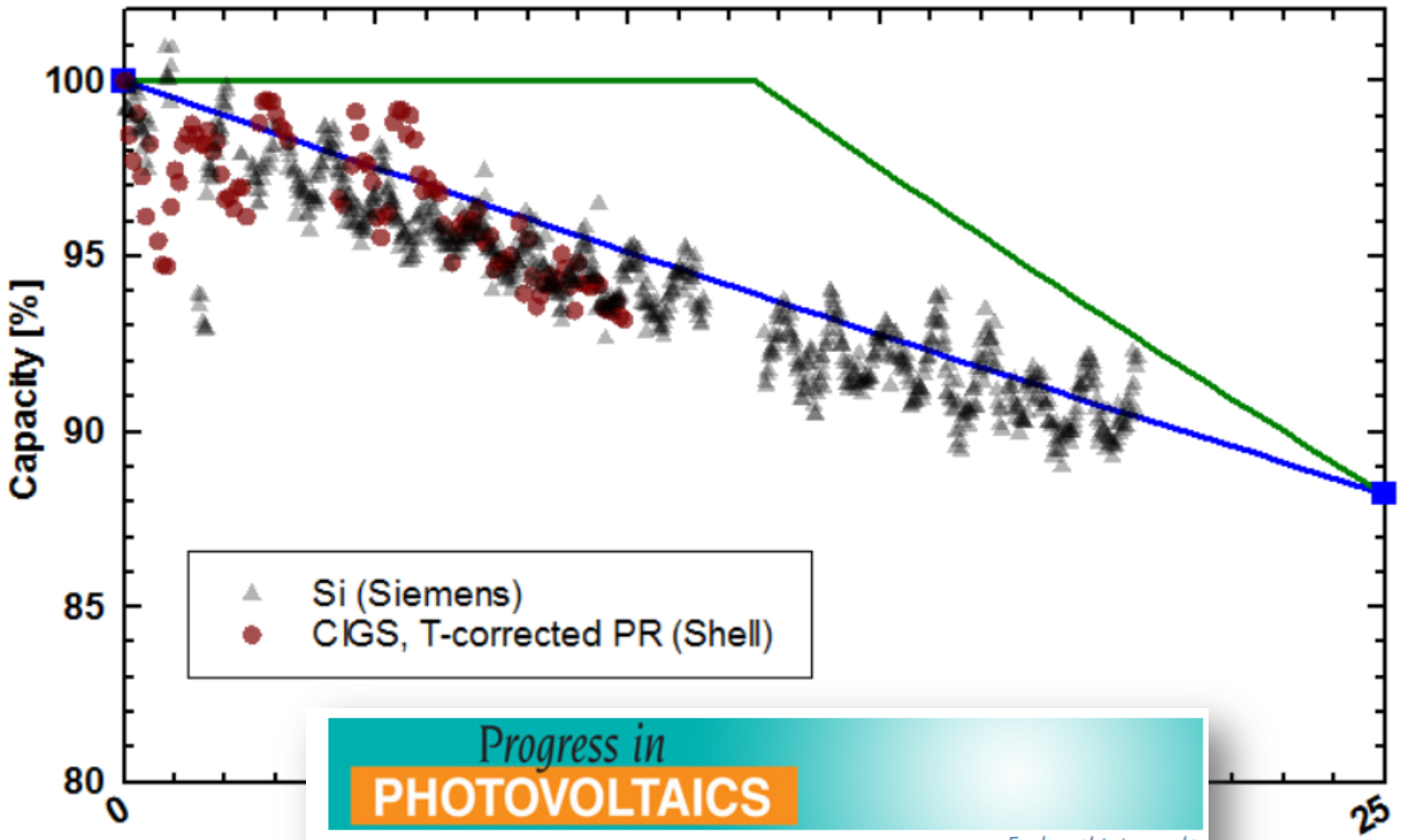
Degradation "profile" determination



- Uncertainty in the measurement
- Initial point is usually "nameplate rating"

Degradation profiles



Progress in PHOTOVOLTAICS

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Research Article

Compendium of photovoltaic degradation rates

Dirk C. Jordan ✉,Sarah R. Kurtz,Kaitlyn VanSant,Jeff Newmiller

First published: 7 February 2016 Full publication history

Reliability/durability/lifetime: 2016-2018

SunShot U.S. Department of Energy

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PV Risk Reduction through Quantifying In-Field Energy: $4.5M

Sandia National Laboratories Regional Test Centers Program: $8.3M

Coupled Thermo-Mechanical and Photo-Chemical Degradation Mechanisms - CPV Technologies (PREDICTS, Stanford): $0.6M

Module-Level Exposure and Evaluation Test for PV Modules (PREDICTS2 CWRU): $1.4M

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Non-destructive evaluation of water ingress in photovoltaic modules (PREDICTS2, LLNL): $0.6M

Backsheets: Correlation of Long-Term Field Reliability with Accelerated Laboratory Testing (PREDICTS2 UL): $1.3M

Predictive Models and Novel Accelerated Tests for the Reliability of Cell Metallization and Solder Joints in Photovoltaic Modules (PREDICTS2, SunPower): $1.3M

PV Lifetime Project: $XXX M

funding total (FY16-FY18): $48M

Backsheets: Correlation of Long-Term Field Reliability with Accelerated Laboratory Testing

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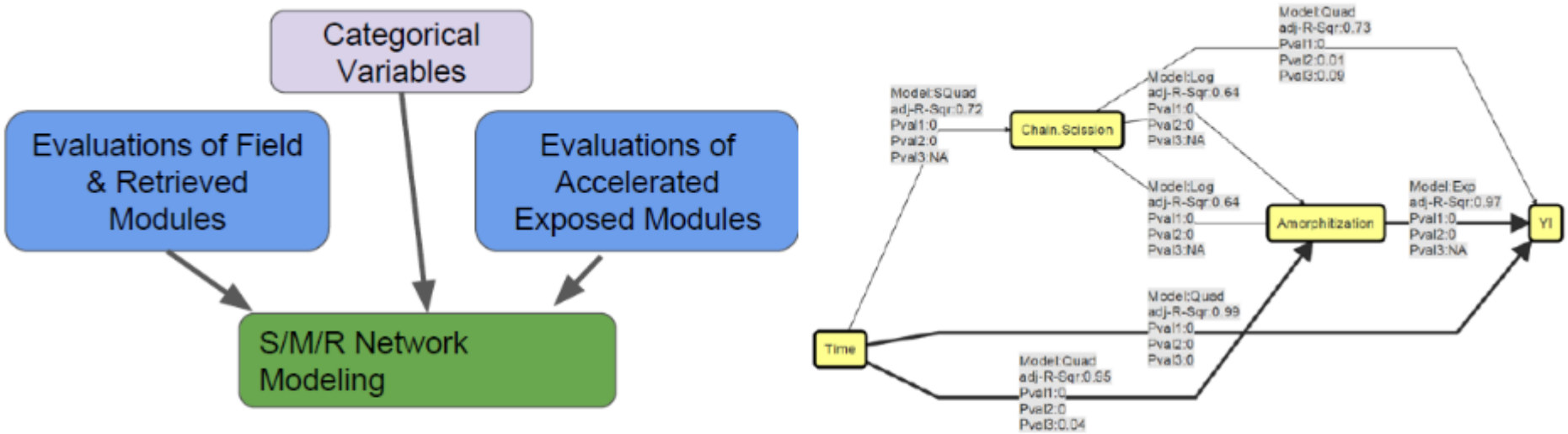
UL 3M ARKEMA CASE WESTERN RESERVE UNIVERSITY EST. 1826 NIST NREL Northeastern University



- S/M/R Network Modeling links stressor to degradation mechanisms & to a response (performance loss)
- Includes dependent and independent variables and serve as either statistical or physical sub-models
- Develop a predictive model to understand lifetime performance
  - Including an understanding of real-world degradation mechanisms.
- Cross-correlation between real-world exposed modules and accelerated sample coupons

Reliability/durability/lifetime: 2016-2018

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PV Lifetime Project: $XXX M

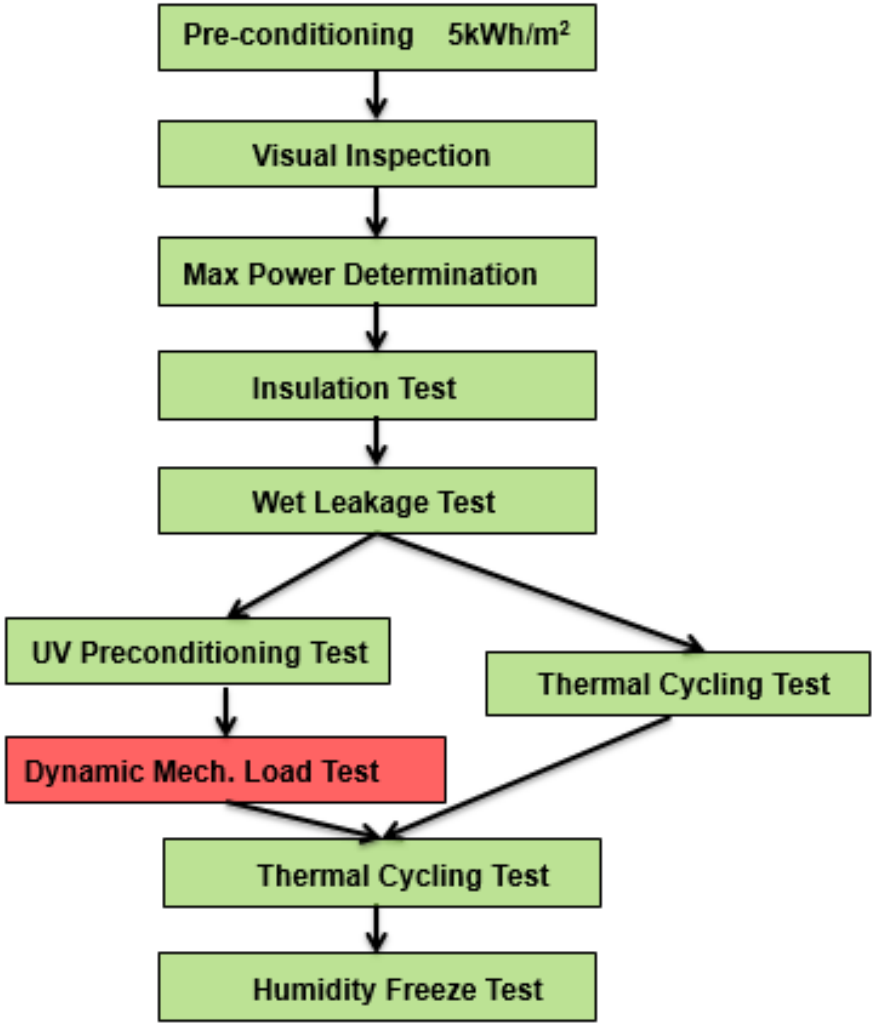
funding total (FY16-FY18): $48M

Novel Accelerated Aging Protocols for Photovoltaic Modules

SunShot U.S. Department of Energy

Novel Accelerated Aging Protocols

- Beyond IEC 61215 testing
  - Addition of dynamic load test leg
- Application of accelerated aging protocols with destructive evaluation (DE) and non-destructive evaluation (NDE) at intermediate steps
- On-sun testing
- Screening PV modules with micro-cracks and other mechanical defects
- Forensic aging analysis
- Recover aged (not failed) modules from commercial installations and correlate performance degradation with accelerated-aged modules



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EPRI ELECTRIC POWER RESEARCH INSTITUTE

Reliability/durability/lifetime: 2016-2018

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Support of International PV Module Quality Assurance Task Force (PVQAT): $10.0M

Manufacturing and Reliability Science for CIGS Photovoltaics: $4M

Degradation Assessment of Fielded CIGS Photovoltaic Module Technologies: $3.0M

Scientific Approach to Reducing PV Module Material Costs While Increasing Durability: $2.5M

Improving PV performance estimates in the System Advisor Model with component and system reliability metrics: $0.6M

From Modules to Atoms: Increasing Reliability/Stability of Commercially-Relevant PV Technologies: $6M

PV Risk Reduction through Quantifying In-Field Energy: $4.5M

Sandia National Laboratories Regional Test Centers Program: $8.3M

Coupled Thermo-Mechanical and Photo-Chemical Degradation Mechanisms - CPV Technologies (PREDICTS, Stanford): $0.6M

Module-Level Exposure and Evaluation Test for PV Modules (PREDICTS2 CWRU): $1.4M

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PV Lifetime Project: $XXX M

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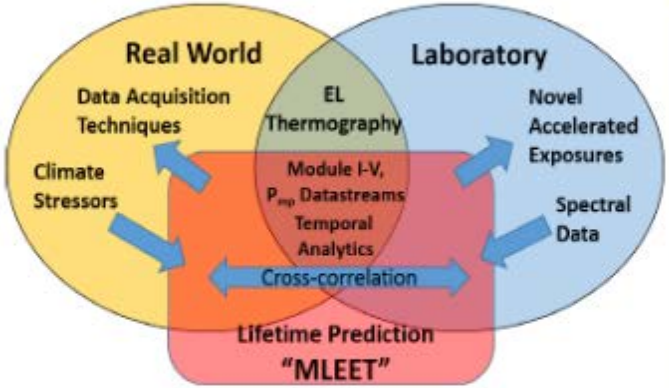
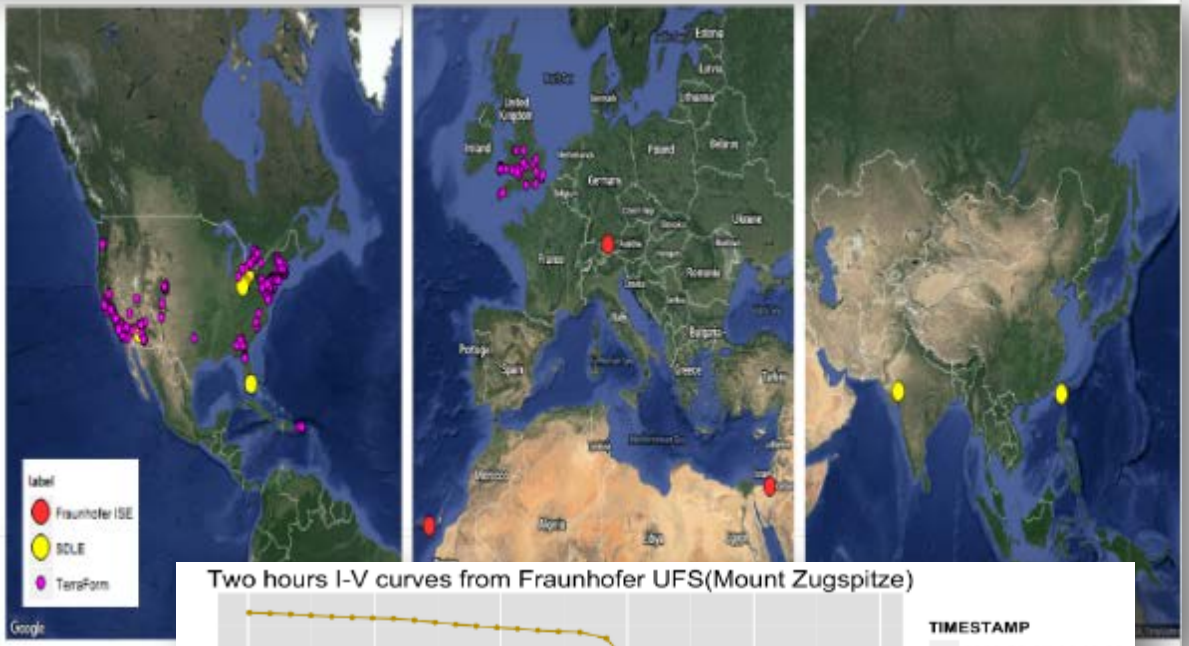
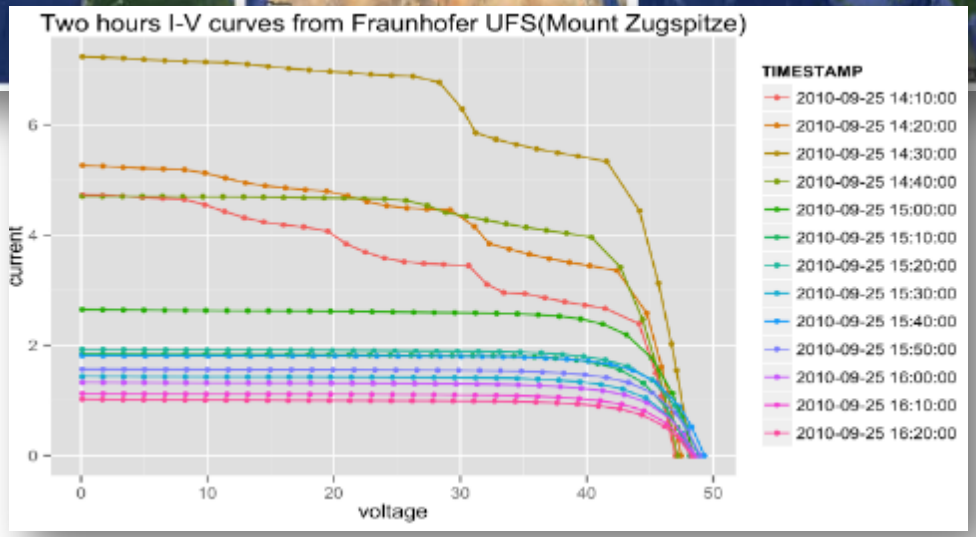
Module-level Exposure and Evaluation







Reliability/durability/lifetime: 2016-2018

SunShot U.S. Department of Energy

Support of International PV Module Quality Assurance Task Force (PVQAT): $10.0M

Manufacturing and Reliability Science for CIGS Photovoltaics: $4M

Degradation Assessment of Fielded CIGS Photovoltaic Module Technologies: $3.0M

Scientific Approach to Reducing PV Module Material Costs While Increasing Durability: $2.5M

Improving PV performance estimates in the System Advisor Model with component and system reliability metrics: $0.6M

From Modules to Atoms: Increasing Reliability/Stability of Commercially-Relevant PV Technologies: $6M

PV Risk Reduction through Quantifying In-Field Energy: $4.5M

Sandia National Laboratories Regional Test Centers Program: $8.3M

Coupled Thermo-Mechanical and Photo-Chemical Degradation Mechanisms - CPV Technologies (PREDICTS, Stanford): $0.6M

Module-Level Exposure and Evaluation Test for PV Modules (PREDICTS2 CWRU): $1.4M

Novel Accelerated Aging Protocols for Photovoltaic Modules (EPRI): $1M

Unified Numerical Solver for Device Meta-stabilities in CdTe Thin-Film PV (PREDICTS, ASU): $0.7M

Generalizable Mechanistic Understanding of Module-level Light-, Moisture- and Thermal-Induced Instabilities in CIGS (PREDICTS2 UI): $1.4M

Non-destructive evaluation of water ingress in photovoltaic modules (PREDICTS2, LLNL): $0.6M

Backsheets: Correlation of Long-Term Field Reliability with Accelerated Laboratory Testing (PREDICTS2 UL): $1.3M

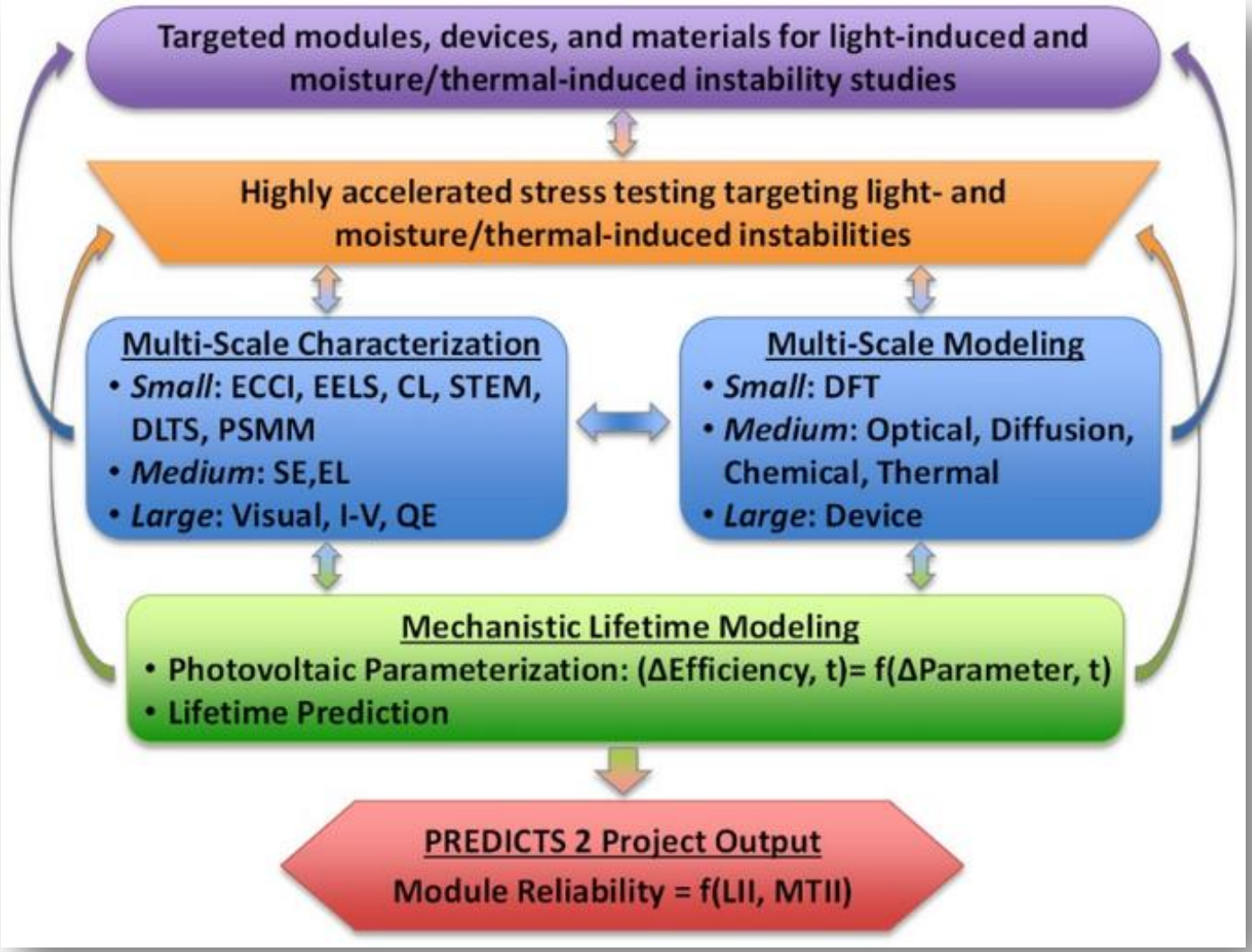
Predictive Models and Novel Accelerated Tests for the Reliability of Cell Metallization and Solder Joints in Photovoltaic Modules (PREDICTS2, SunPower): $1.3M

PV Lifetime Project: $XXX M

funding total (FY16-FY18): $48M

Generalizable Mechanistic Understanding of Module-level Light-, Moisture- and Thermal-Induced Instabilities in CIGS Photovoltaics

UIUC: Angus Rockett
ODU, OSU, MiaSolé High Tech & Solibro



Reliability/durability/lifetime: 2016-2018

SunShot U.S. Department of Energy

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PV Lifetime Project: $XXX M

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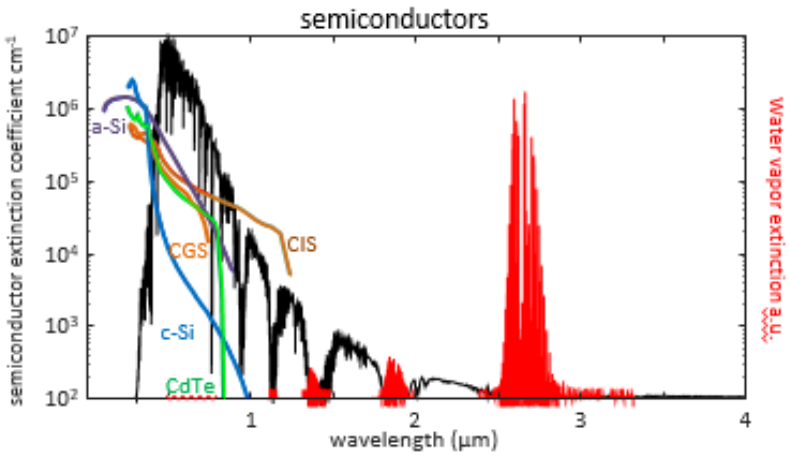
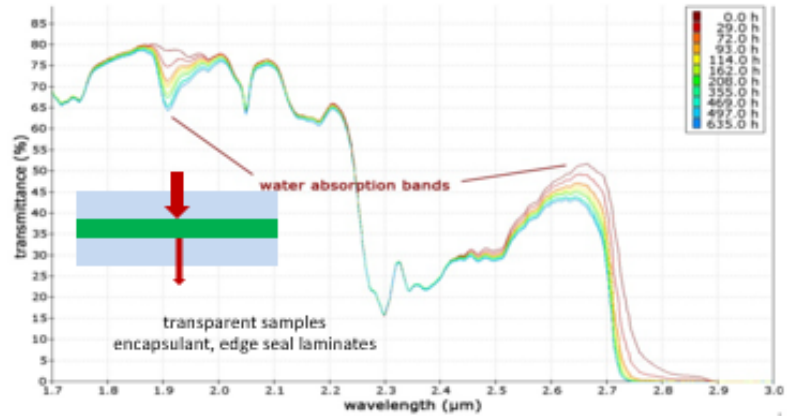
Water content measurement





- Transparency window in photovoltaic modules in the 1-3 µm range is bound by semiconductor and glass absorbance
- Three absorption bands of water at 1.4, 1.9, 2.7 µm will be used to relate spectral measurements with moisture content for field deployed and accelerated tested samples
- In-situ water mapping for c-Si and CIGS modules, transmission and transflection (reflection and double pass transmission)

Reliability/durability/lifetime: 2016-2018

SunShot U.S. Department of Energy

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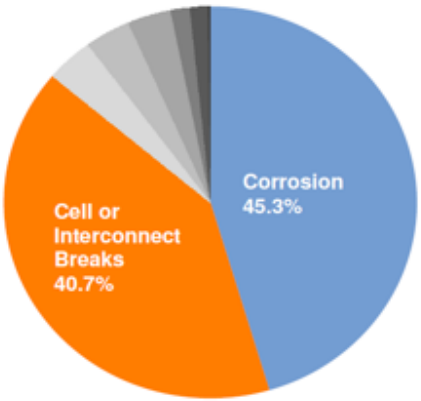
Predictive Models and Novel Accelerated Tests for the Reliability of Cell Metallization and Solder Joints in Photovoltaic Modules

SunPower, NREL

- *Focus:*
  - Metallization corrosion and solder joint degradation.
  - **Front-contact** and back-contact cells.
- *Key outcomes of research:*
  - Predictive models to determine degradation in 25 to 40 years..
  - Accurate and fast accelerated tests useful for qualification, certification, and ongoing reliability.
- *Research Plan: Closed Loop Learning*



Failure mode pareto: >85% are due to interconnect, solder, and metallization failures. (Wohlgemuth, 20th Eur. Photov. Solar Energy Conf. and Exhibition, 2005.)

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U.S. Department of Energy

THE IMPORTANCE OF QA AND STANDARDS IN EMERGING MARKETS

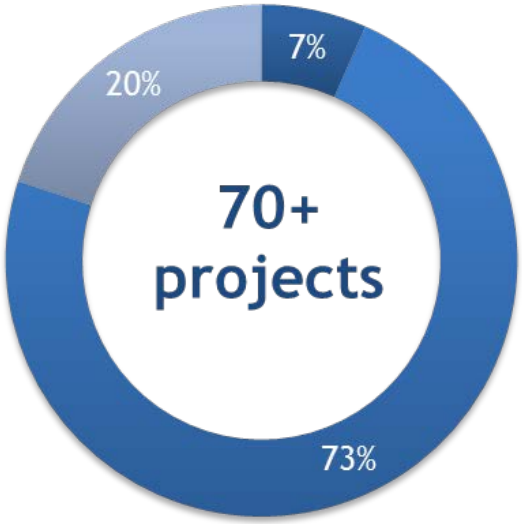
Guido Agostinelli
Senior Industry Specialist

March 6, 2016

The International Finance Corporation (IFC)

IFC is the largest development bank focused solely on the private sector

Part of the World Bank Group, total portfolio of $52 billion, 108 offices in 98 countries



Captive Power
Power Generation
Manufacturing

Solar portfolio and project execution in emerging markets

- More than $1.5bn committed in solar energy assets
- 1.5GWp in PV generating capacity
- Over $300m committed in manufacturing projects
- Financing first-of-a-kind projects
- Established relationships with industry's top tier suppliers, developers, operators, service providers

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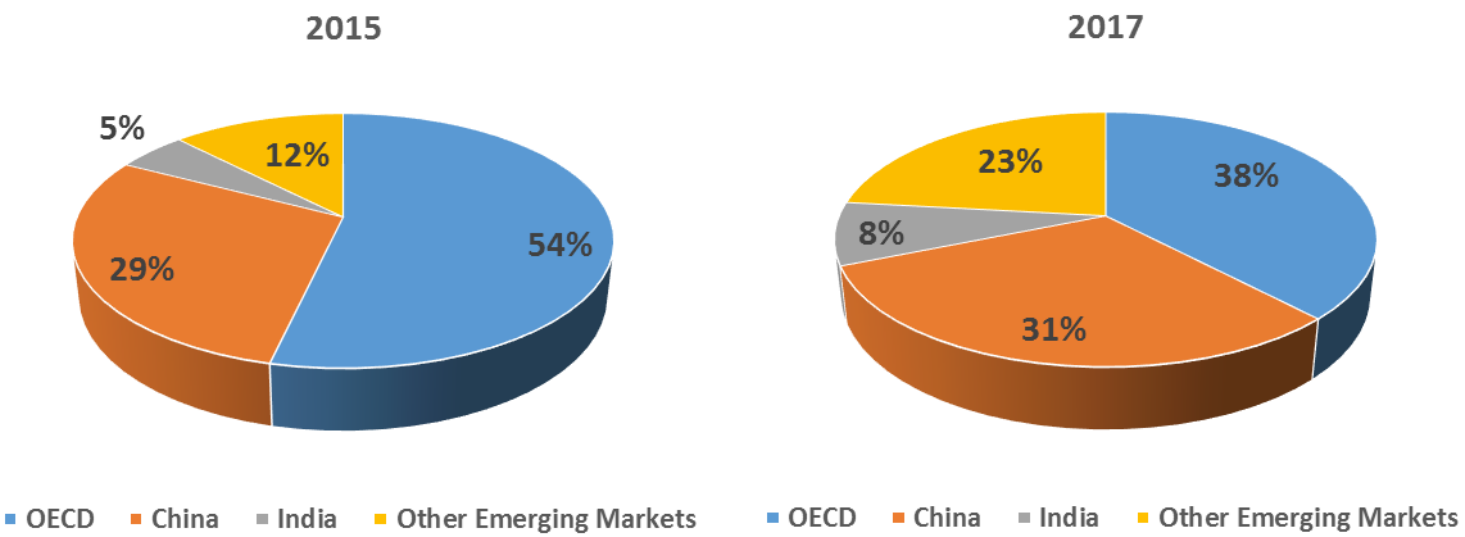
The weight of emerging markets in PV

EMs are rapidly growing to become the driver of global PV demand

Significant market opportunity, exposed to varying degrees of Business risk

Need for adequate diffusion of standards, best practices



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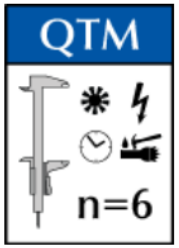
QA: The example of Lighting Global

The Lighting Global QA program provides buyers with reliable technical information on (p)SHS and connects them with manufacturers and sellers of quality-verified products

Lighting Global QA Framework

- Test methods and standards
- Testing and Verification
- Communicating Quality to Market



IEC Technical Specification 62257-9-5, Ed. 2.0

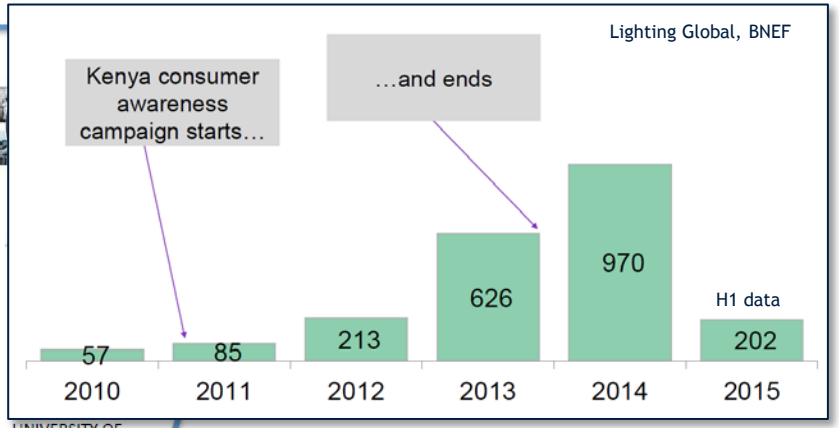
SCHATZ ENERGY RESEARCH CENTER

Fraunhofer ISE

Lighting Research Center

Rensselaer

UNIVERSITY OF NAIROBI



LIGHTING GLOBAL

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Could a similar QA framework be extended to larger PV systems?

Pico- and Solar Home Systems are plug and play consumer products

Each (p)SHS is produced in hundreds of thousands of units

Well defined quality test method (QTM), performed on limited number of samples allows to predict if a (p)SHS will perform as intended

PV systems are engineering solutions

QA need to reach beyond components to include

- System design
- Installation
- Commissioning
- O&M

Why such a stress on Quality?

A Project is considered to be 'Bankable' when its minimum projected cash flow is sufficient to repay the invested capital

A Bankable Project requires bankable sponsors, bankable suppliers, bankable technology

Bankable Technology: a proven technology *solution* for which an investor can precisely estimate *worst case* project yields, system degradation, failures

Yield, degradation, failures are strongly correlated to the Quality and Reliability of the entire solution

Quality and Reliability Standards should be comprehensive and play a key role in *informed* investors' decisions

Investors' awareness

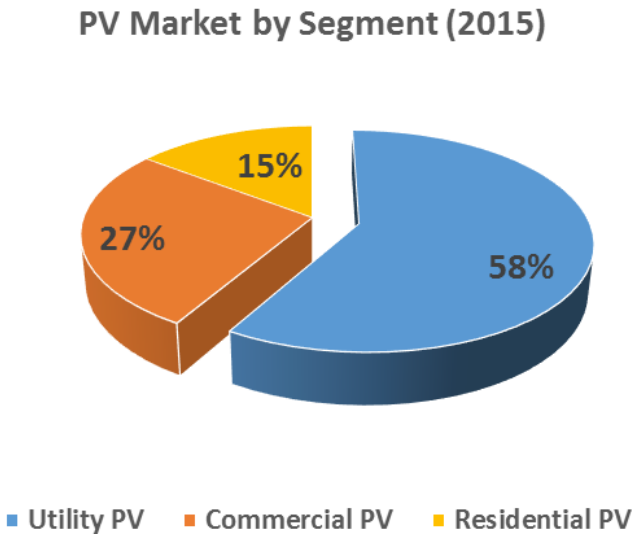
There are sophisticated investors and less sophisticated investors

Quality Standards and Technical Quality Assurance Procedures (PAT, FAT,..) are not necessarily 'transparent' to investors, moreover:

- Many investors perceive quality based on recommendation
  - By a technical advisor
  - By another investor
- Many do not differentiate between quality and reliability, regardless of location or application

There is a knowledge gap, there is asymmetry of information, particularly in new and emerging PV markets; more awareness needed

Market Segmentation



On a global scale, institutional money keeps flowing primarily in the utility scale segment: volumes, professional partners, balance sheets..

Distributed PV systems amount to nearly as large an opportunity and have higher pricing points, but present higher barriers to investments:

<u>Smaller volumes</u>, <u>complex credit risk assessment</u>

Barriers to invest in DG systems

Volumes

- Transaction volumes could be increased by aggregating pools of assets and creating PV portfolios. To be effective this requires a high degree of standardization

Credit risk assessment

- Two types of credit risk: offtake risk and performance risk
- Offtake risk: related to the ability to dispatch electricity and get paid for it
- Performance risk: related to quality, reliability of the entire technical solution and O&M
- Vast majority of DG systems too small to justify cost of technical advisors

Standards?

Certification?

Insurance?

Quality Management?

Training?

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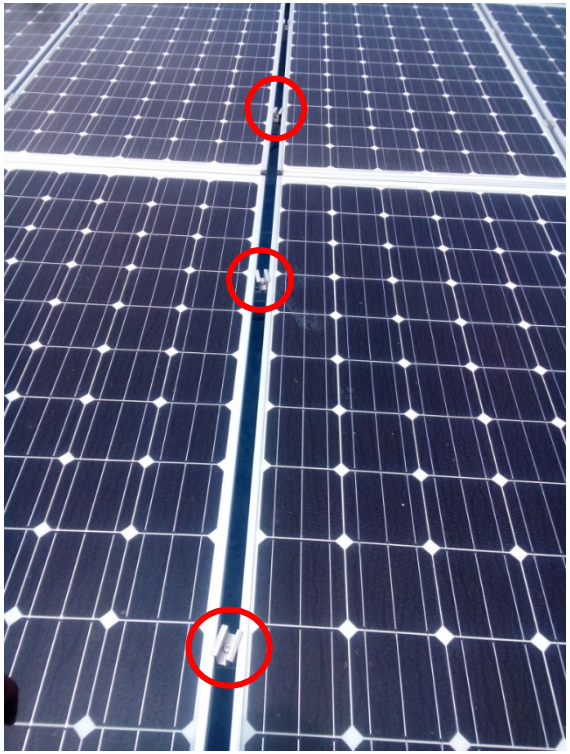
Anecdotal Evidence for the need for adequate diffusion of standards and best practices (1)

Asia - 150kWp PV Rooftop; Top tier modules, inverters

- Components from B/C grade batches, near shading, sub-standard wiring, serious safety issues



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Anecdotal Evidence for the need for adequate diffusion of standards and best practices (2)

Asia - 48KWp PV Rooftop; tender requirement PR>85%

- 1.2 DC/AC ratio, PR calculated on rated AC power; 3rd tier 72 cells/300Wp modules with multi-tiered performance guarantee

Africa - 350kWp PV Rooftop; excellent build

- Poor solar resource assessment, no Irradiance sensors, no meteo data, no PR measurements, monitoring and reporting limited to meter readout

Implementation of QS in emerging markets

The objective is to have an effective Quality System in place, asap

Key issues to be considered:

- QS rely on standards, but PV standards are often unknown in end markets as well as to key stakeholders
- IEC standards going through major revision
- Some major gaps yet to be filled, e.g. how to address quality of installations for smaller projects
- QS need to strike a reasonable balance between quality complexity and costs, if they are to be widely adopted. Particularly true for emerging markets.

Possible solutions: operational manuals largely based on IEC standards, training programs with ratings for installers

Need for coordinated action, as opposed to various entities (reputable institutes) working solo with public stakeholders and coming up with dozens of different operational manuals & technical specs

PV system certification – would it be relevant?

Private transactions related to large scale systems (> ~5MWp)

- Maybe/maybe not: typically technical advisors provide sufficient comfort to stakeholders on whether they can proceed with a transaction or not

Private transactions related to small/medium scale systems (~1kWp-5MWp)

- Yes: systems too small to justify cost of technical advisors.
  But, can the certification process be cheaper and reliable?

Other situations in which it could matter

- Secondary PV market
- Insurances (e.g. performance insurance) and secondary financial instruments
- Retail Finance

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Outlook & Conclusions

QS and standards would play a key role in accelerating the development of emerging PV markets and catalyzing, scaling investments

It's where best practices don't exist yet that the dissemination of standards can have the greatest impact

What we lack though is a fast, minimal, convenient tool to rate PV systems and mitigate performance risk

Awareness and communication campaigns play a major role in the implementation of QS which is often overlooked

Thank you

Email: gagostinelli@ifc.org

Potential Methods to Streamline Data Communications in the Solar Power Industry and Benefits
February 23, 2016

SGIP PAP25

XBRL-CET Working Group
SGIP PAP25
Mission Statement

XBRL-CET Construction Energy Transportation

Provide specific “Data Sets” to enable data interoperability between systems

Solar System Construction

Progress Payments

Energy Interconnection

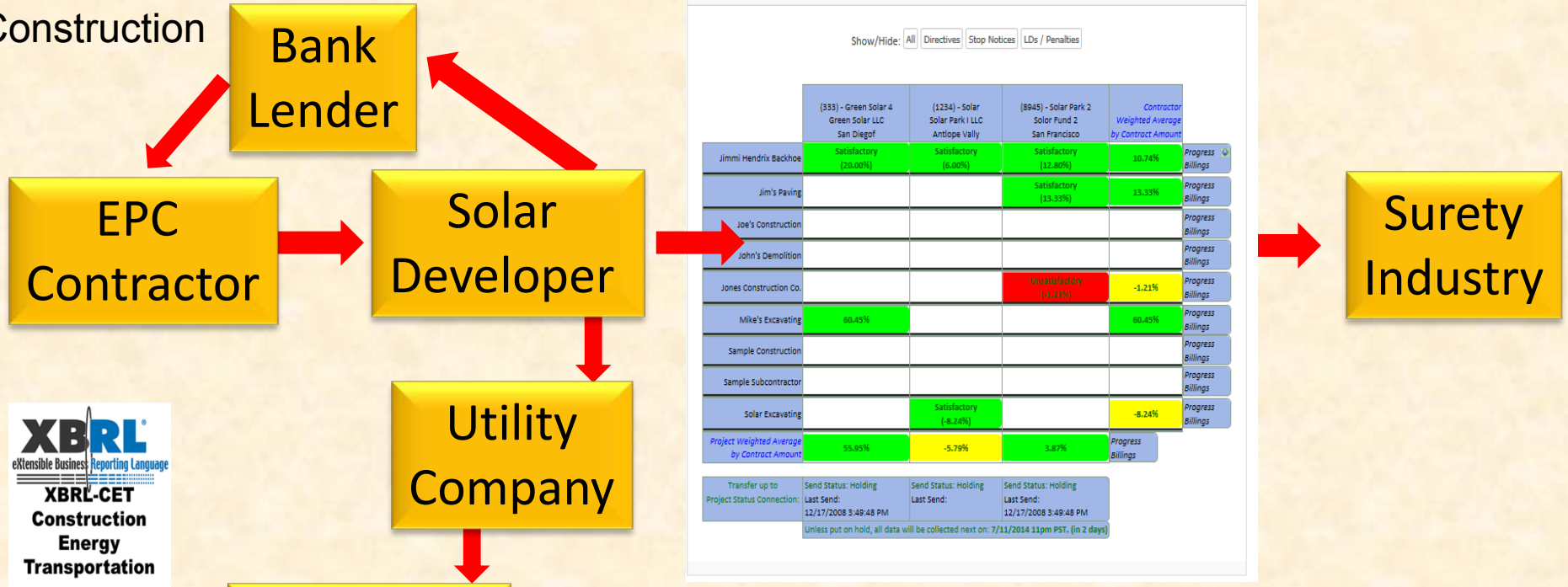
Solar System Operation

IECRE RENEWABLE ENERGY

PV OMC
Working Group 404

Progress Payments – Performance Measurement

Solar System Construction



Progress Payments

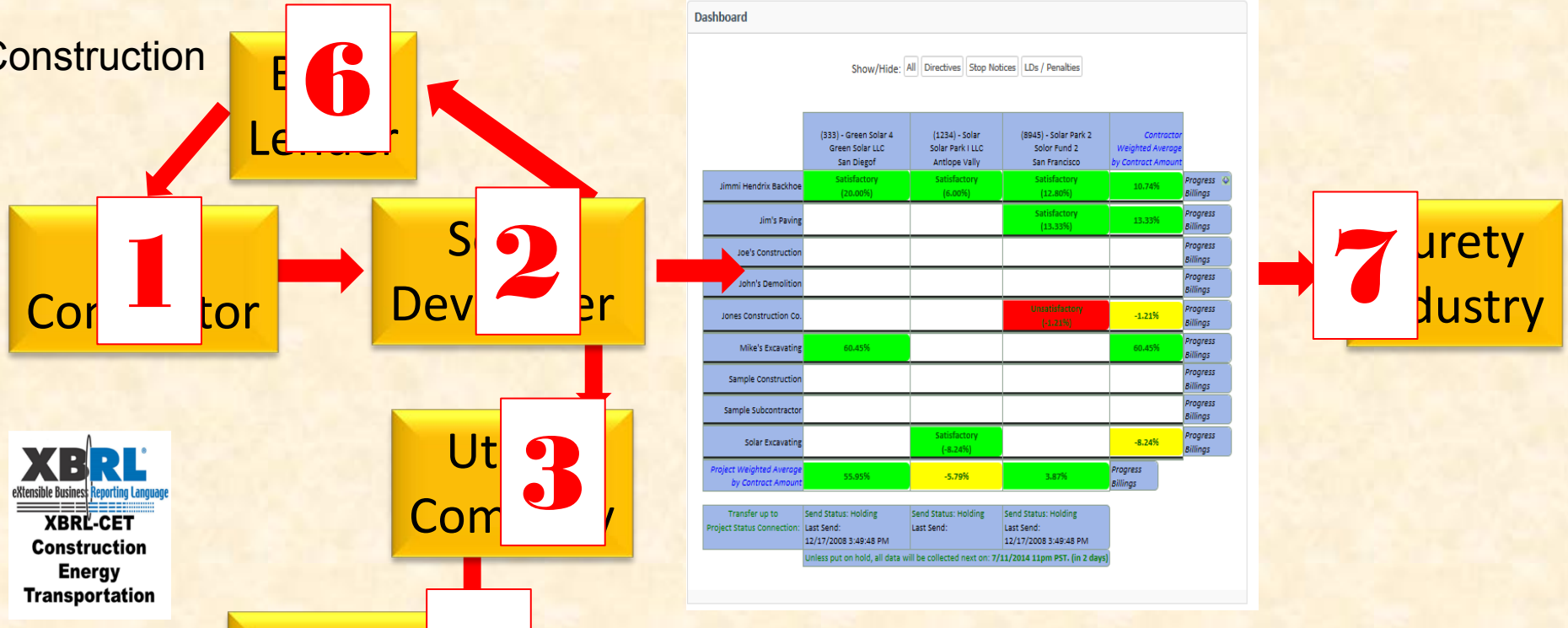
Energy Interconnection

U.S. DEPARTMENT OF ENERGY

DIGITAL ACCOUNTABILITY & TRANSPARENCY ACT

Progress Payments – Performance Measurement

Solar System Construction



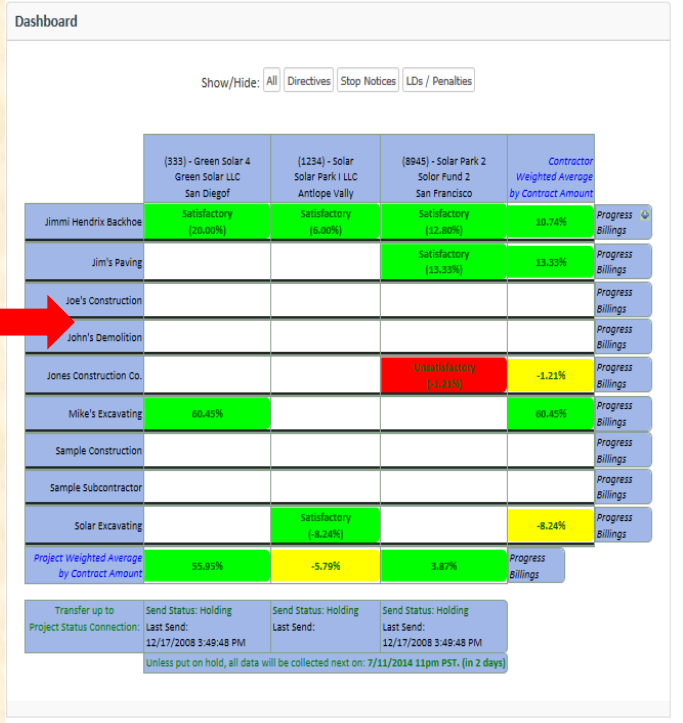
Progress Payments

Energy Interconnection

System Performance Measurement – IECRE 61724

Solar System Operation

Solar Developer



Dashboard

Show/Hide: All | Directives | Stop Notices | LDs / Penalties

	(333) - Green Solar 4 Green Solar LLC San Diegof	(1234) - Solar Solar Park I LLC Antlope Vally	(8945) - Solar Park 2 Solor Fund 2 San Francisco	Contractor Weighted Average by Contract Amount	
Jimmi Hendrix Backhoe	Satisfactory (20.00%)	Satisfactory (6.00%)	Satisfactory (12.80%)	10.74%	Progress Billings
Jim's Paving			Satisfactory (13.33%)	13.33%	Progress Billings
Joe's Construction					Progress Billings
John's Demolition					Progress Billings
Jones Construction Co.			Unsatisfactory (-1.21%)	-1.21%	Progress Billings
Mike's Excavating	60.45%			60.45%	Progress Billings
Sample Construction					Progress Billings
Sample Subcontractor					Progress Billings
Solar Excavating		Satisfactory (-8.24%)		-8.24%	Progress Billings
Project Weighted Average by Contract Amount	55.95%	-5.79%	3.87%	Progress Billings	

Transfer up to Project Status Connection:	Send Status: Holding Last Send: 12/17/2008 3:49:48 PM	Send Status: Holding Last Send:	Send Status: Holding Last Send: 12/17/2008 3:49:48 PM

Unless put on hold, all data will be collected next on: 7/11/2014 11pm PST. (in 2 days)

IECRE 61724

Partners

Bank Lender

Surety & Insurance

Utility Company

Future Buyer

Investors

Solar Bankability Data

Data for Individual Panel
and Panel Array Performance

What we knew Yesterday

What we will know tomorrow

Not Working
Working

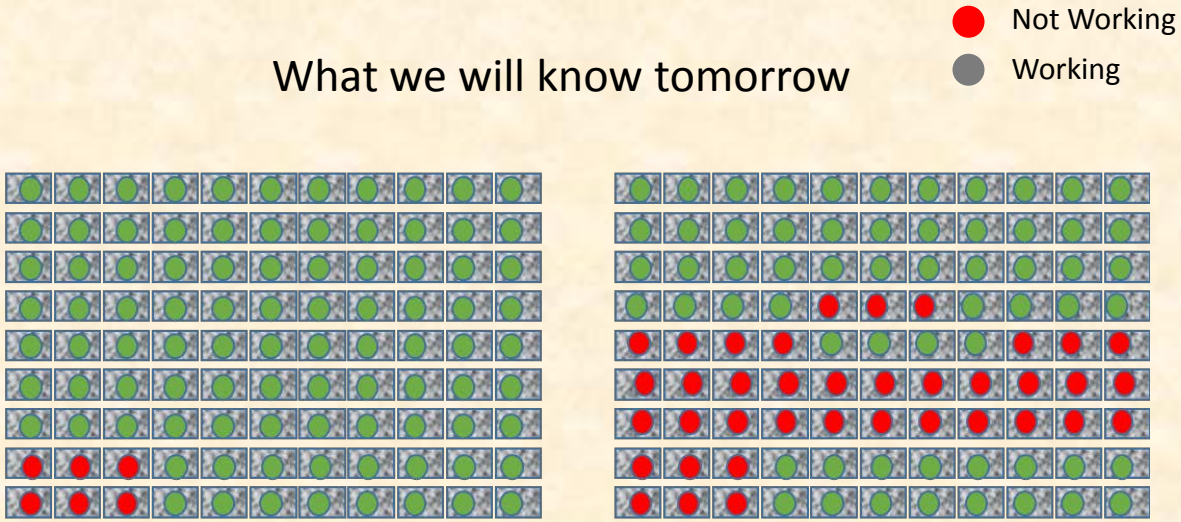
Question: Which Panel Array of Tomorrow Will Get Better Financial Terms

Answer: The One Whose Data Can Demonstrate Predictable Performance

= Solar Bankability Data

The Connection between Cost and PV Reliability

What we will know tomorrow



Question: Which Panel Array of Tomorrow Will Get Better Financial Terms

Answer: The One Whose Data Can Demonstrate Predictable Performance

= Solar Bankability Data

Method to Streamline Data Communication in the Solar Power Industry and Benefits

Jon Previtali, K. Dixon Wright
2016 PV Module Reliability Workshop, NREL

Summary

Wells Fargo has financed over 300 DG and utility scale solar power projects since 2007. Its portfolio sums to over 350 MW. The bank also provides substantial surety bonds to support construction of solar power projects. As these business lines have grown, the bank has experienced business continuity issues due to obstacles to data processing needed to monitor construction progress, ongoing financial performance, energy production and operations. It also has seen issues stemming from QMS (quality management system) data from module manufacturers through its factory audit procedures. Streamlining data communication within the solar power industry between collaborating firms' business systems using standard, open source data communication tags from sources such as XBRL, IEP XML, the Green Button program and BuildingSync (a subset of BEDES) would facilitate construction performance bonding, project finance, asset management, and sales and acquisitions of solar power projects.

The Big Data Challenge

The cost to a project financier of manually acquiring and processing data is material, but not large compared to profit margins for wind and solar projects. However, the difficulty of this work hinders growth because it relies heavily on highly trained staff and thus is not easily scalable. The issue also creates barriers to information sharing that hinder sales of projects to less experienced investors, an activity that would unlock more funding from the handful of financiers supporting new construction. The overall cost of manual data handling to the entire industry is likely adding significant cost to the price of solar, particularly DG.

Case Study 1: *Impact of Data Issues to Solar Power Finance*

Project Origination & Due Diligence

Ten staff support project origination and due diligence. Funding each project requires review of about 100 documents, information sharing between over a dozen organizations (see Figure 5) and generally the creation of at least three bank accounts: revenue, expenses, reserves.

Portfolio Management

The bank has eight staff supporting portfolio management of its renewable energy portfolio that includes both wind and solar power projects. They work with asset managers generally employed by project sponsors and third-party collateral agents who manage operations and financial transactions. Portfolio managers monitor energy production, financial performance and financial transactions . They update reports manually on a quarterly basis and write more fulsome reviews of project funds annually using monthly operating reports they receive from project sponsors and bank statements from over 900 accounts. The work is arduous.

Until 2014, monitoring of solar power assets included tracking lease payments, energy production, plant operations and credit ratings of PPA counterparties, equipment companies and operators, but reports did not include ongoing revenue and expenses thus it was difficult to see declining profitability. In late 2013, lower than expected revenue projections for a non-solar renewable energy investment fund came to light. Although the issue was unavoidable, the timing of its discovery was slower than desired. The bank financed about 40 MW of solar power projects in 2014 that had been previously committed to, but renewable project origination (wind and solar) was suspended while internal reviews were conducted, a new financial reporting process was developed and new portfolio management staff was hired.

The new process took about a year to bring online during which no new wind or solar power projects were accepted for financing. It is hard to say how much solar investment opportunity was lost in 2014. Wind power investment was flat after adding about 1 GW per year over the last 4 years. New project finance was reinitiated in early 2015 and the bank is back on track.

The new financial reporting process relies on spreadsheets, business systems and people who receive unique training. Data is obtained manually from a range of sources that include PDF documents, spreadsheets and bank portals, and then manually entered into data models from which analyses and reports are generated. System integration with third-party databases (the sources of data) is hindered by security requirements and the large disparity of data formats. A result of the time required to perform this work and its lack of scalability has been a hesitancy to finance significant number of distributed generation projects compared to the utility scale projects.

Case Study 2: *Identifying a Module Quality Issue Using Data*

Wells Fargo organizes inspections of module factories and manufacturing processes prior to and during module production. This work includes the manual review of Quality Management System (QMS) data. A module factory inspector noted an anomaly in the time stamp of an electroluminescent (EL) image file. Upon investigation a duplication of one of the cells intended to hide a cracked cell was discovered. A root cause analysis found that technicians were being compensated by the number of modules passing EL inspection. The manufacturer ceased this form of incentive and locked down imaging software to prevent manipulation. Approximately 100 EL images taken of modules undergoing accelerated age testing at an independent test lab were compared to factory images and no other alterations were found.

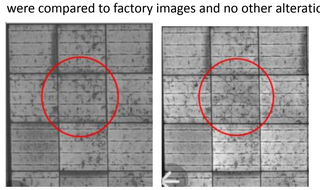


Figure 1: PV EL images altered to hide cracks.

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Wells Fargo Insurance Services USA, Inc.
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Dixon.Wright@wellsfargo.com

Case Study 3: *Streamlining Construction Work on Hand Reports*

Wells Fargo offers construction performance bonding to the solar power industry in the form of surety bonds. Sureties require regular updates on construction progress using Work on Hand (WOH) reports. Traditionally, WOH reports have been delivered in a wide range of formats resulting in logistical challenges for construction staff who assemble the report and for the bank and surety underwriters. XBRL-CET is leveraging the XBRL data taxonomy to turn the WOH report into a data file that can be uploaded for the surety to review. The same data can be used by construction lender's to release progress payments and by utilities to streamline the interconnection process. See Figure 2.

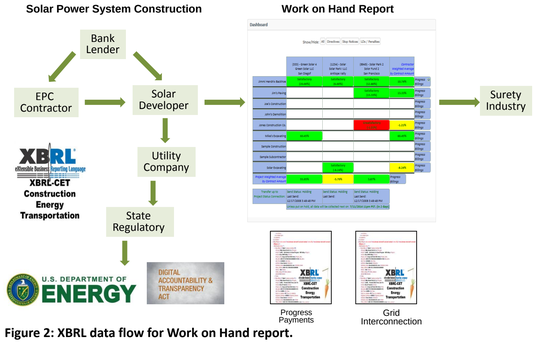


Figure 2: XBRL data flow for Work on Hand report.

Method Proposed

The problem could be solved if the solar power industry adopted a defined set of terms and data tags and then used them to automate data communication between business systems and streamline data collection from people, e.g. with web-based forms. See Figure 3. System integrators are familiar with this sort of work. For example, XBRL is an XML-based data language required for use by all public companies when submitting forms to the SEC. Although some new terms and tags will need to be created, a whole new data language is not needed because four taxonomies (dictionaries) of defined terms with XML tags exist that can be used for most data communication for solar power projects (please see Resources). One of the languages, IEP XML was developed specifically for solar power projects.

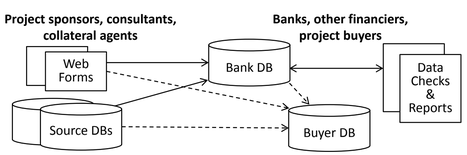


Figure 3: Proposed industry-wide system integration using common, open source data tags.

Resources

Open source data tag dictionaries

1) XBRL – accounting and more (the catch-all), used worldwide and for all SEC filings
- 2016 US GAAP Financial Reporting Taxonomy, ttps://xbrl.us/xbrl-taxonomy/2016-us-gaap/

2) IEP XML – solar power and energy efficiency project components
- Integrated Energy Project Portal, http://www.iepmodel.net/

3) Green Button – consumer Smart Meter reporting
- Application developer resources, http://www.greenbuttondata.org/build/

4) BuildingSync (based on **BEDES**) – building energy audits
- See link to XML schema, http://www.nrel.gov/buildings/buildingsync.html

Other Resources

XBRL-CET (Construction Energy Transportation) Working Group, http://www.xbrl-cet.com/

BEDES (Building Energy Data Exchange Specification)
- Dictionary of English terms (not XML tags), definitions, and field formats, http://energy.gov/eere/buildings/building-energy-data-exchange-specification-bedes

Technology	Site	Name of the site
	Location	Name of town, state
	Type Interconnection	Behind the meter / In front of the meter
	Type Installation	Ground / Carport / Rooftop
	Type Mounting	Fixed Tilt / 1-Axis
	Capacity	In kWp DC and AC
	Energy Production	GHI
		Net Energy Yield
		Year 1 PR
		Year 1 Output
		Availability
		Degradation
	Modules	Manufacturer
		Model
		Warranty terms
	Inverters	Manufacturer
		Model
		Warranty terms
	Tracker	Manufacturer
		Model
		Warranty terms
	Collection Substation	GSU Specs
		Interconnection Voltage
		Length of Gen Tie line
	DAS / SCADA	Name and type of DAS / SCADA system
		Communication lines
	Meteo Station	Is there a met station at the site
	Security	Summarize security provisions (i.e. fence, cameras, on site staff,...)

Figure 4: Example of data collected during project due diligence for asset management (list under development).

Example Solar Power Project Timeline

			Year	Month												Year			
								Project Finance Period											
								Sale Lease-Back											
								Partnership Flip											
Activities			**varies**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**7**	**20**	**30**	**31**	**60**	**61**
Project Development																				
Engineering																				
Land Lease Payments																				
Permitting																				
Equipment Procurement																				
Equipment Manufacturing																				
Module Factory Inspections and Accelerated Age Testing																				
Construction																				
Construction Financing																				
Project Finance Due Diligence																				
Commissioning																				
Performance Testing																				
Energy Sales																				
Operation & Maintenance																				
Asset Management (Primary)																				
Asset Management (Project Financier)																				
Finance Payments																				
Recommissioning																				
Decommissioning																				

Approximate Count of Documents or Data Files

Source Organization*	Project Financier Due Diligence (delivered once)	Project Financier Asset Management (delivered periodically, count per year)																		
Project Developer and/or Sponsor	38	-	1	-	-	-	-	-	-	1	6	14	14	3	-	-	-	-	-	5
Interconnection Utility	1	-	1	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	1
Land Owner	1	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	1
Power Offtaker 1	1	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Independent System Operator	1	-	1	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	1
Engineering, Procurement, Construction (EPC) Contractor	30	-	-	9	6	4	2	1	1	1	1	1	2	2	-	-	-	30	-	10
Project Financier	20	-	-	-	-	-	-	-	1	2	4	5	5	3	-	-	-	20	-	-
Module Factory Inspector	12	-	-	-	-	-	-	-	-	-	2	4	4	1	-	-	-	12	-	-
Law Firms (Project Sponsor, Project Financier)	11	-	-	-	-	-	-	-	-	-	2	4	4	1	-	-	-	11	-	2
Independent Engineer (Project Financier)	6	-	-	-	-	-	-	-	-	-	1	1	2	2	-	-	-	6	-	-
Module Performance Test Lab	3	-	-	-	-	-	-	-	-	-	-	1	1	-	-	-	-	3	-	-
Pricing Consultant	3	-	-	-	-	-	-	-	-	-	-	1	1	-	-	-	-	3	-	-
Appraiser	2	-	-	-	-	-	-	-	-	-	-	1	1	-	-	-	-	2	-	-
Transmission/Curtailment Consultant	1	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	1	-	-
FERC (large utility scale only)	1	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-
Operator and/or Primary Asset Manager	13	12	-	-	-	-	-	-	-	-	-	-	-	12	12	12	12	-	12	-
Insurance Provider	3	1	-	-	-	-	-	-	-	-	-	-	-	3	1	1	1	-	1	-
Project Collateral Agent/Bank	1	4	-	-	-	-	-	-	-	-	-	-	-	1	4	4	4	1	4	1
REC Tracking System	1	4	-	-	-	-	-	-	-	-	-	-	-	1	4	4	4	-	4	-
Project Trustee	1	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	1	-	1
Insurance Consultant	1	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	1	-	-
Collateral Agent	1	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	1
Power Offtaker 2	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-

Project Financier Level of Effort

Documents or Data Files per Period								22	2	4	16	32	36	34	147	273				
Handling & review time per period (hrs)								22	2	4	16	32	36	34	74	137				
Cost per period ($)								1,925	175	350	1,400	2,800	3,150	2,975	6,431	11,944				
Total Documents or Data Files								22	24	28	44	76	112	146	293	566				
Total handling & review time (hrs)								22	24	28	44	76	112	146	147	283				
Total cost with inflation ($)								1,925	2,100	2,450	3,850	6,650	9,800	**12,775**	**15,765**	**30,455**				

Approximate LCOE Impact ($/kWh)

Project Size (kWdc)	**Partnership Flip**	**Sale Lease-Back**
500	0.000842	0.000814
5,000	0.000084	0.000081
50,000	0.000008	0.000008

Approximate Staff Impact

Portfolio Size (# projects)	**Cost ($)**		**Staff Count (FTE)**	
	Project Finance Due Diligence	Asset Management per Year	Project Finance Due Diligence	Asset Management per Year
5	63,875	9,156	0.4	0.1
50	638,750	91,563	3.7	0.5
500	6,387,500	915,625	36.5	5.2

Assumptions	
Typical time to handle & review document or data (hrs)	
Project finance due diligence	1
Asset management	0.5
Typical fully loaded staff cost per year ($)	175,000
Typical fully loaded staff cost per hour ($)	88
Inflation	3%
Energy Yield (kWh/kWdc/year)	1,400
Power Degradation Rate (%/yr)	0.75
Expected Useful Life (yrs)	30

***Additional parties in a typical project**
Performance Bond/Surety Provider
Law Firm (Project Developer)
Law Firm (Project Sponsor)
Law Firm (Construction Lender)
Independent Engineer (Construction Lender)
Construction Lender

Figure 5: Impact of manual document and data file handling on solar project finance activity.

EPC	Effective Date	Date on which agreement was executed
	Contractor	Name of legal entity
	Type Contract	I.e. Fixed price turnkey
	Contract Price	Price in $ and $/W, taking into account change orders
	Scope of Work	Is procurement included?
		Does it cover the collection substation, gen tie line, work at the utility substation?
		Does it include spare parts?
	Major Subcontractors	List major subcontractors (if known)
	Milestone Dates	NTP Date
		Target and actual Substantial Completion
		Target and actual Final Completion
	Guaranties	Guaranteed completion dates, delay LDs, cap on LDs
		Guaranteed capacity, capacity LDs, cap on LDs
		Guaranteed P.R. or availability,...
	Warranty	Term of workmanship warranty
		Type of warranty (full wrap, pass-through)
	Cap on Liabilities	Pre- and post substantial completion
	Financial Assurances	Describe financial assurances delivered by contractor (i.e. parent guaranty, Standby LC, surety bond,...)
Regulatory	Power Market	Name Power Pool (i.e. CASO, SPP)
		Nature of the power market (bi-lateral, open)
	QF / EWG Status	NA, QF or EWG, when obtained
	FERC 205	Does the project have Market Rate Base Authority, if so, when obtained
	FERC 203	Status of FERC 203 approval, target date
	PUC Approval	Status, when was approval obtained
Environmental	Type Site	Describe nature of the site (i.e. fallow land, agricultural land, landfill,...)
	Acreage	Acreage of the site
	ESA	Date of Phase I ESA report
		Name consultant
		Where there any RECs?
	Environmental Impact	Was there an environmental impact study?
		Major conclusions & recommendations in the study
	Cultural & Biological Resources	Are there any critical cultural or biological resources identified on the site
		Mitigating measures
	Natural Disasters	Proneness to EQ risk, flood risk, wildfires, windstorms
Zoning / CUP Permits	Date	Date on which CUP was issued
	Issuing Authority	Which regulatory entity issues permit (i.e. county,...)
	Term	Term of the permit
		Renewal Options
	End of Term Provisions	System removal & site restoration obligations
		Financial security for the above
	Restrictions	Summarize restrictions placed on use of site
	Fees	Any up front or recurring fees
Site Control	Type Control	Ownership, leasehold interest, easements, combination,...
	Contractual Structure	# of Deeds of Trust
		# of Site Leases
		# of Easements as Grantee
		# of Easements as Grantor
	Minimum Term	Minimum Term across all leases, easements and crossing consents
	Rent	Sum of all up-front rent payments across leases, easements and crossing consents
		Sum of all rn of recurring annual rent payments across leases, easements and crossing consents
	Title Policy	Title company
		Date of the policy
		Insured value
		Major exceptions in policy

Site Lease	Redacted	
PPA	Redacted	
Interconnection	Effective Date	Date on which the agreement was executed
	Utility	Name of the utility
	Customer	Is the site host or the project company the customer?
	Type Interconnection	Behind the meter, to distribution grid, to transmission grid
	Interconnection Voltage	Interconnection voltage (ie. 480 V, 122 kV)
	Term	Term of the agreement
	Net Metering	Does the agreement allow for grid injections
	Resource Status	Does the project have network or energy resource status?
	Curtailment	Summarize curtailment provisions in the agreement
	Point of Interconnection	Name of substation
	Point of Change of Ownership	Who owns the collection substation, the gen tie line, the transmission substation
	Network Upgrades	Describe upgrades
		Estimated cost
		Cost responsibility
		True Up process & timing
		Who's building the upgrades
	Maintenance	Who's responsible for cost of substation maintenance
		Estimated cost
	Financial Assurances	Type, amount & cost of financial assurances
O&M	Effective Date	Date on which the contract was executed
	Commencement Date	Date on which the services start
	O&M Contractor	Name of the contractor
	Term	Initial term
		Renewal provisions
	Termination Provisions	Can the contract be terminated for convenience
		Break up fee
	Scope of Work	Frequency of preventive maintenance
		Is corrective maintenance covered (parts & labor)?
		Is high voltage work covered
		How many panel cleanings
		Is vegetation abatement covered
		Is civil works / road maintenance covered
		Is snow removal covered (panels, roads)
		Is site security covered
		Is DAS / SCADA fee covered
		Is telecom fee covered
	Fee	Annual fee and escalator
		Billing & payment terms
		Payment withholding provisions
	Guaranties	Production or availability guarantee
		Guaranteed level
		Settlement frequency
		LD calculation
	Cap on Liabilities	For O&M indemnities
		For performance guaranty
ECCA	Redacted	
LLCA	Redacted	
MPA	Redacted	
Continuity of Operations	Redacted	
MSA	Redacted	
Lender's Consent	Redacted	
Construction Forbearance	Redacted	
Back-Leverage Forbearance	Redacted	
Sponsor Guarantee	Redacted	

TRENDS IN
SOLAR PV MODULE BANKABILITY

Project stakeholders rely on impartial third-party bankability assessments of potential solar PV equipment to provide an understanding of their risk exposure before investing in significant solar PV projects. During the past five years, Black & Veatch has completed more than 100 assessments of solar PV module manufacturers and their products, representing over $200 million in solar investments. The following highlights trends in solar PV technology and manufacturing that are having an impact on bankability.

Limited Performance Data

While unbiased performance data availability is limited, Black & Veatch has seen mixed results from manufacturers. However, manufacturers report limited warranty claims.

More Global Module Manufacturing

While most manufacturing currently occurs in China, lack of capacity and increased U.S. government regulations on Chinese PV modules are leading to an increase in manufacturing across Southeast Asia, India and other areas.

Component Quality Assurance

Manufacturers are working to decrease costs of their solar PV panels. Sources for parts used during manufacturing are shifting from well-known Western companies to lesser known Chinese sources, generating concern for the quality of these components.

Evolving Designs

Leading PV module offerings contain 60 or 72 six-inch polycrystalline silicon cells. Module manufacturing has seen several improvements, including the expansion of automated cell tabbing and stringing and electroluminescence (EL) testing. In addition, junction boxes have improved to address some failures modes.

Increasing Conversion Efficiency

Solar PV module conversion efficiency has increased from approximately 14.5 percent in 2010, to approximately 16.2 percent in 2015. Maximum system voltage has also grown, from 600 Volts to 1,500 Volts.

BANKABILITY STUDY COMPONENTS

Black & Veatch's bankability studies take into consideration technical and commercial factors developed through extensive knowledge of the solar PV industry.

- Will the product meet the manufacturer's technical specifications?
- Are quality materials from reliable sources and the highest manufacturing standards being used by the manufacturer?
- How reliable is the product?
- How will performance change over time?
- Can the warranty be trusted to compensate the buyer if the equipment does not meet its technical specifications?

PV MODULE RELIABILITY FROM AN OWNER'S PERSPECTIVE

D. Shively and J. Lars Dorr

Clēnera

Abstract

As a developer, owner, and operator of over 500 MW_{DC} of utility-scale PV solar projects, reliability and consistency is paramount to our business. We maintain a thorough process and stringent requirements for component selection. This extends from field data and factory audits to contractual obligations and warranty riders. Many times in the industry, a develop-flip structure has been employed which typically results in a project that is designed, permitted, and even contracted under conditions that do not present the best configuration nor the lowest LCOE but provide a potentially attractive, turn-key project to sell. By maintaining the perspective of lifetime cost, reliability and performance assurance become even more critical.

About Clenera

Clēnera is an end-to-end utility-scale solar development and asset management service provider. The Company relies on the deep solar expertise of its executive team and staff to identify the industry's best projects and then manage those same projects from pre-construction acquisition through construction and into commercial operations.

Performance Modeling

- Congruence with Independent Engineers
- Condition-specific performance metrics – soiling, shading, temperature, humidity
- Degradation benchmarks obligated by contract

Vendor Selection

- Industry diversification – stable balance sheet
- Price – must be cost competitive
- Technology offering and roadmap – plans for new technology and efficiencies
- Third-party factory inspection – must cooperate with factory audit and QA/QC
- Thorough internal Quality Process
- Shipping & handling – reliable and consistent between contract and delivery
- Track record – real world performance data to support contractual assertions
- UL certification
- Successful IEC testing

Degradation Modes

- Soiling
- Shading – row-row spacing, land use efficiency, flexibility in site design
- Micro-cracks – bending of modules
- Snail trails
- Bubbles
- Quality during shipping and handling
- Bullet holes

PV Project Owner & Operator Concerns

Module Warranty

- Full Wrap – Replacement at OEM cost for first five years (including labor and shipping)
- Documented and guaranteed degradation schedule
- Spare parts – 100 module inventory on-site

Future Technologies of interest

- Higher voltage – 1500V and up
- Bifacial
- Advanced CIGS
- Higher efficiency – reduced BOP
- Multi-PERC
- Glass/glass

2016 NREL PV Module Reliability Workshop
February 2016

Importance of Quality and Reliability for SolarCity

Andreas Meisel, Karen Natoli Maxwell

SolarCity

2016 NREL Photovoltaic Reliability Workshop
February 23, 2016

Golden, Colorado

SolarCity

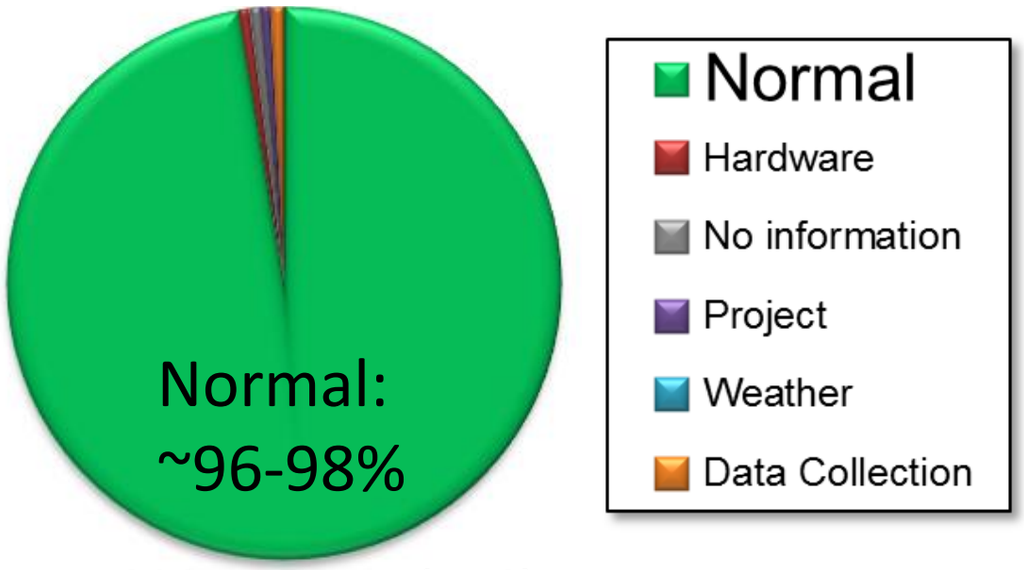
Outline

- Quality Risks in the Solar Industry
- Doing It the Right Way – SolarCity Total Quality Program
- How SolarCity's Program is Paying Off

SolarCity

Meta-Analysis Shows PV Systems Perform Quite Well

Year 3 – 4



5,800 systems (Yr 3)
480 systems (Yr 4)

D. Jordan, S. Kurtz, IEEE, 2015.

Collection of field degradation rates
(2,000 rates spanning 40 years):

	Median P(50)	P(90)
Module	0.50% / yr	1.13% / yr
System	0.77% / yr	1.48% / yr

(D. Jordan and S. Kurtz study, 2012.
Data analyzed and filtered by DNV GL, 2015)

- Only 2-4% of all systems have performance-related issues
- Degradation rate for Si-based modules has been at ~0.5% per year

SolarCity

Factors Affecting Quality in the Solar Industry

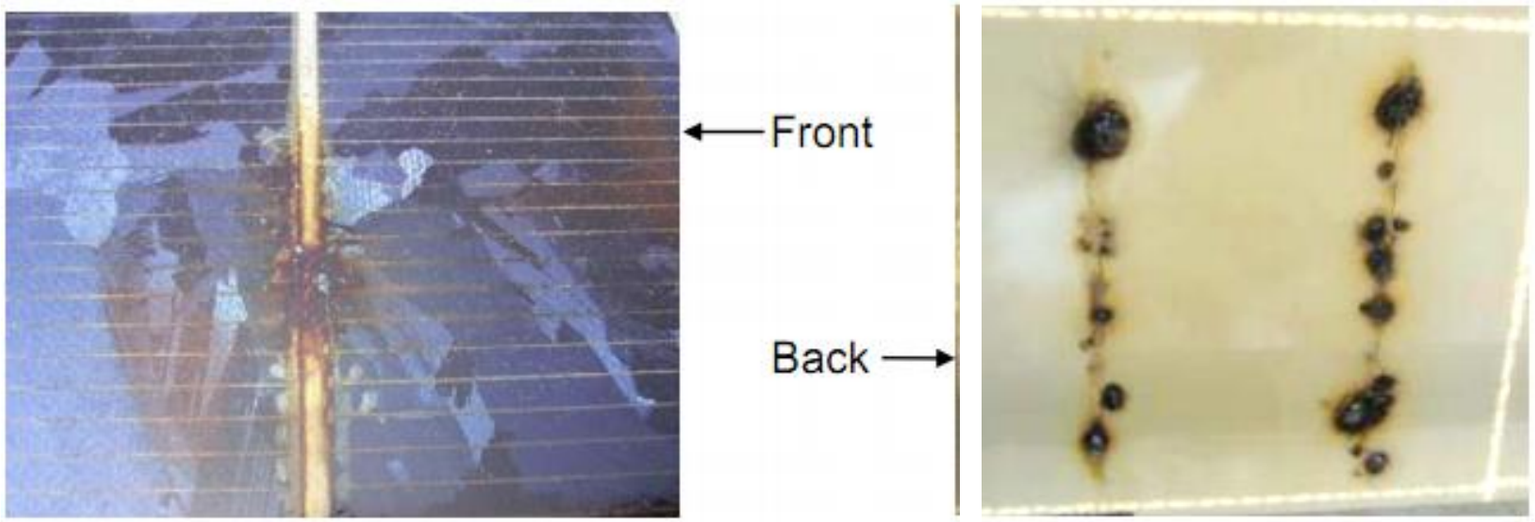
- Low-price competition
- Lack of effective quality control mechanisms
- Short production history
- Introduction of new materials
- New suppliers and factory locations

SolarCity

Examples of Quality Problems in the Solar Industry

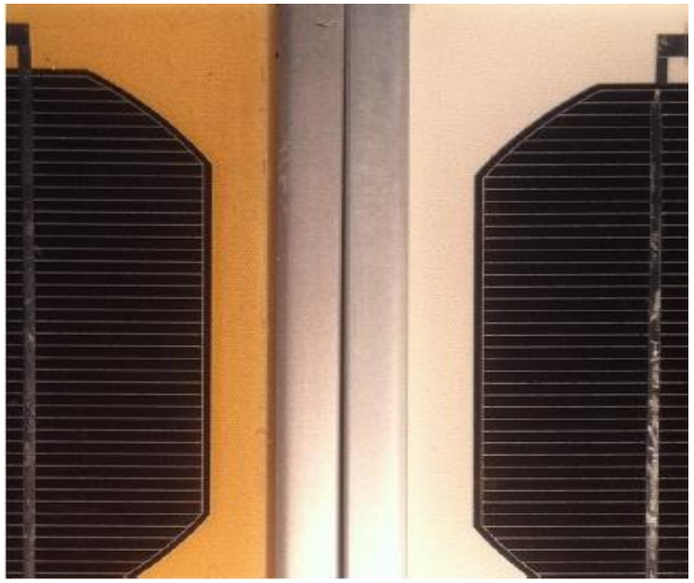
J-box Arcing

Solder Joint Degradation



Connector Failures

Backsheet Yellowing



Bubbles

[Images from Borrego Solar, 2011 and DNV GL]

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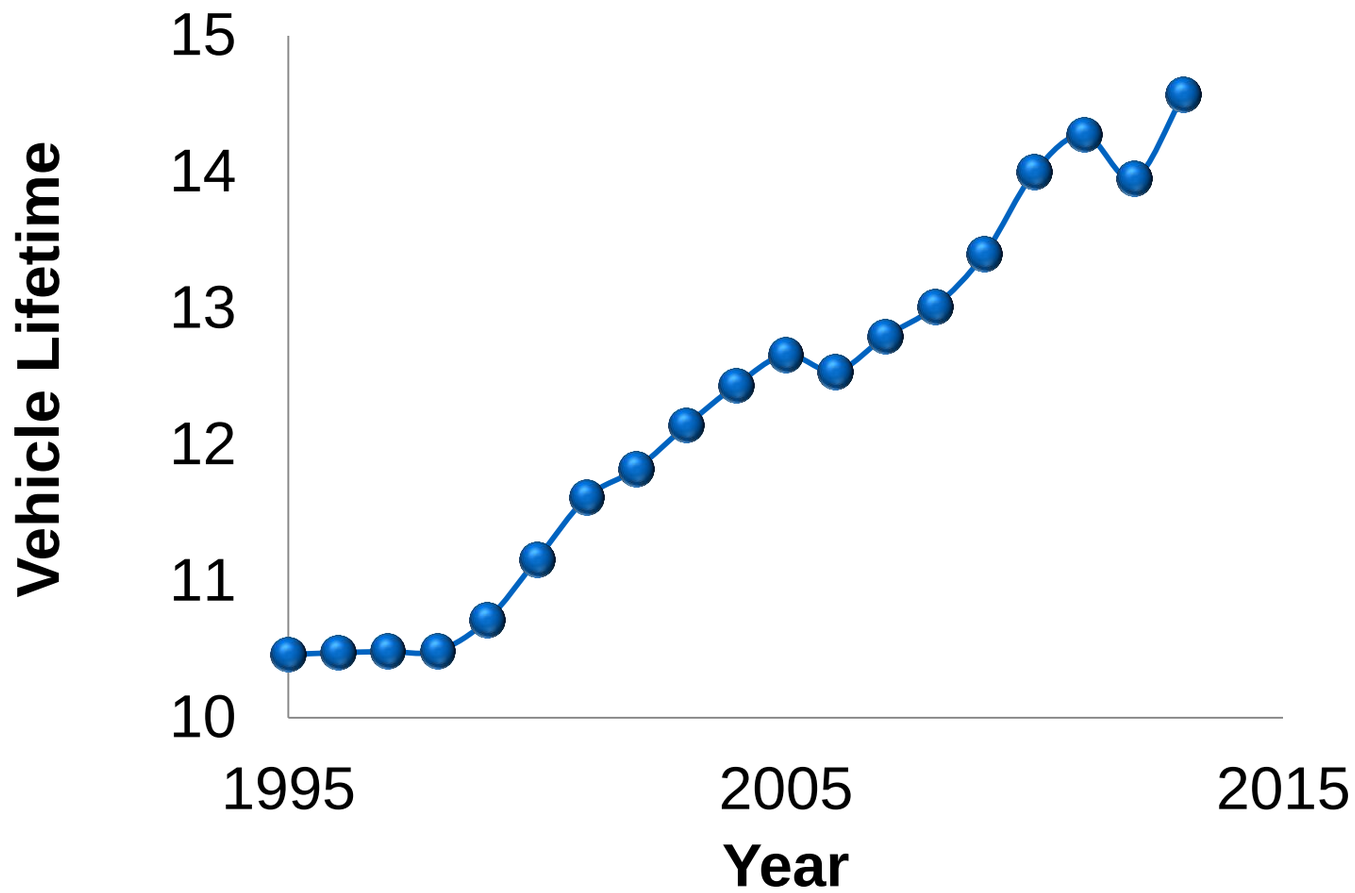
SolarCity Quality Program – Learning From the Best



- Features Adopted from Automotive Industry
- Total Quality Program for Key System Components
- Pushing Excellence in the Solar Industry

SolarCity

SolarCity Total Quality Program

Conventional Method	SolarCity Method
✋ Choose suppliers offering lowest cost ✋ No supplier qualification ✋ Buy off the shelf	☺ Tier-1 suppliers only ☺ Rigorous supplier qualification ☺ Design to spec
✋ Implicit Quality/Reliability	☺ Automotive-based Q&R programs: For all key system components ☺ Define/control/validate ☺ Gates with sign-off, involvement
✋ No feedback loops ✋ No learning from past experiences	☺ Constant feedback between Installers, O&M, Engineering ☺ Analyze field and warranty data
✋ No Quality philosophy	☺ Company-wide Quality philosophy ☺ Industry thought-leadership in Q&R

SolarCity

SolarCity Total Quality Program For Modules, Inverters, Batteries, BOS & More

Initial Vendor & BOM Qualification

- Initial Factory Audit
- BOM, Q&R and Testing specified in purchasing contract
- Extended Durability Qualification Testing

Production Oversight

- Periodic Factory Audits
- Verification of BOM
- Pre-Shipment Inspections

Ongoing QA/QC Testing

- Ongoing Testing required from suppliers
- Periodic Testing at approved 3rd party labs

SolarCity

We Won’t Stop Here

- Implemented industry-leading accelerated test procedures
  - Required for all suppliers
  - Hotspot, Snail Trail Testing, PID
  - Advanced Backsheet Tests to detect UV damage and cracking
  - Field Testing & Correlation with Accelerated Testing
  - More stringent Degradation Thresholds
- Minimize Turn-Around time for fastest response
- Collaborations

SolarCity

Summary

- Industry-leading Quality & Reliability Program
  - Strong Quality Control Processes adopted from Automotive
  - Consistent Quality across Production
  - Rigorous Reliability and Testing Program
- Program is paying off: SolarCity modules perform better than industry-wide selection in accelerated testing
- Continuous efforts to improve – Testing and Correlation with Field

Thank you!

Acknowledgements:

Jon Hewlett, Alex Mayer, Sam Beyene, Zach Kinyon, Sandeep Narla, Nate Coleman

SolarCity

SUNPOWER

Integration of Physics of Failure Research and Performance Degradation Modeling with Business Processes at SunPower

Mukul Agrawal, Yu-Chen Shen, Ernest Hasselbrink and David DeGraaff

PVMRW 2016, Denver, Colorado

Feb 23-25, 2016

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Safe Harbor Statement

This presentation contains “forward-looking statements” within the meaning of the Private Securities Litigation Reform Act of 1995, including, but not limited to, statements regarding (1) our technological evolution and research and development activities; and (2) estimates regarding the future performance and reliability of our products. These forward-looking statements are based on our current assumptions, expectations and beliefs and involve substantial risks and uncertainties that may cause results, performance or achievement to materially differ from those expressed or implied by these forward-looking statements. Factors that could cause or contribute to such differences include, but are not limited to: (1) competition in the industry and downward pressure on average selling prices; (2) our liquidity, substantial indebtedness, and our ability to obtain additional financing for our projects and our customers; (3) our ability to meet our cost reduction targets; (4) regulatory changes and the availability of economic incentives promoting use of solar energy; (5) challenges inherent in constructing and maintaining certain of our large projects, such as the Solar Star projects; (6) the success of our ongoing research and development efforts and commercialization of new products and services; (7) fluctuations in our operating results; (8) manufacturing difficulties that could arise; and (9) challenges managing our joint ventures. A detailed discussion of these factors and other risks that affect our business is included in filings we make with the Securities and Exchange Commission (SEC) from time to time, including our most recent reports on Form 10-K and Form 10-Q, particularly under the heading “Risk Factors.” Copies of these filings are available online from the SEC or on the SEC Filings section of our Investor Relations website at investors.sunpowercorp.com. All forward-looking statements in this presentation are based on information currently available to us, and we assume no obligation to update these forward-looking statements in light of new information or future events.

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Outline

- Metrics Matter!
  - The $/kWh metric
  - Integration into business processes and closed-loop learning
- Physics of Failure Research
  - PVLife: SunPower's reliability/degradation model
  - New research areas

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Metrics Matter!

$/kWh Metric

- At SunPower we measure ourselves by the same metric as our customers and investors do — i.e. the cost of energy produced over several decades.

This is what our customers and investors care about. They want this as low as possible (but with low uncertainty/risk) →

$$\$/kWh = \frac{\$/W}{kWh/W}$$

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$/kWh Metric

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$$\$/kWh = \frac{\$/W}{kWh/W}$$

Traditional performance metric. RELIABILITY only appears as a COST here

Using ONLY $/W as a performance metric means you are ignoring reliability

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$/kWh Metric

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$$\$/kWh = \frac{\$/W}{kWh/W}$$

Traditional performance metric. RELIABILITY only appears as a COST here

Reliability and Quality play a big role here … IF you account for evolution in time

- **kWh/W** (Energy Yield) is NOT constant but changes over time as panels age.
- Quantifying Energy Yield requires
  - Field-verified reliability models.
  - Short loop accelerated tests that are calibrated against field degradation and reliability models.
  - Good process control and understanding of variability in reliability sensitive process parameters.

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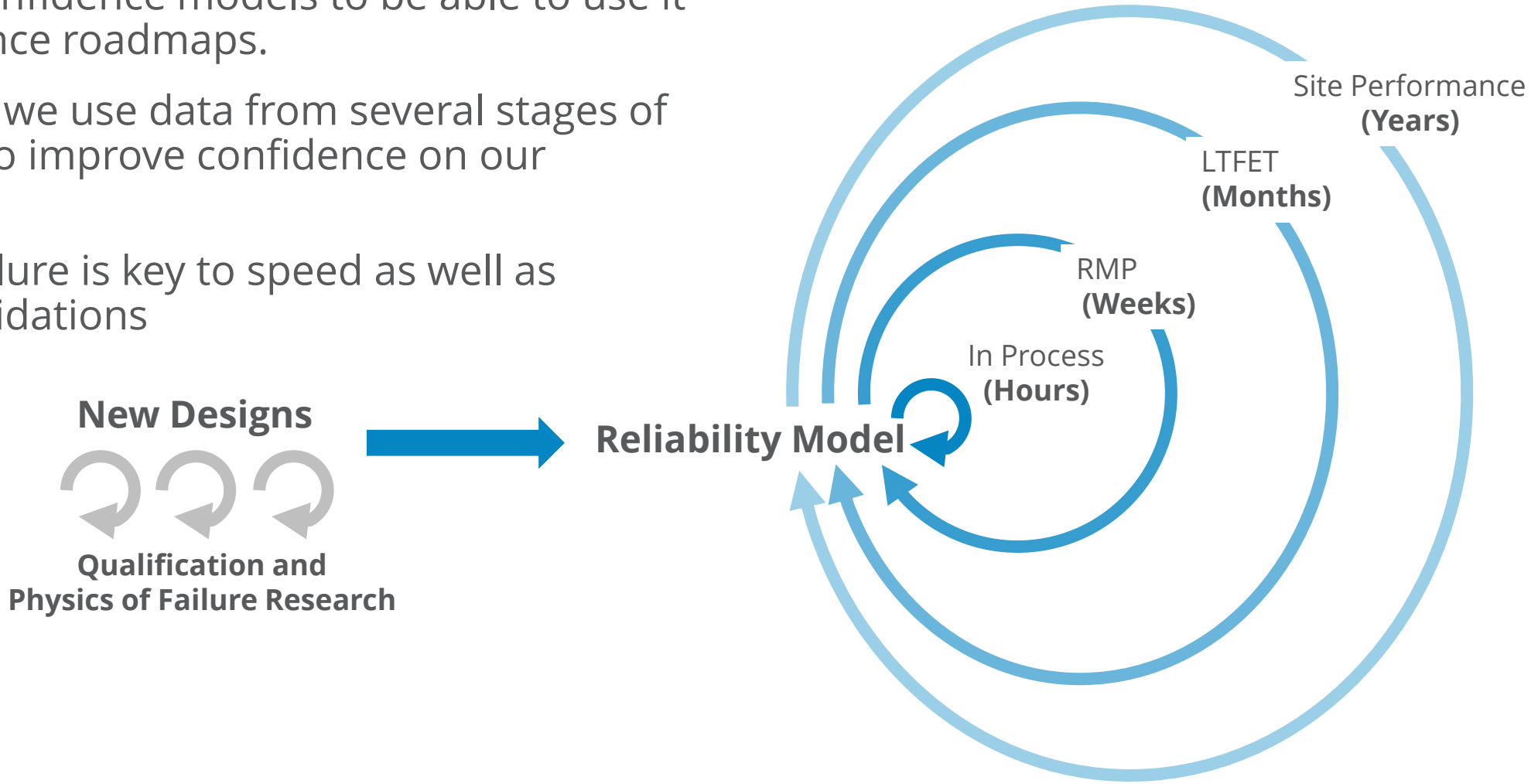
RMP = reliability monitoring program
LTFET = long-term field exposure testing

Closed Loop Learning

- $/kWh is a model-centric approach.
- Need high confidence models to be able to use it as performance roadmaps.
- At SunPower we use data from several stages of product life to improve confidence on our models.
- Physics of failure is key to speed as well as confident validations



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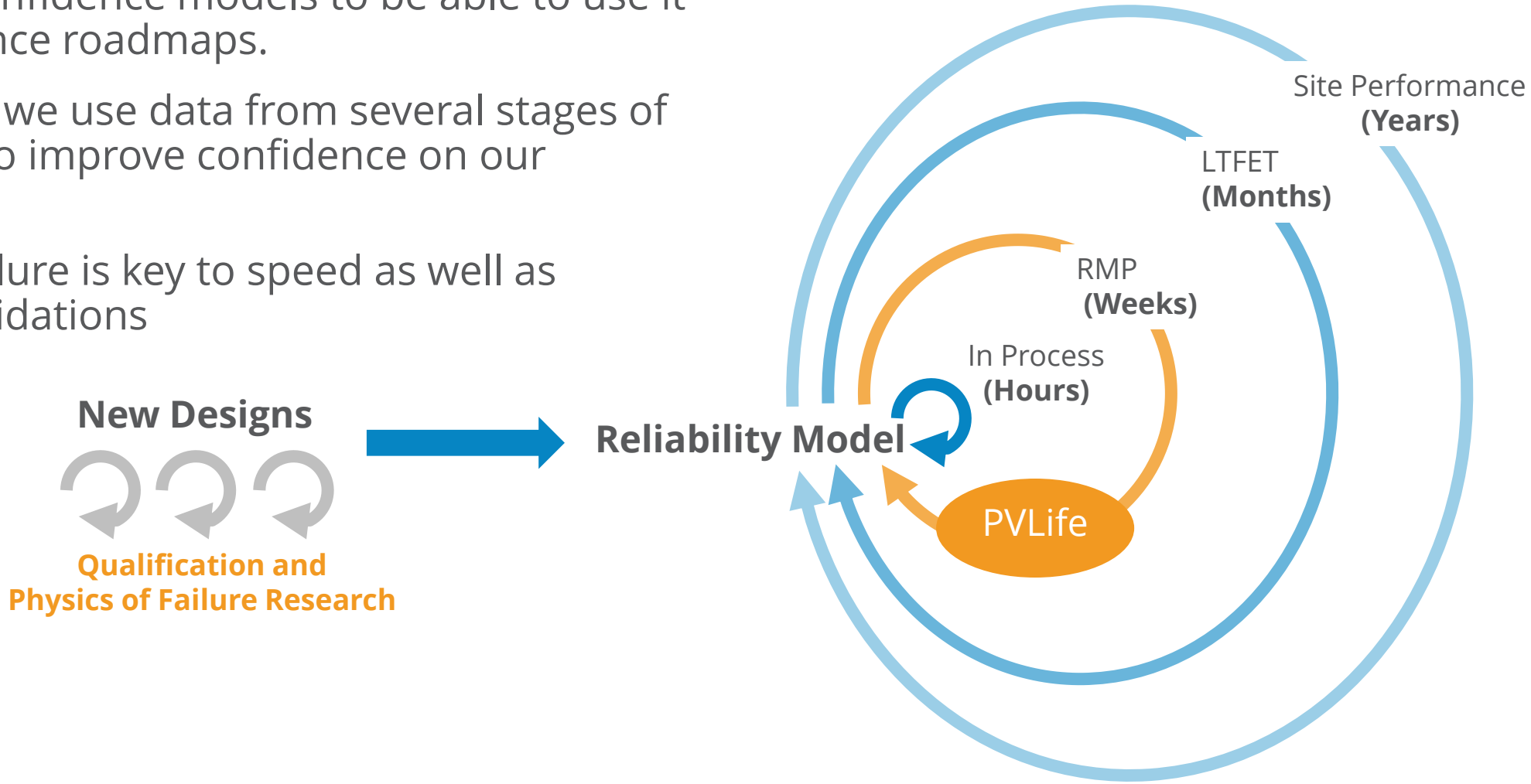

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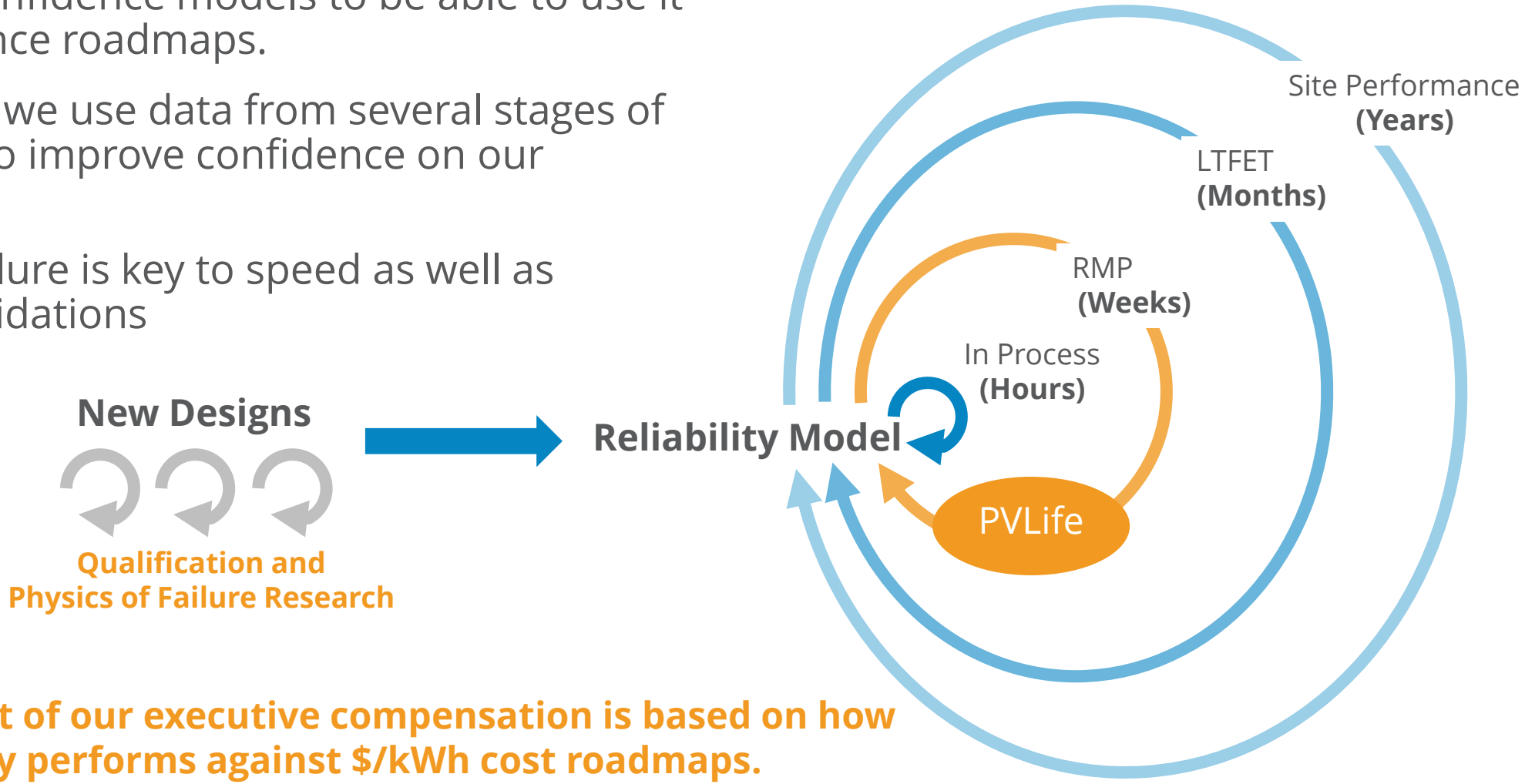
- At SunPower we use data from several stages of product life to improve confidence on our models.
- Physics of failure is key to speed as well as confident validations



At SunPower part of our executive compensation is based on how well the company performs against $/kWh cost roadmaps.

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Quarterly Tracking of Product Reliability

$$\$/kWh = \frac{\$/W}{kWh/W} \longrightarrow \frac{\$/W}{DE * (kWh/W)_{First\text{-}Year}}$$

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Quarterly Tracking of Product Reliability

$$\$/kWh = \frac{\$/W}{kWh/W} \rightarrow \frac{\$/W}{DE * (kWh/W)_{First\text{-}Year}}$$

First year energy yield

- AR Glass
- Temp Co
- Low Light Performance

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Quarterly Tracking of Product Reliability

$$\$/kWh = \frac{\$/W}{kWh/W}$$

$$\frac{\$/W}{DE * (kWh/W)_{First\text{-}Year}}$$

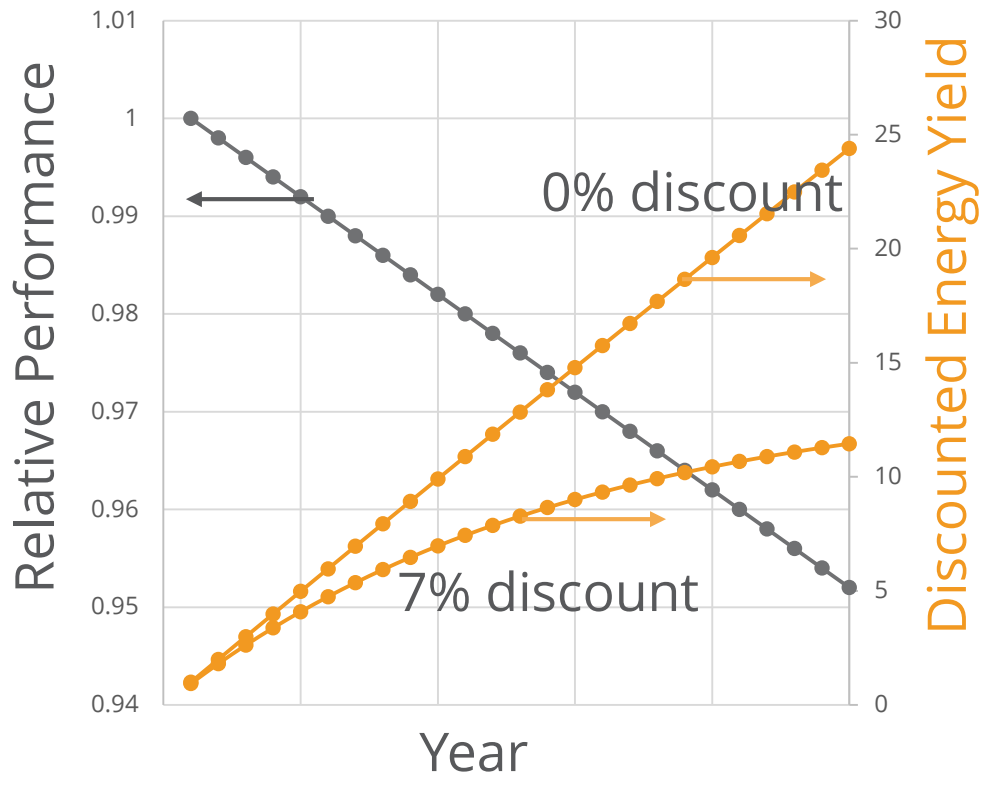
First year energy yield

- AR Glass
- Temp Co
- Low Light Performance

Discounted energy yield

Reliability

$$\sum_{Year=1}^{EOL} \frac{(Relative\ Performance)}{(1+discount\ rate)^{year}}$$



To estimate future degradation in performance we use our PVLife model + accelerated test data from random manufacturing samples

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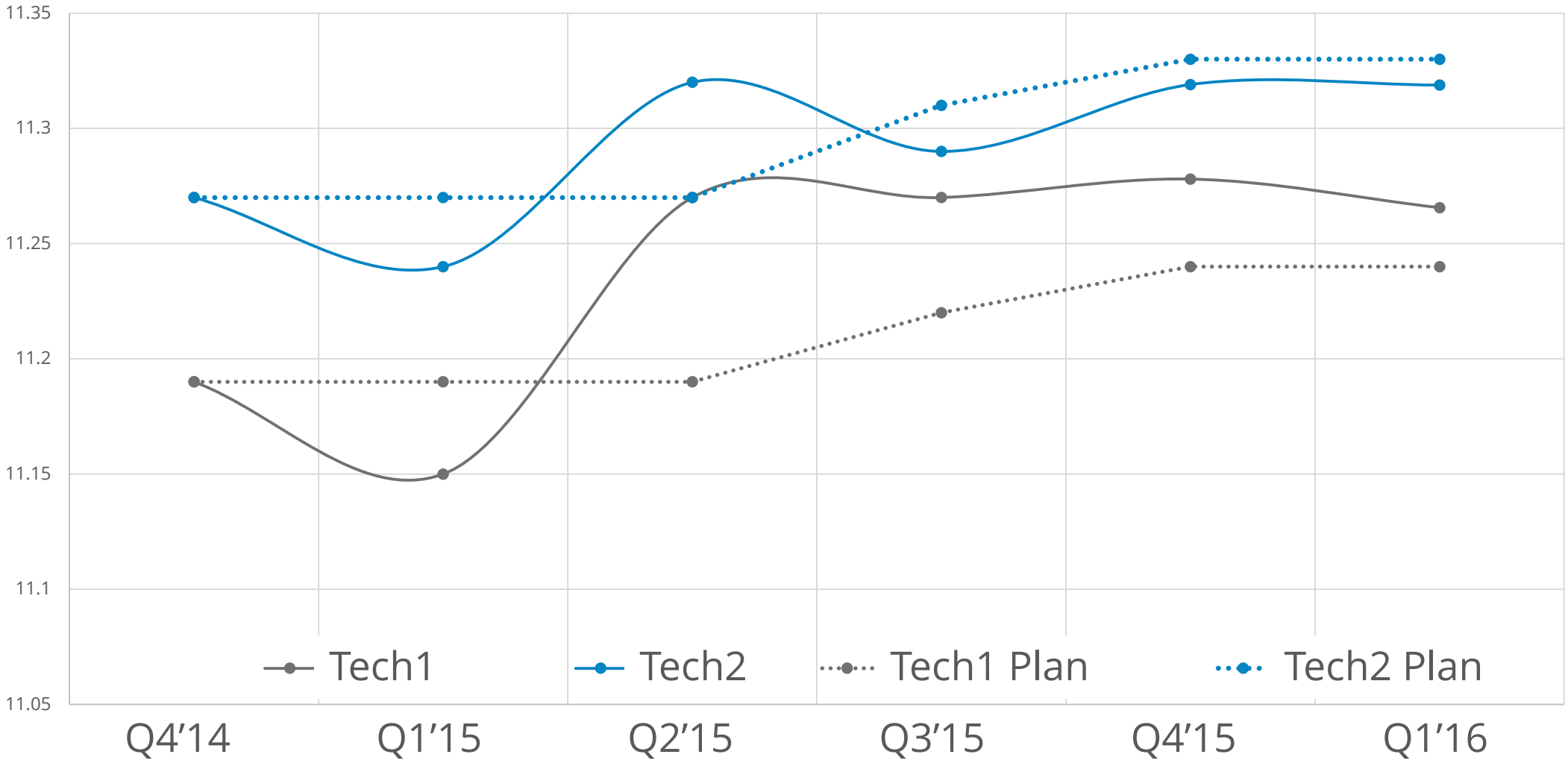
Tracking of Product Reliability



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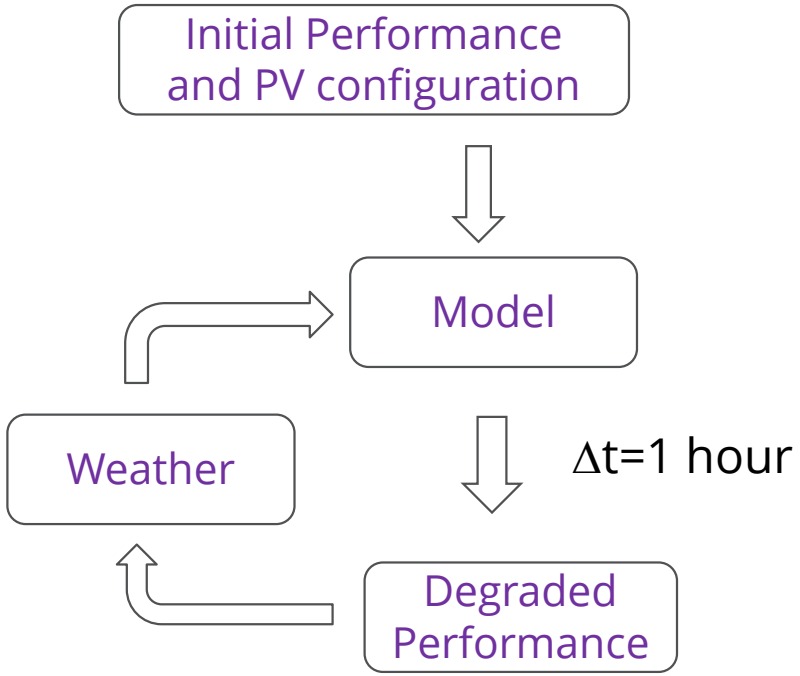
Physics of Failure Research

PVLife: SunPower's Reliability/Degradation Model

- Using array configuration, weather data, and pre-evaluated technology parameters, PVLife computes cell performance and failure probabilities over time



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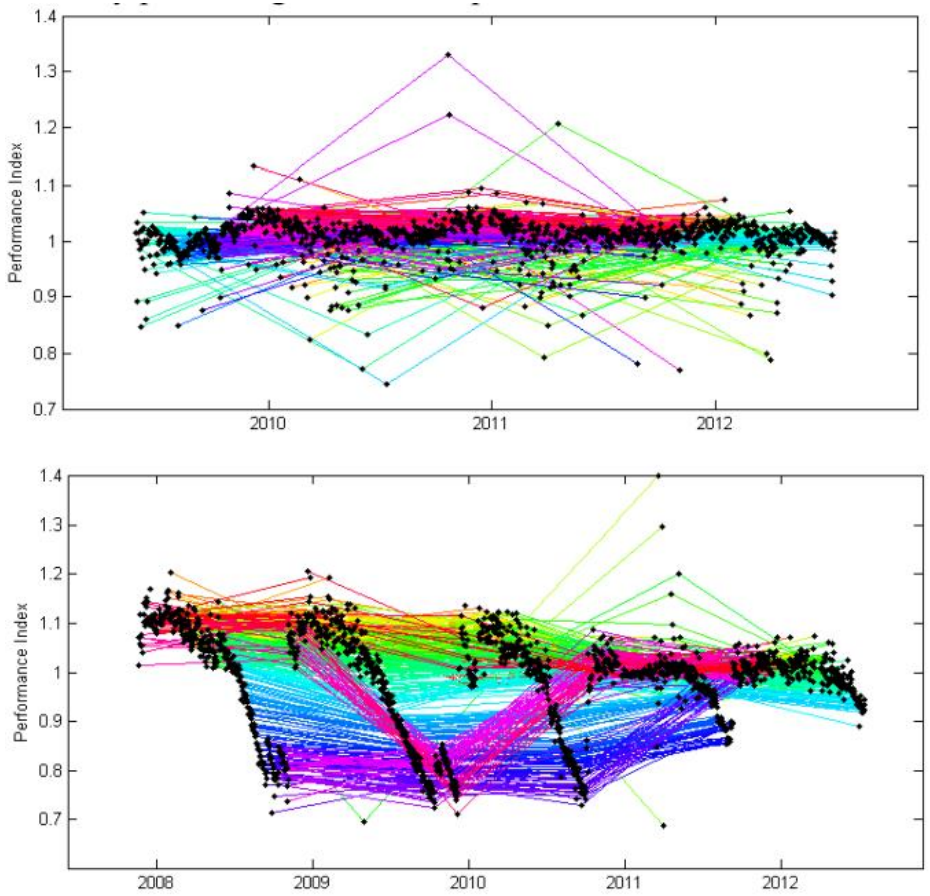
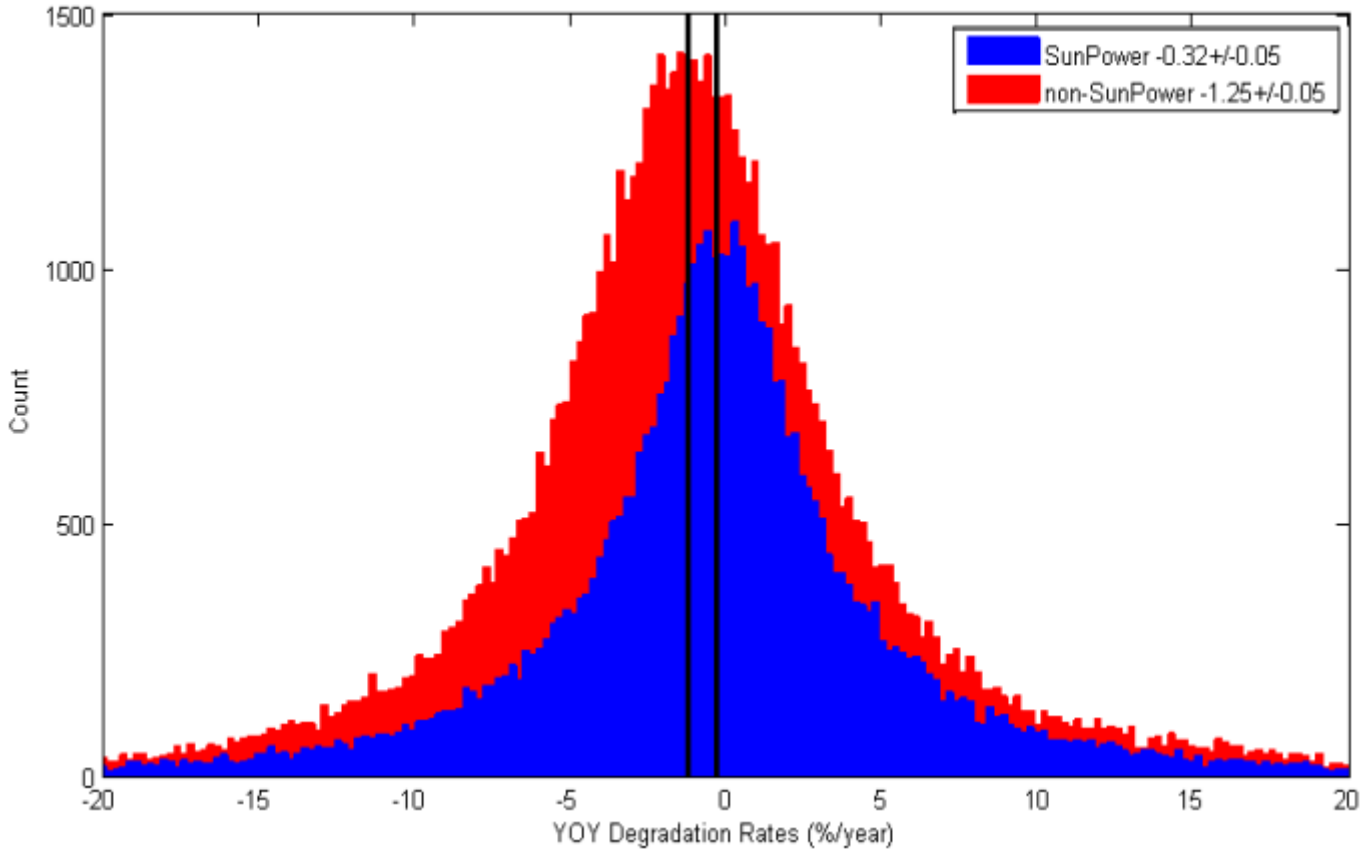
PVLife: Example of Model Validation





- Year-on-year performance index of 3 million module-years of live site data

E. Hasselbrink et al., "Validation of the PVLife model using 3 million module-years of live site data," *IEEE 39th Photovoltaic Specialists Conference,* pp. 0007–0012 (2013). doi:10.1109/PVSC.2013.6744087.

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PVLife: Example of Model Validation

Degradation modes included in this study are:

- Cell UV Degradation
  - surface recombination rate increase modeled using power law
- Encapsulant Yellowing
  - modeled using a simplified 2-step chemical reaction model
- Potential Induced Degradation
  - leakage current driven model modulated by encapsulant temperature and humidity

Failure modes included in this study are:

- Solder Joint Failure
  - Modeled via a strain energy model fitted with a Weibull
- Backsheet Cracking
  - Hydrolysis reaction with rate proportional to $[RH]^n \exp(-E_a/RT)$
- Diode Failure
  - Temperature dependent aging modeled via a lognormal-Arrhenius function

E. Hasselbrink et al., "Validation of the PVLife model using 3 million module-years of live site data," *IEEE 39th Photovoltaic Specialists Conference*, pp. 0007–0012 (2013). doi:10.1109/PVSC.2013.6744087.

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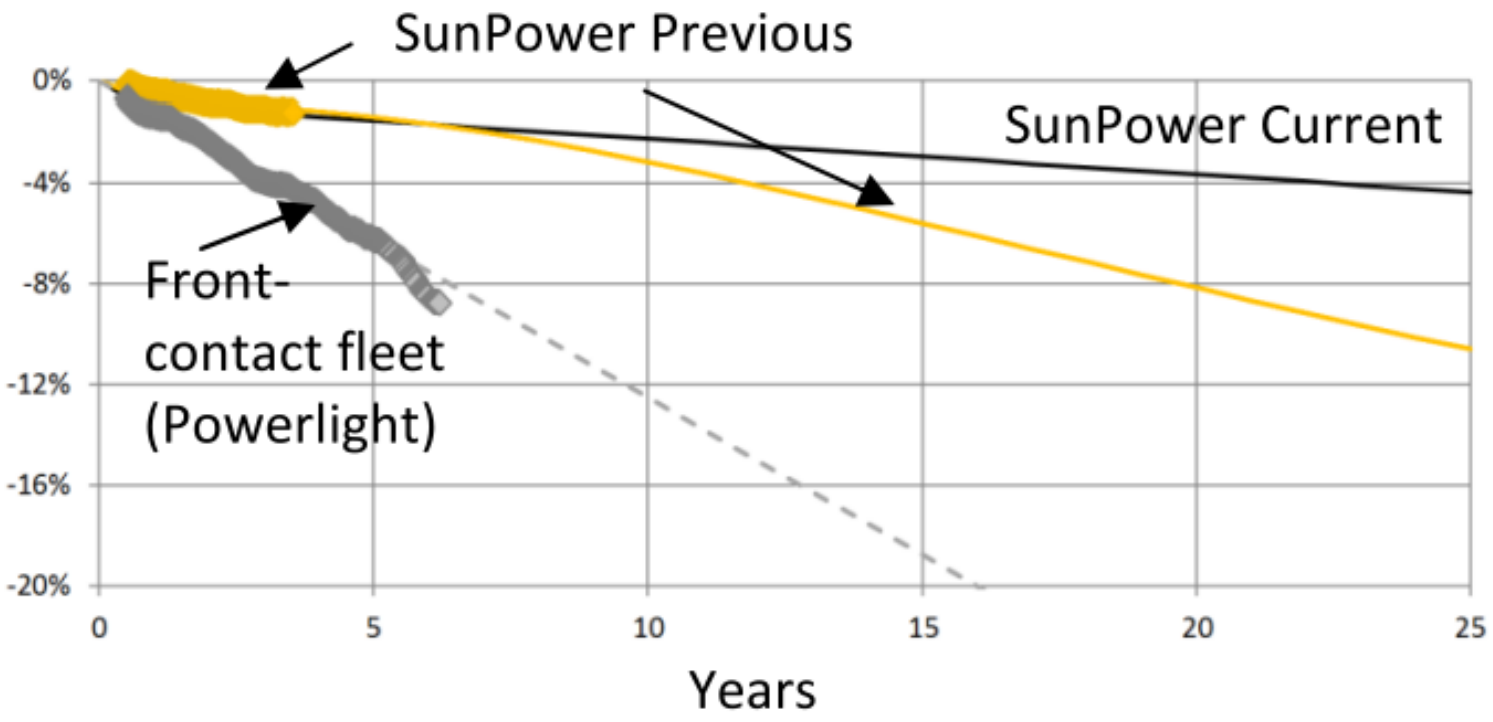
PVLife: Example of Model Validation

Source: E. Hasselbrink et al., "Validation of the PVLife model using 3 million module-years of live site data," *IEEE 39th Photovoltaic Specialists Conference,* pp. 0007–0012 (2013). doi:10.1109/PVSC.2013.6744087.



- Model has been validated for previous generation of SunPower back contact fleet.

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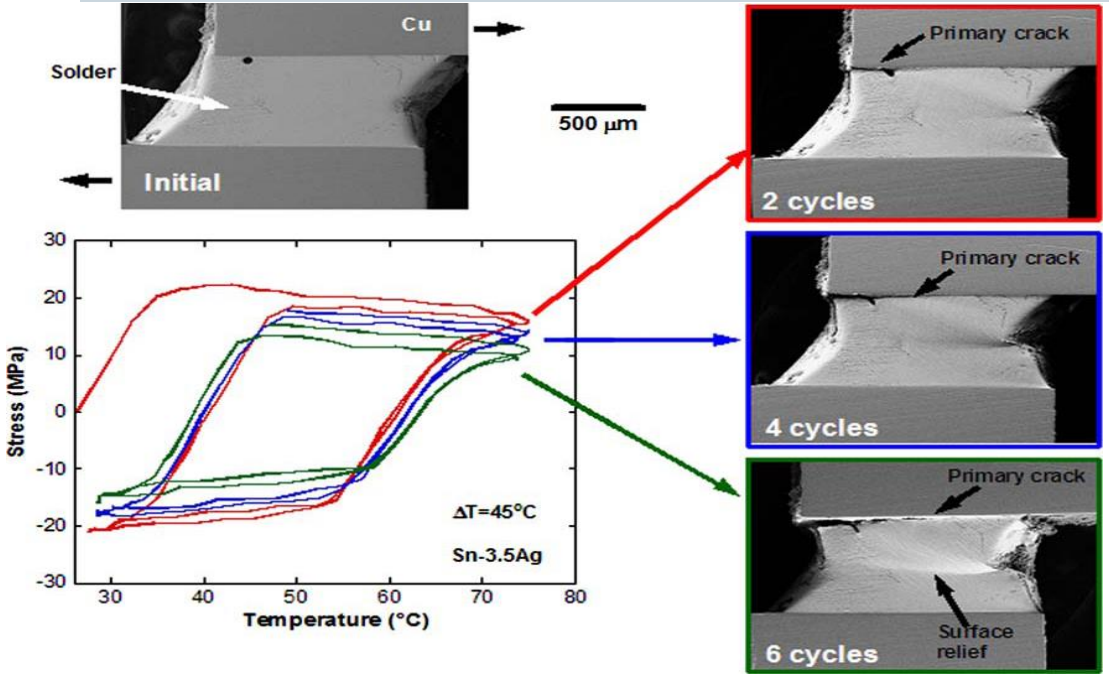
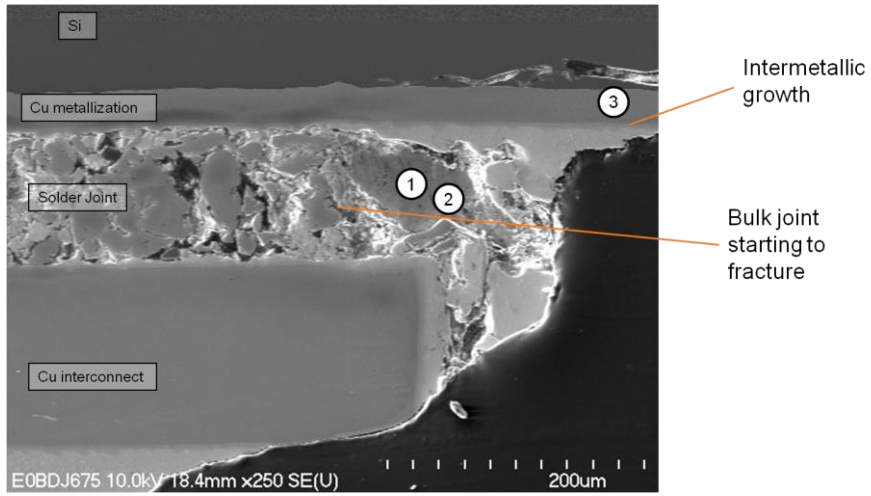
New Research

Solder Joint Failure





- Key degradation mechanism is strain-energy hysteresis loop due to creep; dominant source of stress is CTE mismatch.
- Difficulty: dependencies on solder formulation, process , and geometry. Each design/process requires testing; TC is slow. Bosco (NREL) effort to determine if TC can be replaced with dynamic mechanical load.

See NREL reports by Bosco; also J.-P. Clech, "Acceleration Factors and Thermal Cycling Test Efficiency for Lead-Free Sn-Ag-Cu Assemblies," Proc. SMTA Intl, Chicago, IL, Sept. 25-29, 2005

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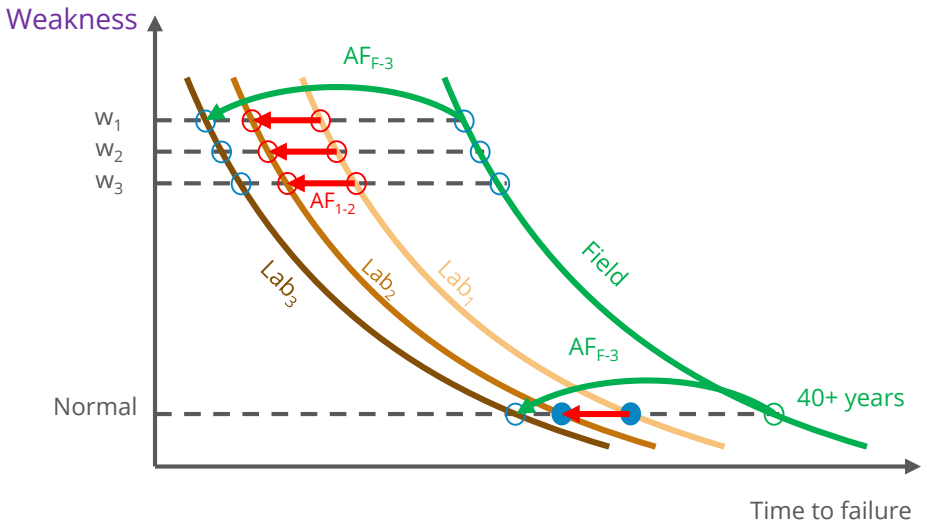
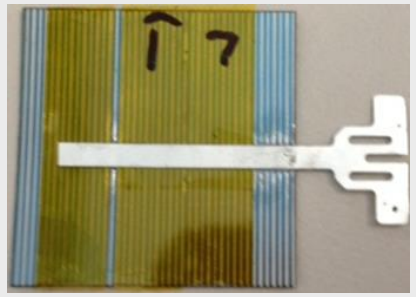
PREDICTS2: Solder Joint Fatigue

- Goals: Improve the industry's speed of cycles-of-learning! Find TC-based AF for solder joint testing; find highest-efficiency test method with proven correlation to field.
- Strategy: Develop a controllably weakened solder joint so that crack initiation can be measured via resistance change (non-destructive) in fielded samples that mimic poor (high stress) solder joints
  - Time zero characterization
  - Microstructure characterization
  - Microstructure evolution during aging
  - Finite Elements Analysis (FEA)



Ring shaped joint	Bridge design
Test Structure1	Test Structure2
	

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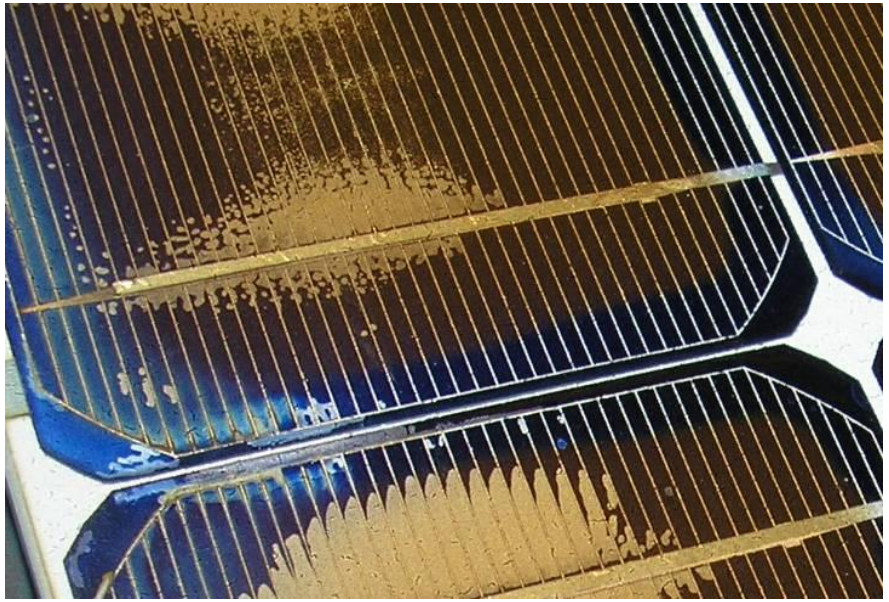
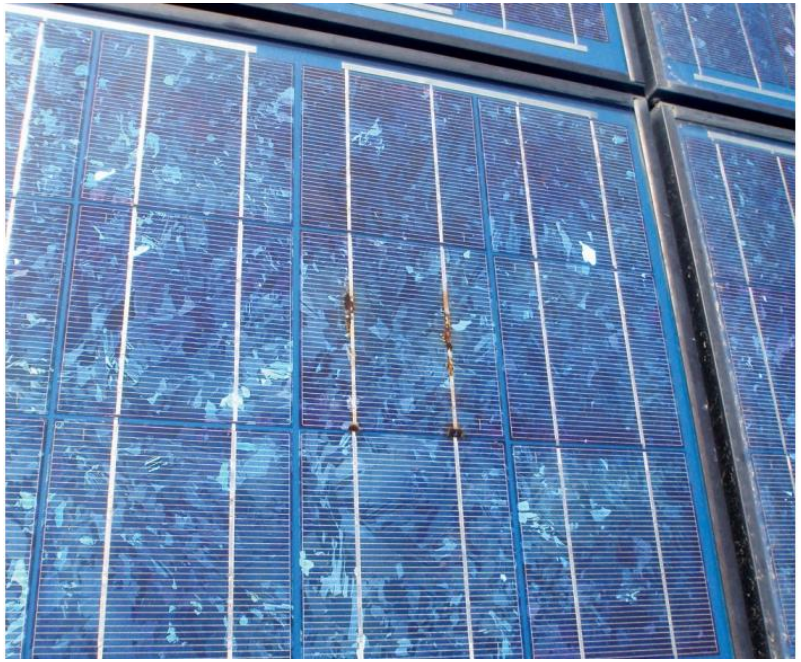
Field observations of Metal Corrosion





- Metal corrosion leads to power degradation → increased series resistance and drop in I_{sc} leading to hot cells
- Mechanism enhanced by moisture ingress through encapsulants* and possible corrosive environment in encapsulant
- ***What about electrolytic corrosion?***

*see M. Kempe, "Modeling of rates of moisture ingress into photovoltaic modules," Solar Energy Materials and Solar Cells, V90, p.2720-2738

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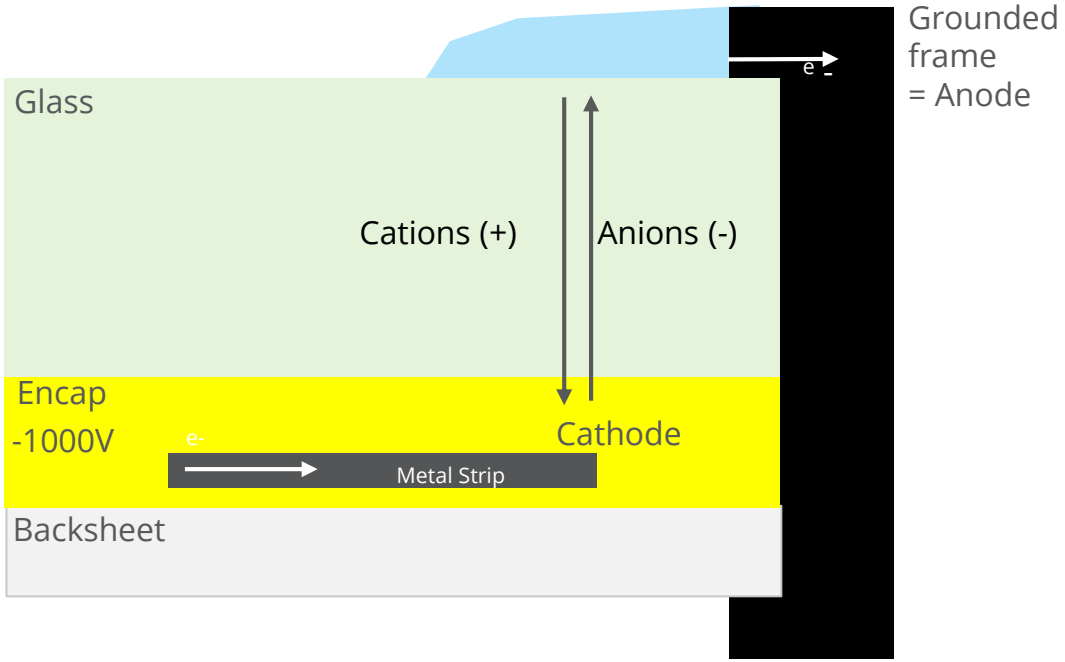
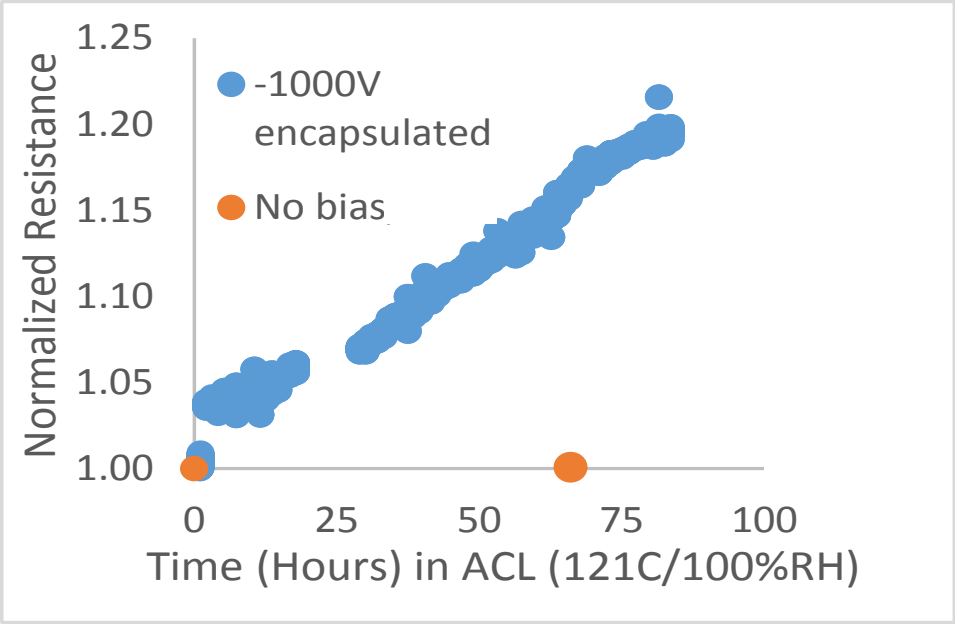
PREDICTS2: Electrolytic corrosion

- Test structure shows far more corrosion when leakage current is present





See poster by Shen et al, this conference

1. Electrolytic corrosion may be dominant.
2. Potential Vicious cycle: Corrosion → small delamination → worse corrosion

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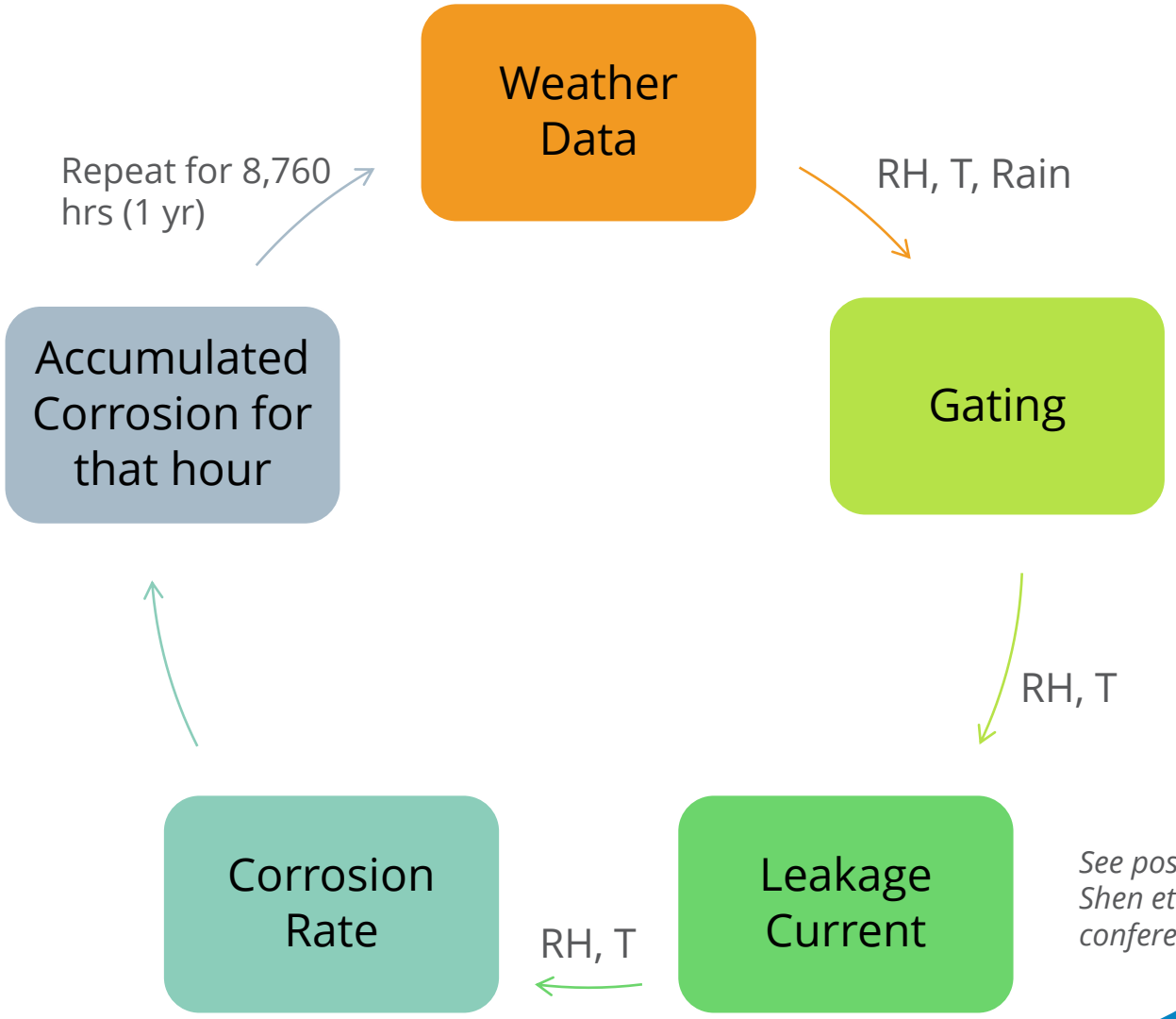
Working Corrosion Lifetime Model

- Weather data: 1 year from Fort Myer, Florida; 1 hr intervals
  - Module temperature calculated from wind, illumination, and ambient T.
- Gating (Leakage Current when moisture is present on the module)
- Leakage Current vs RH,T at 1kV
- Corrosion Rate vs Leakage Current Case (Transport or Reaction limited?)
- Calculation for uniform corrosion



See poster by Shen et al, this conference

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Key Messages

- Customers and investors care about cost of energy produced over several decades
  - Energy yield and reliability has a direct impact on real cost of energy to customers and investors
- Accurate physical models and quantitative degradation predictions will increase investor confidence in PV
- Detailed physical models are great! But we need measurables that we can use for monitoring in a closed-loop-learning system
  - Models that use results from short loop testing and provides assessment of long term reliability are needed
  - Understanding, monitoring and controlling the variability in reliability sensitive process parameters is very important

PV community can contribute to and benefit from accurate physical models and quantitative tests

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Validating 20 Year Reliability Of POWERHOUSE™ 2.0 Solar Modules Using Fault Tree Analysis

Ankur Khare, Leo López, Jay Tudor, Kwanho Yang
Dow Solar R&D

Presented at PV Module Reliability Workshop
Feb 23rd 2016

Outline

- Introduction to POWERHOUSE™ 2.0
- Dow Solar's Product Reliability Methodology
- Overview of Fault Tree Analysis
- 20 yr Reliability for Connector Welds

DOW POWERHOUSE™ Solar Modules

Cost	Reduced installation cost Competitive PV cost
Aesthetics	Fully integrated with the roof
Warranty	20 years, both as a roof and as a power generator
Simple, safe	Installs like an asphalt roof No live wiring on the roof No conductive surfaces

DOW®

POWERHOUSE™ SOLAR

POWERHOUSE™ 2.0 Expands Dow Solar Portfolio

POWERHOUSE™ DPS – 1000
- Reduced installation complexity
- Small pixel fills complex roofs

POWERHOUSE™ 2.0
- Further reduction in installation cost
- Higher power density

- Use of NuvoSun™ Flex PV cells enables holistic approach to reliability
  - » Vertically integrated from CIGS process to field performance
  - » Reduces cycle time for qualification of CIGS PV improvements
- Leverage learnings from DPS-1000 to accelerate POWERHOUSE™ 2.0 development

Typical Reliability Testing Methodology

- Exposure to combinations of T, relative humidity (RH), ΔT, UV, light, voltage bias and mechanical stress
  - » Stressors intended to identify/accelerate potential real world f
  - » No combination of tests can validate 20-year perform

Test	Condition	Regulatory limit /	Modes
Damp Heat	85°C /85%RH		encapsulant adhesion, device stability
Thermal Cycling	-40°C		Interconnect, encapsulant adhesion
Humidity Freeze		cles	Encapsulant adhesion, current leakage
Wet Insu R		>40MΩ-m²	Ground faults, current leakage paths
	p/Ambient Humidity	N/A	Adhesion, device stability, oxidation
U re	Super UV chamber / Xenon Arc	N/A	Encapsulant/adhesive yellowing, adhesion

Is this sufficient?...

Reliability Requires Deeper Thinking

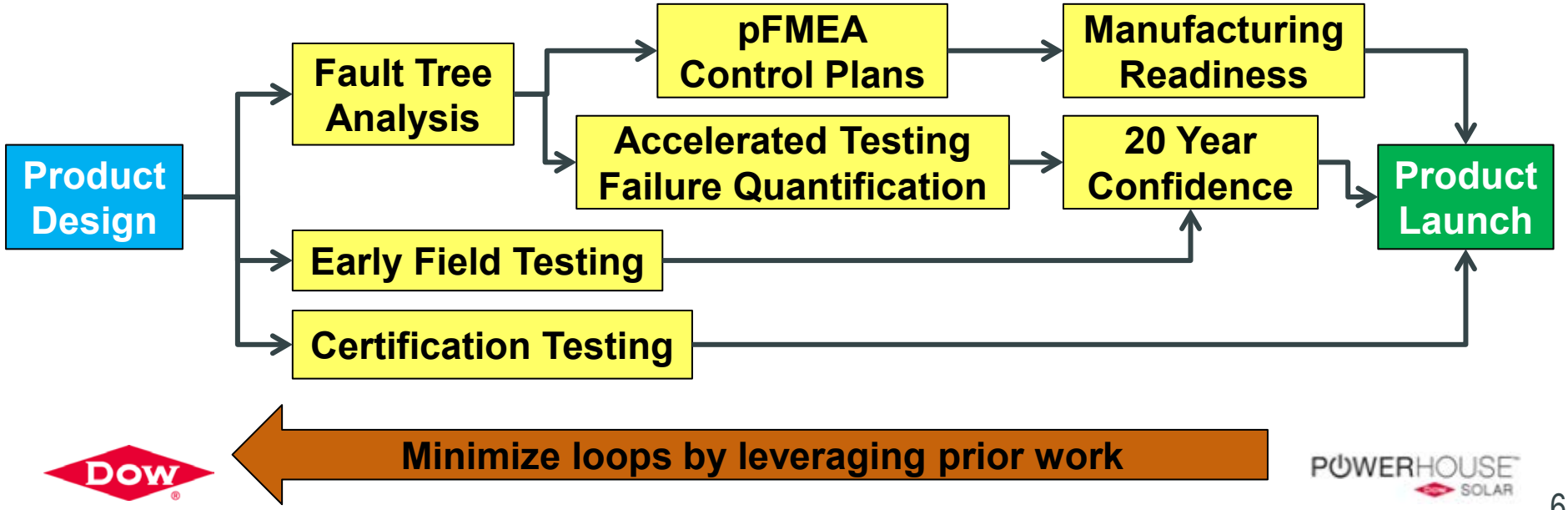
Why are we testing

- Products must be safe for the duration of their usable life
- Mainstream solar products require 20+ year power warranty

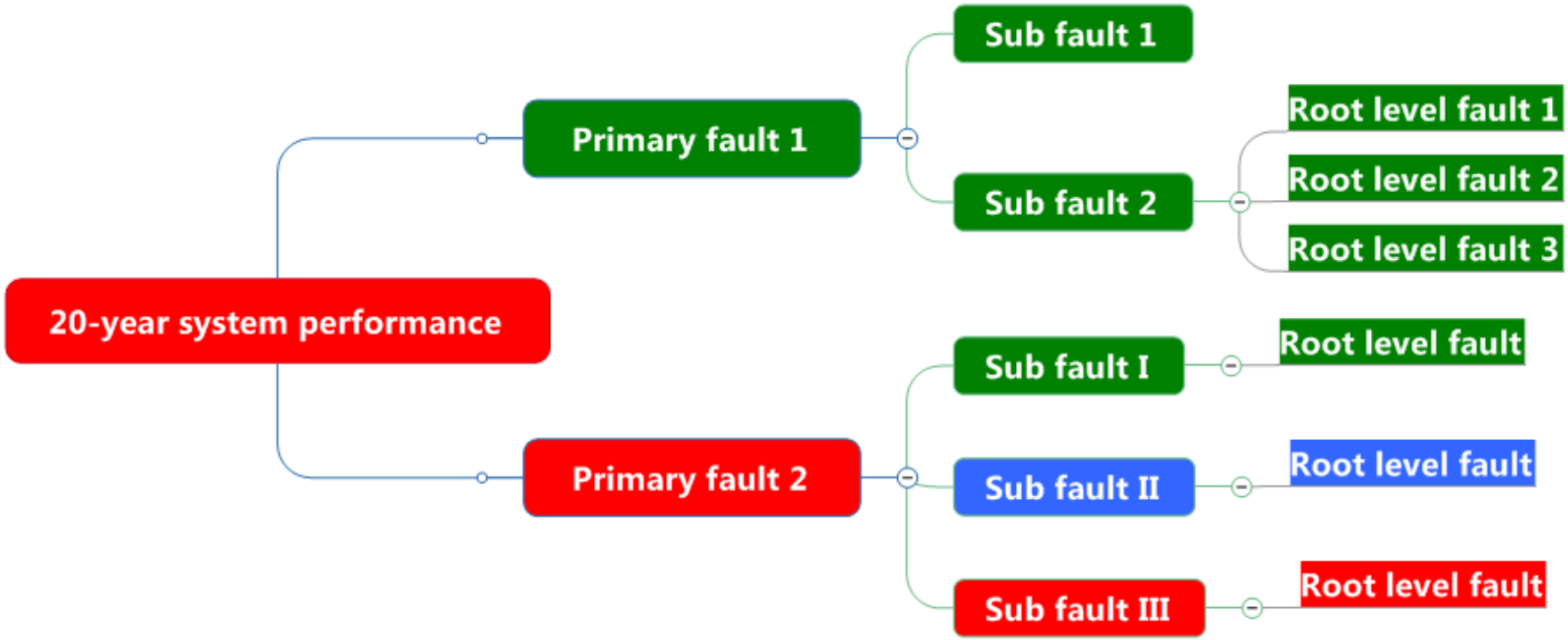
The challenge

- Industry cannot wait 20 years to validate
- 20 yr warranty performance can never be 100% validated

Our Methodology



Fault Tree Approach Towards Reliability



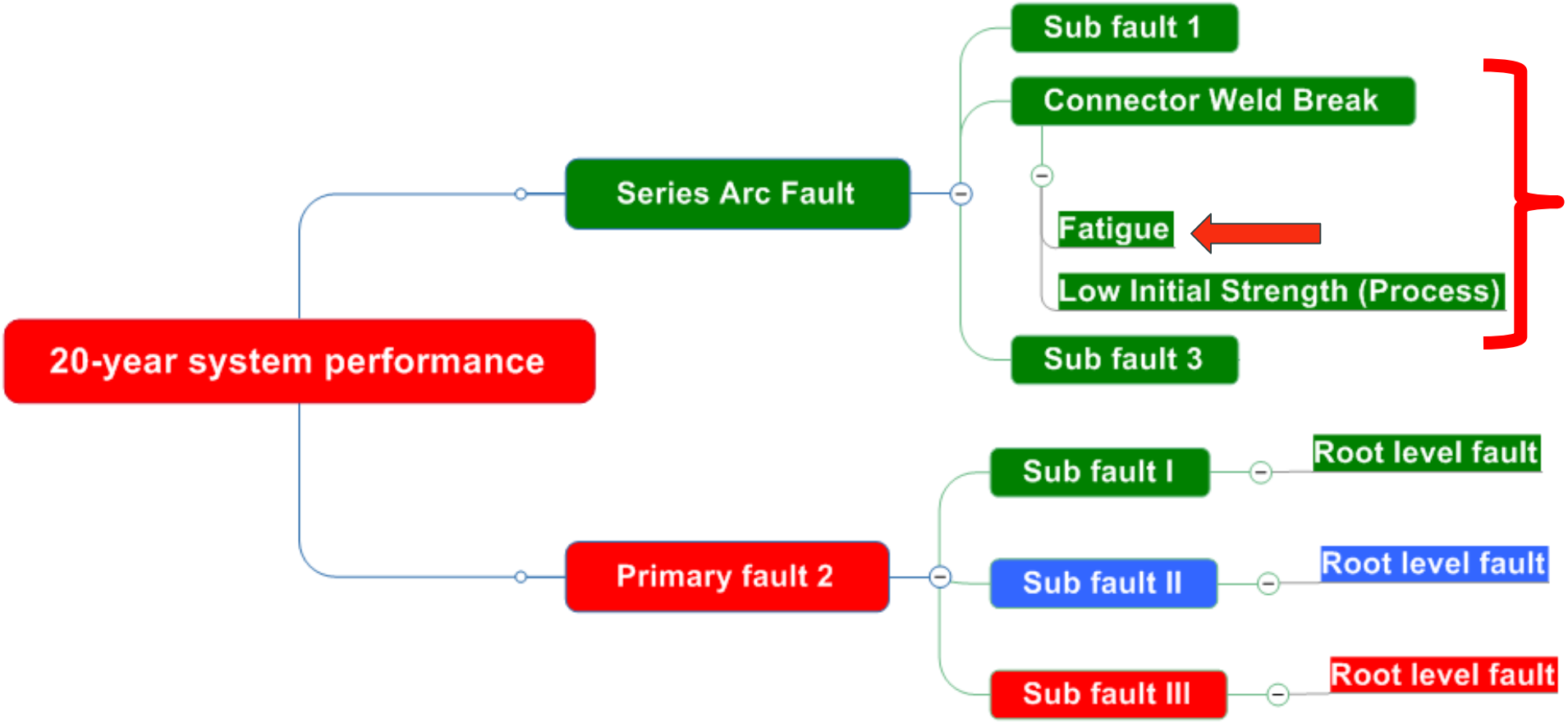
- Fault trees help in reliability testing for system design
- Failures can be broadly classified by failure type
- Different colors indicate difference in risk based on available data
- System reliability can be clearly related to component reliability
- Tests can be designed to retire individual fault tree items

Fault Trees and FMEAs are Complementary

Fault Trees	FMEAs
Top-down approach	Bottom-up approach
Clearly relates failure modes to system failure	No clear correlation of individual failure modes to system failure
System reliability calculated based on reliability of failure modes	No information on system reliability
Helps test resistance of system to single or multiple initiating faults	Helps delineate all possible failure modes and their local effects
No structured resource prioritization	Resource prioritization based on Risk Priority Number

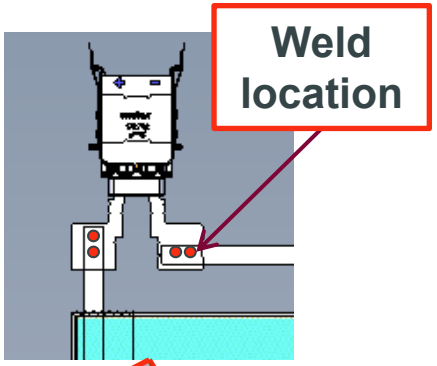
- Fault trees and FMEAs are complementary techniques
- Both aim at addressing reliability concerns for a given design

Fault Tree for Weld Reliability



20-Year Reliability for Weld Joints

- POWERHOUSE™ 2.0 string uses welds for metal bonding
- Weld failure may lead to series arc (fire hazard)
- Modules on roof experience thermal cycling (TC) from -40°C to 90°C
- Surrounding polymers stress welds through TC
- Need relationship between TC stresses and weld reliability



Fatigue Lifetime Prediction of Weld Joints

Instron pull test

Fatigue testing

F

Tab

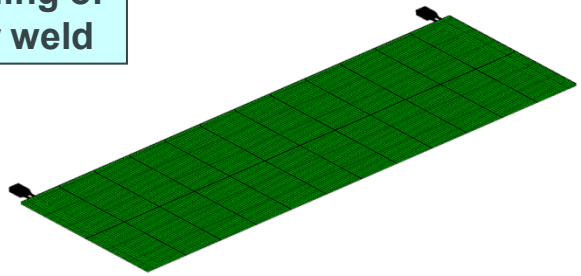
Weld

Busbar

F

FEA modeling of connector weld

POWERHOUSE™ 2.0 Laminate

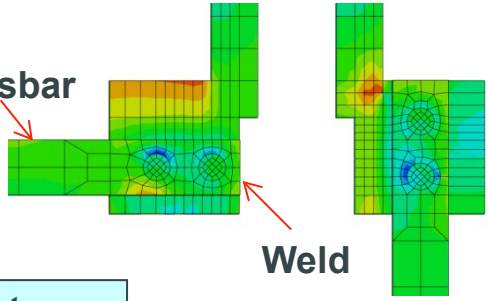


Stress in weld Joint

Tab

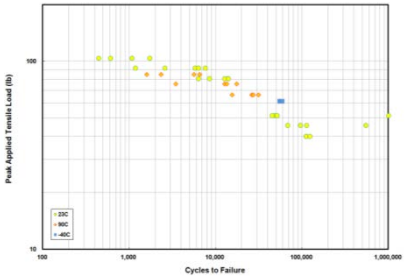
Busbar

Weld



FEA modeling of Instron pull test

F(force)-N(cycle) Curve



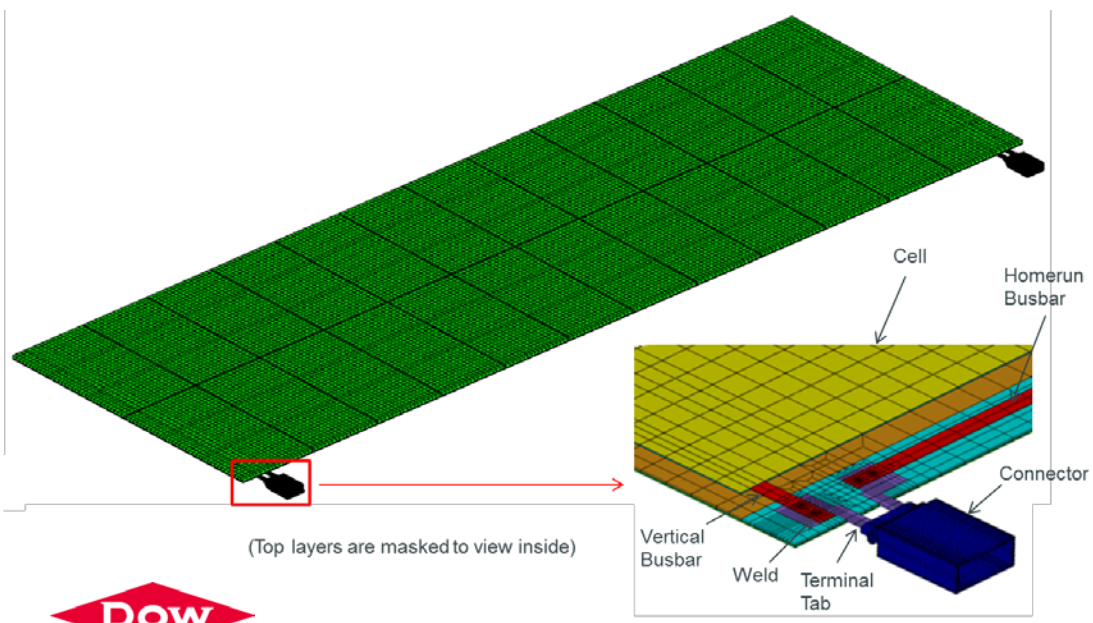
F-N curve

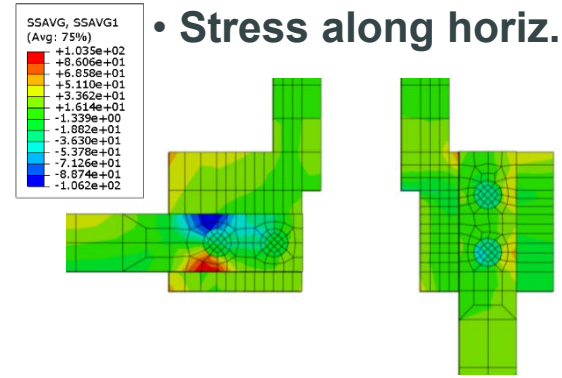
Equivalent Instron pull force

Fatigue lifetime prediction of weld joint

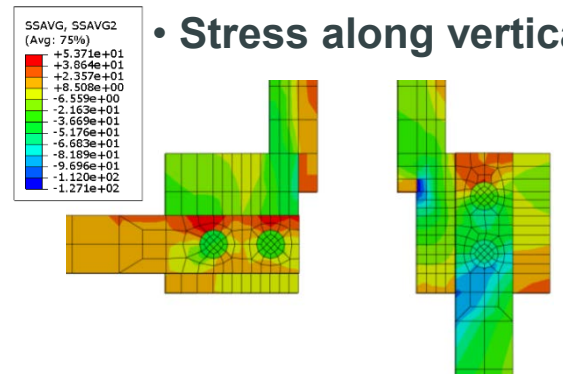
FEA Modeling of Connector Weld

- 3D FEA model developed using continuum shell elements
- Perfect bonding assumed between different layers of the laminate stack
- Encapsulant melting temperature assumed to be stress free state

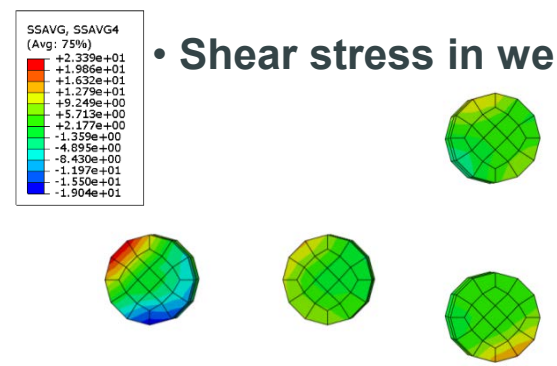




- **Stress along horiz. axis**



- **Stress along vertical axis**

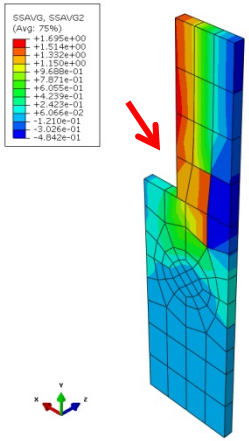


- **Shear stress in welds**

FEA Modeling (Instron Pull) Correlates with Experiments

Instron pull test

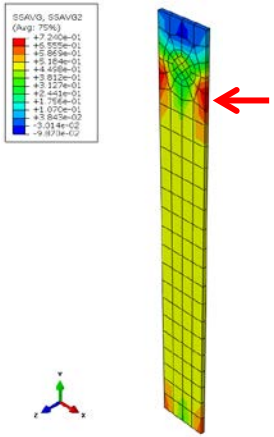
Vertical Stress (MPa)



(Busbar is masked)

Fatigue failure at low stress

Vertical Stress (MPa)

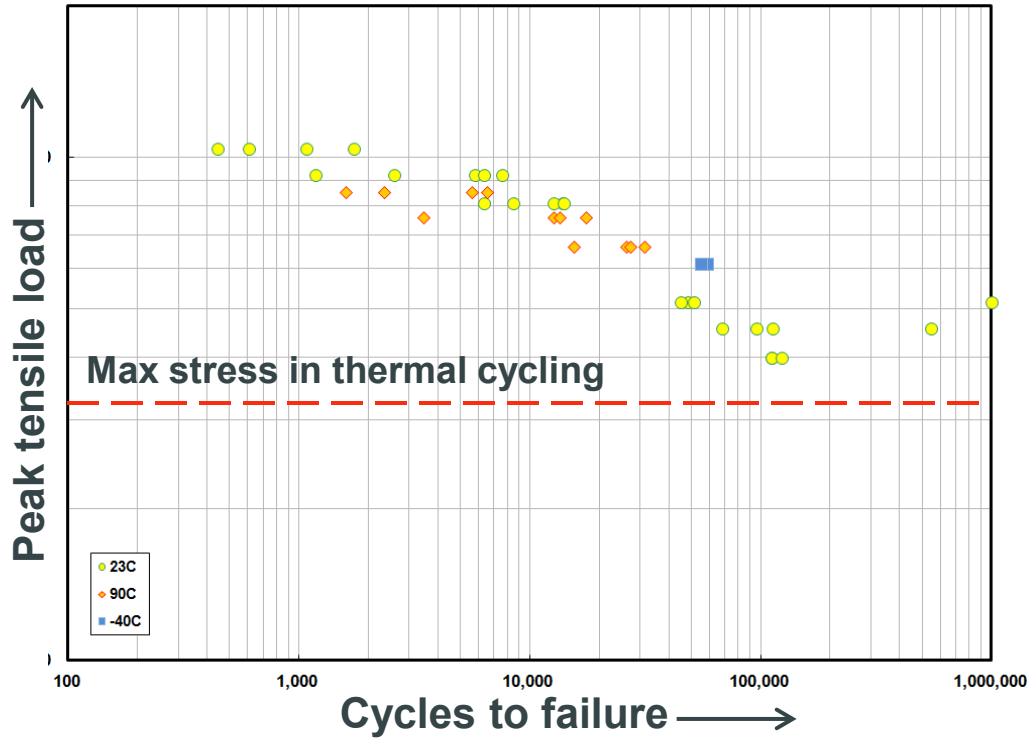


(Terminal tab is masked)

Fatigue failure at high stress

Endurance Limit Higher than Maximum Weld Stress

Weld fatigue testing @ multiple temperatures



- Maximum stress in welds/ bus bar due to thermal cycling is less than endurance limit for weld break
- Welds are reliable for 20 years in the field

Summary

- Combination of FMEAs and fault trees required to capture and document long term reliability risks
- ‘Physics of failure’ critical to properly design tests for retiring reliability risks
- Short term tests that simulate long term physics of failure are required
- Component level testing shortens timeline for reliability assessment and validation

Thank You!

Risk Priority Number (RPN) for Warranty Claims

Quantifying Risk for Every Defect

"Mani" G. TamizhMani

manit@asu.edu

PVreliability.asu.edu

Funding support of SERIIUS/DOE is acknowledged and appreciated.

Objective of this presentation

Analyze the measured module reliability data for the use of off-take transactions or for the plant owners to make objective and statistically quantitative warranty claims with manufacturers.

Outline

- Plant survey approach
- Warranty claims for defects
- Warranty claims for degradation
- Conclusions

Outline

- Plant survey approach
  - Goal 1: Define a statistical approach to obtain the distribution of degradation rates in the PV plant
  - Goal 2: Define a plant survey approach for the quantitative determination of risk level for every defect observed in the PV plant.
- Warranty claims for defects
- Warranty claims for degradation
- Conclusions

Statistical Approach – Sample Sizing

Sample size determination

- Identify the number of strings and number of modules in the plant
- Assume normal distribution for string and module degradations

String size (>95%CL; <5%CI)

- Select the locations in the plant to measure I-V of required number of strings (typically center and corners)
- Perform I-V measurements on the selected strings

Module size (>95%CL; <5%CI)

- Identify the best, worst and median performing strings
- Perform I-V measurements of all modules on the selected strings (66% modules from median strings; 17% modules from best stings; 17% modules from worst strings)

Note: For small systems (<300 modules), apply 100%CL. For large systems, apply between 95%-100%CL

Plant Survey Approach – Field Tests

A 12-Step Plant Evaluation Approach of ASU-PRL

Review (step 1):
Module construction info, System configuration & layout, Metered kWh data, Weather data and Previous reports (if any)

Safety Visual Inspection (step 7): All modules

Megger Test (step 8): All safety failed modules as needed

Material Defect Visual Inspn. (step 9): Statistically selected modules from step 3

Megger Test (step 10): All potential-safety issue modules

IR Imaging & Diode Test (step 11): Statistically selected modules from step 3

I-V and Megger Tests (step 12): All hot-spot and diode-failed modules

Primary goals:
Identification of safety failures & Identification of material defects

String I-V Test (step 2): Statistically selected strings (before cleaning)

Module I-V Test (step 3): Statistically selected modules in the best, worst and median strings (before cleaning)

Soiling Loss (step 4): I-V of three modules in the best string (after cleaning)

Module Reflectance (Browning) & FTIR (Plastics) (step 5): One module in a median string (after cleaning)

Data Check for PID (step 6): All modules in the statistically selected median strings (before cleaning)

Primary goals:
Determination of degradation rates, performance ratio, performance index & identification of degradation-causing defects

Note: BOS evaluation is also conducted as requested (inverter, wiring, racks/trackers, vegetation, shading)

Plant Survey – Equipment

Powerplant Testing Toolkit (PTT)

I-V Curve Tracer

Reference Module

Reference Cell

IR Camera

Shade Analyzer

Bypass Diode Checker

Multimeters

Camera/Video

Inverter Power Quality Analyzer

Handheld Reflectance Spectroradiometer

(for early browning detection)

Handheld FTIR

(for early backsheet, cable and connector failure detection)

Outline

- Plant survey approach
- Warranty claims for defects
  - Not all defects are necessarily risky or eligible for warranty claims
    - Quantify the impact of defect on safety or performance using RPN
- Warranty claims for degradation
- Conclusions

What is RPN (Risk Priority Number)

- For quantifying criticality of failure modes, FMECA depends on Risk Priority Number (RPN).
- RPN is one of the approaches for quantification of the criticality of the failure mode as indicated in IEC 60812 2006-01 standard

$$\mathbf{RPN = S * O * D}$$

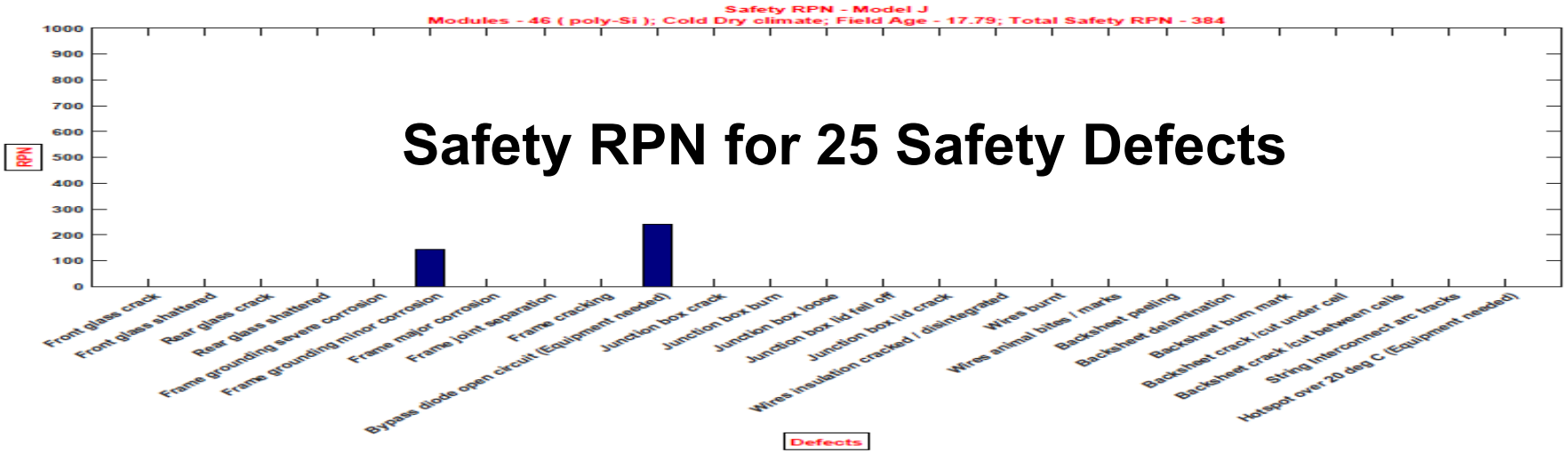
  - **S** means Severity which is an estimate of how strongly the effects of the defect will affect the system or the user **(S = 1 through 10)**
  - **O** means Occurrence which denotes probability of occurrence of a failure/defect mode for a predetermined or stated time period **(O = 1 through 10)**
  - **D** means Detection which is an approximate level easiness to identify the failure mode **(D = 1 through 10; Easy = 1; Difficult = 10)**

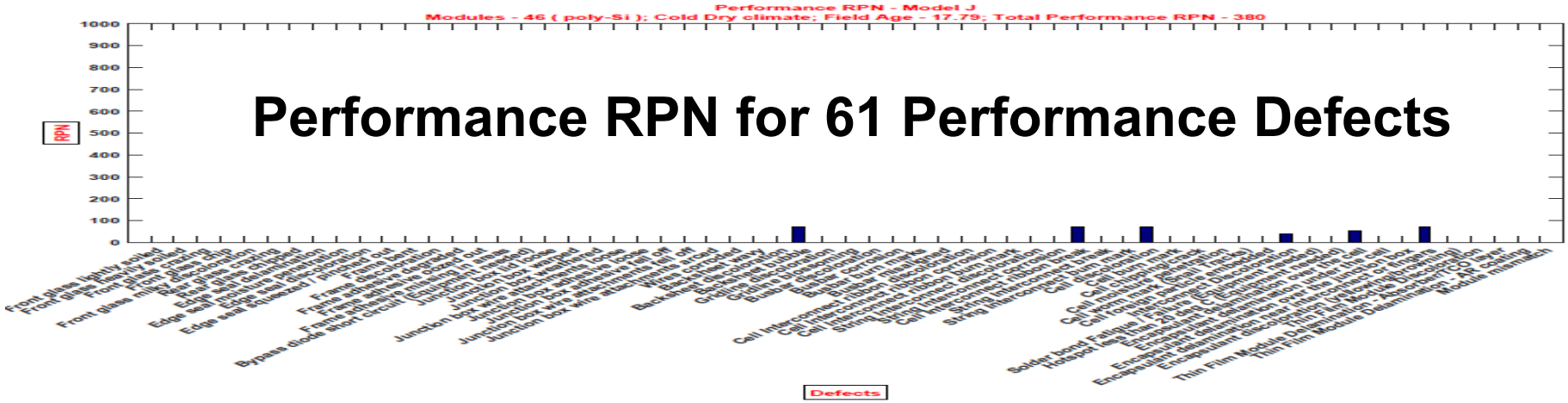
- Higher the RPN, severe the failure mode.

Types of Defects – 86 Possible Defects

There are about 86 defects that can be found in fielded PV modules

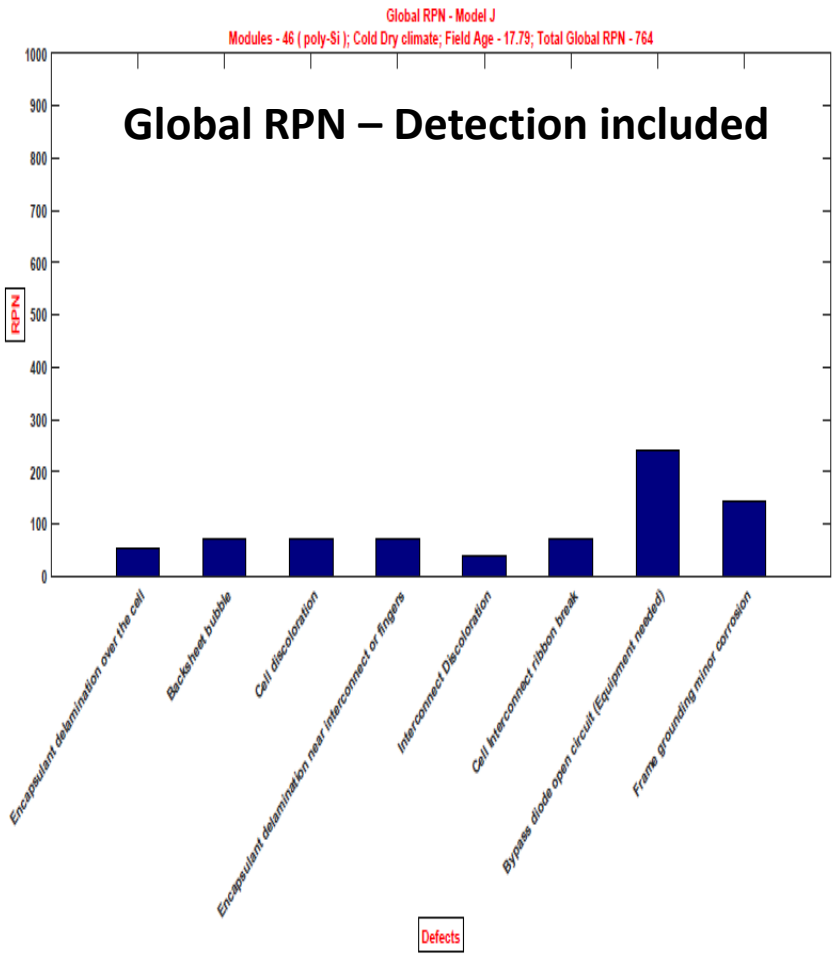
- Some defects are purely cosmetic with low or zero RPN score
- Some defects pose safety risks or performance risks with high RPN score
- Some defects pose degradation risks with high RPN scores

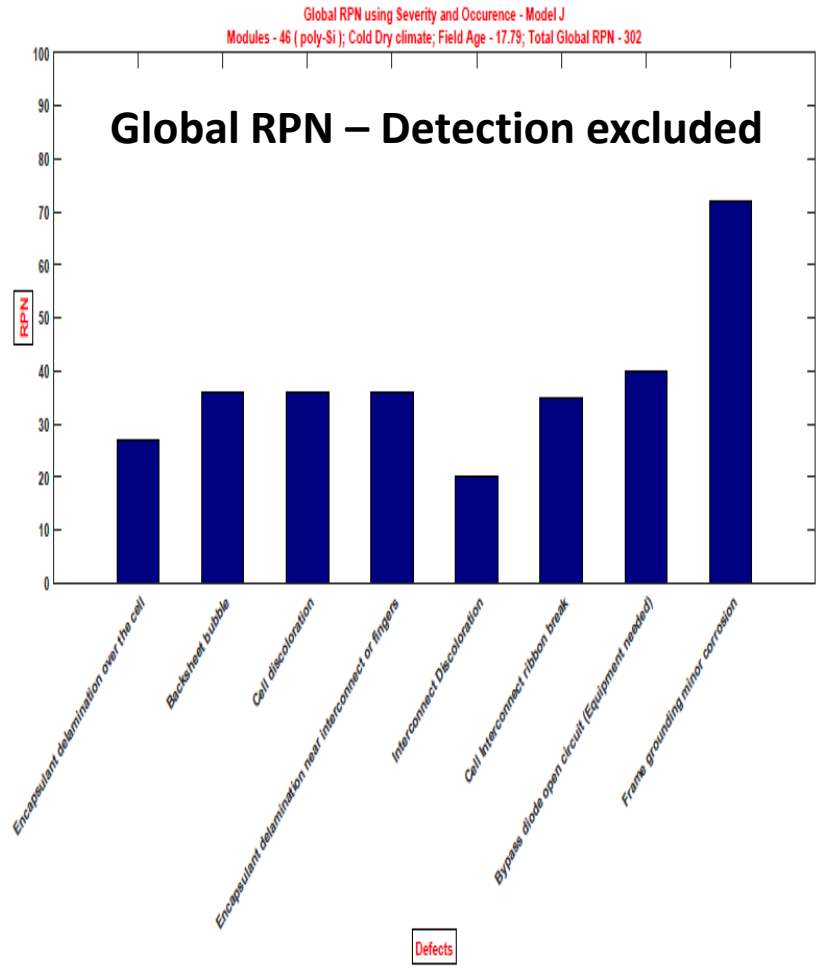




Global RPN = Safety RPN + Performance RPN

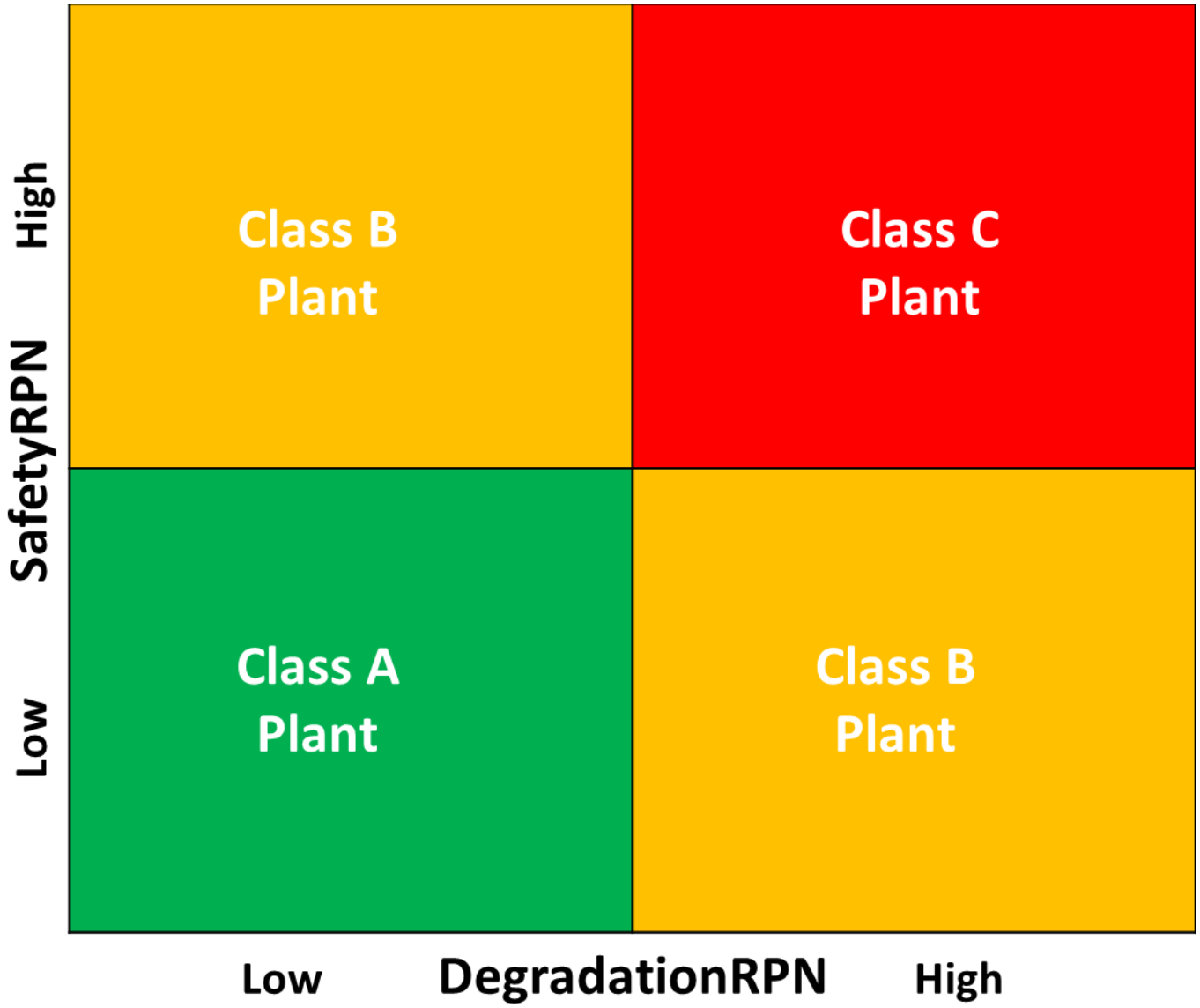
- Global RPN can be used for grading the power plant
- RPN calculation is now automated to reduce processing time and reduce human errors *(Please contact me if you are interested to receive a free copy of the software)*





Note: You may decide to exclude “detection” in the RPN calculation if you ignore diode failures and hotspot issues

Grading Power Plants using RPN – A conceptual approach

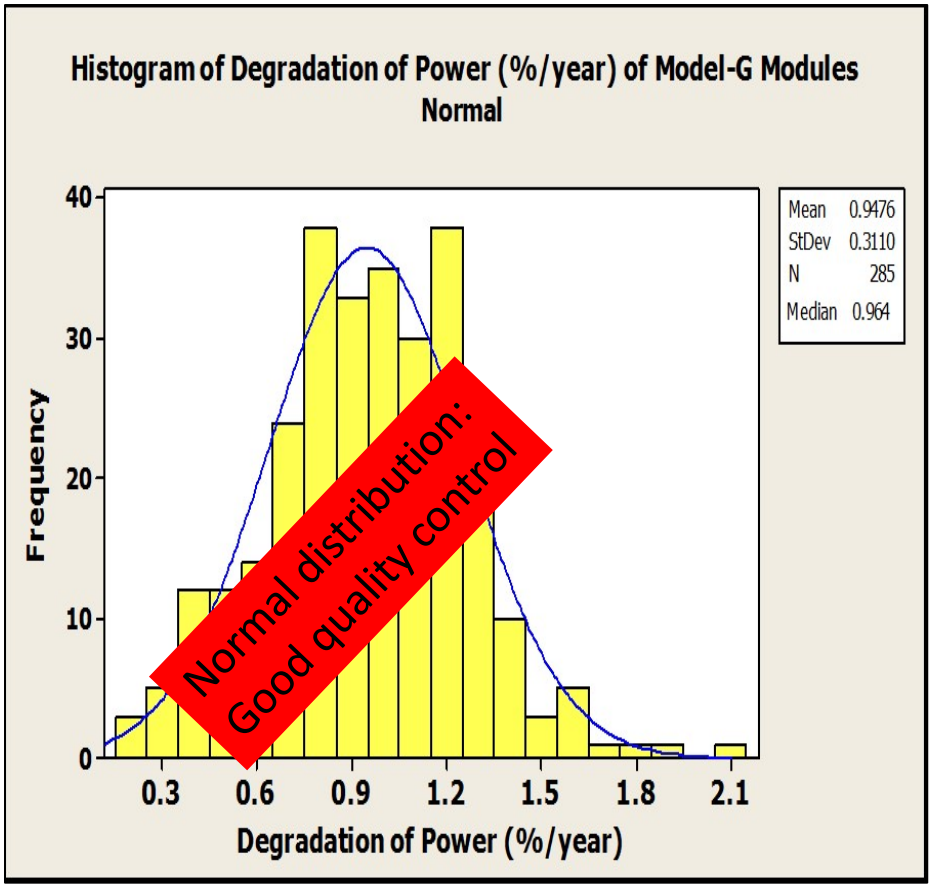


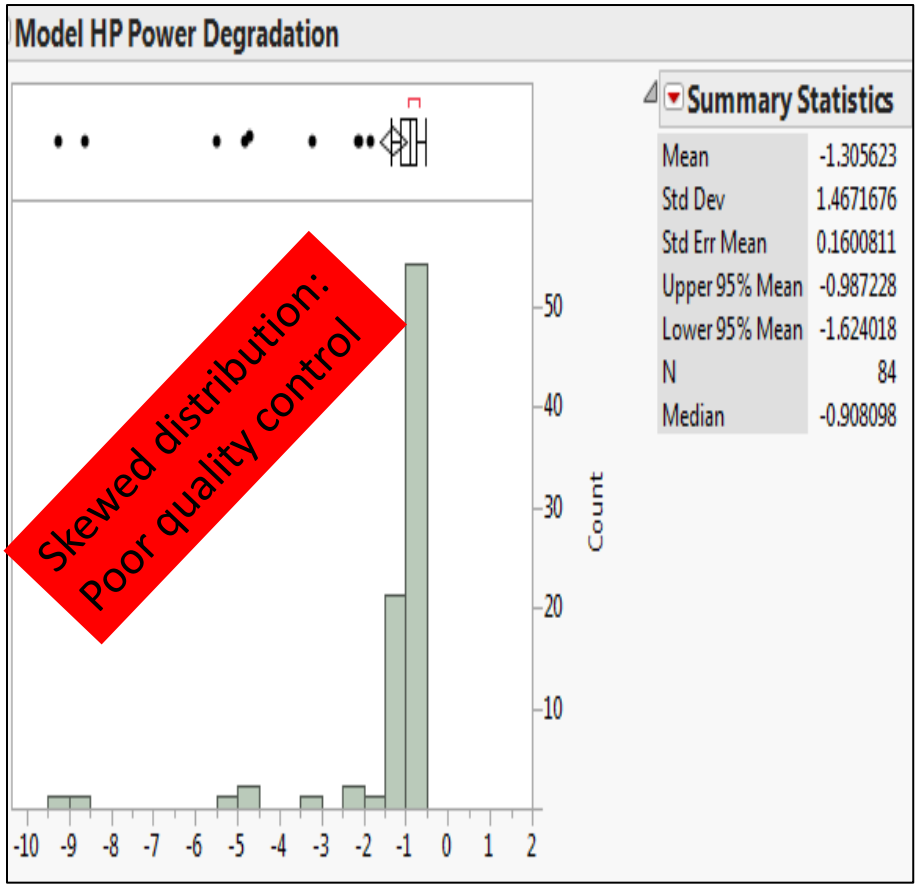
Outline

- Plant survey approach *(ASU-PRL approach presented)*
- Warranty claims for defects *(Results from Arizona presented)*
- Warranty claims for degradation
- Conclusions

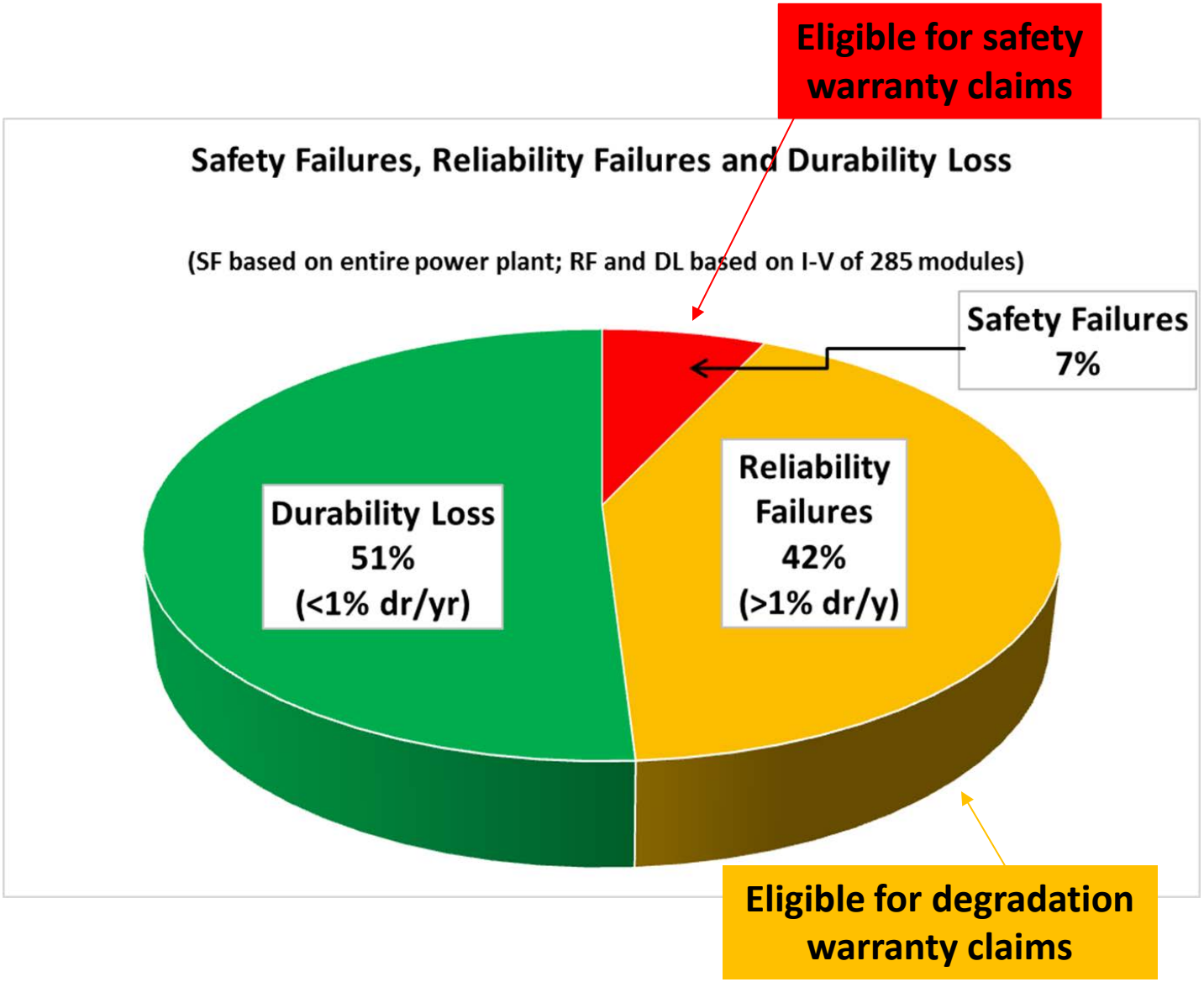
Manufacturing QMS – Good vs. Poor

- To avoid skewed QMS influence on degradation rate determination, the median (not the average) should be considered as a true representation of degradation rate
  - Model G = 0.96 %/year
  - Model HP = 0.91%/year





Warranty Claims based on Degradation Rates



Outline

- Plant survey approach *(ASU-PRL approach presented)*
- Warranty claims for defects *(Results from Arizona presented)*
- Warranty claims for degradation *(Results from Arizona presented)*
- Conclusions

Conclusions

- A statistical field test methodology has been developed for warranty claims
- A statistically quantitative RPN approach has been developed for defect warranty claims
- A statistically quantitative distribution approach has been developed for degradation warranty claims

Thank You!

Mani: manit@asu.edu

Questions?

Visit us: PVreliability.asu.edu

Automation of RPN Calculation

The automation is based on the information shown in the following slides.

Table for determining Detection (D) & Severity (S) for PV Modules

Ranking	Detection Criteria (D)	Severity Criteria (S) (see the next slide for a minor revision)
1	Monitoring System itself will detect the failure mode with warning 100%	No effect, Rd < 0.3%
2	Very high probability (most likely) of detection through visual inspection	Insignificant,Rd approx. to 0.3%
3	50/50 probability (less likely) of detection through visual inspection	Minor Cosmetic defect, Rd < 0.5%
4	Very high probability (most likely) of detection using conventional handheld tool e.g. IR, Megger	Cosmetic defect with Rd < 0.6%
5	50/50 probability (less likely) of detection using conventional handheld tool e.g. IR, Megger	Reduced performance, Rd < 0.8%
6	Very high probability (most likely) of detection using non-conventional handheld tool e.g. diode/line checker	Performance loss approx. to typical warranty limit, Rd approx. to 1%
7	50/50 probability (less likely) of detection using non-conventional handheld tool e.g. diode/line checker	Significant degradation, Rd approx. to 1.5%
8	Very high probability (most likely) of detection using performance measurement equipment e.g. IV tracer	Remote safety concerns, Rd < 1%
9	50/50 probability (less likely) of detection using performance measurement equipment e.g. IV tracer	Remote safety concerns, Rd < 2%
10	Detection impossible in the field	Safety hazard, Catastrophic

Revised Severity Table

- The reason for the revision is to accommodate the performance defects showing degradation rates higher than 1.5% in the field.

Severity Ranking	Severity Criteria	Changes to the severity table (used in automation)
1	No Effect, Rd < 0.3%	No change
2	Insignificant, Rd approx to 0.3%	No change
3	Minor Cosmetic Defect, Rd < 0.5%	No change
4	Cosmetic defect with Rd < 0.6%	No change
5	Reduced performance, Rd < 0.8%	No change
6	Performance Loss approx to typical warranty, Rd approx to 1%	No change
7	Significant degradation, Rd approx to 1.5%	No change
8	Remote safety concerns, Rd < 1%	Rd > 1.5 & Rd <= 2 for performance defects with bypass diode OC failure
9	Remote safety concerns, Rd < 2%	Rd > 2 for performance defects
10	Safety Hazard, Catastrophic	Rd > 2% with 18 catastrophic safety failures

Table for determining Occurrence (O) for PV Modules

Failure Mode Occurrence	Frequency CNF/1000	Ranking O
Remote: Failure is unlikely	<= 0.01 module per thousand per year	1
Low: Relatively few failures	0.1 module per thousand per year	2
	0.5 module per thousand per year	3
Moderate: Occasional failures	1 module per thousand per year	4
	2 module per thousand per year	5
	5 module per thousand per year	6
High: Repeated failures	10 module per thousand per year	7
	20 module per thousand per year	8
Very high: Failure is almost inevitable	50 module per thousand per year	9
	>= 100 module per thousand per year	10

The cumulative number of module failures per thousand per year (CNF) is computed as follows:

$$CNF/1000 = \sum_{system} (\%\ defects)*10 / \sum_{system} (operating\ time)$$

Visual Inspection data – Spreadsheet format for automated RPN calculation

- Total number of columns excluding "Module" column: 86 for 86 defects
- Do not change the title name of the defect in the spreadsheet
- 0 - Absence of defect/failure in the module
- 1 - Presence of defect/failure in the module

Module	Front glass lightly soiled	Front glass heavily soiled	Front glass crack	Front glass crazing	Front glass shattered	Front glass chip	Front glass milky discoloration	Rear glass crazing	Rear glass crack
C2-S1-T1	0	0	0	0	0	0	0	0	0
C2-S1-B1	0	0	0	0	0	0	0	0	0
C2-S1-T2	0	0	0	0	0	0	0	0	0
C2-S1-B2	0	0	0	0	0	0	0	0	0

IV data – Spreadsheet format for automated RPN calculation

- Do not change the title name of any column

Module	Rated Isc	Rated Voc	Rated Imax	Rated Vmax	Rated FF	Rated Pmax	Measured Isc	Measured Voc	Measured Imax	Measured Vmax	Measured FF	Measured Pmax	Age
C2-S1-T1	3.87	42.10	3.56	33.70	73.63	120.00	3.65	41.26	3.13	33.84	70.30	105.77	17.79
C2-S1-T2	3.87	42.10	3.56	33.70	73.63	120.00	3.87	41.38	3.22	35.28	70.79	113.44	17.79
C2-S1-T3	3.87	42.10	3.56	33.70	73.63	120.00	3.71	41.33	3.31	33.51	72.48	111.04	17.79
C2-S1-T4	3.87	42.10	3.56	33.70	73.63	120.00	3.71	40.54	3.35	32.46	72.30	108.67	17.79
C2-S1-T5	3.87	42.10	3.56	33.70	73.63	120.00	3.70	41.07	3.33	33.31	73.08	111.00	17.79
C2-S1-T6	3.87	42.10	3.56	33.70	73.63	120.00	3.68	41.05	3.31	32.91	72.07	108.89	17.79
C2-S2-T1	3.87	42.10	3.56	33.70	73.63	120.00	3.75	41.05	3.36	33.07	72.12	111.16	17.79

Figure 1: IV data format

Segregation of defects/failures – Performance defects

- **Total number of performance defects: 61**

Glass	Frame	Junction box	Cell
Front glass lightly soiled Front glass heavily soiled Front glass crazing Front glass chip Front glass milky discoloration Rear glass crazing Rear glass chipped	Frame bent Frame discoloration Frame adhesive degraded Frame adhesive oozed out Frame adhesive missing in areas	Junction box lid loose Junction box warped Junction box weathered Junction box adhesive loose Junction box adhesive fell off Junction box wire attachments loose Junction box wire attachments fell off Junction box wire attachments arced	Cell discoloration Cell burn Mark Cell crack Cell moisture penetration Cell worm mark Cell foreign particle embedded Cell Interconnect discoloration Gridline discoloration Gridline blossoming Busbar discoloration Busbar corrosion Busbar burn marks Busbar misaligned Cell Interconnect ribbon discoloration Cell Interconnect ribbon corrosion Cell Interconnect ribbon burn mark Cell Interconnect ribbon break String Interconnect discoloration String Interconnect corrosion String Interconnect burn mark String Interconnect break Hotspot less than 20˚C
Edge Seal	**Encapsulant**	**Backsheet**	
Edge seal delamination Edge seal moisture penentration Edge seal discoloration Edge seal squeezed / pinched out	Encapsulant delamination over the cell Encapsulant delamination under the cell Encapsulant delamination over the junction box Encapsulant delamination near interconnect or fingers Encapsulant discoloration (yellowing/browning)	Backsheet wavy Backsheet discoloration Backsheet bubble	
Wires	**Thin Film**	**Bypass diode**	**Others**
Wires corroded	Thin Film Module Discoloration Thin Film Module Delamination - Absorber coating Thin Film Module Delamination - AR coating	Bypass diode short circuit	Module mismatch Solder bond Fatigue / Failure

Segregation of defects – Safety failures

- **Total Number of Safety failures: 25**

Glass	Frame	Bypass diode	Junction box
Front glass crack Front glass shattered Rear glass crack Rear glass shattered	Frame grounding severe corrosion Frame grounding minor corrosion Frame major corrosion Frame joint separation Frame cracking	Bypass diode open circuit	Junction box crack Junction box burn Junction box loose Junction box lid fell off Junction box lid crack
Wires	**Backsheet**	**Cell**	
Wires insulation cracked / disintegrated Wires burnt Wires animal bites / marks	Backsheet peeling Backsheet delamination Backsheet burn mark Backsheet crack /cut under cell Backsheet crack /cut between cells	String Interconnect arc tracks Hotspot over 20˚C	

Fixed severity ranking for some safety failures

- 18/25 safety failures are given a severity ranking of 10 based on research experience from PV power plant.
- Bypass diode open circuit failure was given a severity ranking of 8 as it is not a major safety hazard unless repeated shading occurs.

Safety failures	Severity
Front glass crack	10
Front glass shattered	10
Rear glass crack	10
Rear glass shattered	10
Frame grounding severe corrosion	10
Frame joint separation	10
Frame cracking	10
Junction box crack	10
Junction box Burn	10
Junction box loose	10
Junction box lid fell off	10
Junction box lid crack	10
Wires burnt	10
Wires animal bites / marks	10
Backsheet peeling	10
Backsheet delamination	10
Backsheet crack /cut under cell	10
Backsheet crack /cut between cells	10
Bypass diode open circuit	8

2016 PVMRW@Sheraton West, Lakewood, CO.

Japanese Challenges to Improve Confidence in PV Module Reliability

Feb.23, 2016

Japan standard development project for PV module reliability

Tadanori Tanahashi(AIST), Takashi Ishihara(Mitsubishi Elec.),

Tadashi Obayashi(JET), Yasunori Uchida(JET),Kohji Masuda (JET)

Masaaki Yamamichi (AIST), and Isao Yoshida(JEMA)

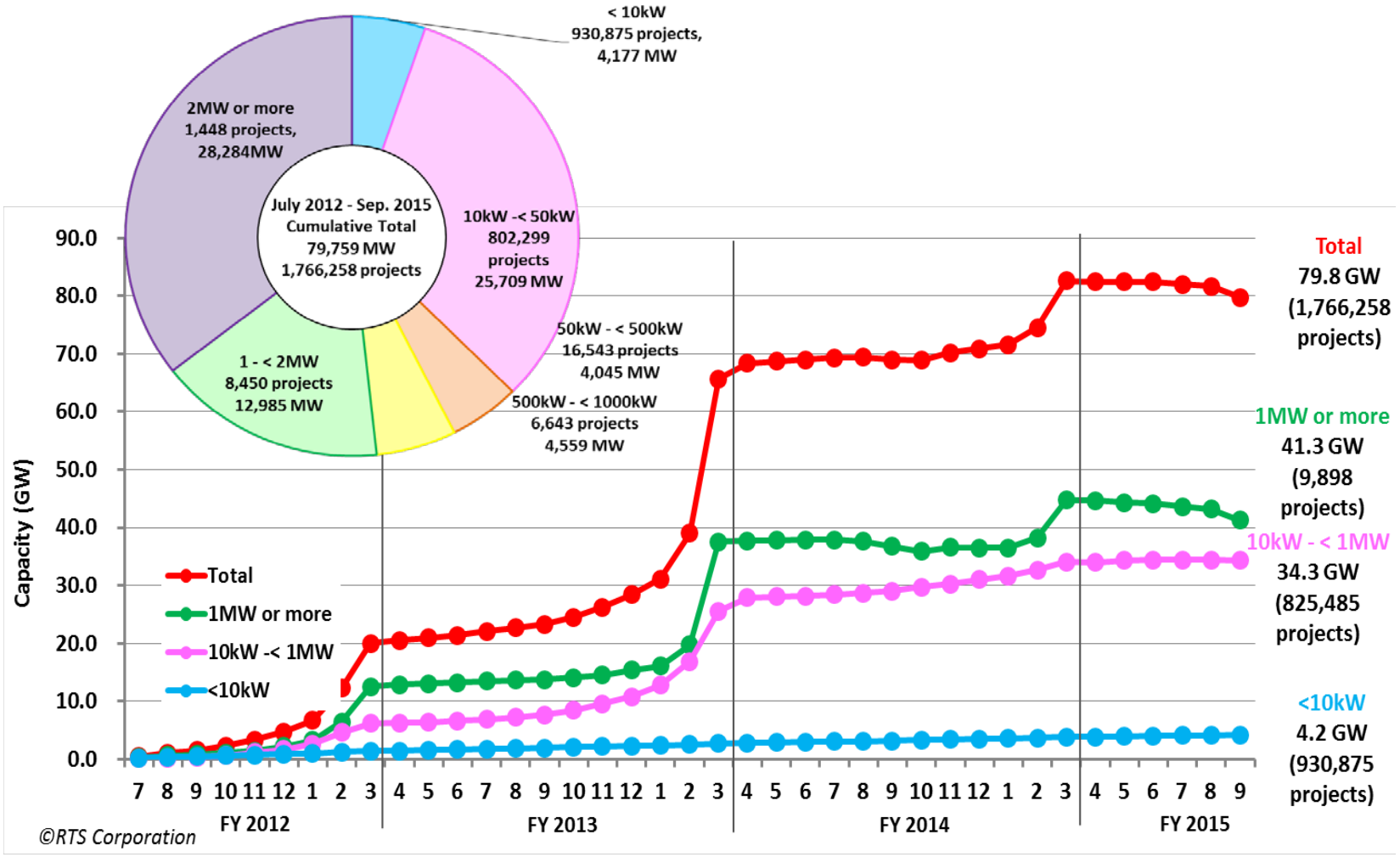
Today's Topics

1. **Current Status of PV Deployment in JP**

2. **Degradation Causes**
   Identified by the Extended Thermal Cycling Test on Commercially Available c-Si PV Modules

3. **"Standard Development Project for PV Module Reliability (SDEP-PV)" Activities**

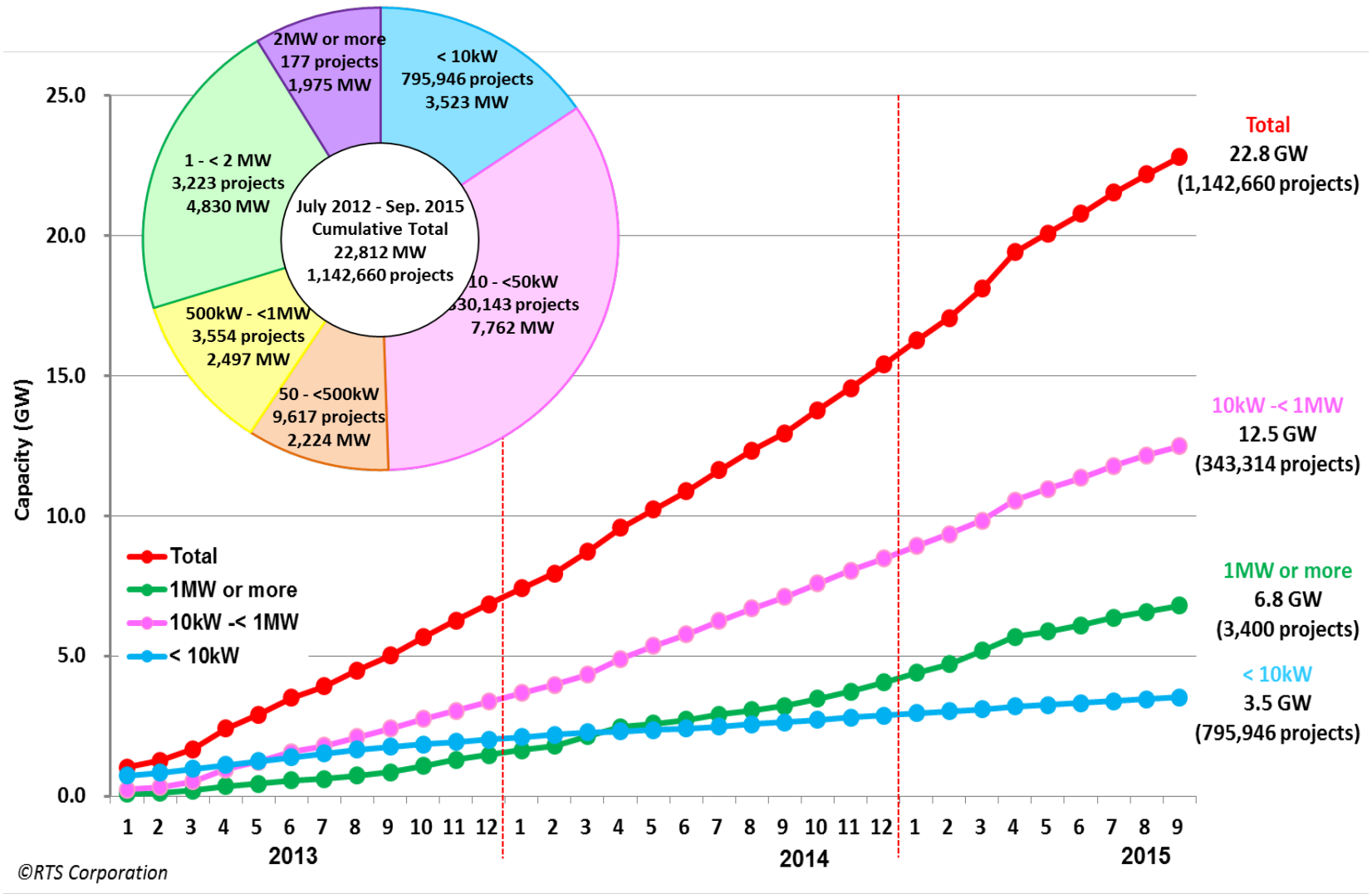
Status of the FIT Program: Approved Capacity as of Sept. 2015



Source: METI, compiled by RTS Corporation

RTS Corporation

Status of FIT Program: Commissioned Capacity as of Sept. 2015



Source: METI, compiled by RTS Corporation

RTS Corporation

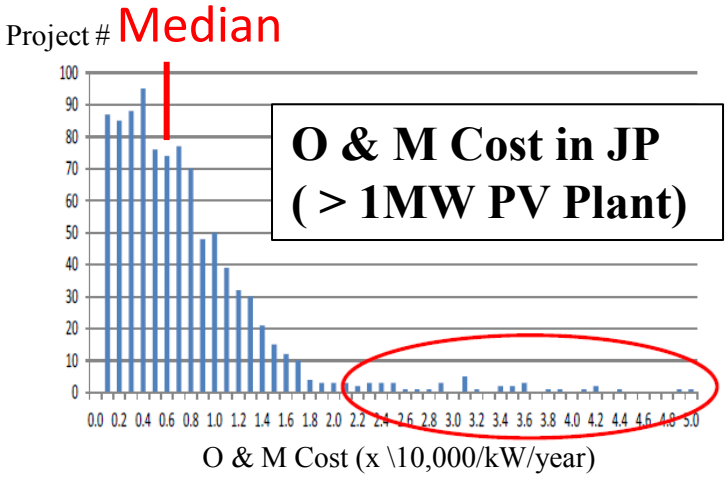
Current Status of PV Deployment in JP

- **Approved Capacity : ca. 80 GW (as of Sept. 2015)**
  Commissioned Capacity: ca. 23 GW (as of Sept. 2015)

  29% of METI approved capacity already installed.
  57GW await for implementation.

- **Under Discussion on the Cost-conscious PV Deployment**
  Amendment of FIT Law (Approved by Cabinet on Feb. 9, 2016)
  Auction for Large PV Projects (FY2017~?)
  Obligation of Maintenance (Inspection /Repair)

- **O & M Cost (>1 MW Plant)**
  Median = \6,000 /kW/y
  = ca. $53 /kW/y
  in CY2015



Source: METI
Jan. 19, 2016

Standard Development Project for PV Module Reliability
Facilitated by JEMA and JET (Supported by AIST)

Background

- Increasing need for more information on PV module safety and reliability to help users and investors in their decision making
- Concerns among module manufactures on excessive stress test leading to over quality, higher test cost, and longer time to market.

Goal

- Develop new PV module reliability test methods and prepare NWIP proposals to IEC

Organization

- Project Leader: Takashi Ishihara (Mitsubishi Electric)
- Project Members: Experts from module manufacturers, materials suppliers, AIST, JET

Approach

- Collect field data of modules exposed outdoor in Japan for many years
- Execute indoor/outdoor tests to verify findings obtained from the field data
- Develop PV module reliability test methods for local climates in Japan (temperate zone)

Today's Topics

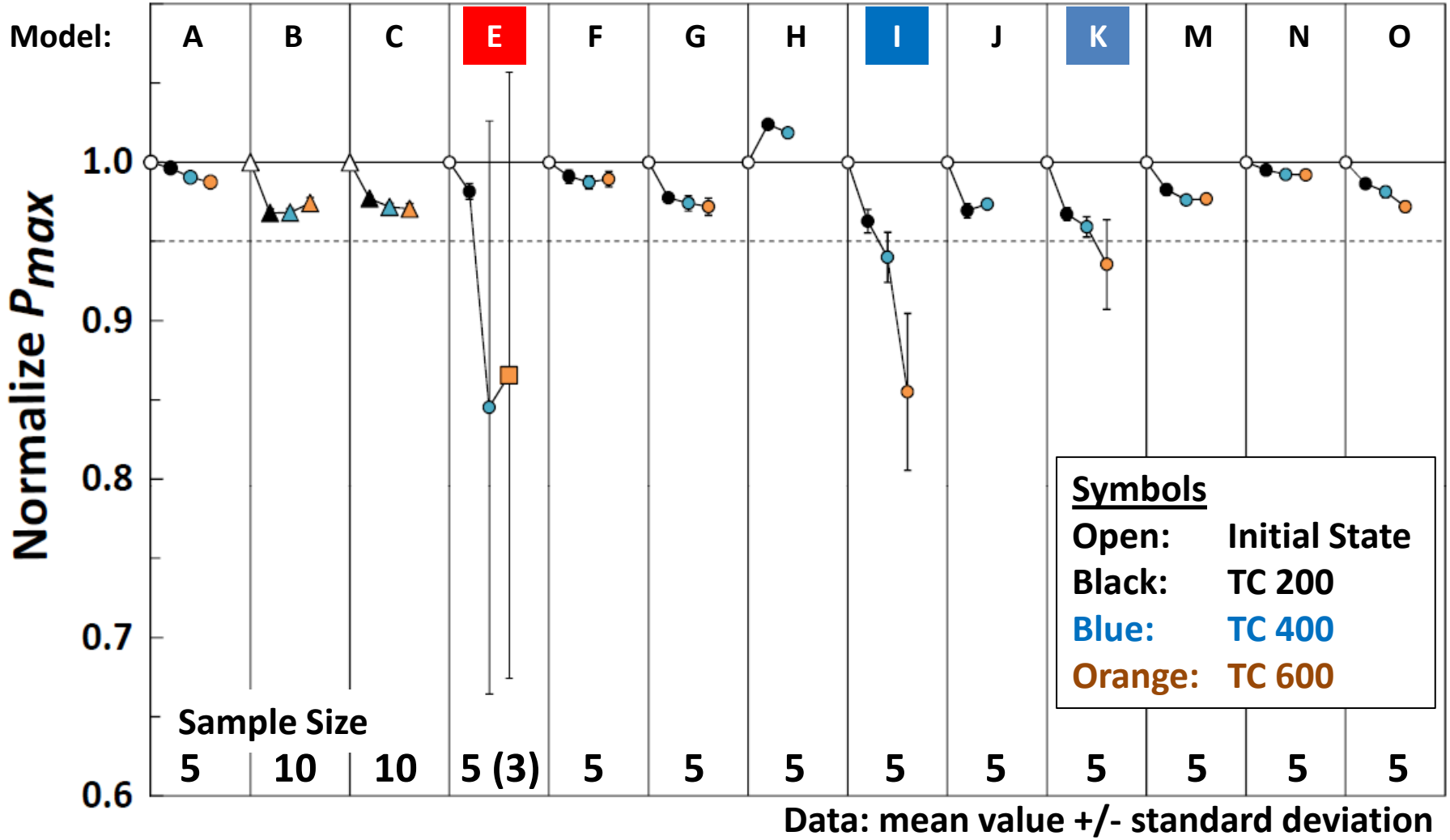
1. Current Status of PV Deployment in JP

2. **Degradation Causes**
   Identified by the Extended Thermal Cycling Test on Commercially Available c-Si PV Modules

3. "Standard Development Project for PV Module Reliability (SDEP-PV)" Activities

Degradation Causes Identified by the Extended Thermal Cycling Test on Commercially Available Crystalline Silicon Photovoltaic Modules

Degradation Profiles of Recent c-Si PV Modules (13 models / 2011~) during Thermal Cycling Test (~600 cycles)

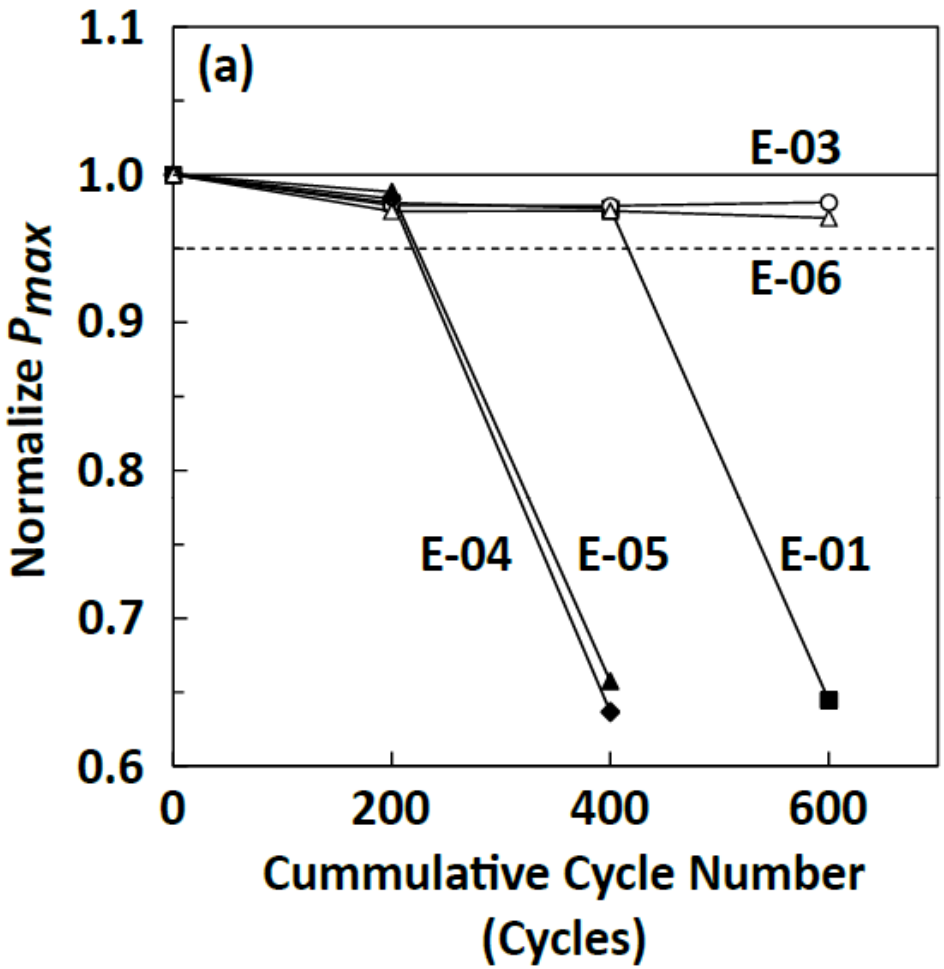


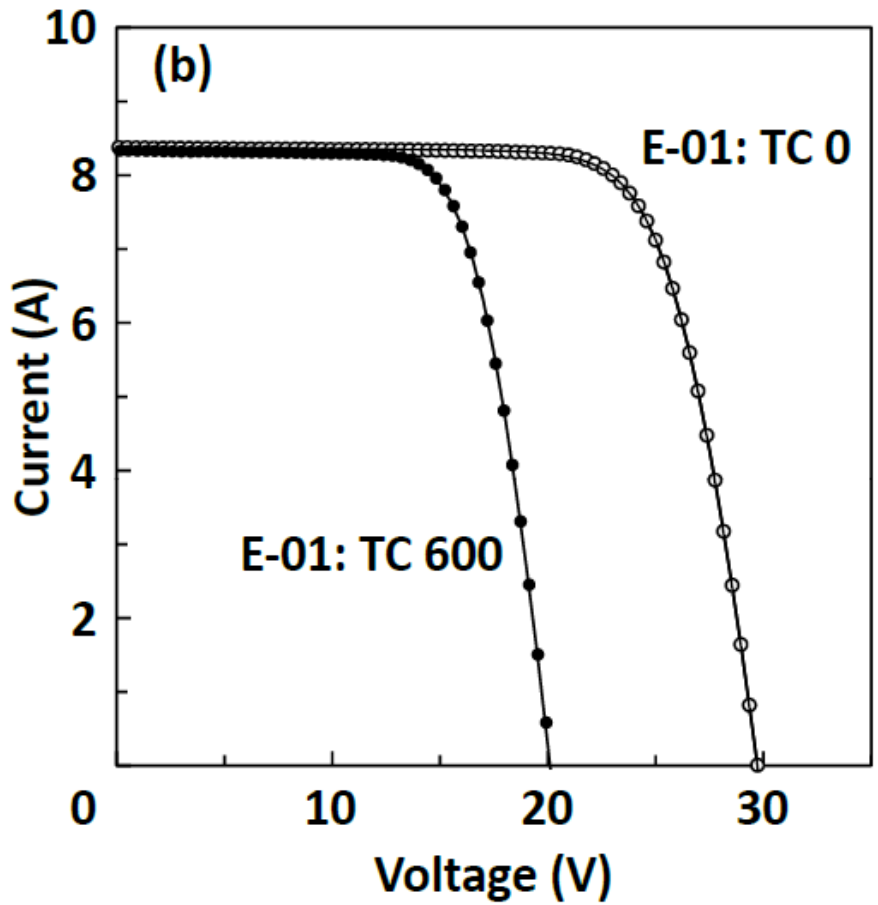
Data: mean value +/- standard deviation

Asia Standards and Conformity Assessment Promoting Project (JP), 2011-2014

Degradation Causes Identified by the Extended Thermal Cycling Test on Commercially Available Crystalline Silicon Photovoltaic Modules

Model E



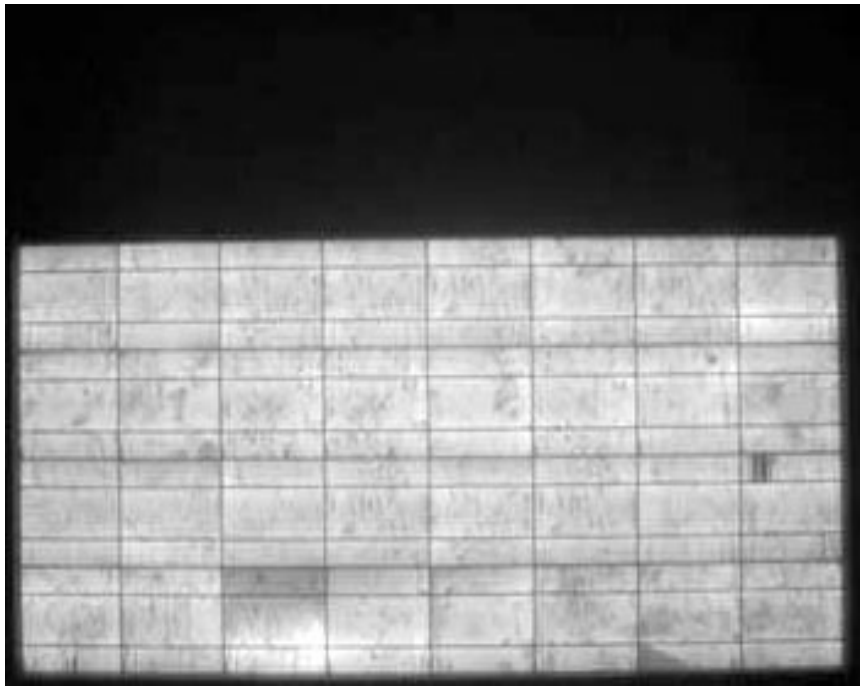


Observed failure is due to the obvious decline in Voc.

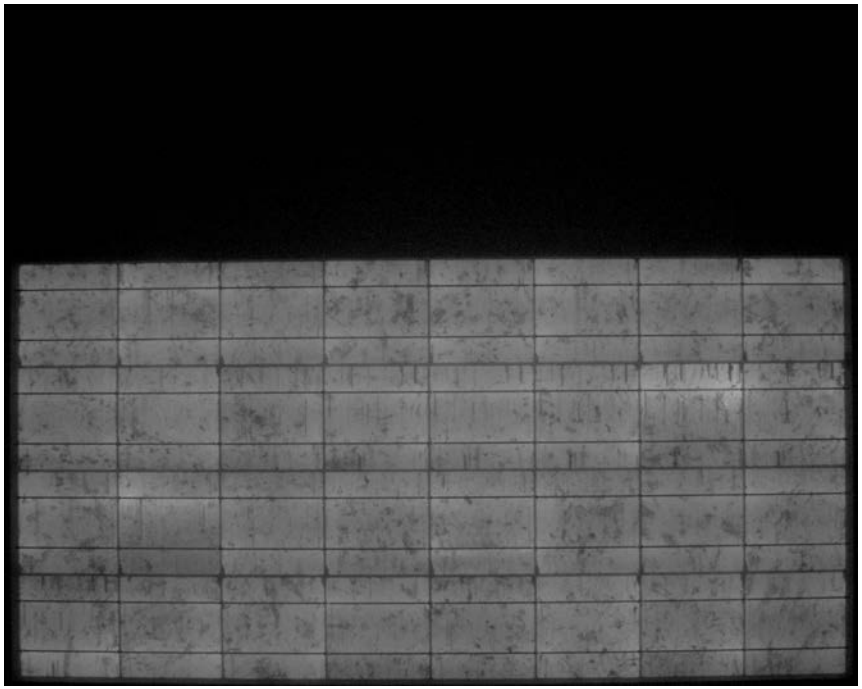
Degradation Causes Identified by the Extended Thermal Cycling Test on Commercially Available Crystalline Silicon Photovoltaic Modules

Model E

E_04 Module @ TC 400

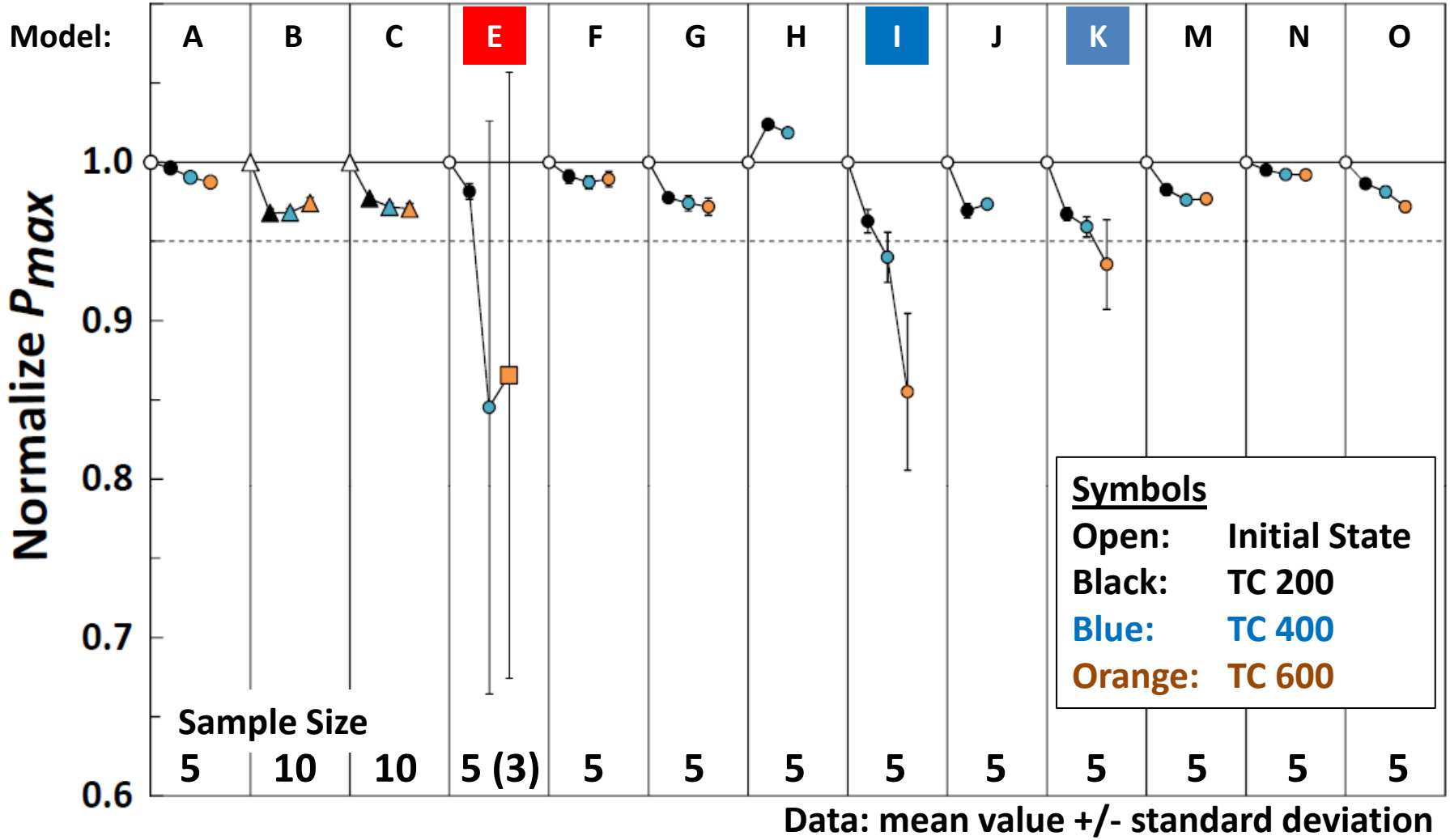


E_05 Module @ TC 400



Degradation Causes Identified by the Extended Thermal Cycling Test on Commercially Available Crystalline Silicon Photovoltaic Modules

Degradation Profiles of Recent c-Si PV Modules (13 models / 2011~) during Thermal Cycling Test (~600 cycles)

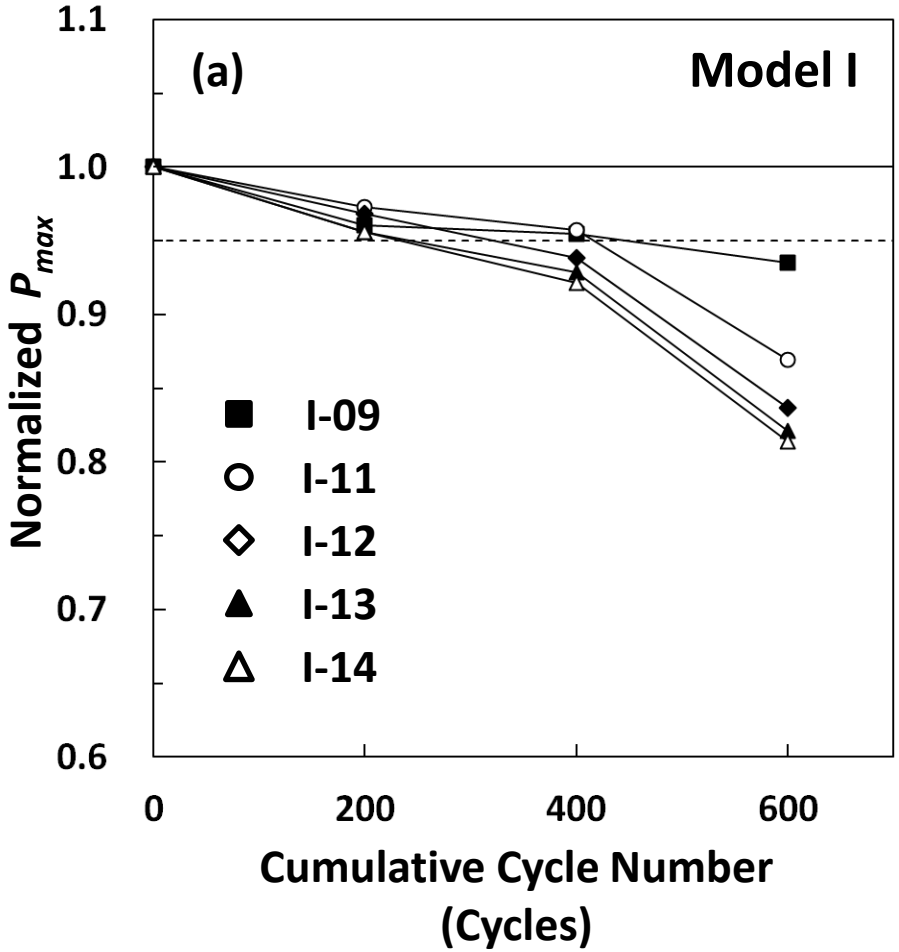


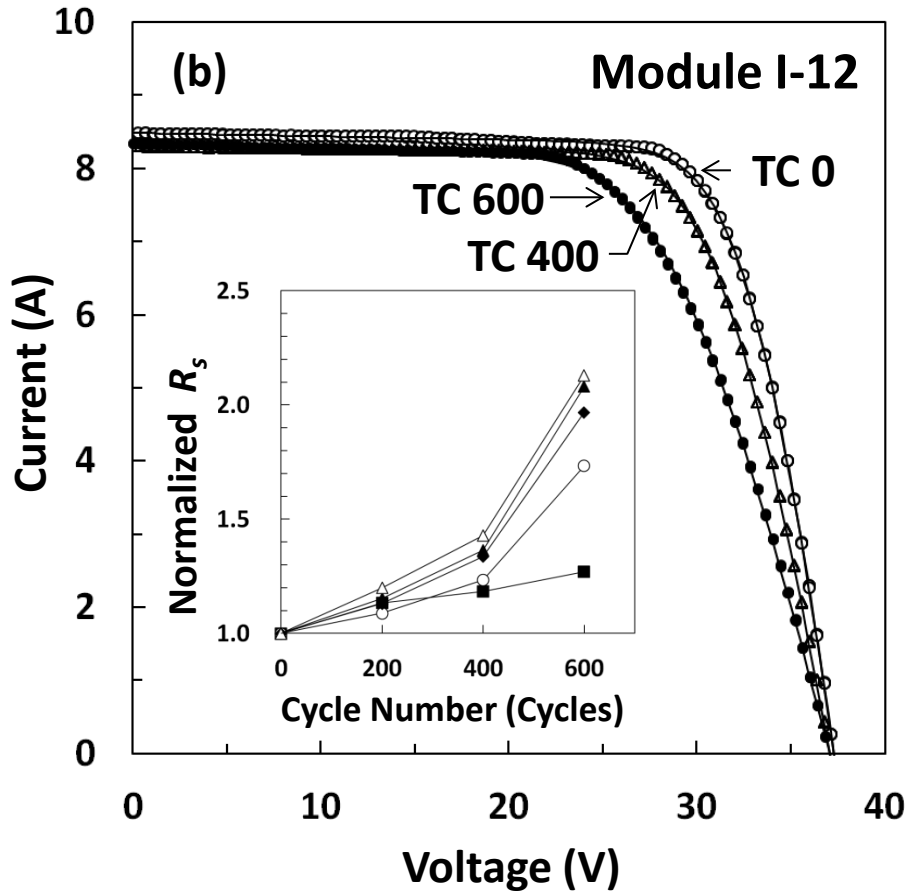
Data: mean value +/- standard deviation

Asia Standards and Conformity Assessment Promoting Project (JP), 2011-2014

Degradation Causes Identified by the Extended Thermal Cycling Test on Commercially Available Crystalline Silicon Photovoltaic Modules

Model I & Model K

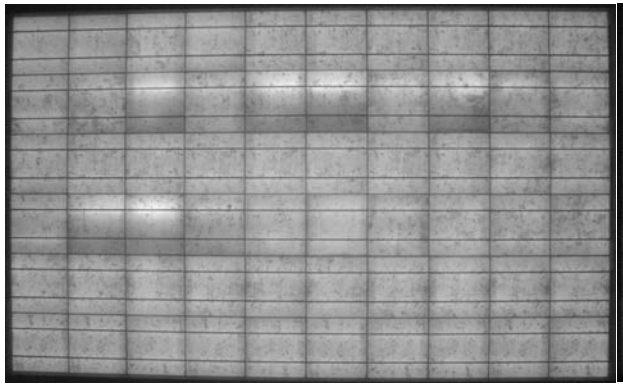




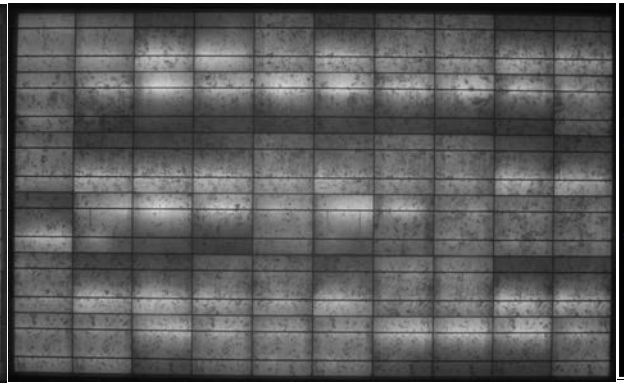
Observed failure is due to the increase in Rs.

Degradation Causes Identified by the Extended Thermal Cycling Test on Commercially Available Crystalline Silicon Photovoltaic Modules

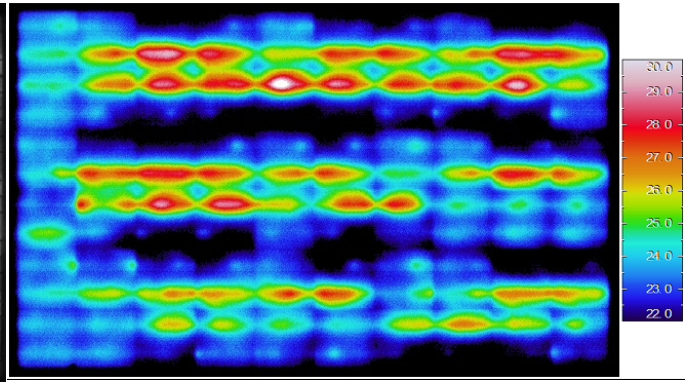
Model I & Model K



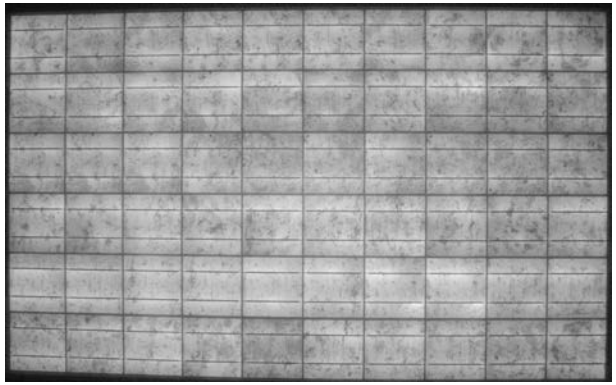
EL Image: I-12
TC 400



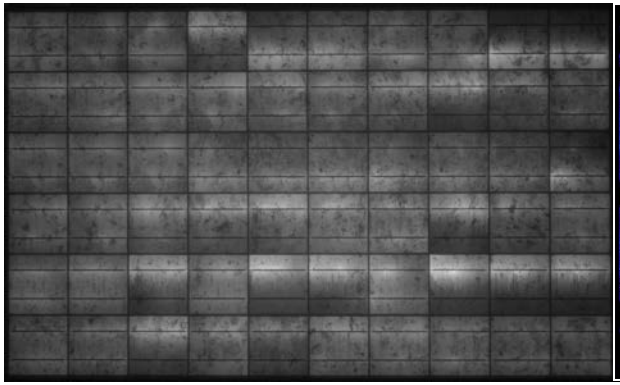
EL Image: I-12
TC 600



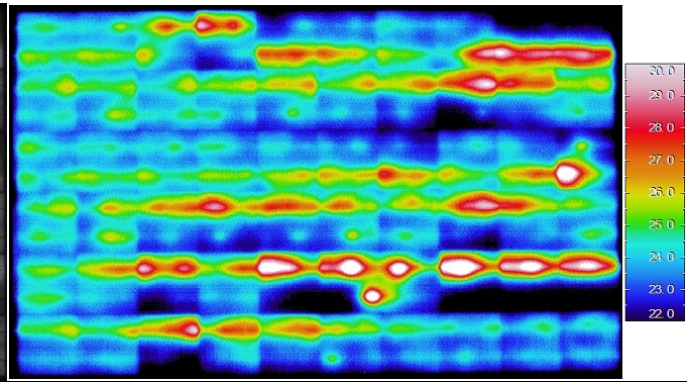
IR Image: I-12
TC 600



EL Image: K-24
TC 400



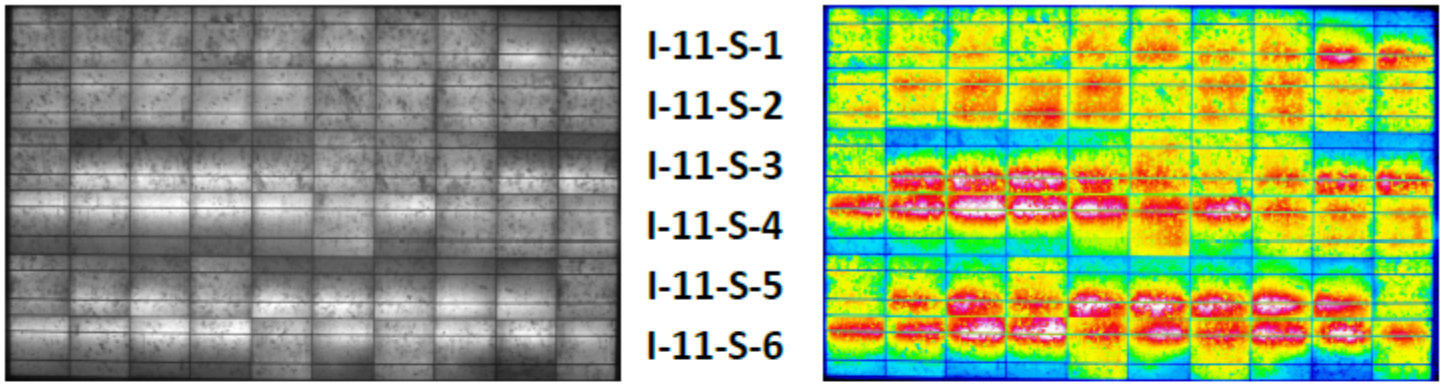
EL Image: K-24
TC 600



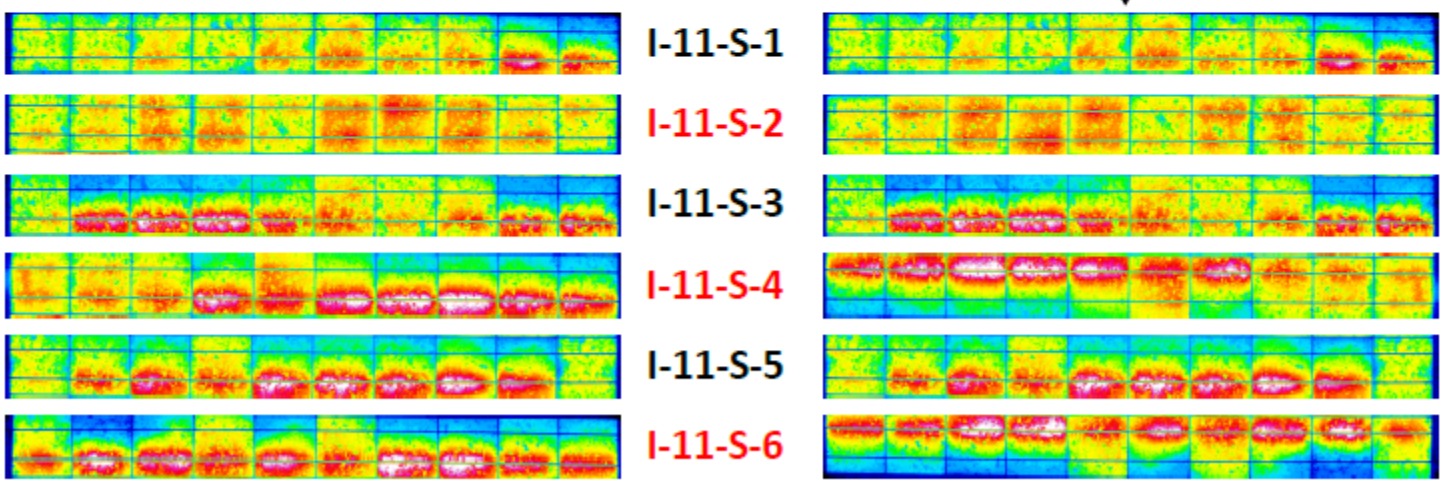
IR Image: K-24
TC 600

Degradation Causes Identified by the Extended Thermal Cycling Test on Commercially Available Crystalline Silicon Photovoltaic Modules

Model I: Alignment of Cell-Strings by Polarity



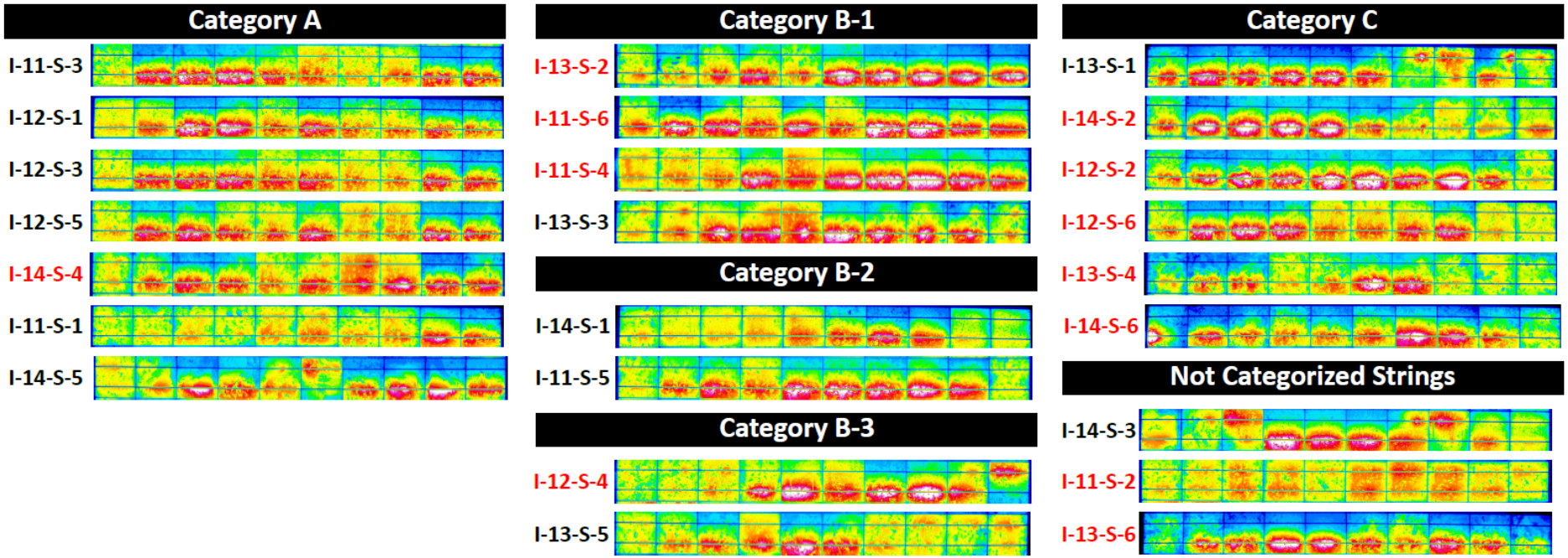
EL Image (Model: I, Module: 11) → Pseudo Color Mapping (16 colors)



S-2, S-4, and S-6 were Rotated (180 °) to Align the Polarity of Cell-Strings ← Stripped Cell-Strings (S-1 to S-6)

Degradation Causes Identified by the Extended Thermal Cycling Test on Commercially Available Crystalline Silicon Photovoltaic Modules

Model I: Categorization (Module I-11 / I-12 / I-13 / I-14)



- Almost blue area (= dark area in EL image) were positioned at the upper portion of each cell-string.
- By the distribution of yellow-red area (=intact area) at upper portion of each cell-string, these cell-strings were divided into 4~5 categories.
- All categories consisted of cell-strings derived from two /three modules.

→ This failure was highly likely a quality issue caused by not well controlled soldering process.

Auditor's Experience (from a literature)

The partially assembled PV module in the above picture was randomly picked from an automated tabbing and stringing machine.

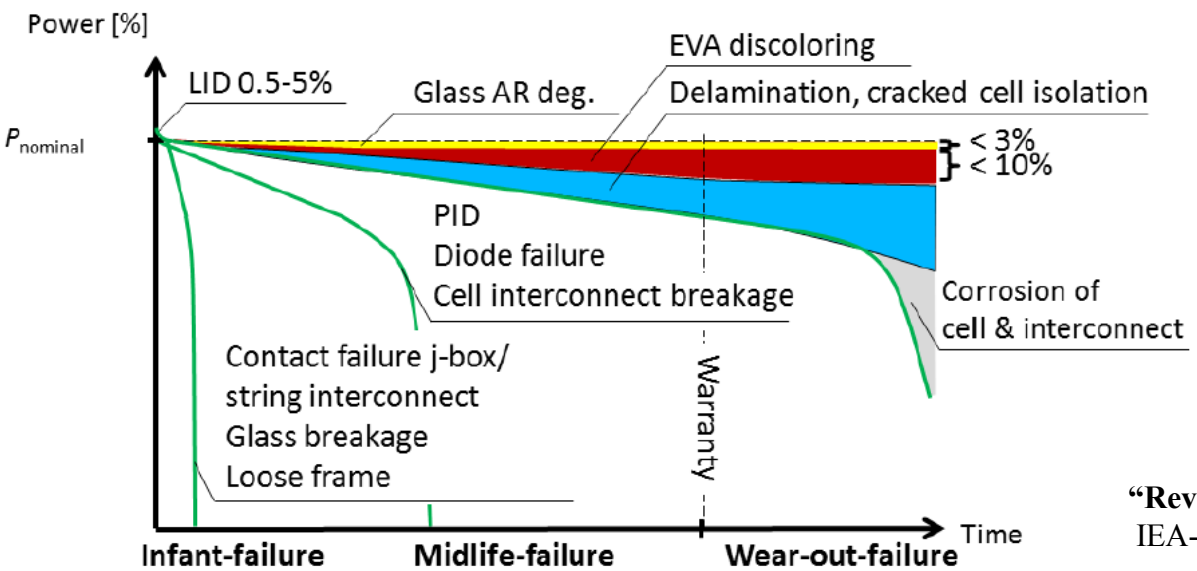
"**Reducing investment risk in PV projects** " by **Peter Rusch and Ian Gregory (2013)**
http://www.solarbusinessfocus.com/articles/reducing-investment-risk-in-pv-projects

Degradation Causes Identified by the Extended Thermal Cycling Test on Commercially Available Crystalline Silicon Photovoltaic Modules

To be Discussed:

- Failures detected by TC 600 in recent c-Si PV modules
  - = not Infant Failure
    - Pass: TC 200
  - = not Wear-Out Failure
    - Because, wear-out failure can not be generated by poor adjustment of soldering machines.
  - = Midlife Failure?
    - Probably, it would be prevent by QMS (JIS Q 8901 / IEC TS 62941).

- Sample Size to Test: 1 module = not enough / more than 3 or 5 modules?
  - for Qualification?
  - for Lifetime Estimation?



"Review of Failures of PV Modules"
IEA-PVPS T13-01 2014

Today's Topics

1. Current Status of PV Deployment in JP

2. Degradation Causes
   Identified by the Extended Thermal Cycling Test
   on Commercially Available c-Si PV Modules

3. **"Standard Development Project for PV Module Reliability (SDEP-PV)" Activities**

Standard Development Project for PV Module Reliability
Facilitated by JEMA and JET (Supported by AIST)

Activities

- Collect field data of modules exposed outdoor in Japan for many years
- Execute indoor/outdoor tests to verify findings obtained from the field data

Poster 160 : **Study of PV module degradation which has been exposed over 20 years in representative climates of Japan**

- Develop PV module reliability test methods for local climates in Japan (temperate zone)

Poster 118 : **Testing Procedures for Highly Reliable Photovoltaic Modules**

Poster 173 : **Electrical Detection of Gap Formation underneath Finger Electrodes on c-Si PV Cells Exposed to Acetic Acid Vapor under Hygrothermal Conditions**

- Verification of practical issues on our proposed draft

Poster 175: **Behavior of bypass diode during thermal runaway test**

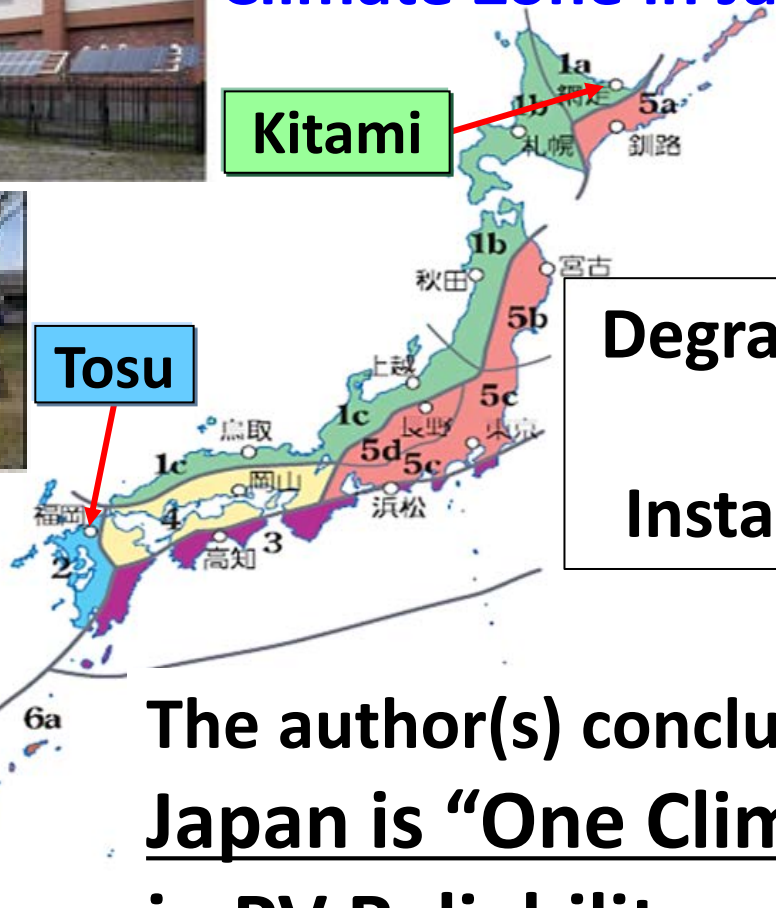
Study of PV module degradation which has been exposed over 20 years in representative climates of Japan

Poster #: 160

Tadashi Obayashi

Japan Electrical Safety & Environment Technology Laboratories (JET)

Climate Zone in Japan



Degradation Behavior of PV Modules Installed in Early 1990s

The author(s) concluded that

<u>Japan is "One Climate World" in PV Reliability</u>

Poster #: 118

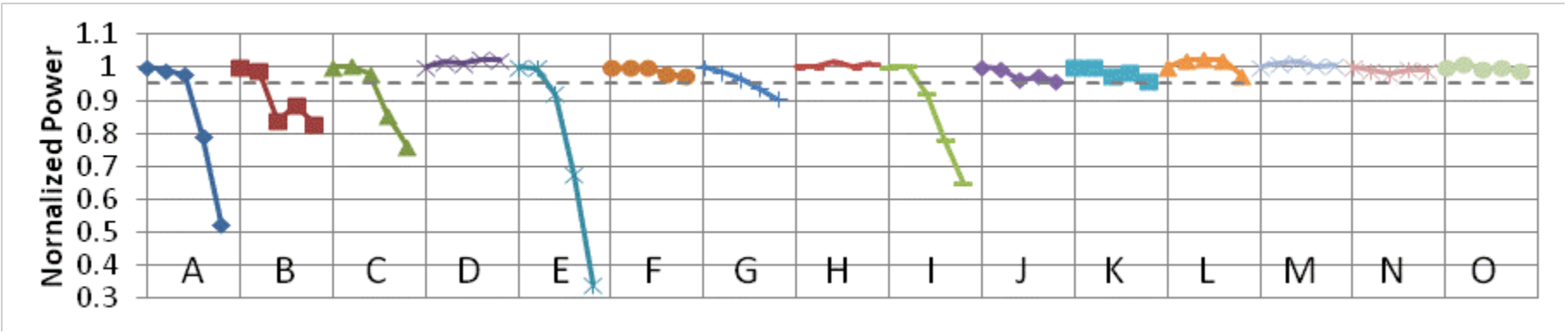
Testing Procedures for Highly Reliable Photovoltaic Modules

Kohji MASUDA, Yasunori UCHIDA, Tadashi OBAYASHI (JET)

Repetition (RE) Test (≈ "Alternative Test" in Test to Failure [TTF] Protcol)

DH 1000 (w/o Sys-V) → TC 200 → DH 1000 (w/o Sys-V) → TC 200

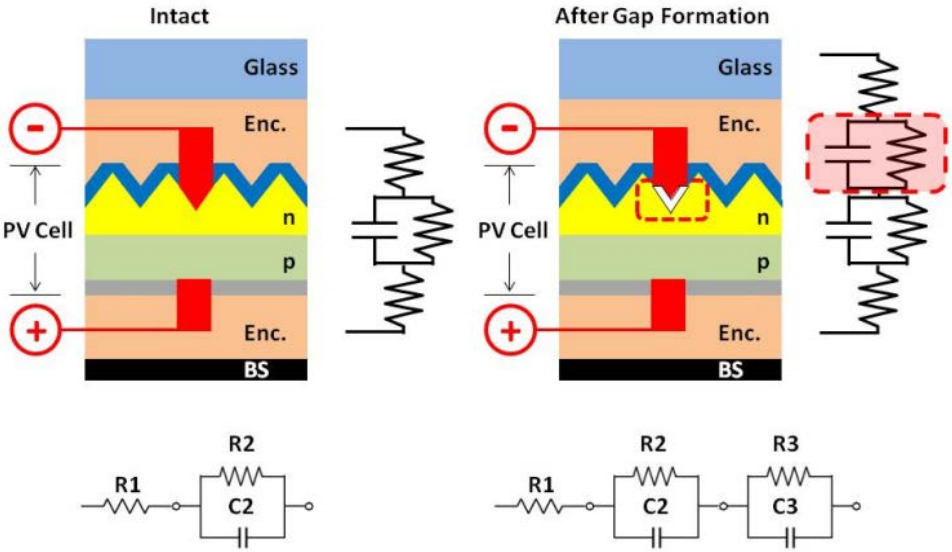
on Recent 15 Models of Commercially Available PV Modules

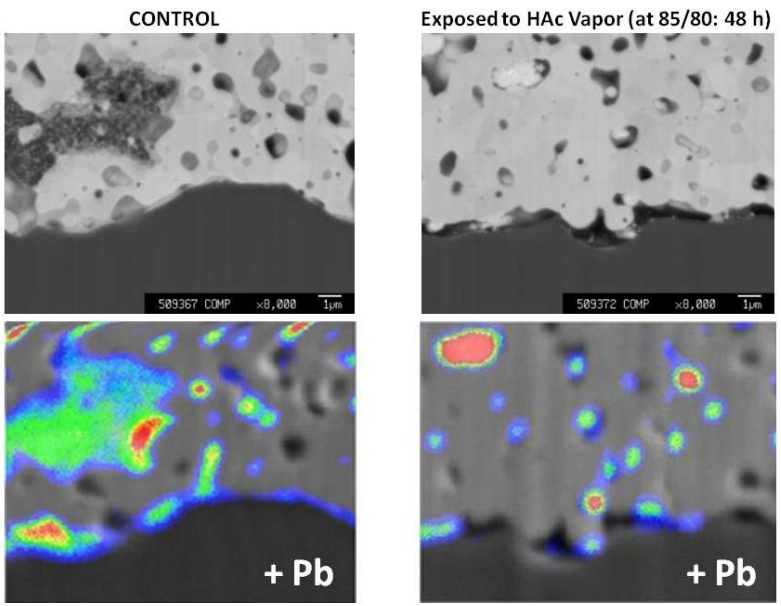


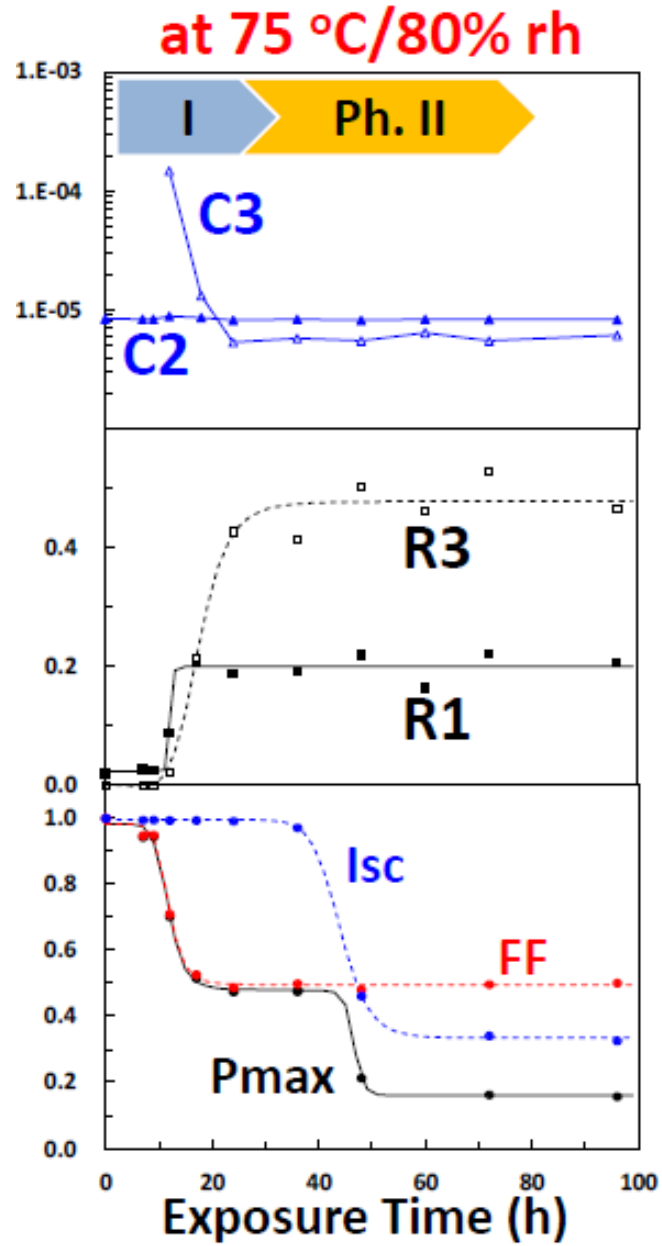
Repetition (RE) Test is likely to reproduce the defects with cracks in backsheet and PV cells, therefore it would be a new testing procedure involved in **snail trail** and other defects (e.g., insulation problems).

Electrical Detection of Gap Formation underneath Finger Electrodes on c-Si PV Cells Exposed to Acetic Acid Vapor under Hygrothermal Conditions T. Tanahashi, et al.

Poster #: 173







Poster #: 175

Behavior of bypass diode during thermal runaway test

Yasunori Uchida

JET (Japan Electrical Safety & Environment Technology Laboratories)

QA Forum started in July 2011 in order to establish the criteria, guidelines and technical requirements for high reliability PV modules.
As one of the TG4 activities, I proposed a new work item for international standard of "**Bypass diode thermal runaway test (future IEC 62979)**" in October 2014 which is currently in the CD stage.
From the results of repeated experiments to establish the test method, the bypass diode (BD) behavior during thermal runaway test has become clear.

❶ Conditions of thermal runaway occurrence
❷ Influence of a switching time until applying of reverse bias voltage after shutting off forward current
❸ How to detect the thermal runaway occurrence
❹ The estimated junction temperature (Tj) during thermal runaway

Summary

- PV deployment in Japan has reached up to 23GW as of Sep. 2015 due to successful FIT program started in 2012 and 57GW project await for implementation. The government decided to **amend FIT program** recently to support more cost conscious deployment of new PV systems.
- To respond to increasing need for more information on reliable PV modules, JEMA and JET initiated **Standard Development Project for PV Module Reliability** to develop reliability test methods applicable to PV modules to be installed in Japan and other mid-latitude areas and propose them to IEC.
- Degradation Causes identified by **Extended Thermal Cycling Test** on commercially available c-Si PV Modules are presented.
- Some other topics currently being discussed in the project are introduced. Many of them are presented at the Poster session of 2016 PVMRW.

Contributors:

- Extended TC

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Special Thanks to Izumi Kaizuka (RTS Corporation)
Keiichiro Sakurai (AIST)

Analytical methods to detect metal migration in PV modules from the service environment

Alex Bradley, Kate Stika, Gail Raty, Bill Gambogi
DuPont Photovoltaic Solutions Wilmington, DE, USA

Tony Sample
Joint Research Centre Ispra, Italy, EU

Introduction

Motivation:

Understanding how to optimize photovoltaic (PV) module design over its lifetime is vital to the sustainable growth of solar. As the number of installations and system size continues to grow, this understanding becomes increasingly important. A systematic understanding of degradation mechanisms that are induced as a result of variables such as the service environment, installation, module design, material, weather, operation & maintenance, and manufacturing is required for reliable operation throughout a system's lifetime.

ESTI Outdoor Test Field

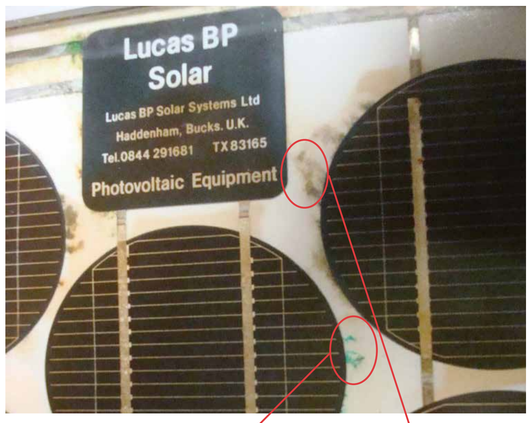
Analytical Methods

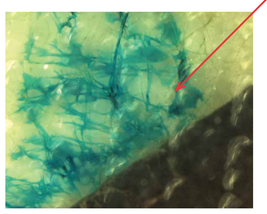
Destructive Analysis and Core Samples:

We describe our recent experience mapping the physical and chemical changes observed in degraded PV modules. Examples will highlight the application of Scanning Electron Microscopy – Energy Dispersive X-Ray (SEM-EDX) for the study of ion migration from the solar cell into the encapsulant. In addition, we use FTIR spectroscopy to identify polymeric materials through comparison to a library of known materials.

Cross section analysis – materials of construction:

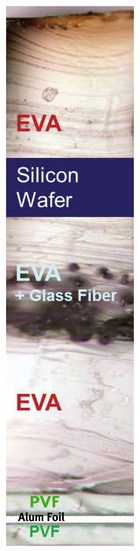
- Frontside EVA – Discoloration at glass interface does not penetrate through bulk encapsulant
- Backside EVA – uses glass fiber reinforced mesh
- Backsheet – PVF/Al Foil/PVF





The green dendritic growth appears to be 3-dimensional growth identified as Cu containing by EDX.

Under low magnification stereo microscope the discoloration appears to be clusters of brown needles.



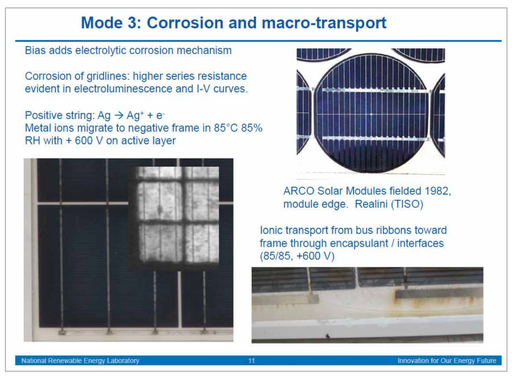
not to scale

Literature

A similar observation was reported by NREL as a mechanism associated with PID. The modules documented by Realini used PVB as encapsulant.

Hacke, P. **Degradation Mechanisms of PV Modules at System Voltage**. PV Module Reliability Workshop, Berlin, 2011.

D. Chianese, A. Realini, N. Cereghetti, S. Rezzonico, E. Bur& G. Friesen, A. Bemasconi **ANALYSIS OF WEATHERED c-Si PV MODULES.** 3rd World Conference on Photovoltaic Energy Conversion May 11-18., 2003. Osaka, Japan.



Goals

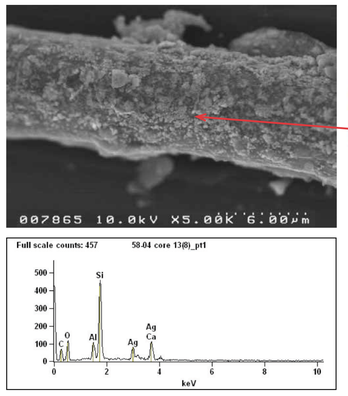
An understanding of material interactions and degradation pathways in fielded modules is important to determine how photovoltaic (PV) materials affect reliability. As part of the effort to build this understanding, a suite of destructive and non-destructive testing protocols has been developed to compare material performance and reliability in the service environment.

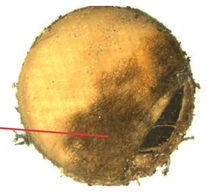
Collaboration:

We report the results from an analysis of commercial c-Si PV modules provided to DuPont by the Joint Research Center (JRC) in Europe. This evaluation provides valuable PV module field data and will quantify key performance metrics and degradation modes. The objective is to develop a library of known PV module degradation modes and an analytical suite of tools for detection and measurement.

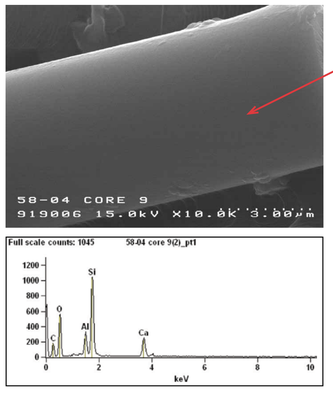
Scanning Electron Microscopy – Energy Dispersive X-Ray

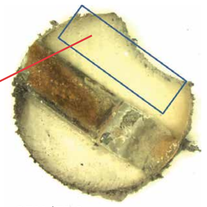
SEM images and EDX confirm macro transport of Ag





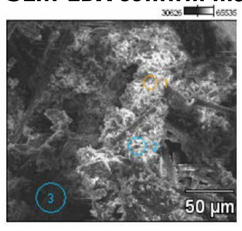
Glass fiber exposed by cutting into the encapsulant. Brown needle-like growth appears to originate at cell edge. The needles appear to be the glass fibers in the inner layer which have become "stained" by growth of silver particulates on the fiber surface.

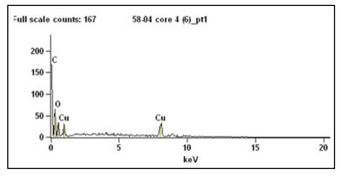




SEM/EDS analysis of glass fibers with no discoloration indicate no Ag detected.

SEM-EDX confirm macro transport of Cu

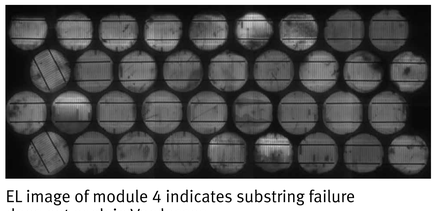




Change in IV Parameters after 22 years (compared to original IV)

Module	dFF [%]	dVoc [%]	dVmp [%]	dPmax [%]	dIsc [%]	dImp [%]
1	-7%	-1%	0%	-14%	-6%	-14%
2	-8%	-54%	-57%	-61%	-8%	-10%
3	-5%	-1%	-3%	-11%	-5%	-8%
4	-13%	-55%	-58%	-65%	-11%	-17%
Average	-8%	-28%	-30%	-38%	-8%	-12%

Variable power and Voc losses may indicate manufacturing inhomogeneity.



EL image of module 4 indicates substring failure does not explain Voc losses.

Summary

- A better understanding of the role of metallization paste durability in modules from the field is required.
- Analytical methods and destructive analysis can be used to characterize visual defects and material degradation modes.
- Optical images and SEM-EDX spectroscopy confirm macro transport of Cu and Ag.
- Product performance through field analysis is needed to ensure long term performance of PV modules.

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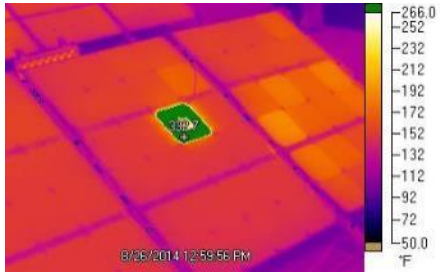
Polymer Encapsulated Photovoltaic Solar Panel Abusive Testing

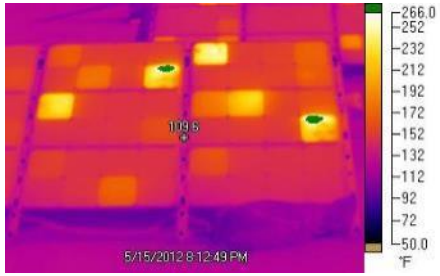
Overview

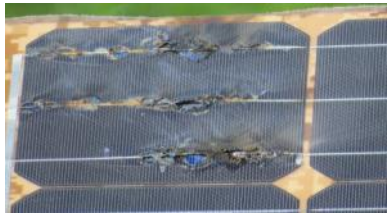
The USMC utilizes photovoltaic solar panels to power equipment such as laptops, radios, battery chargers, and lighting in austere locations. **Weight, volume,** and **transportability** are key attributes of such panels.

To reduce weight and volume and improve transportability for expeditionary applications, specialized panels employing polymer encapsulation on semi-rigid or flexible backings and lightweight composite deployment structures have been evaluated. Crystalline silicon, amorphous silicon, and CIGS are the common semiconductor types.

However, the transition from glass and metal framing to polymers has introduced unique stability and safety issues that were discovered in testing.







Clockwise from bottom left: Traces burning under short circuit, partial shading heating, short circuit heating

Solar Panel Abusive Testing

In 2014, Carderock experienced a fire at a solar test facility that originated from a prototype solar array. The root cause was determined to be short circuiting with partial shading.

Carderock has developed abusive test procedures aimed specifically at polymer encapsulated panels to uncover potential performance and safety design issues:

- Short circuit at high irradiance and temperature
- Partial shading at high irradiance and temperature
- Partial shading with short circuit

Electrical design, materials selection, and **manufacturing processes** were all found to have strong impacts on panel performance and safety.

Lessons Learned

- Short circuit leads to pronounced heating effects on panels with crystalline silicon cells
- Partial shading leads to localized heating
- Partial shading under short circuit is the most abusive condition
- Heating is most pronounced at high irradiance and high temperature
- Sufficient bypass diode layout and internal insulating layers improves panel survivability:
  - Additional specialized polymer layer reduces or eliminates severe heating and fires
  - Addition of bypass diodes reduces heat generation in shaded cells

Tech POC: Matt Huffman, NSWC Carderock, 301-227-4206

Distribution A – Approved for Public Release; Distribution is unlimited.

US DoD Expeditionary Solar Power Needs

Overview

The DoD utilizes specialized photovoltaic solar panels to power equipment such as laptops, radios, battery chargers, and lighting in austere locations.

Solar is best suited for low power scenarios such as observation posts and combat operations centers, where saving fuel provides the greatest logistical benefits and where silence is a major operational benefit.

However, the needs and constraints of the DoD for expeditionary power vary significantly from commercial needs and constraints.

Advanced GREENS array (AISPCA), 1680W in 296lbs (5.68W/lb*)

* Values include deployment structure

Early GREENS array (ISPCA), 1720W in 620lbs (2.77W/lb*)

SPACES array, 80W in 6.3lbs (12.7W/lb)

Commercial Vs. Expeditionary Solar

Metric	Commercial	Expeditionary
Installation	Predictable, planned installation	Set up in diverse, challenging environments
Setup Time	Not typically critical	Must be rapidly deployed and recovered
Number of Deployments	One Time	Many lifetime deployments
Voltage Configuration	High voltage	Low voltage
Mounting	Typically heavy, robust structures	Low weight AND physical robustness
Environmental Conditions	Known global location and weather	Can be deployed in many locales
Setup Personnel	Well-trained, specialized for solar	Minimally trained, have other focuses
Weight Metric	6.1W/lb	15.3W/lb to 22.9W/lb
Volume Metric	106W/ft^3	629W/ft^3

Current DoD Approach

- Combine high efficiency solar cells with lightweight polymer encapsulation to reduce panel weight & volume
- Deployment methods are adaptable, quick, and easy, and structures are optimized for weight & volume
- Incorporate adjustable deployment angle, MPPT, and bypass diodes to maximize solar array effectiveness
- Solar is used where it provides the most benefit in expeditionary, tip-of-the-spear situations, NOT at large bases, where tactical generator power is widely available
- GREENS ISPCA: ~17% efficiency, mono-Si
- GREENS AISPCA: ~16% efficiency, mono-Si (~double W/lb to ISPCA)
- SPACES: ~4% efficiency, CIGS
- Future goals/targets:
  - GREENS: Prototype a-Si array delivers reduced weight and increased power (10.5W/lb deployed, ~84% improvement) at the cost of aerial power density
  - SPACES: Prototype a-Si array delivers reduced weight and increased power (22.9W/lb deployed, ~80% improvement)
  - Gallium Arsenide may improve all power density metrics, but has been perceived as cost prohibitive

Tech POC: Matt Huffman, NSWC Carderock, 301-227-4206

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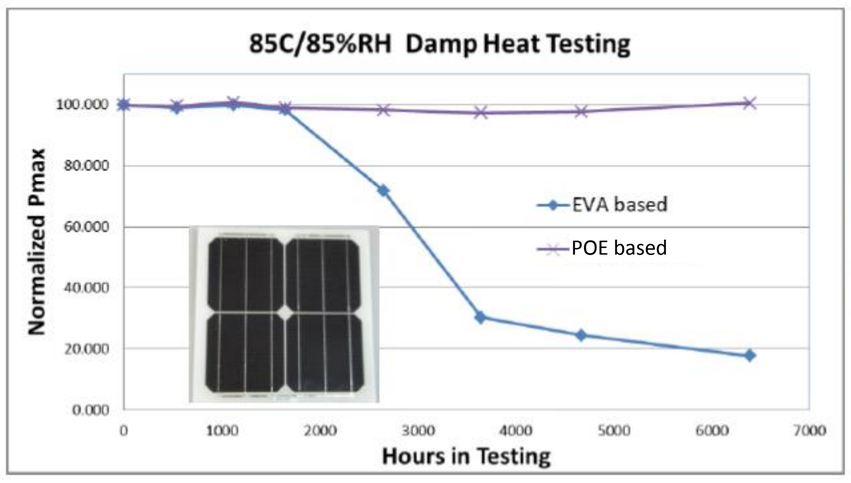
Polyolefin Encapsulants for Driving Reliability

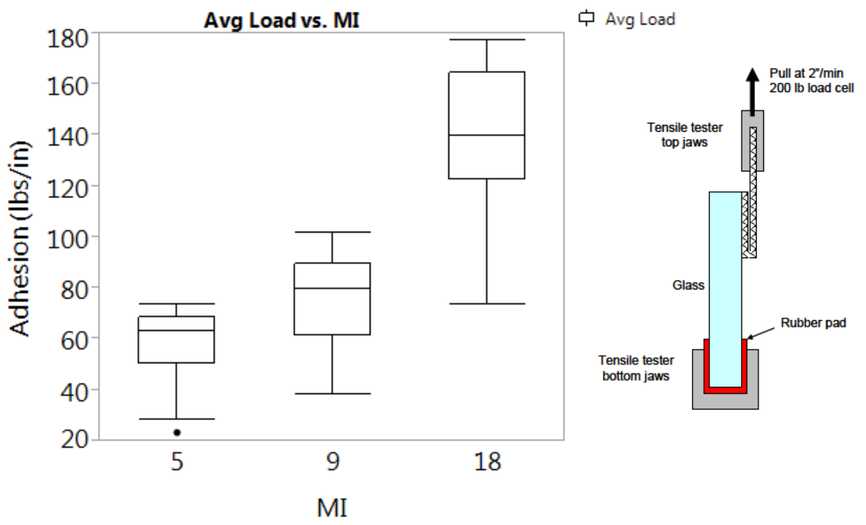
Lisa Madenjian, Brian Habersberger

The simple hydrocarbon structure of a polyolefin elastomer makes it the ideal structure for encapsulating vulnerable photovoltaic cells. As such, it should be the preferred encapsulation solution to maximize lifetime module power output. To make it fully functional for the application and to ensure lifetime performance, it must be formulated.



Data average of 3 four cell crystalline silicon modules

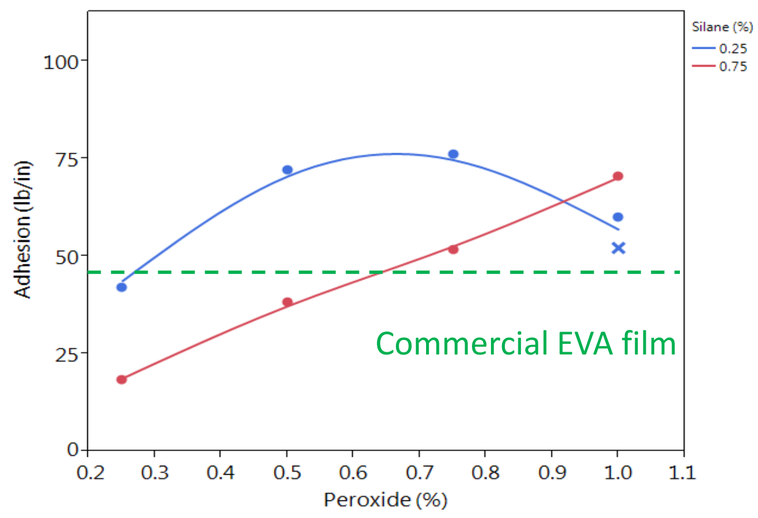
Higher MI improves adhesion



Broad study investigating adhesion in a cured system

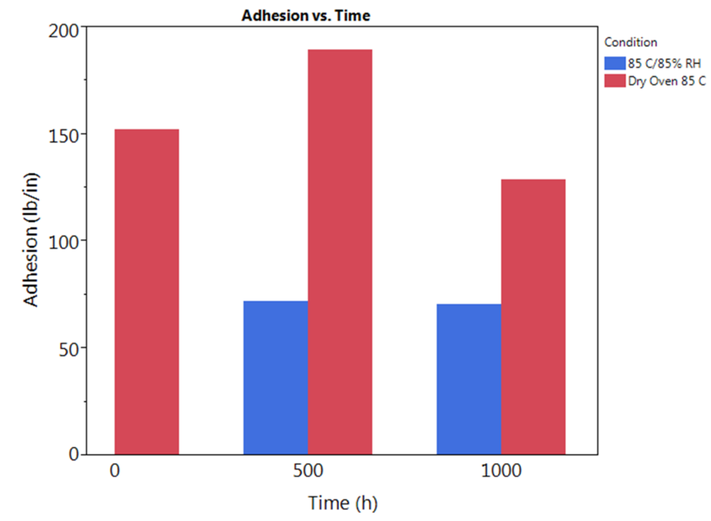
- Different amounts of peroxides, coagents, and silanes
- Major finding: MI of resin has strongest effect

Peel adhesion after 1000 h @ 85 °C/85% RH



More silane, peroxide, and TAIC does not necessarily lead to better adhesion

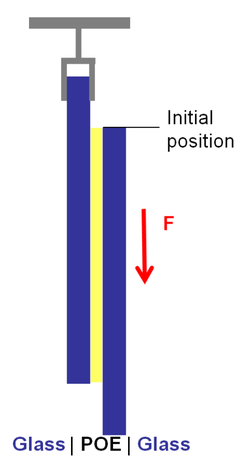
Adhesion: Damp vs. dry aging



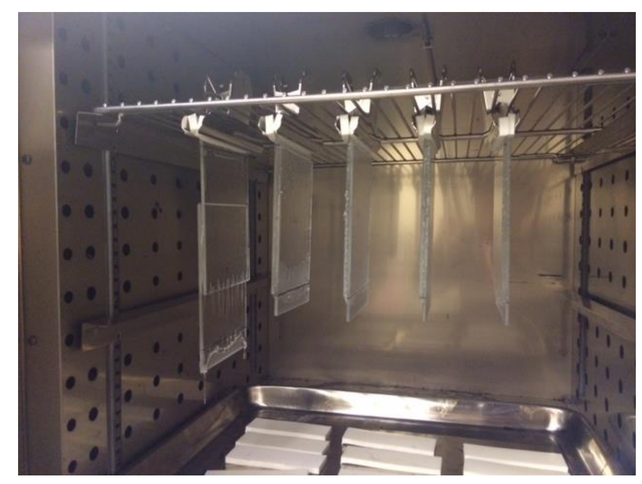
Initial adhesion retained in dry oven, falls to plateau in 85 °C/85% RH

Higher % gel is considered desirable to prevent creep, but how serious of a concern is creep and how much % gel is needed to prevent it?

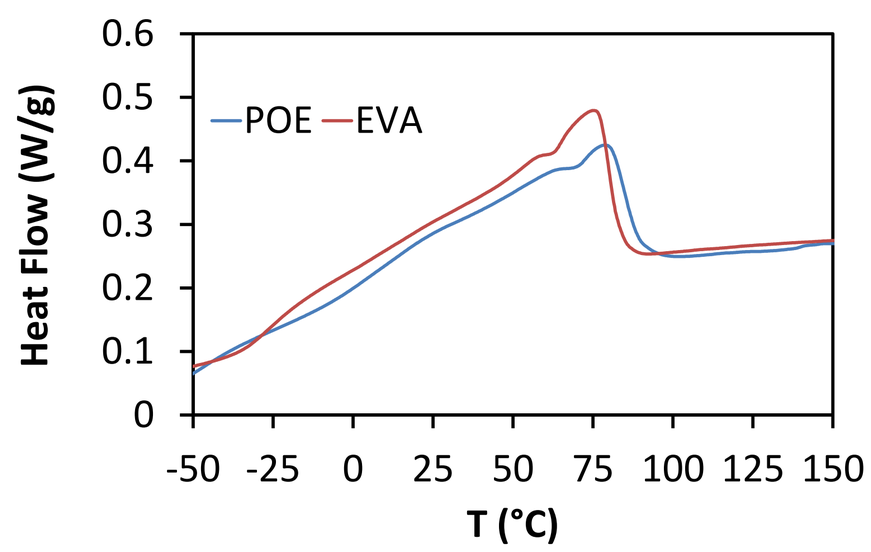
Less aggressive curing packages may meet creep needs at lower expense and reduce the amount of reactive byproducts.

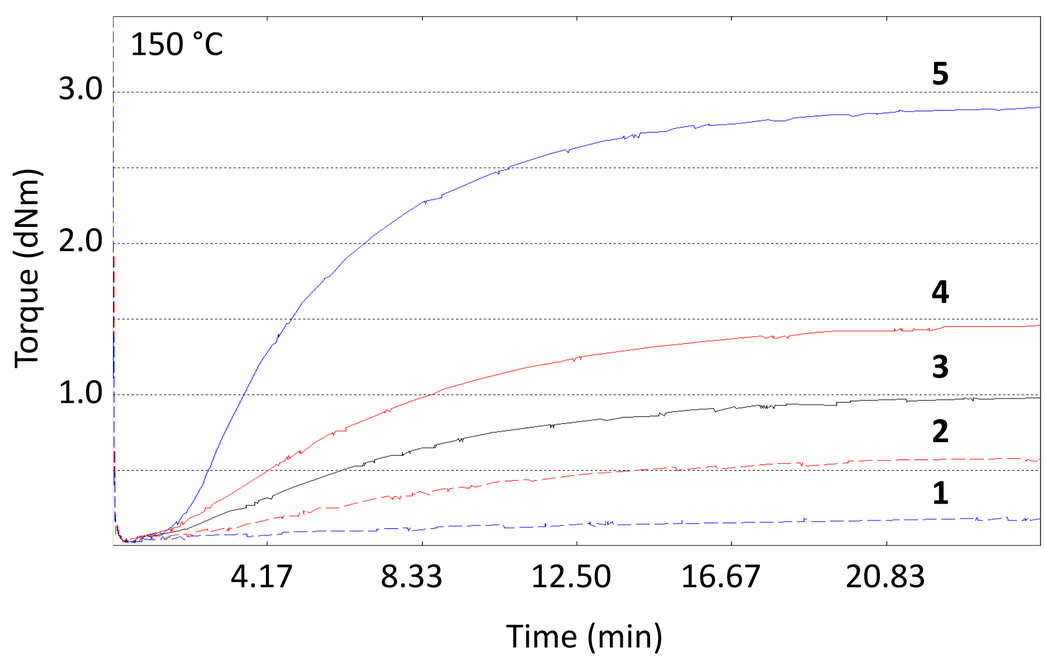


1 day @ 105 °C



Sample	Peroxide	Silane	TAIC	Gel	Time in oven with no creep: 85 C	95 C	105 C	120 C
1	0.25	0.25	0	0%	> 30 Days			
2	0.5	0.25	0	0.30%	> 30 Days			
3	0.75	0.25	0	4.40%	> 30 Days			
4	1	0.25	0	50%	> 30 Days	> 30 Days		
5	1	0.25	0.5	72%	> 30 Days	> 30 Days	> 30 Days	> 30 Days





Creep testing

- All samples pass at 85 C
- Sample with 72% gel can pass very extreme test
- How does extreme test reflect application?
- How much curing is really needed in POE?
- What are the unintended consequences of excess additives and their byproducts?

Accelerated testing methods must provide a meaningful extrapolation of performance at the relevant application conditions.
You can't predict the long-term performance of an igloo in Antarctica by melting it in a lab.

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"This presentation contains no confidential information."

Climate Dependent Degradation Rates

Based on Nationwide Onsite I-V Measurements

"Mani" G. TamizhMani

manit@asu.edu

PVreliability.asu.edu

Funding support of SERIIUS/DOE, EPRI, APS and SRP is acknowledged and appreciated.

Outline

- Approach for statistical degradation rate determination
- Arizona power plants degradation data (old survey)
- Nationwide power plants degradation data (new survey)
- Conclusions

Outline

- Approach for statistical degradation rate determination
- Arizona power plants degradation data (old survey)
- Nationwide power plants degradation data (new survey)
- Conclusions

Statistical Approach – Sample Sizing

Sample size determination

- Identify the number of strings and number of modules in the plant
- Assume normal distribution for string and module degradations

String size (>95%CL; <5%CI)

- Select the locations in the plant to measure I-V of required number of strings (typically center and corners)
- Perform I-V measurements on the selected strings

Module size (>95%CL; <5%CI)

- Identify the best, worst and median performing strings
- Perform I-V measurements of all modules on the selected strings (66% modules from median strings; 17% modules from best stings; 17% modules from worst strings)

Note: For small systems (<300 modules), apply 100%CL. For large systems, apply between 95%-100%CL

Degradation Rate Survey – Only first four steps required

A 12-Step Plant Evaluation Approach of ASU-PRL

Review (step 1):
Module construction info, System configuration & layout, Metered kWh data, Weather data and Previous reports (if any)

Safety Visual Inspection (step 7): All modules

Megger Test (step 8): All safety failed modules as needed

Material Defect Visual Inspn. (step 9): Statistically selected modules from step 3

Megger Test (step 10): All potential-safety issue modules

IR Imaging & Diode Test (step 11): Statistically selected modules from step 3

I-V and Megger Tests (step 12): All hot-spot and diode-failed modules

String I-V Test (step 2): Statistically selected strings (before cleaning)

Module I-V Test (step 3): Statistically selected modules in the best, worst and median strings (before cleaning)

Soiling Loss (step 4): I-V of three modules in the best string (after cleaning)

Module Reflectance (Browning) & FTIR (Plastics) (step 5): One module in a median string (after cleaning)

Data Check for PID (step 6): All modules in the statistically selected median strings (before cleaning)

Primary goals:
Identification of safety failures & Identification of material defects

Primary goals:
Determination of degradation rates, performance ratio, performance index & identification of degradation-causing defects

Note: BOS evaluation is also conducted as requested (inverter, wiring, racks/trackers, vegetation, shading)

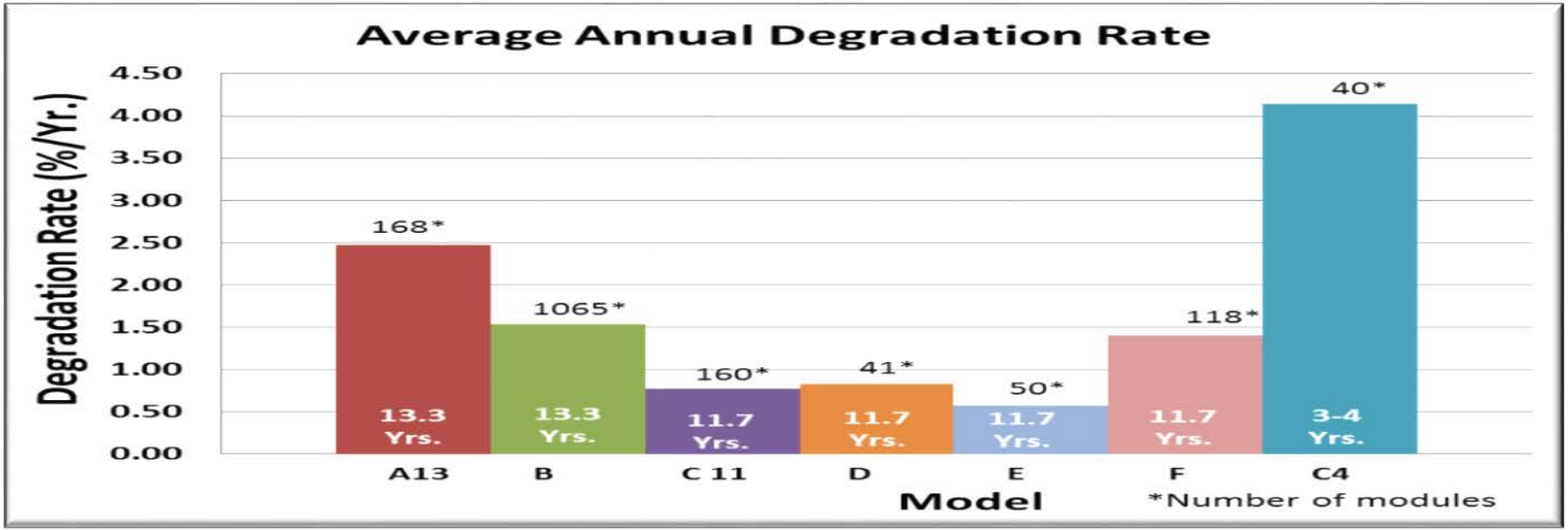
Outline

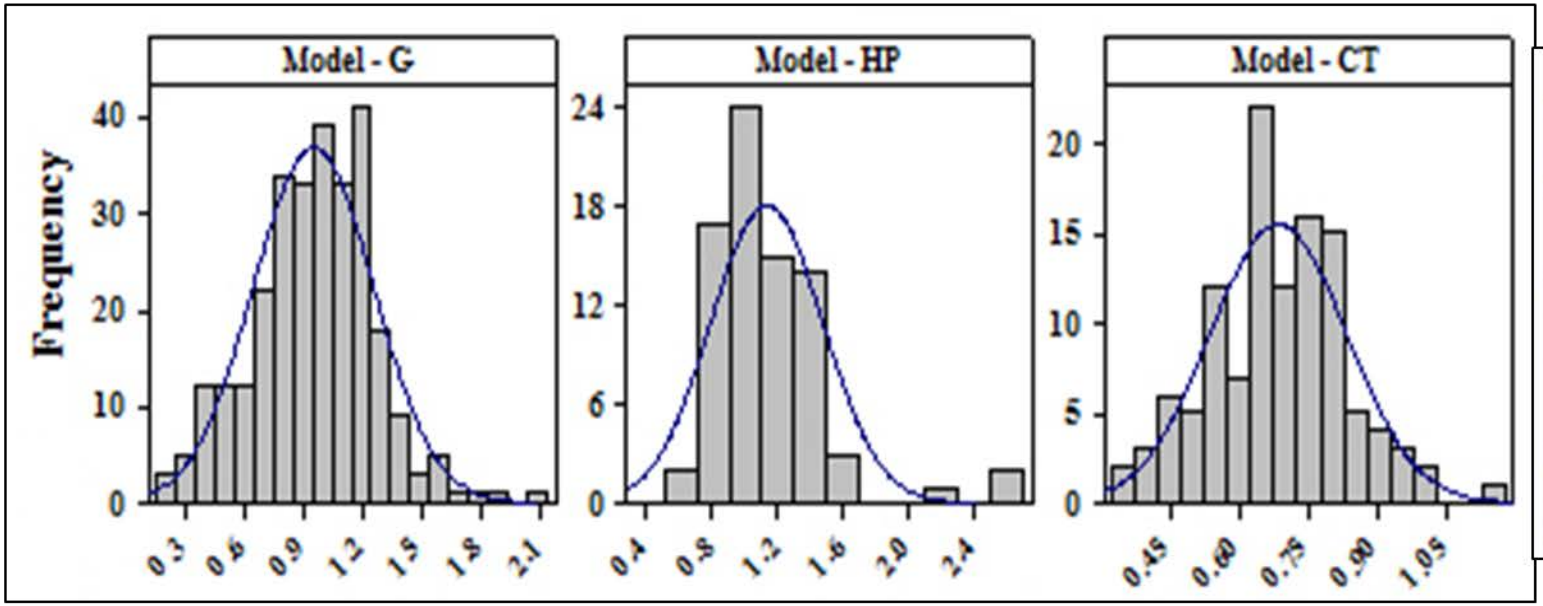
- Approach for statistical degradation rate determination
- Arizona power plants degradation data (old survey)
- Nationwide power plants degradation data (new survey)
- Conclusions

Degradation Data – Arizona *(old surveys: 2008-2014)*

Hot-Dry Climate **(mostly old systems)**

Degradation Data – Arizona (Hot-Dry Climate)





Model - G	
Mean	0.9561
StDev	0.3090
N	285

Model - HP	
Mean	1.131
StDev	0.3449
N	78

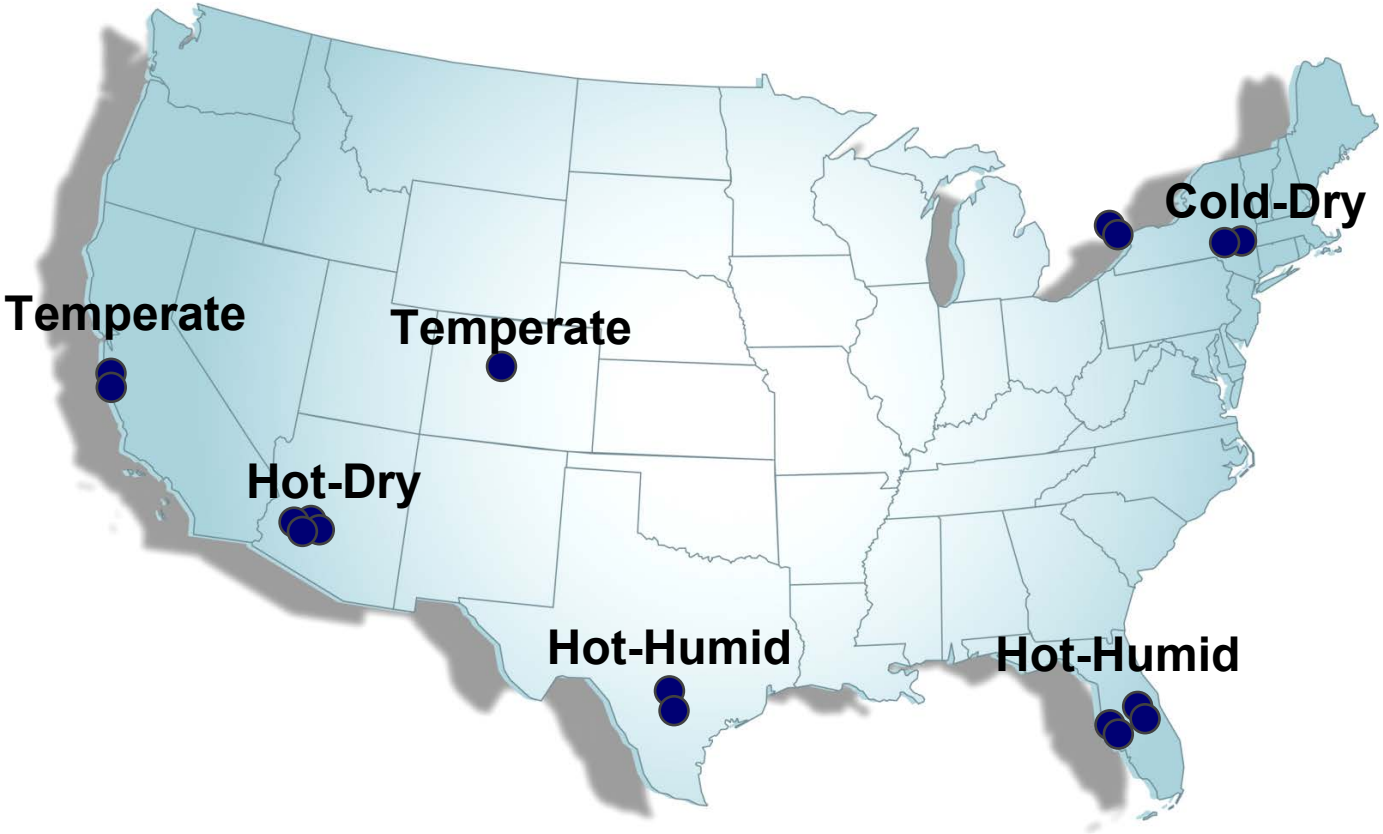
Model - CT	
Mean	0.6837
StDev	0.1481
N	115

Outline

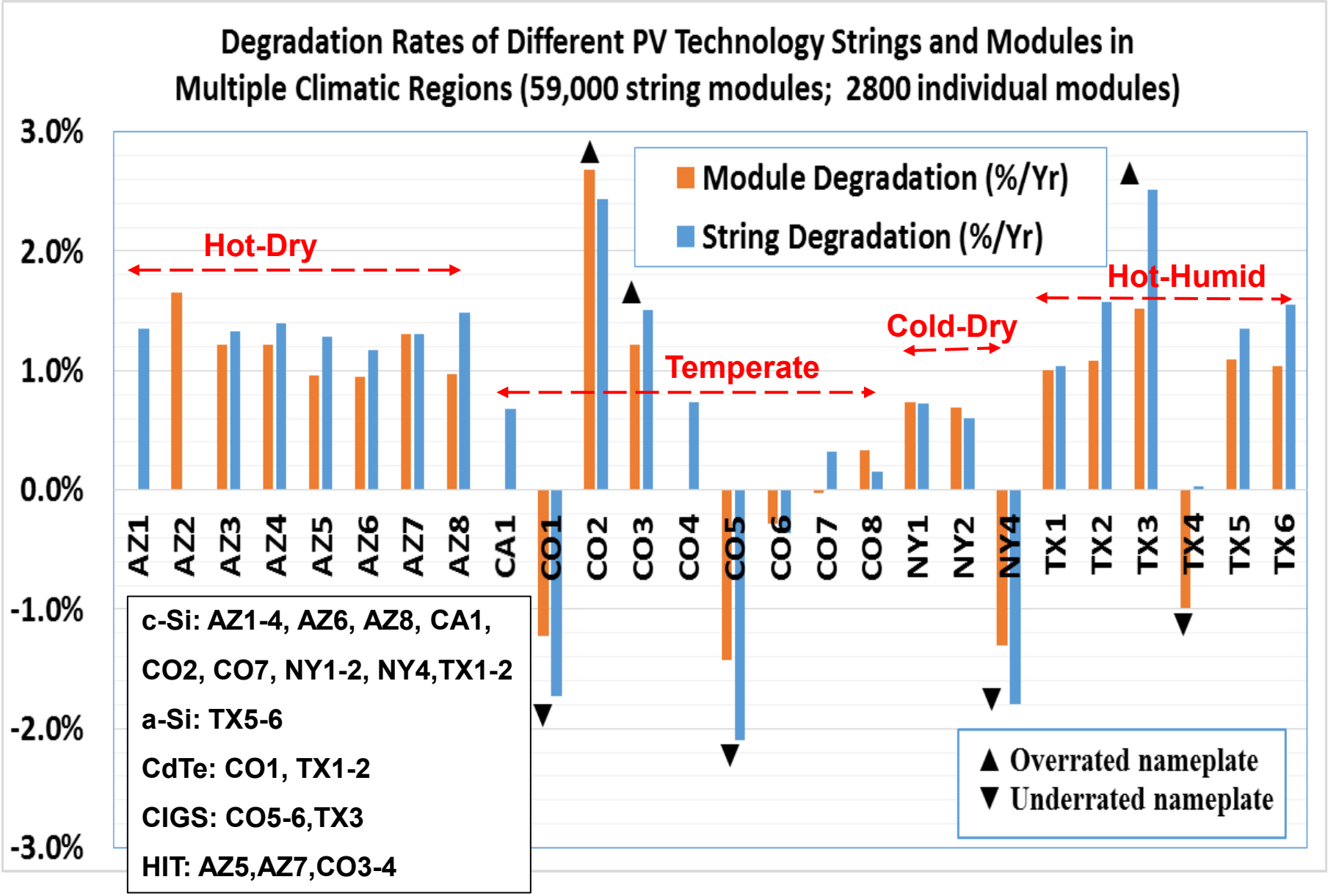
- Approach for statistical degradation rate determination
- Arizona power plants degradation data (old survey)
- Nationwide power plants degradation data (new survey)
- Conclusions

Degradation Data – Nationwide *(new surveys: 2014-2015)*

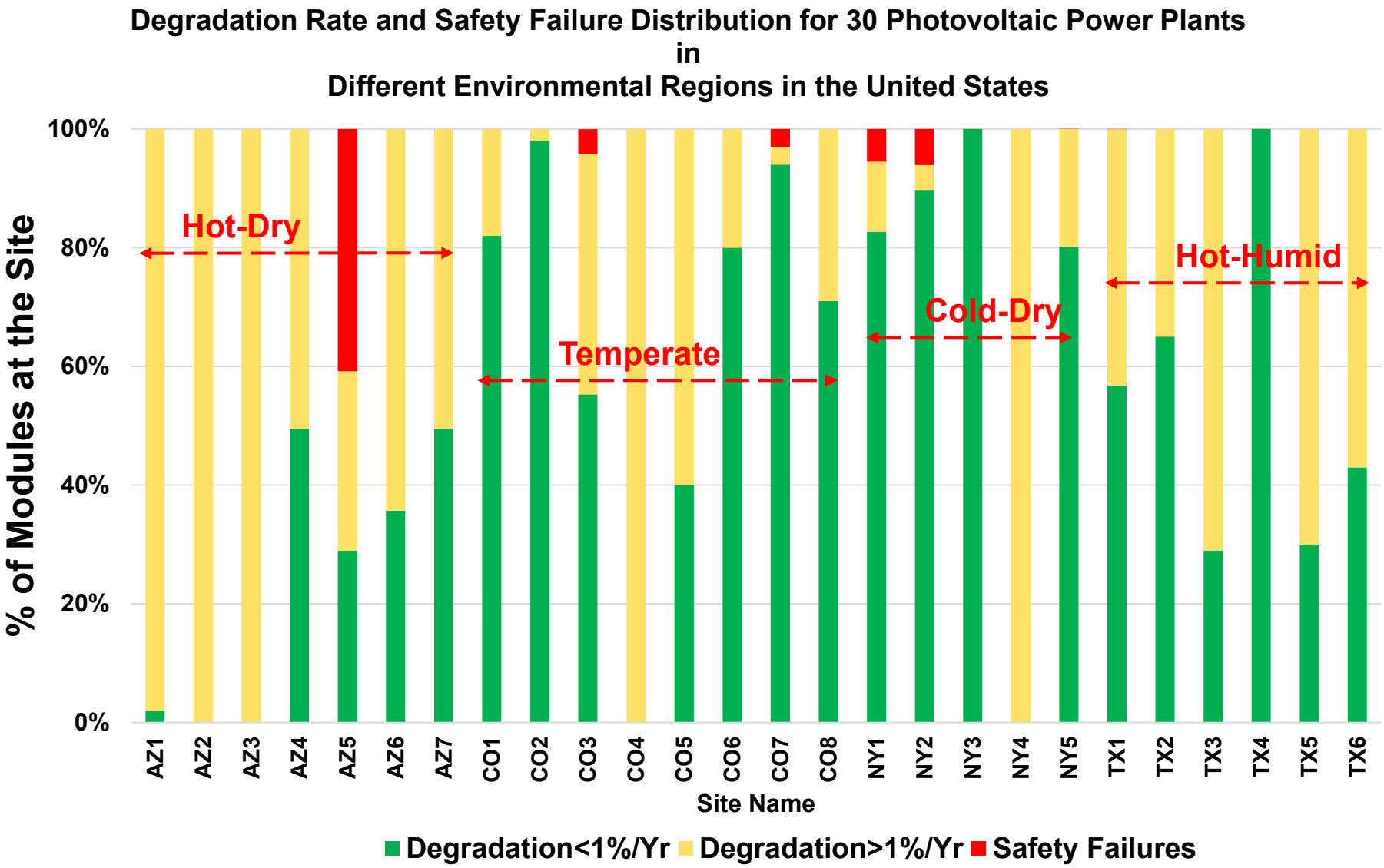
Four Climates in Six Regions (both old and new systems)



Degradation Rates – Nationwide (representing more than 250,000 modules)



Degradation Distribution



Note: In a few sites, either I-V or visual inspection could not be completed due to bad weather and they are not included in this plot.

Outline

- Approach for statistical degradation rate determination
- Arizona power plants degradation data (old survey)
- Nationwide power plants degradation data (new survey)
- Conclusions

Degradation Rate Calculation – Age Sensitivity

CAUTION

Degradation rate (%/year) =

$$(P_{rated} - P_{field\ measured}) * 100 \ / \ (P_{rated} * Age)$$

- **If nameplate is overrated, the calculated degradation rate for newer plants will be unrealistically high (excessive power loss!) because P_{rated} is fixed and age (denominator) is small.**
- **If nameplate underrated, the calculated degradation rate for newer plants will be unrealistically low (even negative; excessive power gain!) because P_{rated} is fixed and age (denominator) is small.**

Degradation Rate Calculation – Soiling Sensitivity

CAUTION

Degradation rate (%/year) =

$$(P_{rated} - P_{field\ measured}) * 100 \ / \ (P_{rated} * Age)$$

- **If the string or module is soiled, the $P_{field\ measured}$ data will be unrealistically low and the calculated degradation rate will be unrealistically high.**
- **If the string or module is soiled, obtain the $P_{field\ measured}$ data on a clear day within few days after a heavy rain fall.**
- **If the string or module is soiled, obtain the $P_{field\ measured}$ data of a few modules before and after cleaning so the soiling loss can be calculated and the measured data can be corrected.**

Conclusions

- The climate dependent degradation rates of several 10's of thousands of modules for four climates covering entire United States are presented.

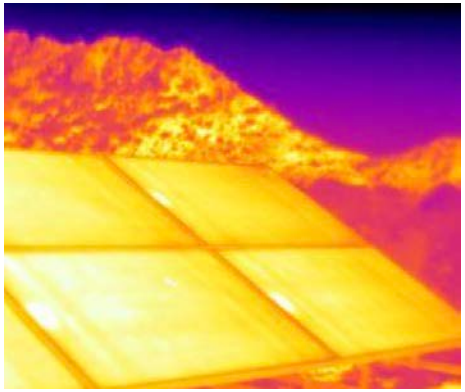
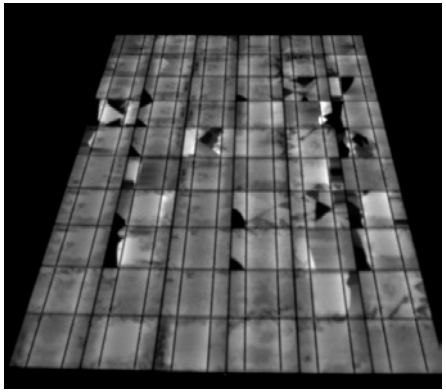
- The sensitivity of degradation rate calculations to the nameplate rating for the new plants and to the soiling is presented.

Thank You!

Mani: manit@asu.edu

Questions?

Visit us: PVreliability.asu.edu

Lessons learned from the all India Survey of photovoltaic modules

Anil Kottantharayil

National Centre for Photovoltaic Research and Education

Indian Institute of Technology Bombay

PVMRW 2016, Denver

Contributors to All-India Survey

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Outline

- The broad context
- All-India Survey of PV Module Degradation
  - Details of Survey
  - Power Degradation Rates
  - Visual, EL and IR Assessment
- Conclusions and Recommendations

India has ambitious targets

- End of 2015
  - Total electricity generation capacity = 271 GW
  - Solar PV ~ 4 GW
- 2022 target
  - Total generation capacity ~ 400 GW
  - Solar PV ~ 100 GW
    - 40 GW rooftop and 60 GW ground mounted
- Photovoltaic industry is poised for 25 x growth in 6 years!

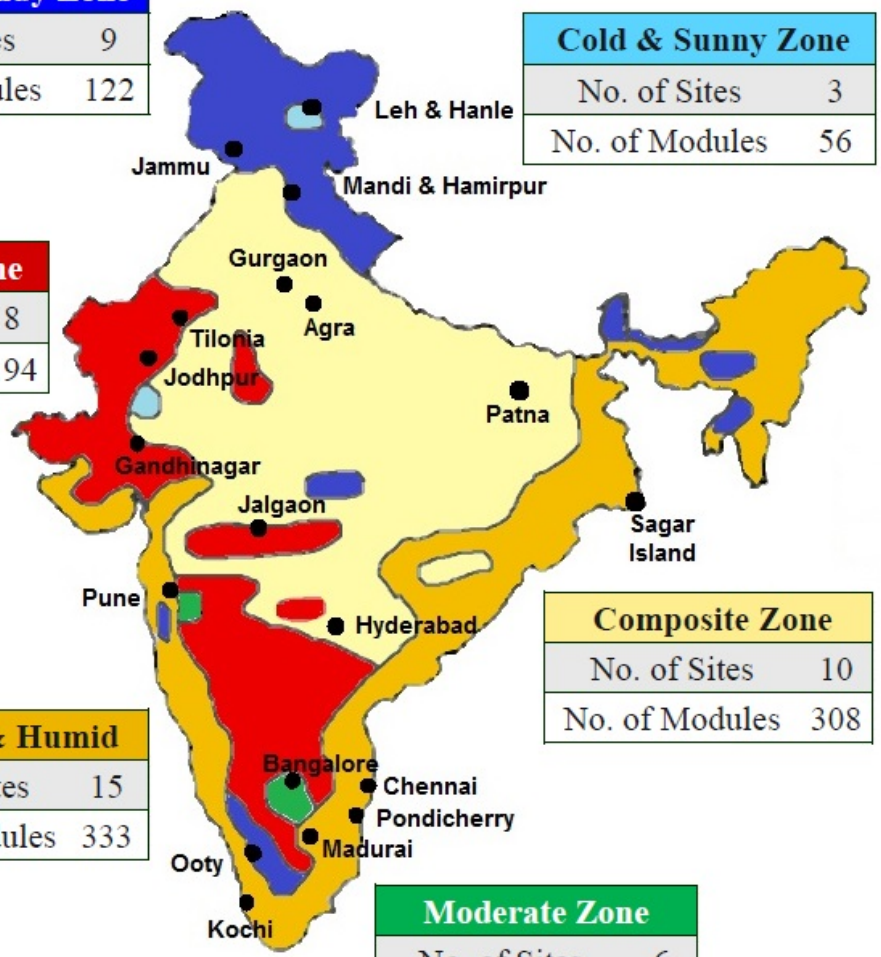
NCPRE

All India Survey of PV Modules 2014

Cold & Cloudy Zone	
No. of Sites	9
No. of Modules	122

Cold & Sunny Zone	
No. of Sites	3
No. of Modules	56

Hot & Dry Zone	
No. of Sites	8
No. of Modules	194



Composite Zone	
No. of Sites	10
No. of Modules	308

Warm & Humid	
No. of Sites	15
No. of Modules	333

Moderate Zone	
No. of Sites	6
No. of Modules	135

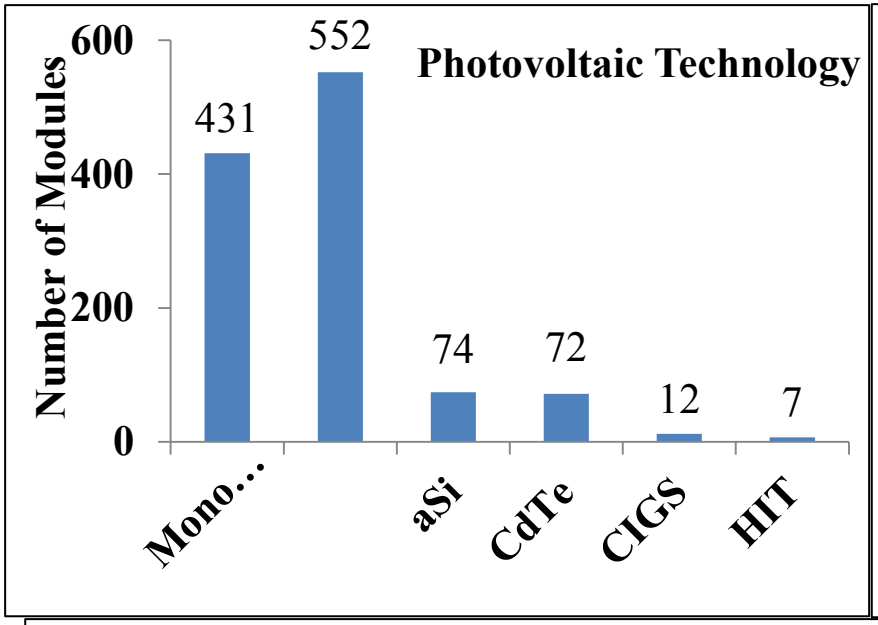
Characterization Techniques Used
Illuminated *I-V* and Dark *I-V* tracing
Illuminated IR and Dark IR imaging
Daylight Electroluminescence imaging
Interconnect failure test
Insulation resistance test
Visual degradation checklist
Inverter performance test
Socio-economic checklist

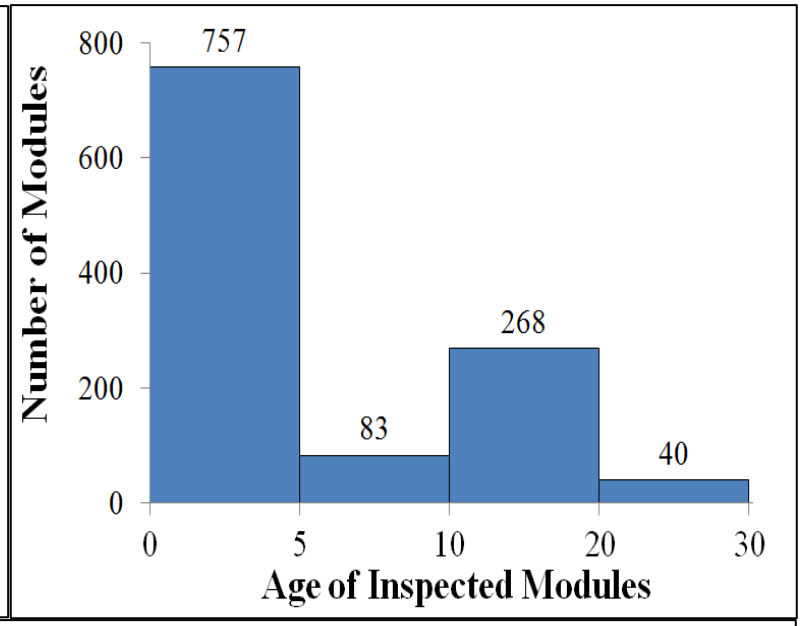
Total No. of Sites: 51

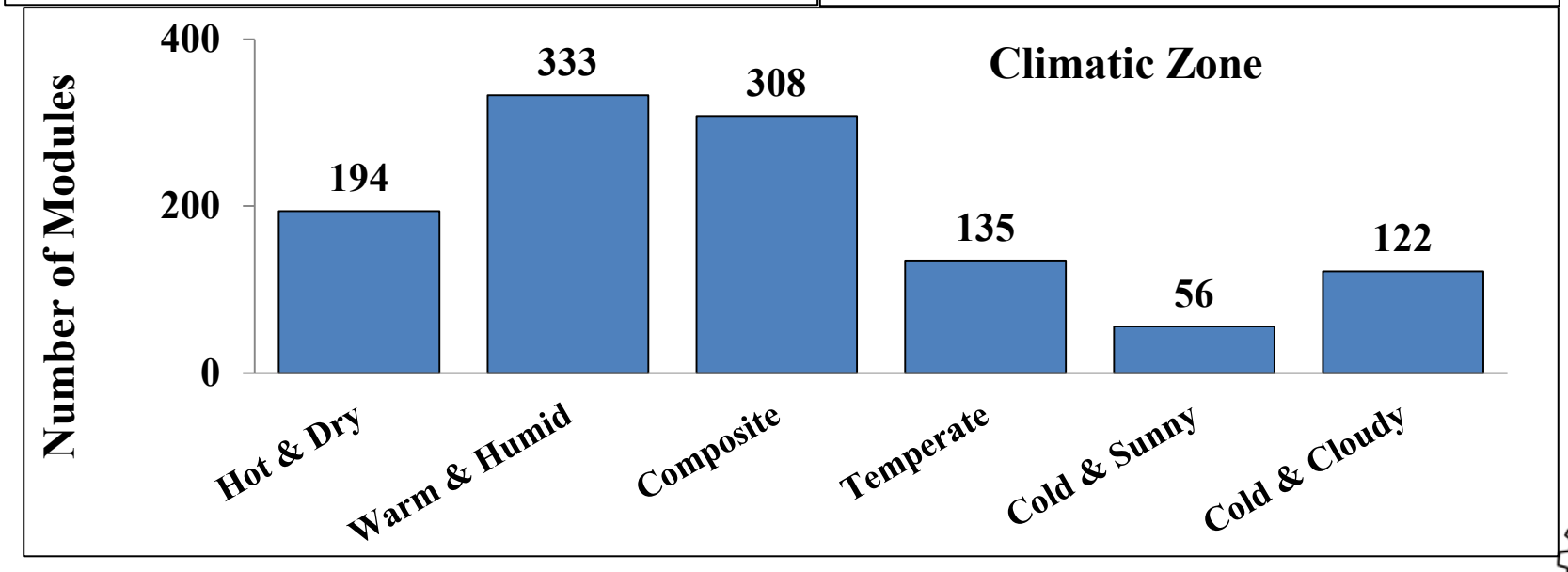
Total No. of Modules: 1148

2014 Survey

2014 Survey Sample Details







Definition of Degradation

Annual Degradation Rate (%/year) of a parameter Y is calculated as

$$\textbf{Degradation rate of Y (\%)} = \frac{(Y_{nominal} - Y_{present}) \times 100}{Y_{nominal} \times \text{age of the module}}$$

Here, Y can be

- Power, P
- Short Circuit Current, I_{sc}
- Open Circuit Voltage, V_{oc}
- Fill Factor, FF

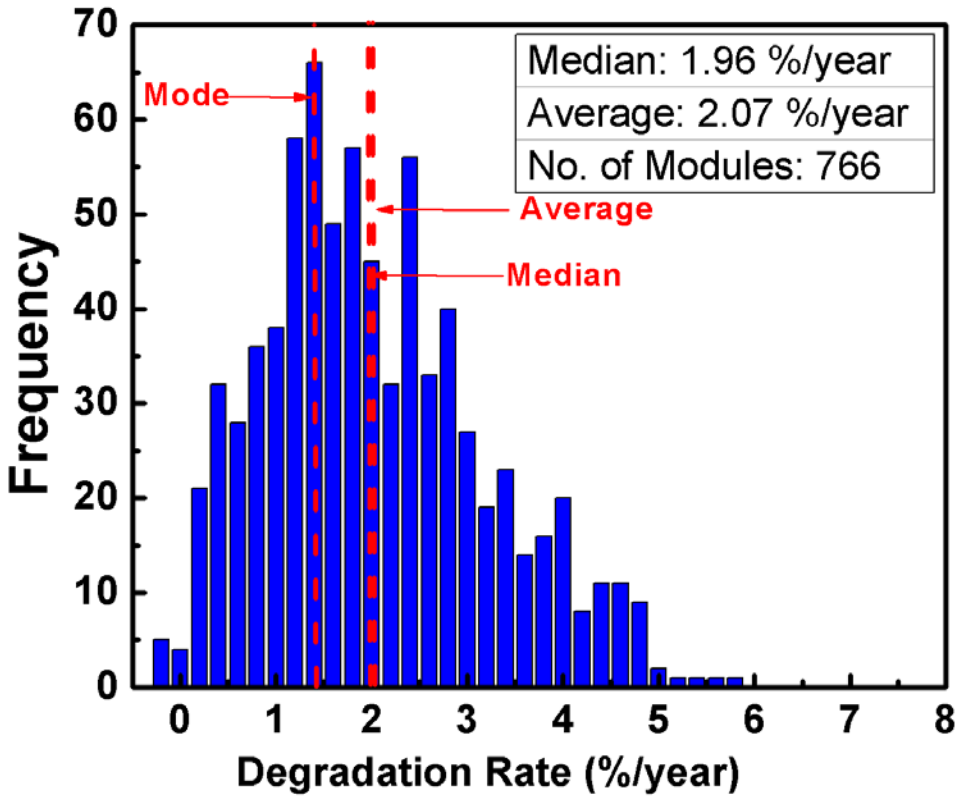
@ Standard Test Conditions

Errors and uncertainties in the calculation of degradation rate due to:

- *Instrument Error*
- *Error due to translation to STC*
- *Nameplate uncertainty*

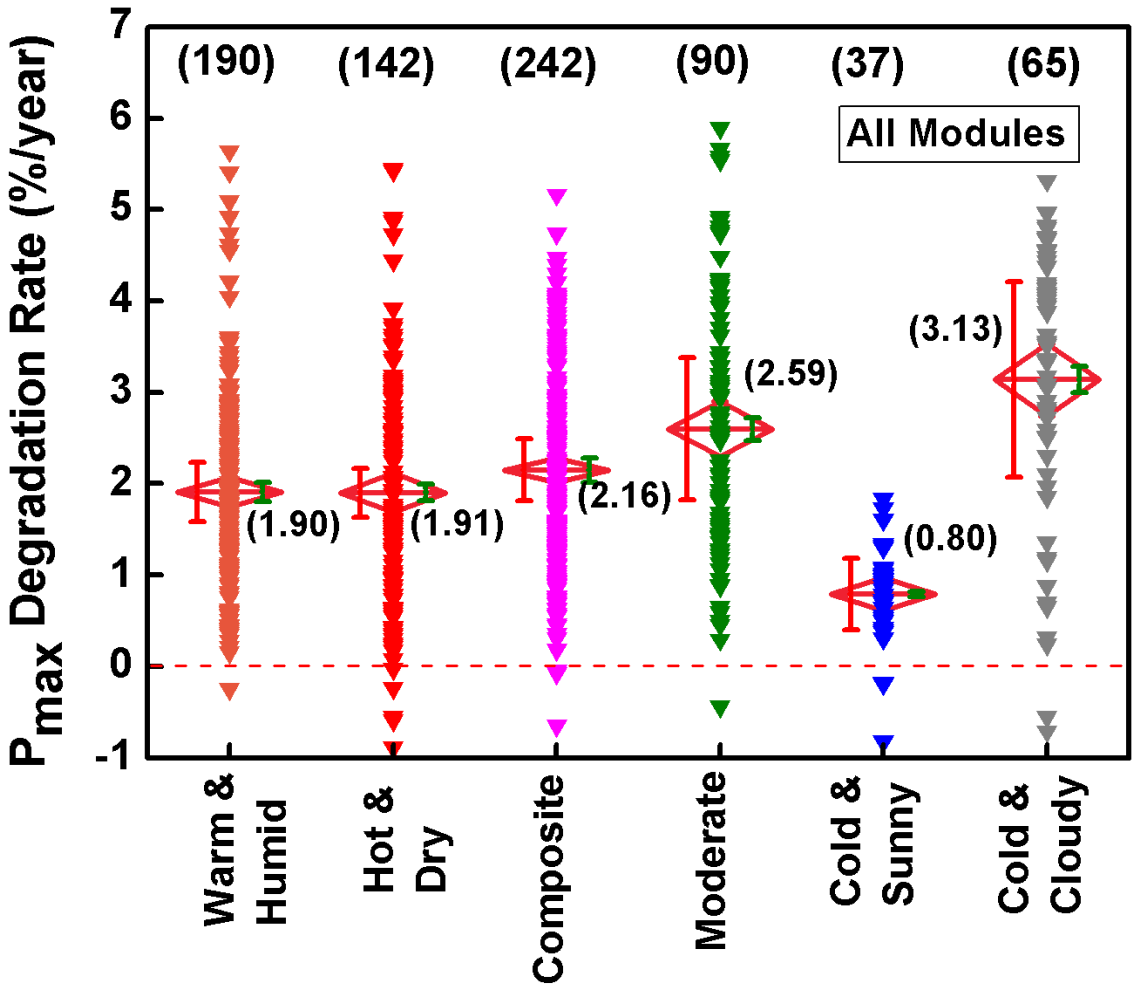
Detailed Error Analysis has been performed. Nameplate uncertainty is especially important for young modules.

Power Degradation Rates



22% of modules showed degradation rates above 6% per year – not included in analysis

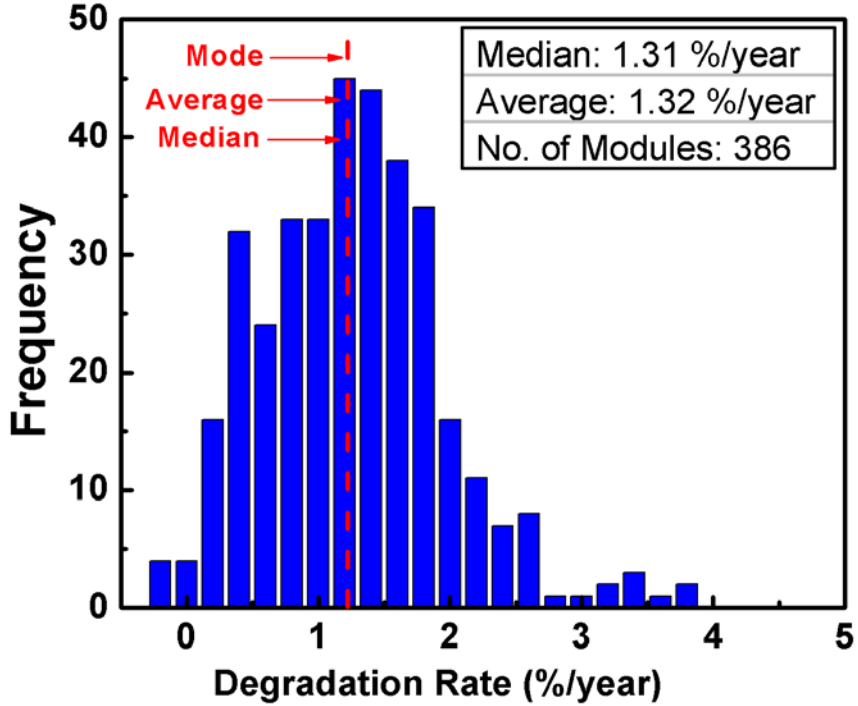
Dependence on Climate

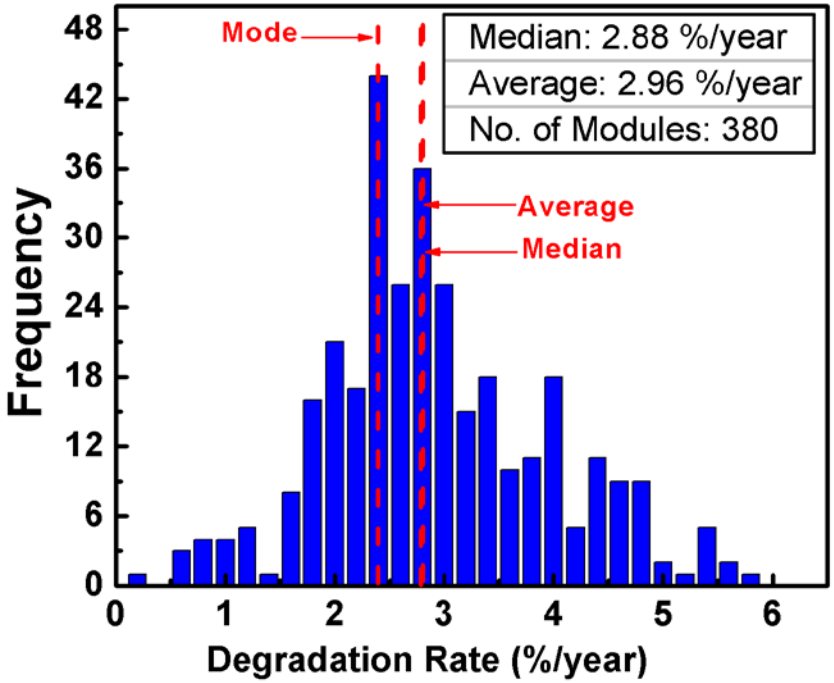


No clear climatic dependence observed in degradation

Classification into X and Y groups

Sites with average degradation < 2%, Group X
Sites with average degradation > 2%, Group Y

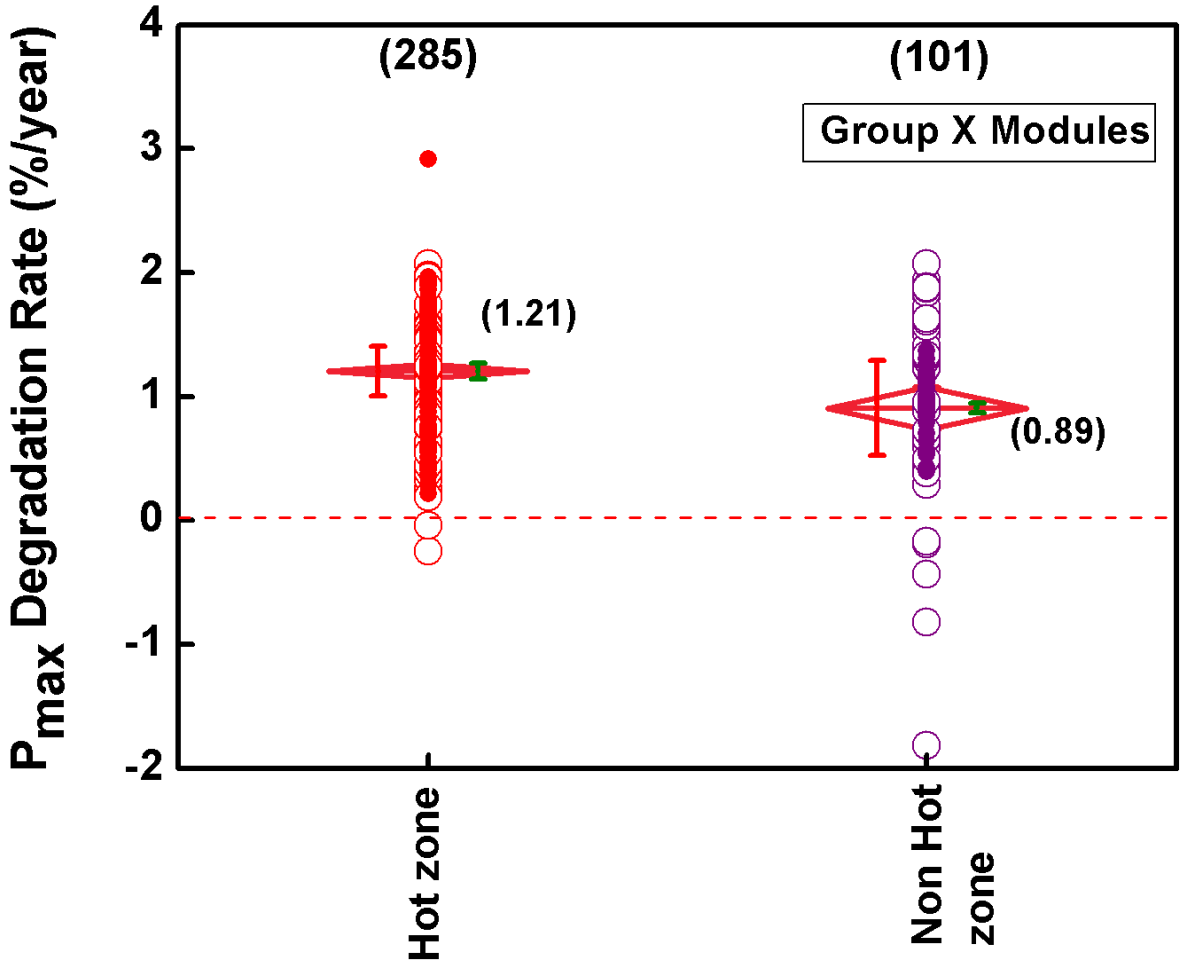




Group X
Average degradation = 1.3 %

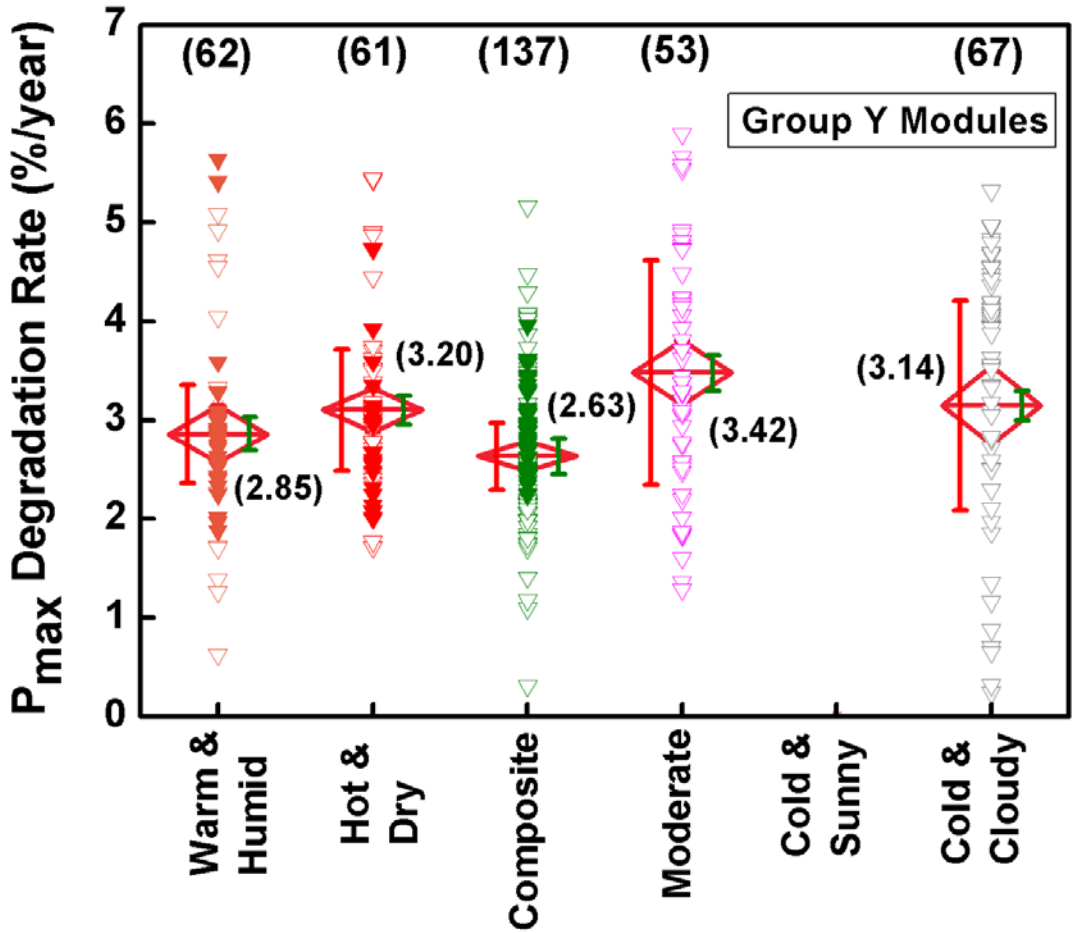
Group Y
Average degradation = 3 %

Dependence on Climate: Group X



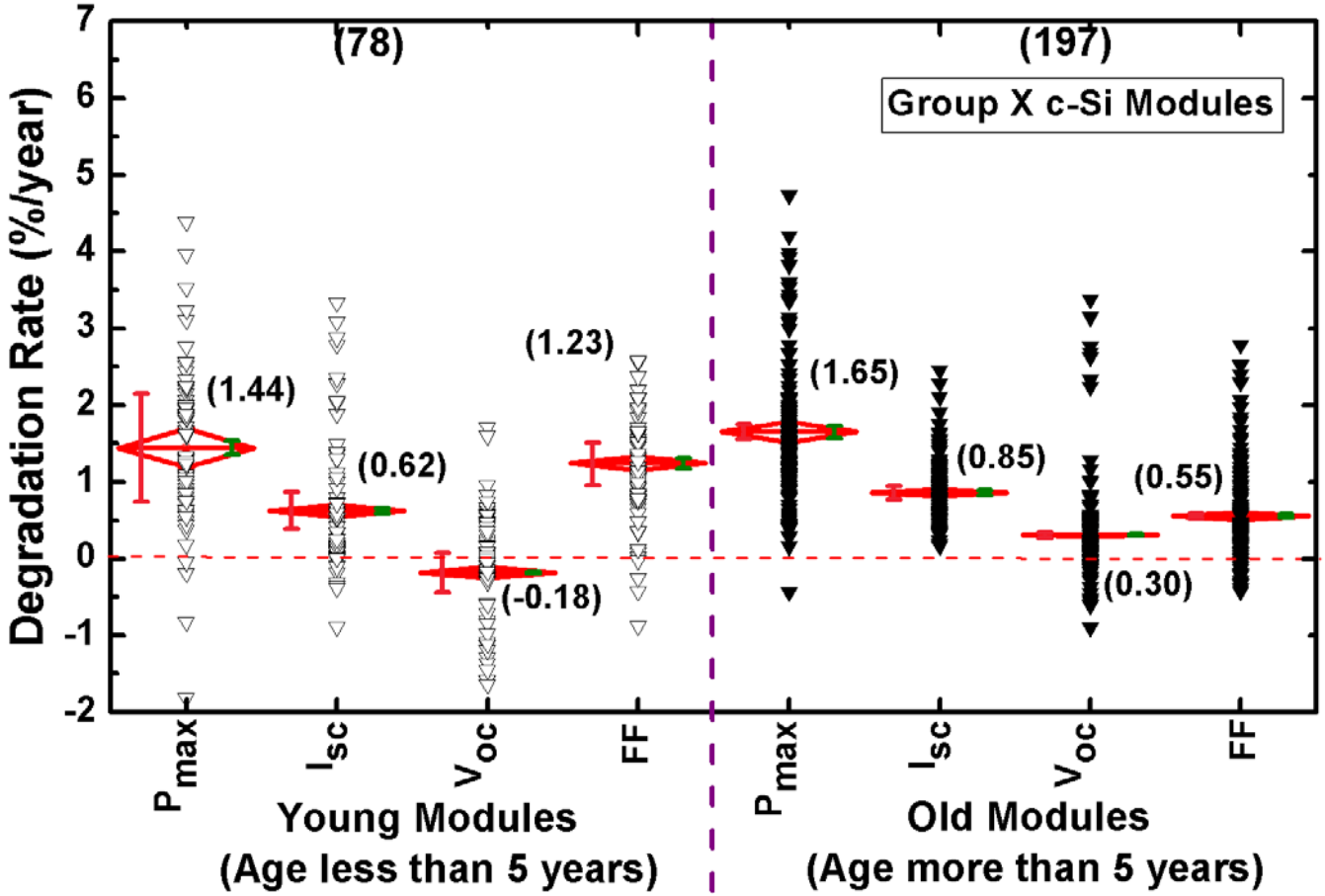
Higher degradation in hotter climates.

Dependence on Climate: Group Y



No clear climate dependence.

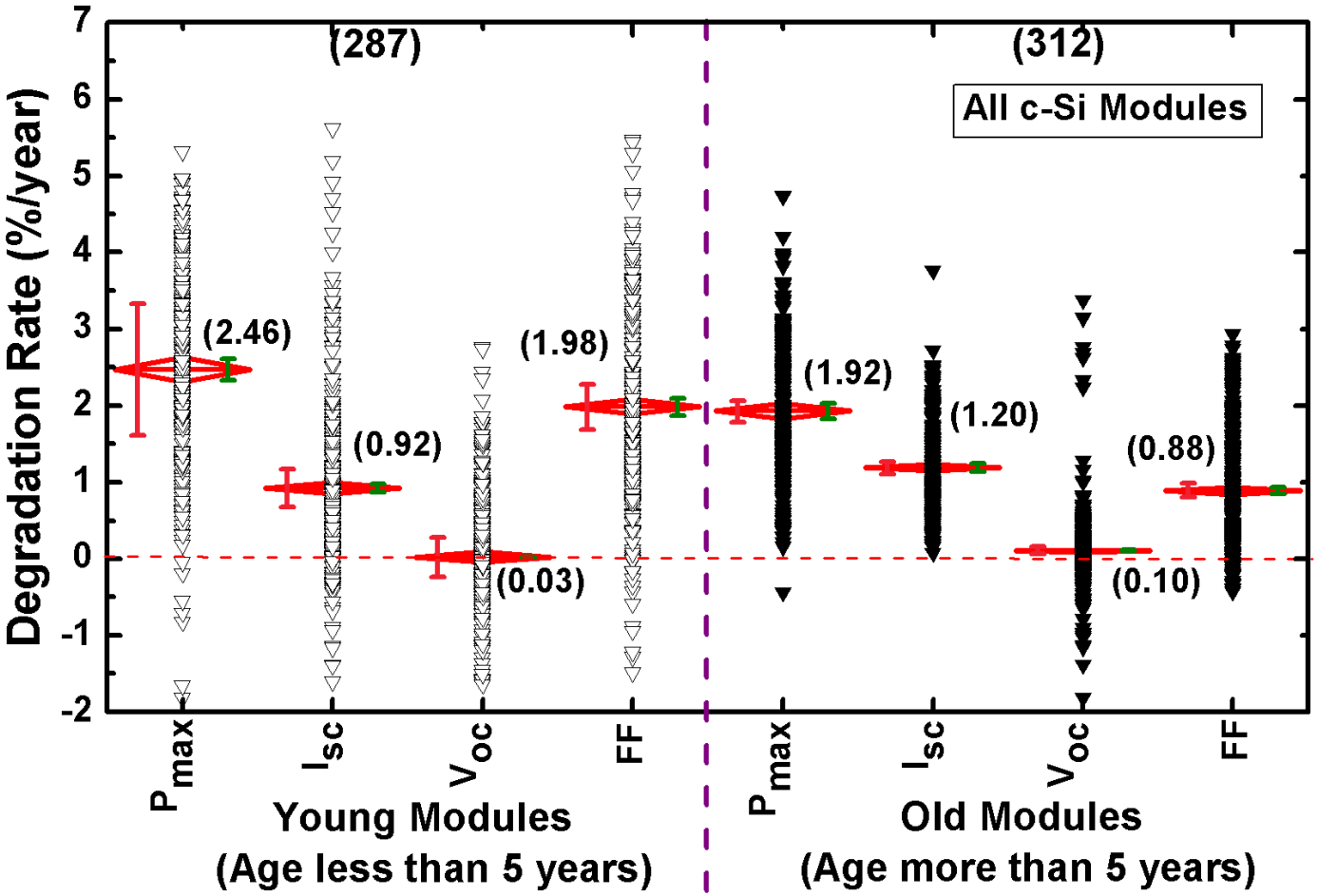
Age of modules: c-Si group X



Improved technology

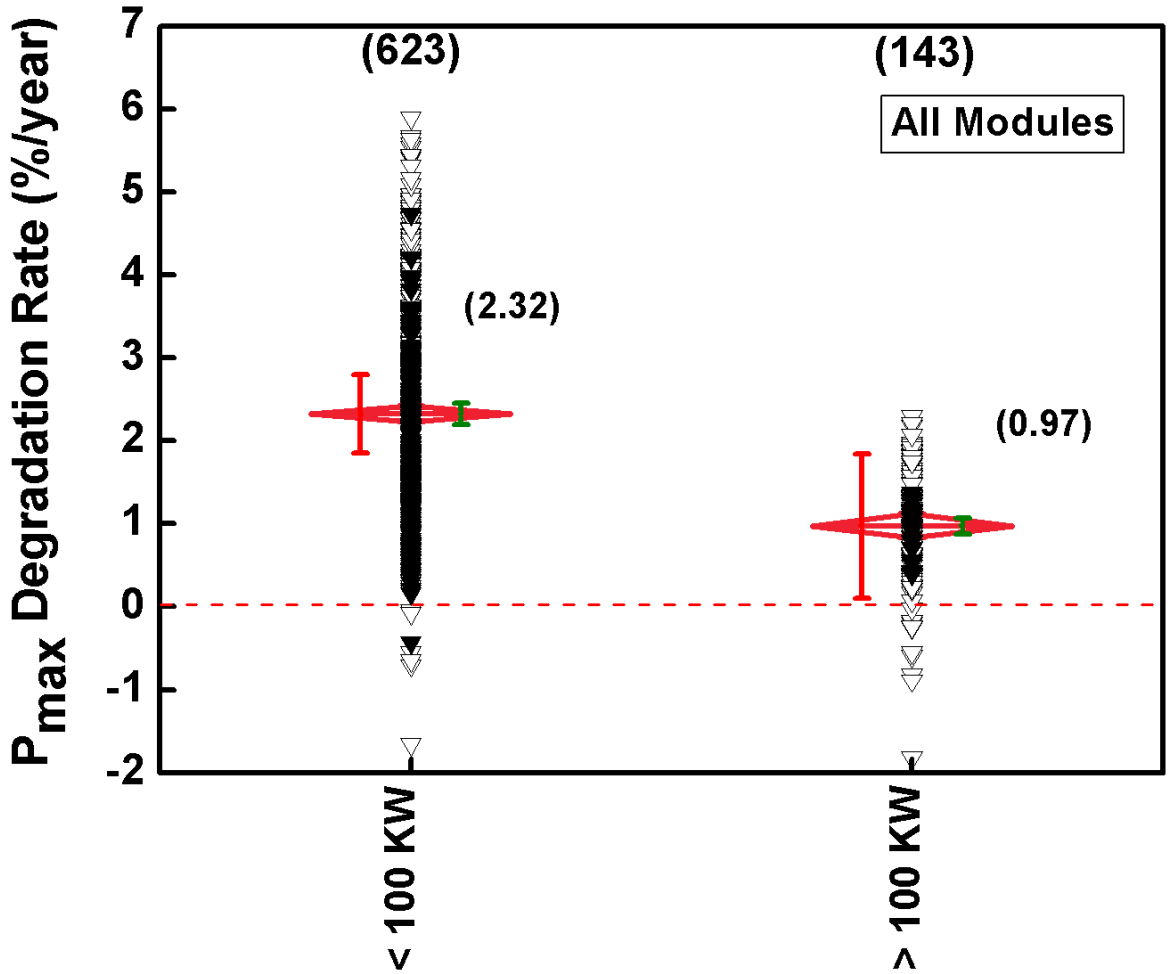
FF losses dominate

Age of modules: c-Si group X & Y



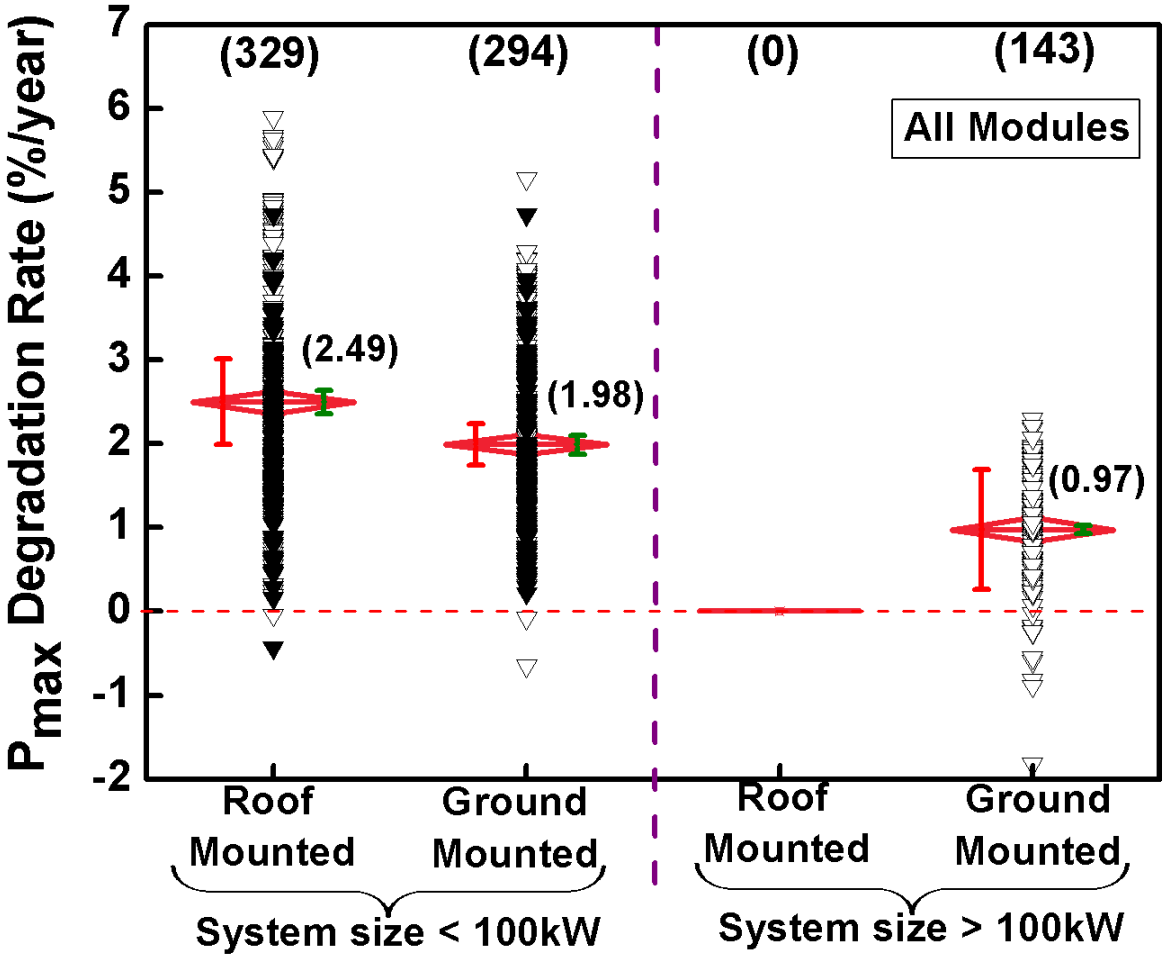
Young modules of group Y - serious concerns

Size of installation



Larger installations have lower degradation rates.

Roof and ground mounted

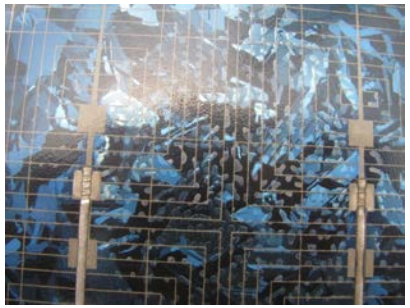


Roof mounted modules have higher degradation rates

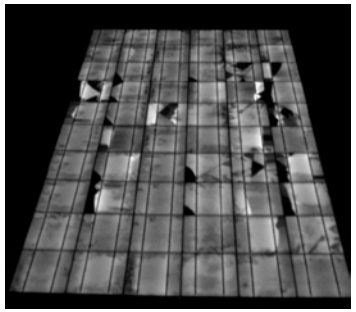
Various degradation modes in silicon PV modules

Shattered glass

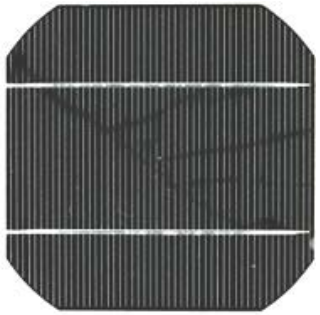
EVA discoloration



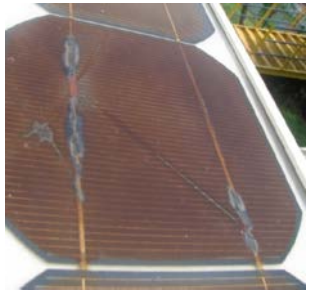
EVA delamination



Cell cracks



Snail trails



Metal corrosion

Backsheet chalking

Pre stress Stress 1

Potential induced degradation

Hot spots

EVA Discoloration: c-Si

Climatic Zone	Age Groups				Total
	0-5 Years	5-10 Years	10-20 Years	20-30 Years	
Hot & Dry	4% (74)	NA	100% (29)	100% (1)*	24% (104)*
Warm & Humid	8% (93)	93% (58)	92% (119)	100% (2)	63% (272)
Composite	32% (125)**	0% (7)	60% (124)	NA	44% (256)
Moderate	0% (123)	NA	91% (12)	NA	8% (135)
Cold & Sunny	0% (34)	NA	77% (22)	NA	35% (56)
Cold & Cloudy	0% (112)	NA	NA	NA	0% (112)

* Excluding 38 nos. glass-glass modules that have shown no discoloration.
** All surveyed modules of a particular batch and make are showing discoloration.

EVA Delamination: c-Si

Climatic Zone	Age Groups				Total
	0-5 Years	5-10 Years	10-20 Years	20-30 Years	
Hot & Dry	8% (74)	NA	24% (29)	79% (39)	31% (142)
Warm & Humid	0% (93)	59% (58)	45% (119)	100% (2)	33% (272)
Composite	7% (125)	0% (7)	20% (124)	NA	13% (256)
Moderate	28% (123)	NA	17% (12)	NA	27% (135)
Cold & Sunny	0% (34)	NA	0% (22)	NA	0% (56)
Cold & Cloudy	2% (112)	NA	NA	NA	2% (112)

Less than 5% of the module area

Snail Trails: c-Si

Climatic Zone	Age Groups				Total
	0-5 Years	5-10 Years	10-20 Years	20-30 Years	
Hot & Dry	35% (74)	NA	0% (29)	0% (39)	18% (142)
Warm & Humid	17% (93)	0% (58)	0% (119)	0% (2)	6% (272)
Composite	0% (125)	0% (7)	6% (124)	NA	3% (256)
Moderate	56% (123)	NA	8% (12)	NA	52% (135)
Cold & Sunny	50% (34)	NA	0% (22)	NA	30% (56)
Cold & Cloudy	44% (112)	NA	NA	NA	44% (112)

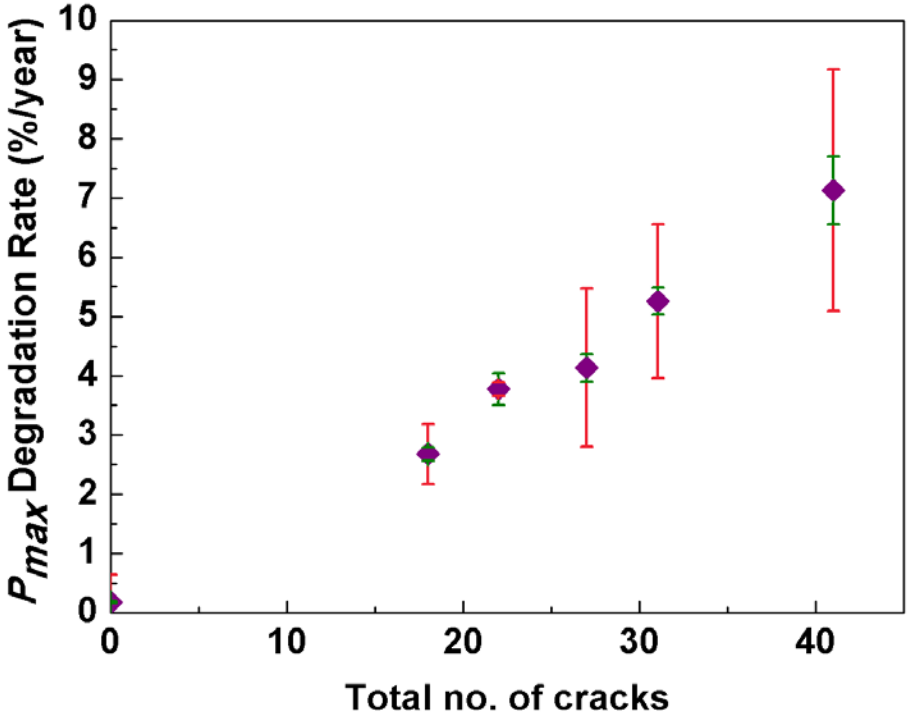
High occurrence of snail trails in young modules

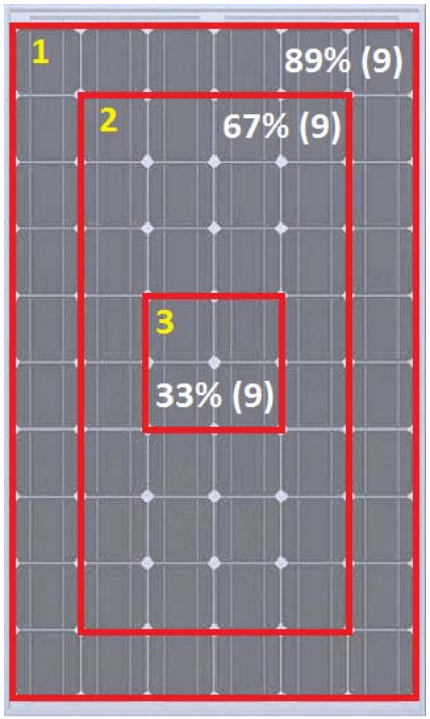
Discoloration of metallization: c-Si

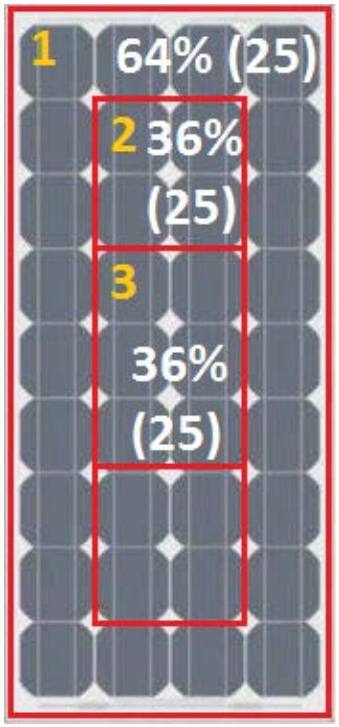
Climatic Zone	Age Groups				Total
	0-5 Years	5-10 Years	10-20 Years	20-30 Years	
Hot & Dry	35% (74)	NA	97% (29)	100% (39)	65% (142)
Warm & Humid	34% (93)	100% (58)	92% (119)	100% (2)	74% (270)
Composite	44% (125)	0% (7)	94% (124)	NA	67% (256)
Moderate	54% (123)	NA	100% (12)	NA	59% (135)
Cold & Sunny	60% (34)	NA	76% (22)	NA	67% (56)
Cold & Cloudy	16% (112)	NA	NA	NA	16% (112)

Noticeable in young modules also

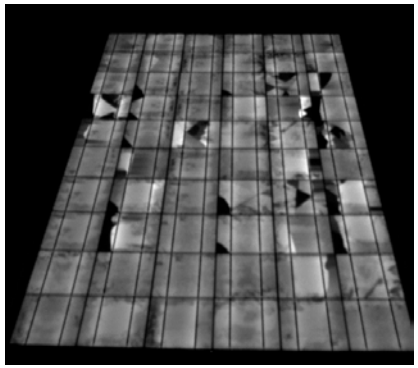
Field Electroluminescence: c-Si







- P_{max} degradation in these cases related to FF losses
- More occurrence of cracks in cells near the edges – transportation, handling?



Infra-red thermography: c-Si

- Poster by Shashwata Chattopadhyay

- Message:
  - Modules with hot cells in hot climates running at much higher temperature than in non-hot climates
  - Leading to higher degradation rates

Conclusions from Survey

- Wide dispersion in degradation rates
  - Group ‘X’ sites show reasonable performance
  - Group ‘Y’ sites show poor performance
- Group ‘X’ sites show significant climatic variation
  - Sites in Hot climates show high degradation rates
  - Sites in Cold and Moderate climates show good durability
- Materials used in modules and manufacturing practices are concerns in many cases
- Quality of modules, as well as transport / handling / installation protocols all appear to play a role
- Many ‘young’ modules show several durability and reliability issues – perhaps related to aggressive pricing, procurement, manufacturing and installation practices
- Due diligence seems to be exercised by large system owners

NCPRE

Recommendations

- Quality of modules can vary significantly, so due diligence should be exercised while selecting modules
- Materials used in modules is important, and should be specified
- Independent audit of modules recommended
- Installation procedures are important, field based EL recommended
- Study of degradation phenomena in hot climates, need increased focus
- IEC certification protocols (eg. 61215), currently being updated, need hot climate inputs
- Small asset owners, considering the 40 GW installations foreseen, need to give sufficient importance to quality considerations in their decisions

NCPRE

Detailed report to come out in a couple of weeks.

www.ncpre.iitb.ac.in

Acknowledgments

Ministry of New and Renewable Energy (MNRE), Government of India, is gratefully acknowledged for funding NCPRE and the Survey.

The authors also acknowledge the help and assistance received from many people at the sites surveyed.

Renewable Energy Institute,
National Autonomous University of Mexico
IER-UNAM

Degradation of Veteran Si Modules in Hot Locations in Mexico

Dalia Martínez, Andrés Sánchez, Aarón Sánchez
Rocío de la Luz Santos, José Ortega.

PV Reliability Workshop NREL 2016

Objectives

- Give a background about PV status in Mexico.
- Show the principal defects and degradation modes in veteran Si modules in hot climates in Mexico.

OUTLINE

- **Background**
  - Mexico in PV technology
  - Climates condition in Mexico
- **Sites of Installation**
  1. Xoxocotla, Mor.
  2. Xochicalco, Mor.
  3. Campeche
  4. Temixco, Mor.
- **Analysis and results**
  - Visual Inspection
  - IR images
  - Fluorescent Images
  - IV curves
- **Conclusion and remarks**

Background

Twenty six years ago Mexico did not have big power plants. In that time PV modules were only used for low voltage installation in water pumping and self sufficiency systems.

Actually, we can still find these low voltage installation with an average of 10-15 modules

Background

In the last years PV market has grown significantly in Mexico. Mexican government has approved utility scale power plants due to the reform of the electrical sector that opens the power market. According to the report of IEA-PVPS these are the numbers for Mexico

MEXICO		
Final electricity consumption in 2014	234	TWh
Habitants	124	MILLION
2014 PV installed capacity	67	MW
2014 PV cumulative capacity	179	MW
PV penetration	0.1	%

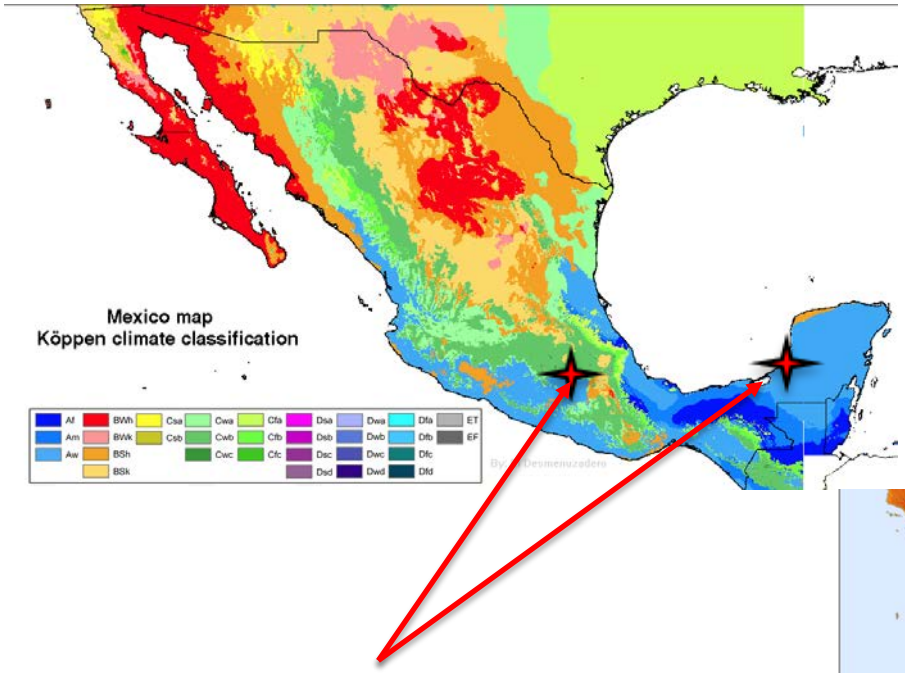
Background

Also:

- Two utility-scale power plants have been developed in 2014, one of 17 MW and another one of 39 MW.
- At the beginning of 2015, more than 200 projects have been approved with a total capacity of 5 GW.
- 900 MW were under development at the end of 2014
- The Mexican government has announced a target of 600 MW of PV system in 2018 and 6 GW of self-consumption by 2024.
- Large power plants have been announced and could increase the PV market to several hundreds of MW a year.

Background

Climate condition in Mexico

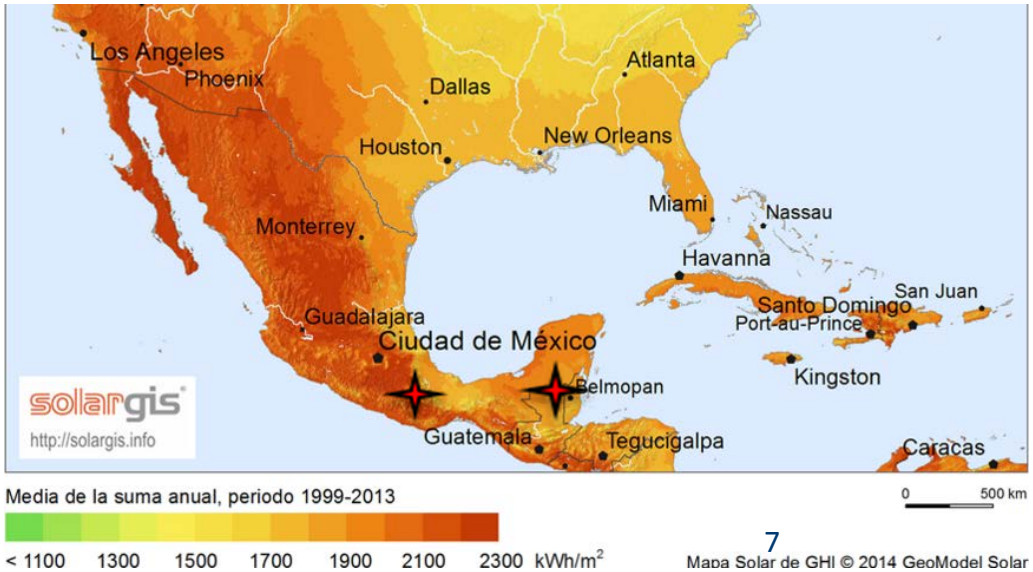


Solar resource

- ✓ Average Global Horizontal Irradiation (GHI) is approximately 5 kWh/m2/day.
- ✓ 70% of the territory has GHI values greater than 4.5kWh/m2

Two regions of interest and four different sites:

- Morelos Mex (3 sites)
- Campeche, Campeche (1 site)



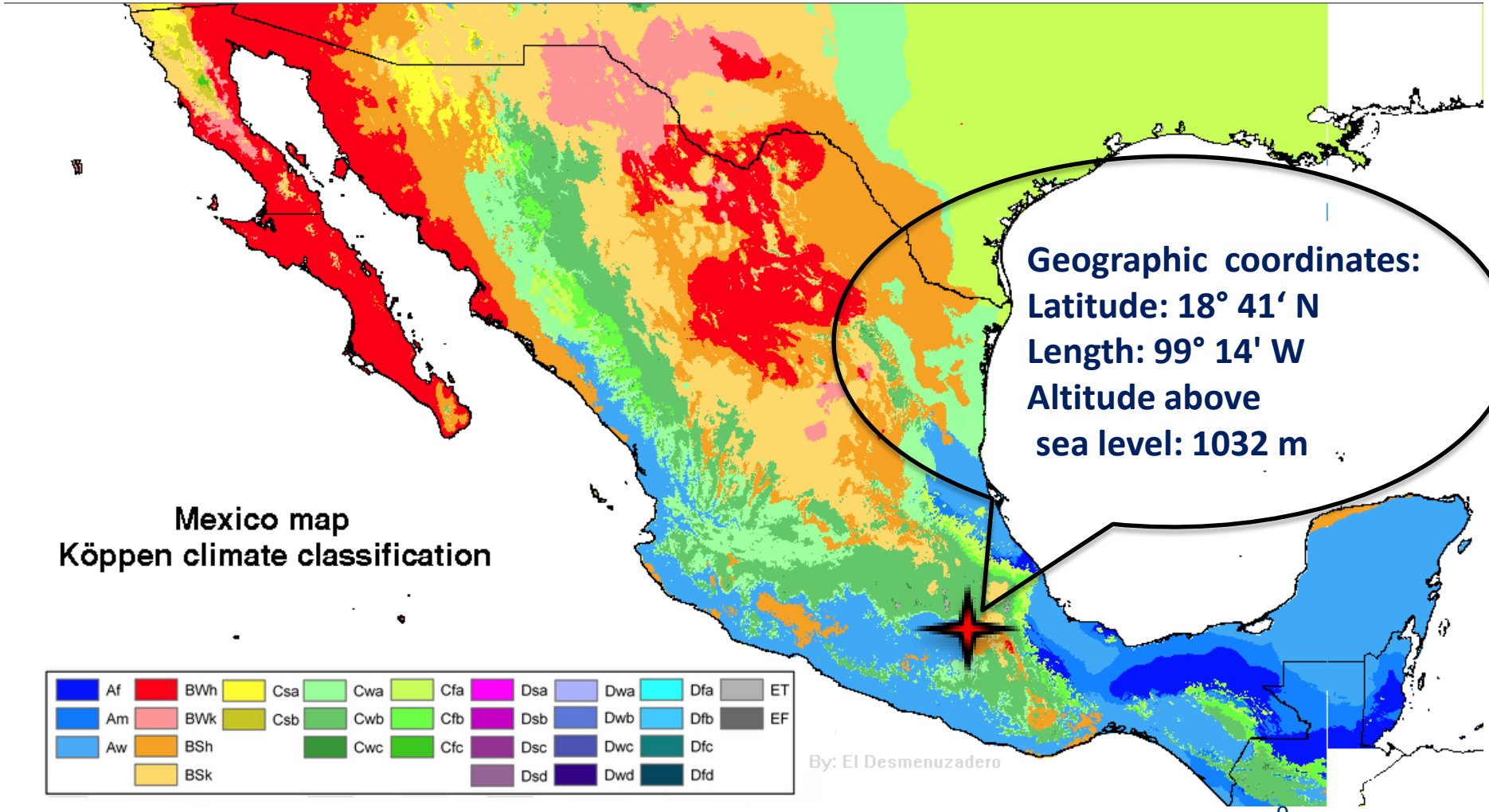
Analysis of veteran Si modules

Sites of installation

Site	System features	Climate condition	Module	Years exposed
1. Xoxocotla Morelos	Stand alone system	Hot and sub-humid	Siemens M65	23
2. Xochicalco Morelos	Stand alone system	Hot and Sub-humid	Siemens M75	20
3. Campeche Campeche	Stand alone system	Hot and humid	Siemens AP 75	15
4. Temixco, Morelos	Not connected, modules in open circuit 18 years	Hot and sub humid	Astro power AP 75	20

Analysis and results

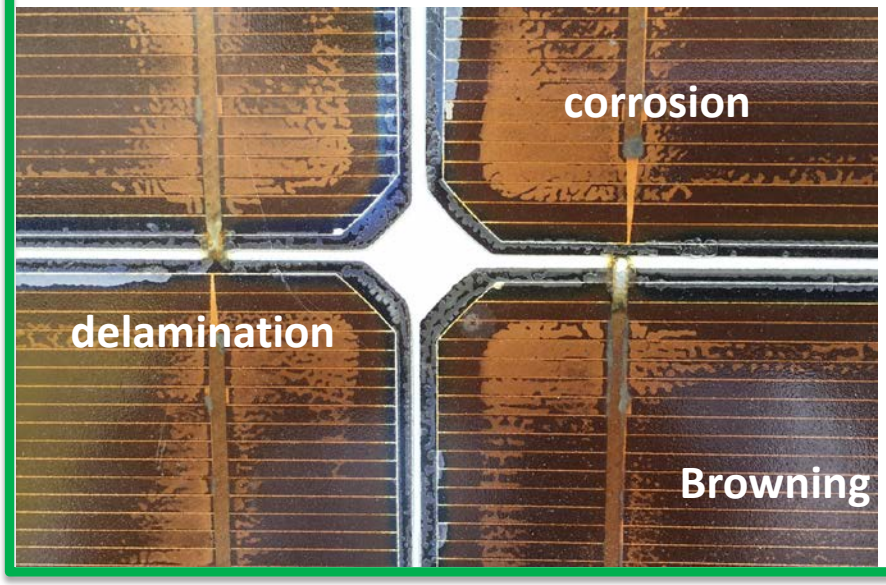
Site 1: Xoxocotla, Morelos.

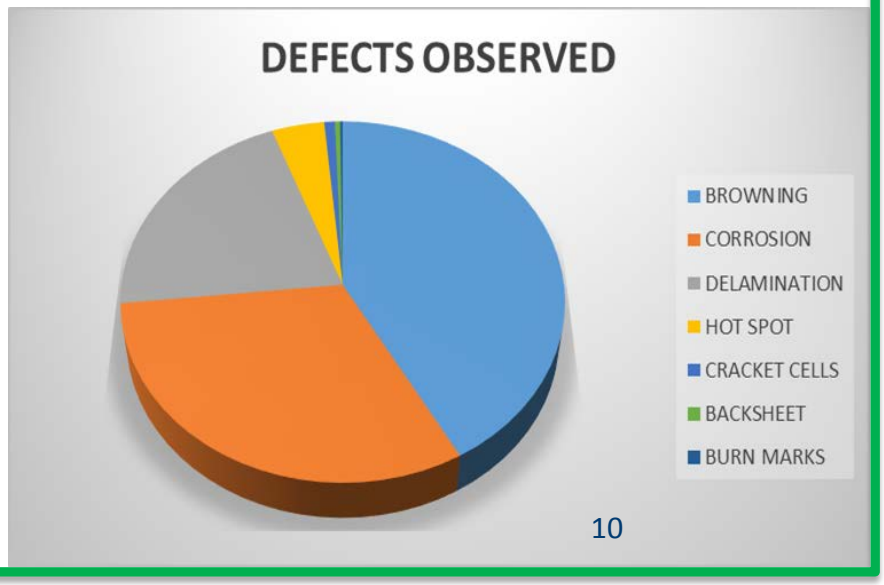


Analysis and results

Site 1: Xoxocotla, Morelos.

Visual Inspection

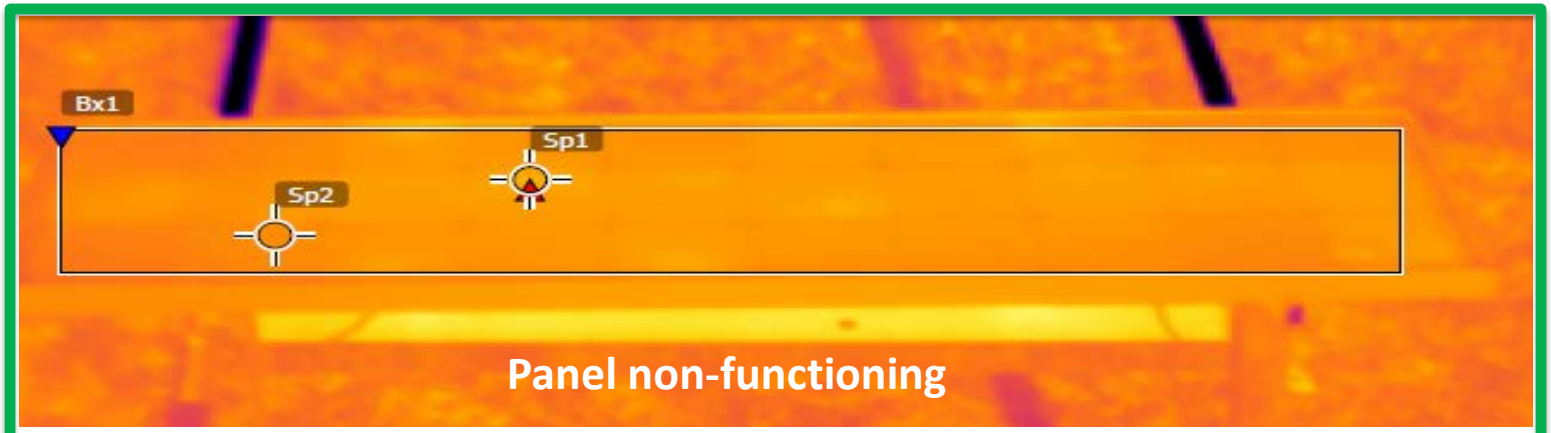


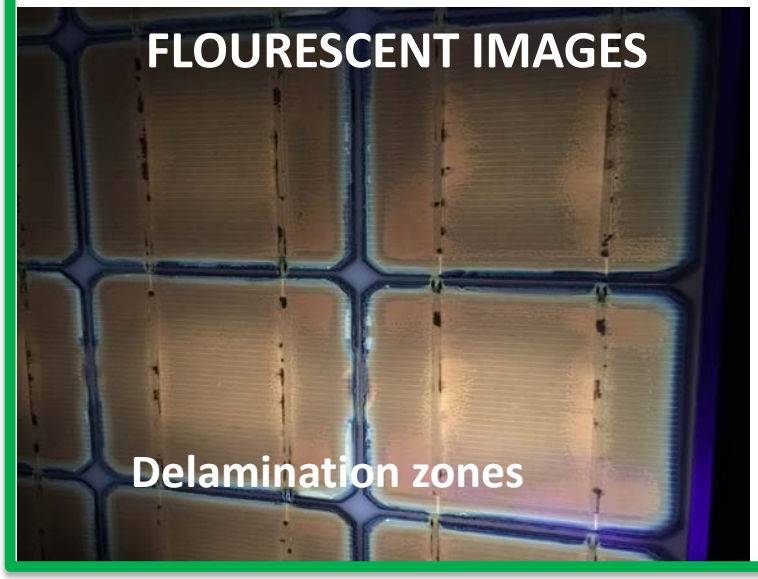


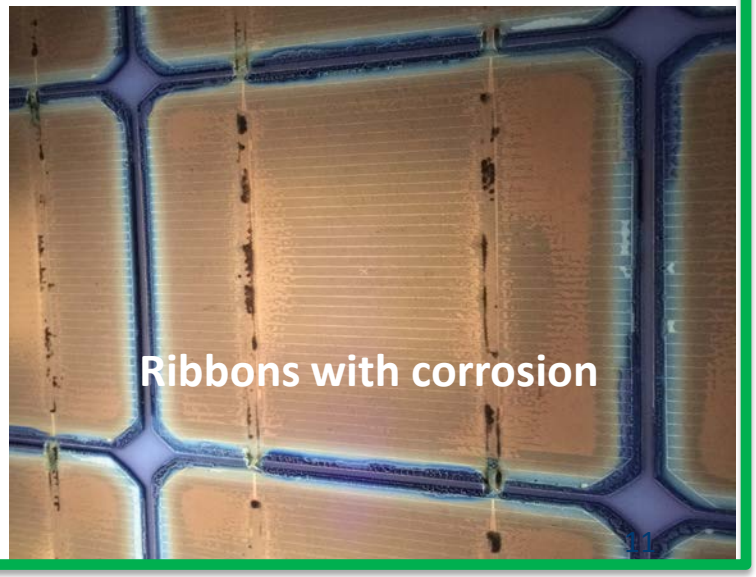
Analysis and results

Site 1: Xoxocotla, Morelos.

IR and Fluorescent images



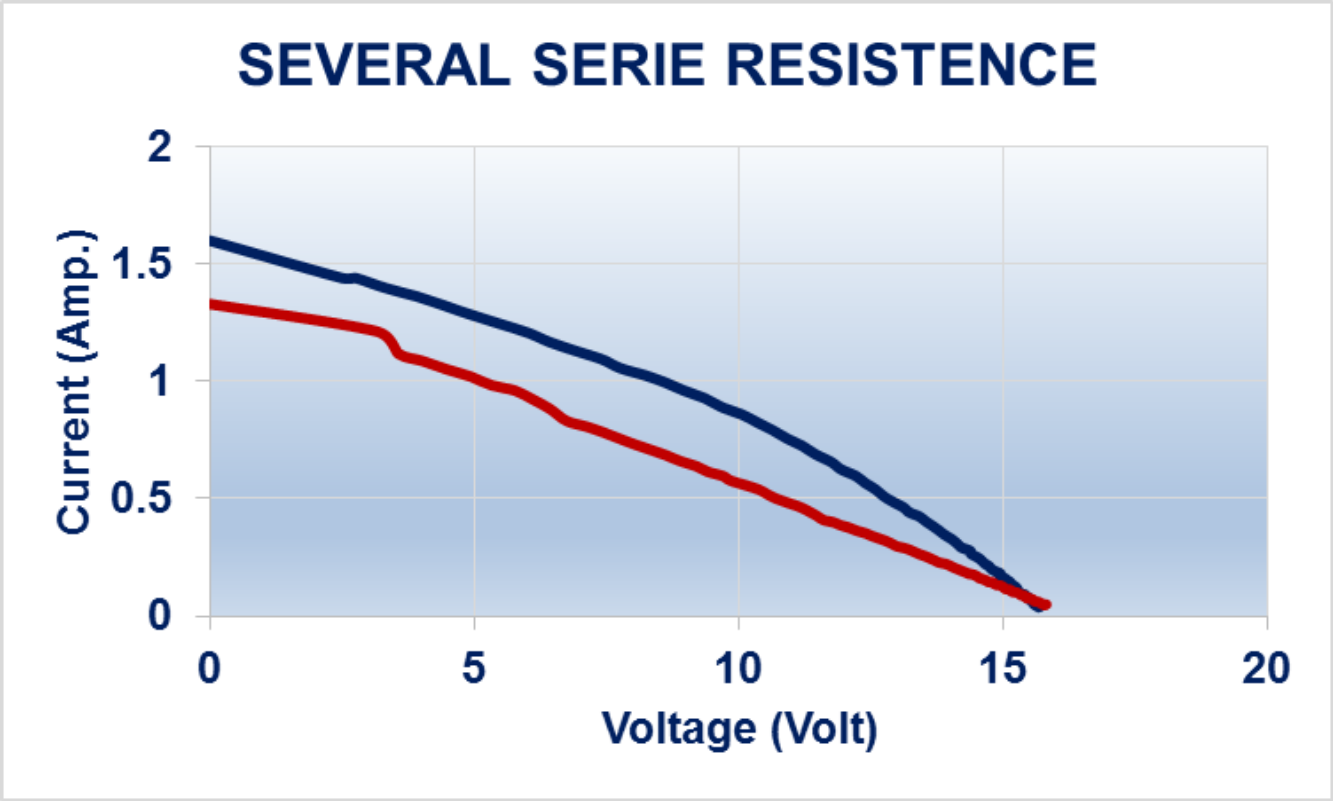




Analysis and results

Site 1: Xoxocotla, Morelos.

IV Curves for 2 Siemens M65 modules with 23 years exposed

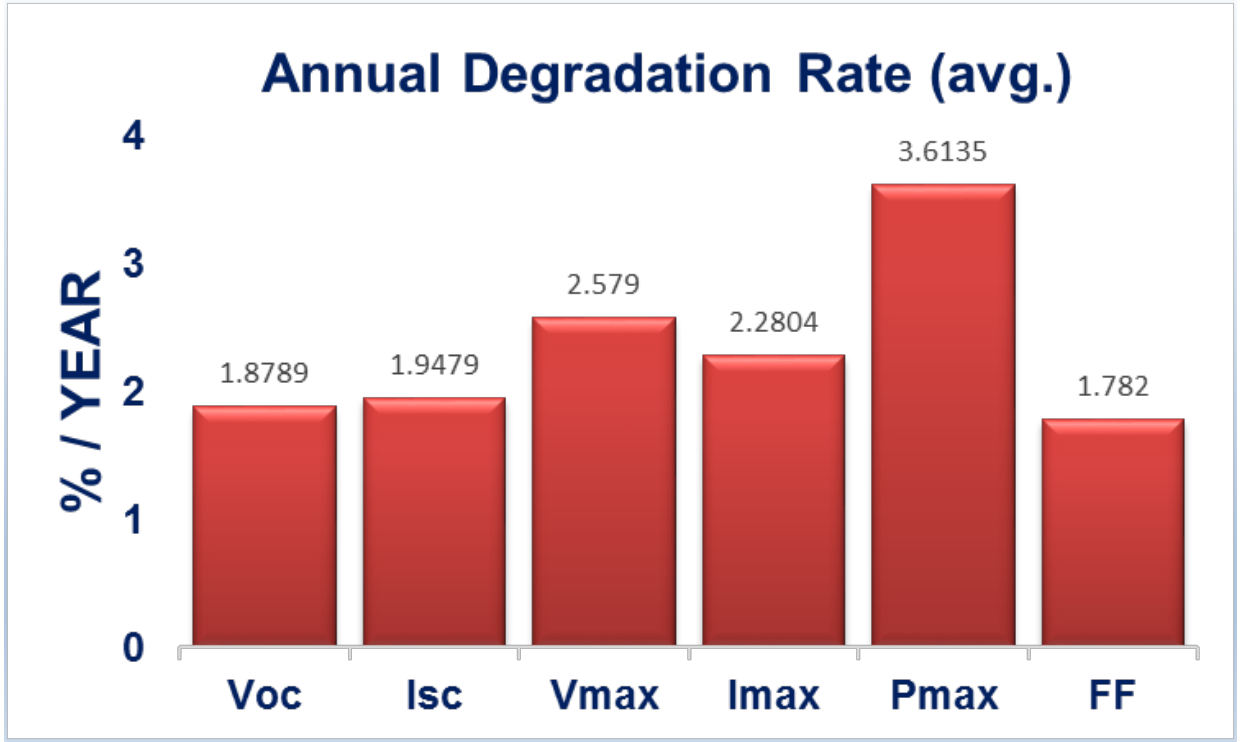


Power loss arise from voltage drop and current drop

Analysis and results

Site 1: Xoxocotla, Morelos.

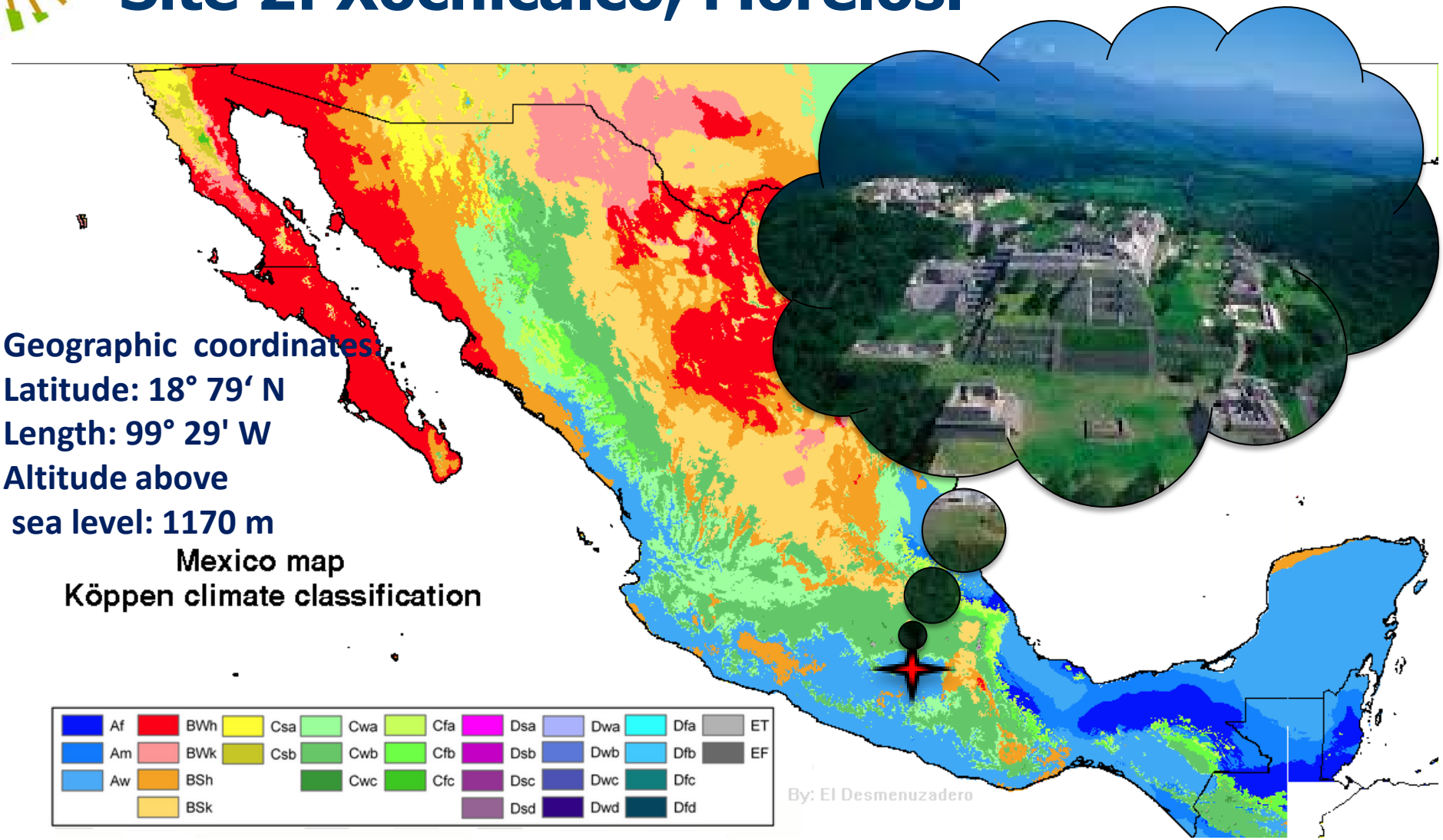
Electrical Results: SIEMENS M65 23 years old



Annual degradation rate between measure data and nameplate data of Pmax was 3.61 % in this specific hot and sub humid location.

Analysis and results

Site 2: Xochicalco, Morelos.

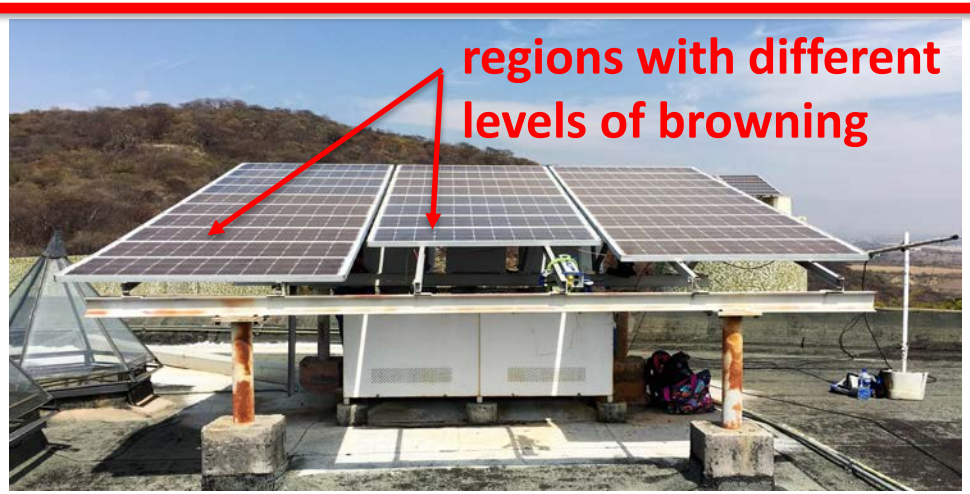


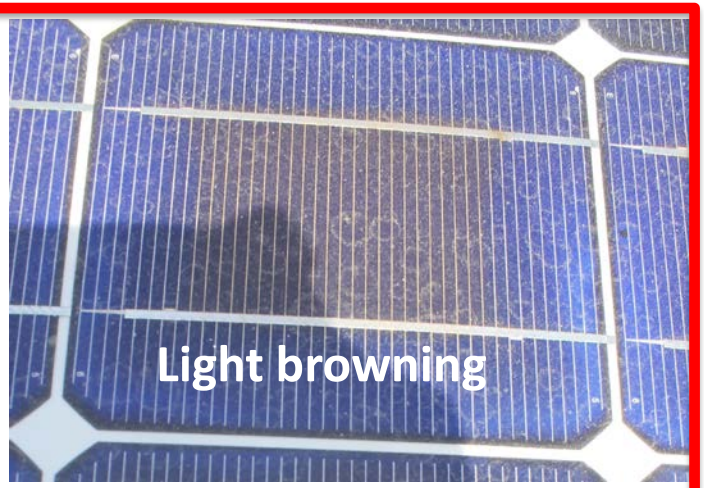
Geographic coordinates:
Latitude: 18° 79‘ N
Length: 99° 29' W
Altitude above sea level: 1170 m

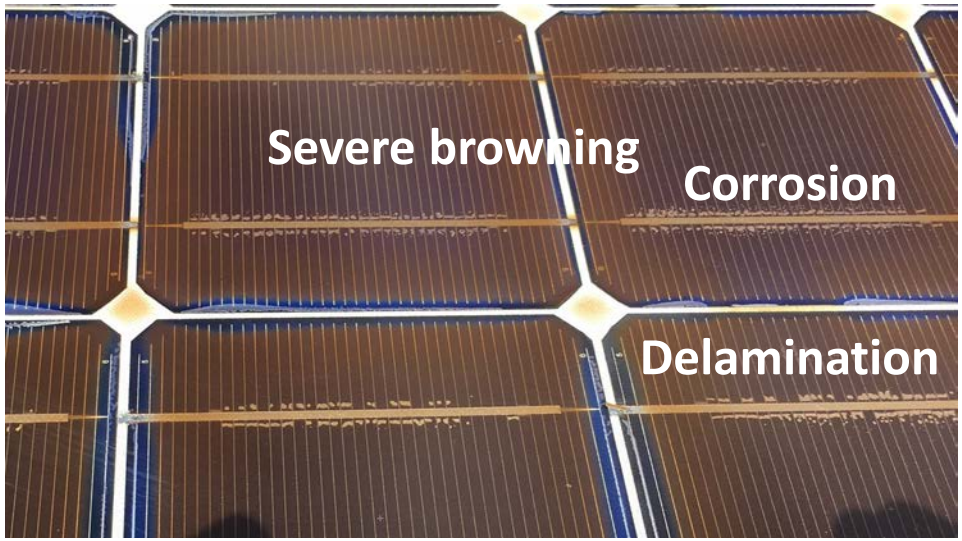
Analysis and results

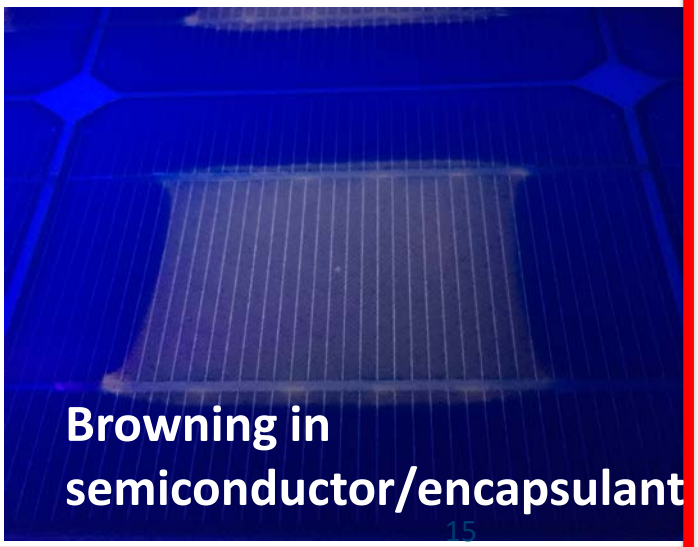
Site 2: Xochicalco, Morelos.

Visual Inspection and fluorescent images





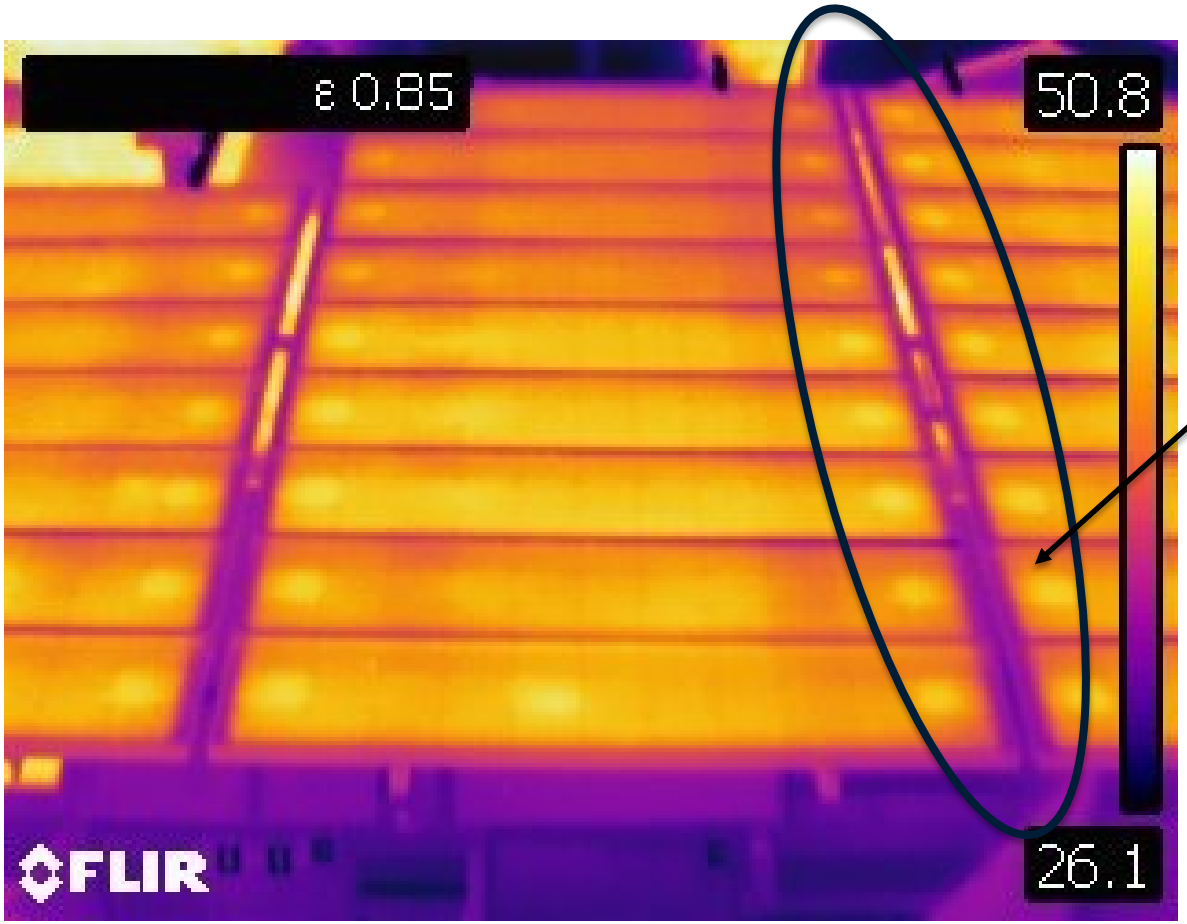




Analysis and results

Site 2: Xochicalco, Morelos.

IR images

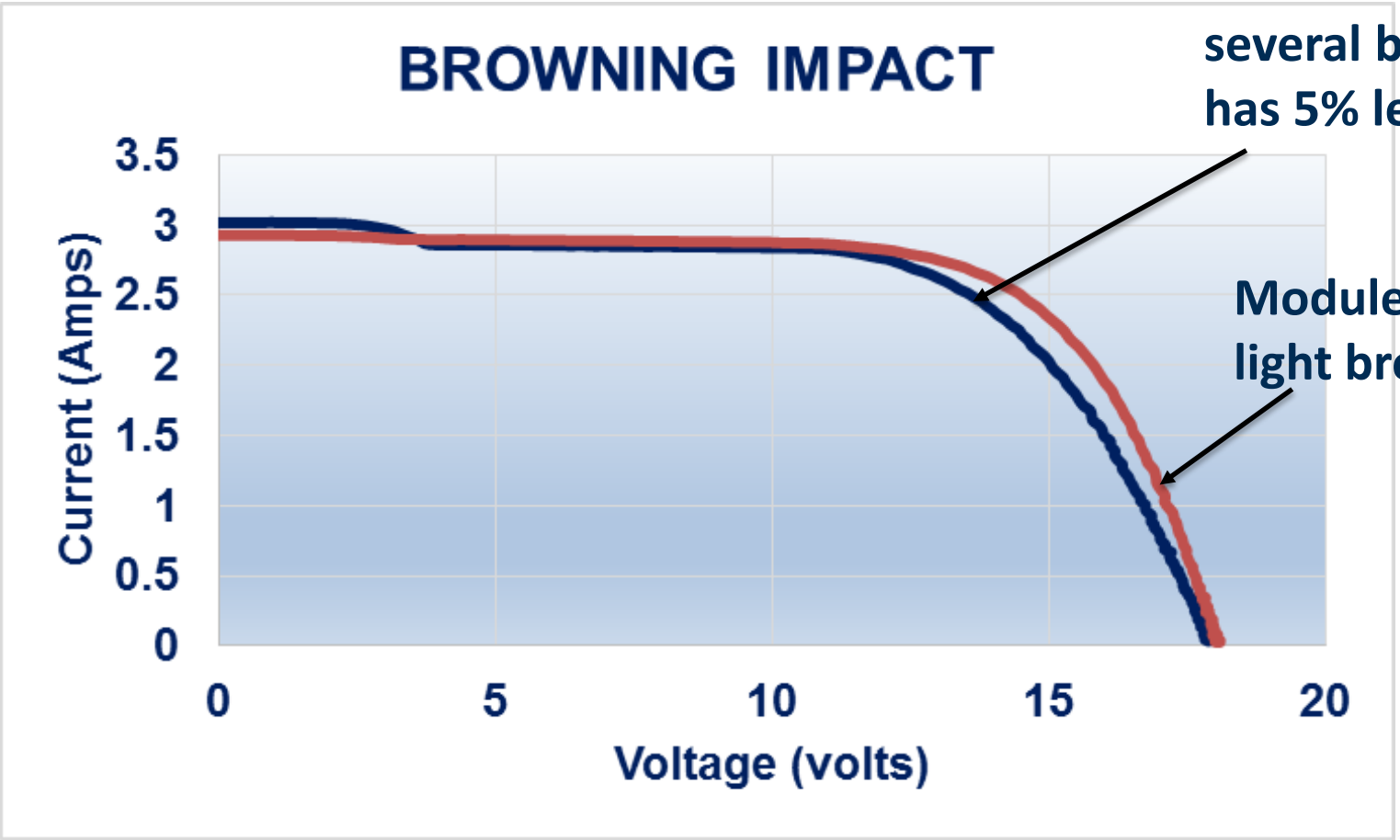


Hot spots in junction box area in the whole string

Analysis and results

Site 2: Xochicalco, Morelos.

IV curves



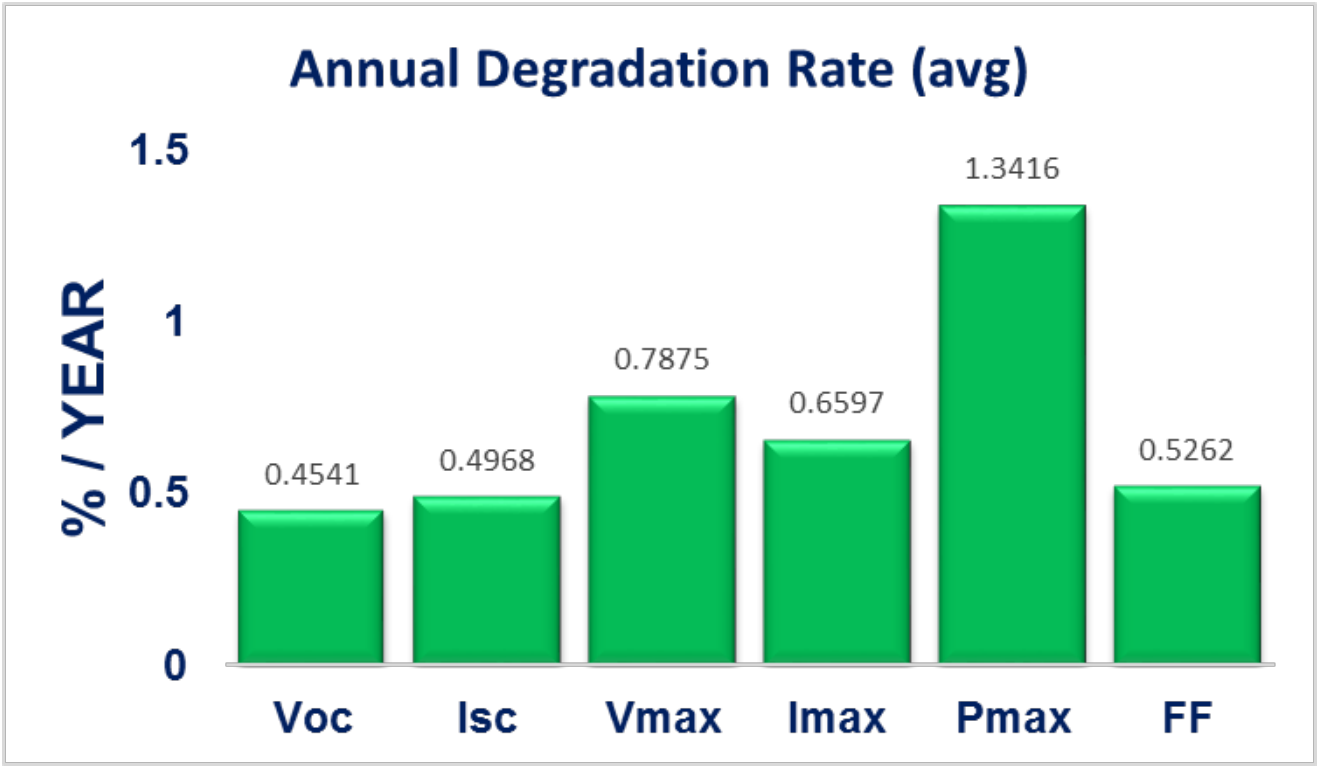
Modules with several browning has 5% less Pmax

Modules with light browning

Analysis and results

Site 2: Xochicalco, Morelos.

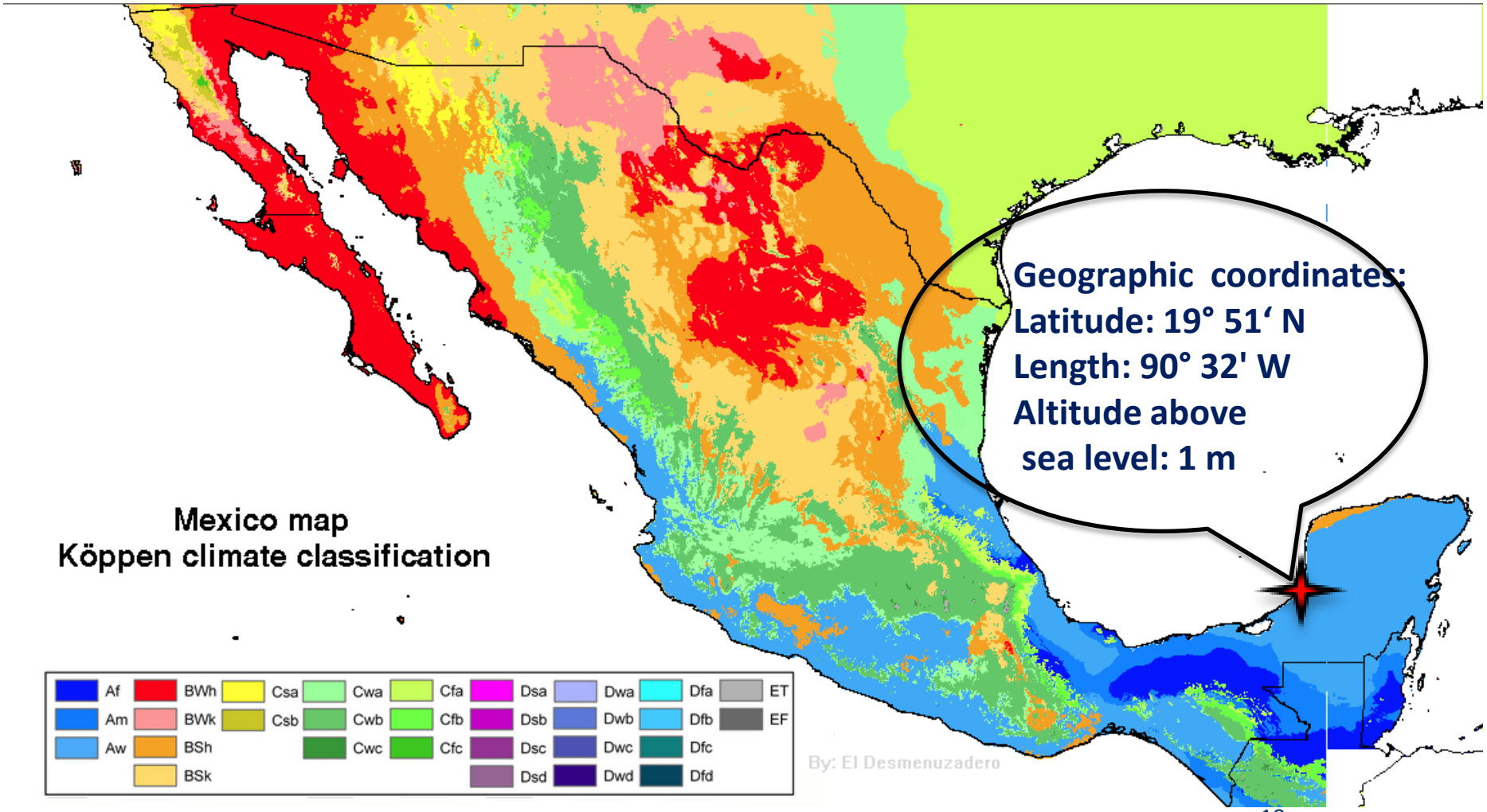
Electrical Results: SIEMENS M75 20 years old



1.34 % / year power degradation is due fill factor decrease and current drop in this specific hot and sub humid location.

Analysis and results

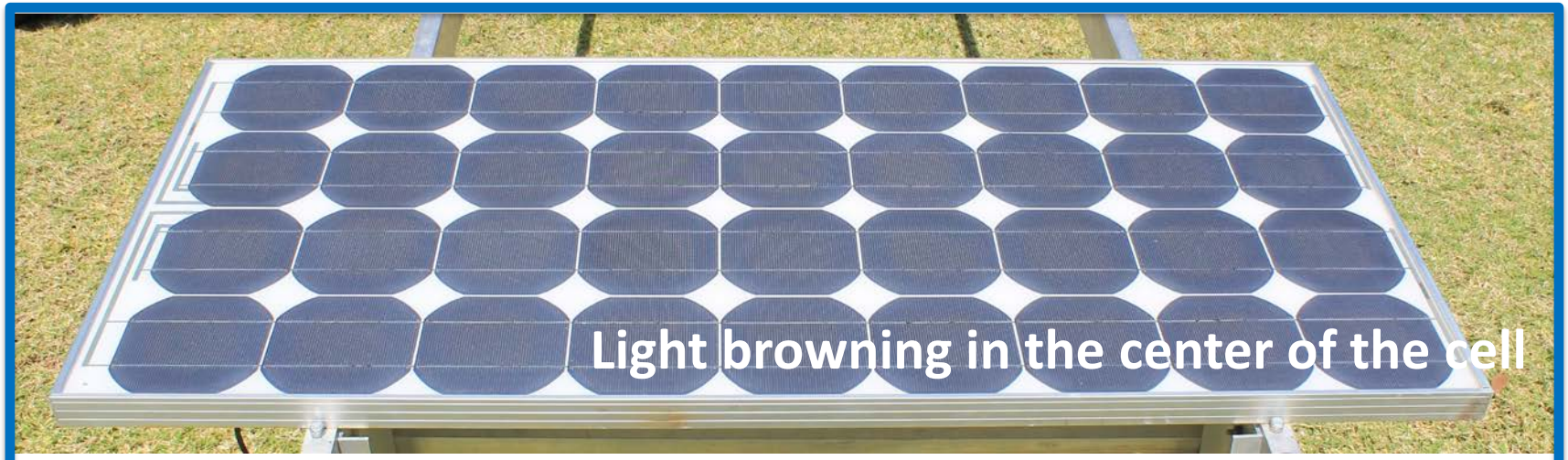
Site 3: Campeche.

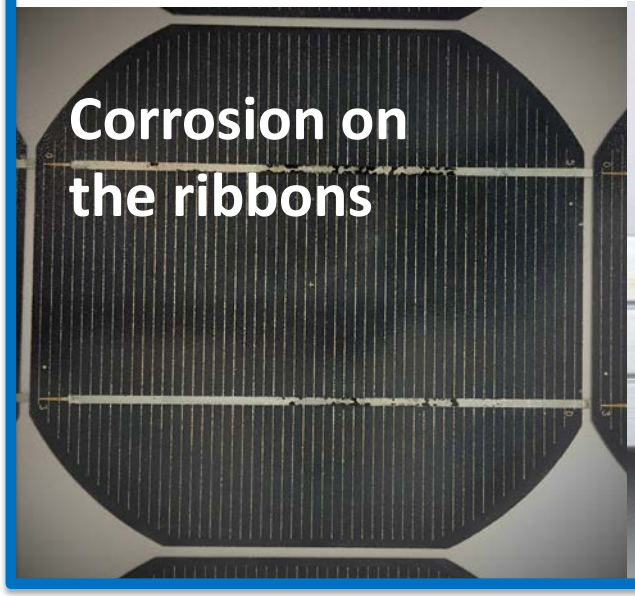


Analysis and results

Site 3: Campeche

Visual Inspection

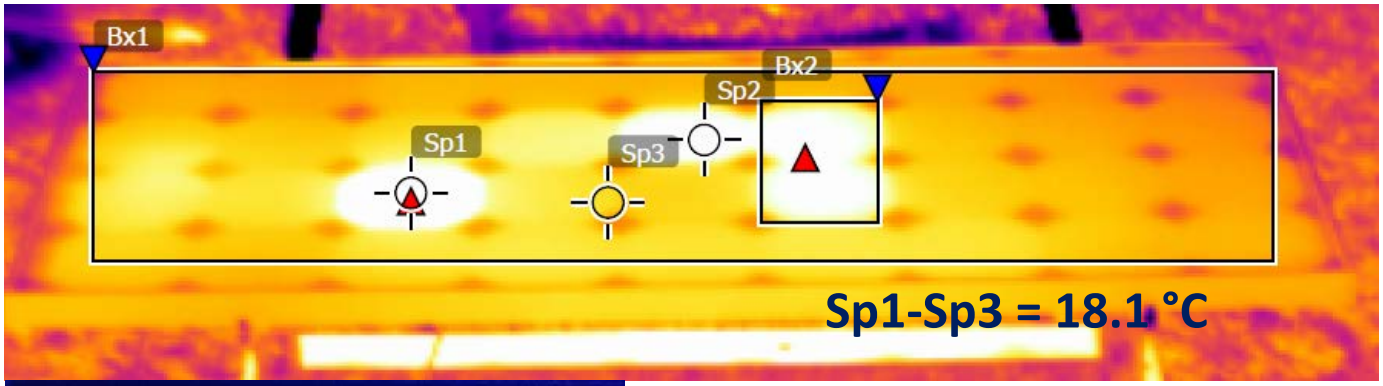


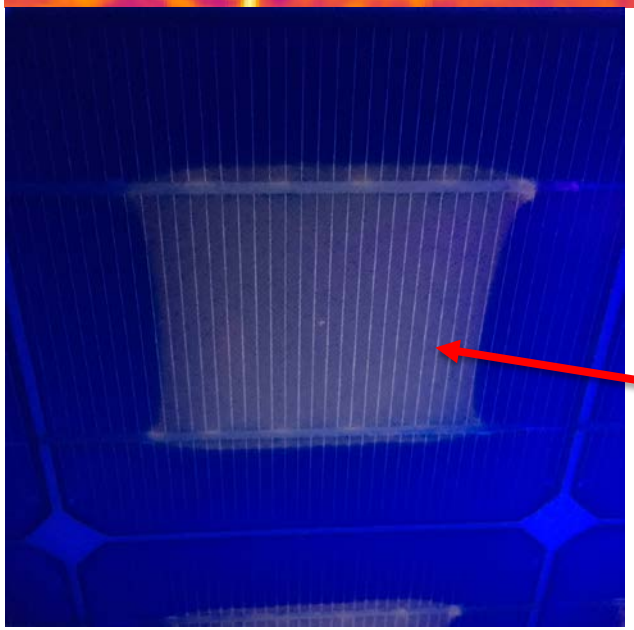


Analysis and results

Site 3: Campeche

IR and fluorescent images

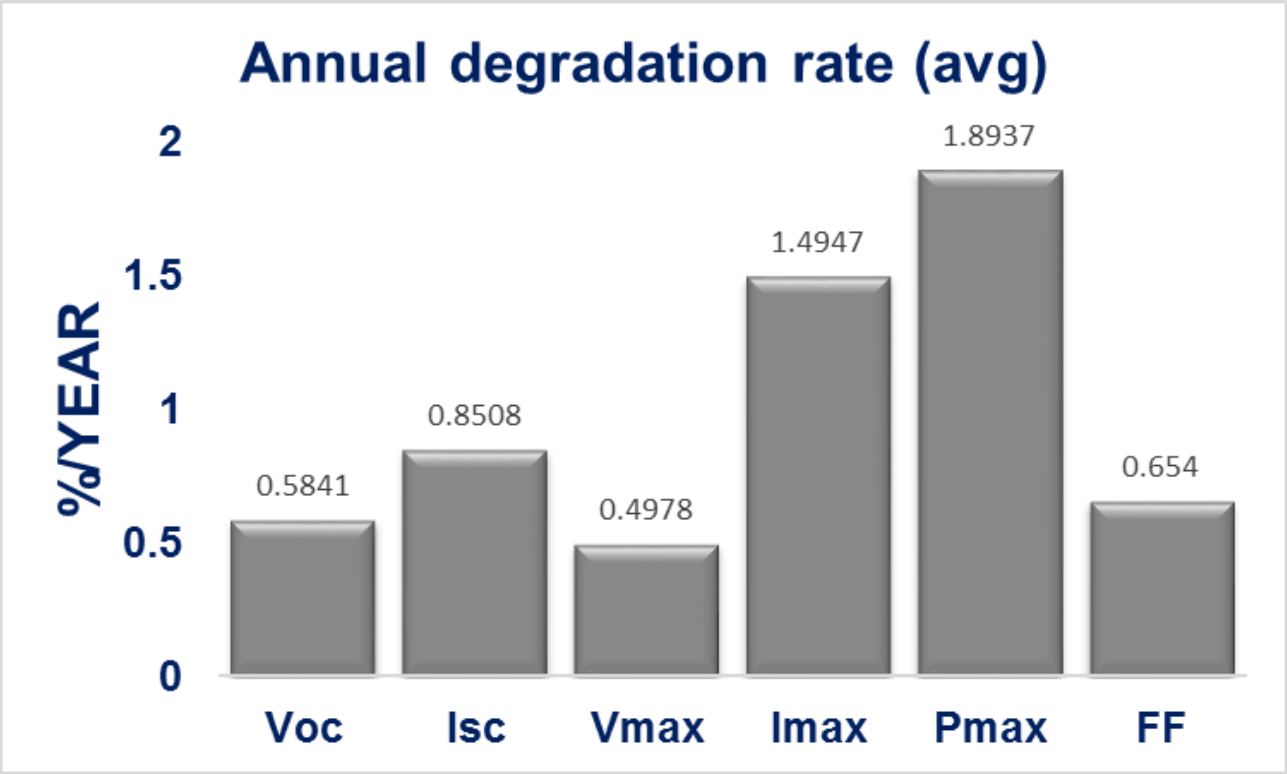




Light encapsulant browning in the center of the cell.

Analysis and results

Site 3: Campeche, Campeche



The annual degradation of Pmax obtained was 1.89 %/year due Isc losses and FF

Analysis and results

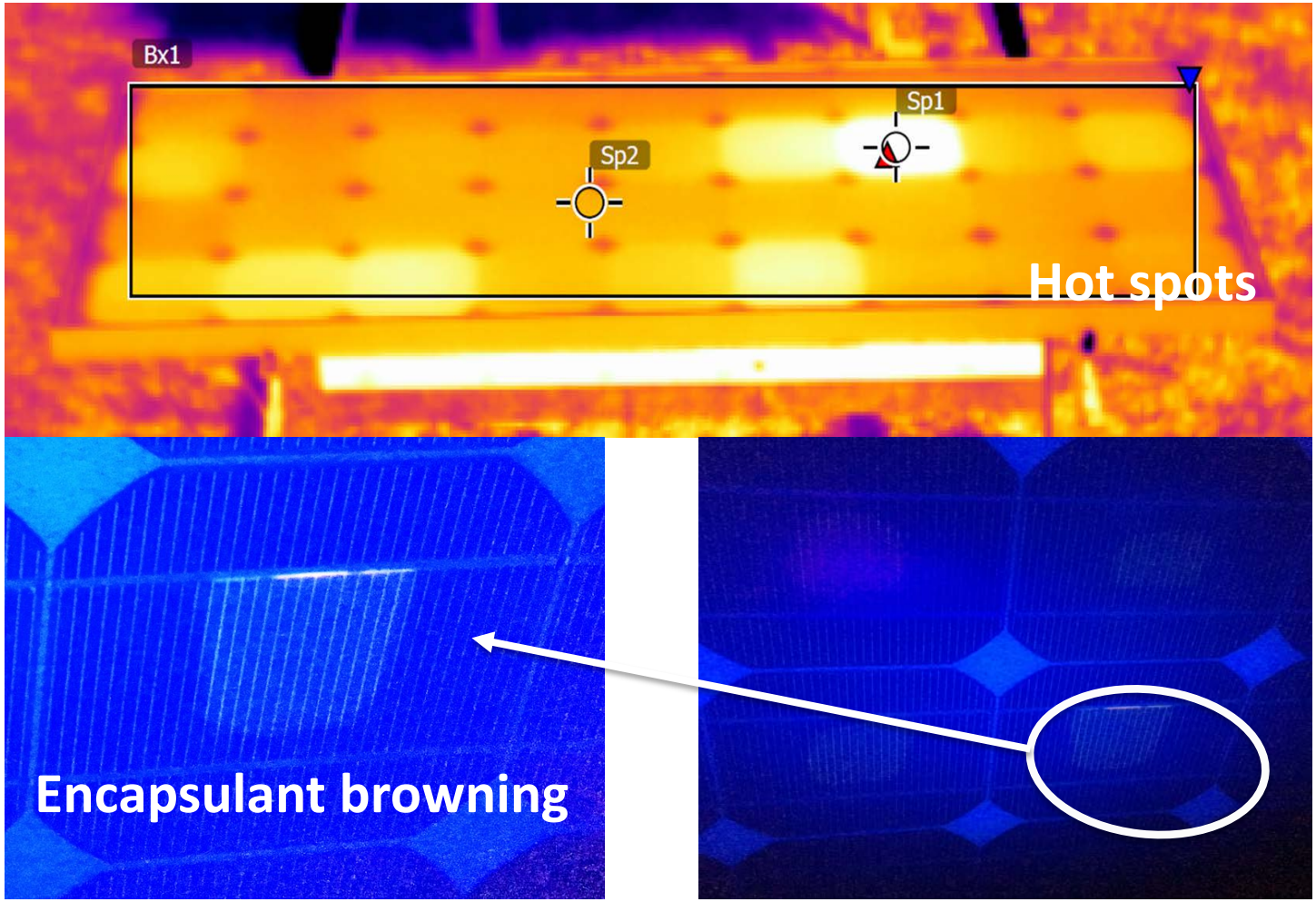
Site 4: Temixco, Morelos

Visual Inspection

Analysis and results

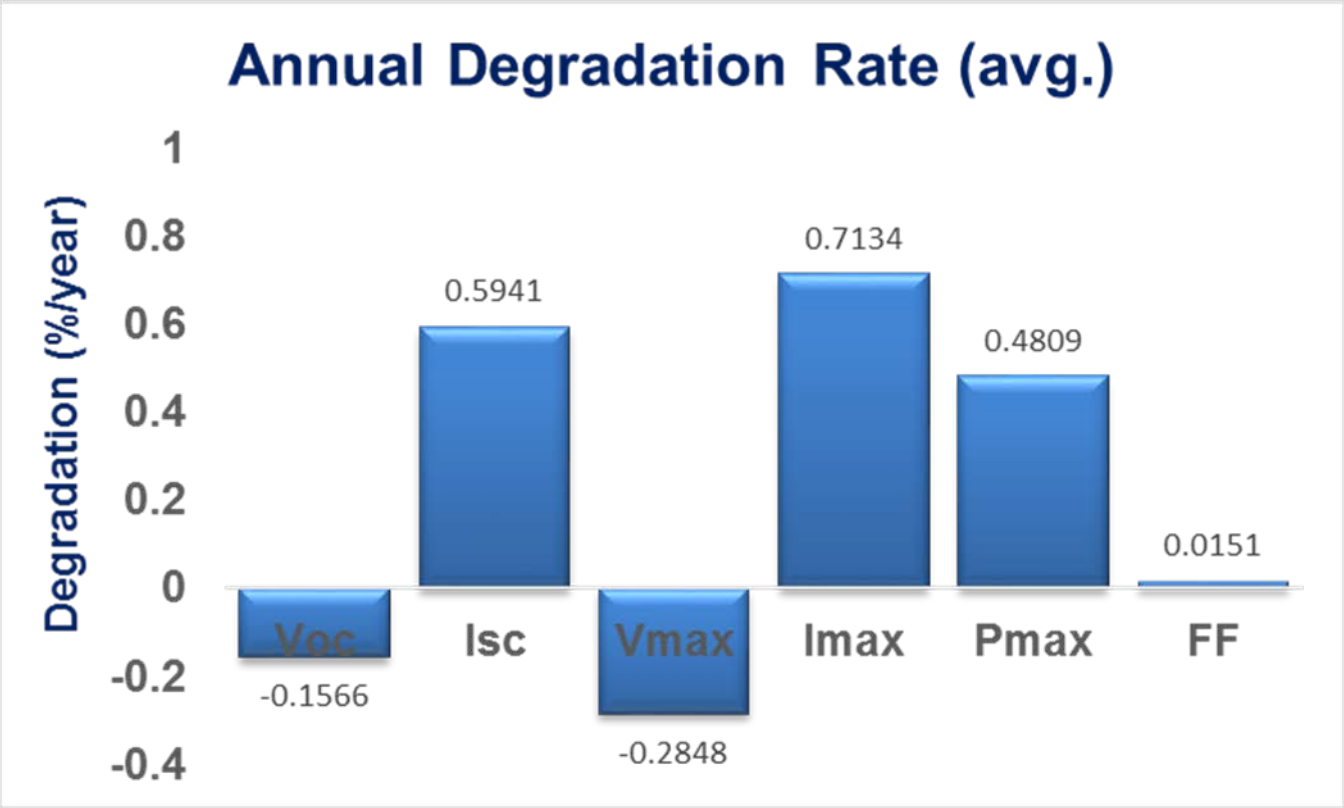
Site 4: Temixco, Morelos

IR and fluorescent images



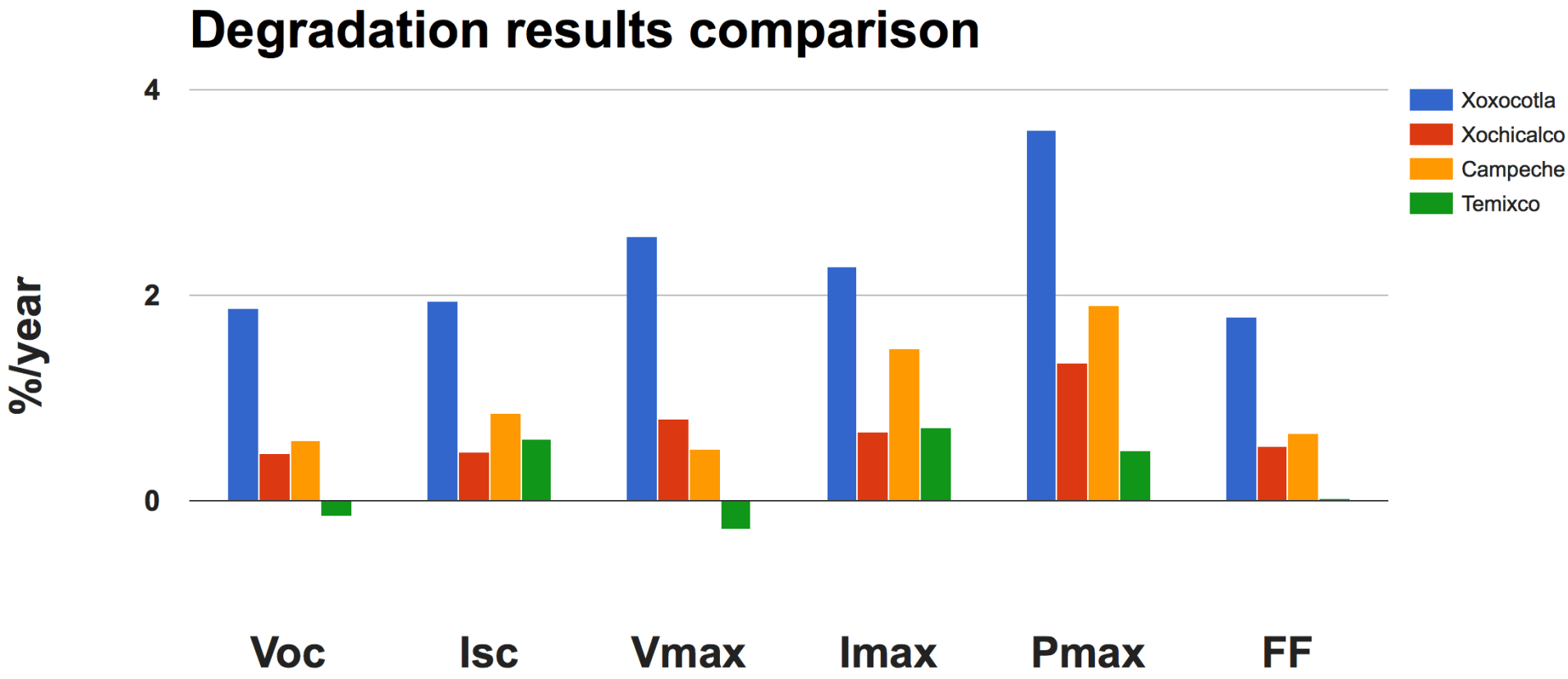
Analysis and results

Site 4: Temixco, Morelos



The annual degradation of Pmax obtained was 0.71 %/year due Isc losses.

Analysis and results



Site 1 was the most aggressive climate conditions. Higher degradation rate in these place..
In site 2, we have losses in voc.
Site 3 has aggressive conditions because of salinity, temperature and humidity

Conclusions remarks (1/2)

- **Mexico has multiple old installation for low voltage and current demand**

- **Old PV modules may proportionate rich information of typical degradation modes for large PV power plants in specific sites.**

- **Site 1 (Xoxocotla) presents the higher degradation rate found with 3.6%/year for 23 years old module.**

- **In open circuit mode, degradation rate found was 0.48%/year due climate and sun.**

Conclusions remarks (2/2)

- **Principal degradation modes found were corrosion, encapsulant browning and delamination.**

- **New opportunities in reliability research in Mexico.**

- **First steps for a Reliability survey in multiple installation in Mexico.**

Photovoltaic UNAM team

Thanks !

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UNAM
CAMPUS MORELOS

IER
Instituto de Energías Renovables

The present work was carried with the financial support received from the Institute for Renewable Energy (IER-UNAM), through the Mexican Center for Innovation in Solar Energy (CeMIE-Sol), with the Strategic Project No P29 and the FORDECYT project No. 190603

Field performance and degradation analysis of two brands of modules in a 1 MW PV power plant in Acapulco, Guerrero, Mexico.

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Affiliation: Renewable Energy Institute-UNAM
Address: Privada Xochicalco S/N, Temixco, Morelos. ZC 62580
Corresponding author: pesap@ier.unam.mx

Introduction

1 MW PV power plant with two brand of modules is located in Acapulco, Guerrero, Mexico. The power plant was installed mid 2013 but left in open circuit due gubernamental problems.

UNAM has monitoring the installation since module exposure and detected one brand of module (brand 1) with high series resistance values and snail tracks in more than 30% of the cells. The other module (brand 2) does not present snail tracks or series resistance increase.

Side by side comparison in a high salinity and humidity climate was performed

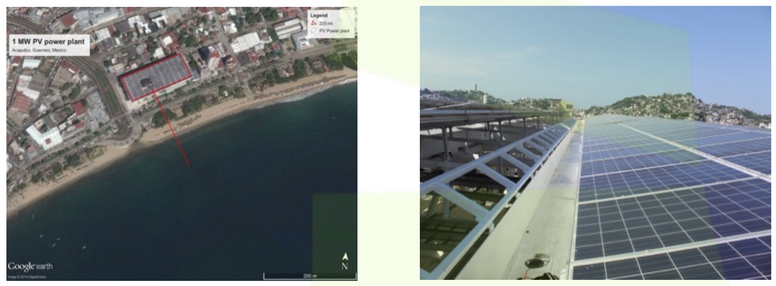

Fig 1. Photographs of the PV power plant site

IV measurements

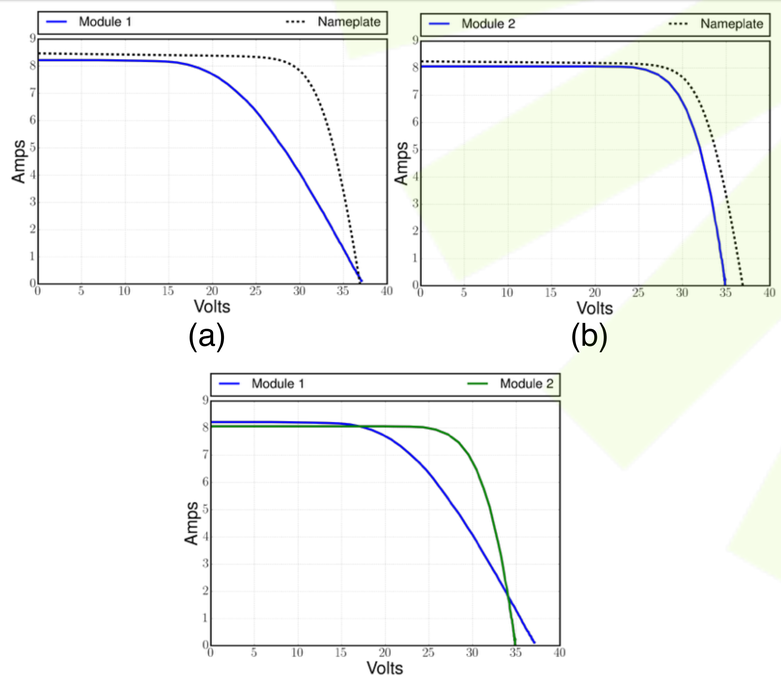

Fig 1. Normalized IV curves vs nameplate IV. Two brand of modules (a), (b) and comparison between both (c).

Field inspection

Field evaluation inspection was performed. Ten modules from each brand were retrieved from the installation to the perform non-destructive degradation analysis.

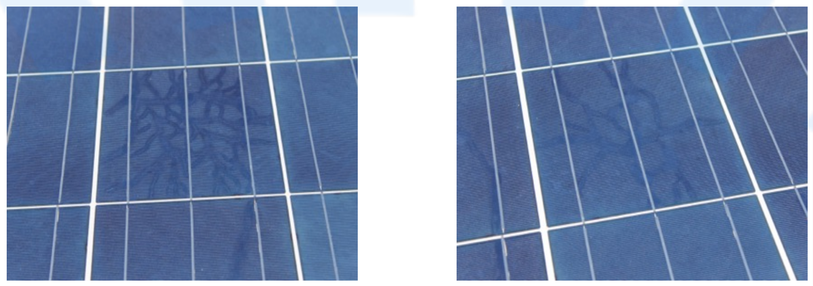

Fig 2. Snail tracks in brand 1.

IR Image

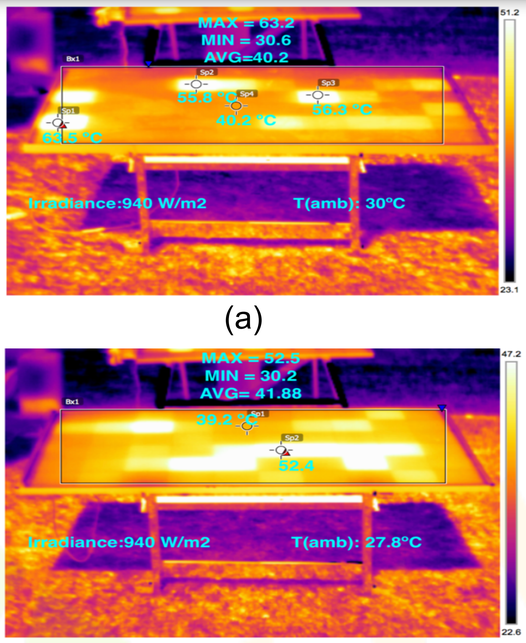

Fig 3. IR image for brand 1 (a) and 2 (b).

Both modules presents hotspots in more than 3 cells with a temperature difference greater than 10 ºC. Brand 1 hotspots are located in cells with snail tracks while brand 2 no specific pattern was found.

Degradation analysis

Total degradation results for brand 1 can be observed in Figure 3. High percentage of power degradation where obtained for brand 1

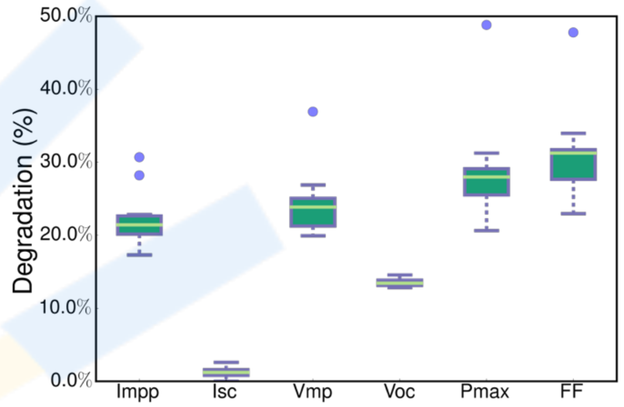

Fig 3. Total degradation results for brand 1

Table 1 shows the results of series resistance. Highly resistive curves has been observed in most of the strings from brand 1. Less aggressive series resistance increase was observed in brand 2.

Table 1. Average Rs result for two brand of modules. using linear fit for a outdoor IV curve. Increase ratio was calculated using fresh module

Brand	Method	Rs (Ω)	%
1	Ref	0.31	367.74
	Out	1.45	
2	Ref	0.32	96.88
	Out	0.63	

Conclusions

- Brand 1 presents series resistance increase in most of the modules.
- Pmax total degradation obtained for brand 1 is 28% due series resistance increase.
- High salinity and water vapor concentration might accelerate chemical reaction inside the brand 1. Maybe back sheet defect.
- To determine the cause of power loss further research is required.

Acknowledgment: The present work was carried with the financial support received from the Institute for Renewable Energy (IER-UNAM), through the Mexican Center for Innovation in Solar Energy (CeMIE-Sol), with the Strategic Project No P29 and the FORDECYT project No. 190603

Module Reliability Workshop, Denver Colorado, February 2016
Andrew Thomson, Julian Ciempka, Luke Johnson and Ingrid Haedrich
Research School of Engineering
ANU College of Engineering & Computer Science

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Australian National University

Reliability testing for the Australian market

Introduction

- In Australia, 4.7 GWp of PV panels
- 2 million rooftop system
- Here, baseline material degradation results
- UV and DH degrade the module optics
- Observe reductions of mini-module I_{sc} in the order of 2%.

Extreme UV exposure for modules because:

1) The ozone layer is thinner in the southern [1],
2) there are less particulates in the atmosphere (See Figure 1), and
3) Australia receives high solar insolation (See Figure 1).

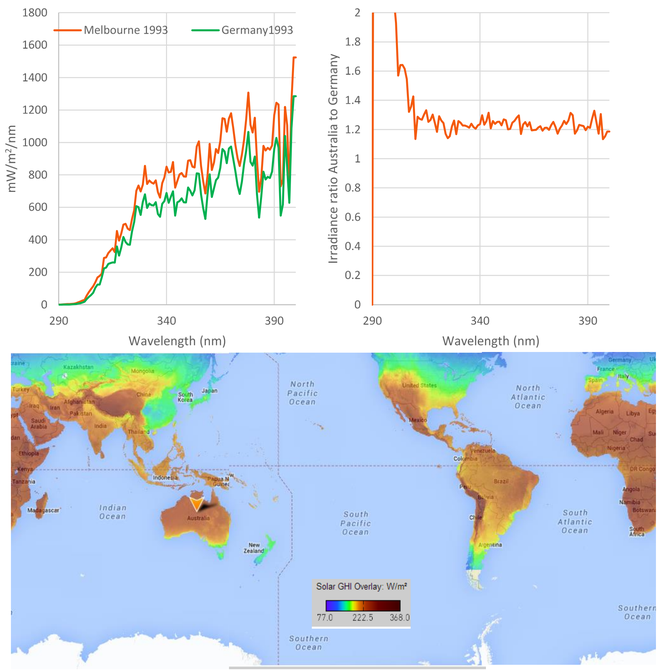

Figure 1: (Top) spectral comparison of irradiance in Melbourne Australia and Germany [1]. (Bottom) yearly averaged satellite measured GHI [2].

Experimental

- Two UV tests were performed compared in Table 1
- Radiation source was a Q-Sun Xe-1 xenon lamp
- Test 1 applied and illumination dose of 800 kWh over 464 hrs with a day light filter
- Test 2 applied 1400 kWh over 744 hours with extended UV quartz filter
- Temperature held constant at 60 C.
- Global reflectance was measured

Table 2: **Integrated UV exposure for test 1 and test 2 with different filters.**

		UV-C (260 - 280nm)	UV-B (280 - 315)	UV-A (315nm - 400nm)	Total UV (260 - 400nm)
Test 1 464 hrs (daylight filter)	Energy (kWh)	0	0.653	36.8	37.4
	Number of equivalent IEC61215 tests	n/a	1.5	8.2	7.6
	Hours at 1sun AM1.5G	n/a	880	800	804
Test 2 744 hrs (Quartz)	Energy (kWh)	2.51	7.26	54.9	64.68
	Number of equivalent IEC61215 tests	n/a	16	14	13
	Hours at 1sun AM1.5G	n/a	9800	1200	1400

- By Beer Lamberts law, at 500 nm, increased absorption in the order of 1.8%
- If the degradation is restricted to the front of the EVA the reduction in transmission could be 7%

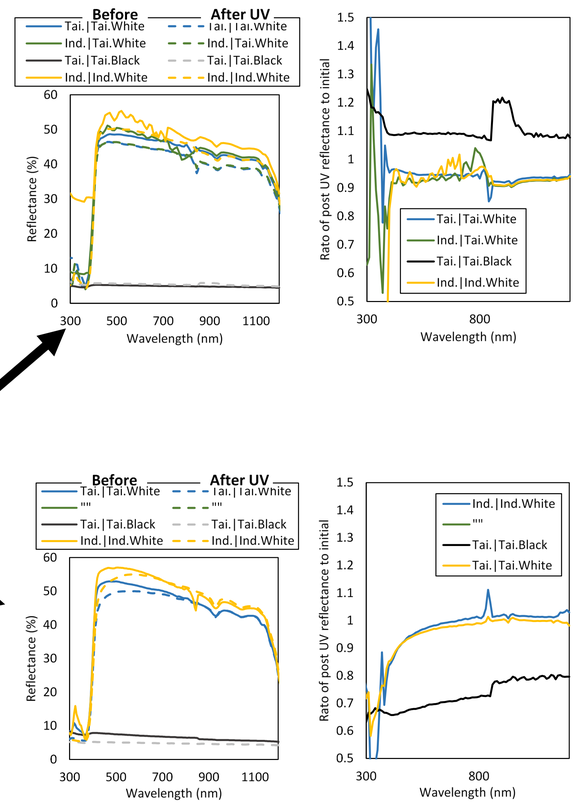

Figure 2: Reflectance of test samples pre and post UV exposure, absolute (left) and relative (right). For samples expose with a xenon lamp and daylight filter, test 1 (top), and samples exposed by a xenon Lamp and quartz filter, test 2 (bottom).

- laminated samples exposed to DH for 2500 hours
- Reflectance of the samples pre- and post-DH exposure are plotted in Figure 3.
- Observe a reduction in reflectance for all samples indicating either higher absorption on increase light scattering
- Observing the relative change there is up to an 8% reduction in reflectance

- IV tests were performed with full area or cut multi-crystalline
- Changes in the electrical performance of cells with different encapsulation Observed
- Relative changes in I_{sc}, V_{oc}, and *FF* in Figure 3
- The degradation is dominated by the reduction in I_{sc}

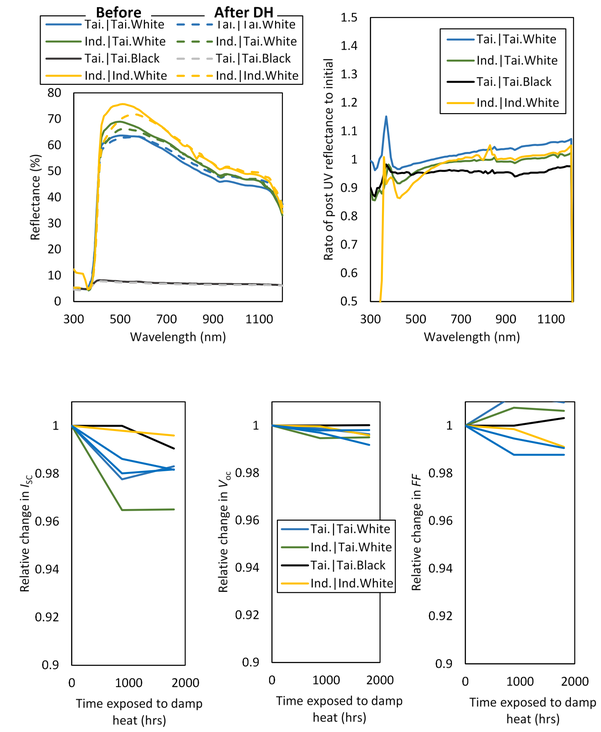

Figure 3: (Top) Reflectance of test samples pre and post DH exposure, absolute (left) and relative (right). (Bottom) Relative change in I_{sc}, V_{oc} and FF with damp heat exposure.

NOCT of double glass

We aim to improve module performance in Australia by considering

1) Modularization losses: or cell to module (CTM) losses [3].
2) Degradation losses: typically observed is a year on year relative performance loss of 0.5%, however degradation rates of 4% and higher have been observed [4].
3) Running losses: from soiling [5] and temperature

We investigate is double glass NOCT modules:

- Modelling and tests in Figure 4
- Modelled NOCTs under cloudy conditions to be 49.5 and 49.2° C for standard and double glass
- Methodology similar to Notton *et al.* [6].

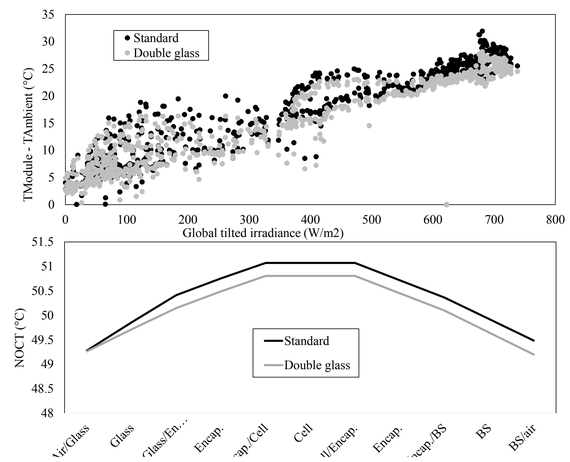

Figure 4: (Top) Measured operating module temperature in cloudy cloudy conditions. (bottom) modelling of layer temperatures under NOCT conditions.

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5. Mejia FA, Kleissl J. Soiling losses for solar photovoltaic systems in California. Solar Energy. 2013 9//;95(0):357-63.
6. Notton G, Cristofari C, Mattei M, Poggi P. Modelling of a double-glass photovoltaic module using finite differences. Applied Thermal Engineering. 2005;25(17):2854-77.

Acknowledgment

We acknowledge the Australian Renewable Energy Agency funding of this work through grants 3-F006, 3-F020, and 2014/RND008.

Brisbane Materials
Sunpulse
PV LIGHTHOUSE
Australian Government
Australian Renewable Energy Agency
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PVLABAUSTRALIA

Effect of Hot Cells on Power Degradation Rate of PV Modules

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Introduction

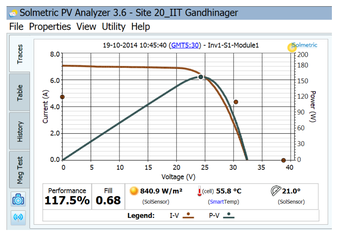
- The All India Survey of Photovoltaic Module Degradation 2014 [1] was undertaken to understand the degradation mechanisms of PV modules in different climatic zones in India.
- 1148 numbers of PV modules at 51 different sites, spread across 6 different climatic zones, were inspected. About 60% of surveyed modules are recently installed (less than 5 years old) and about 90% are crystalline silicon modules.
- Current-Voltage (*IV*) characterization and Infrared (IR) thermography were performed on the inspected modules, in addition to visual inspection, Electroluminescence imaging, interconnect breakage test, insulation resistance test etc. The analysis of the IR data and its correlation to electrical degradation is presented here.

Field Methodology

Current-Voltage (*IV*) Characterization

- Done using Solmetric PVA-1000S and PVPM *IV* tracers.
- POA irradiance, module temperature, ambient temperature and humidity recorded for analysis.

Solmetric *IV* tracer

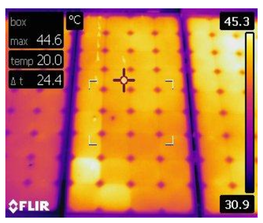


IV curve of a PV module

Infrared (IR) Thermography

- Module terminals were short-circuited and IR image is taken from back-side (where possible, else taken from the front).
- FLIR E-60 camera was used to take the IR images.

FLIR E-60 IR camera



IR image taken during survey

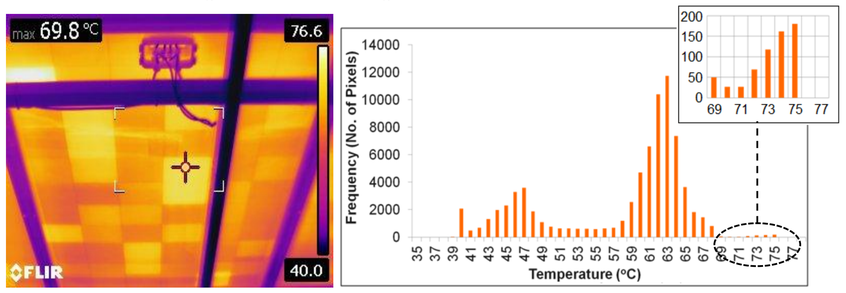
Data Analysis

Analysis of *IV* data

- The analysis of the *IV* data has been presented in details elsewhere by Dubey *et al.* [2], and only an overview is being presented here.
- The *IV* curves were translated to STC condition using a simplified version of **IEC 60891 translation procedure 1** (by assuming the series resistance and the curve correction factor as zero).
- Since module nameplates do not specify the actual measured power of the module but instead provide representative data with a tolerance band, the nominal power rating was calculated for each module, based on the average of the tolerance limits.
- The degradation rates were then calculated using the nominal ratings.

Analysis of IR data

- The temperature at different points of the PV modules are extracted from the IR images and a temperature histogram is plotted for each module, as shown below.
- The maximum temperature of the histogram is the maximum temperature observed in the module. The mode of the histogram is taken as the representative temperature for the module.



IR image of a 2 year old module and its temperature histogram

- Based on the works of Moreton *et al.* [3] and Oh *et al.* [4], the temperatures were normalized to 1000 W/m² irradiance and 40 °C ambient temperature, using the following relations:

$$T_{normalized} = 40 + \frac{(T_{measured} - T_{ambient}) \times 1000}{\text{Irradiance}}$$

Where, $T_{normalized}$ = translated (normalized) temperature

$T_{measured}$ = temperature obtained from IR image

$T_{ambient}$ = ambient temperature measured at site

- Above normalization was done only for modules having IR data at irradiances greater than 700 W/m² and IV data at irradiances greater than 500 W/m², to avoid excessive error in translation and the rest of the modules were screened out.
- The extent of mismatch in the temperature of different parts of the module has been quantified using the following relation:

$$\text{Module } \Delta T = T_{maxcell,norm} - T_{module,norm}$$

where,

$T_{maxcell,norm}$ = Normalized max. cell temperature of the module

$T_{module,norm}$ = Normalized modal temperature of the module

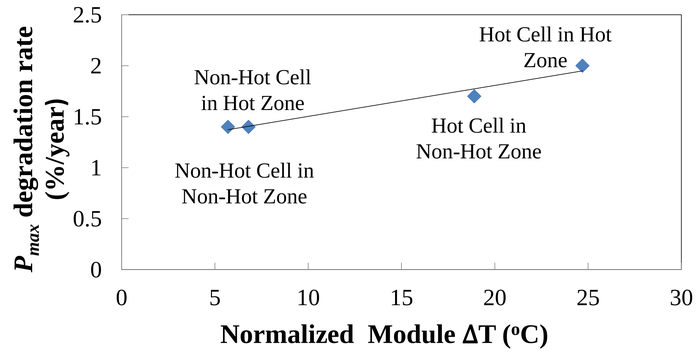
- We have considered modules having module ΔT greater than 10 °C as modules with "Hot Cells", based on Vodermayer *et al.* [5]. Also, the modules were grouped into two broad climate categories – Hot zone and Non-hot zone (mean monthly temperature less than 30 °C)

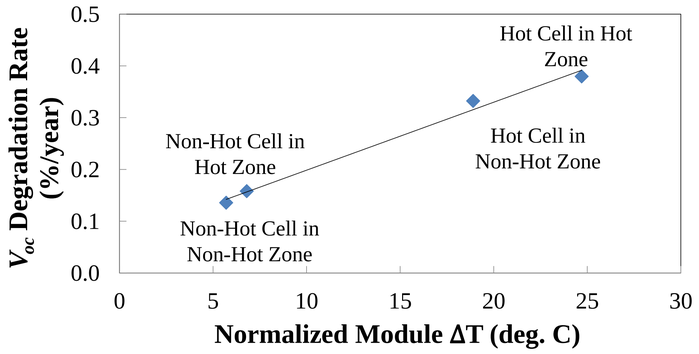
Results

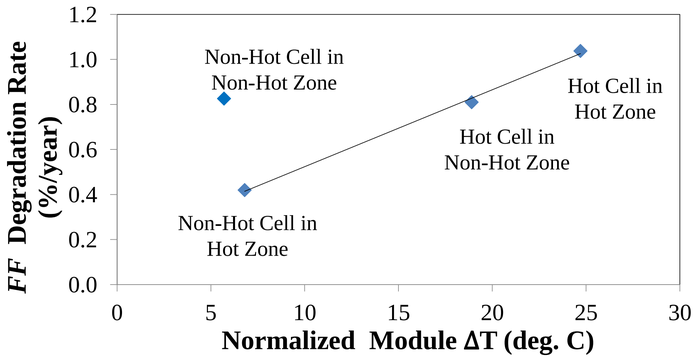
Effect of Hot Cells on Power Degradation Rate

Parameter (average of many samples)	**Hot zone**		**Non-Hot zone**	
	without Hot Cells	**with Hot Cells**	**Without Hot Cells**	**with Hot Cells**
Power degradation rate (%/year)	1.39	2.02	1.39	1.70
Normalized module ΔT (°C)	6.8	24.7	5.7	18.9
Normalized max. cell temperature (°C)	68.8	86.1	50.3	58.6
No. of Samples	10	18	14	17

Correlation of Electrical Degradation with Module ΔT







Conclusions

- Modules having Hot Cells are degrading faster than other modules, and this degradation is accelerated in the Hot Zone.
- The power degradation rate correlates well with the extent of mismatch in temperature of the module.
- The temperature mismatch in the module seems to degrade the open circuit voltage and the fill factor.

References

[1] S. Chattopadhyay *et al.*, "All India Survey of Photovoltaic Module Degradation 2014: Survey Methodology and Statistics", *42nd IEEE Photovoltaic Specialist Conference*, New Orleans, 2015.

[2] R. Dubey *et al.*, "Correlation of Electrical and Visual Degradation seen in Field Survey in India", submitted to *43rd IEEE Photovoltaic Specialists Conference*, Portland, 2016

[3] R. Moreton *et al.*, "Dealing in Practice with Hot Spots," in *Proceedings of the 29th European Photovoltaic Specialists Conference*, Amsterdam, 2014.

[4] J. Oh and G. TamizhMani, "Temperature Testsing and Analysis of PV modules per ANSI/UL 1703 and IEC 61730 standards", in *Proceedings of the 35th IEEE Photovoltaic Specialists Conference*, Honolulu, 2010.

[5] C. Vodermayer,*et al.*, "First Results – Correlations between IR images and Electrical Behaviour and Energy Yield of PV Modules", in *Proceedings of the 23rd European Photovoltaic Specialists Conference*, Spain, 2008.

Acknowledgements

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Potential Induced Degradation Testing in SERIS

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SERIS
Solar Energy Research Institute of Singapore

Introduction

- In Singapore, a PV module temperature can easily reach 60°C, with highest recorded value of 79°C. The average relative humidity is 81%.
- Conventional PID test as per IEC 62804 (with -1000V bias voltage, 60°C and 85% R.H. for 96 hours) is not sufficient for Singapore.
- For floating PV deployment, high salt concentration could contribute to PID and corrosion.
- SERIS developed and evaluated the salt mist PID test method for Singapore marine environment. Comparative results using commercial standard modules are shown below.

PID Test Method and Results

- **Conventional PID test as per IEC 62804 (**60°C**,** 85% R.H., -1000V, 96 hours**).** The maximum power of modules measured at STC before and after PID is summarized in Table 1. Both Modules degraded less than 5%.

	Before PID	After PID	Power Loss
M1	258.3W	246.8W	4.46%
M2	258.0W	245.9W	4.47%

Table 1: Module STC performance before and after IEC 62804 PID test

- **PID Testing in Salt Mist Chamber (**50°C**,** >95% R.H., -1000V, 112h**).** All four modules with applied voltage degraded significantly with more than 15% power loss.

	Before PID	After PID	Power Loss
M3	258.6W	221.5W	14.37%
M4	258.8W	208.0W	19.65%
M5	256.4W	214.5W	16.35%
M6	259.6W	218.5W	15.83%
M7 (Ref.)	258.0W	257.4W	0.23%

Table 2: Module STC performance before and after PID testing in salt mist chamber

- **Extended PID Testing in Salt Mist**

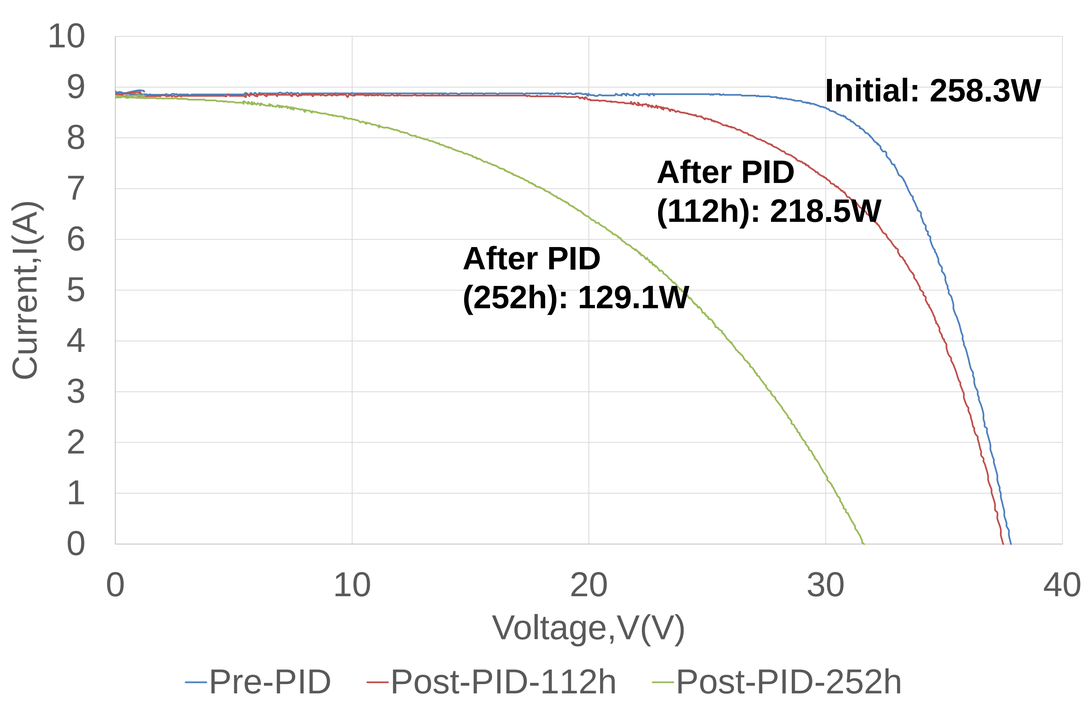

Figure 1: Module M6 I-V Measurements before and after PID in salt mist chamber

- **EL Imaging.** EL images were also captured. The damaged cells appeared as dark spots. Modules tested with salt mist PID showed more severe shunting.

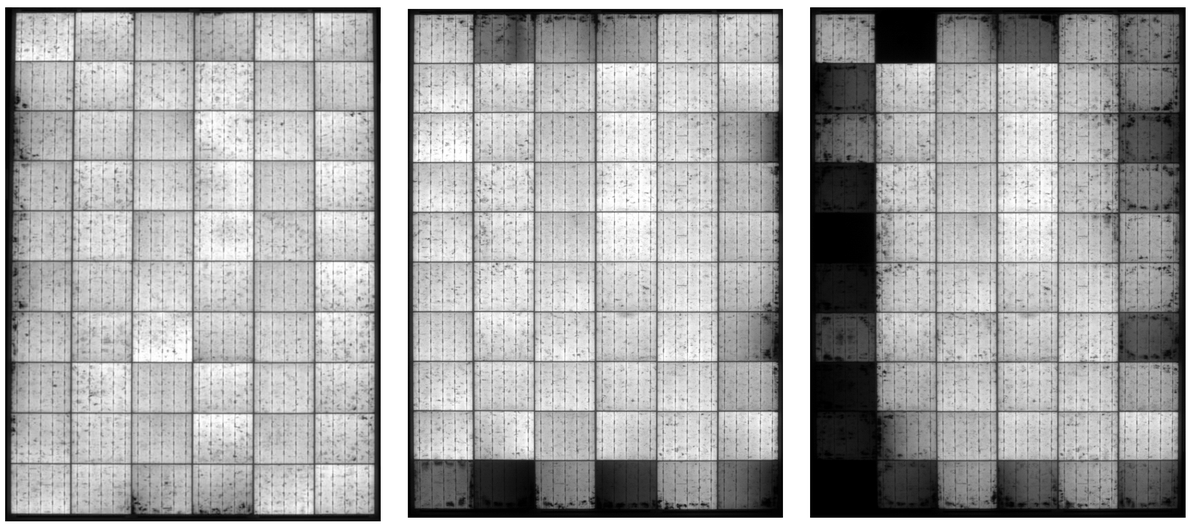

Figure 2: EL Images of modules tested with IE62804 (left), salt mist 112h (mid), and salt mist 252h (right)

In-Situ Dark I-V Measurement

- During salt mist PID test, M5 and M6 were continuously monitored through *in-situ* Dark I-V measurement.
- The dark I-V measured results correspond well with STC measurements.

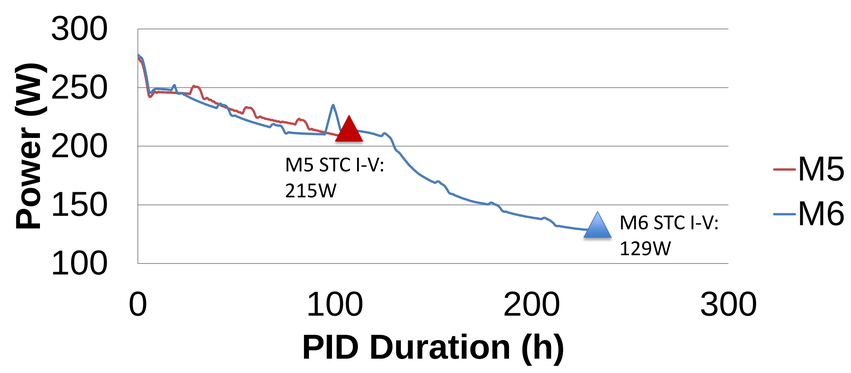

Figure 3: Continuous measurement of power using in-situ dark I-V for M5 and M6

Outdoor PID Testing Facility

- Bias voltage was applied to modules working at MPP in outdoor.
- System was up and running since January 2016. Outdoor testing results will be shared during next year's workshop.

Figure 4: Outdoor PID testing facility at SERIS, Singapore

Conclusions

- Salt mist PID testing, which is of relevance to Singapore and coastal installations, accelerates power degradation,.
- PID affects module's fill factor and open-circuit voltage significantly.
- Dark I-V is a promising method for continuous monitoring of module power during PID testing.

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NUS National University of Singapore

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CENTER FOR SUSTAINABLE ENERGY SYSTEMS CSE

Photovoltaic Durability Initiative (PVDI) Long Term Outdoor Exposure Update

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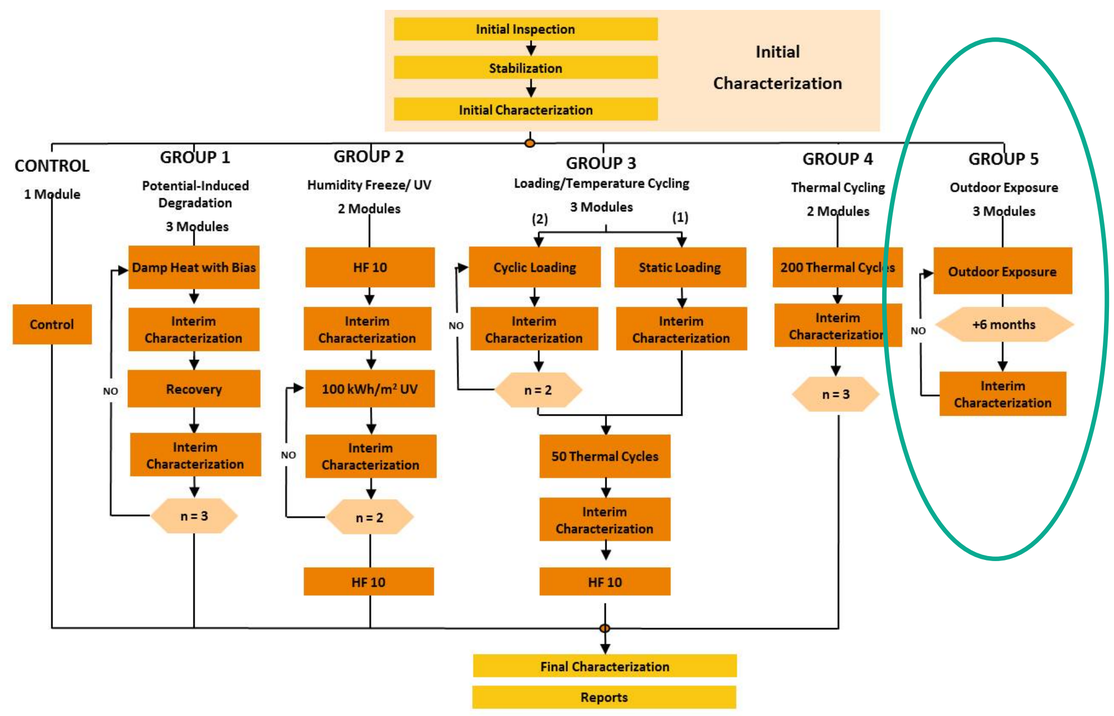
INTRODUCTION

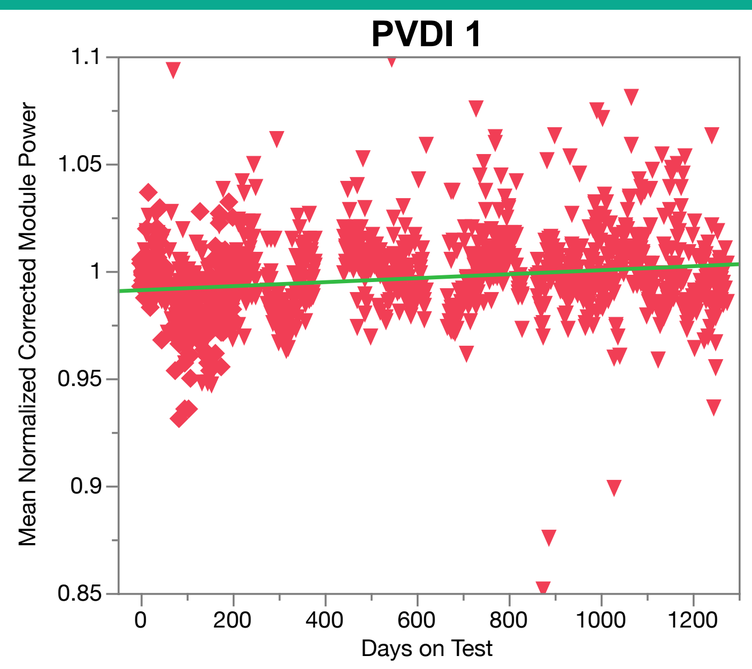
A goal of the PVDI project is to provide a PV module durability assessment program with worldwide participation and acceptance. In this program, a rating of PV modules relative to their likelihood to perform reliably over their rated service life is provided. Modules are subjected to accelerated stress testing intended to reach the wear-out regime for a given set of environmental conditions. In parallel with the accelerated tests, modules are subjected to long-term outdoor exposure; the correlation between the accelerated tests and actual operation in the field is an ultimate goal of the program.

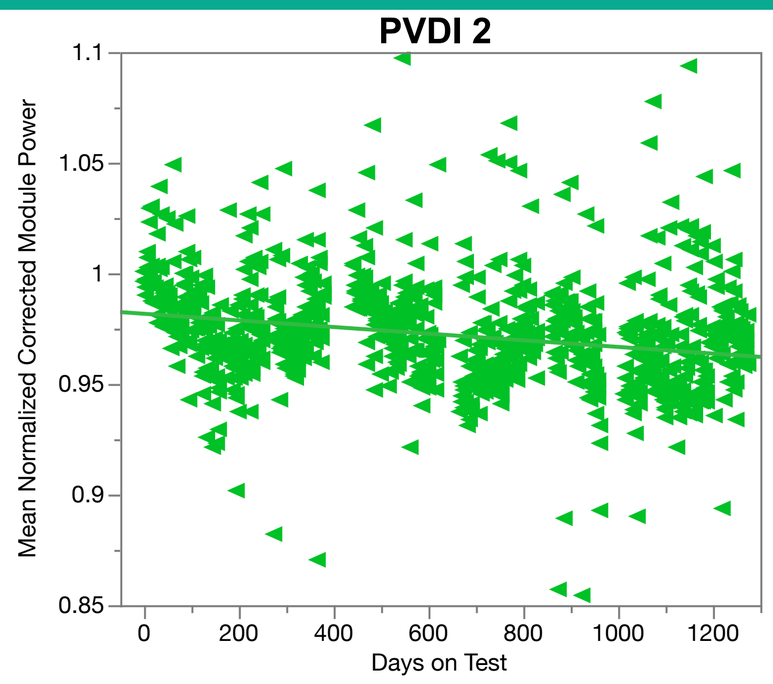
After three and a half years of outdoor data there exists enough data to provide a general update on the outdoor performance of the first five modules in the PVDI program. A set of each module type are fielded in Fraunhofer CSE's Outdoor Test Lab in Albuquerque, NM. They are continually I-V tested and biased at their maximum power point between measurements.

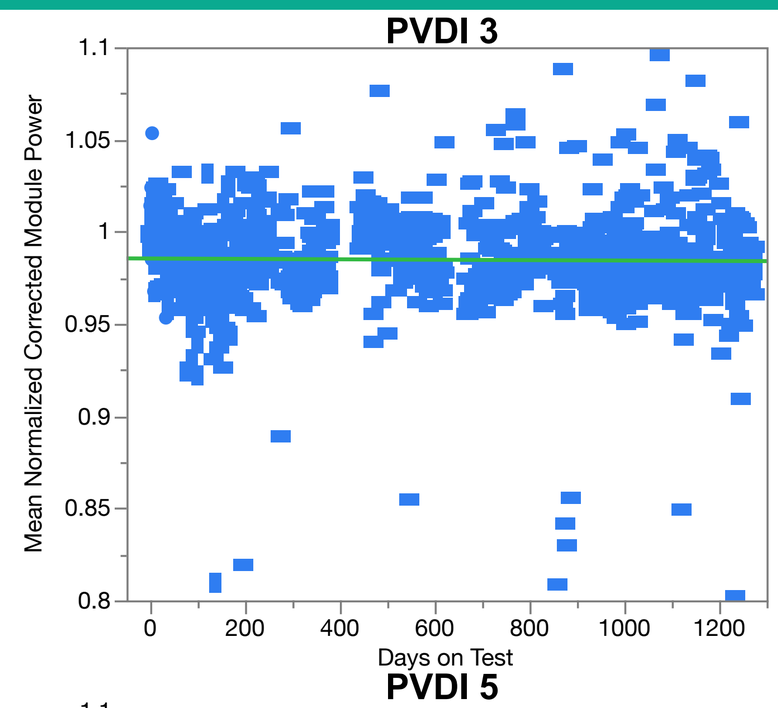
TEST FLOW

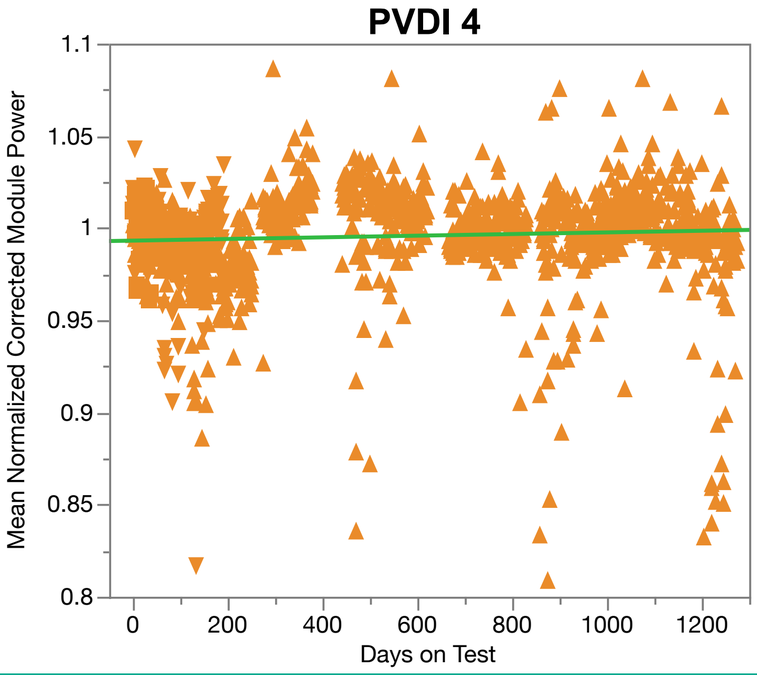


LONG TERM OUTDOOR EXPOSURE SUMMARY DATA



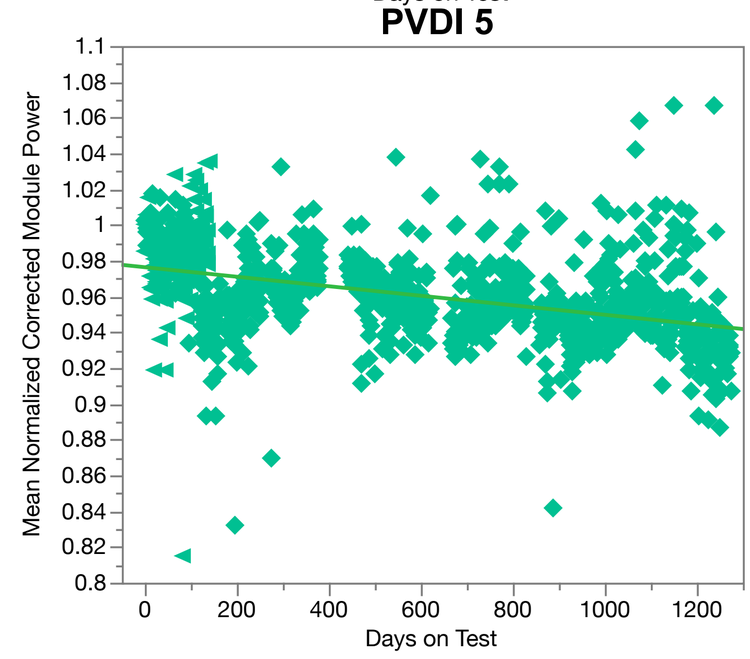






PVDI ID	Normalized Intercept	Slope ($*10^{-6}$)	Projected Yearly Degradation Rate
1	0.991	9.30	+0.34%
2	0.982	-15.0	-0.54%
3	0.985	-1.09	-0.04%
4	0.993	4.46	+0.16%
5	0.976	-26.6	-0.97%

A summary of the linear fit equations relative to days on test of each module. The calculation of a projected yearly degradation rate is based on the slope of the fit



ANALYSIS METHOD

- Initial module performance is used as a baseline performance
- All power measurements are normalized to this baseline
- A linear regression line characterizes a daily degradation rate
- Daily rate (slope) is scaled to provide a yearly degradation rate

CONCLUSIONS

- Only two modules, PVDI 2 and 5 displayed any quantifiable degradation over the 3.5 year duration
- All five Tier 1 modules that are participating in the first round of PVDI have less than a 1% yearly degradation rate so far

An Update on IEC 61730 – PV Module Safety Qualification

Christopher Flueckiger
Principal Engineer – Renewable Energy

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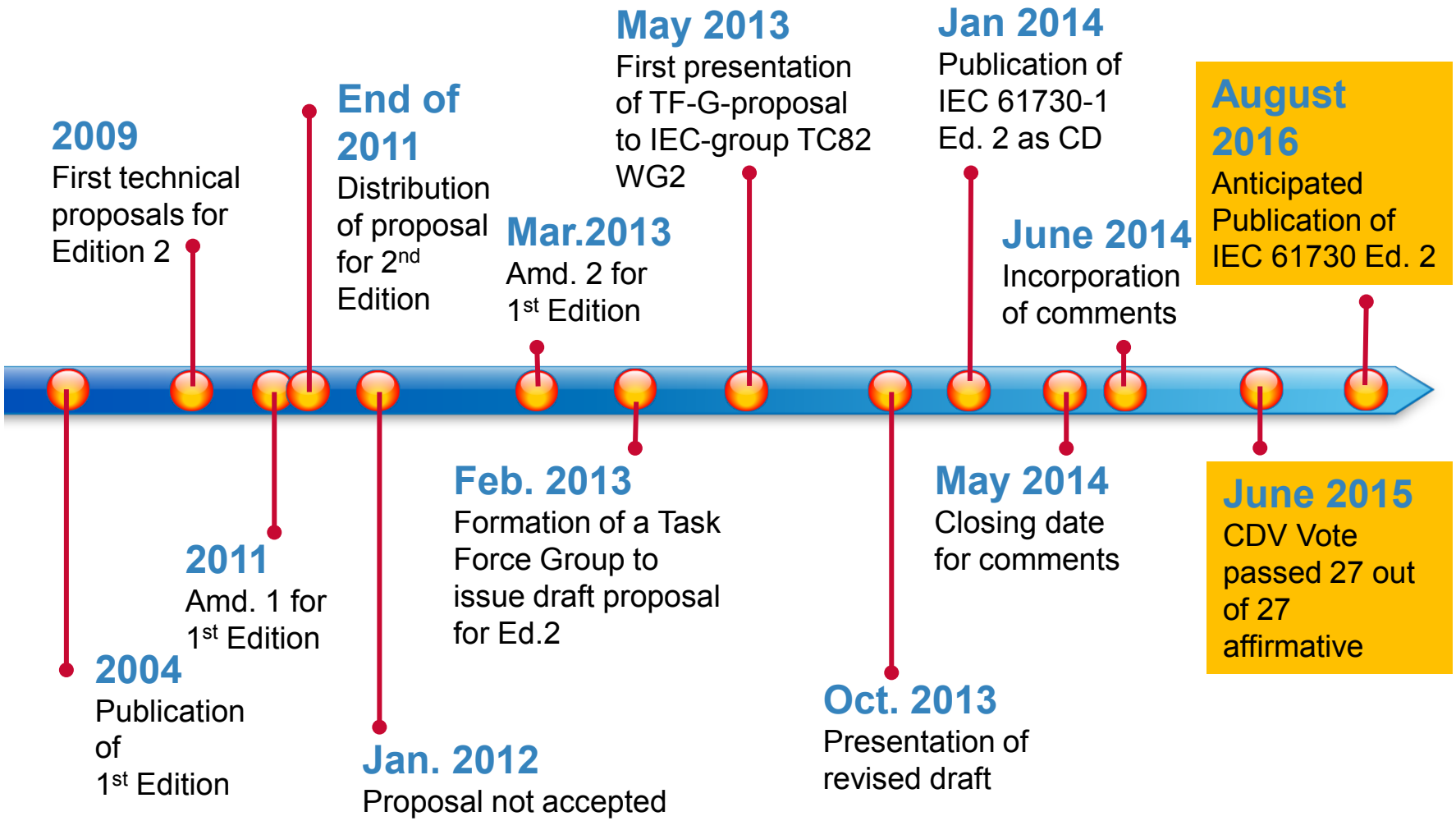
Development of 61730



Adapted from: IEC 61730 Series update, Guido Volberg, Joerg Althaus, Gerhard Kleiss, Peter Seidel, Markus Beck, Arnd Roth, Eguchi Yoshihito, Chris Flueckiger and Bengt Jaeckel

Introducing Horizontal Standards

IEC definition of a horizontal standard:

•fundamental principles, concepts, terminology, or technical characteristics

•relevant to a number of technical committees, and

•critical to ensure the coherence of standardization documents

Horizontal standards are assigned by the Standardization Management Board (SMB) with the purpose of:

•Ensuring the coherence of standardization documents

•Avoiding duplication of work and contradictory requirements

•Meet IEC Guide 108 “Guidelines for ensuring the coherency of IEC publications – Application of horizontal standards

Main concepts for use in PV

1. Insulation Coordination
2. Overvoltage Category
3. Classes
4. Pollution degree (PD)
5. Material Groups (MG)

Taken from: IEC 61730 Series update, Guido Volberg, Joerg Althaus, Gerhard Kleiss, Peter Seidel, Markus Beck, Arnd Roth, Eguchi Yoshihito, Chris Flueckiger and Bengt Jaeckel

Clearance and Creepage in First Edition

Table 3 – Minimum acceptable creepage and clearance distances between field wiring terminals

Voltage V	mm
0 – 50	6,5
51 – 300	9,5
301 – 600	12,5
601 – 1 000	16
1 001 – 1 500	25

Table 4 – Minimum acceptable clearance distances between internal current-carrying parts and accessible points

Maximum system voltage V	Clearance mm		
	Class C	Class B	Class A
0 – 50	2	2	2
51 – 300		3,2	6,4
301 – 600		3,2	6,4
601 – 1 000		4,2	8,4
1 001 – 1 500		8	11

Clearance and Creepage in 2nd Edition (part 1)

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1359

Table 3 – Distances through insulation, creepage distances (cr) and clearances (cl) for Class II PV modules

	pollution degree	Distances in mm																													
		≤35 V DC [a,d]				100 V DC [a]				150 V DC [a]				300 V DC [a]				600 V DC [a]				1 000 V DC [a]				1 500 V DC [a]			
		cl	cr			cl	cr			cl	cr			cl	cr			cl	cr			cl	cr			cl	cr		
			Material group				Material group				Material group				Material group				Material group				Material group				Material group		
Between			I	II	III		I	II	III		I	II	III		I	II	III		I	II	III		I	II	III		I	II	III
1a) Internal live parts and outer accessible surfaces	1	0,5 [b, c]	0,4			1,5 [b]	0,5			3,0 [b]	0,6			5,5 [b]	1,4			8,0 [b]	3,4			14,0 [b]	6,4			19,4 [b]	10,4		
	2		1,2	1,7	2,4		1,4	2,0	2,8		1,6	2,2	3,1		3,0	4,2	6,0		6,1	8,6	12,0		10,0	14,2	20,0		15,0	20,8	30,0
	3		3,0	3,4	3,8		3,6	4,0	4,4		3,9	4,3	4,9		7,5	8,5	9,4		15,2	17,1	19,1		25,0	28,0	32,0		37,7	41,7	47,1
1b) Thickness of thin layers (see 5.6.4.3)	-	0,01				0,01				0,01				0,01				0,06				0,15				0,3			
2) Live parts of different potential inside a PV module	1	0,1	0,2			0,5 [b, c]	0,3			1,5 [b]	0,3			3,0 [b]	0,7			5,5 [b]	1,7			8,0 [b]	3,2			11,0 [b]	5,2		
	2	0,2	0,6	1,0	1,2		0,7	1,0	1,4		0,8	1,1	1,6		1,5	2,1	3,0		3,0	4,3	6,0		5,0	7,1	10,0		7,5	10,4	15,0
	3	0,8	1,5	1,7	1,9		1,8	2,0	2,2		2,0	2,2	2,5		3,8	4,2	4,7		7,6	8,6	9,5		12,5	14,0	16,0		18,9	20,9	23,6
3) Terminals of different polarity of rewireable junction boxes	1	0,5 [b, c]	0,4			1,5 [b]	0,5			3,0 [b]	0,6			5,5 [b]	1,4			8,0 [b]	3,4			14,0 [b]	6,4			19,4 [b]	10,4		
	2		1,2	1,7	2,4		1,4	2,0	2,8		1,6	2,2	3,1		3,0	4,2	6,0		6,1	8,6	12,0		10,0	14,2	20,0		15,0	20,8	30,0
	3		3,0	3,4	3,8		3,6	4,0	4,4		3,9	4,3	4,9		7,5	8,5	9,4		15,2	17,1	19,1		25,0	28,0	32,0		37,7	41,7	47,1
4) Distance through cemented joints	-	0,2				0,3				0,5				1,0				1,5				2,0				3,5			

[a] For lines 1a), 1b), 3) and 4) the relevant voltage which is applicable shall be the system voltage. For line 2) the working voltage between parts of different potential at STC is relevant. All values given in this table are rounded to one digit from IEC 60664-1.

[b] If a measured clearance is smaller than the minimum required clearance an impulse voltage test as specified in IEC 60664-1 shall show that the distance is adequate. To assess clearances between internal live parts and outer accessible surfaces IEC 61730-2, MST 14 may be applied.

[c] This value is increased to 0,8 mm for pollution degree 3.

[d] For designs where working voltage is below 20 V values directly from IEC 60664-1 can be applied

Introducing Horizontal Standards

Source of values for Table 3:

Values for creepage distances for lines 1a) and 3) are extracted from Table F.4 of **IEC 60664-1**, doubled for reinforced insulation according to rules of section 5.2.4 of **IEC 60664-1**.

Values for creepage distances for line 2) are extracted from Table F.4 of **IEC 60664-1** (for basic insulation).

Values for clearences for lines 1a), 2) and 3) are extracted from Table F.2 of **IEC 60664-1** for condition A (inhomogeneous field). The values for 2) are determined according to relevant impulse voltage of overvoltage category III, those for lines 1a) and 3) are evaluated or calculated according to section 5.1.6 of **IEC 60664-1** (one step higher in preferred values of impulse voltages, for system voltage of 1500 V d.c. 160% of value for basic insulation).

Taken from: IEC 61730 Series update, Guido Volberg, Joerg Althaus, Gerhard Kleiss, Peter Seidel, Markus Beck, Arnd Roth, Eguchi Yoshihito, Chris Flueckiger and Bengt Jaeckel

Clearance and Creepage in 2nd Edition (part 2)

1360 **Table 4 – Distances through insulation, creepage distances (cr) and clearances (cl) for Class 0 and class III PV modules**

Between	pollution degree	Distances in mm																												
		≤35 V DC [a, d, e]				100 V DC [a]				150 V DC [a]				300 V DC [a]				600 V DC [a]				1 000 V DC [a]				1 500 V DC [a]			
		cl	cr Material group			cl	cr Material group			cl	cr Material group			cl	cr Material group			cl	cr Material group			cl	cr Material group			cl	cr Material group		
			I	II	III		I	II	III		I	II	III		I	II	III		I	II	III		I	II	III		I	II	III
1a) Internal live parts and outer accessible surfaces	1	0,1	0,2			0,5 [b, c]	0,3			1,5 [b]	0,3			3,0 [b]	0,7			5,5 [b]	1,7			8,0 [b]	3,2			11,0 [b]	5,2		
	2	0,2	0,6	1,0	1,2		0,7	1,0	1,4		0,8	1,1	1,6		1,5	2,1	3,0		3,0	4,3	6,0		5,0	7,1	10,0		7,5	10,4	15,0
	3	0,8	1,5	1,7	1,9		1,8	2,0	2,2		2,0	2,2	2,5		3,8	4,2	4,7		7,6	8,6	9,5		12,5	14,0	16,0		18,9	20,9	23,6
1b) Thickness of thin layers (see 5.6.4.3)	-	0,01				0,01				0,01				0,01				0,06				0,15				0,3			
2) Live parts of different potential inside a PV module	1	0,1	0,2			0,5 [b, c]	0,3			1,5 [b]	0,3			3,0 [b]	0,7			5,5 [b]	1,7			8,0 [b]	3,2			11,0 [b]	5,2		
	2	0,2	0,6	1,0	1,2		0,7	1,0	1,4		0,8	1,1	1,6		1,5	2,1	3,0		3,0	4,3	6,0		5,0	7,1	10,0		7,5	10,4	15,0
	3	0,8	1,5	1,7	1,9		1,8	2,0	2,2		2,0	2,2	2,5		3,8	4,2	4,7		7,6	8,6	9,5		12,5	14,0	16,0		18,9	20,9	23,6
3) Terminals of different polarity of rewireable junction boxes	1	0,5 [b, c]	0,4			1,5 [b]	0,5			3,0 [b]	0,6			5,5 [b]	1,4			8,0 [b]	3,4			14,0 [b]	6,4			19,4 [b]	10,4		
	2		1,2	1,7	2,4		1,4	2,0	2,8		1,6	2,2	3,1		3,0	4,2	6,0		6,1	8,6	12,0		10,0	14,2	20,0		15,0	20,8	30,0
	3		3,0	3,4	3,8		3,6	4,0	4,4		3,9	4,3	4,9		7,5	8,5	9,4		15,2	17,1	19,1		25,0	28,0	32,0		37,7	41,7	47,1
4) Distance through cemented joints	-	0,1				0,2				0,25				0,5				0,7				1,0				1,7			

[a] For lines 1a), 1b), 3) and 4) the relevant voltage which is applicable shall be the system voltage. For line 2) the working voltage between parts of different potential at STC is relevant. All values given in this table are rounded to one digit from IEC 60664-1.

[b] If a measured clearance is smaller than the minimum required clearance an impulse voltage test as specified in IEC 60664-1 shall show that the distance is adequate. To assess clearances between internal live parts and outer accessible surfaces IEC 61730-2, MST 14 may be applied.

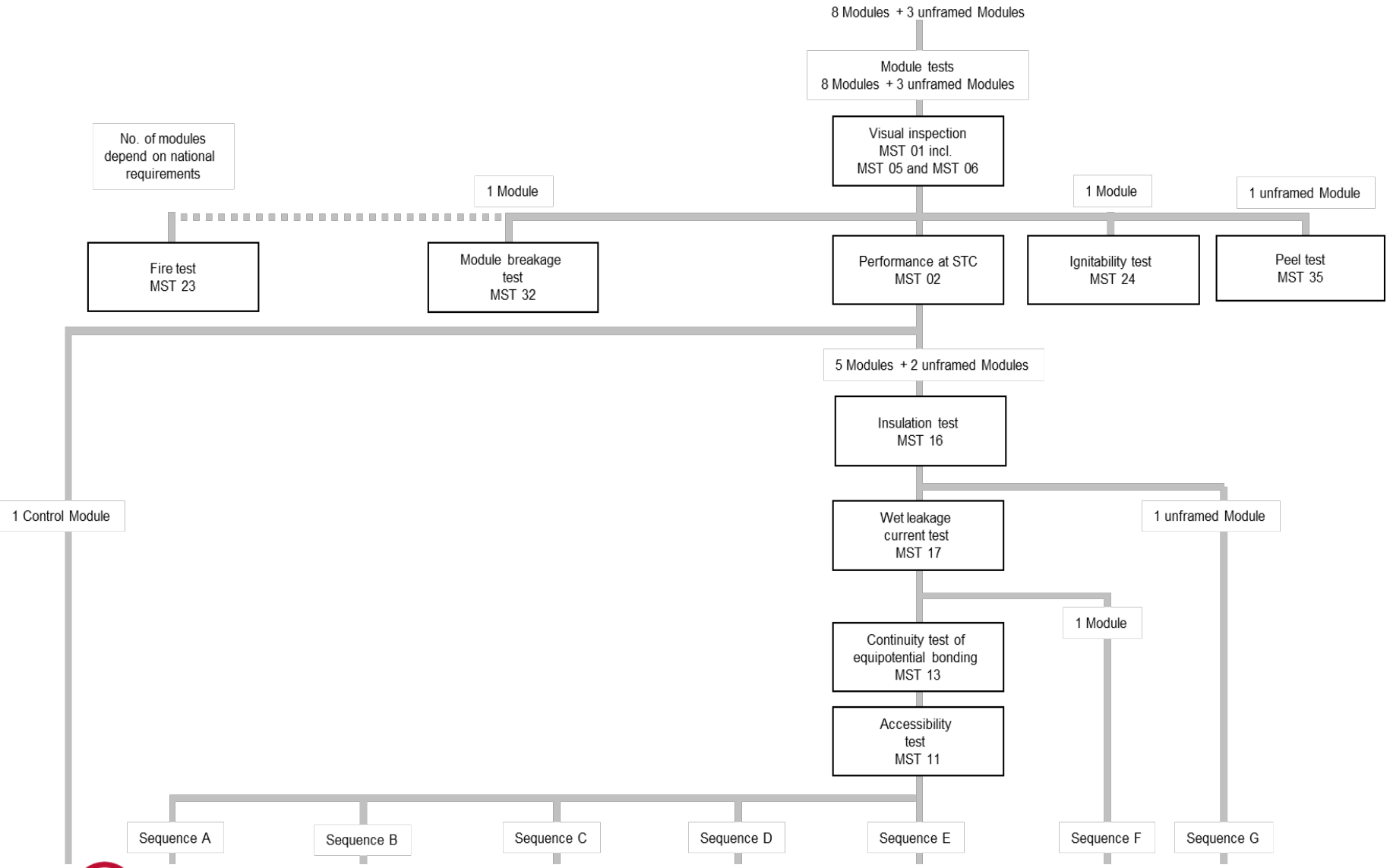
[c] This value is increased to 0,8 mm for pollution degree 3.

[d] For class III PV modules only this column (≤ 35V) and lines 2) and 3) apply.

[e] For designs where working voltage is below 20 V values directly from IEC 60664-1 can be applied

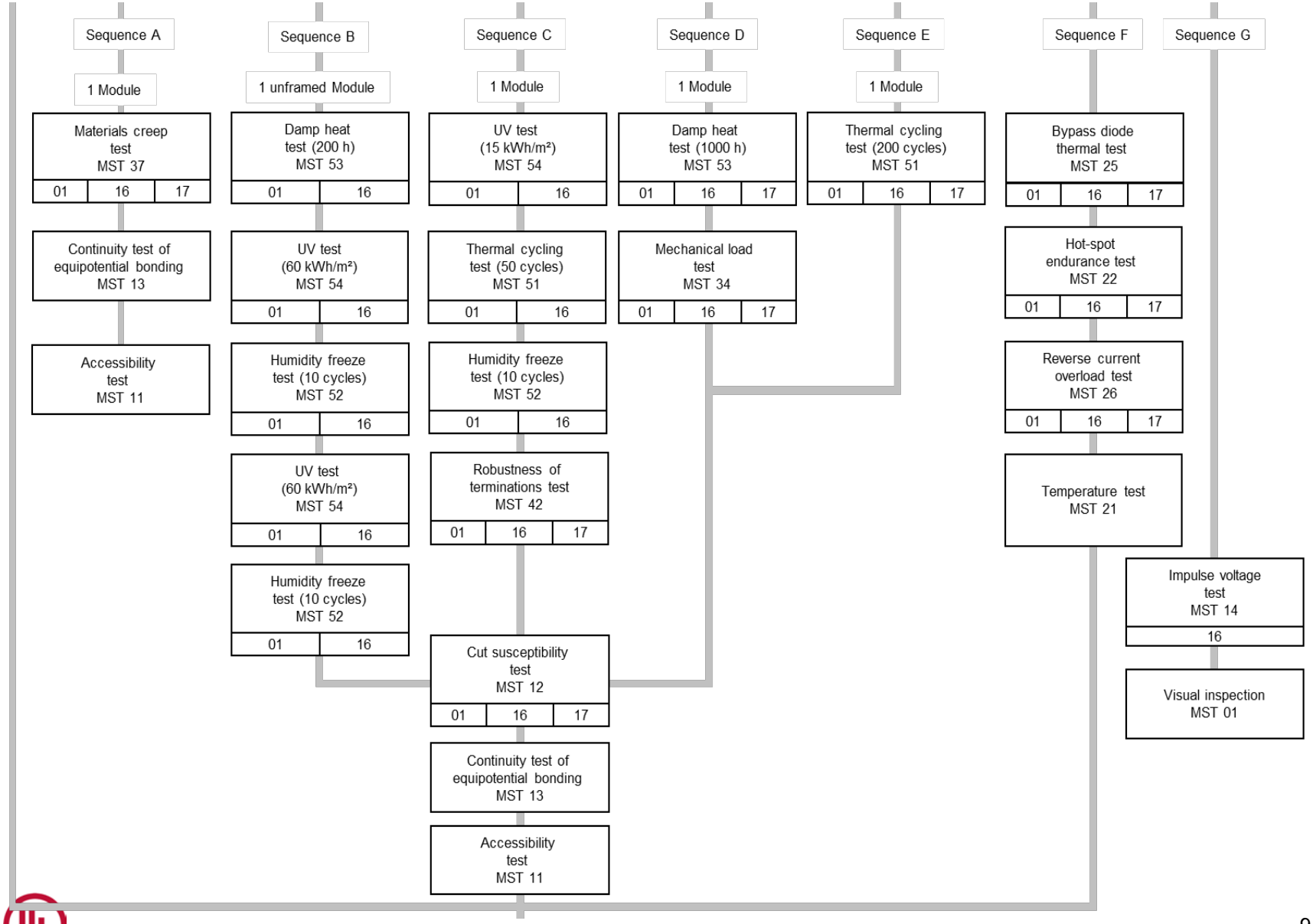
1361

61730-2 Test Flow



Taken from: ROADMAP IEC 61730, Guido Volberg, Joerg Althaus, Gerhard Kleiss, Peter Seidel, Markus Beck, Arnd Roth and Bengt Jaeckel

61730-2 Test Flow



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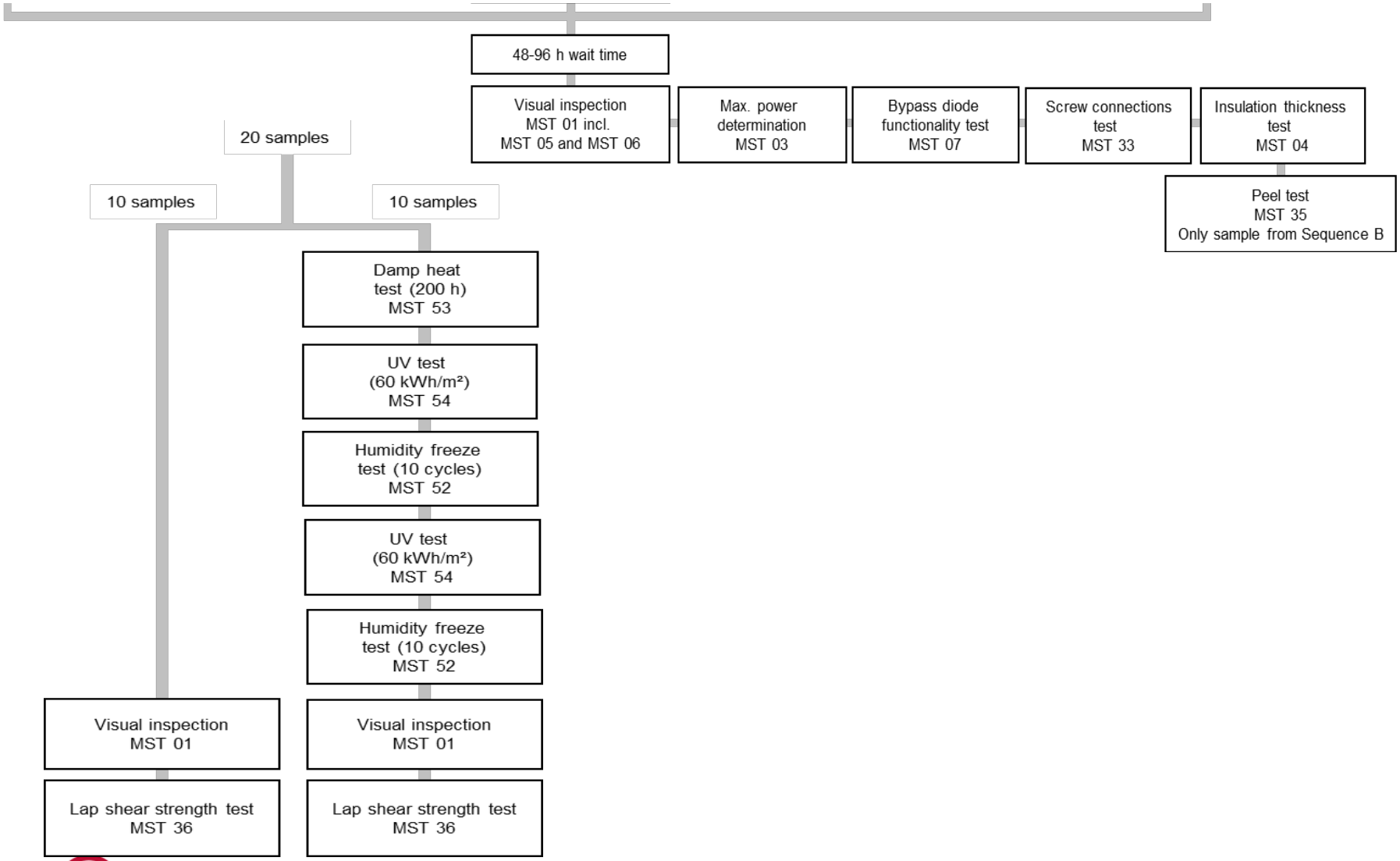
61730-2 Test Flow



Taken from: ROADMAP IEC 61730, Guido Volberg, Joerg Althaus, Gerhard Kleiss, Peter Seidel, Markus Beck, Arnd Roth and Bengt Jaeckel

61730-2 New Sequence

Sequence for subsequent Peel Test, etc.

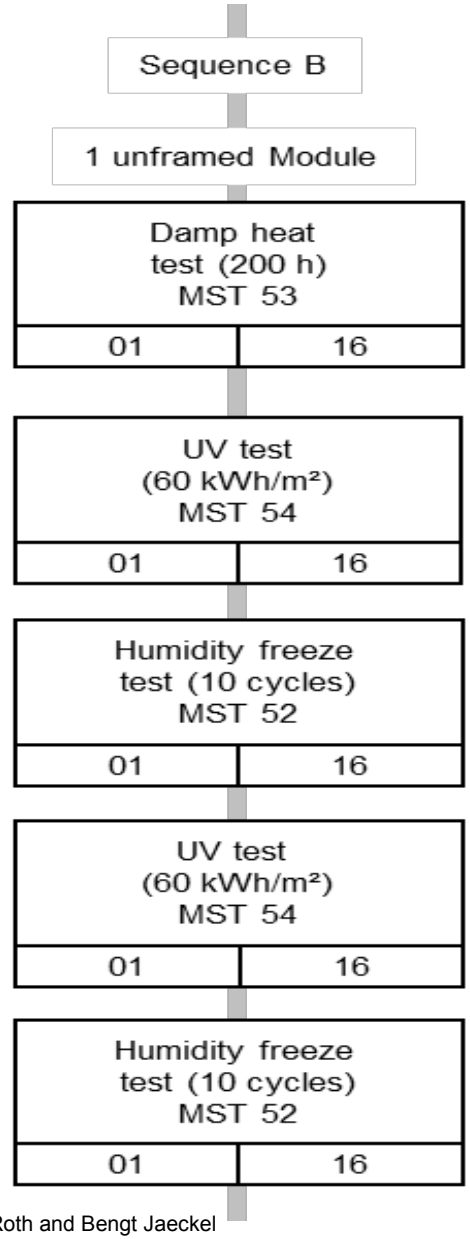
No module level weathering feasible

Coupon testing not representative

Use of existing test methods and equipment for sequential approach

- Wetted samples (200 hrs DH)
- UV stress (samples dries out)
- Humidity and temp. cycles
- UV stress (sample dries out)
- Humidity and temp. cycles

- UV/HF is known to stress polymers and adhesion



Taken from: ROADMAP IEC 61730, Guido Volberg, Joerg Althaus, Gerhard Kleiss, Peter Seidel, Markus Beck, Arnd Roth and Bengt Jaeckel

Summary

- **61730-1 and -2 currently in translation for FDIS**
- **Expectation is that the documents will be published in August of this year**
- **US Harmonization efforts are underway, with John Wohlgemuth chairing the US Harmonization Committee of the UL 1703 STP**
- **Harmonized document(s) anticipated to be published end of 2016/1st quarter 2017 with an effective date TBD**

Other US National Standard Adoption

New STP Formed:

- **IEC 62446 series Grid connected photovoltaic systems - Minimum requirements for system documentation, commissioning tests and inspection**
- **IEC 62093 Balance-of-system components for photovoltaic systems - Design qualification natural environments**

UL 1741 STP

- **IEC 62891 Indoor testing, characterization and evaluation of the efficiency of photovoltaic grid-connected inverters**
- **IEC 62509 Battery charge controllers for photovoltaic systems - Performance and functioning**

New STPs in process of development

- **IEC 62738 Design guidelines and recommendations for photovoltaic power plants**
- **IEC 62548 Photovoltaic (PV) arrays - Design requirements**
- **IEC 61724 Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis**

We Need Your Assistance!

We are soliciting members to participate in the STPs for the following Adoptions:

- **IEC 62738 Design guidelines and recommendations for photovoltaic power plants**
- **IEC 62548 Photovoltaic (PV) arrays - Design requirements**
- **IEC 61724 Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis**

Please contact:

Christopher Flueckiger
Christopher.flueckiger@ul.com

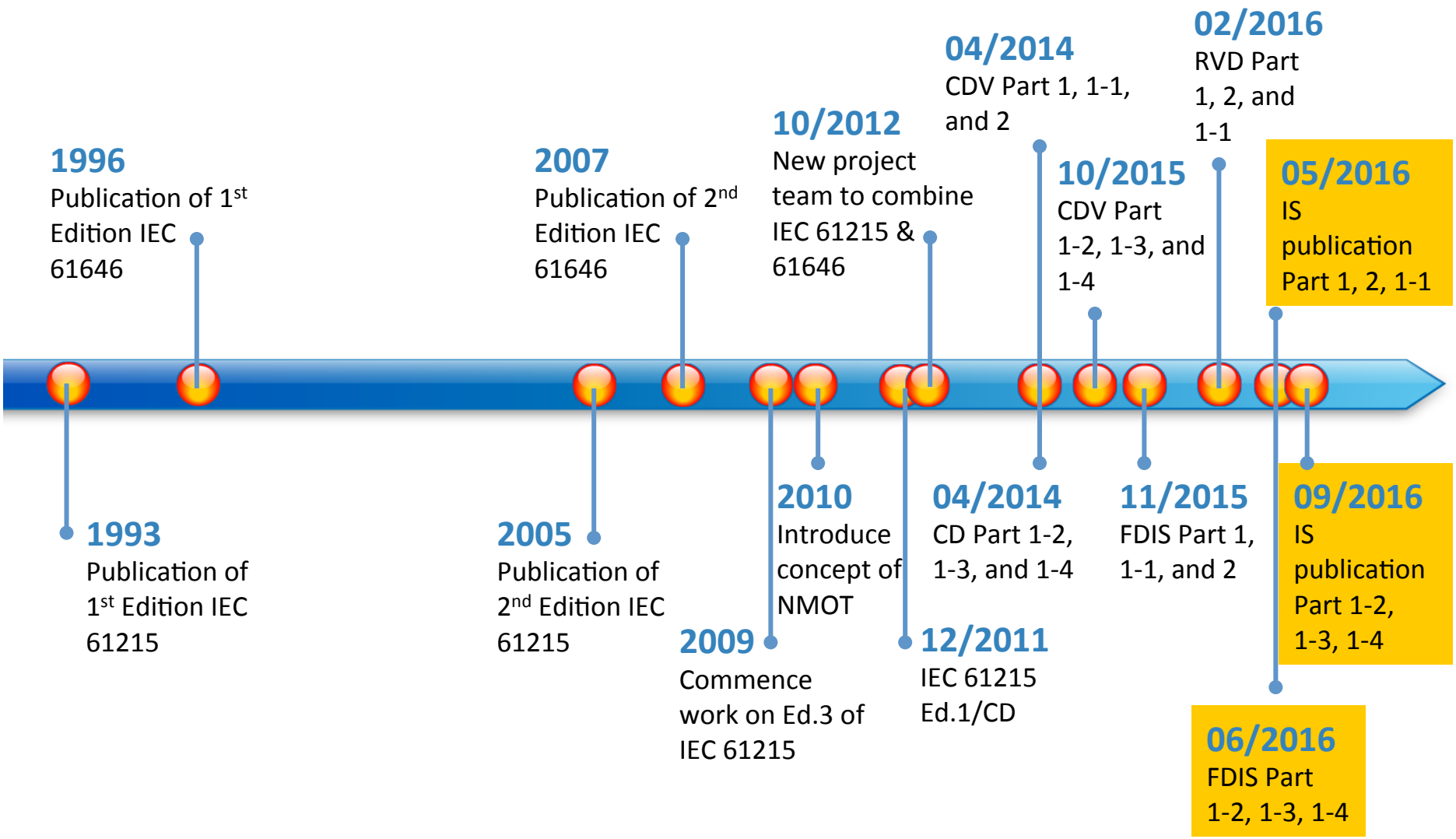
PV Module Design Qualification & Type Approval – NEW IEC 61215 Series

Markus Beck (Siva Power), Arnd Roth (VDE), Bengt Jaeckel (UL), Peter Seidel (First Solar), Jörg Althaus (TÜV Rheinland), Guido Volberg (TÜV Rheinland), and Gerhard Kleiss (Solar World)

Introduction

- Commercial success of PV modules strongly dependent on module long-term reliability:
  - Compete with investment horizon of traditional sources of electricity ≥ 30 years
  - Predictable module performance – annual degradation rate; voltage & power temperature coefficients; spectral and intensity dependency of current, voltage & power
  - Climatic dependency – e.g. hot & humid, hot & dry, moderate
  - Typical PV module warranties today 20-25 years
  - 2015 utility-scale module ASP $0.58/W – 42% of total system cost
  - PV modules mostly qualified to IEC 61215 or IEC 61646 "Type Approval Standards"
- Module Quality Tests (MQT) tests have shown to adequately identify design, material, and process flaws that could lead to premature field failures
  - Accelerated stress testing
  - Customers have come to appreciate the criticality of tests set forth in IEC 61215 & 61646
- New IEC 61215 series
  - Over the past 3½ years Working Group 2 (WG2) within IEC Technical Committee 82 for Solar Photovoltaic Energy Systems (TC82) updated and merged the terrestrial PV module design qualification and type approval standards into a single IEC 61215 series.

History of IEC 61215 & 61646

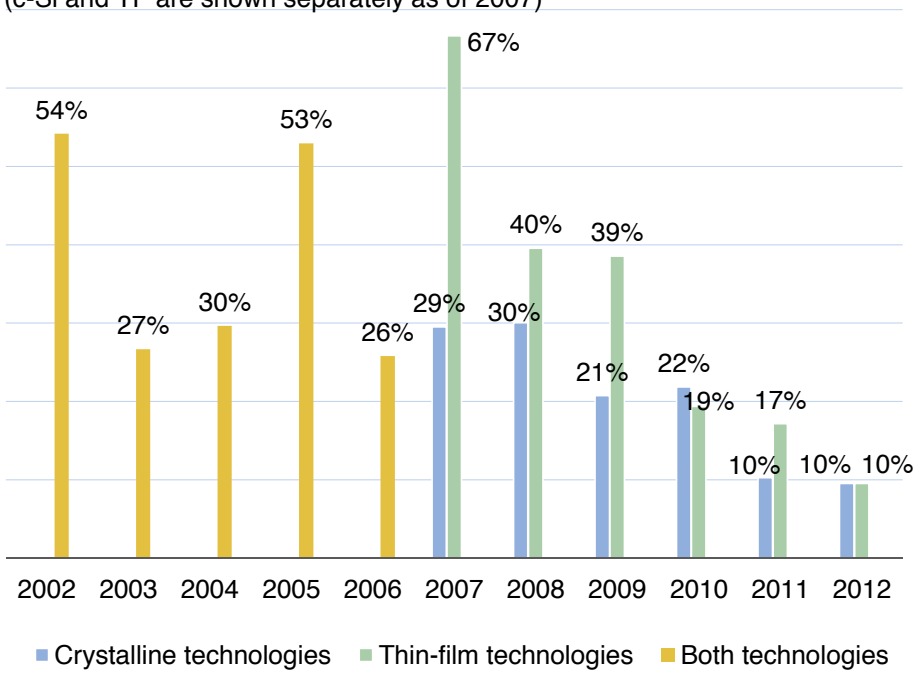


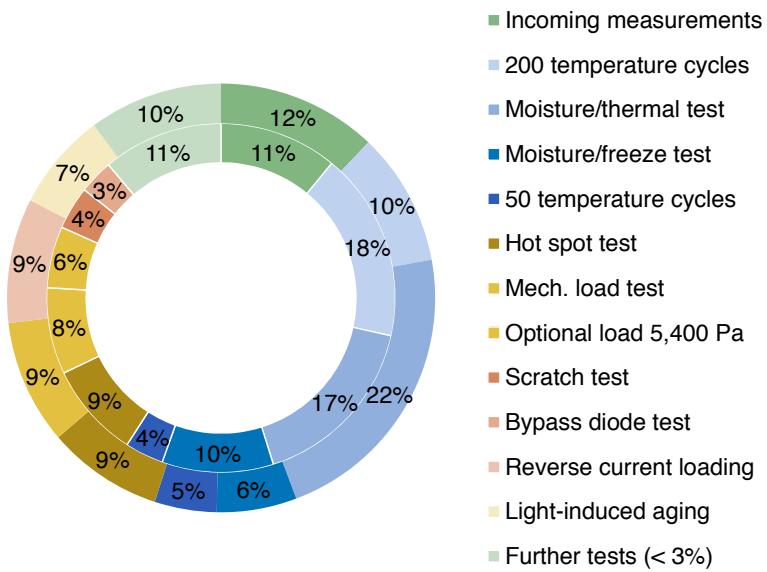
IEC 61215 & IEC 61646

- Define a minimum set of specific requirements a PV module design needs to meet
- Resulted in a significant reduction in module field failures
  - Screen out design flaws leading to infant mortality
  - PV modules tend to be the most reliable components in PV systems

Failure Statistics from Module Certification

2,000 certification projects in Germany from 2002 to 2012
(c-Si and TF are shown separately as of 2007)





TÜV Rheinland – Solar 2013 Quality Monitor – June 19, 2013

IEC 61215 & IEC 61646

- Define a minimum set of specific requirements a PV module design needs to meet
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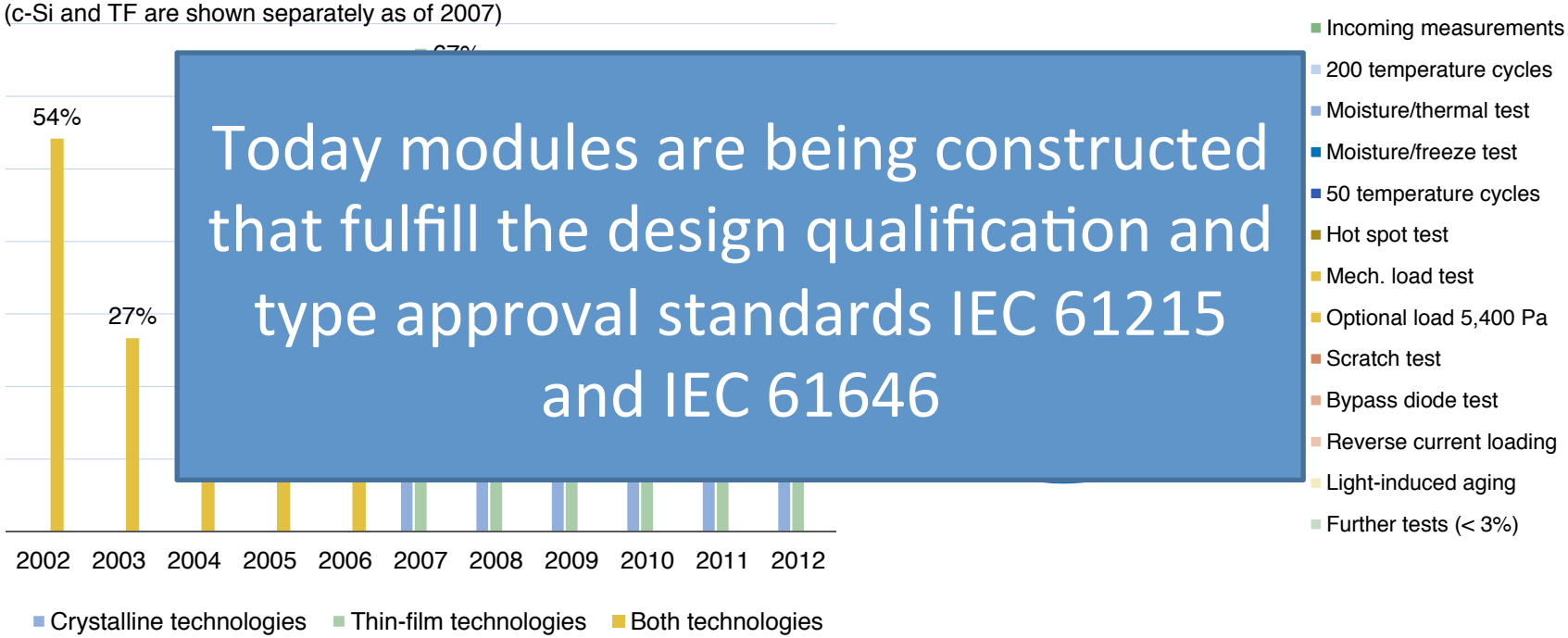


Today modules are being constructed that fulfill the design qualification and type approval standards IEC 61215 and IEC 61646

TÜV Rheinland – Solar 2013 Quality Monitor – June 19, 2013

Objectives and Motivation

- Merge today's IEC 61215 Ed. 2 & IEC 61646 Ed. 2 into a single standard:
  - Harmonize tests (e.g. UV-test) and procedures (continuity vs. current) for crystalline Si and TF technologies
  - Unified requirements for all module types
  - Enhance transparency of testing requirements and criteria
  - One sole 'identifier' for stakeholders not too familiar with the underlying technologies

➡ **One hurdle with same height to be passed by all PV modules**

- Make standard structure consistent with other IEC standards:
  - Part 1 requirements for testing
    - Subsequent PV technology specific parts
  - Part 2 defines all tests or reference standards
  - MQT = Module Quality Test to differentiate to MST (Module Safety Test in IEC 61730)
- Unified test conditions for all non-technology specific severities
  - E.g. continuity, UV
- Enable more flexibility, faster response to changes in any given technology
  - Stabilization procedures for thin film modules
  - Integration of Organic-PV (OPV)
- Provides foundation for application specific requirements
  - Free-filed vs. roof top
  - Climatic regions

Layout of the new Standard series

Today's status

IEC 61215 Ed 2 requirements

IEC 61215 Ed 2 tests

IEC 61646 Ed 2 requirements

IEC 61646 Ed 2 tests

Retesting Guidelines for Photovoltaic

New IEC 61215 series ed.1

Part 1 – General requirements

- Part 1-1 c-Si
- Part 1-2 CdTe
- Part 1-3 a-Si & µ-Si
- Part 1-4 CIS&CIGS
- ⋮
- Part 1-n New Technologies – e.g. OPV
- Part 1-x Rooftop
- ⋮
- Part 1-z Application / Climate Specific

Part 2 – Test procedures

IEC 62915 TS – Retesting requirements for Photovoltaic

Test Nomenclature

Introduction of:

Module **Q**uality **T**ests (MQT) → IEC 61215 Type Approval

to differentiate from

Module **S**afety **T**ests (MST) → IEC 61730 Safety requirements

Test have been renamed: Former test nomenclature 10.xx now as MQT xx (Module Quality Test)

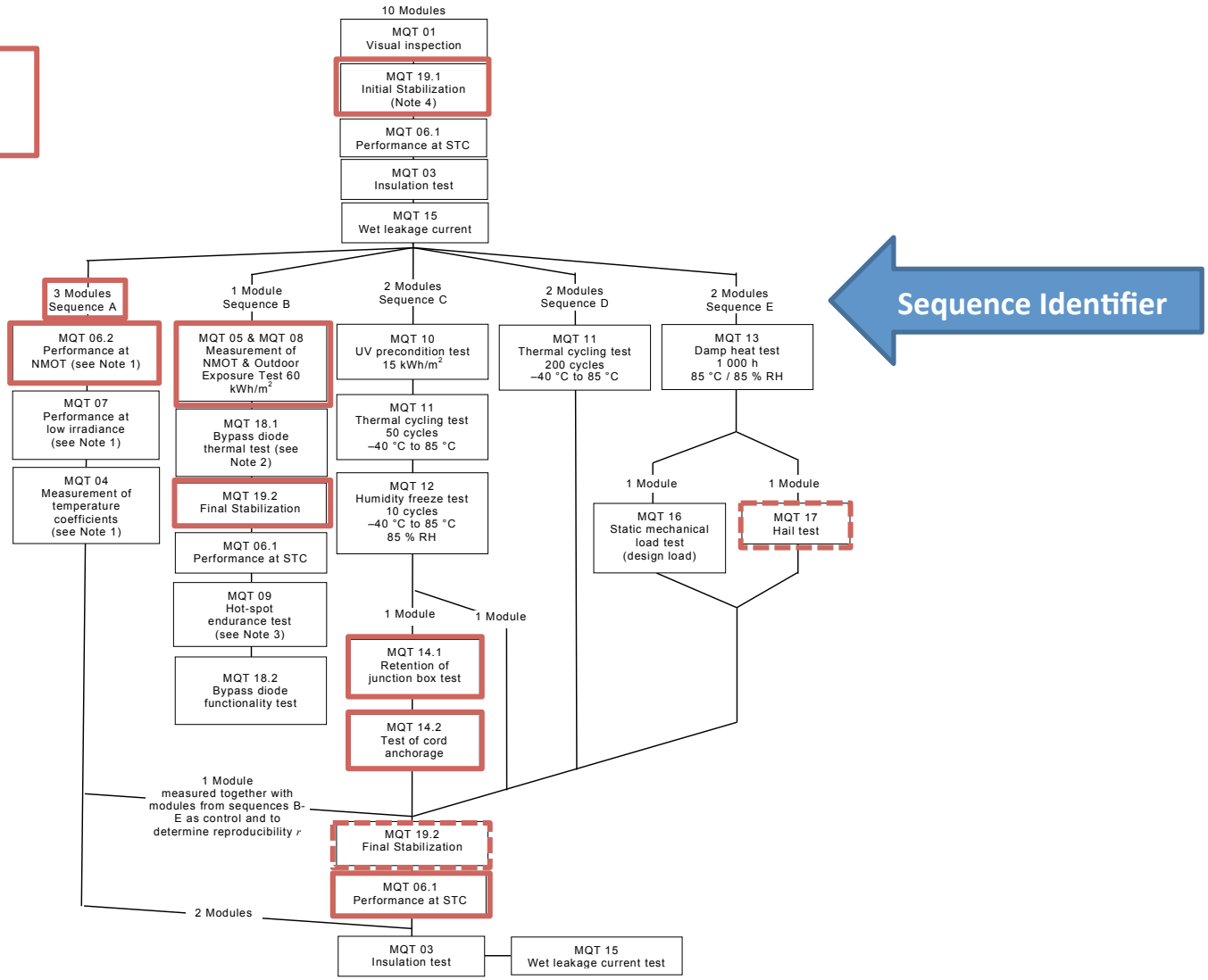
Table 1 – Summary of test levels

Test	Test reference per old standards	Title	Test conditions
MQT 01	10.1	Visual inspection	See detailed inspection list in Clause 8
MQT 02	10.2	Maximum power determination	See IEC 60904-1, requirements see Clause 6
MQT 03	10.3	Insulation test	Dielectric withstand at 1 000 V d.c. + twice the maximum systems voltage for 1 min For modules with an area of less than 0,1 m^2, the insulation resistance shall not be less than 400 MΩ. For modules with an area larger than 0,1 m^2 the measured insulation resistance

Advantage: Tests can be directly referenced within the standard and also in other standards

Test Sequence - overview

Modified or new tests



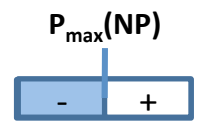
Details

i. Renewed '*Visual Inspection*' to comply with MQT 1 → Bubbles (!)
ii. Transferred all revision proposals for 61215 Ed.3 into Parts 1 & 2 and new c-Si part 61215-1-1, e.g. MQT 14 (J-Box testing)
iii. Eliminated power measurement after individual MQTs
iv. 10.2 and 10.6 are more clearly defined and with unique identifiers: MQT 2, MQT 6.1 (STC) and MQT 6.2 (Performance @ NMOT)
v. NOCT (10.5) updated to NMOT (MQT 5)
vi. Hot spot test (MQT 9) now technology specific → details see Part 1-x, power is no P/F
vii. Lightsoaking and precondition are now technology specific and defined in MQT 19.1 and MQT 19.2 depending on their position in the test flow
viii. UV preconditioning test and stabilization tests now at P_{mpp} (MQT 10 and MQT 19)
ix. Measurement ***uncertainty***: Any Laboratory uncertainty will be handled as defined in IEC Guide 98-3 – "*Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement*"
→ this is **NOT** the ***manufacturer's tolerance!***

Details: Part 1 – Pass Criteria

Three key aspects:

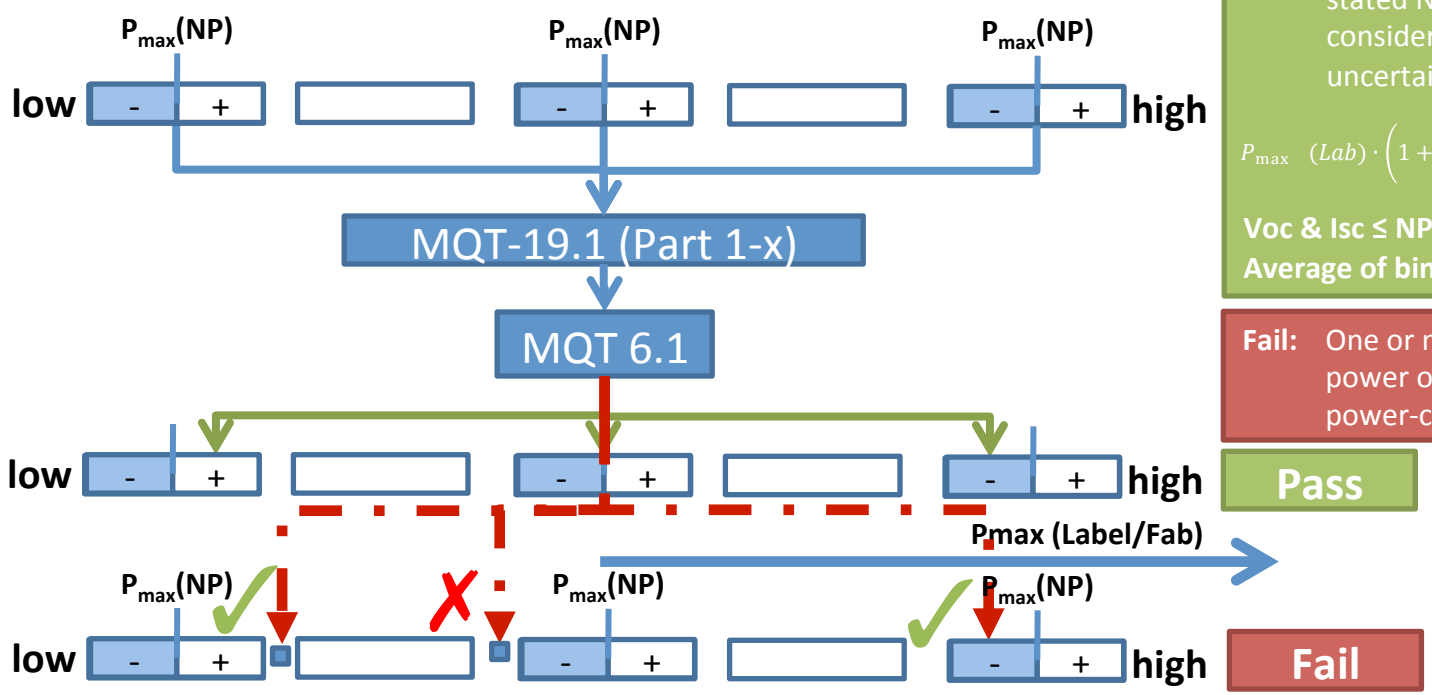
1. Power output (Clause 7)
   - **Verification of rated values → Name Plate (Gate #1) – includes tolerances**
   - **Maximum power degradation during type approval testing (Gate #2)**
2. Visual defects (Clause 8)
   - Same requirements as before
3. Electrical safety
   - Same requirements as before



P_{max} (NP): rated power output on Name Plate (NP)
- : negative tolerance on NP
+ : positive tolerance on NP

Name Plate verification (Gate #1):

All Power classes within the certification shall be covered



Pass: Individual power output ≥ the stated Name Plate value, considering stated tolerance t and uncertainty m.

$$P_{\max}\ (Lab)\cdot\left(1+\frac{|m_1|[\%]}{100}\right)\geq P_{\max}\ (NP)\cdot\left(1-\frac{|t_1|[\%]}{100}\right)$$

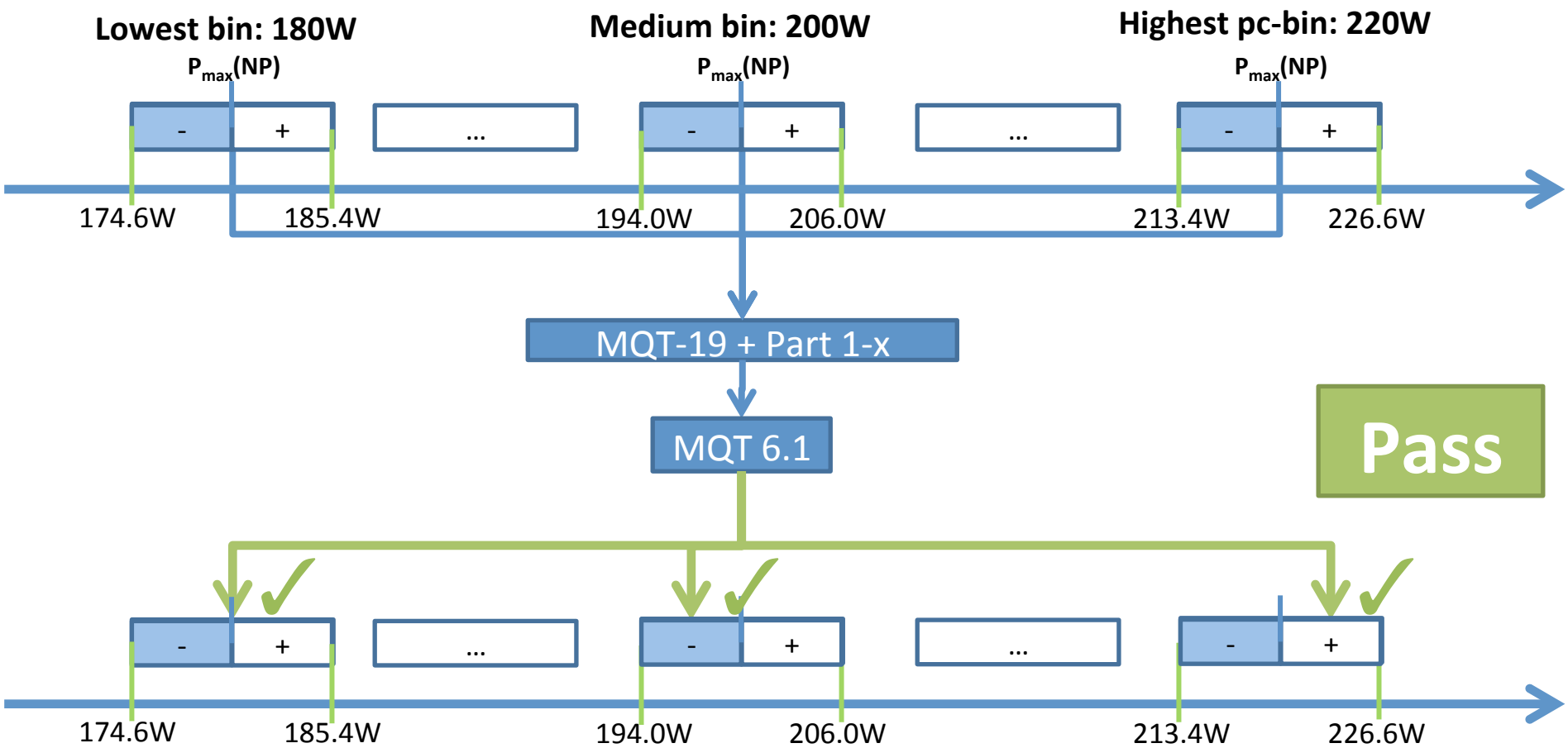
Voc & Isc ≤ NP incl. tolerances
Average of bin class wo tolerances is met

Fail: One or more modules show power output outside the Name Plate power-class including tolerance

Example 1 Gate #1

Assumed modules under certification:

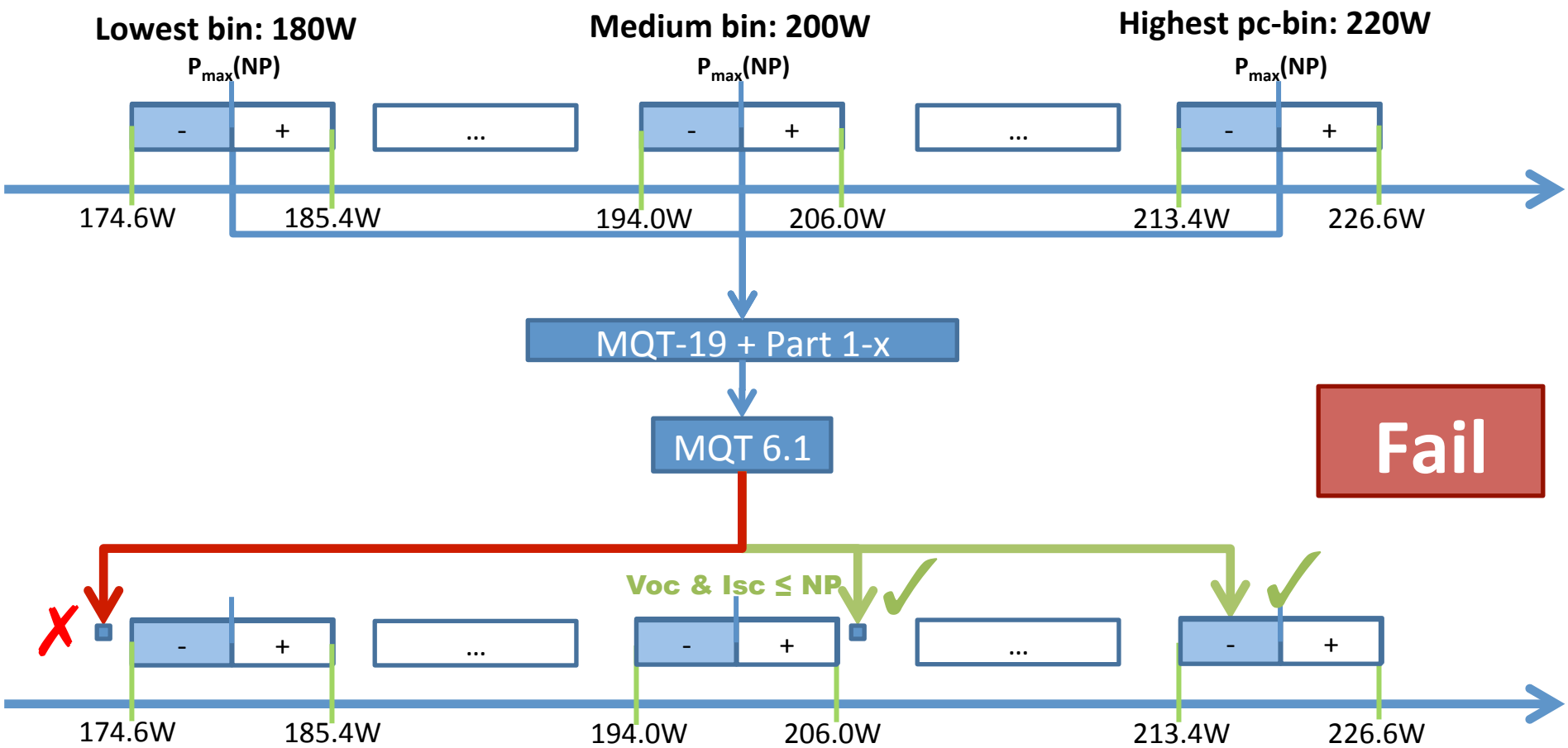
1. 180W to 220W with Power class (PC) binning: +5W/-0W
2. Tolerance on name plate: **+/-3%**



Example 2 Gate #1

Assumed modules under certification:

1. 180W to 220W with Power class (PC) binning: +5W/-0W
2. Tolerance on name plate: **+/-3%**



Details: Part 1 – Clause 7 P/F Gate #2

Maximum power degradation during type approval testing (Gate #2):

Reference is name plate rating (→ same as in IEC 61646)

All modules for certification testing (x modules)

↓

Measured power $P_{max}(Lab)$ of Gate #1 of each **individual** module

↓

Definition: 100% Power of each **individual** module

↔

Example for Module binning:

- Name Plate #1: 100W +/-3% bin
  - Modules from 97W to 103W
- Name Plate #2: 200W +5W/-0W bin
  - Modules from 200W to 205W

↓

Example of 4 modules (Gate #1 values)
#1.1: 97W
#1.2: 101W
#2.1: 205W
#2.2: 201W

→ Applying 5% criteria

↓

#1.1: > 92.2W
#1.2: > 95.9W
#2.1: > 194.7W
#2.2: > 190.9W

#1.1: ≤ 92.2W
#1.2: ≤ 95.9W
#2.1: ≤ 194.7W
#2.2: ≤ 190.9W

→ **Stress-tests**

↓

MQT-19 + Part 1-x → MQT 6.1 of Gate #2

→ **> 95%** of Gate #1 → **PASS**

→ **≤ 95% P_{max}** of Gate #1 → **FAIL**

Summary: Gate #1 and Gate #2

<u>Gate #1 compliance</u>:
All 3 tested power classes (low, medium, high power classes) comply with Name Plate rating with respect to

- Manufactures states tolerances t
- Laboratory uncertainties m

$$P_{\max} \quad (Lab) \cdot \left(1 + \frac{|m_1|[\%]}{100}\right) \geq P_{\max} \quad (NP) \cdot \left(1 - \frac{|t_1|[\%]}{100}\right)$$

$$\bar{P}_{max}(Lab) \cdot \left(1 + \frac{|m_1|[\%]}{100}\right) \geq P_{max}(\mathrm{NP})$$

<u>AND</u>

$$V_{\mathrm{OC}} \quad (Lab) \cdot \left(1 + \frac{|m_2|[\%]}{100}\right) \leq V_{OC}\ (NP) \cdot \left(1 + \frac{|t_2|[\%]}{100}\right)$$

$$I_{\mathrm{SC}} \quad (Lab) \cdot \left(1 + \frac{|m_3|[\%]}{100}\right) \leq I_{SC}\ (NP) \cdot \left(1 + \frac{|t_3|[\%]}{100}\right)$$

<u>Gate #2 compliance</u>:
All tested modules comply with:

$$P_{max}(Lab\_Gate\ \#2) \geq 0.95\ \cdot\ P_{max}(\mathrm{Lab\_Gate\ \#1}) \cdot \left(1 - \frac{2 \cdot r[\%]}{100}\right)$$

Details – Hail Test (MQT 17)

Increased severity

Diameter [mm]	Mass [g]	Test velocity [m × s^{-1}]
~~12.5~~	~~0.94~~	~~16.0~~
~~15~~	~~1.63~~	~~17.8~~
25	7.53	23.0
35	20.7	27.2
45	43.9	30.7
55	80.2	33.9
65	132.0	36.7
75	203.0	39.5

Changes in 61215-2 vs. 61215 Ed. 2

Test	Changes
Visual inspection (MQT 01)	- no -
Maximum power determination (MQT 02)	- no -
Insulation test (MQT 03)	- no -
Measurement of temperature coefficients (MQT 04)	- no -
Measurement of nominal module operating temperature (NMOT) (MQT 05)	**at Pmax / was Voc**
Performance at STC and NMOT (MQT 06)	- no -
Performance at low irradiance (MQT 07)	- no -
Outdoor exposure test (MQT 08)	- no -
Hot-spot endurance test (MQT 09)	**no longer pass/fail wrt power modified MLI procedure**
UV preconditioning test (MQT 10)	identical procedure for c-Si & TF
Thermal cycling test (MQT 11)	- no -
Humidity-freeze test (MQT 12)	- no -

Changes in 61215-2 cont.

Test	Changes
Damp-heat test (MQT 13)	- no -
Robustness of terminations test (MQT 14)	- no -
Test of cable anchorage (MQT 14.1)	**NEW**
Retention of Junction Box on Mounting Surface (MQT 14.2)	**NEW**
Wet leakage current test (MQT 15)	- no -
Mechanical load test (MQT 16)	- no -
Hail test (MQT 17)	**ball size**
Bypass diode testing (MQT 18)	updated
Bypass diode thermal test (MQT 18.1)	new figure, single procedure
Bypass diode functionality test (MQT 18.2)	new figure and procedure
Stabilization (MQT 19)	**NEW**
Initial Stabilization (MQT 19.1)	**NEW**
Final Stabilization (MQT 19.2)	**NEW**

Conclusions

- The new structure allows for a faster and flexible response to technological advances and updates
- Ease of incorporating new technologies – e.g. OPV
- Foundation to add application specific requirements – e.g. hot climate
- Single, unified standard enhancing comprehension for all stakeholders
- Clearer definition of test references – e.g. MQT 6.1 or MQT 19.1
- Harmonized with construction and test requirements from IEC 61730
- Timeline: IS publication of all parts throughout 2016

The New IEC 61215 Ed.1 Series … a major and important update for PV to enable INNOVATIONS

Thank you for your attention!

Sivapower

First Solar

SolarWorld REAL VALUE

DVE

TÜVRheinland Precisely Right.

UL

BACKUP

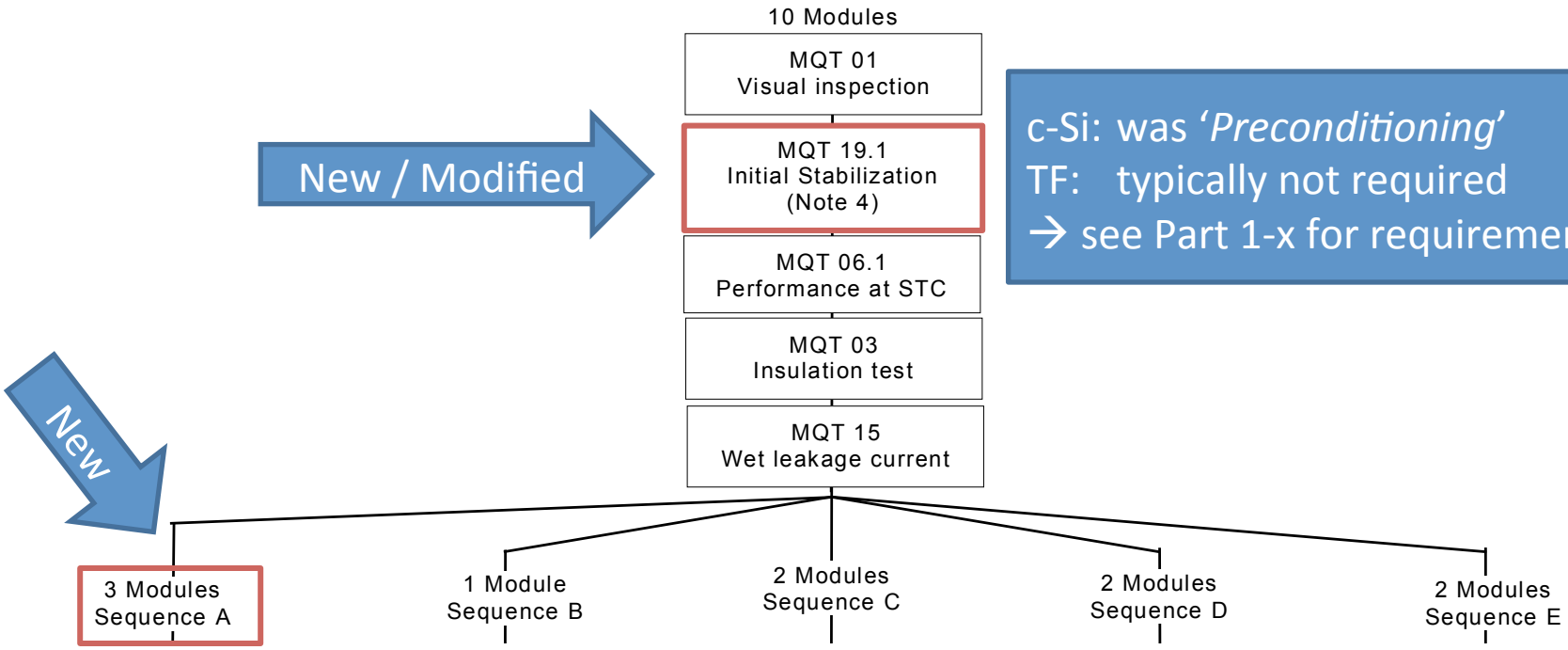
History

- 1975-1981: JPL '*Block Buys*' I-V (c-Si)
  - Based on NASA tests for space arrays
  - Thermal cycling extremes (-40 & +90°C) based on assumed worst case for terrestrial deployment
  - Short exposure to humidity rooted in space array payload pre-launch time
  - Mechanical load, hail and high pot testing added through Block V
  - OD deployment predominantly in desert environments
  - Block VI fell victim to Regan administration budget cuts
- 1981-1991: ESTI – EU Specifications 501-503
  - Similar to JPL Block V plus UV and OD exposure tests; TC maximum reduced to +85°C
  - EU 503 draft for IEC 61215
- 1990: SERI IQT modifications for TF (a-Si)
  - Added wet insulation resistance test, bypass diode test, cut susceptibility test and ground continuity test (last two from UL 1703)
- 1993: IEC 61215 Ed. 1 (c-Si)
  - Incorporated best practices from around the world
- 1995-2000: IEEE 1262 – all PV technologies
  - Hybrid between IQT and IEC 61215
- 1996: IEC 61646 Ed. 1 (TF – a-Si)
  - Based on IEEE 1262 plus light soak and anneal cycles

History cont.

- 2005: IEC 61215 Ed. 2 (c-Si)
  - Added wet leakage test from IEC 61646
  - Added bypass diode test from IEEE 1262
  - Added I_{mp} during TC 200
- 2007: IEC 61646 Ed. 2 (TF – a-Si, CdTe, CIGS)
  - Attempt to adapt Ed. 1 to different types of TF modules (CdTe, CIGS)
  - Modified pass/fail criteria to rated module power after HAST and post-stabilization
  - Modified hot spot test
  - Added bypass diode thermal test
- 2014: New IEC 61215 Ed.1
  CDV parts 1, 2, and 1-1
  CD parts 1-2, 1-3, and 1-4
- 2015: New IEC 61215 Ed.1
  FDIS parts 1, 2, and 1-1
  CDV parts 1-2, 1-3, and 1-4
- 2016: February IEC 61215 Ed.1 RVD parts 1, 2, and 1-1 → IS April/May
  February FDIS sent to CO for IEC 61215 Ed.1 parts 1-2, 1-3, and 1-4
  June FDIS parts 1-2, 1-3, and 1-4
  September IS parts 1-2, 1-3, and 1-4

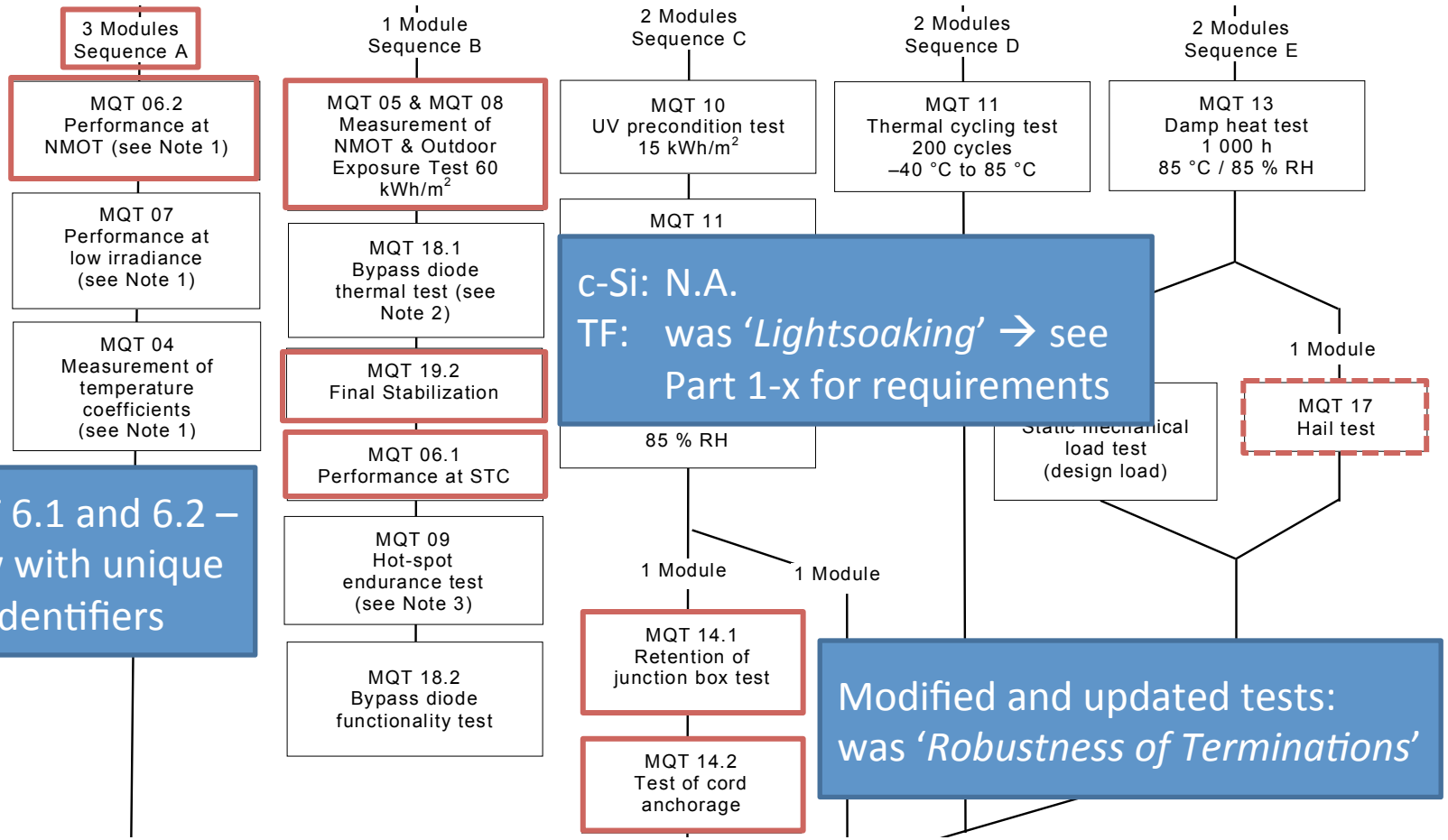
Test Sequence: Details



c-Si: was '*Preconditioning*'
TF: typically not required
→ see Part 1-x for requirements

Test Sequence: Details

Modified and split into two sequences (A+B)

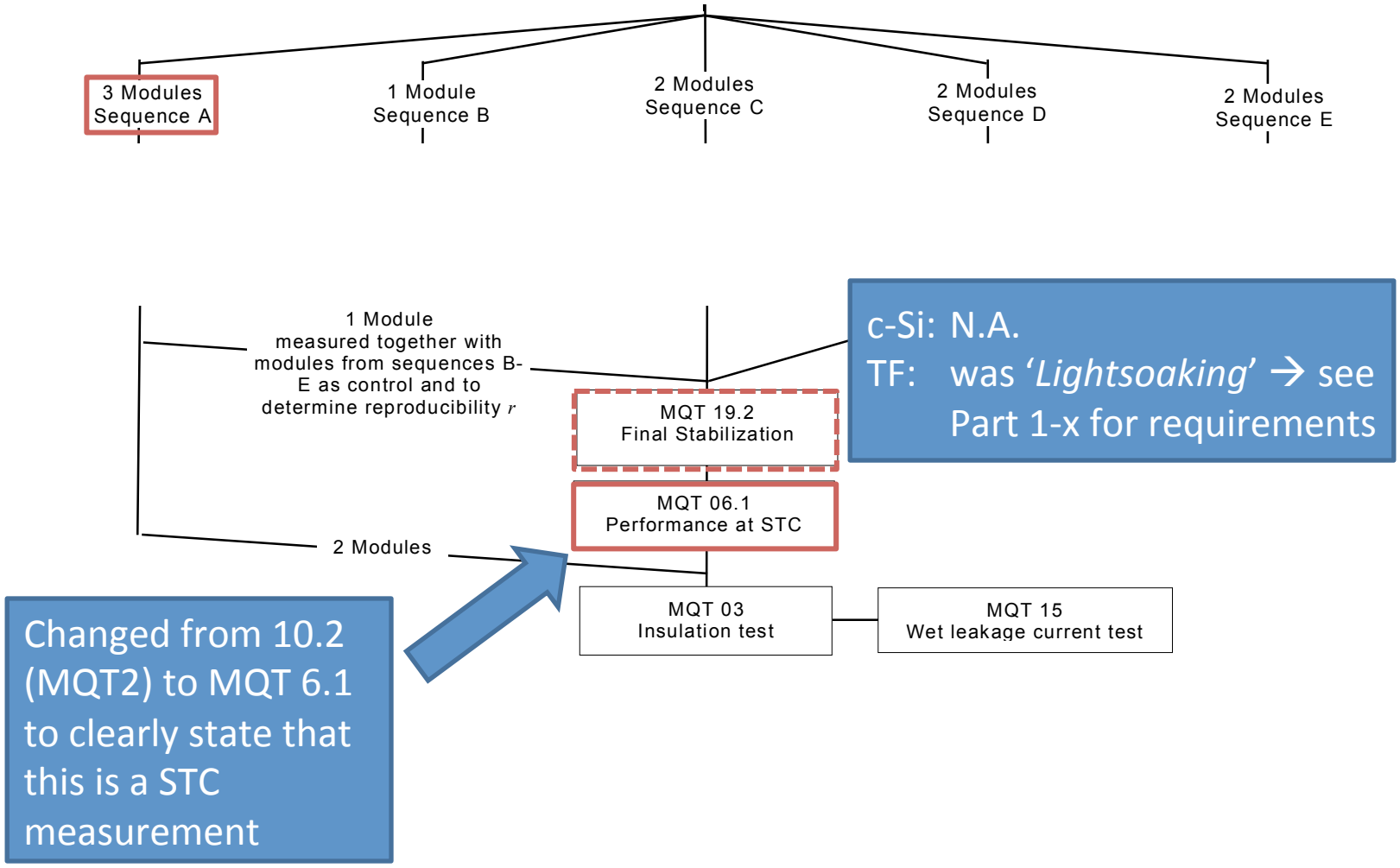


c-Si: N.A.
TF: was '*Lightsoaking*' → see Part 1-x for requirements

MQT 6.1 and 6.2 – now with unique identifiers

Modified and updated tests: was '*Robustness of Terminations*'

Test Sequence: Details



PVMRW 2016, Denver, CO

Standards for Higher Value of PV: From Desert to BIPV

FREA, AIST
Michio Kondo

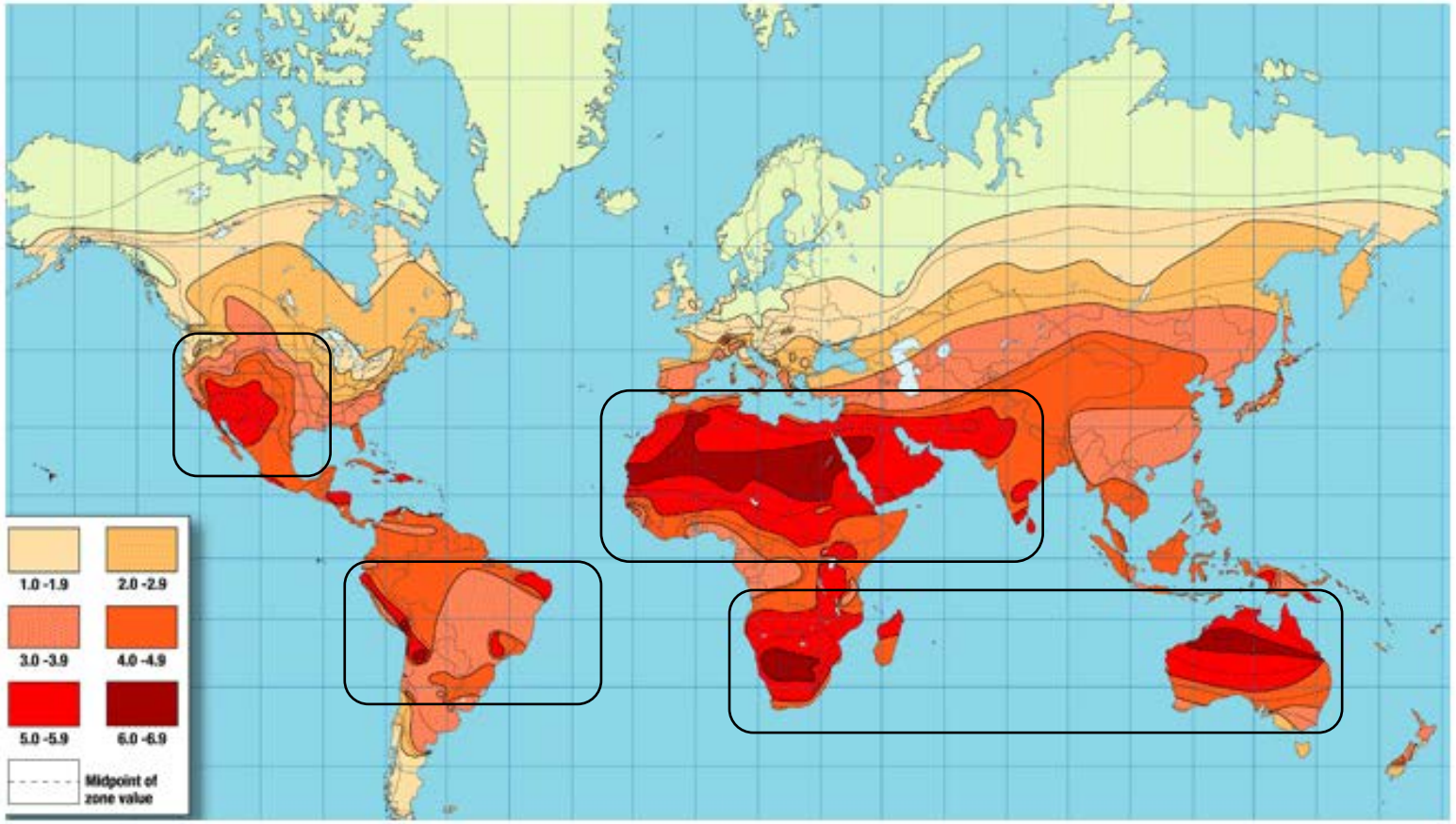
FREA
FUKUSHIMA RENEWABLE ENERGY INSTITUTE, AIST

Enhance the Value of PV

- Low emission, low carbon to mitigate climate change
- Less dependency on fossil fuel
- Energy security
- Sustainability
- 3E + S (Energy security , Economic efficiency, Environmental, Safety)
- Preservation of the fossil resource

- More energy, more value
  - ✓Higher yield ⇒ efficiency, irradiance ⇒ Reliability ?
  - ✓Multi-function ⇒ power generation + more ⇒ Cost Benefit ?
  - ➢ Lack of guidelines or standards
  - ➢ Convincing for investors ?

Robust Global Solar Resource



Source: http://howto.altenergystore.com/Reference-Materials/Solar-Insolation-Map-World/a43/

NREL National Renewable Energy Laboratory

Technical Requirements of PV Module for High Temperature Environments : Case study for Saudi Arabia

Faisal Al Omar, Abdulaziz Baras, Russ Jones, Hiroko Saitoh, Michio Kondo

K.A. CARE, AIST, PVTEC

PVTEC
Photovoltaic Power Generation Technology Research Association

AIST

Basic Idea for Standards for Hot Regions

- Products should be tested under operating or harsher conditions.
- If ambient temperature ranges up to 50 C, it should be tested at higher temperatures.
- Acceleration factor is influenced by difference between ambient and test conditions.
- Start with the assessment of environment, propose technical requirements and finally determine the standards after compromising multiple factors.

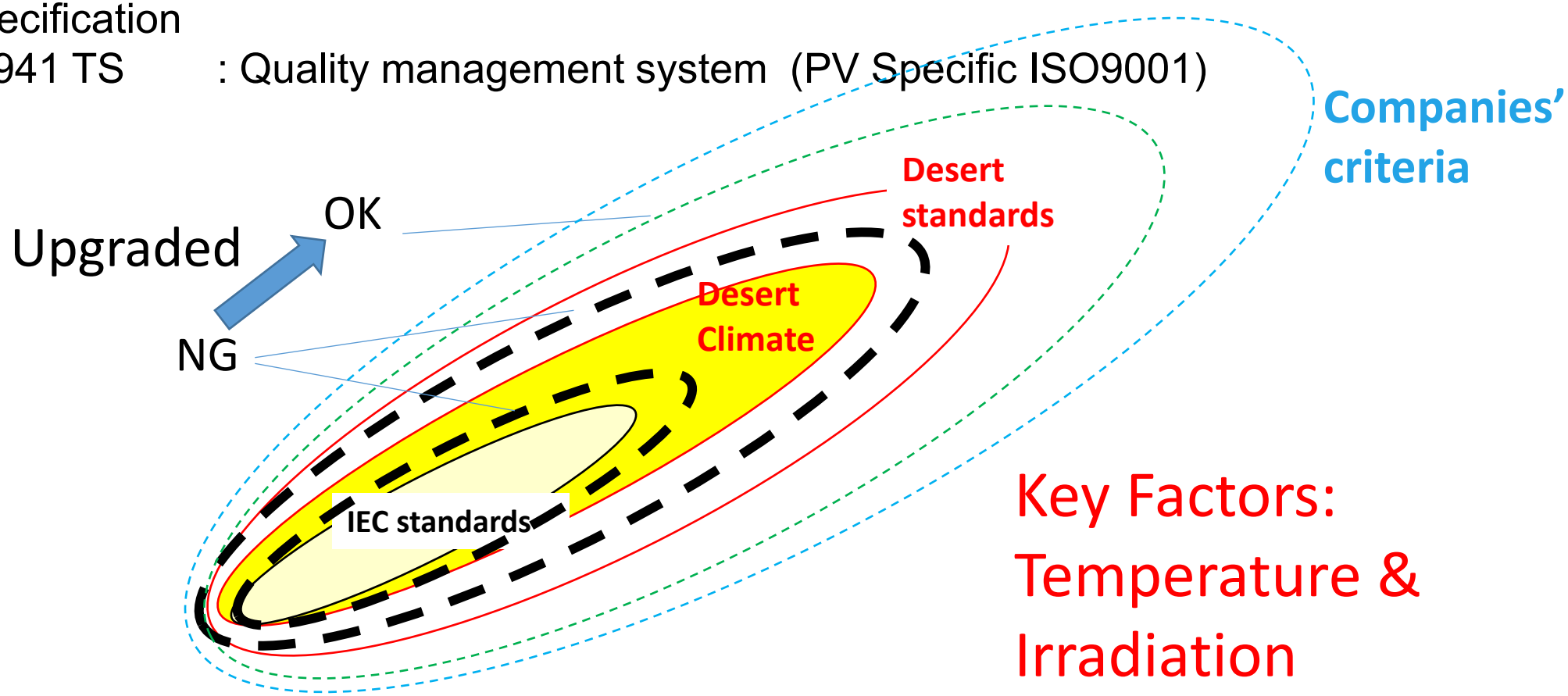
Basic Idea for Climate Specific Standards

Published

61215/61646 : Performance standards. Type approval.
61730 : Safety standards. Type approval.

To be published

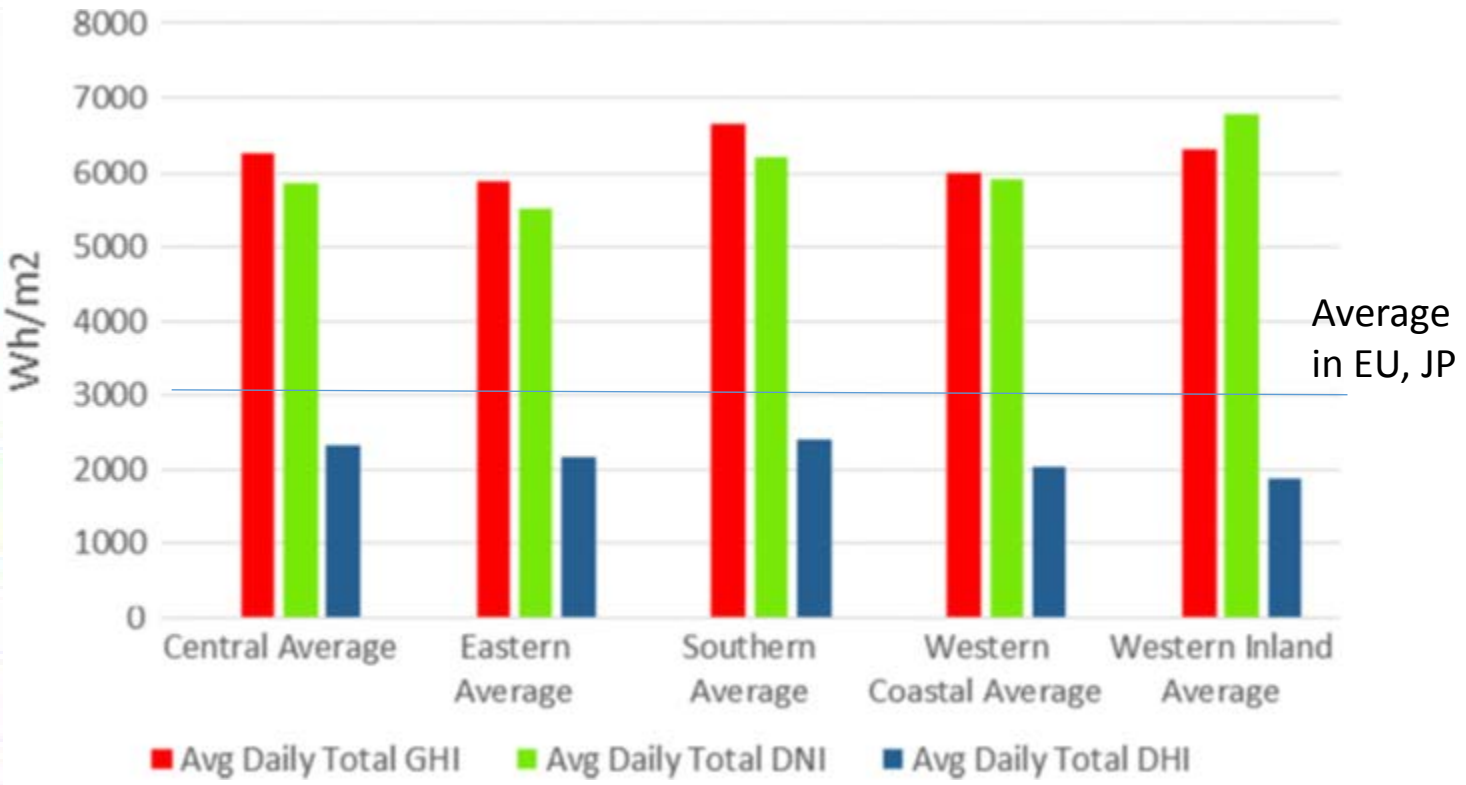
62804 TS : Potential Induced Degradation TS: Technical Specification
62941 TS : Quality management system (PV Specific ISO9001)



Key Factors: Temperature & Irradiation

Annual Irradiation in KSA

Source: RRMM project



Annual irradiation is nearly double as compared to temperate regions

اطلس مصادر الطاقة المتجددة
Renewable Resource Atlas

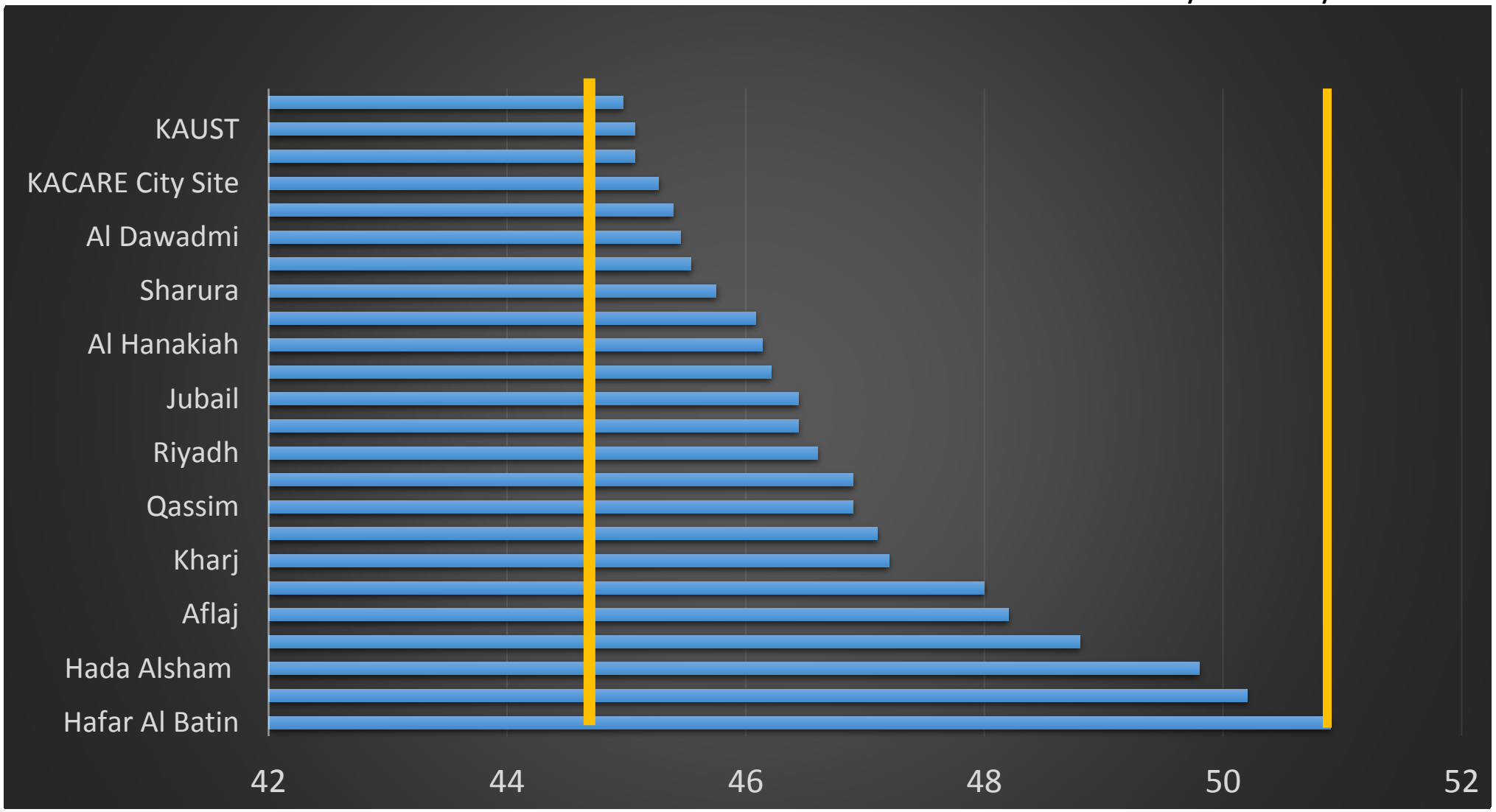
Climate zone in IEC standards (Theoretical limit of environments)

	Climate Zone	Absolute Extreme Value of Temperature	
		High temperature (C)	Low temperature (C)
IEC 60721-3-4 ed.2 (1995)	4K6 (Arid)	55	-20
	4K3 (AB8)	40	-50

- IEC PV standards are designed for temperate climate conditions “in mind”.
- 61730 covers environmental condition type AB8 (equivalent to 4K3) as specified in 61730-1, Clause 4.1.1
- Arabic countries (including KSA) belongs to climate zone 4K6 (not covered by IEC standards).

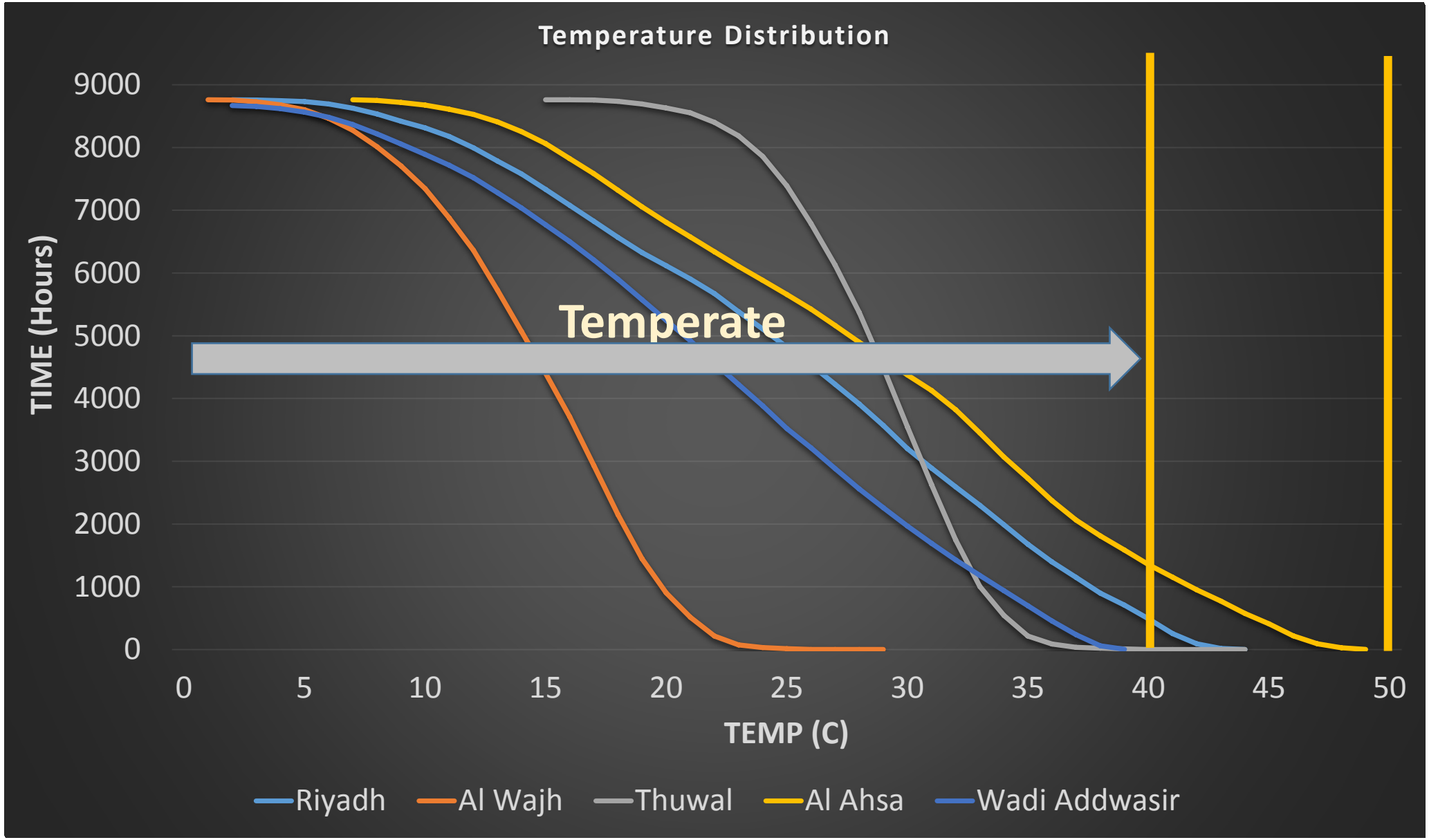
Assessment of Extreme temperature in Saudi Arabia 2015

By Courtesy of RRMM Project



Which temperature is the most appropriate in Saudi Arabia ?

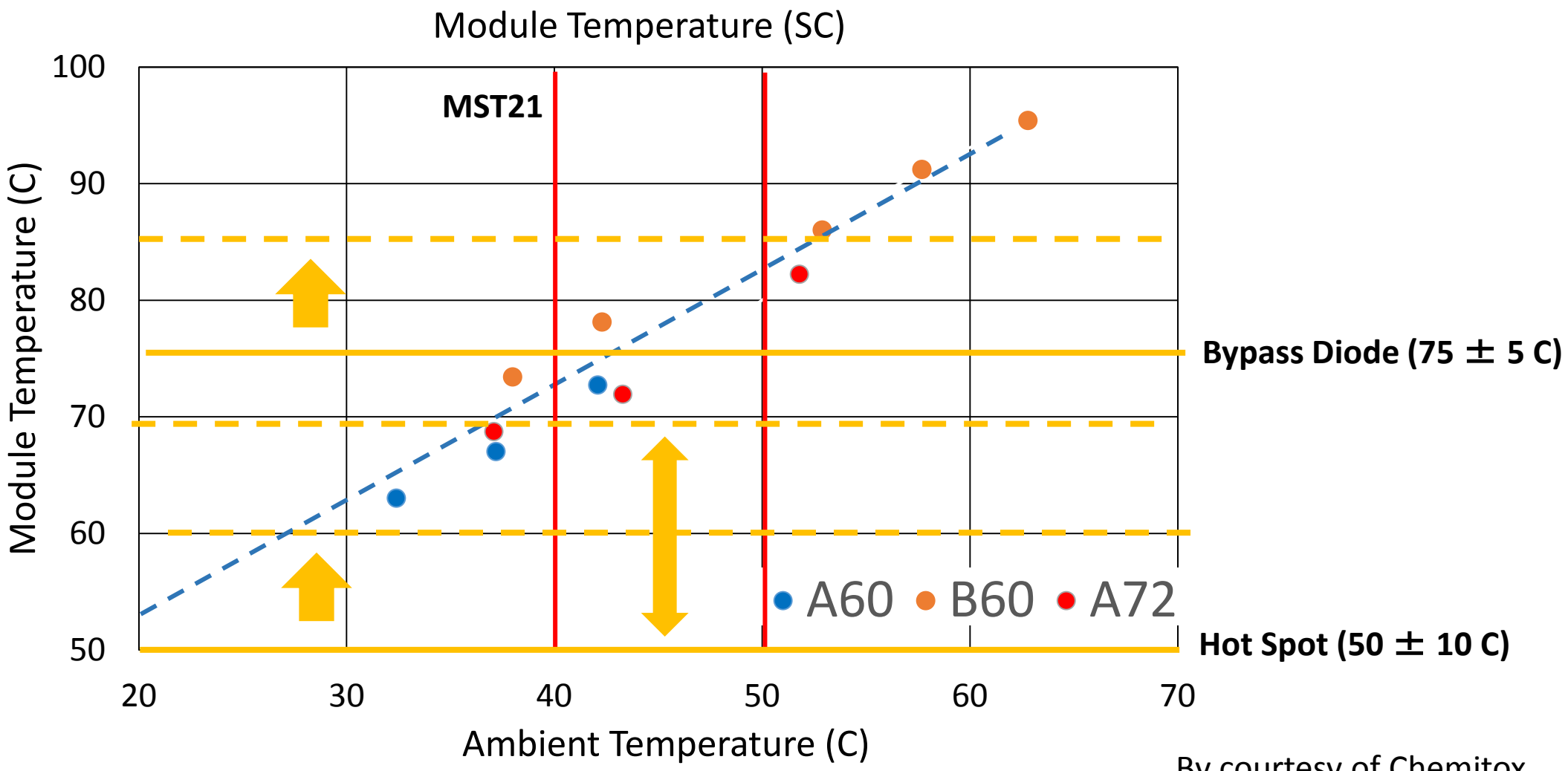
Distribution of Extreme Temperature



By Courtesy of RRMM Project

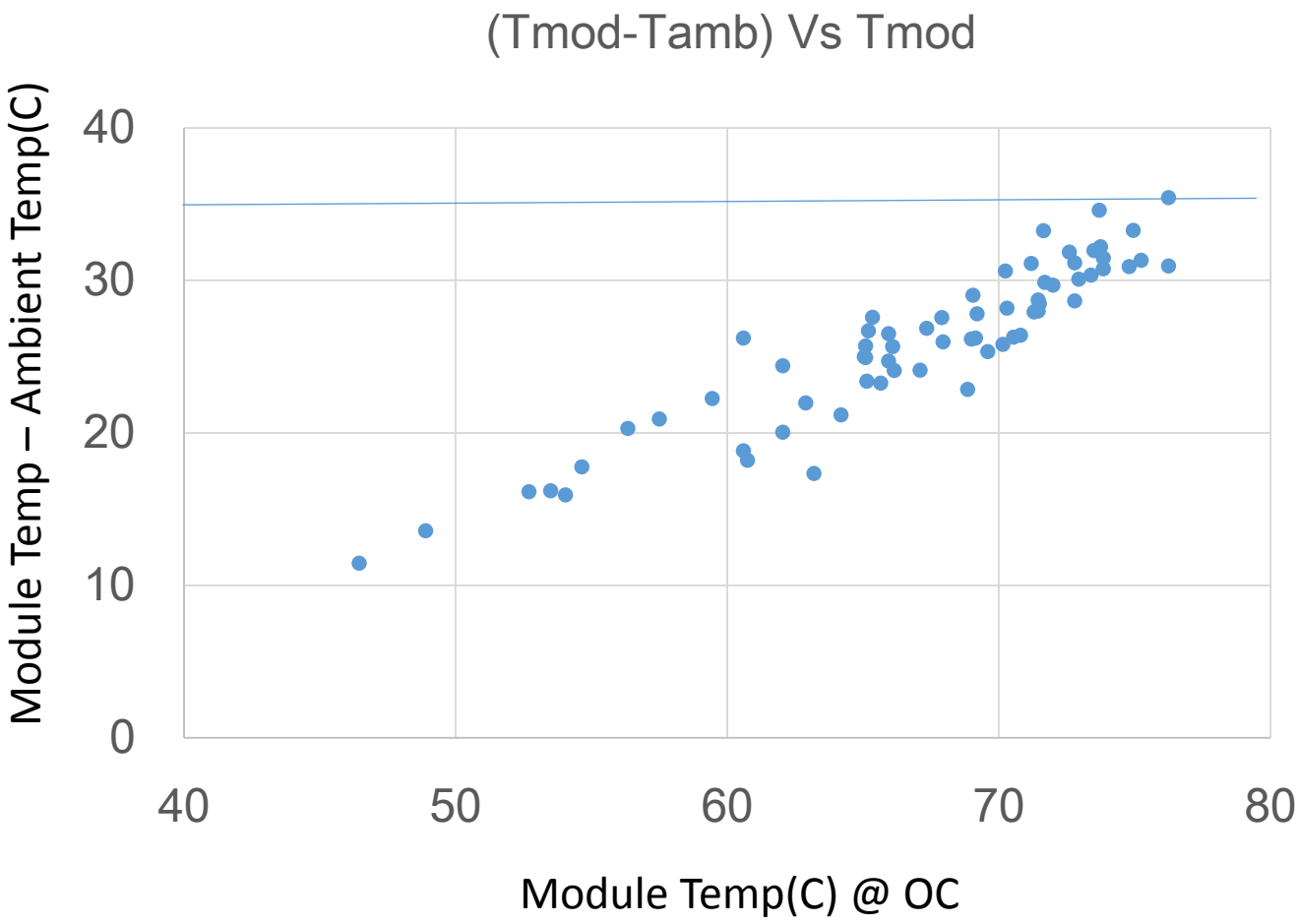
Module Temperature Vs Ambient Temperature

(Indoor @ 1000 W/m2 Class BBA)



By courtesy of Chemitox

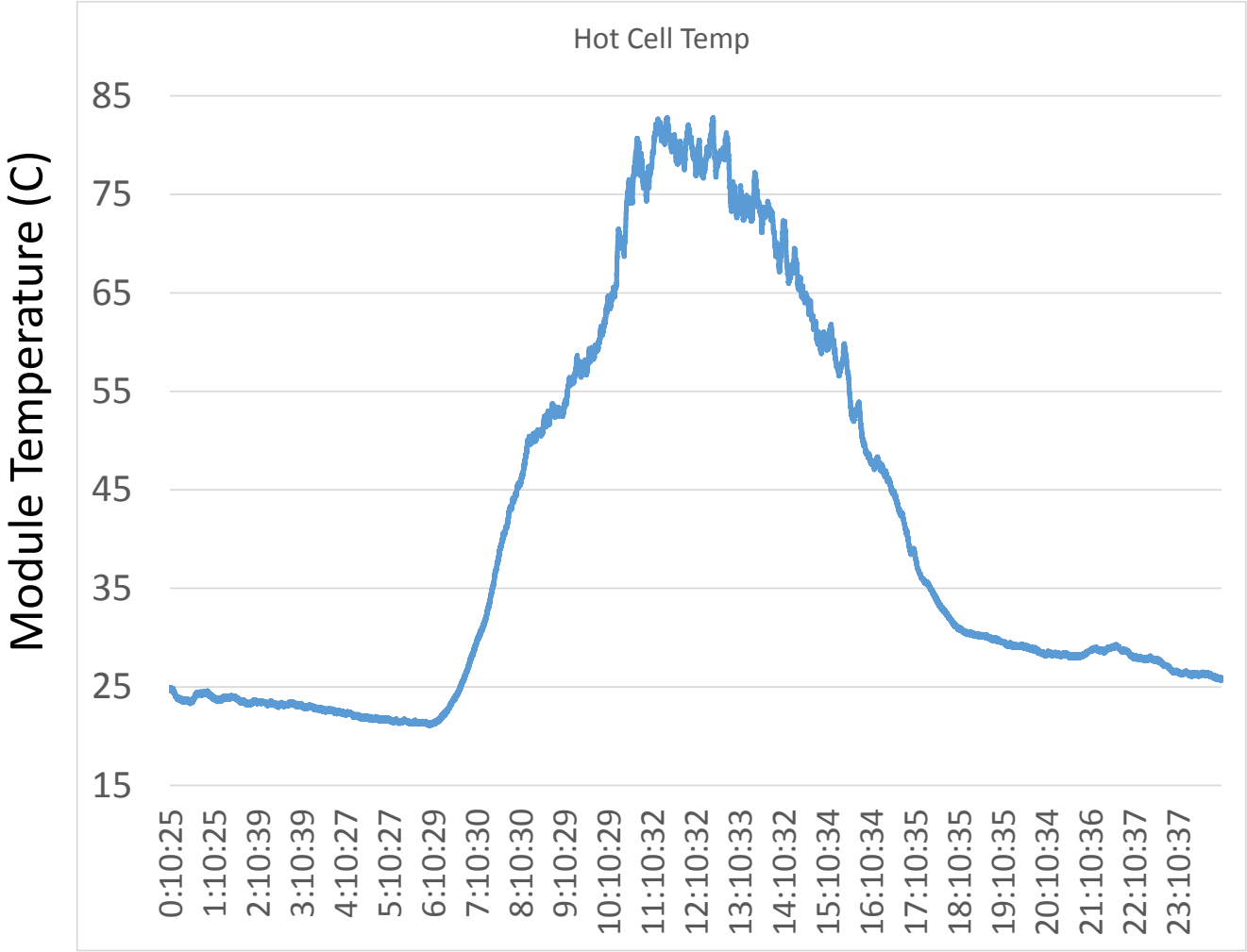
Outdoor test in Riyadh (KACST)



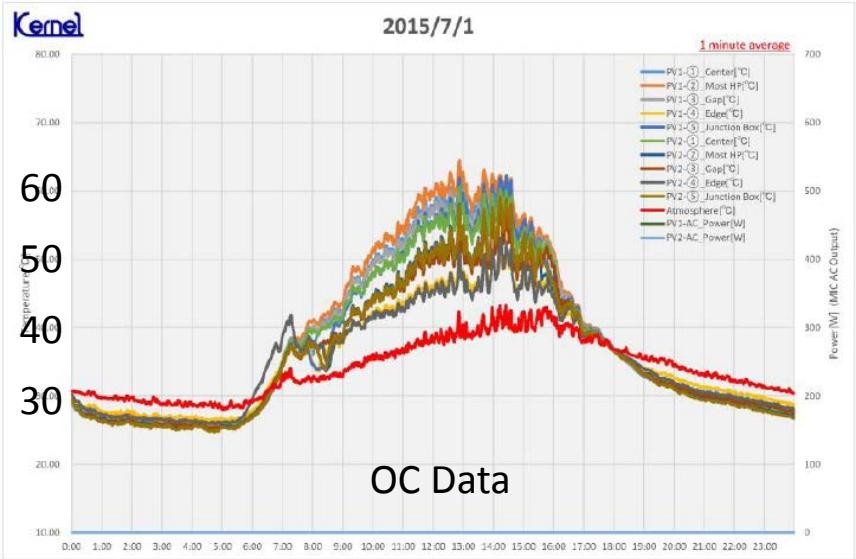
Module Temp. Tmod
Ambient Temp. Tamb

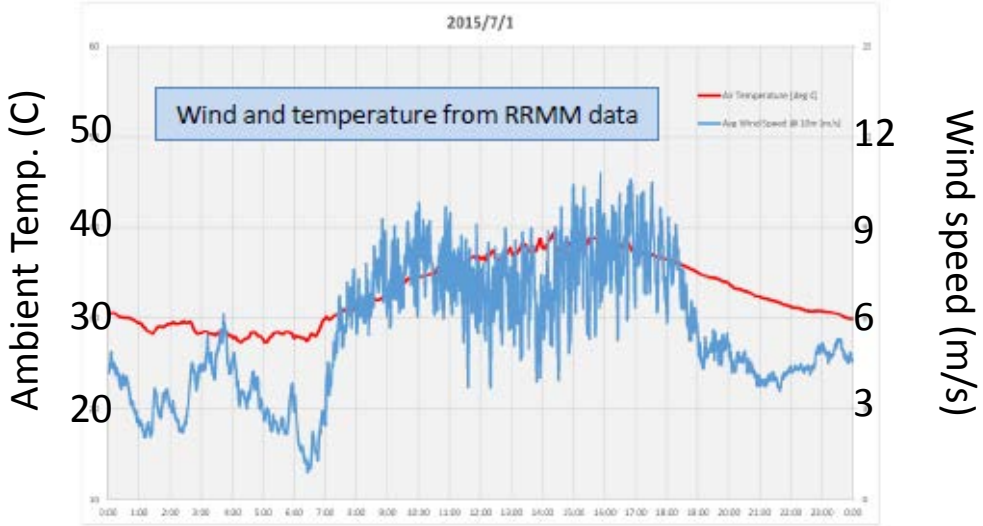
- (Tmod-Tamb) have a wide variation due to Wind & Irradiance
- Maximum value of Tmod-Tamb ~ 35C
- Maximum temperature difference at lower module temperature

Example of Highest Module Temperature ~82 C (SC, October) Tamb = 35 C



Impact of Wind -1





- Typical data of module temperature at lower cases

  Tmod ~ 60 C

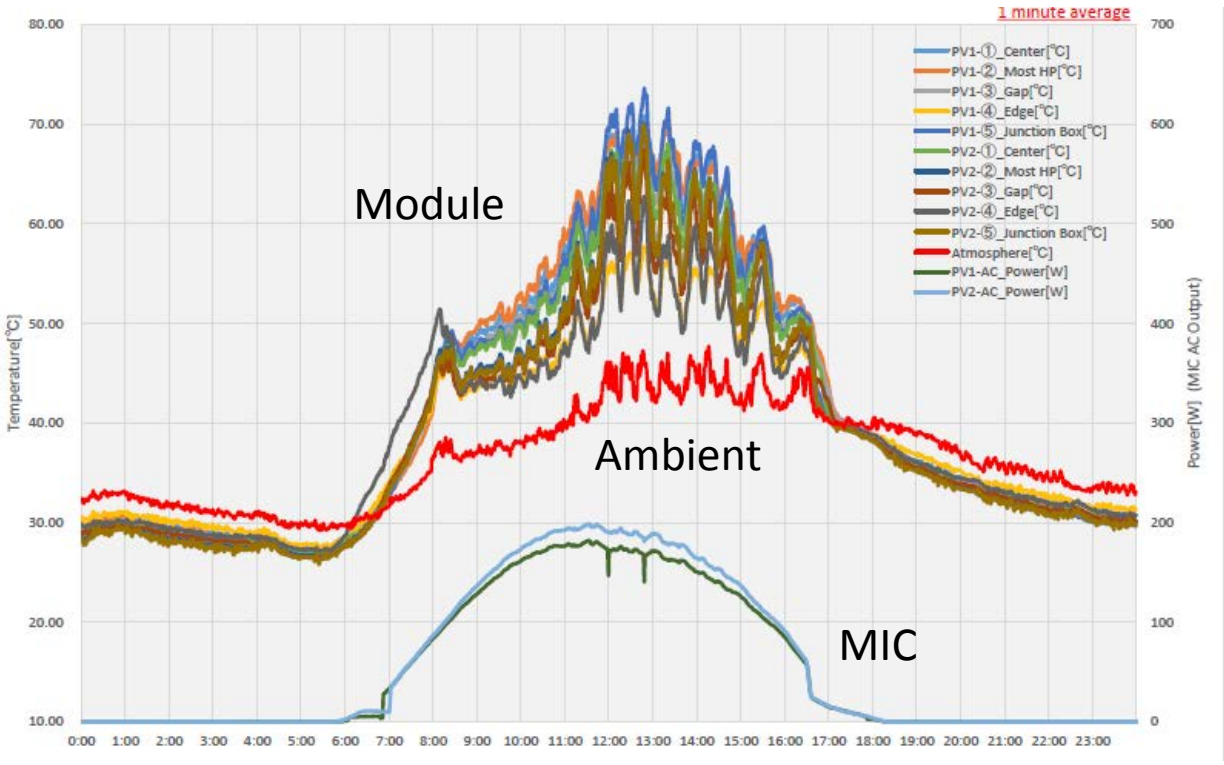
- Wind speed is stable and high

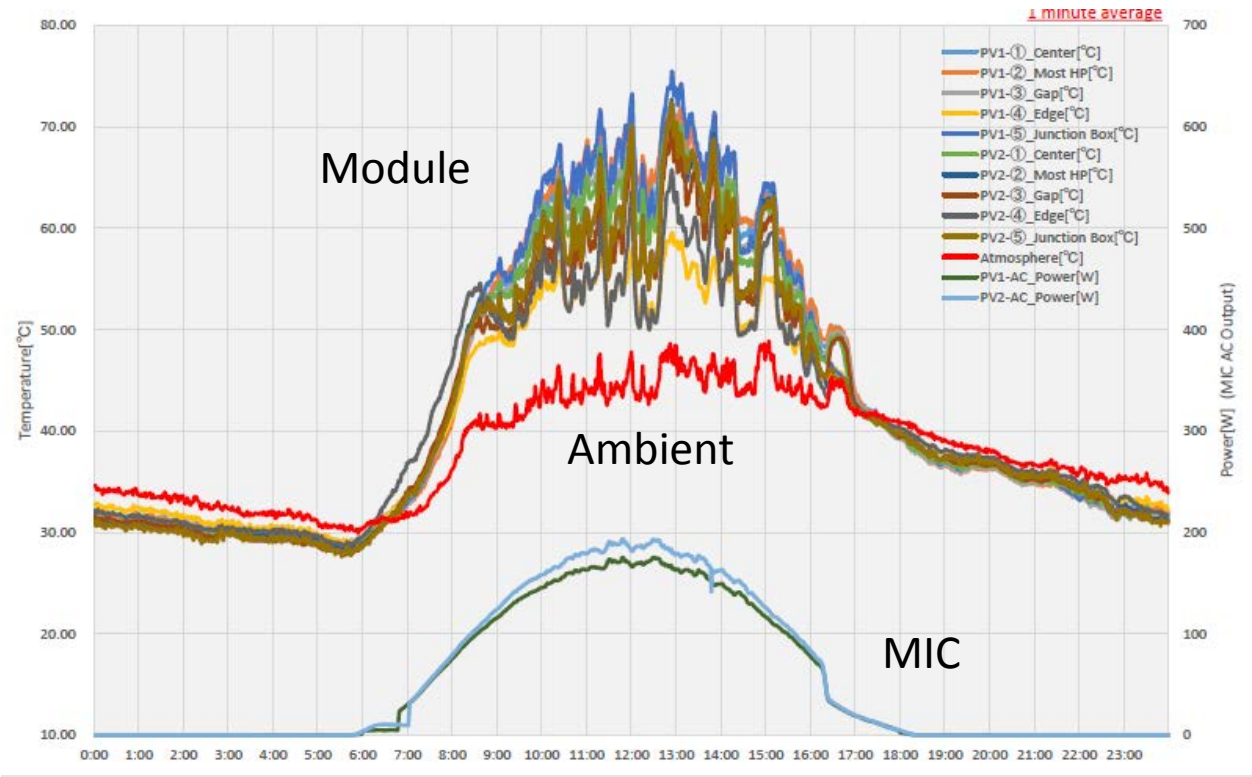
  Wav ~ 8m/s

Expected decrease ~ 10 C

⇒ Scattered data of Module Temperature

Fluctuation of Module Temperatures





Proper PV Standards in Saudi Arabia

- Tmod = Tamb + 30 ~35 C (Indoor Test)

- Testing temperature should be higher than corresponding temperature at extreme ambient temperature.
  - ✓Module is trustful even if tested only at low temperatures ?
- Based on the assessment of KSA climate, technical requirements are determined and standards are proposed.
- Testing temperatures should be raised by 10 C. (ambient and module)

From *Scope* of IEC 62892 (Climate Specific Qualification)

IEC 61215 “Terrestrial photovoltaic (PV) modules – Design qualification and type approval” already provides a set of tests that indicate that the module design is likely to be free of flaws that will result in early module failure. However, IEC 61215 does not address long term wear-out of PV modules. This standard is designed to specifically address accelerated stress testing of PV modules to identify their potential to suffer from specifically identified field wear-out mechanisms.

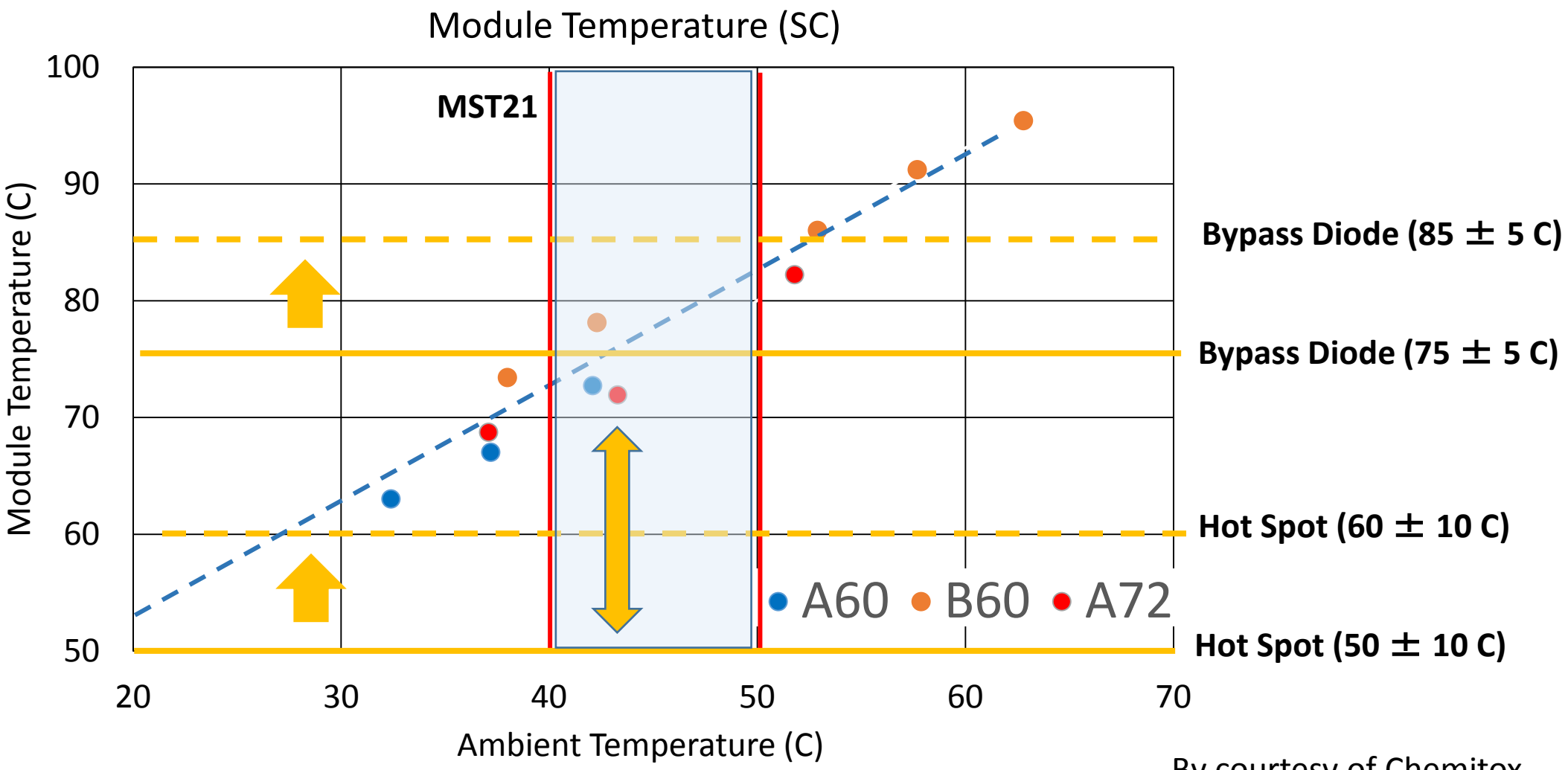
Modification of Test Conditions

IEC Standards #	Title	Test Conditions	Proposal for revision	Remarks
61215-10.9	Hot Spot Endurance Test	Module Temperature (50 ºC +- 10ºC)	60 ºC +- 10 ºC	Frequently appear in KSA
61215-10.18	Bypass Diode Test	Module Temperature (75 ºC)	85 ºC	Ambient Temp in KSA +10 C

- Module temperature often exceeds 50 C.
- Bypass diode test at higher temperature is more effective than at longer current injection.

Module Temperature Vs Ambient Temperature

(Indoor @ 1000 W/m2 Class BBA)



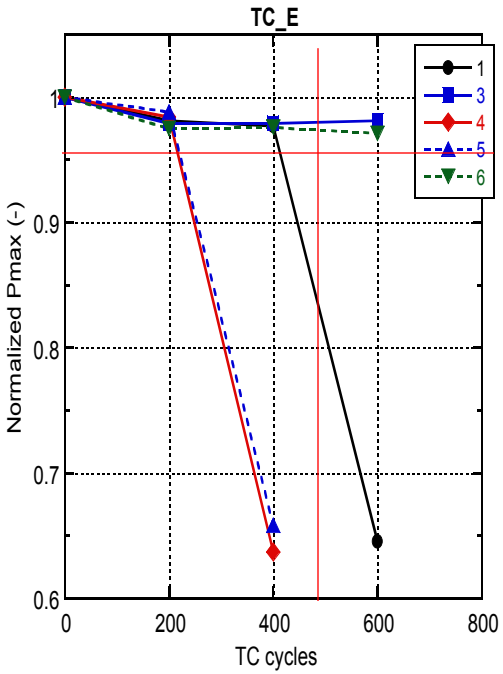
By courtesy of Chemitox

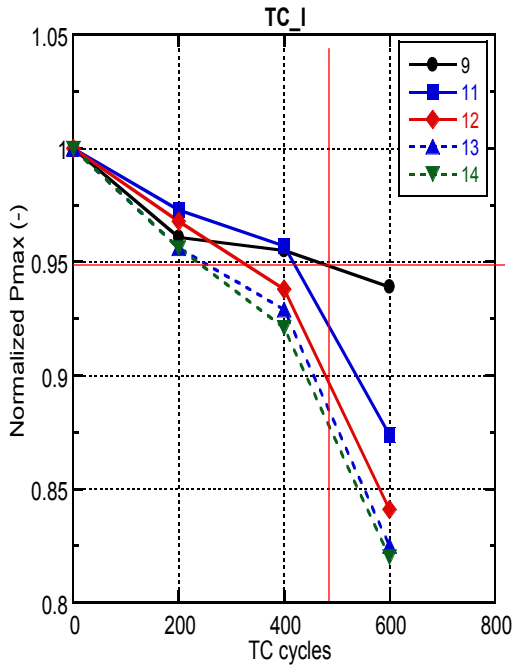
New requirements - thermal Cycling

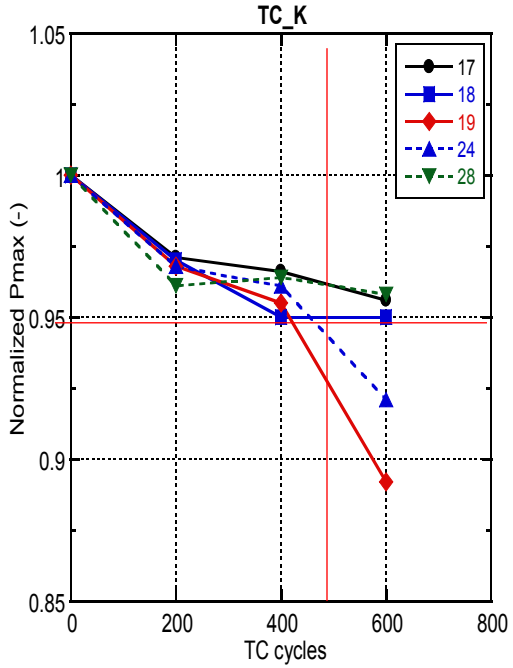
IEC Standards #	Title	Test Conditions	Proposal for revision	Remarks
61215-10.11	Thermal Cycling Test	Temperature range (-40/85ºC) and Cycle # (200)	Temperature range (-40/85ºC) and Cycle # (500)	IEC62892 propose higher temperature tests (NWIP)

- Greater thermal cycle range in desert climate could cause a failure in interconnection (solder bonding).
- TC 500 will be adopted in new IEC standards for all the climate region.
- Higher test temperatures are being discussed in TC82.

Thermal Cycle Test up to 600 cycles







(Source: PVTEC)

- ☐ Some modules show a failure between 400 and 600 thermal cycles.
- ☐ TC 500 is recommended .

Note: Maximum cycle time = 6 hrs/cycle : TC 500 < 3000 hrs
Minimum may be > 3hrs

IEC Standards #	Title	Test Conditions	Proposal for revision	Remarks
61215-10.8	Outdoor Exposure Test	Total Amount of Irradiation (60 kWh/m^2)	120 kW/m^2	Annual irradiation in KSA is X2
61215-10.9	Hot Spot Endurance Test	Module Temperature (50 ºC +- 10ºC)	60 ºC +- 10 ºC	Frequently appear in KSA
61215-10.11	Thermal Cycling Test	Temperature range (-40/85ºC) and Cycle # (200)	-40/85C & 500 cyc..	Two options TBD by the stake holder opinion
61215-10.18	Bypass Diode Test	Module Temperature (75 ºC)	85 ºC	Ambient Temp in KSA
61646-10.18	Light Soaking Test	Module Temperature (40~60ºC)	50~60 ºC	Frequently appear in KSA
61730-10.7	Temperature Test MST-21	Ambient Temperature 40 ºC	50 ºC	Ambient Temp in KSA Suspended until 61730-2 Ed2 is published
Component Test for Encapsulant	Measurement conditions	Testing temperature, UV intensity and duration	BPT = 90 ºC UV = 56 W/m^2 4000 hrs	Pass/fail criteria is decrease in transmittance less than 2%.
Component Test for Backsheet	Measurement conditions	Testing temperature, UV intensity and duration	BPT = 70ºC UV = 81 W/m^2 4000 hrs	Pass/fail criteria visual inspection
IEC TS 62804	PID test	Voltage, temperature, humidity, duration	System voltage 60 ºC 85% 96 hrs (chamber test)	▪Published Pass/fail criteria with < 5% decrease in output power is added
Quality Management System (IEC TS 62941)	QMS procedure			To be published

Next Step

- Implementation Process of KSA Standards by SASO
  ⇒ Public Comments
- Standards for multiple climate at an international level
  ⇒ Variety of climates, multiple standards, compromise
- Sophisticated approach for matured industry
  ⇒ Acceleration factor rather than test conditions ?
- Challenge to life time prediction

- Information on failure or degradation should be shared
  ⇒ Field Data

Stakeholders Engagement

AIST

PVTEC
Photovoltaic Power Generation Technology Research Association

東京大学
THE UNIVERSITY OF TOKYO

UL

SUNPOWER

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

King Saud University

First Solar

مدينة الملك عبد العزيز للعلوم و التقنية KACST

European Commission
Joint Research Centre

SASO

معهد قطر لبحوث البيئة والطاقة
Qatar Environment & Energy Research Institute
Member of Qatar Foundation

Trinasolar

DUPONT

Masdar CITY مدينة مصدر

وزارة البترول والثروة المعدنية
المملكة العربية السعودية

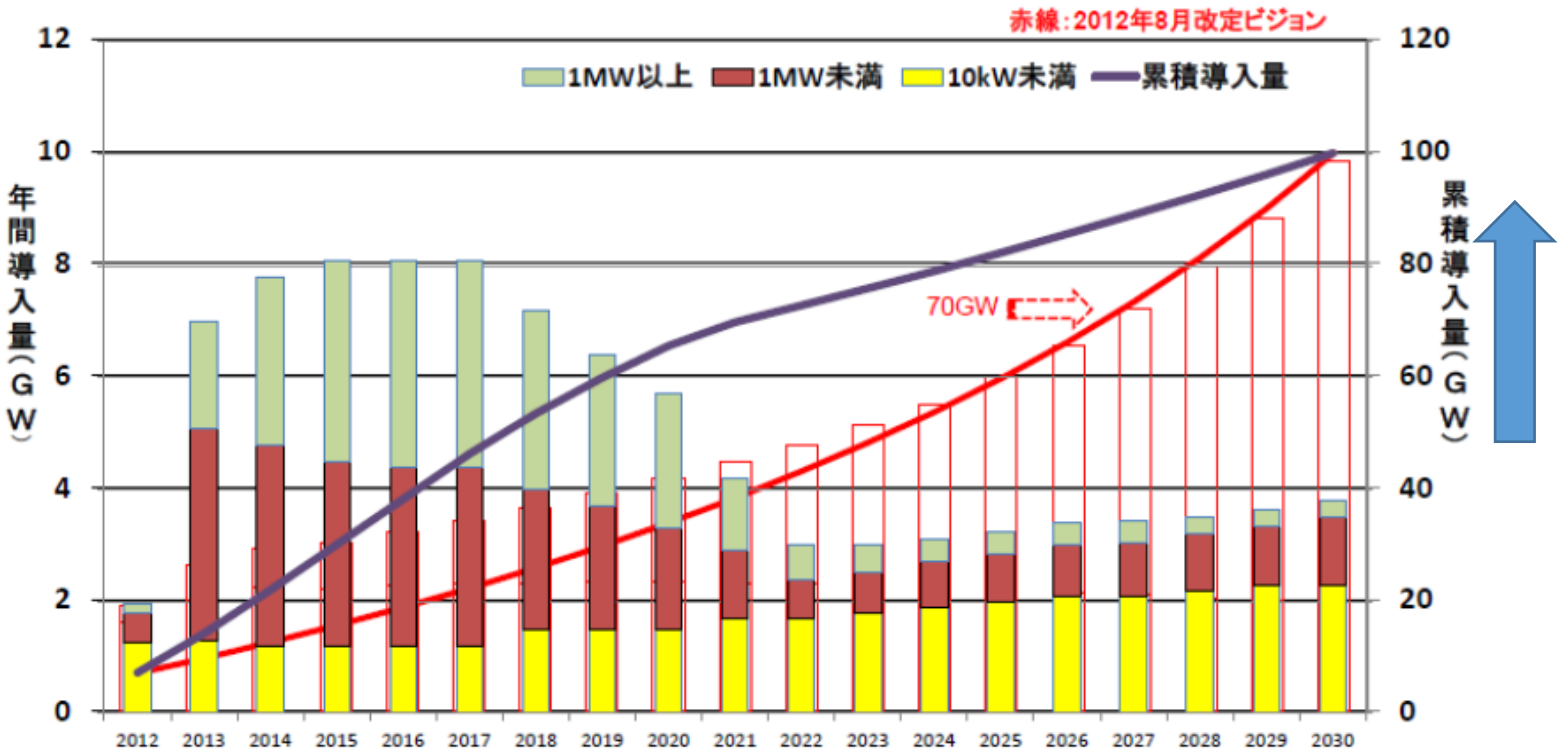
المملكة العربية السعودية
وزارة المياه والكهرباء
MINISTRY OF WATER & ELECTRICITY

Reviewers

- Eng. Abdurhman AlAbdulkarim; **Saudi Standards Organization** (**SASO**)
- Dr. Bengt Jaeckel; UL Germany GmBH
- Dr. Abdurhman Alodhaibi; KACST PV Lab; King Abdulaziz City for Science and Technology (KACST)
- Dr. Tony Sample; European Commission Joint Research Centre (JRC)
- Salah Kurtz; National Renewable Energy laboratory (NREL)
- John Wohlgemuth; National Renewable Energy laboratory (NREL)
- Dr. Abdullah M. Al-Shaalan; King Saud University,
- Saudi Electricity Company
- Sumanth Lokanath; First Solar
- Dr. Ernest F. Hasselbrink Jr.; SunPower
- Martinez, Diego & Figgis, Ben; Qatar Environment & Energy Research Institute (QEERI)
- Zhang Zhen; Trinasolar Ltd.

Why BIPV ?

Outlook of Japanese Market



累積GW	2020年			2030年		
	住宅用	1MW未満	1MW以上	住宅用	1MW未満	1MW以上
今回姉妹編	16.3	25.2	24.2	36.4	34.6	29.1
2013年改訂版	18.3	17.0	14.1	39.9	41.5	24.0

PV OUTLOOK2030 JPEA

Standardization of BIPV supported by METI (2015~2017)

Scope

To clarify
Technical requirements for BIPV
Metrics to evaluate BIPV
(technical, economical)
To investigate
Potential of flexible module for BIPV

Higher value of PV: Why BIPV ?

- Japanese market started for roof top application
  High electricity cost for residential use
  Supported by subsidy
  Limited land area

- BIPV has been attempted but not been successful
  Too costly
  Benefit is unclear

- Trend of low carbon society
  ZEB and ZEH will be more emphasized (COP21)
  On-site generation and consumption to mitigate conflict with grid

- Cost of solar cells is declining

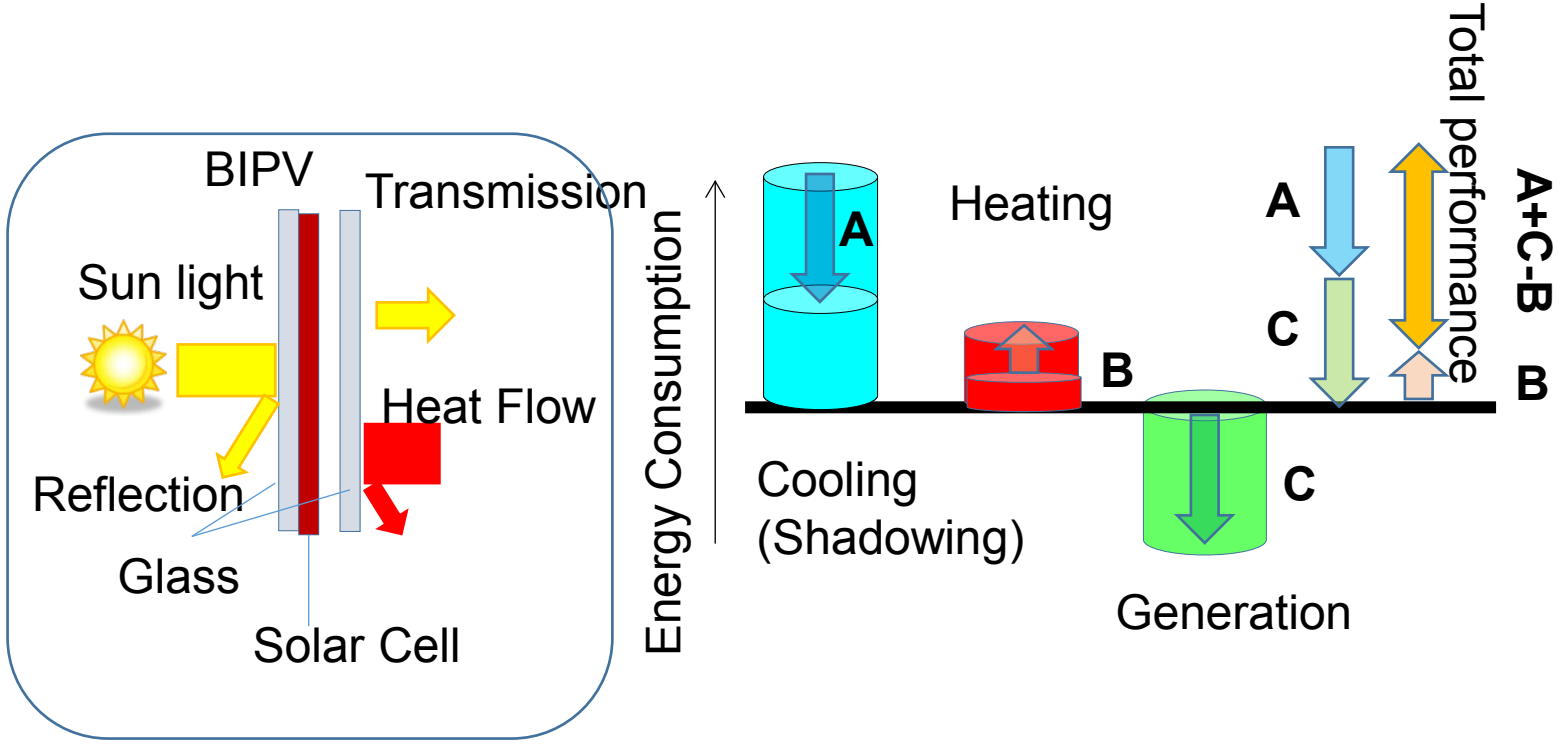
For development of BIPV market

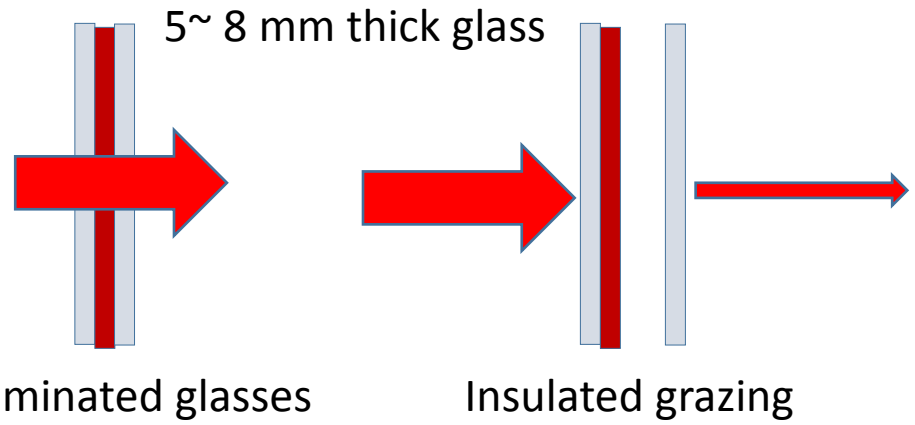
- Technical Barrier
  - Long life for building (~60 years)
  - Safety as building components
  - Performance as energy saving (needed for ZEB and ZEH)

- Non-technical Barrier
  - Unclear cost performance
  - Potential of cost reduction
  - Custom made ⇒ Certification Cost, difficulty for standardization

- Proper standards are needed
  - Rooftop, Integrated
  - Curtain Wall (Custom size, Heavy, Large) Typically 8mm laminated glass
  - Flexible (not compatible with test standards for rigid module)

Energy Balance in BIPV





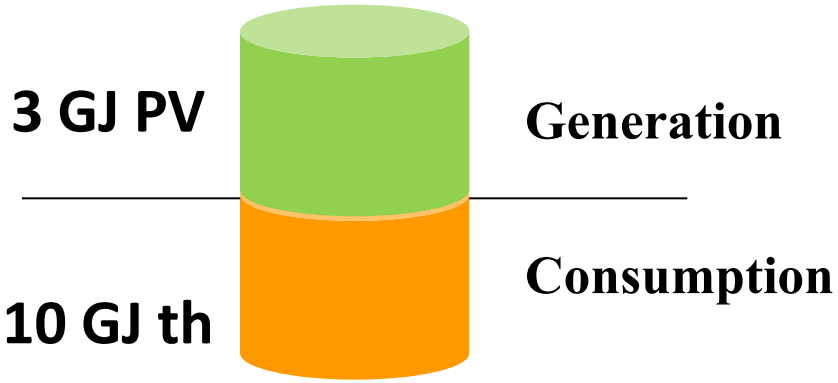
Thermal Insulating Value

Solar Heat Gain Coefficient

ZERO-Energy Building (ZEB)

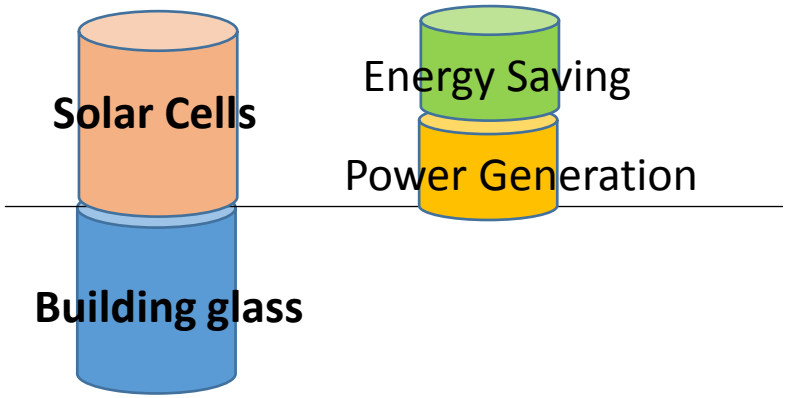
Demonstration of ZEB

~60 kW PV
Rooftop c-Si
Façade organic



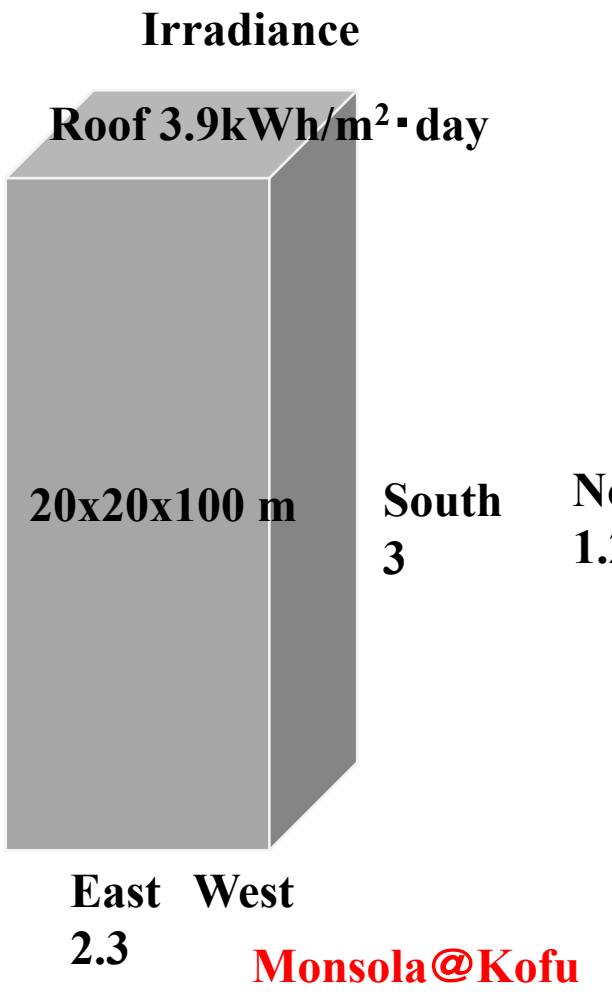
Source: Taisei Corporation

Benefit of BIPV



Cost Benefit Energy Benefit

BIPV Potential

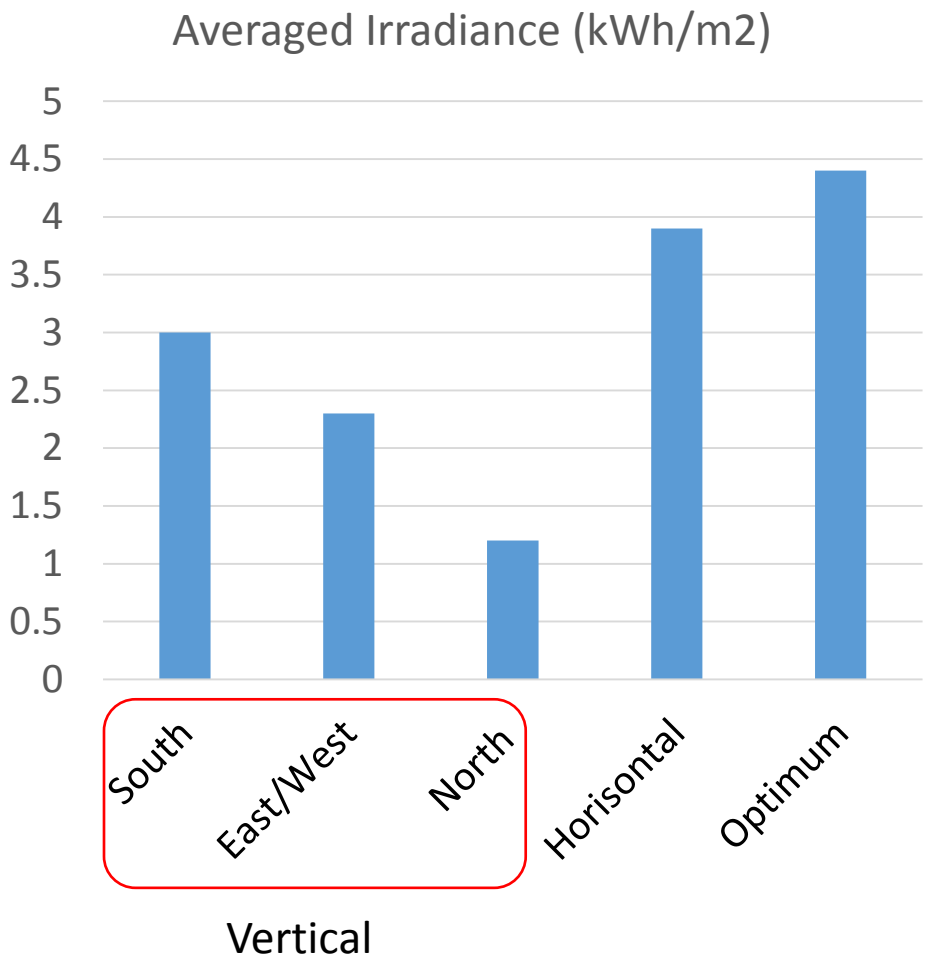


20x20x100m 30floor Building
Horizontal 3.9kWh/m² day
Power 110 MWh/year（@20%）

Perpendicular 8.8kWh/m² day
Power 1280 MWh/year（@20%）
Capacity ：1680kW
Total BIPV Power：1400 MWh/year

Power consumption
152 kWh/m²year (average)

Annual Consumption 1800 MWh/year



Less cost efficient due to vertical installation

Relevant Standards

- IEC 61215 – 1-X , -2 Design qualification
- IEC 61730 -1,-2 Safety qualification
- IEC 62980 Curtain wall
  (mainly on structural requirements)
- ISO 18178 (electrical requirements refer to IEC)
- EN 50583 Specific to BIPV
- No standards for measurements of energy efficiency (Cost benefit)

ISO18178 DIS

Glass in building — Laminated solar photovoltaic glass for use in building

Table 2 — The number, type and size of test specimens

Test	Number	Size (mm x mm)
High-temperature test	3	300×100 (Min Size)
Damp heat test	2	300×100(Min Size)
Radiation test	3	300×150[a](Min Size) 300×75(Min Size)
Thermal cycling	2	Product size
Humidity freeze	2	300×100(Min Size)
Hot-spot test	1	Product size
Measurement of NOCT	1	Product size
Impact test	4	876×1938 or the product size, whichever is smaller
Ball drop test	6	500 × 500(Min Size)

a The minimum size of method A for radiation test is 300mm×150mm,the minimum size of method B for radiation test is 300mm×75mm.

Issues

Independent standardization in multiple communities

Different culture and approach for standards between IEC and ISO (electronics and architecture)

Harmonization of IEC and ISO (EN and IEA)

Acknowledgements (BIPV)

Committee members
Sharp, Panasonic, Kyocera, Kaneka, Taisei Corp, Shimizu Corp, Lixil, F-Wave, NEDO, Mizuho IR, Toyo Univ. Univ. of Tokyo, Shibaura IT, AGC,NSG, JPEA,JEMA,PVTEC, Flat Glass Manufactures Association,

Supported by METI

Summary

- Standards to navigate the industries towards high-value market are crucial
- High insolation is beneficial and unknown risk should be considered
- High temperature test is a key to mitigate the risk
- BIPV is promising application and cost benefit should be quantified
- Proper standards (or guideline) are helpful to explore new markets.

Thank you for your kind attention !

IEC TS 62941 (QMS for PV Module Manufacturing) and PVQAT TG1 Survey

Feb.23, 2016

PVQAT Task Group 1

Govind Ramu(SunPower), Sarah Kurtz(NREL),

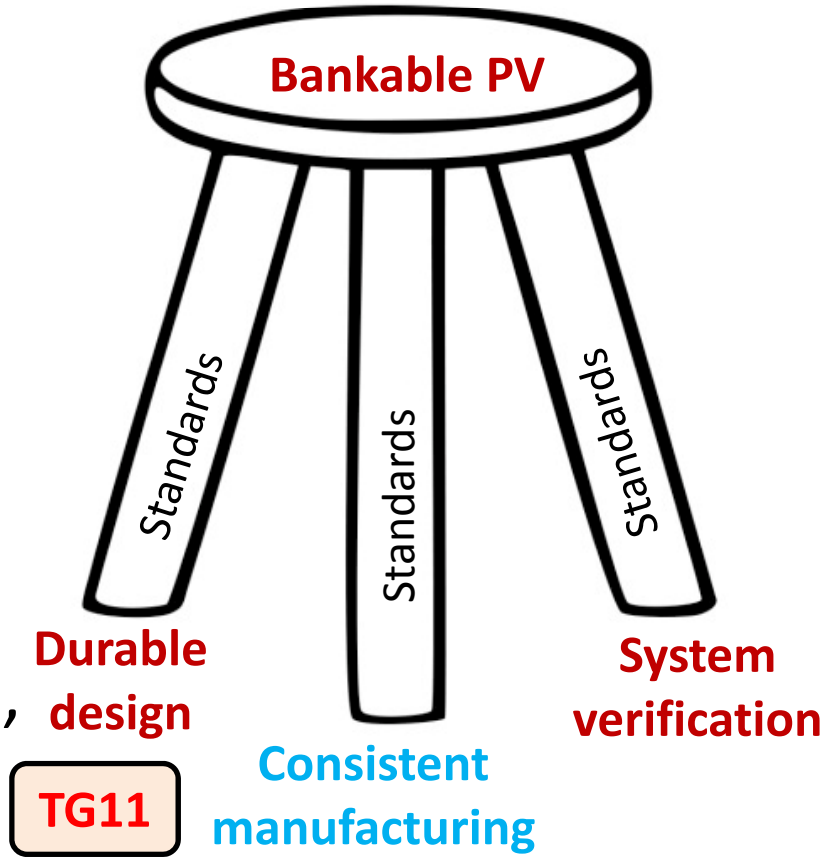
George Kelly(Sunset Technology), Masaaki Yamamichi(AIST)

Technical Challenges of PVQAT

1. How can we determine that a module design is adequate for the warranty?
   - Compressing 25 years of testing into 3 months is like trying to hatch a chick in 6 hours!
2. How can we ensure that modules coming off the production line reflect the intended design?
   - If something goes wrong and it takes us 3 months to discover it, we'll have a lot of out-of-spec modules!
3. How can we ensure that the entire system is put together and functioning correctly?
   - Even if all of the components are perfect, the system can fail in many ways

Three-prong efforts of PVQAT

1. *Qualification of durability of design of products* for chosen climate and mounting **Other TGs**
2. *Guide for audit of consistent manufacturing* of products built to that design **TG1**
3. *Certification process for system verification* to ensure adequacy of design, installation, and operation **TG11**



Manufacturing Consistency

- *How can we ensure that modules coming off the production line reflect the intended design?*
- PVQAT TG1 started discussion in 2011 to develop technical specification based on ISO9001-2008 to lay out best practices used in the manufacture of PV modules
- For more details of the discussion, please visit http://www.nrel.gov/docs/fy15osti/63742.pdf
- IEC TS 62941 *Guideline for increased confidence in PV module design qualification and type approval* was published Jan-29, 2016

Implementation of IEC TS62941

The following documents were developed and proposed to IECRE-PV for authorization

a) **Requirements for certification of a quality system for PV module manufacturing based on ISO/IEC 17021**

b) **Factory Audit checklist**

c) **Auditor requirements**

PVQAT Task Group 1 Next steps

- As IEC 62941 is now published and can be purchased from IEC website, we need to consider the next directions for PVQAT Task Group 1.
- Please take a few moments to complete the survey to identify efforts you would like to support toward implementation of IEC 62941 and toward taking it to the next level.

  https://www.surveymonkey.com/r/XSP5YXT

  or, email sarah.kurtz@nrel.gov
- We hope that we can launch new efforts with a renewed vigor.

volunteers needed

Survey to identify next challenges of TG1

The followings are topics covered in the Survey

- Development of IEC 62941 auditor guide and training materials
- IEC 62941 interpretation committee
- Strategies for marketing IEC 62941
- Extend IEC 62941 to module components (similar to Automotive industry PPAP)
- QMS guide for System components (e.g. Inverter, tracker, combiner box, etc.)
- Develop a standard on QMS for Module installation and O &M
- Benchmarking Metrics (similar to Telecom industry metrics program)
- translation of the IEC 62941 documents into other languages

Interim summary of the Survey results

Topics	# of TG1 Volunteers
Interpretation committee	8
Marketing strategies	5
Extend IEC TS62941 to component level	6
QMS guide for system components (inverters – 5, transformers – 1, sensors – 3)	5
QMS guide for installation and O &M	7
Benchmarking metrics	6
Translation help (Spanish, Japanese)	3

THANK YOU
FOR YOUR ATTENTION

Call for Working Group Members

CSA Group – Standardization for PV Module Durability (C450)

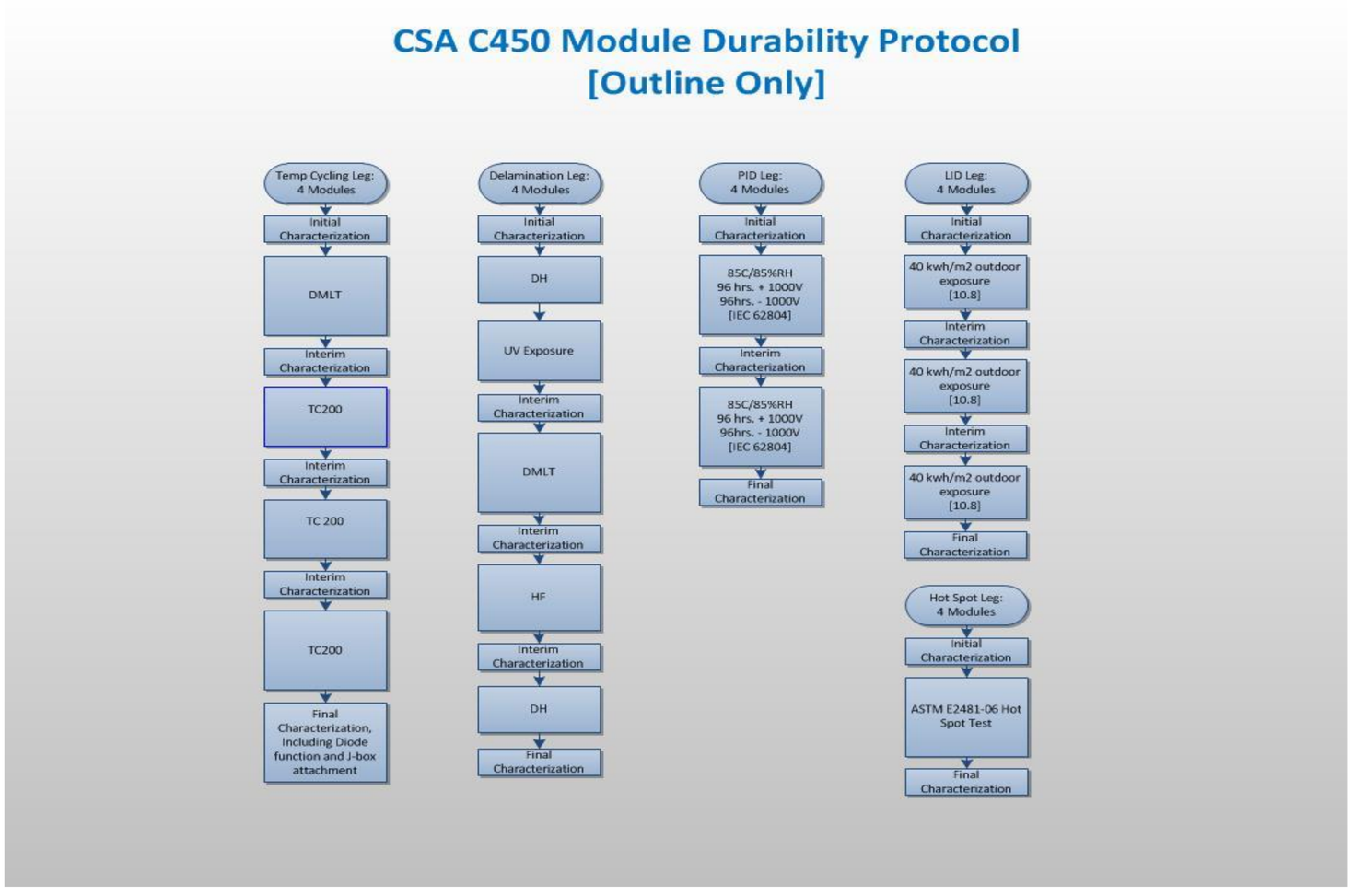
Based on a recent survey completed by CSA Group we had an overwhelming interest level from manufacturers, developers, banks and insurance companies to participate with CSA on the development of requirements for PV module durability.

We have taken the results of the survey and developed a durability protocol ("C450") which we are now pleased to solicit your comments on. The protocol incorporates much of the work done to date by NREL and the PVQAT Task Force, and feedback from many sources.

The guiding principles of C450 are:

- **A testing layer to augment existing qualification testing requirements**
- **Designed to provoke only failures that have been, or could be, seen in the field**
- **Module technology agnostic – i.e. should be adaptable to Si, CdTe, CIGS, etc.**
- **Preference for multiple exposures legs as opposed to long single exposures**
- **Interim characterizations as well as pass/fail to help map trends and create relative scores**
- **Reasonable testing times and cost (<5 months, < 100k USD, from survey averages)**
- **Climate specific parameters may be incorporated, but only after basic protocol established**

For further clarification or assistance with the application process, please contact Muktha Tumkur at 416-747-4045 or via email at muktha.tumkur@csagroup.org or Jim Crimmins at jim.crimmins@cfvsolar.com.

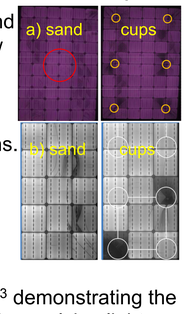


A Better Way to Bend:
Vacuum and Air Pressure for Mechanical Load Testing of Solar Panels

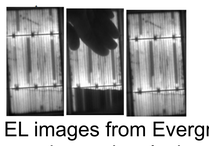
Andrew M. Gabor, Rob Janoch, Andrew Anselmo
BRIGHTSPOT AUTOMATION LLC, WESTFORD, MA 01886, USA

1. Background/Motivation

- Mechanical load testing is important to probe the durability of modules with respect to cell cracking, interconnect wire fatigue, solder bond integrity, and other concerns
  - IEC 61215 requires static load testing 1hour/side (3 times) at 2400Pa +/- 120Pa
  - Cyclic (dynamic) load testing is defined by IEC DTS 62782 as 1000Pa +/- 100Pa in both directions at 3-7 cycles/min for 1000 cycles
  - Faster and longer cyclic loading or loading at higher levels is often implemented by R&D groups for accelerated durability testing
- Point loading by the suction cup method can lead to excessive cell cracking under the suction cups, especially if they are spaced too far apart
- Prior work at Evergreen Solar showed that pre-existing cracks can be temporarily opened by applying light pressure to the front side
  - This allows visualization (EL) and quantification (IV) of the impact of these cracks were they to open up in the field
  - But the standard suction cup, air bladder, and sandbag methods block access to the front side for such characterization
- We have designed the *LoadSpot* tool to apply uniform pressure and to allow characterization from the front side by using the approach of vacuum/air-pressure applied to the rear side of the modules



EL images from a) Samsung[1] and b) Fraunhofer ISE[2] showing how suction cups load tools can introduce point loading that damages cells preferentially beneath the suction cup locations.

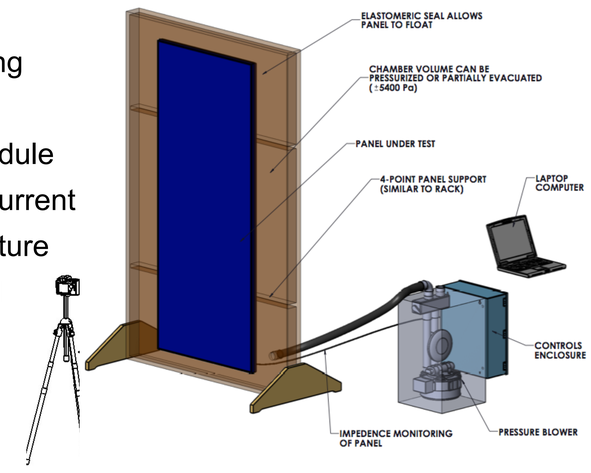


EL images from Evergreen Solar[3] demonstrating the opening and reclosing of cracks by applying light pressure on the glass

Load testing by a) Sand bags (Solarworld), b) air pressure bag (DNV-GL), c) vacuum cup system (PSE AG), and vacuum/air-pressure cavity (Jabil)

2. *LoadSpot* Design

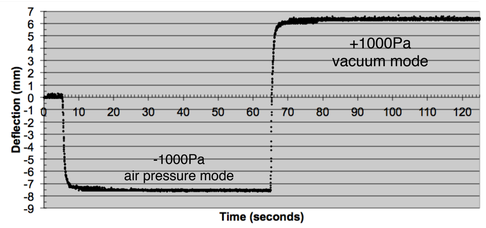
- The prototype *LoadSpot* tool was designed and built to:
  - Be easily adjustable for a wide range of module sizes (framed and unframed) and clamping hardware and clamping locations
  - Allow effective sealing of the rear vacuum/air-pressure cavity without applying significant forces on the module's edges that would restrict their movement
  - Apply > +/-2400Pa static loads
    - +5400Pa heavy snow-load goal
  - Apply cyclic loads at rates > 7 cycles/min
  - Allow completely open access to the front side for characterization and access to the rear-side J-box or cables
  - Apply forward voltage bias for EL testing
  - Monitor continuity of the circuit
  - Measure deflection in the center of module
  - Resistively heat module with forward current
  - Allow testing under controlled temperature
    - Temperature range to be determined

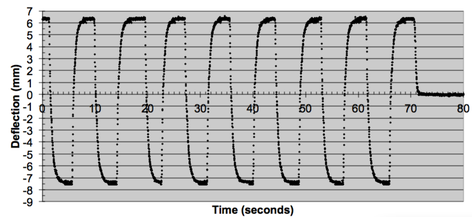


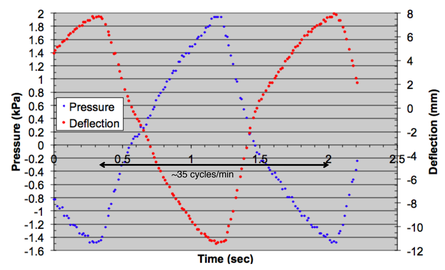
Simplified conceptual schematic of *LoadSpot* design

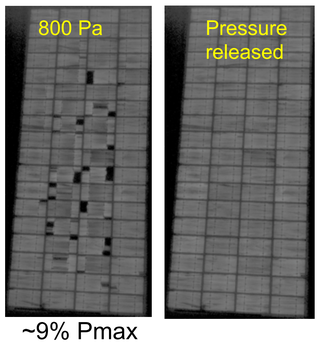
3. Prototype *LoadSpot* Data

- Manual actuation of the valve controlling rear-side vacuum/air-pressure shows:
  - Static tests at a fixed valve position indicate stable control of pressure and deflection even before implementation of feedback control
  - Static values in excess of +/-2400Pa have been achieved. However, a stronger blower is needed to reliably reach 5400Pa.
  - Flipping the valve between vacuum and air-pressure easily shows a cycling rate faster than the required 7 cycles/min
  - If no dwell is required at the peak pressure values, then we can achieve cycling rates > 35 cycles/min at pressures much higher than +/-1000 Pa









~9% Pmax degradation

- With application of vacuum from the rear side (800Pa front side pressure):
  - Pre-existing cracks can be opened up and imaged by EL
  - The difference in IV measurements between the crack-open and crack-closed states can be calculated to predict the potential future Pmax degradation in the field were these cracks to open up

4. Conclusions

- We have built a prototype mechanical load testing tool that has some advantages over traditional testing methods and tools in terms of pressure uniformity and the ability to perform IV and EL testing under load
- We have demonstrated a crack-opening test under low front-side loads that can serve as a quick predictor of potential module degradation in the field
  - The test is much quicker, easier, and non-destructive in comparison to using humidity-freeze and thermal cycling to "open up cracks" and thus R&D cycles can be performed more quickly at lower cost
  - By gradually increasing pressure, one can observe when/where cracks form to help optimize panel design and manufacturing[4]
- All load tests in IEC 61215 and IEC DTS 62782 can be performed
  - Cyclic loading can occur as fast as 35 cycles/min (0.58Hz) if no dwell is required
- The *LoadSpot* prototype design appears sound. Final market input is being collected for the commercial design, with shipments to commence by Q3 2016.

COMPARISON OF MECHANICAL LOADING METHODS

Factor	Sand bags	Suction Cups	Air bladder	Vacuum/ Air Pressure
Static test	Manual Flip	Auto	Manual Flip	Auto
Cyclic test	No	Yes	One direction	Yes
Point loading	No	Yes	No	No
Test with racking	Top static	Yes	Top static	No
Simultaneous EL/IV	No	No	No	Yes

5. References

[1] D. Baek, Presentations of the 2014 NREL Photovoltaic Module Reliability Workshop (Golden, CO, USA, 2014), Retrieved 15Jan2016 from www.nrel.gov/pv/performance_reliability/pvmrw_2014.html
[2] G. Mülhöfer, et. al., Proceedings 28th EUPVSEC (WIP, Paris, France, 2013) p. 2968
[3] A. M. Gabor, et. al., Proceedings 21st EUPVSEC (WIP , Dresden, Germany, 2006) p. 2042
[4] A. M. Gabor, et. al., to be published, Proceedings 43rd IEEE PVSC (Portland, OR, USA) 2016.

Calibration of Photodiodes for UV Irradiance Measurement in Module-Scale UV Exposure Chambers

Michael Gostein and Bill Stueve
Atonometrics, Inc.

NREL PV Module Reliability Workshop, February 2016

ATONOMETRICS

www.atonometrics.com

This presentation does not contain confidential information.

Introduction

- UV exposure key part of PV reliability testing
- UV irradiance must be measured in situ
- IEC 61215 requires irradiance measurement uncertainty < 15%
- SiC photodiodes good UV sensors
- Accurate sensor calibration must consider *spectral* and *angular* response of sensor
- Module-scale UV exposure chambers may have broad angular distribution of irradiation
- We use an angular correction factor to calibrate sensor for use in module-scale chamber

Measurement Equation

$$G = K_a \cdot K_s \cdot \frac{I_{sc}\left(1 - \alpha\left(T - T^{cal}\right)\right)}{I_{sc}^{cal}} \cdot G^{cal}$$

G	Measured UV irradiance
K_a	Angular correction factor
K_s	Spectral correction factor
I_{sc}	Photodiode short-circuit current
I_{sc}^{cal}	Photodiode short-circuit current at calibration
α	Photodiode short-circuit current temperature coefficient
T	Photodiode temperature
T^{cal}	Photodiode temperature at calibration
G^{cal}	UV irradiance at calibration

Angular Correction Factor

$$K_a = \frac{\int F^{cal}(\theta) \cdot R(\theta)\, d\theta}{\int F(\theta) \cdot R(\theta)\, d\theta}$$

$F^{cal}(\theta)$	Fraction of the incident irradiance at angle θ, per unit angle, at time of calibration
$F(\theta)$	Fraction of the incident irradiance at angle θ, per unit angle, at time of measurement
$R(\theta)$	Relative response of sensor at angle θ

Spectral Correction Factor

$$K_s = \frac{\int F^{cal}(\lambda) \cdot R(\lambda)\, d\lambda}{\int F(\lambda) \cdot R(\lambda)\, d\lambda}$$

$F^{cal}(\lambda)$	Fraction of the incident irradiance at wavelength λ, per unit wavelength, at time of calibration
$F(\lambda)$	Fraction of the incident irradiance at wavelength λ, per unit wavelength, at time of measurement
$R(\lambda)$	Relative response of sensor at wavelength λ

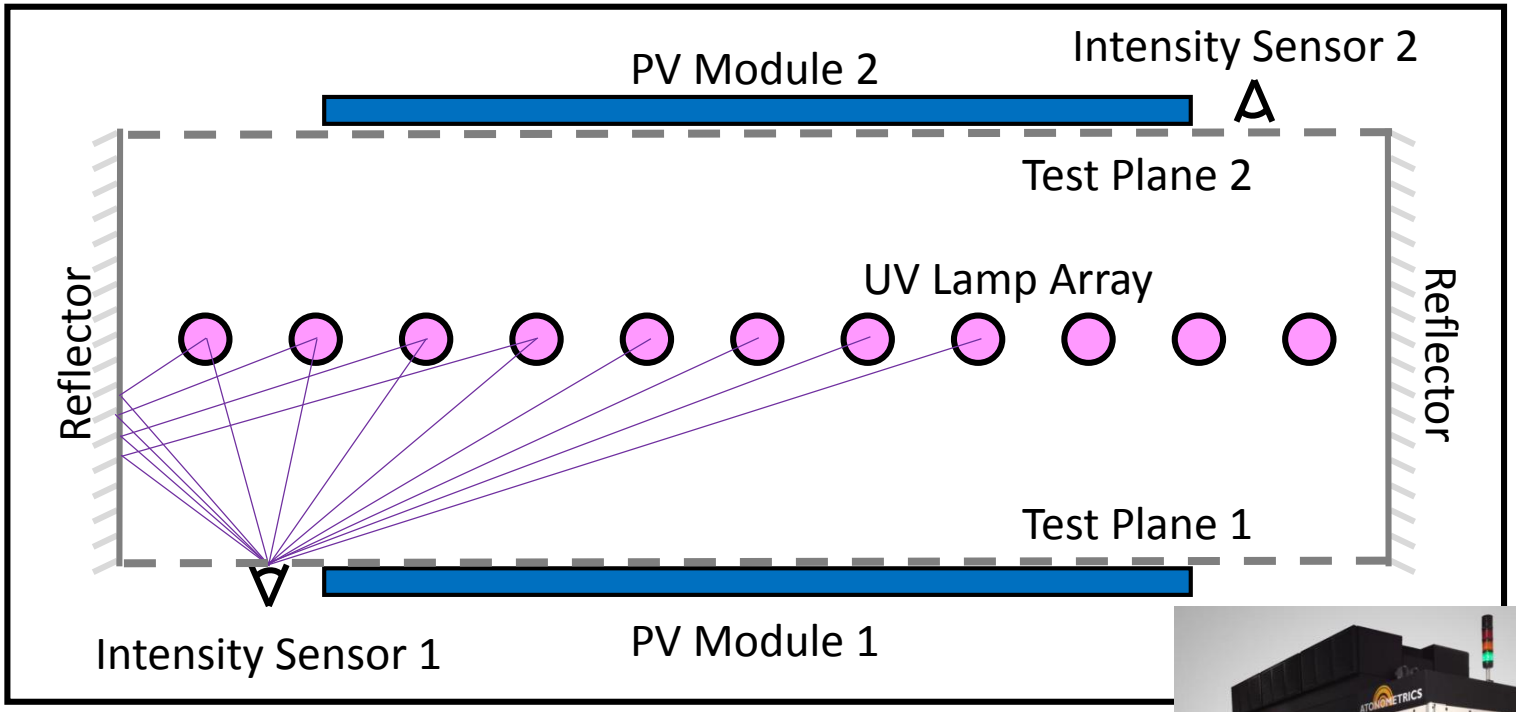
Module-Scale UV Chamber

- Module-size target planes
- Compact footprint

- → broad angular distribution of irradiance

UV Chamber Geometry

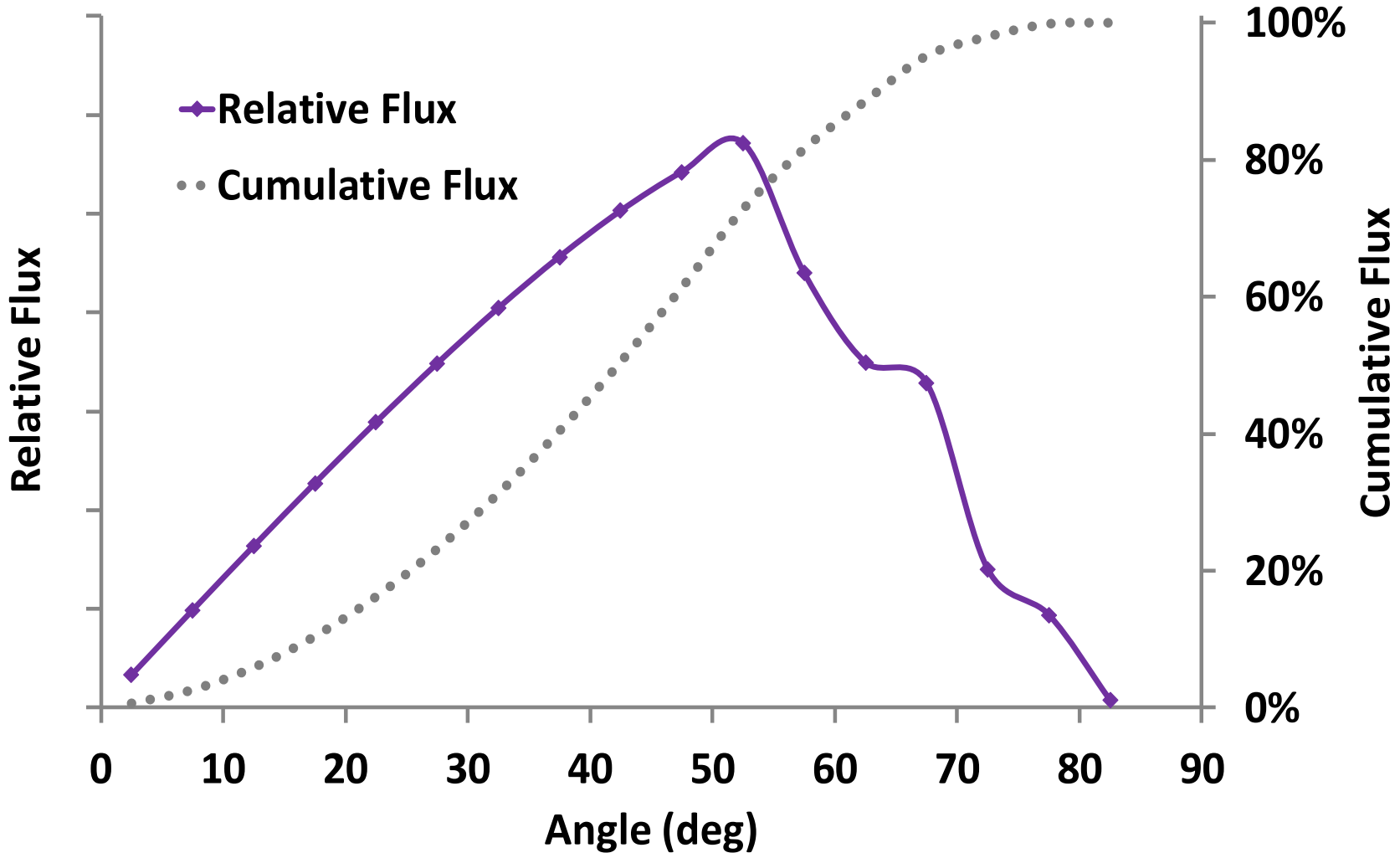
Test Chamber, Plan View



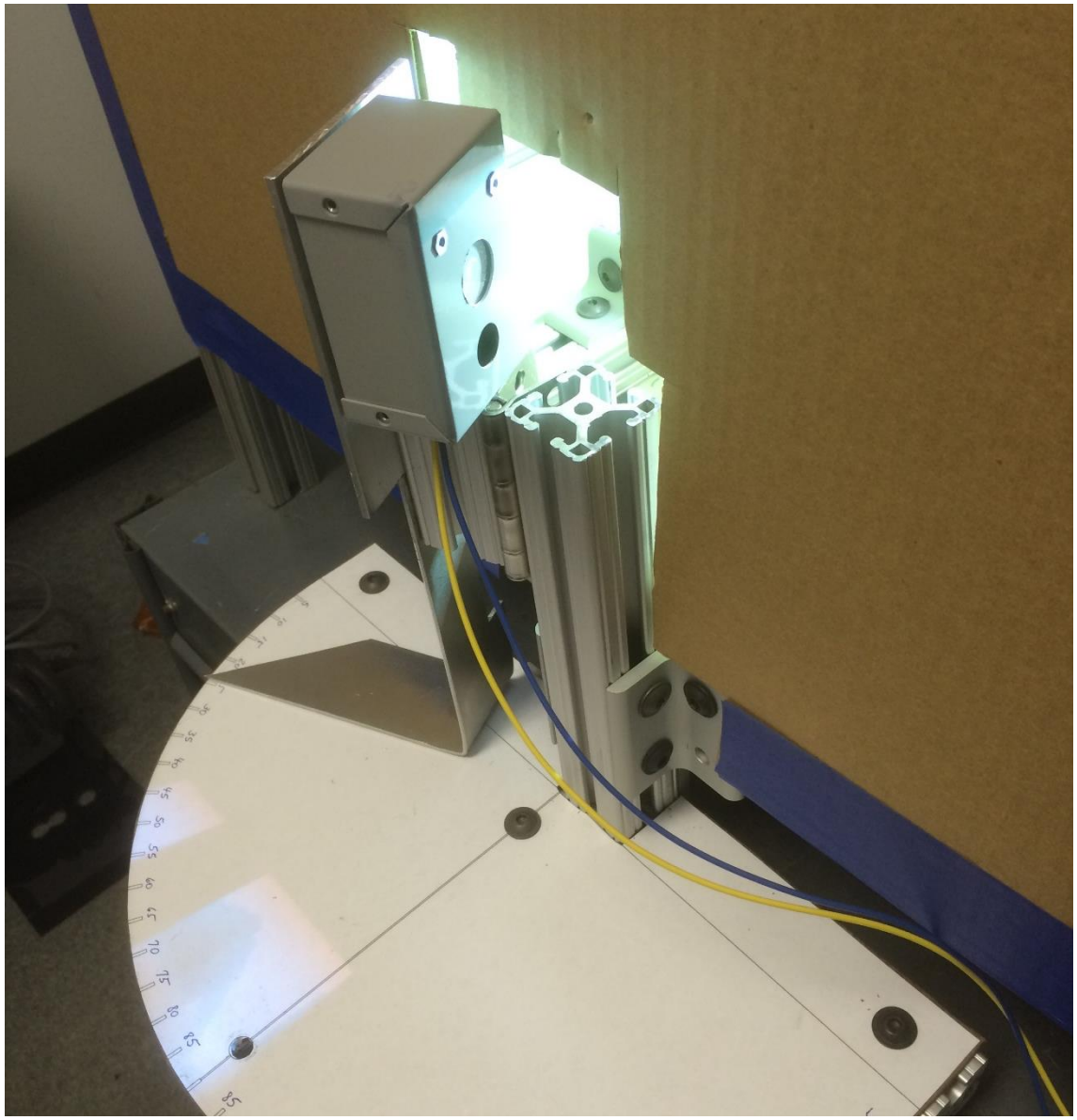
Large lamp array + compact footprint

→ broad angular distribution of irradiance

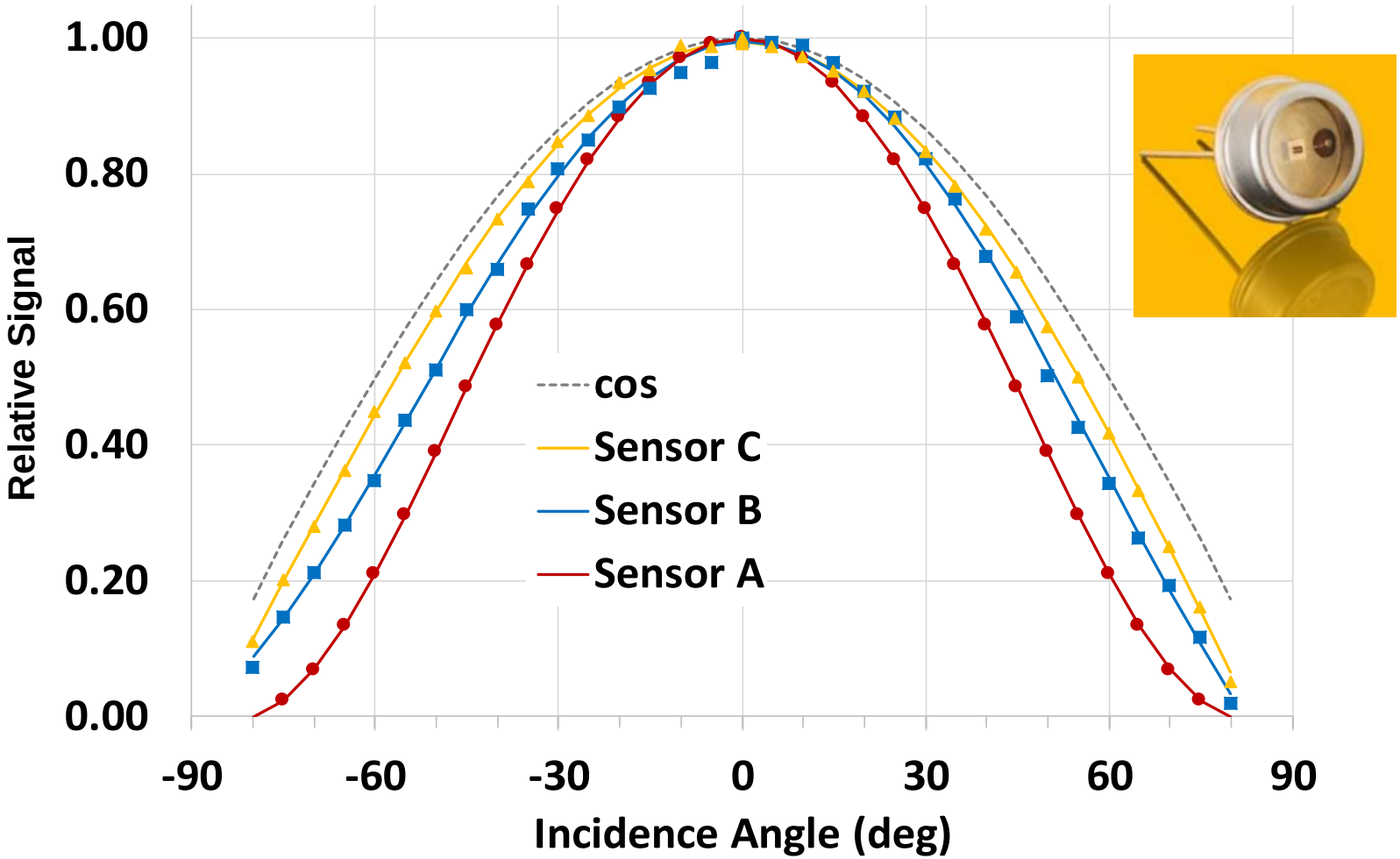
UV Irradiance Versus Incidence Angle



Irradiance Sensor Goniometer

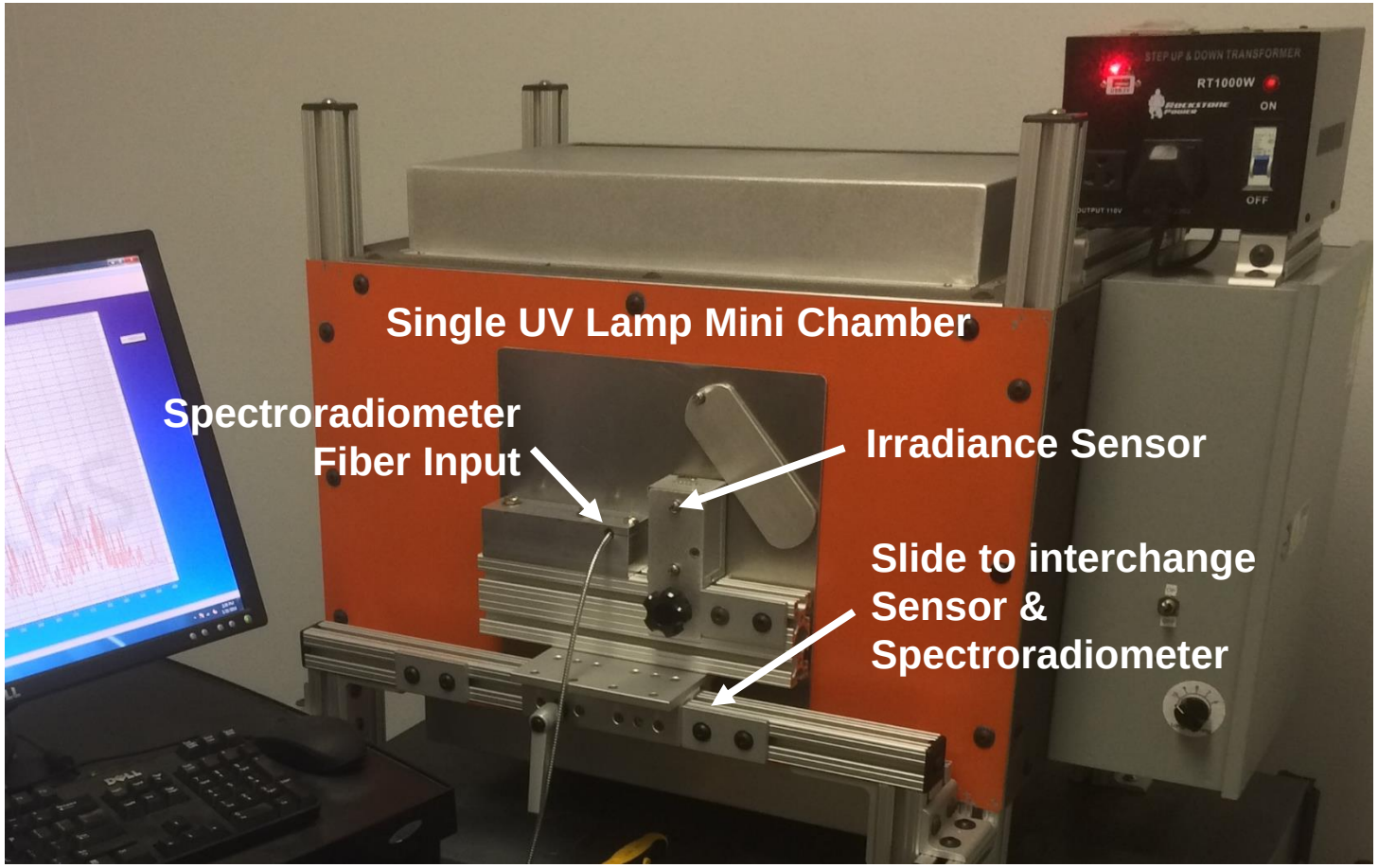


UV Sensor Angular Response



$R(\theta)$ = Relative Signal / $\cos(\theta)$

Calibration Fixture



Single lamp + aperture = collimated beam → Simplifies K_a

Same lamp as UV chamber → Simplifies K_s

Angular Correction Factor Results

	Photodiode	Diffuser	K_a
Sensor A	SG01M-18S	None	1.53 ± 0.06
Sensor B	SG01S-5	Quartz DGUV10-120	1.22 ± 0.03
Sensor C	SG01S-5	Teflon sheet	1.12 ± 0.02

Conclusions

- Careful calibration is required for accurate measurement of UV irradiance in a module-scale UV exposure chamber
- Both spectral and angular corrections to the calibration are required
- The angular correction depends on the sensor angular response AND the light source angular distribution – calibration is chamber-specific
- Angular correction factors can be significant, e.g. 1.1 to 1.5
- Ignoring angular correction factor may lead to additional 10-50% measurement error

Coordination of International Standards with Implementation of the IECRE Conformity Assessment System

NREL PVMRW

February 23-25, 2016

Lakewood, Colorado, USA

George Kelly (Sunset Technology)

Summary

- Projected Development Times
  - TC82 standards
  - PVOMC operational documents
  - IECRE PV Certificates
- Performance Indicators
  - TC82 in ‘Top 10’ for Sales
  - ‘PVQAT Effect’ on TC82 Work
  - TC82 Productivity ‘Outstanding’

TC82 Standards Development

Item	Resp	2015 O	N	D	2016 J	F	M	A	M	J	J	A	S	O	N	D	2017 J	F	M	A	M	J	J	A	S	O	N	D
TC82 Documents																												
62446-1 Ed 2 Commissioning	WG3				PUB																							
62446-2 Maintenance	WG3									CD						CDV						FDIS			PUB			
TS 62446-3 Outdoor IR	WG3				CD					DTS				PUB														
61724-1 Monitoring	WG3						CDV						FDIS			PUB												
TS 61724-2 Capacity evaluation	WG3	CD					DTS				PUB																	
TS 61724-3 Energy evaluation	WG3				DTS				PUB																			
TS 61724-4 Degradation rate	WG3				NP					CD					DTS				PUB									
TS 63019 Availability	WG3					CD					DTS				PUB													
62548 Ed 2 Array design	WG3	CDV								FDIS				PUB														
TS 62738 Power plant design	WG3						DTS				PUB																	
TS 6xxx Installation QMS	WG3	NP						CD					DTS				PUB											
TS 62941 Module QMS	WG2				PUB																							
TS 62915 Retest guidelines	WG2						DTS				PUB																	
61215 Ed 3 Module qual	WG2		FDIS				PUB																					
61730 Ed 2 Module safety	WG2					FDIS				PUB																		
TS 62915 Ed 2 Retest guidelines	WG2									NP					CD					DTS					PUB			
62093 Ed 1 BOS qual	WG6																											
62093 Ed 2 BOS qual	WG6										CD						CDV						FDIS			PUB		
62109-2 Inverter safety	WG6																											
62817 Tracker qual	WG7							Am1																				
TS 6xxxx Disposal	tbd									NP					CD					DTS					PUB			

Key:

International Standard							CD						CDV						FDIS			PUB						
Technical Specification	NP						CD					DTS				PUB												
Critical Path Item	NP							CD					DTS				PUB											
Example - minimum time	NP						CD					DTS				PUB												

PVOMC operational documents

Item	Resp	2015 O	N	D	2016 J	F	M	A	M	J	J	A	S	O	N	D	2017 J	F	M	A	M	J	J	A	S	O	N	D
PVOMC Documents																												
RoP Ed 2	WG401				WG		NC	OMC																				
OD 405-1 QMS cert	TG1				WG			NC	OMC																			
OD 405-2 audit checklist	TG1				WG			NC	OMC																			
OD 405-3 auditor reqmts	TG1					WG		NC	OMC																			
OD 410-1 conditional cert	WG401				WG		NC	OMC																				
OD 410-2 annual cert	WG401				WG		NC	OMC																				
OD 410-4 design cert	tbd					WG		NC			OMC																	
OD 410-8 annual maint	tbd					WG		NC			OMC																	
OD 420 Data Reporting	WG404						WG		NC			OMC																
Additional Categories under discussion:																												
Site Qualification Cert																												
Plan qualification																												
Asset transfer/Residual value																												
Annual maintenance cert																												
Disposal Cert (EXAMPLE)											=== =		=== =		=== =		=== =	=== =		=== =		=== =		=== =		=== =	>>> >
TS 6xxxx	TC82										NP					CD					DTS				PUB			
OD 410-x	OMC																	WG		NC		OMC						
RECB Setup	RECB																											
Certificate Available																												

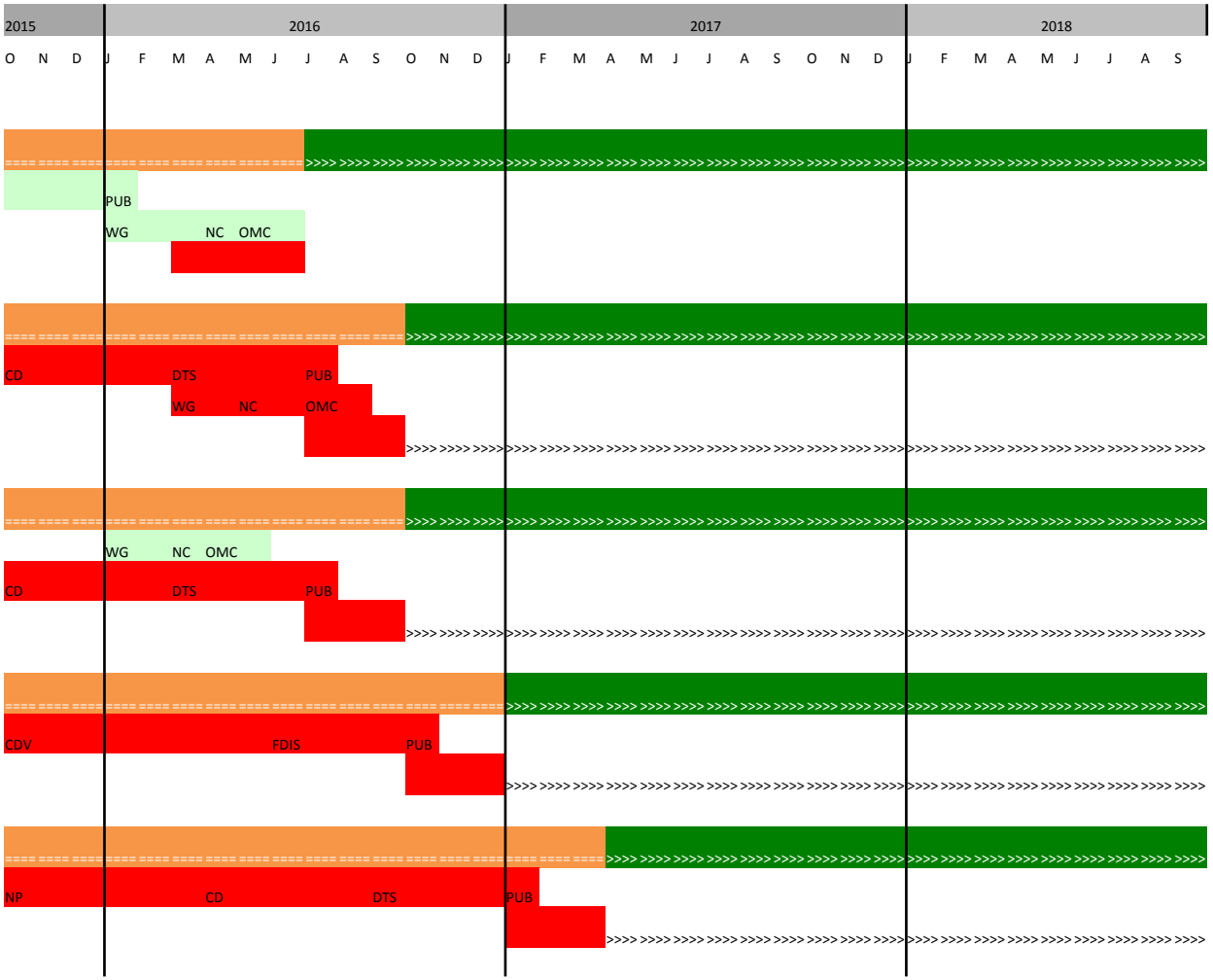
Key:

Document in progress	WG	NC	OMC
Critical Path Item	WG	NC	OMC
Example - minimum time	WG	NC	OMC

WG = Working Group
NC = National Commmittees
OMC = Final Approval

IECRE PV Certificate Categories

Item	Resp
Certificate Offerings	
name / reference	Resp
QMS Cert	
TC82 documents	WG2
PVOMC documents	OMC
RECB Setup	RECB
Conditional Cert	
61724-2	WG3
OD 420	OMC
RECB Setup	RECB
Annual Cert	
OD 410-1	OMC
61724-2	WG3
RECB Setup	RECB
Design Cert	
62548	WG3
RECB Setup	RECB
Construction completion	
Installation QMS	WG3
RECB Setup	RECB



TC82 in ‘Top 10’ for Sales

Financial overview

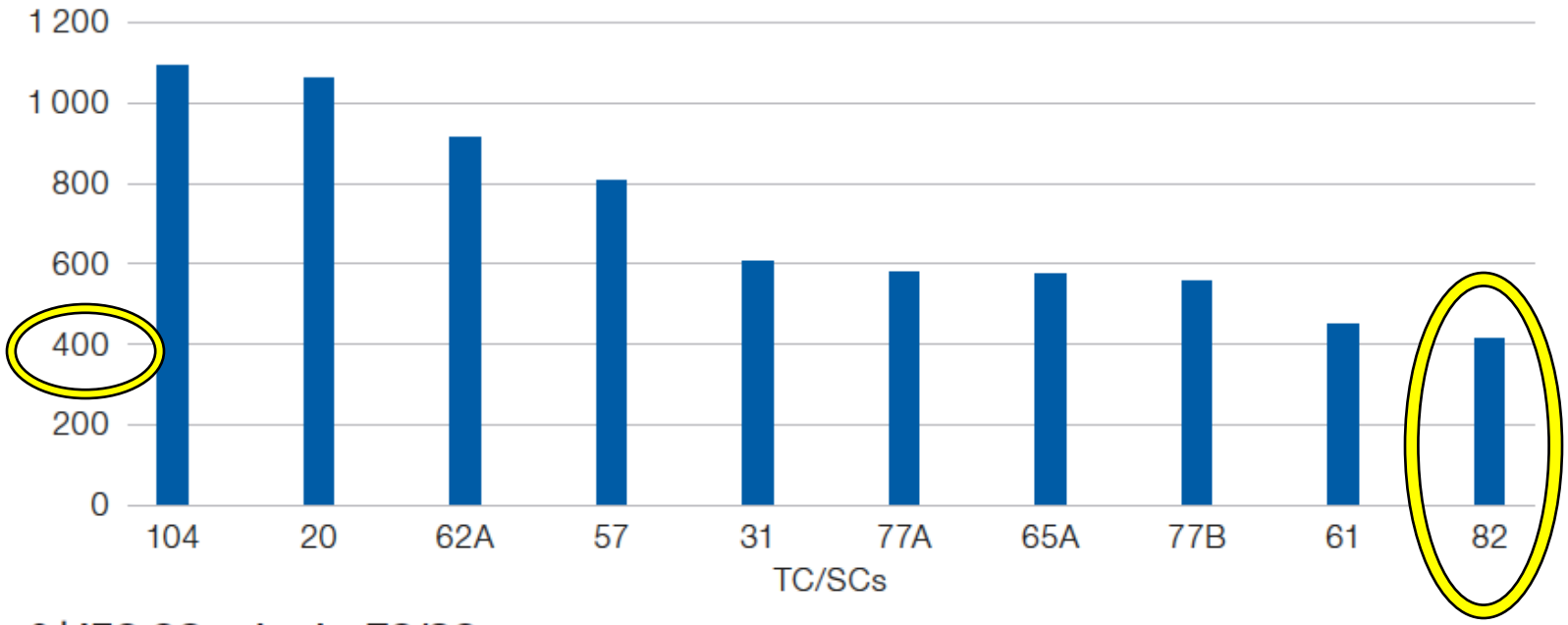


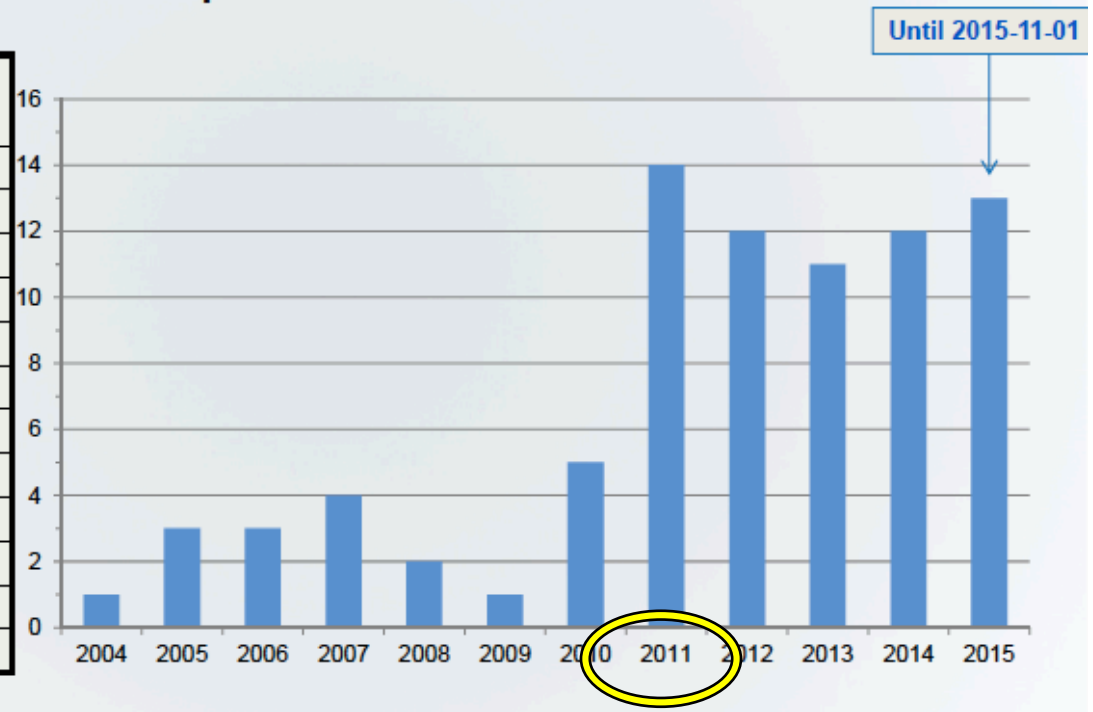
Figure 9 | IEC CO sales by TC/SCs

Source: 2015 IEC General Secretary’s Report

‘PVQAT Effect’ on TC82 Work

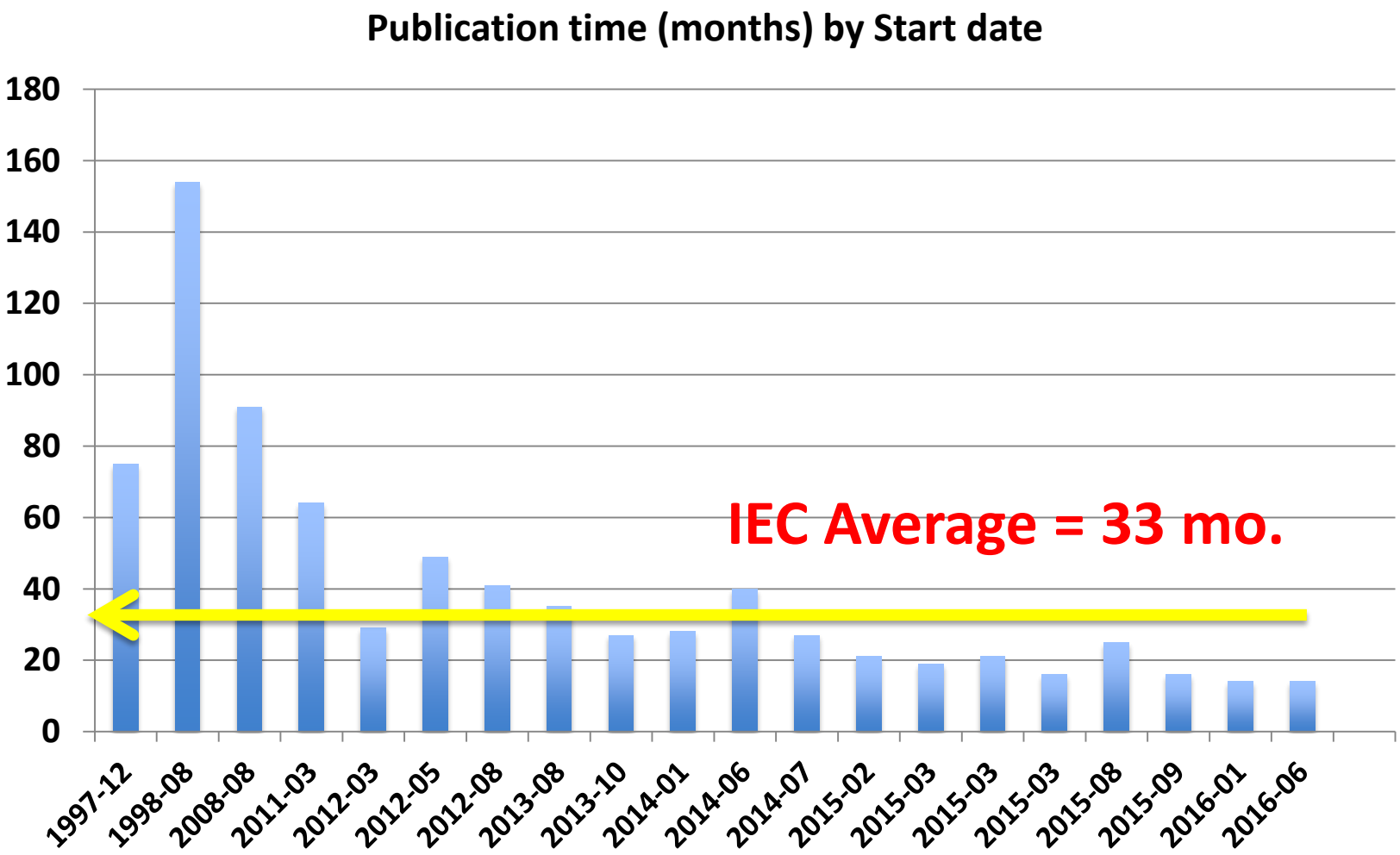
Number of New Proposals launched in IEC TC 82

Year	No. of NWIPs
2004	1
2005	3
2006	3
2007	4
2008	2
2009	1
2010	5
2011	14
2012	12
2013	11
2014	12
2015	(13)



Remarkable development, demonstrating importance and visibility of IEC standards in the field of solar photovoltaics

TC82 Productivity 'Outstanding'



Thank You !!

Photo Credit: K. Kurokawa

Mechanical Load Test of PV Modules:
Physical Contact between Backsheet and Rails at 5400 Pa

We build a better future
HYUNDAI HEAVY INDUSTRIES CO.,LTD.
GREEN ENERGY

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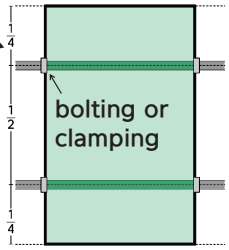
Motivation

- For the static mechanical load testing (MLT) of PV modules, IEC 61215 (ed.2, 2005) includes the following clauses:
  1. *10.16.2 Apparatus, a) ... The test base shall enable the module to **deflect freely** during the load application.*
  2. *10.16.3 Procedure, b) Mount the module on a rigid structure using the **method prescribed by the manufacturer**...*
- Many module manufacturers specify that their products can withstand 5400 Pa front normal load when installed directly on two rails like this.
- In reality, a module under 5400 Pa bows more than the frame thickness when allowed to deflect freely. Applying 5400 Pa on a rail-mounted module results in physical contact between the backsheet and the rails.
- Which is more important?
  "Free deflection" or manufacturer-prescribed mounting method?
  What is the correct method of doing the 5400 Pa MLT?



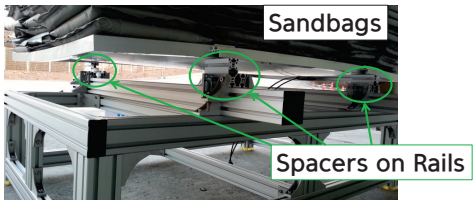
Glass Thickness	ΔZ*
3.2 mm	−44 mm
2.8 mm	−55 mm

* Maximum vertical displacement of the backsheet along the rail lines under 5400 Pa at 25°C, for 1.6 m² glass/cell/polymer modules with 35 mm frames, when allowed to deflect freely

Proposed Approach

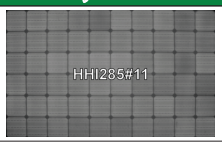
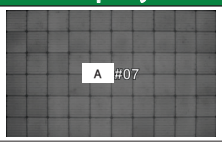
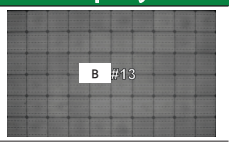
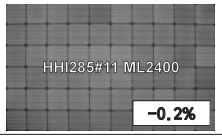
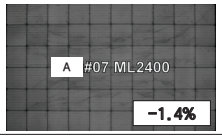
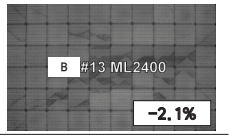
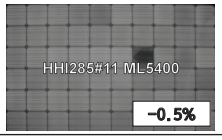
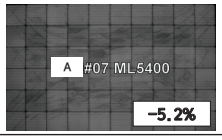
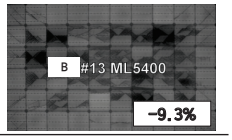
Test with free deflection and Inform customers of the necessary bottom clearance.

1. Design test bases to allow free deflection.



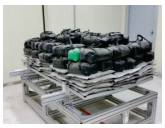
2. Provide **max displacement versus load** information on the installation manual.

We tested PERC modules from 3 manufacturers.
All modules specify maximum front load of 5400 Pa on the datasheets.

Stage	Hyundai	Company A	Company B
Initial			
2400 Pa (3 cycles front/back)			
5400 Pa (additional 5400 Pa front /2400 Pa back)			

Alternative Approach?

Accept limited deflection and Develop a new standard for backsheet durability.



1. Mount directly on rails, and accept physical contact at 5400 Pa.
   In the new 61215-2 draft:
   *4.17.2 Apparatus, a) ... The test base shall enable the module to deflect freely during the load application **within the constraints** of the manufacturers' prescribed method of mounting.*

   In this setup, a module deflects less because it is supported underneath. When tested this way, even B's module shows acceptable power loss.

2. Develop a new standard to test **the reliability of backsheet after repeated contacts with the supporting structure.**

Discussion

- Module manufacturers, and possibly even the certification bodies, seem to have different opinions on how to do the 5400 Pa MLT correctly.
- The upcoming revision to IEC 61215 allows backsheet-rail contact during MLT.
- Should we complement the revised IEC 61215 with a new standard on the durability of the backsheet against physical damage?
  - How can a supporting structure be defined? With surface roughness?
  - Can the standard represent real-world cases? Soiling? Railess mounting on roof tiles?

The US TAG

What is it?

Why should I care?

What is It?

The term **TAG** stands for **"Technical Advisory Group"**

It is a group of experts from businesses, Government, Financial Interests, Universities, & Research Laboratories from around the world that have a common interest in the betterment of a need or philosophy by establishing an international standard.

Why should I care?

The need to be involved or "care" is because the Group originates, refines, determines performance, acceptance, applicability, and heavily influences standards that are established to unify the behavior of the idea or in this case a **"product"** called **Photovoltaic's**.

Within the US, the Photovoltaic Technical Action Group or TAG is assigned to the American National Standards Institute called **ANSI**, headquartered in Washington DC and New York City, who act as the official voice of the US interests within the International Electrotechnical Commission (**IEC**) which is part of the International Standards Organization (**ISO**) headquartered in Geneva Switzerland. In the case of Photovoltaic's the TAG is part of an IEC Technical Committee number 82.(**TC 82**)

What does being a member of the US TAG do for me or my company?

Joining the US TAG allows you to propose new items to be considered for standardization and play a role in the evolution of the standards. Furthermore it allows you to contribute to the technical accuracy and applicability of the standard.

What are my Responsibilities?

Your responsibilities as a TAG member are to read and consider new proposals for standards. Read and provide improvements for standards in the process of achieving acceptance within the IEC TC 82 and eventually the world community.

What is the Cost to be a member?

At present, the cost of joining the US TAG is $295.00 participation dues that are paid to ANSI as part of their operating cost. (Unlike other countries, the US Standards organizations are funded through the collection of dues and are not directly supported by the Government.)

How do I join the US TAG?

You may join the US TAG by contacting either one or both of the following people, and expressing your interest with a short description of your expertise and providing your official contact and billing information. George, and I will inform Mr. Kevin Sullivan of ANSI to send you a $295.00 invoice. Upon payment of the invoice you will receive a user name and a temporary password to be able to use any of the website materials.

Our contact information is:

Alex Mikonowicz, US TAG TA or Manager
AlexMikonowicz@Powermark.org

George Kelly, TC 82 Secretary and US TAG Secretary
solarexpert13@gmail.com

Both of us will be happy to assist you.

Solar cell Reliability Simulator (SORES)

And

Its Applications

2016. 2. 23.

Soo-Young Oh, Wonshoup So, Minsoo Kim, Jae Hak Jung

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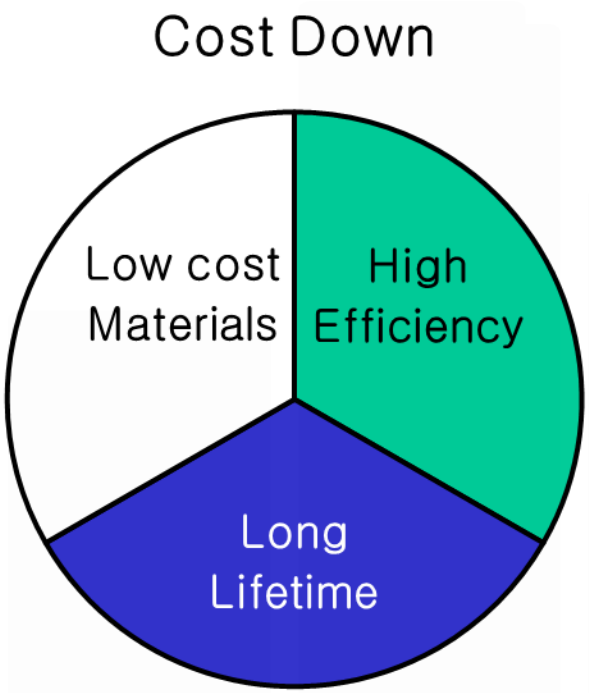
Email: syoh@ynu.ac.kr

1. Introduction : Cost Down

○ **The Name of the Game in PV Industry is "Cost Down".**

○ **The Means of Cost Down need Reliability testing**



1. Introduction : Reliability Testing

○ Problems of PV Reliability Testing

► **Qualification** : Pass/Fail (No data available)

(Lab Acelerated Stress Test : AST) : No Guarantee of Lifetime

Time-consuming(3~6Month) & Expensive

► **Outdoor Field Testing** : Too Long to get Results. (>20 Years)

- Existing PV Power Plants have a lot of Data:

  * Not well Characterized & Monitored.

  * Difficult for quantitative analysis

1. Introduction : Missing Link

Quantitative Relation : ?

Qualitative Relation : Yes

Lab Accelerated Stress Test (AST)

Outdoor Field Performance

1. Introduction : Missing Link

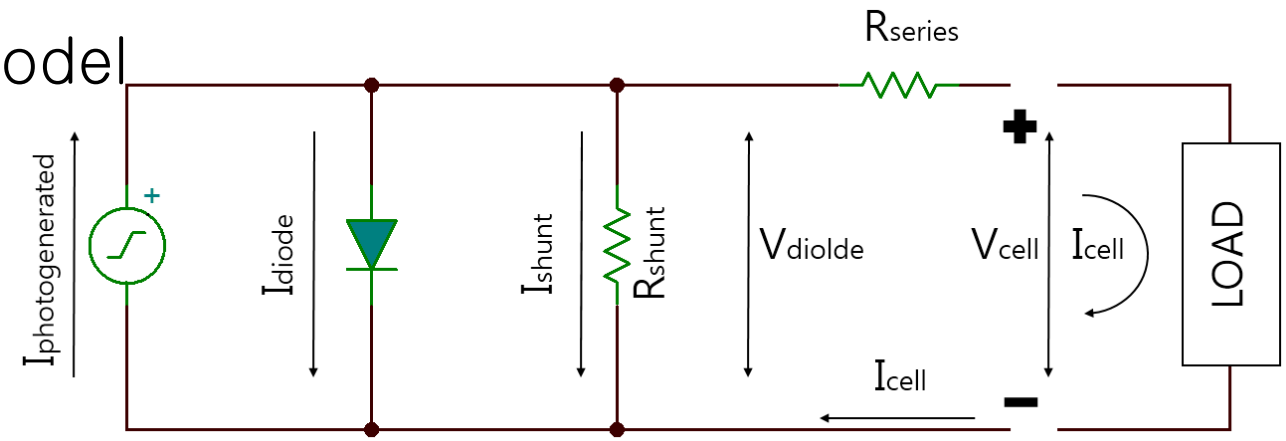
Missing Link = Solar Cell Numerical Simulation

Quantitative Relation : SORES

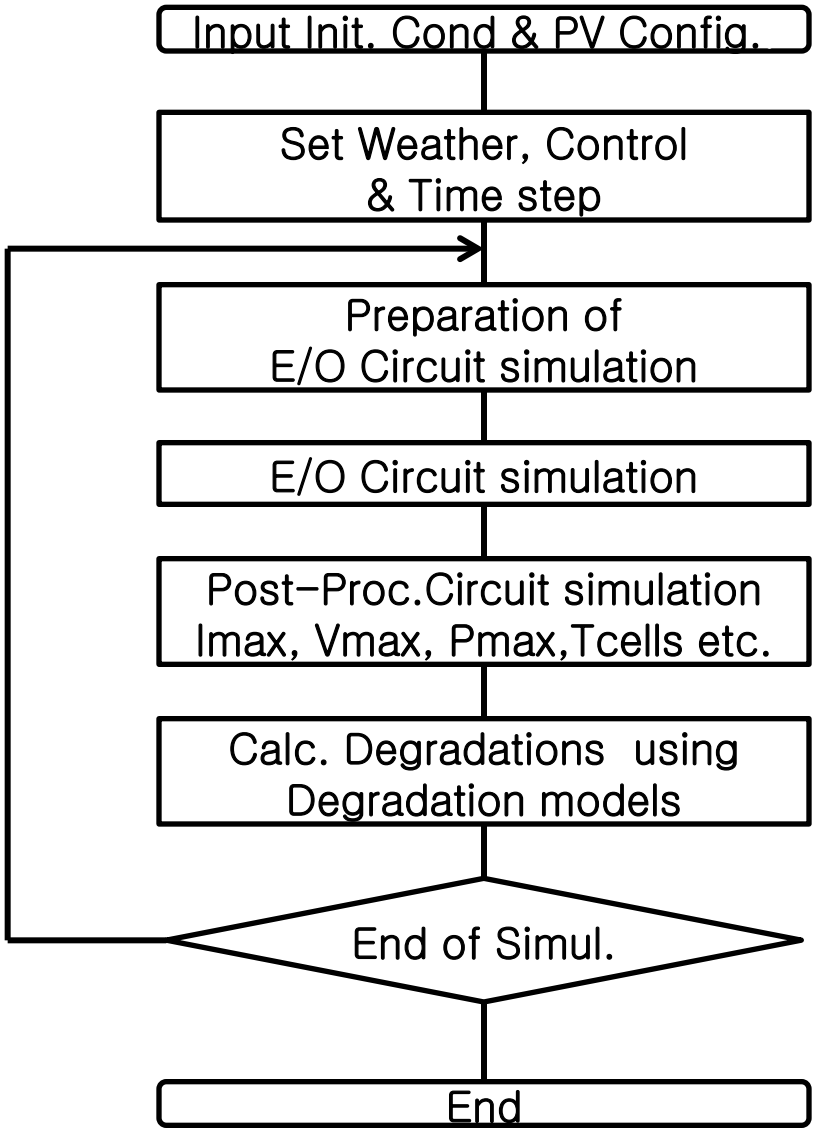
Need Relation

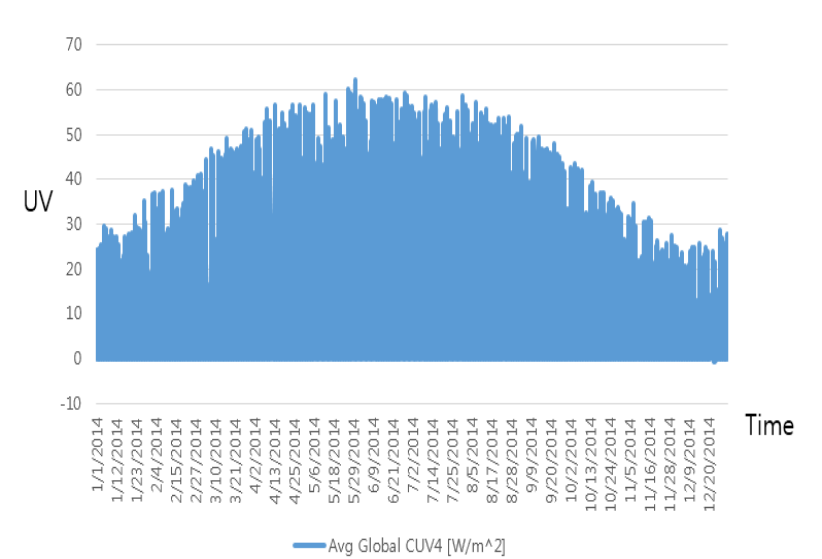
Qualitative Relation : Yes

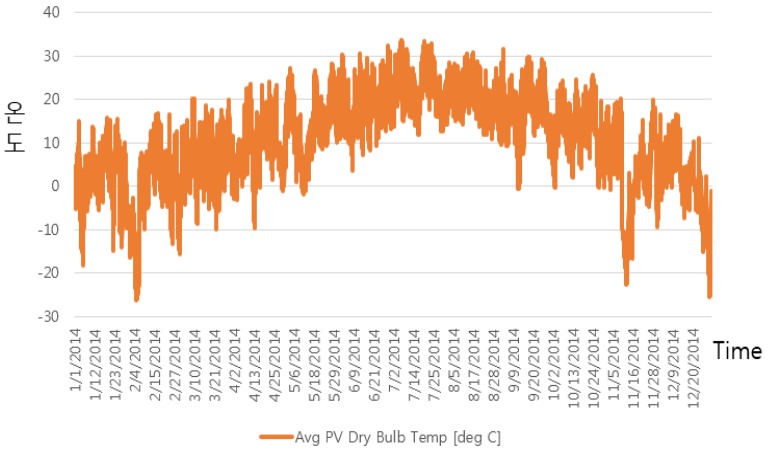
Diode Model



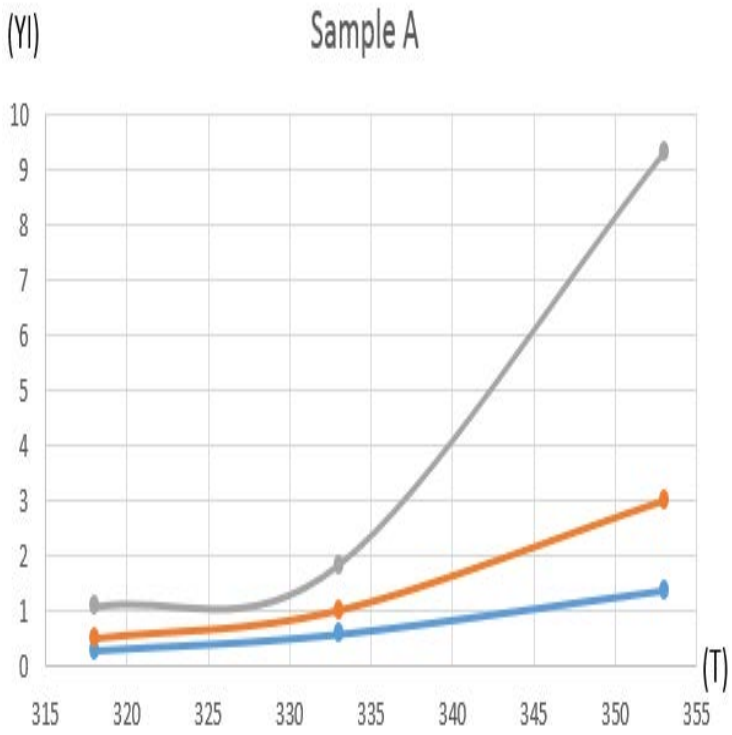
2. SORES : Flow Chart & I/O

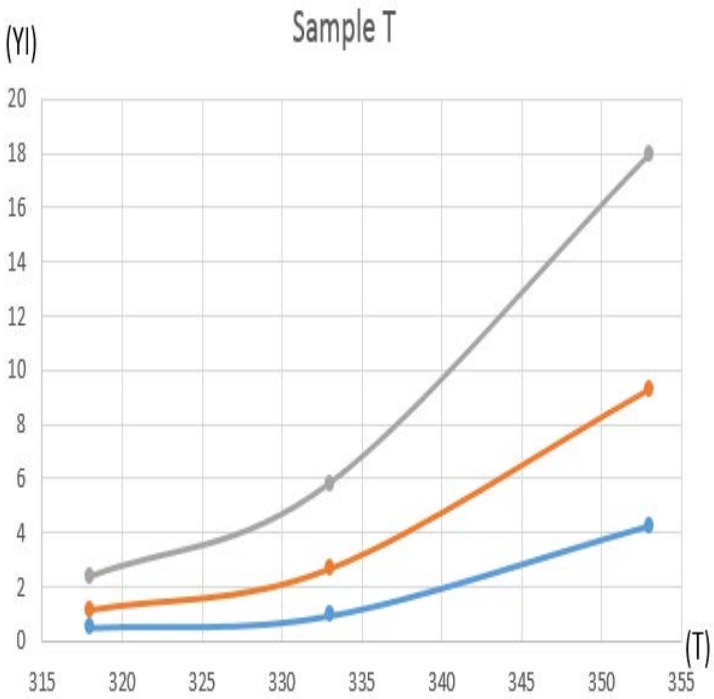






2. SORES : UV Degradation Lab Data by 3M

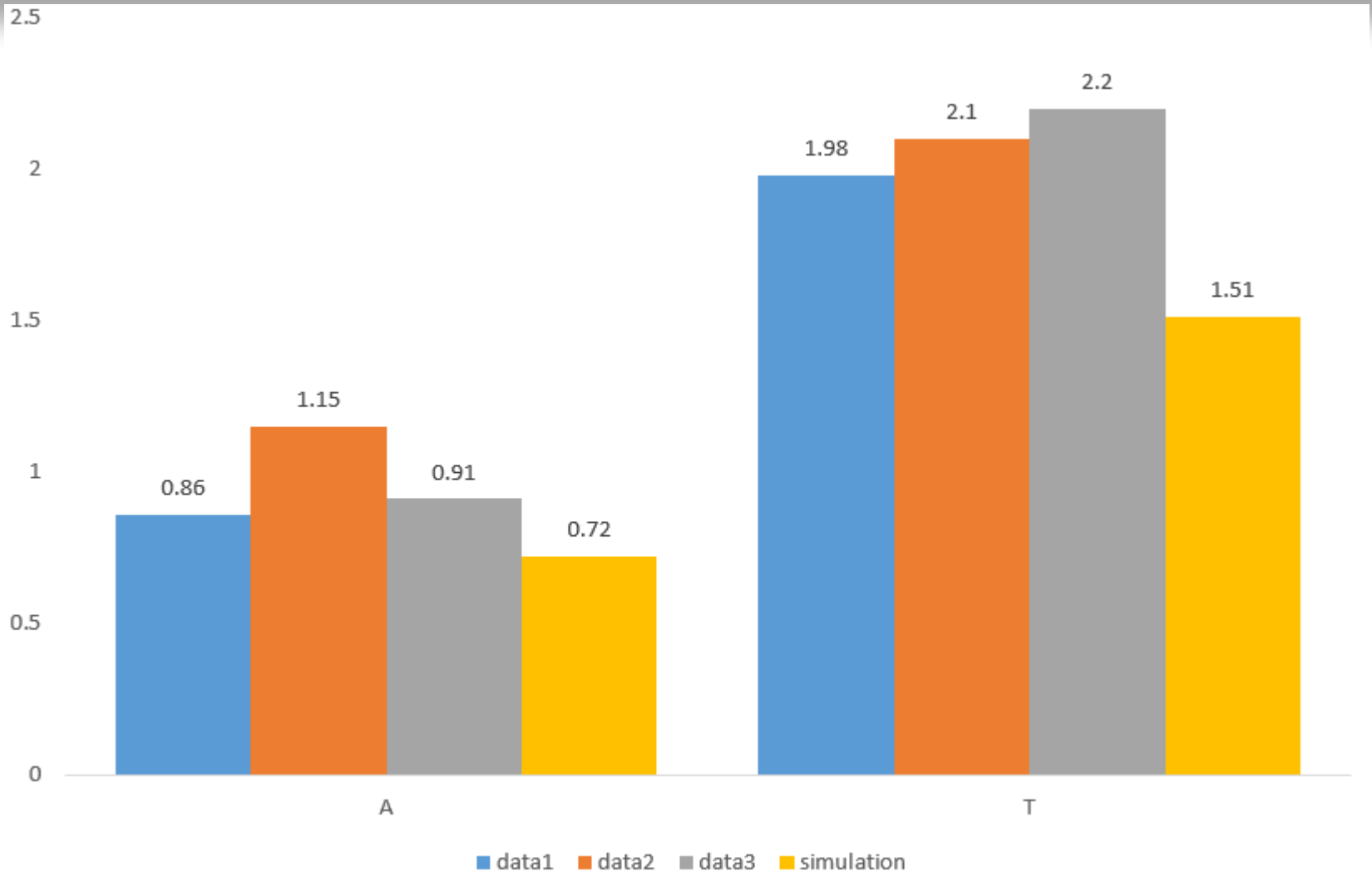




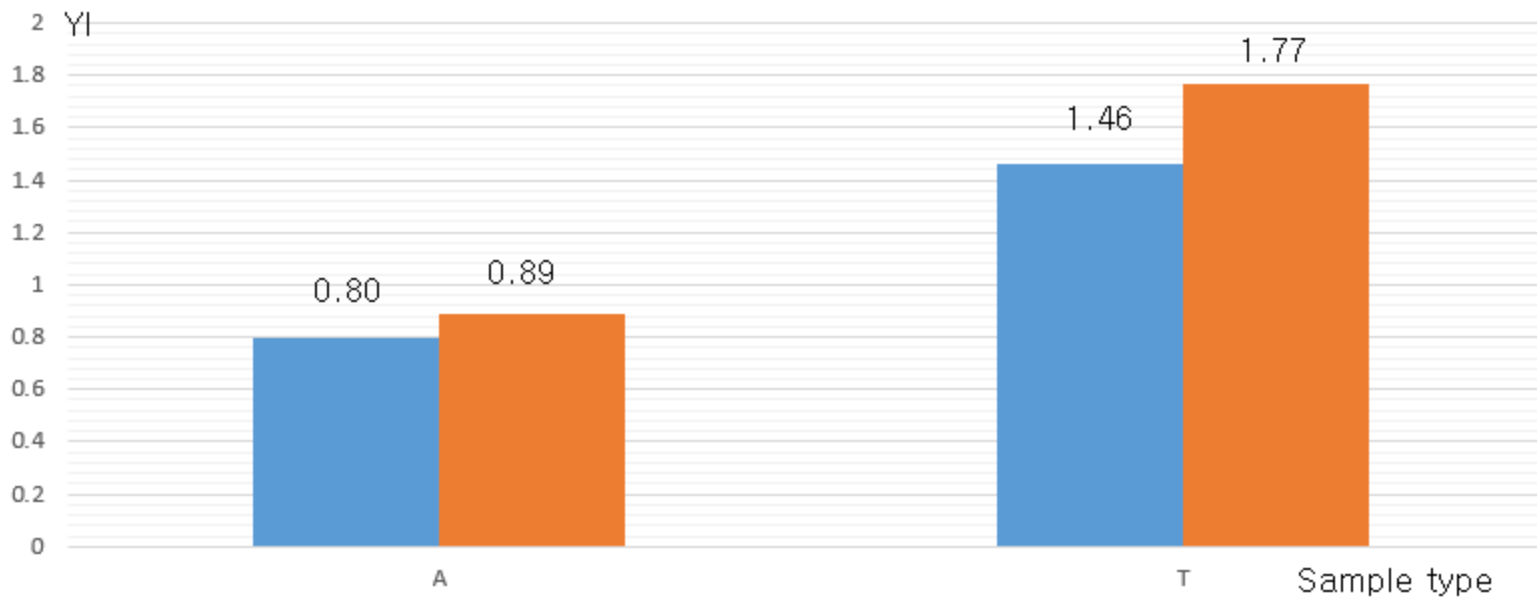
Date of Test(day)

A(15) A(30) A(60)

3. SORES : Benchmarking with NREL Field Data



4. SORES : Prediction of UV Degradation



Miami	Total Sun Irradiation	6.218 (GJ/m2)
	Average Temperature	23.2 (℃)
	maximum Temperature	35 (℃)
Phoenix	Total Sun Irradiation	8.378 (GJ/m2)
	Average Temperature	23.8 (℃)
	maximum Temperature	44.4 (℃)

Miami

Phoenix

5. Summary & Future Plan

- **SORES provides the Quantitative Link between Lab. AST & Outdoor Field Testing.**

- **SORES is benchmarked with NREL UV field Degradation using 3M Lab AST data. 3M UV Lab AST data only includes irradiance and temperature effects. It agrees within 20~30%. Other effects such as humidity will be investigated and included in SORES simulations to improve the accuracy..**

- **Using the same 3M UV Lab AST data, the field degradations at Miami & Pheonix are predicted by SORES simulations. They will be benchmarked with the field data when the Miami & Pheonix field testing is available this year.**

Acknowledgements

This work was supported by Korea Institute of Energy Technology Evaluation & Planning Project 214C000290. The authors would like to thank Nancy Phillips of 3M for the UV Lab. stress data and David Miller of NREL for the UV field stress data.

CFV solar test laboratory

Module Deflection Profiles for Mechanical Load Test

Larry Pratt*, Nicholas Riedel, Erica Moss and Michael Yamasaki, Greg Peacock
CFV Solar Test Laboratory, Inc., Albuquerque, NM

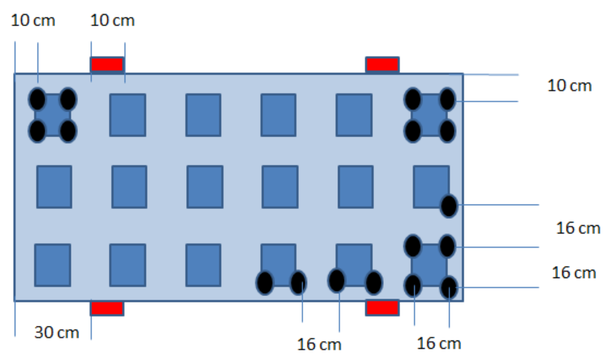
Introduction

This work was motivated by a review of the IEC 62782 draft standard for Dynamic Mechanical Load Testing (DMLT) and conducted to provide data to support the minimum spacing for piston style mechanical load testers. The work was also intended to characterize the deflection of the PV module frame under two standard methods for mounting modules: 4 10 cm side clamps versus two 30 cm center clamps.

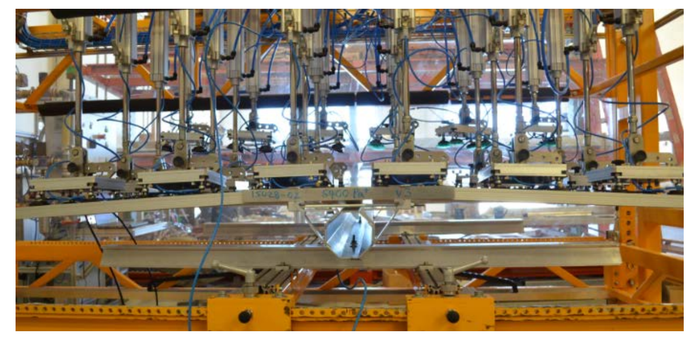
Procedures

A standard 72-cell crystalline PV module with 40 mm frame was selected. The module was mounted to the mechanical load test bed using four Schletter clamps on two rails. The module was subjected to a 1000 Pa load with various methods: center load with 4 pistons, even load with 18 pistons (72 cups), 24 pistons (96 cups), and finally with sandbags. The module was also mounted using two 12" center clamps and loaded with 18 pistons. Finally, the module was tested at 2400 Pa using standard clamps with sandbags and using center clamps with 18 pistons. The deflection was measured every 5 cm along the long and short axis of module for each test.

Sandbag load with 4 edge clamps



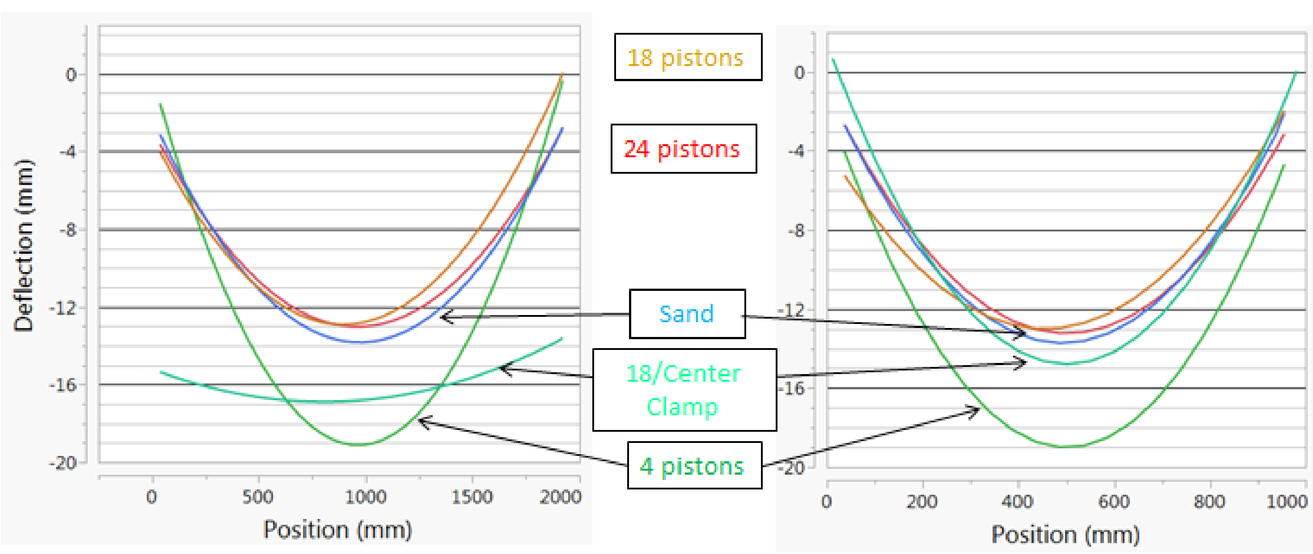
18 piston setup with 4 cups per piston



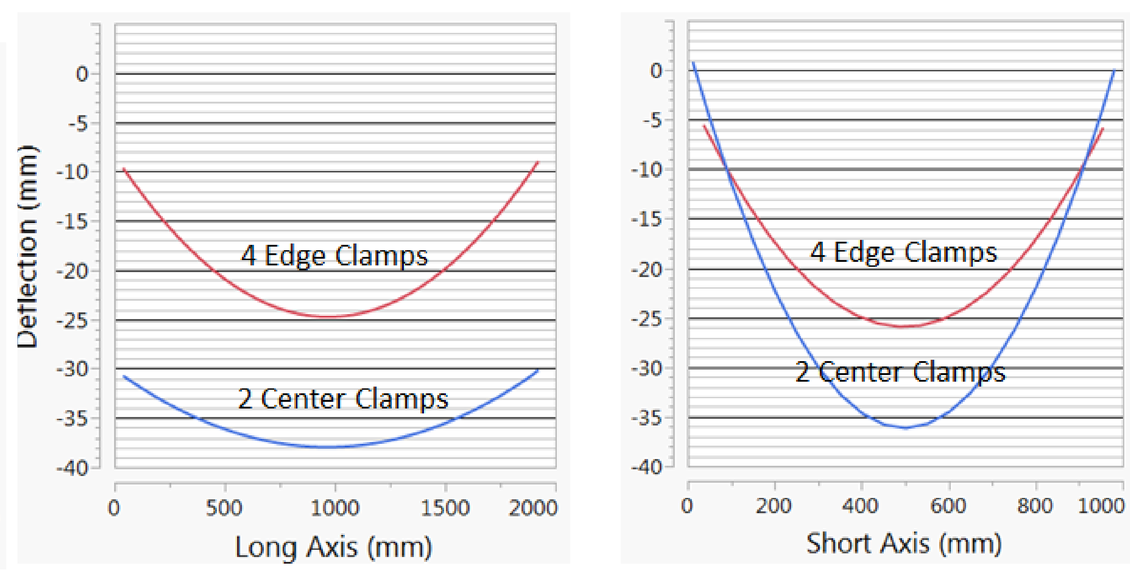
Piston load with center clamps (> 1000 Pa)

Results

1000 Pa



2400 Pa



- Similar deflection (+/- 1 mm) at the center of the module for 18 piston, 24 piston, and sandbags
- Additional 5 mm of deflection at the center of the module with 4 pistons applied at the center of the module
- Additional 1 to 3 mm of deflection at the center of the module with 18 pistons on the center clamp configuration (center deflection should be the same along the short and long axis)
- Additional 12 mm of deflection at the center of the short edge frame when mounted with the 300 center clamps

- Additional 10 to 13 mm of deflection at the center of the module with the 2 center clamp mounting as compared to 4 edge clamps
- Additional 20 mm of deflection at the center of the short edge frame with the center clamps
- Additional 5 mm of deflection at the center of the long edge frame with the standard 4 edge clamps. The center of the long edge is held rigid with the center clamps, but not with the 4 edge clamps.
- This test used sandbags for the 4 edge clamps and 18 pistons for center clamps.

Conclusions

- Deflection profiles are similar for piston type MLT as compared to sandbag load (+/- 1mm) with reasonable coverage (< 20 cm from center to center of cups) at 1000 Pa
- Mounting configuration (2 center clamps versus 4 standard edge clamps) results in a very different deflection profiles at 1000 Pa and 2400 Pa, so the MLT test bed should allow for the intended field installation to be simulated (i.e., the frame should be allowed to deflect under the load)
- Better deflection metrology should be utilized for future tests

References

- IEC 62782 PHOTOVOLTAIC (PV) MODULES – CYCLIC (DYNAMIC) MECHANICAL LOAD TESTING
- IEC 61215 Section 10.16 Mechanical Load Test

Method for PV degradation under combined loads with in-situ performance monitoring

Dr. M. Theelen [1], Ir. S.J.M. Roest [2], R. van Vugt, Bsc.[2], Ir. A.M. Mulder [2]

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2. Eternal Sun Group, Wolga 11, 2491 BK The Hague, The Netherlands

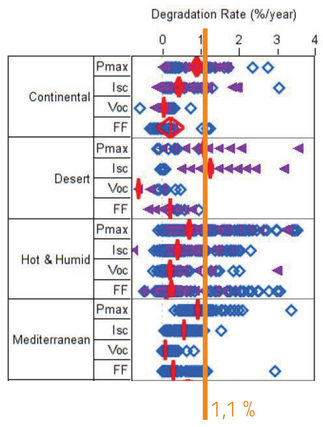
Spire Solar is part of the Eternal Sun Group

ABSTRACT

Determination of the reliability of PV solar cells and modules is critical for the success and reputation of our industry. Current qualification tests are insufficient for lifetime and reliability assessment. Therefore, new testing programs and setups are needed. In-situ solar cell measurements during accelerated lifetime testing are critical to understanding field degradation modes and enhancing the ability to understand and predict module lifetime. This combination demands a test setup which generates any combination of high accuracy solar irradiance, temperature, humidity, and electrical load. An AAA-class steady state solar simulator with integrated climate chamber was developed that illuminates a test surface with <2% non-uniformity and <0.5% temporal instability. Due to an innovative 6 layer solar simulation window the climate chamber is able to reach e.g. damp heat conditions at 85% RH and 85 °C at 1000 W/m^2 irradiance. This allows multi-factor stress testing while monitoring the device characteristics in-situ to allow improved insights into 'reversible" as well as 'non-reversible" degradation. In a first application 12 CIGS cells were placed in 1 sun illumination while treated with damp heat and electrical load. Unprecedented insights were gathered on the fluctuating performance under loads and breakdown mechanisms.

BACKGROUND

Many of currently installed crystalline PV modules show fast degradation in hot and humid climates and do not achieve warranty performance, e.g. 80% after 20 years.



New and promising cell technologies such as CIGS, CZTS, OPV & Perovskites are even more sensitive to moisture and temperature effects. Most damage is observed when the cell is placed under combined loads (humidity, temperarure, light & electrical). Breakdown mechanisms are not yet well understood. Therefore cells and modules must be tested under combined degradation loads and their performance monitored in-situ to observe failures in time to perform material analysis.

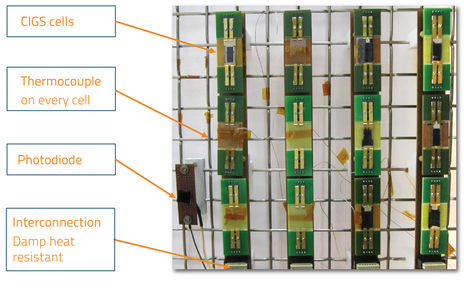
METHOD

1. Place CIGS cells or module under AAA-accuracy sunlight, damp heat conditions (85/85) and electrical load.

2. Measure performance of degrading CIGS cells/module in-situ.

3. Directly remove cells/module from setup when they break down.

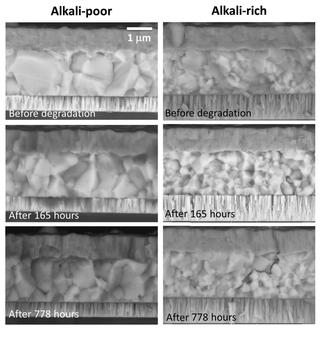
4. Chemical analysis of the cells before and after degradation::XRD, XPS, SEM-EDX, EL, ...



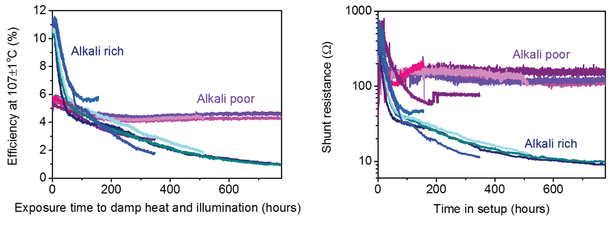
SETUP

RESULTS

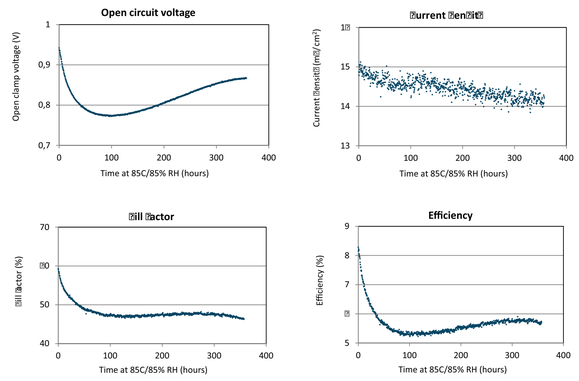
Cross-section SEM pictures before and after exposure to damp heat and illumination of the CIGS samples:



Results of in-situ electrical performance measurements under dampheat + 1 sun:



Results of individual sample:



SUMMARY

1) A test setup and method was developed to load samples with 1 sun (AAA class) illumination, damp heat and electrical loads while their performance was measured in situ.

2) Tests with 12 CIGS samples yielded new insights in failure mechanisms and performance fluctuations under load.

3) In-situ monitoring enables insight into metastable and transient behavior. This is particularly important for thin-film modules and cells as the performance under STC and NOCT may be different due to light induced or heat induced metastability.

4) In-situ monitoring allows for early detection and swapping of bad cells saving test time and costs.

5) The setup and method is suitable for advanced LID and PID testing.

ACKNOWLEDGEMENTS

The authors would like to thank everyone who contributed to the project: TNO, Solliance, Eternal Sun, Delft university of Technology, M2I institute, Hielkema Testequipment & Rera solutions.

REFERENCES

Degradation data of 2074 PV modules - Technology and climate trends in PV module degradation - NREL - 2012

Accelerated performance degradation of CIGS solar cells determined by in-situ monitoring - Theelen, M., Zeman, M. et al. - SPIE Proc. Vol. 9179 91790I-10 (2014)

WANT TO KNOW MORE ABOUT ETERNAL SUN?

Eternal Sun Group recently acquired Spire Solar, LLC.
Check the QR-code for more info.

New monolayer backsheet development and testing

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[2]Department of Physics, University of California, Santa Cruz, CA 95064
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SOLICULTURE

Abstract

As the commercial market for PV systems increases and prices decrease, module makers are finding ways to decrease costs to keep competitive. One area of cost cutting has been in the backsheet, first with the removal of the sun-facing fluorinated layer, and then by finding alternatives to fluorinated layers altogether. The reliability and accelerated aging testing of innovative structures and materials becomes a substitution for field performance, and therefore must be carefully and thoughtfully performed. Keeping this in mind, Soliculture has developed a monolayer backsheet that is inexpensive, water resistant, UV stable, and has good adhesion with EVA without the addition of an adhesion layer. The cost of this backsheet is comparable with current PE-based backsheets.

History of development

-Soliculture: Greenhouse Integrated PV
-Custom dye, custom backsheet
-Testing of several polymeric materials to find stable dye host
-Found stable host, side benefit is monolayer construction

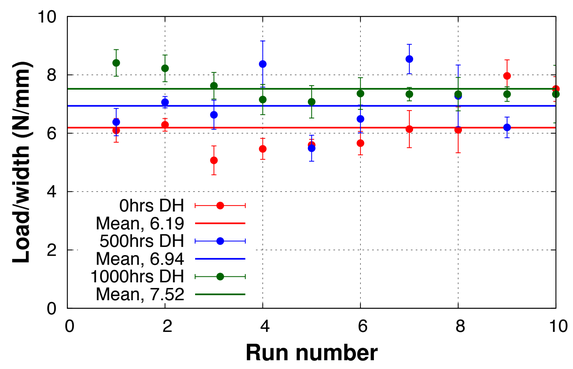
Testing equipment

High intensity UV lamp
Metal Halide D: Broad UV spectrum
1.1 kW/m^2 between 300-400nm
Sample temp: 60C by water bath
High heat/UV lamp
Broad UV and visible spectrum
205 W/m^2 between 300-400nm
BPT: 105C
Damp heat chamber (85C, 85%RH)

Testing emulates greenhouse environment (high UV, humidity)

Damp heat – adhesion and optical properties

180 degree pull test used to test adhesion

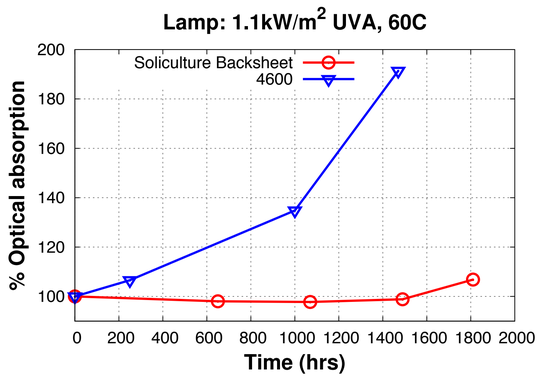


Soliculture backsheet (left) has no change in optical properties after DH, compared to PET (right), aged for same time

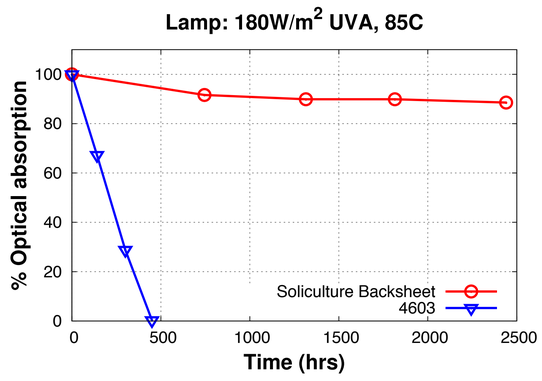
No change in adhesion, optical properties after 1000hrs DH

UV aging – mechanical and optical stability

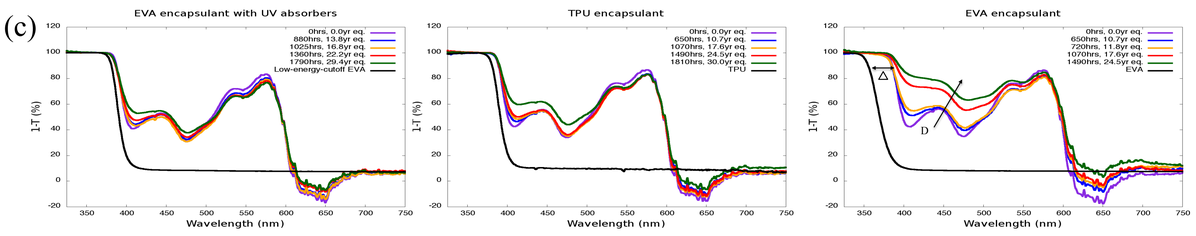
(a) **Stability under high UV**



(b) **Dye stability under high heat/UV**



(c)

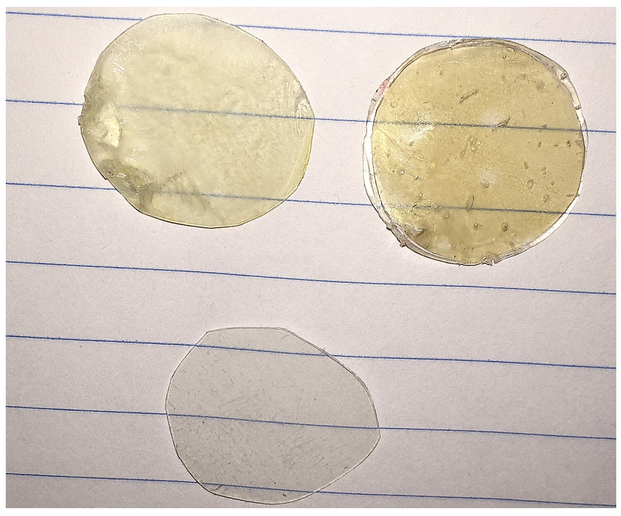


(a)The host material yellows very little over 30 years equivalent, compared to commercial products.

(b)Dye degradation is used as an indicator of the chemical stability of the host material. The dye-impregnated Soliculture backsheet remains stable under high heat and UV, while dye-impregnated EVA shows quick degradation.

(c)UV stability is highly dependant on the UV cutoff of the encapsulant. A white backsheet would be less dependant on the encapsulant.

Comparison with other clear backsheets



Soliculture backsheet (below) remains clear, while a clear backsheet delaminates and yellows (above) after same UV aging

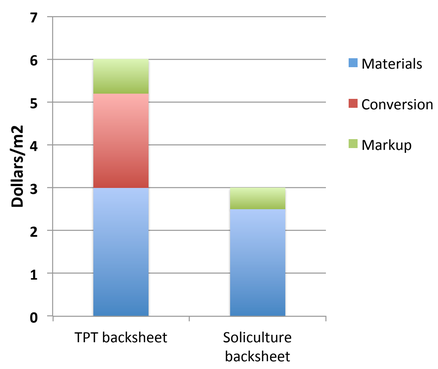
Soliculture backsheet has enhanced reliability over other clear commercial backsheets

Cost comparison

Soliculture backsheet has a cost of current so-called 'monolayer' backsheets, but with enhanced reliability

1) Adhesion is excellent after damp heat
2) No concerns about delamination of tie layers
3) UV aging of clear backsheet is superior to clear commercial backsheets

Product	Price/m^2
Tedlar-PET-Tedlar (TPT)	\$6.87-\$8.25
Tedlar-PET-EVA (TPE)	\$4.50
PET-PET-primer	\$4.12
PEN-based	\$2.75



Conclusion and outlook

1) Soliculture backsheet has lowered cost (like PE-based backsheet)

2) Soliculture backsheet has increased reliability
→ Weathers like a fluorinated polymer
→ Because it is a true monolayer, delamination concern is mitigated

Development of white backsheet and repetition of reliability testing ongoing

Need to perform more testing (WVTR, chemical resistance tests, quantitative mechanical stability after aging, micro-level chemical changes after aging, etc.)

Would appreciate your feedback on whether the monolayer backsheet is resasonable!

Mechanical Reliability of Different c-Si 72-Cell Solar Modules Designs

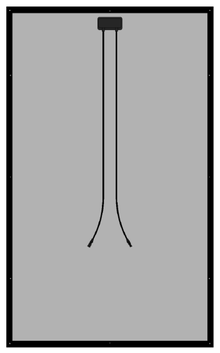
Shandor Daroczi, Bernd Litzenburger and Lars Podlowski
First Solar – Silicon Module R&D Department

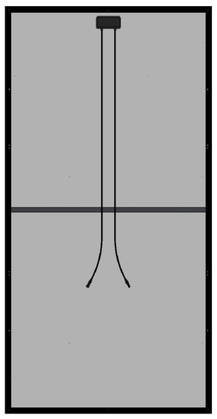
Abstract:

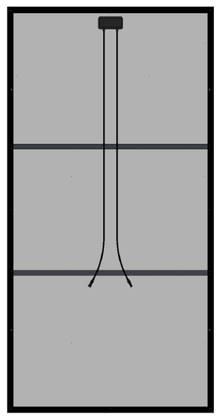
Over the past few years 72-cell panels became more popular for ground-mount PV power plants because they have advantages in terms of racking and installation costs over 60-cell panels. Analyzing the world market for 72-cell panels shows that 3.2mm glass and 4.0mm glass are both widely used, and also a large variety of frame designs can be found -- for basically the same product specifications. According to data-sheets most panels meet IEC61215 requirements with the "heavy-load" version of 5,400 Pa static mechanical load.

In order to find a cost-effective design which ensures good mechanical stability we manufactured 72-cell panels of different designs and conducted extensive mechanical tests. In order to better understand the experiments we also did theoretical FEA modelling which is an important additional tool for a product development project.

This presentation describes our experiments and results. Significant differences can be observed for different product models. We will explain some of the thoughts and debates leading to certain design aspects of the First Solar TS-360 solar module.


Back view: 60-cell module


72-cell module with 1 stabilizer


72-cell module with 2 stabilizers

Test Setup:

72-cell modules bring several issues because of their larger size. Their large area (nominally 2m²) means larger overall forces on the whole structure from wind and snow pressures. Also there are longer spans between supports if the conventional number of four attachment points are used. If the laminate structure is otherwise kept the same, the deflections caused by pressure become larger. Large deflections are undesirable because they can increase stress and damage internal components. Failure modes include catastrophic overall failure with breakage of the glass. Other large scale failures include deformed frames. Internal damage can also occur, and in particular silicon cells can suffer micro-cracks. Extensive cracks can degrade module power over time. The goal is to design the module structure to minimize degradation while controlling costs.

One external approach is to increase the support structure. For example, a third purlin can be added to the two standard purlins in order to increase the number of attachment points to six. This is possible -- and is useful for installations exposed to extreme weather -- but this approach increases racking cost and installation time.

To improve the module structure itself, one possibility that initially seems attractive is to change to thicker glass, from the typical 3.2mm to 4mm. 4mm is a standard thickness of solar glass, but is more expensive and less common so availability can be problematic. We checked different thicknesses of glass as part of this project, and found that thicker glass is not necessarily better in all regards.

An alternative is to add extra braces or "stabilizers" to the structure. This is a common approach that links the outer frames with cross braces. This reduces the tendency of the outer frames to separate from the laminate during loading. The braces can also directly support the glass which reduces deflection. We tested modules with one and with two stabilizers. The stabilizers bring extra cost and assembly time.

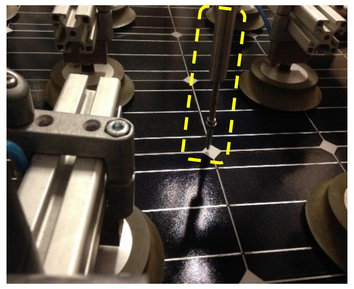
Another alternative structure is to replace the polymer backsheet with back glass. This results in a rigid double glass laminate. Different thicknesses of glass can be used with the double glass structure. We tested thickness down to 2mm for this project. Thinner glass is becoming more common and less expensive, but 3.2mm is still more available and cost-effective.

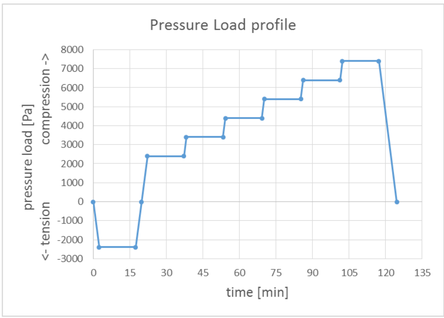
To simulate forces like wind or snow that act on modules in the field, mechanical load tests are often used for internal testing, and are part of the certification process. The standard minimum IEC requirement is 2,400 Pa of pressure which simulates moderate loads.

An optional 5,400 Pa pressure simulates more extreme snow and wind. Even if the overall structure survives the heavy 5,400 Pa test (or severe snow or wind loads in the field), internal damage can occur.

Pneumatic load tester

Module clamped in tester


Sensor to measure load deflection



Load profile

Module with 1 stabilizer under test showing deflection

Results:

Modules with a variety of glass types were tested. The modules were framed with a standard aluminum frame. Different glass thicknesses, double glass, and stabilizer systems were tested. See below for a summary. As expected, the module with thicker glass deflected less during the load testing. The double glass and stabilizer versions deflected even less.

A non-intuitive result was observed with thicker 4mm glass: more cell degradation occurred even though the deflection was less than with 3.2mm glass. With thicker glass, the cells in the laminate are farther away from the neutral bending axis, and are therefore subject to tensile and compressive stresses that can cause damage.

The stabilizers were more effective than thicker glass at reducing deflection, which reduced micro-cracking and power degradation. The one stabilizer version still showed significant deflection. The two stabilizer version reduced the unsupported span of the laminate and further reduced deflection and damage.

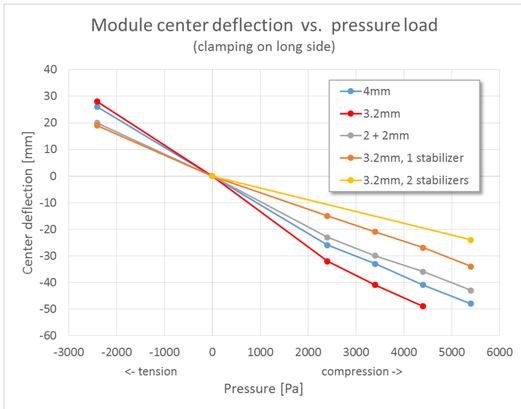
The double glass structure deflected less than the 3.2 and 4mm models, but more than the stabilizer model. In spite of the moderate deflection, no cell cracking or power degradation was found. The cells are ideally located with respect to the neutral axis as shown below.

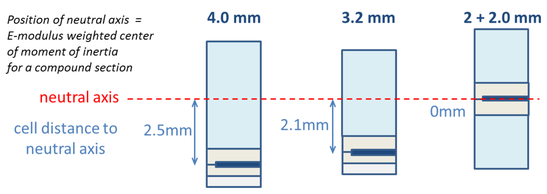
Electro-luminescent (EL) imaging can show micro-cracks in the cells. Small micro-cracks typically have minimal effect on module performance but extensive cracks can cause power loss. This effect can be exacerbated by continued mechanical cycling, such as with cyclical mechanical load tests or with repeated wind and other natural loads in the field.

Note that cell micro-cracking is influenced by many parameters, including cell type, texture, damage, solder conditions during cell stringing, and lamination.

Type	Glass [mm]	Stabilizer	Deflection at 2400 Pa	Deflection at 5400 Pa	Δ Pmax	Cell fractures
Conventional	3.2	-	32	-	-5.3%	many
Thicker glass	4	-	26	49	-7.3%	many
1 Stabilizer	3.2	1	15	34	-2.1%	fewer
2 Stabilizers	3.2	2	11	24	-1.0%	few
Framed double glass	2 + 2	-	23	43	0.1%	none

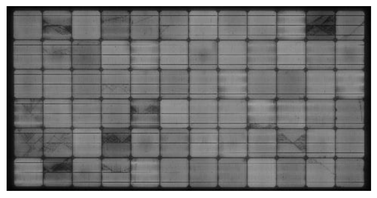
Summary table





	4.0 mm	3.2 mm	2 + 2.0 mm
(Pure) bending stress	yes	yes	yes
Tensile stress (@ compressive loads)	yes	yes	no
Compressive stress (@ tensile loads)	yes	yes	no

Description of neutral bend axis

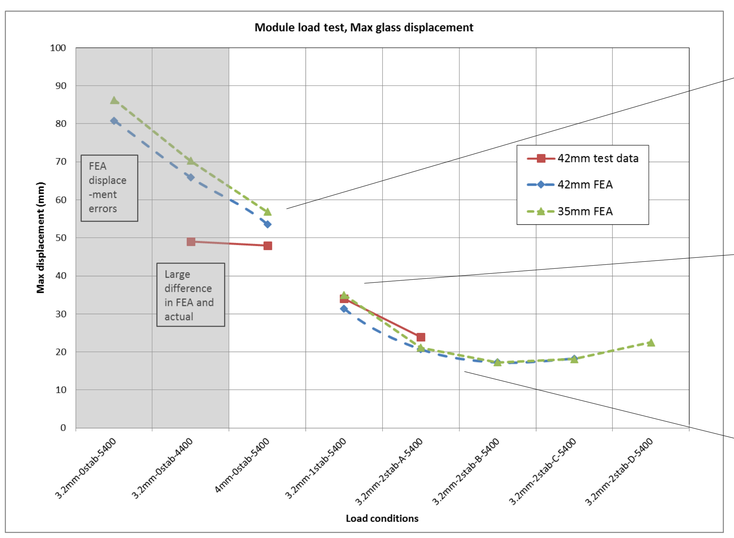

EL image shows cell micro-cracking (dark lines)

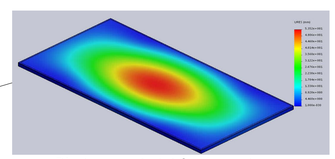
Discussion:

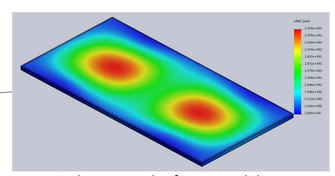
We also used Finite Element Analysis (FEA) to model the deflection of the module structure. It is difficult to completely model cells and stresses, so in this case the FEA was primarily used to study deflections of the overall structure. Studies were done with a 42mm frame to compare with the experimental results. A shorter 35mm frame design was also analyzed. The 35mm frame caused minor additional deflection, but this was deemed acceptable and the lower cost of shorter frames encouraged us to evaluate them. Some FEA results matched well to experimental results, but others did not. This is a potential area of future study, with alternative grid elements, meshing, and boundary conditions.

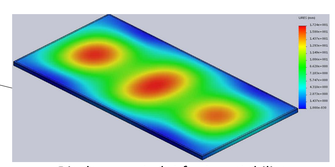
The FEA color plots show displacement with red areas indicating the largest displacement (deflection). The center area of the module shows the largest deflection if no stabilizers are used. Adding one stabilizer reduces deflection in the center, but there is still significant deflection in the unsupported areas between the outer frames and the stabilizer. The two stabilizer setup reduces the distance between frame supports and thereby shows the smallest deflection. The location of the two stabilizers can be tuned to further improve deflection.

The double glass structure showed the best results regarding cell degradation. However, this type still had significant deflection under load which can allow contact with the support structure. Also framed double glass modules are more expensive and heavy if thicker glass is used. We decided to develop a 2 stabilizer model in the short term. After launching that model, we are also developing a frameless double-glass model to take advantage of the neutral bending axis. Frameless modules have attractive properties but are not as common in the market. More manufacturers are now offering this type, and we expect it to become more widely adopted in the future.




Displacement plot for 4mm glass


Displacement plot for one stabilizer


Displacement plot for two stabilizers

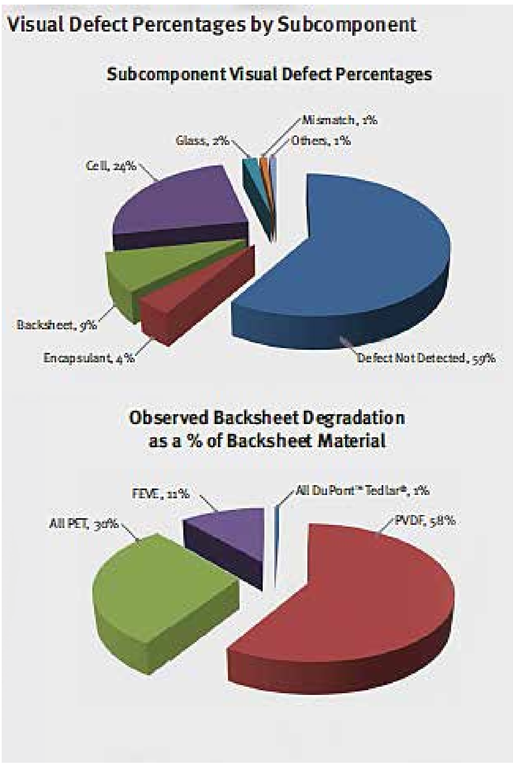
Connecting Outdoor Performance to Accelerated Testing for Photovoltaic Materials

William Gambogi[1], Thomas Felder[1], Alexander Bradley[1], Bao-Ling Yu[1], Lucie Garreau-Iles[2], Hongjie Hu[3] and T.-John Trout[1]

([1]) DuPont, Wilmington, DE, USA; ([2]) Du Pont de Nemours International S.A., Geneva, Switzerland; ([3]) DuPont (China) Research& Development and Management Co., Ltd., Shanghai, P.R.C.

Assessing Materials Performance in the Field

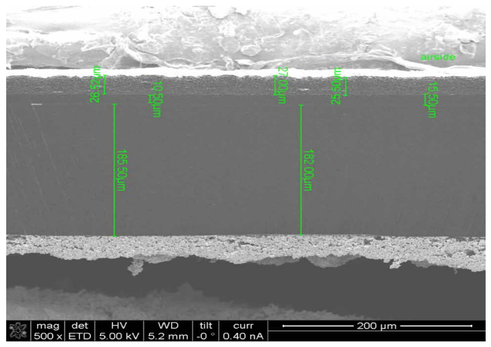
- Global program assessing module performance using visual assessment, IR imaging and FTIR materials identification.
- Representative modules from the field obtained for further analysis:
  - Non-destructive analysis (IV, EL, IR imaging, electrical insulation) is first assessed.
  - Destructive analysis (sampling, optical microscopy, SEM, IR, nano-indentation, mechanical properties, etc.) are then assessed.



A. Bradley, J. Kopchick, B. Hamzavy. "Quantifying PV Module Defects" IEEE PVSC (New Orleans, 2015)

Field Results on Recent PET Backsheet Constructions

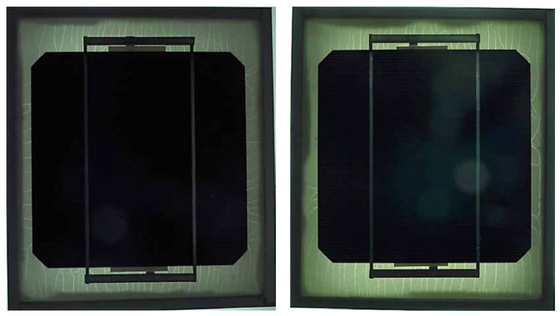
- Modern PET backsheet construction (50 white PET/ clear PET/ E-layer.
- Significant (100%) front side yellowing of PET backsheet due to inner layer degradation.



- Erosion shows 21um thickness loss after 9 years estimated by comparison to thickness under module label.
- Backsheet is also brittle and flaking.

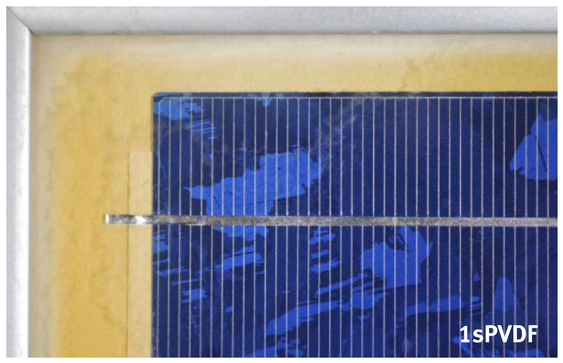
Higher Stress Weathering Results

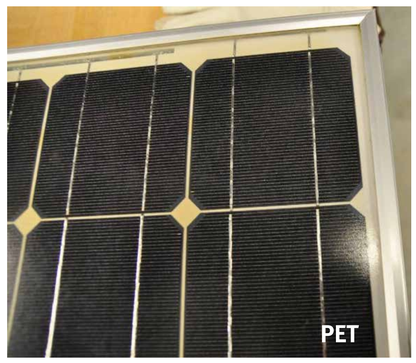
- Exposure at higher BPT (90C) and full structures mini-modules to assess local mechanical stresses and materials interactions.
- Weathering of two single-cell mini-modules (right) showing cracking of the inner layer of the backsheet for two commercial PET-based backsheets.
- Backsheet exposures using glass/EVA filter show similar cracking.



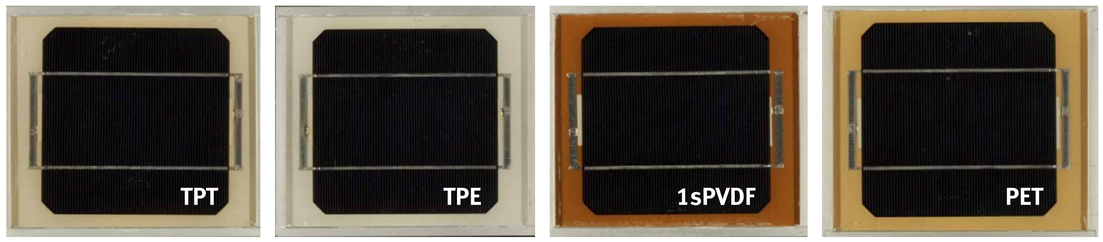
Comparison of Field to Accelerated Testing

- Yellowing of the inner layer of the backsheet has been observed in the field for single-sided PVDF backsheets and PET-based backsheets.





- Front side yellowing of 1sPVDF backsheets (left, <5y in multiple locations) and PET backsheet (right, 4y in AZ).



- Yellowing in single-cell modules with weathering exposure (90C BPT) and front side UV exposure of ~ 4 years equivalent exposure in Arizona.

Conclusions

- UV stress in the field can result in yellowing and degradation from the front and back of the module and loss in mechanical properties leading to cracking and delamination.
- Higher temperature weathering exposures and testing of full structure s results in performance changes better matching field performance.

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Office of Energy Efficiency and Renewable Energy,
operated by the Alliance for Sustainable Energy, LLC.

Electroluminescence and Photoluminescence Imaging for Module Degradation Characterization

Steve Johnston, Peter Hacke, Dirk Jordan, and Mowafak Al-Jassim
National Renewable Energy Laboratory, Golden, CO, USA

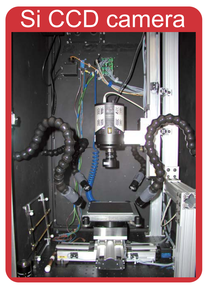
Goal: Use imaging techniques to characterize degradation on photovoltaic modules. Imaging can provide information for better understanding the effects of degradation and possible mechanisms. Imaging can also provide spatial details to use for follow-up coring and microscopy analysis.

Electroluminescence (EL) imaging is widely used and can identify defects, degradation, or poor performing areas of a photovoltaic module. Photoluminescence (PL) imaging is also sensitive to material defects and can be used to supplement the EL images for defect analysis and interpretation. When carriers are optically excited in PL imaging, they can be uniformly distributed without dependence on series resistance. Thus, PL imaging can help differentiate if dark regions of an EL image are due to poor semiconductor lifetime or resistive features of the device, for example, from cracked cells or conductive layer degradation. Thermal images, such as from dark- or illuminated- lock-in thermography can also supplement EL images for improved failure and degradation analysis.

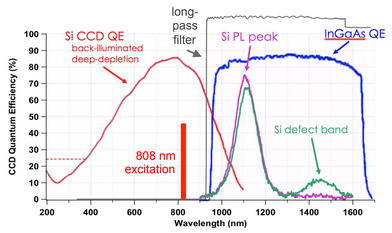
Imaging for photovoltaics

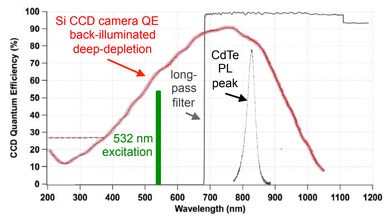
Princeton Instruments
PIXIS 1024BR

Si CCD camera



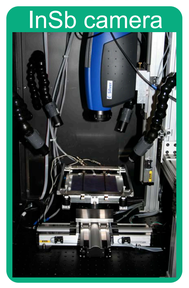
- Photoluminescence (PL) imaging
- Electroluminescence (EL) imaging
- Reverse-Bias EL imaging (ReBEL)



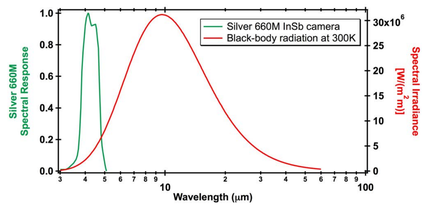


Cedip Silver 660M
FLIR SC5600-M

InSb camera



- Lock-In Thermography
  - Dark (DLIT)
    - Forward bias
    - Reverse bias
  - Illuminated (ILIT)

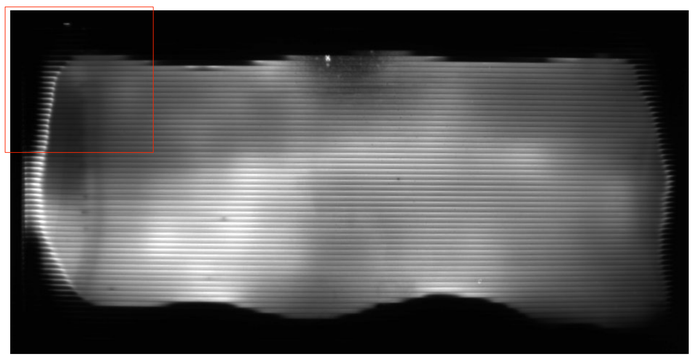


The cameras used for the various techniques are listed below:

- Silicon charge-coupled device (CCD) 16-bit camera with 1024 x 1024 pixels (13μm pixel pitch), cooled to ~-60°C
- InGaAs 14-bit lock-in camera with 320 x 256 pixels (30μm pixel pitch), uncooled
- InSb 14-bit lock-in camera with 640 x 512 pixels (15μm pixel pitch), cooled to ~80K

CdTe module

Zoom into this region.

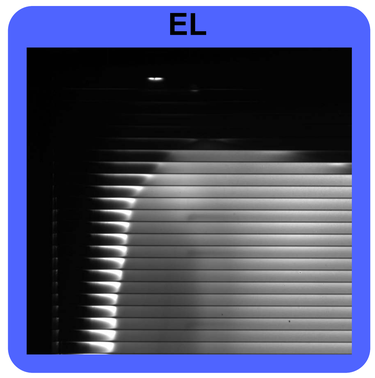


EL shows dark regions around the perimeter of the module. This degradation is mostly due to increased series resistance as seen in the zoom images to the right.

PL

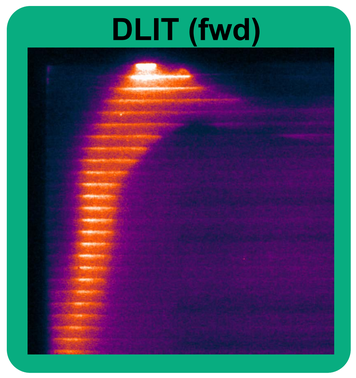
CdTe material in this corner emits PL. The bright band shows increased excess carrier populations where there is higher resistance.

EL



The corner is dark in EL where carriers are not easily injected due to voltage drop across high series resistance.

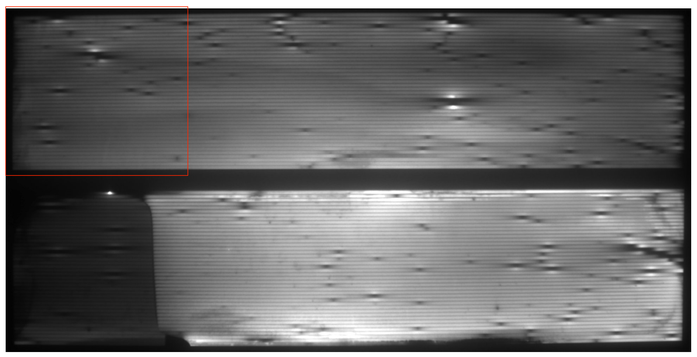
DLIT (fwd)



Increased heating shows where current is driven through higher series resistance and power is dissipated.

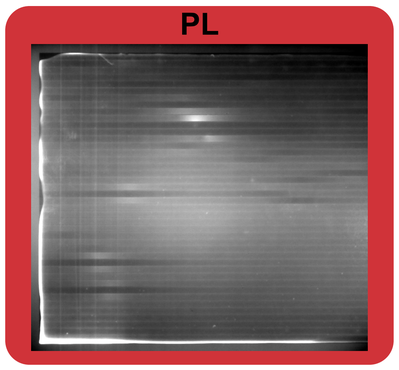
CIGS module

Zoom into this region.



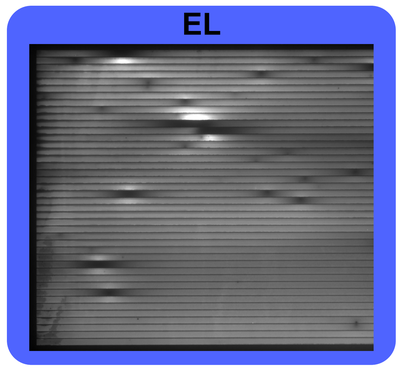
EL shows dark spots throughout the module. The lower left corner is dark due to a crack in the glass. The localized dark regions are mostly shunts in the module, and bright regions near the shunts show current crowding.

PL



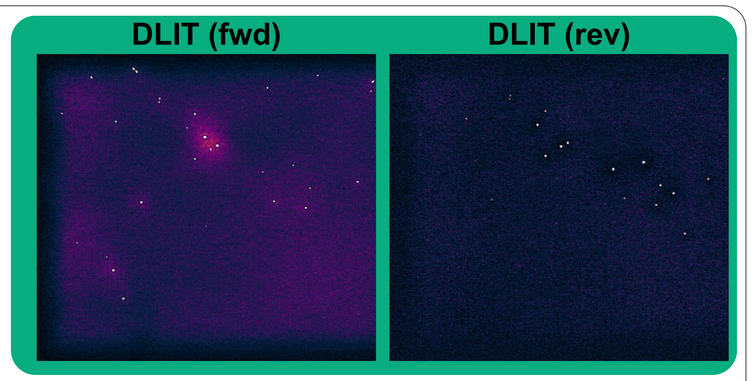
PL appears dark on parts of some cells where the voltage is low due to shunts.

EL

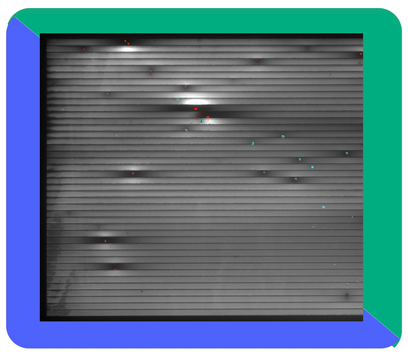


EL shows dark regions of the cells where the voltage is low due to shunts.

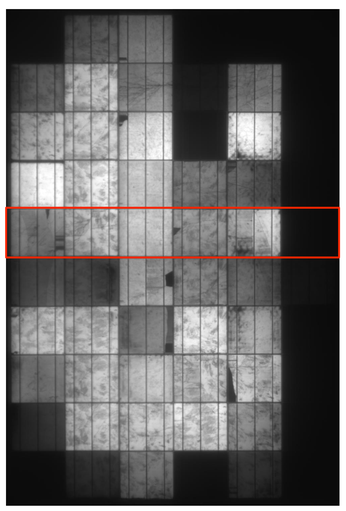
DLIT (fwd) DLIT (rev)



Localized regions of high current show heating. Many of the same areas show heating in both forward and reverse bias. Below, the regions observed to heat under DLIT (forward and reverse) are overlaid on the EL image.



Si module

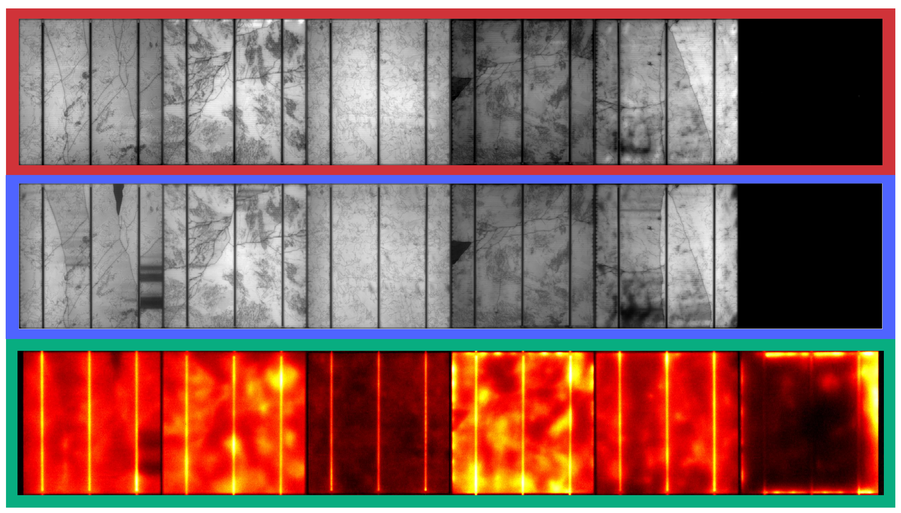


row of interest to compare techniques

PL

EL

DLIT (fwd)



PL shows dark regions within the cells due to excess carrier recombination. EL additionally shows dark regions where sections are isolated or grid fingers are broken due to cracks in the cells. Both PL and EL show a dark cell that contains shunts. DLIT shows heating at carrier recombination areas and gives spatial location of shunted areas on the cell that appears completely dark in both PL and EL.

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Characterization of the Adhesion Integrity in Photovoltaic Panels using Thermomechanical Blister Tests

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Introduction

Our group's focus is in characterizing the adhesion between the layers in photovoltaic (PV) solar panels, using thermomechanical blister tests. Characterization of the adhesion in PV panels is important because adhesive failure is a common mode of failure (see Fig. 1, below). Delamination of the layers can lead to reduced optical transparency, heat dissipation, and protection from outside elements [1]. We are interested in developing the blister test as an accelerated testing method for predicting the long-term adhesive reliability of PV modules.

There are several variations of the blister test, including the pressurized blister test, the shaft-loaded blister test [2], and the thermal blister test [3]. Our focus is currently on the thermal blister test and the shaft-loaded blister test (see Fig. 2, below).

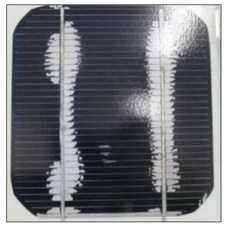
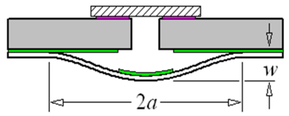


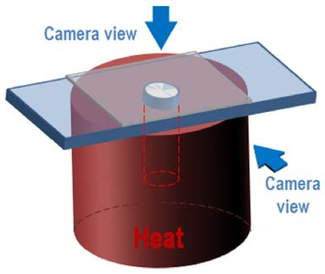
Figure 1. Examples of adhesive delamination in PV panels.

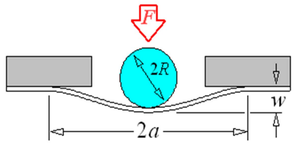
Methods

Figure 2. Variations of the blister test used in our study.



(a) Thermal blister test (TBT). At room temperature, the rear of the hole is covered with a plate, trapping air in the blister cavity. Heat is then applied, causing the air to expand, and driving delamination. Side and top cameras are used to measure the blister radius, *a*, and blister height, *w*. These two parameters, along with the pressure of the entrapped air, *p*, are used to calculate the adhesion energy, *G*, of the film-substrate interface.





(b) Shaft-loaded blister test (SLBT). A shaft (either flat- or spherically-ended), is driven into the freestanding film, causing delamination. The applied force, *F*, punch radius, *R*, blister radius, *a*, and blister height, *w*, are used to calculated the interfacial adhesion energy, *G*.

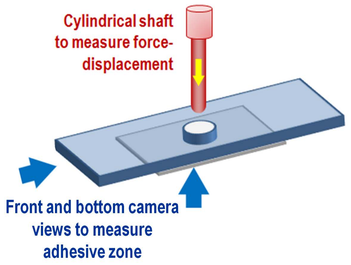
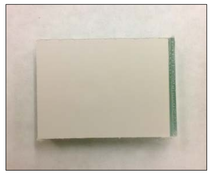


Figure 3. Example of a blister test sample (here, a backsheet-thick glass sample).

(a) Glass-face view



(b) Backsheet-face view

(c) Side view

(d) Layering

Preliminary Results

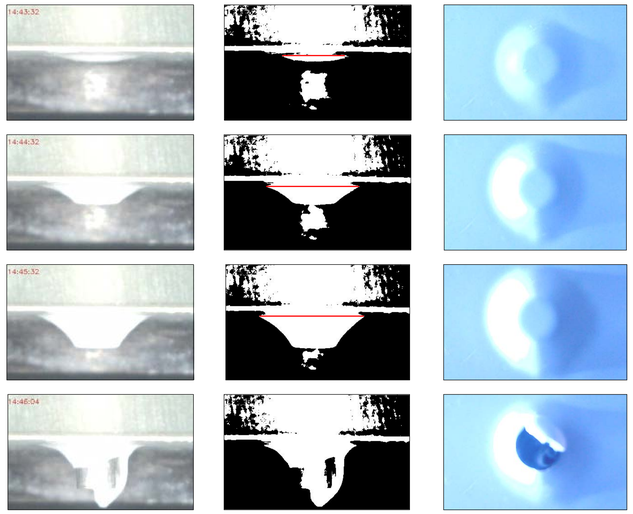


Figure 4. For blister width measurement from SLBT tests, image analysis code was written to convert the side-view camera images from color to grayscale (not shown) and black-and-white. The size of the blister was then measured in terms of pixel count and the pixel-length ratio. (Bottom-view images are shown for reference, only.)

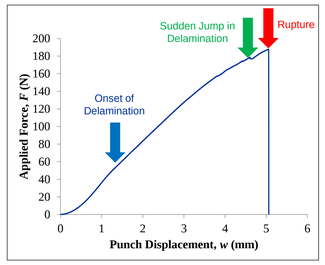


Figure 5. Punch applied force, *F*, vs. displacement, *w*, for the SLBT images above. The blue arrow shows the approximate onset of delamination, prior to which the film simply stretched and deformed. The green arrow shows a sudden "jump" in delamination. The red arrow shows rupture, where the punch broke through the film.

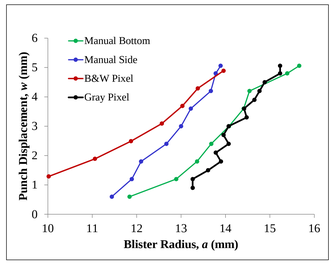


Figure 6. Punch displacement, *w*, vs. blister radius, *a*, for the SLBT images above. The blister radius was measured using two methods: (i) manually measuring the side-view and bottom-view images, using a scale in the image ('Manual Bottom' and 'Manual Side'); and (ii) converting the images to grayscale and black-and-white, and using software image analysis ('B&W Pixel' and 'Gray Pixel'). Improvement of the methods is still needed, so as to get better agreement between the measurements.

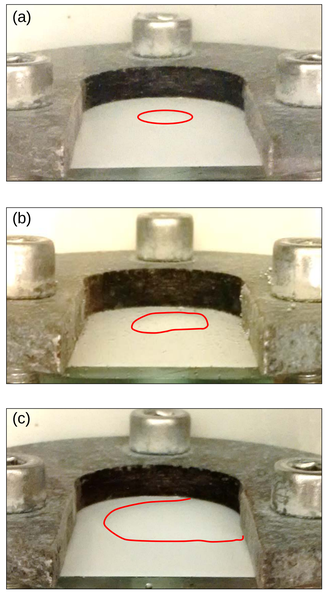


Figure 7. For the thermal blister test, preliminary thermal shock cycle tests were conducted by cycling a backsheet sample between a hot (55 °C) and cold (5 °C) water baths. The samples were immersed in the hot-water bath during the day, and the cold-water bath at night. The figures show the growth of the blister from initial submersion (a), to one day's submersion (b), to two days' submersion (c). (Blisters have been outlined in red, due to low image contrast.) More work will be done in this area, including longer total test duration, faster cycling speeds, and a moist-air environment.

Ongoing Work

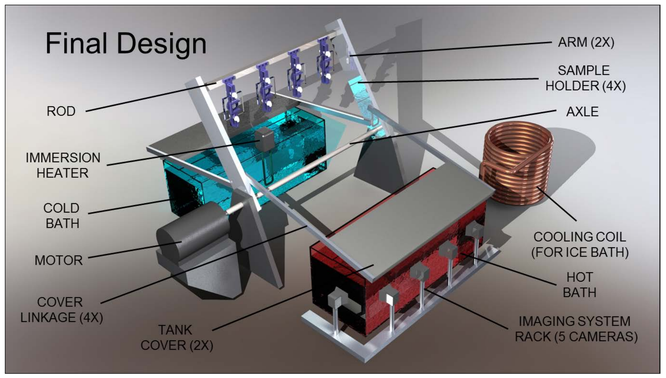


Figure 7 (above). Custom thermal-shock testing apparatus, currently being built. The device will interchange a set of thermal blister test samples between temperature-controlled hot- and cold-water baths, to simulate the thermal cycles experienced by PV materials in the field. Slated completion: Q1, 2016.

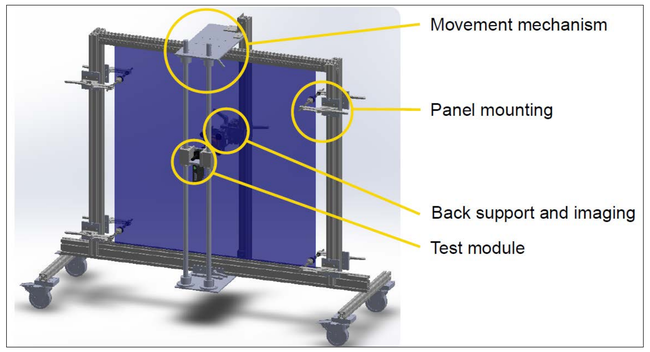


Figure 8. Custom apparatus for blister-testing real, field-weathered PV panel sections, currently being built. The device features an articulating arm that will position a probe for performing shaft-loaded blister tests, anywhere on the panel. Slated completion: QI, 2016.

$$G = \Phi(h, E, \nu, N_0, R, w_0) \cdot \frac{F \cdot w_0}{\pi a^2}$$

Equation 1. A new analytical model for the flat-ended shaft-loaded blister test, currently being developed. It will allow extraction of the interfacial adhesion energy, *G*, from our experimental results. The model will relate *G* to: (i) the properties of the film—the thickness, *h*, elastic modulus, *E*, Poisson's ratio, ν, and initial pre-stress, N_0 — (ii) the size of the punch—the radius, *R* — and (iii) the experimentally measured variables—the applied force, *F*, blister height, w_0, and blister radius, *a*. Slated completion: QI, 2016.

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3. KT Wan, "A novel blister test to investigate thin film delamination at elevated temperature," *Int J Adhes Adhes* 2001 Apr, 20 (2): 141-143.
4. S Julien, KT Wan, "An investigation of delamination in the shaft-loaded blister test." Future publication.

Acknowledgements

We are grateful to Len Magara, Hongdang Zhang, David Chen, and the members of the following Northeastern senior capstone groups: Thermal Shock - Phases I and II, and PV Panel Shaft-Loaded Blister Tester. We are also grateful to the Department of Energy PREDICTS 2 program for providing grant funding.

Effect of Solar Cells Reverse Biased Voltage on PV Modules Partial Shade Performance

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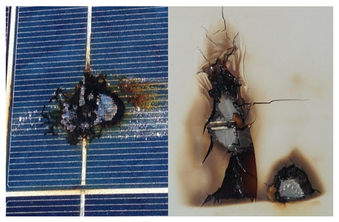
[1]Total New Energies, Solar R&D; [2]University of Arizona, Tucson AZ

ABSTRACT

Power loss due to partial shade was compared for two types of commercial photovoltaic modules, with and without bypass diodes. Modules with uniformly low (4V @ I_{mpp}) ($|V_{BR}|$) reverse bias cell voltage cells lost significantly less power compared to modules with high (18V @ I_{mpp}) $|V_{BR}|$ cells when subjected to partial shade. Differences in power loss were larger when bypass diodes were removed to simulate diode failure. A model to simulate power loss in an array due to partial shading that uses $|V_{BR}|$ as the main parameter was found to be in good agreement with measured power losses in the field. In modules without diodes, temperature monitoring of a shaded cell as the % shaded area was increased, showed significantly lower cell temperatures for a 5.5V $|V_{BR}|$ shaded cell compared to a 14V $|V_{BR}|$ shaded cell. Reverse biased cell voltage ($|V_{BR}|$) measurements of eight photovoltaic cells from different commercial PV module manufacturers are added for reference purposes.



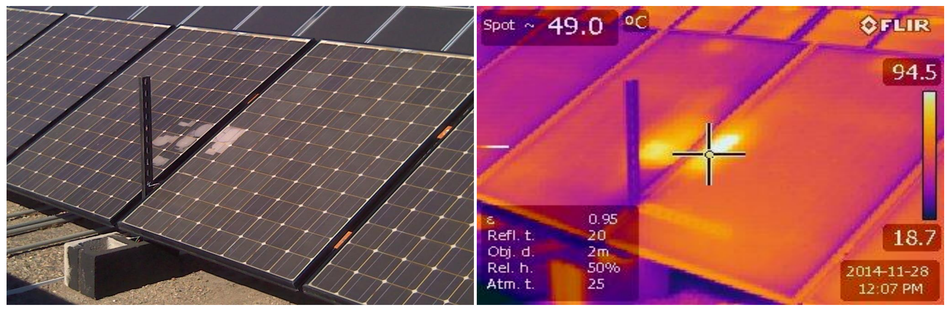
Diodes are subject to failure[1]. What happens to PV modules when diodes fail?

Shown at left is a damaged cell and burnt backsheet from a PV module with a high reverse bias voltage that reached temperatures of over 300°C due to operation under partial shade with diodes removed to simulate diode failure. This failure was caused by high power dissipation in reverse bias operation.

METHOD

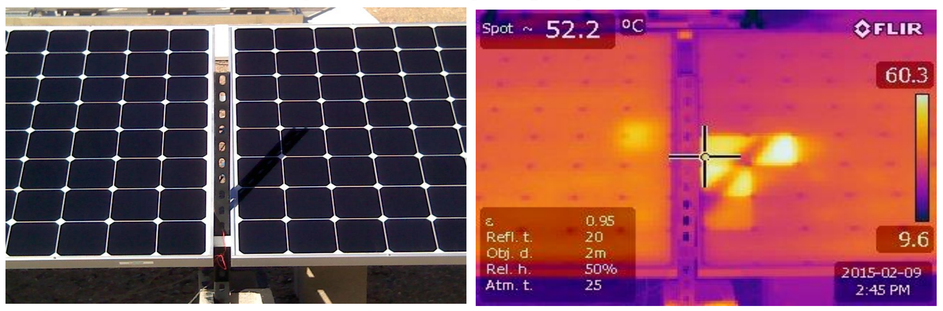
Two commercial PV technologies, one with uniform high (18V $|V_{BR}|$) and one with uniform low (4V $|V_{BR}|$) reverse bias voltage cells were compared. The experiment consisted of two grid-tied strings of four modules of the same PV technology operating simultaneously. One control string operated without applied shade. The experimental string had a short mast obstruction installed between two modules. For both PV systems, strings operated for at least two weeks in this configuration with diodes and 3 days without diodes.

High 18V $|V_{BR}|$ Cells



System suffered 30% energy yield loss within 2 days of exposure with partial shade and no diodes. Irreversible damage (front encapsulant delamination and backsheet bubbling were photo-documented on the 9th day of operation but may have occurred earlier. Hot spots were present. Max cell operating temperature = 94.5C

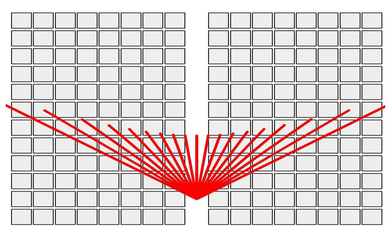
Low 4V $|V_{BR}|$ Cells



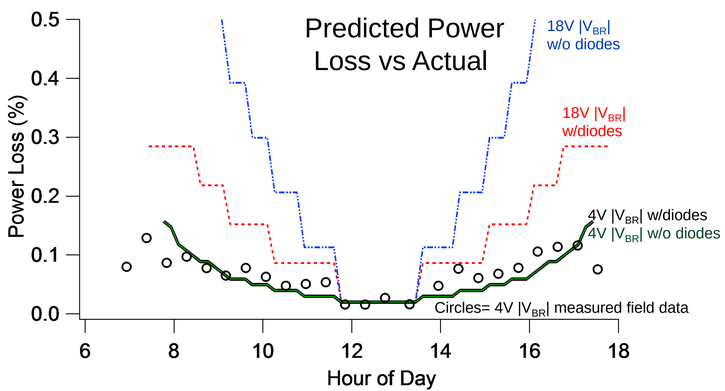
System did not suffer any permanent damage as a result of operating under partial shade without bypass diodes for two months, max cell operating temperature =60°C

POWER LOSS SIMULATION

A solar position algorithm was used to simulate the position of the cast shadow. Based on the number of cells shaded and the system specifications, a model for the relative power loss was derived. The equations used use $|V_{BR}|$ as an input parameter. For cases without permanent damage, the equation can be used to predict power loss and daily energy yield loss. Figure below shows the model output for the two different systems, both with and without diodes. Measured data for the system with 4V $|V_{BR}|$ cells when diodes were present are shown for reference.

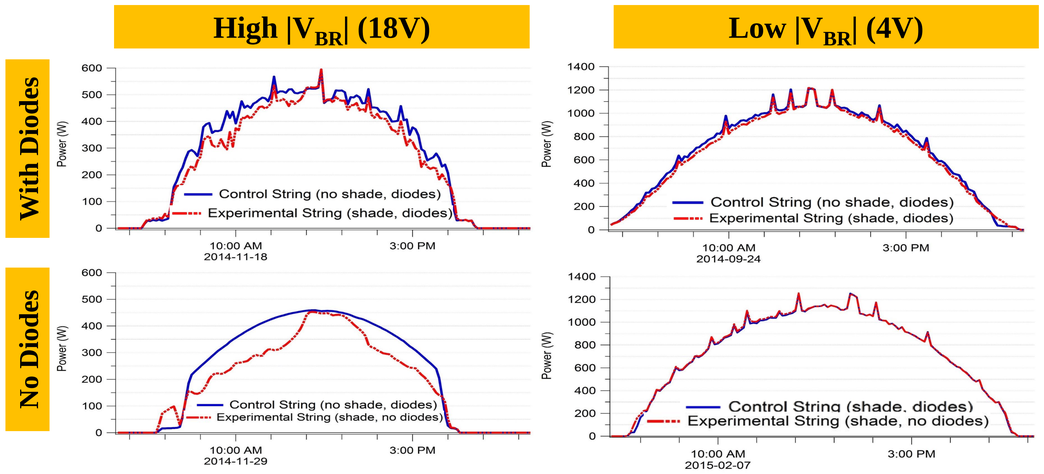


Simulated shadows cast by mast obstruction on two modules every half hour on January 1.

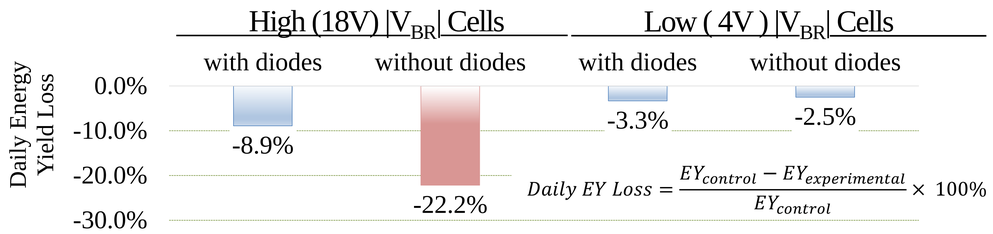


RESULTS

These figures show the measured power output of both strings for both PV technologies when diodes were and were not present. The high $|V_{BR}|$ system lost up to 30% power due to shade when diodes were in place and up to 40% when diodes were removed. The low $|V_{BR}|$ system lost up to 12% power due to shade when diodes were in place. For the 4V $|V_{BR}|$ cells technology, there was no significant difference between the performance of mast shaded modules with diodes removed or in place. The daily energy yield loss values presented in the bar graph below are ratios of the integrated power outputs, averaged over several days of measurements.

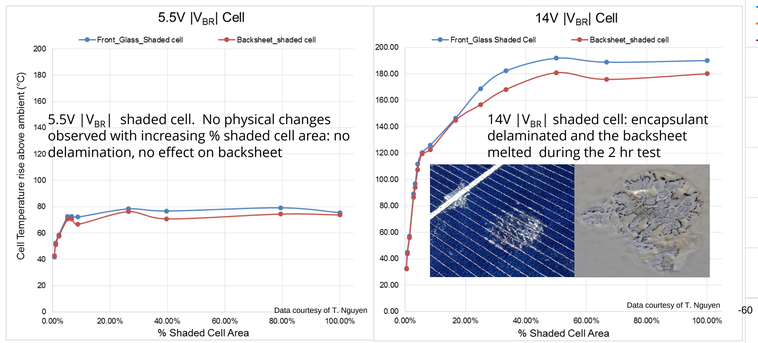


Daily Energy Yield Loss vs $|V_{BR}|$

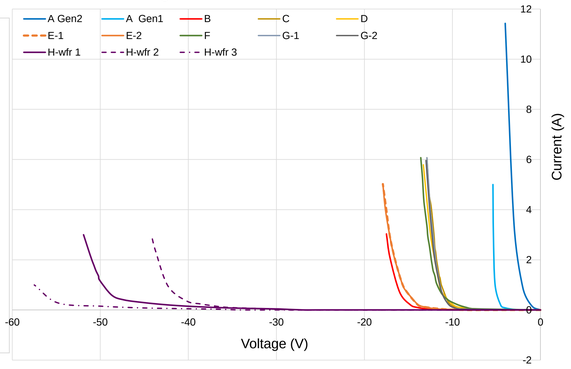


$$Daily\ EY\ Loss = \frac{EY_{control} - EY_{experimental}}{EY_{control}} \times 100\%$$

Cell Temperature Rise Above Ambient vs % Shaded Cell Area in the absence of diodes compared for modules with 5.5V vs 14V cell $|V_{BR}|$



Cell Reverse Characteristics of Eight Commercial PV Module Manufacturers



CONCLUSIONS & RECOMMENDATIONS

- Although many system parameters can influence power loss from partial shading, cell $|V_{BR}|$ is the major contributor to power loss, whether diodes are present or not.
- Without permanent damage, the performance of systems under partial shade and failed diodes can be modeled using $|V_{BR}|$ as the main parameter
- Even with minor shading, modules with uniformly low $|V_{BR}|$ cells outperform modules with high $|V_{BR}|$ cells for energy loss
- Should diodes fail, modules with uniformly low $|V_{BR}|$ cells are more robust than modules with uniformly high $|V_{BR}|$ cells. Uniformly low $|V_{BR}|$ cells are less likely to suffer permanent damage, operate at lower temperatures and have lower energy losses.
- High reverse bias voltage cells + obstruction shading + diode failure resulted in permanent delamination.
- For modules (with solar cells ($|V_{BR}|$ >~10V), diode reliability for the duration of the expected module life is critical to partial shading performance
- The results suggest that for PV modules with uniformly low $|V_{BR}|$ cells, the cells provide built-in fail-safe operation of the module. For typical modules with ($|V_{BR}|$ > ~10V) solar cells, diodes are essential for fail-safe operation of the module.

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Material Characteristics of Polyolefin Encapsulant for PV Module Processing

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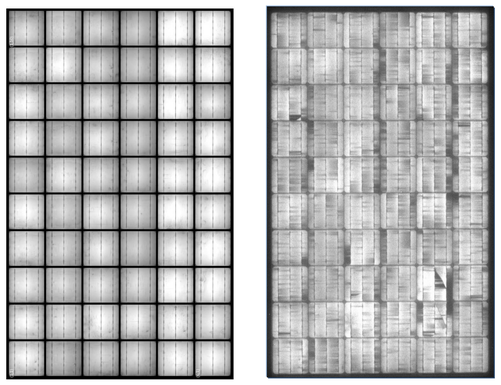
1. Introduction

- The efficiency of industrial solar cells has been enhanced by the improvement of production technique for high-efficiency solar cells such as Double Printing(DP), PERC and PERT.
- Additional processes for the high efficiency and the trend toward thinner wafer make solar cells sensitive to mechanical stress during the lamination process or temperature cycling test.
- Although the excellent durability of Polyolefin encapsulant(POE) for crystalline photovoltaic module has been proven by numerous studies at many institutes, most of PV module manufacturers still prefer EVA to POE due to the familiar process and lower prices.
- POEs are commercialized in both thermoplastic polyolefin(TSPO) and thermosetting polyolefin(TSPO) with the different grades of the base resin, silane coupling agent, UV absorber and additive polymer in the world's PV encapsulation market.
- Both POEs are needed to optimize their polymeric characteristics such as viscosity, heat stability (creep), cross-linked rate
- Here we introduce material characteristics for both polyolefin encapsulants in conventional PV module manufacturing process and reliability in the fields.

PERC solar module(under development) before and after TC50 test according to IEC61215

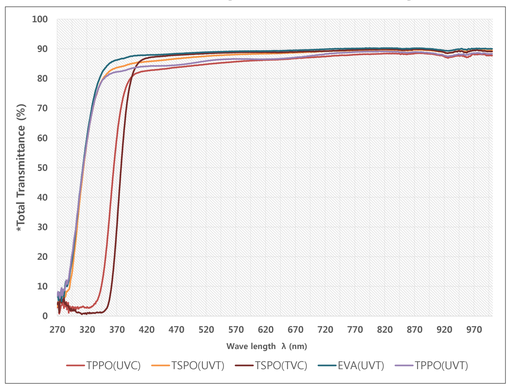


Initial *After*

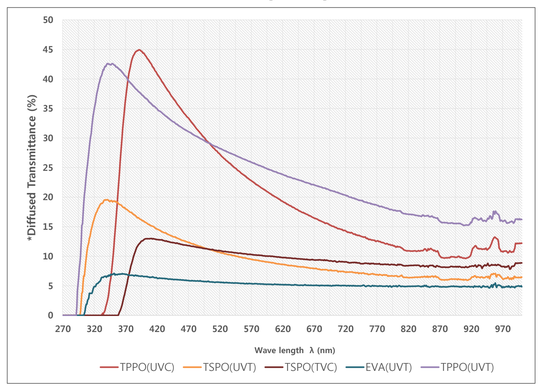
2. Material Characteristic

➢ Light Transmittance

Total Transmittance (Parallel + Diffuse)

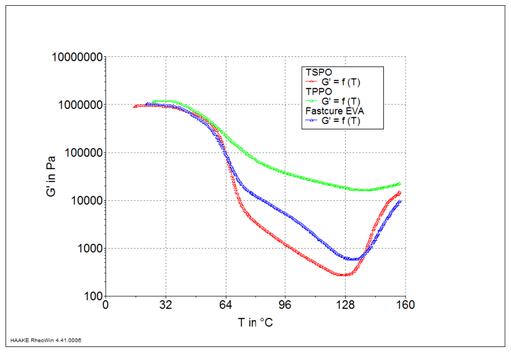


Diffused Transmittance (Haze)

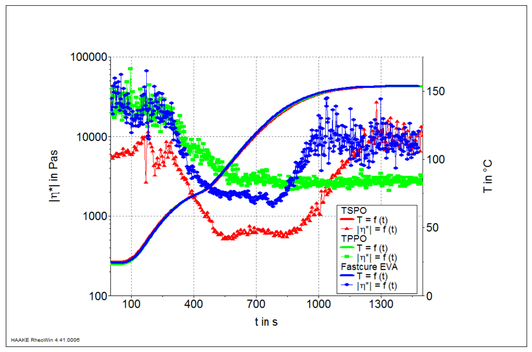


➢ Rheology

Oscillation at linear temperature ramp



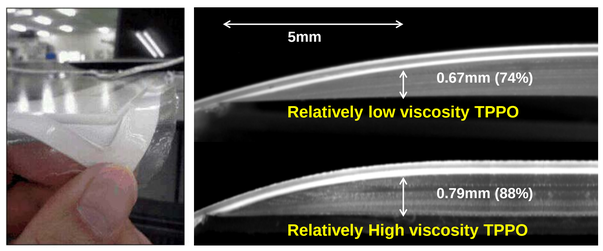
Oscillation at lamination temperature behavior



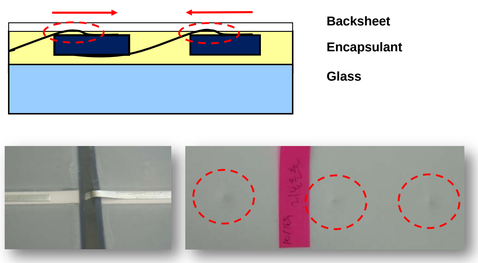
3. Module Lamination Issue

➢ Thermoplastic Polyolefin(TPPO)

- Corner edge delamination of the module.



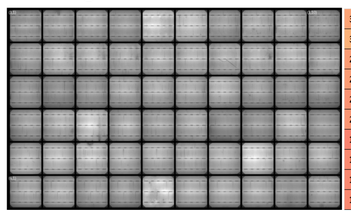
- Inter-ribbon bending caused by backsheet shrinkage



➢ Thermosetting Polyolefin(TSPO)

- Glass warping induces inhomogeneous cross-link rate between the center and edge in the module.
- Weak thermal stability of the uncross-linked thermosetting polyolefin can cause serious failure such as finger interruption, micro crack during the field generation.
- Residual gas can corrode the live metal (cell, ribbon)
- Low modulus (below 1k Pa) of TSPO before cross-linking causes the encapsulant to get thinner in the module during the diaphragm pressing of the lamination, which make the module weaker to the weathering.

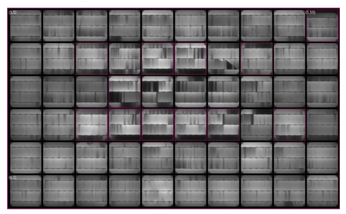
EL Image after the lamination



Cross-linked rate by DSC

32.23%	40.68%	26.43%	42.31%	32.68%	42.45%	54.06%	65.78%	64.60%	68.66%
39.67%	30.83%	32.03%	28.40%	38.23%	35.27%	27.60%	31.73%	50.02%	53.27%
27.91%	42.40%	42.96%	39.28%	28.83%	20.91%	39.32%	40.23%	55.38%	39.96%
28.08%	44.02%	43.51%	16.02%	14.88%	21.70%	41.24%	26.81%	51.33%	10.16%
23.40%	23.68%	23.54%	12.73%	13.69%	18.19%	30.29%	17.67%	40.07%	17.47%
24.91%	26.78%	28.02%	25.00%	6.22%	17.27%	33.19%	27.53%	44.14%	45.39%
15.08%	40.01%	32.63%	3.17%	4.59%	17.13%	36.94%	43.54%	52.87%	52.92%
18.95%	35.61%	27.71%	11.70%	1.59%	27.31%	43.85%	58.49%	73.91%	66.40%
18.38%	45.27%	22.89%	21.18%	27.85%	32.47%	63.14%	72.89%	72.49%	57.14%
18.11%	46.88%	31.85%	32.63%	24.35%	27.91%	68.21%	69.45%	69.25%	62.43%

EL Image after TC200 biased 9.3A

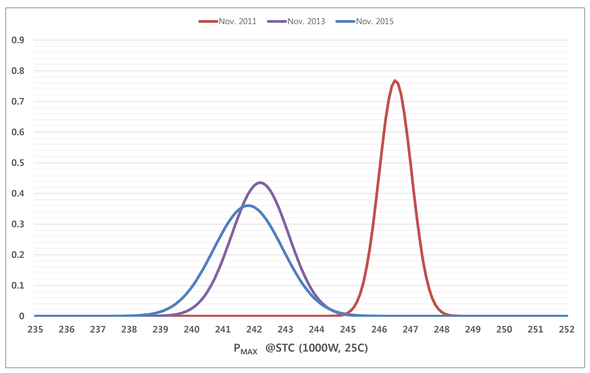


4. Field degradation

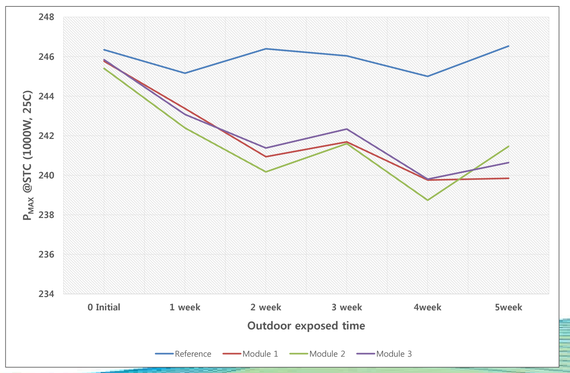
- 100kW Floating PV System was installed with PV modules optimized with TPPO in Nov. 2011, Hapcheon, Korea
- Visual defects such as the delamination, corrosion have not been detected during last 4 years generation.
- We trust that polyolefin is one of the most reliable commercial encapsulation material for the crystalline PV module.

100kW Floating PV System on a dam

Normalized P_{MAX} Distribution



Light-induced Degradation few weeks after Installation



NREL is a national laboratory of the U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Comparison between the application of voltage bias on the module at the start versus after chamber equilibrium in PID testing in damp heat

Peter Hacke[1], Jenya Meydbray[2], Frederic Dross[2], and Sergiu Spataru[3]

1. Goals

- An interlaboratory comparison of PID results for 85°C/85% RH damp heat stress tests.
- Use of in-situ DIV measurements to characterize effects of waiting for chamber equilibrium before applying voltage bias versus applying bias at the start of ramps.
  - Effects of interruptions (intentional or un-intentional)
  - Effects on current transfer
  - Influence on extent of degradation in PID test

2. Introduction & Background

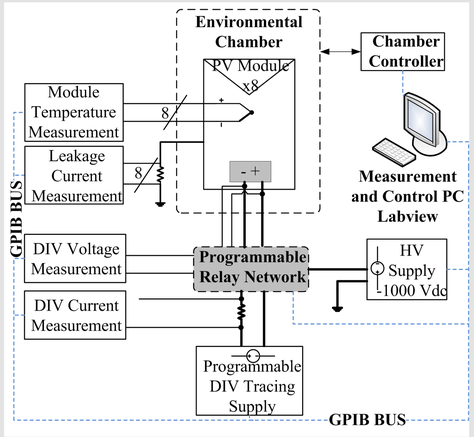
Problem:

- Some PID test protocols specify high voltage bias to be applied at the start of ramps whereas others (*e.g.* IEC 62804-1) require application of bias after the T and RH equilibrium.
  - What is the difference?
- Sometimes, modules are pulled for flash testing, there are module change-outs, and there are unintended pauses due to power outages and equipment failures.
  - What happens?

Approach:

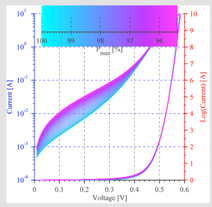
- Perform PID tests at 85°C and 85% RH with bias on at the start versus with bias on after chamber equilibration.
- Use in-situ DIV characterization of P_{max} to see the effects.

3. Apparatus



Switching network used to switch modules intermittently from high-voltage bias for the dark I-V curve trace in 4 h intervals.

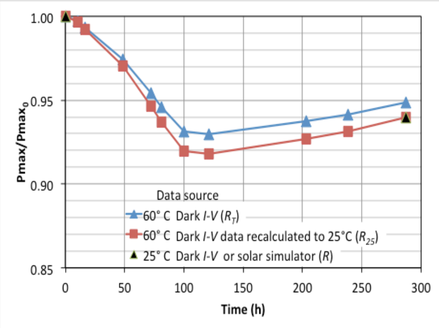
10 A Power supply used to drive forward-bias current through the modules to measure dark I-V curves.



Fully automated experimental setup for performing damp-heat with system-voltage stress testing on PV modules.

4. Method

Determination of STC Pmax from Dark I-V



Example of adjustment from 60° C stress temperature

25°C measured normalized power $R = P_{max}/P_{max0}$

Stress temperature T (°C) measured normalized power $R_T = P_{maxT}/P_{maxT0}$

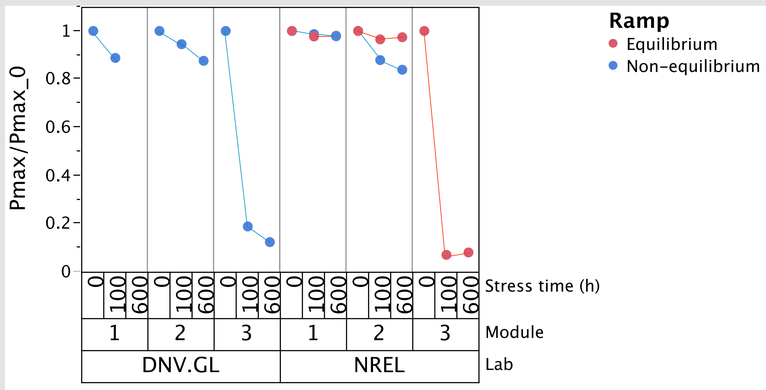
Scaling factor between 25°C and stress temperature T $M = (R_F - R_{T\,F})/(1 - R_{T\,F})$ (F denotes end of test values)

STC normalized power loss $R_{25} = R_T - M(R_T - 1)$

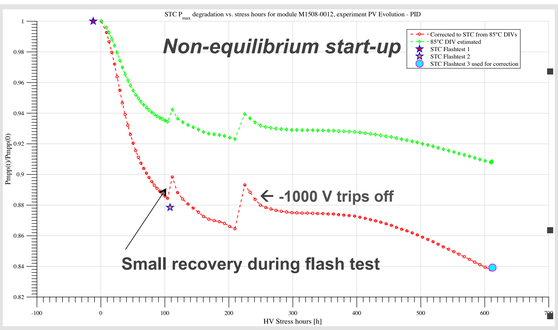
5. Experiment

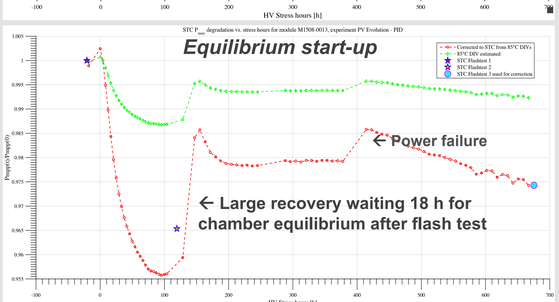
- Samples: three module types, three replicas of each type
  - At DNV.GL and NEL: One replica tested at 85°C/85% RH/ -1000 V bias applied at the start (before simultaneous T and RH ramps) : *"non-equilibrium start-up"*
  - Additionally at NREL: One replica tested at 85°C/85% RH/ -1000V bias applied ~18 h after T and RH have come to equilibrium *"equilibrium start-up"*
- Module pulls for flash test at 100 h and at 600 h
- Measure DIV curves, extract P_{max}
- Measure current transfer

6. Results



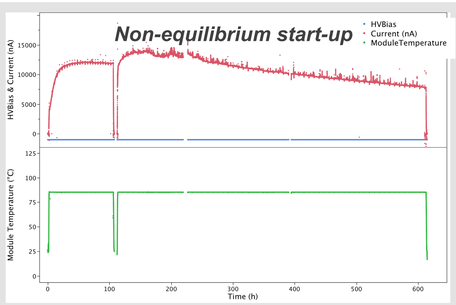
- An interlaboratory comparison of PID results for 85°C/85% RH damp heat stress tests: Comparable results
- Non-equilibrium start-up up to 3.6 x more degradation (sample 2), but with limited data.

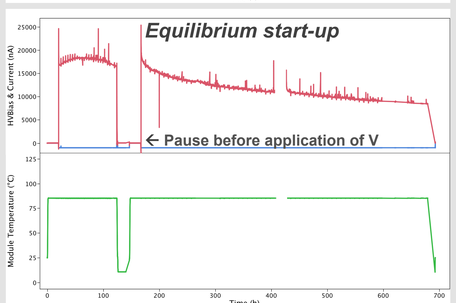


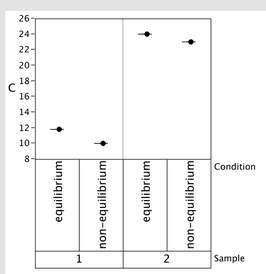


Sample 2

- Strong recovery during equilibrium startup such that final power after 600 h stress higher than after 100 h stress.
- Power bumps and HV trips also lead to recovery.
- When calculating STC P_{max} with aid of final flash test, 100 h calculated STC P_{max} in good agreement indicating success of the DIV method.







We anticipated non-equilibrium startup condition to show significantly greater coulomb transfer because of condensation on modules, but that wasn't the case.

7. Summary & Conclusions

PID in three crystalline silicon module types were examined as a function of test start-up conditions.

A module type with voltage bias applied at the very start of the test exhibited up to 3.6 times more degradation over the course of 600 h of test than a sister module with bias applied 18 h after the chamber reached the set point temperature and humidity (85°C, 85% relative humidity), but more statistics are needed.

When the module was pulled for flash testing, or when the voltage bias was interrupted for any reason, the module power recovered as determined by in-situ monitoring by dark I-V measurements.

Recovery was especially pronounced after 100 h of PID stress and a pull for flash testing when the module was maintained at equilibrium conditions again for 18 h before reapplication of voltage bias. This experiment serves to clarify the effects of interruptions and waiting for chamber equilibrium conditions before application of voltage stress in PID tests.

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[3] Aalborg University, 9220 Aalborg East, Denmark

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2016 NREL PV Module Reliability Workshop (Feb 23-25, 2016, Lakewood, CO)

Durability of Photovoltaic Backsheet Outer Weatherable Layers

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Arkema Inc., King of Prussia, PA

Abstract

Photovoltaic backsheets are an essential part of photovoltaic modules. It is imperative that the backsheet perform and be shown to be weatherable over the 25 year expected module lifetime. This poster reports on findings from a study focused on understanding the durability of the outer weatherable layers of commercial backsheets exposed in south Florida for five years. In general, we have found outer weatherable layers made from fluoropolymers to be much more durable than layers made with other types of polymers. But even within the class of fluoropolymer materials, there are differences in long term durability. These results highlights the need for PV system owners to understand their PV module's bill of materials to ensure long term performance.

Experimental

Outdoor Exposure Conditions:

- Samples exposed in South Florida, USA at 45°angle directly facing the sun.
- Samples exposed since 2011.

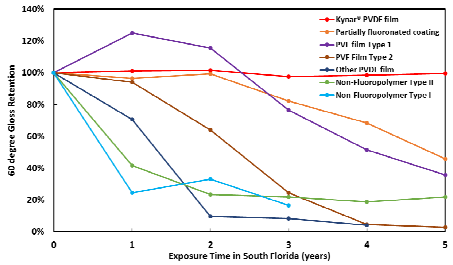
Outer Weatherable Layers Studied:

- Kynar® PVDF film
- Other commercial PVDF film
- Partially fluorinated coating
- PVF film Type I
- PVF film Type 2
- Non-Fluoropolymer Type I
- Non-Fluoropolymer Type II
- All samples washed in accordance to ASTM D6864 prior to testing.

Kynar® is a registered trademark of Arkema, Inc.

Gloss Retention

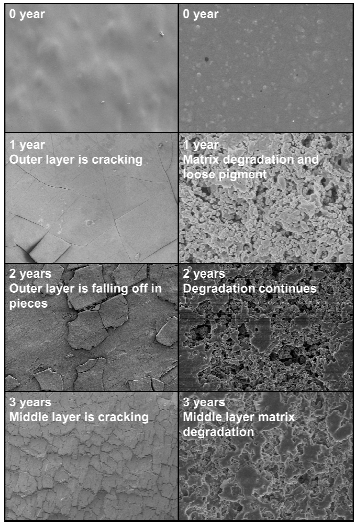
Gloss Retention = Gloss (t_1) / Gloss (t_0)



- Gloss retention monitors surface changes (erosion, cracking).
- Non-Fluoropolymer Type I and Type II gloss retention drops rapidly after 1 year of exposure. This level of gloss loss is visible to the eye when comparing unexposed and exposed samples.
- The Kynar® PVDF film protected backsheet shows exceptional stability and no surface degradation.
- Other fluoropolymer outer weatherable layers show decreased gloss retention at different rates, with the other PVDF film in this study losing gloss retention almost as fast as the Non-Fluoropolymer outer weatherable layers.

Non-Fluoropolymer Type I Weatherability

SEM Images

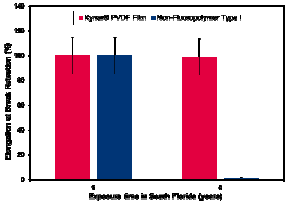


After one year, the Non-Fluoropolymer Type 1 outer weatherable layer is cracking and the polymer matrix is degrading. This is over the same period when a decrease in gloss retention is observed.

Over the next two years, the polymer matrix continues to degrade and sections of the outer weatherable layer fall off.

Once exposed, the inner backsheet layer begins to crack and degrade.

Mechanical Properties

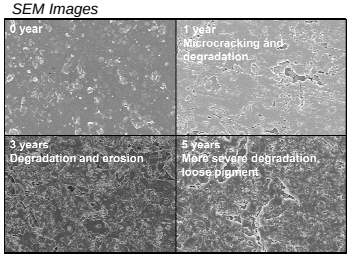


Cracking and degradation of Non-Fluoropolymer Type 1 backsheet has led to a complete loss of mechanical properties.

Tensile and elongational properties were measured in accordance with ASTM D882.

Non-Fluoropolymer Type II Weatherability

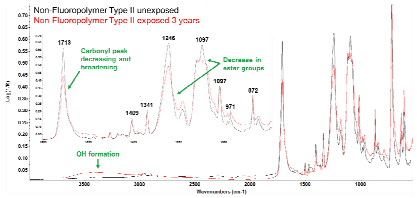
SEM Images



Microcrack formation and polymer matrix degradation occurs within one year. This causes a decrease in gloss retention.

With further exposure polymer matrix degradation continues.

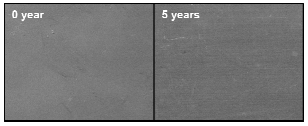
ATR-FTIR Spectra



Changes in the ATR-FTIR spectra indicate photo-initiated chain scission reactions are causing the matrix degradation.

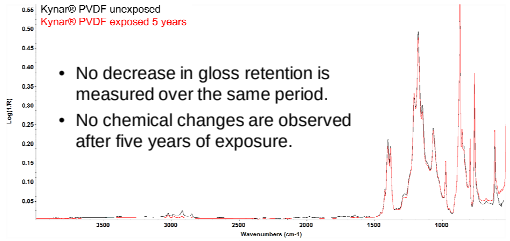
Kynar® PVDF Film Weatherability

SEM Images



No cracking, pitting, or surface erosion is occurring after 4 years of South Florida exposure for backsheets protected with Kynar® PVDF film.

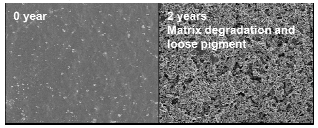
ATR-FTIR Spectra



- No decrease in gloss retention is measured over the same period.
- No chemical changes are observed after five years of exposure.

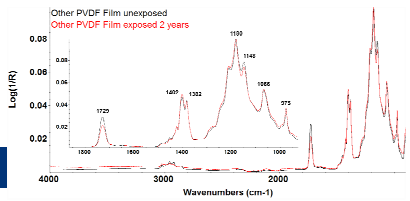
Other PVDF Film Weatherability

SEM Images



The measured decrease in gloss retention within two years of exposure is due to significant matrix degradation.

ATR-FTIR Spectra



ATR-FTIR spectra show that there are changes in the chemical composition of the surface indicating degradation of the material.

Summary

- Gloss retention is a simple method for tracking polymer degradation and correlates with more complex methods such as SEM microscopy and ATR-FTIR spectroscopy.
- Significant differences in the durability of backsheet outer weatherable layers were found.
- Non-Fluoropolymer outer weatherable layers were observed to be degrading after only one year of exposure.
- Backsheets protected with Kynar® PVDF film were not observed to crack or degrade after five years of South Florida exposure.
- Other fluoropolymer outer weatherable layers were found to have varying degrees of durability.
- The other commercial PVDF film in this study was observed to show signs of significant degradation within two years of exposure.
- The difference in durability between Kynar® PVDF film and the other PVDF film is due to differences in formulation.

Effect of Intensity and Wavelength of Spectral UV Light on Discoloration of Laminated Glass/EVA/PPE PV Module

Polymeric Materials Group

Yadong Lyu, Li-Chieh Yu, Chiao-Chi Lin, Deborah Stanley, and Xiaohong Gu

Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

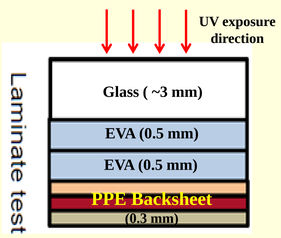
Introduction

Discoloration, one of major failure modes of PV modules, could result in lower efficiency of power output and cause concerns for long-term durability. Studies have indicated that ultra-violet (UV) irradiation is a predominant environmental factor for yellowing occurred in PV modules. However, the quantitative effects of light intensity and wavelength on the discoloration of modules are still unclear.

This work aims to establish a quantitative relationship between the spectral UV irradiance/wavelength and the discoloration of a laminated Glass/EVA/PPE system during UV exposure at elevated temperature. The yellowing mechanism of the model system has been investigated, and the validation of the reciprocity law has been carried out. The dependence of yellowing on wavelength (i.e., action spectrum) has also been established. This study provides foundations for developing accelerated laboratory testing and mathematical models for service life prediction.

Experiments

Sample Construction

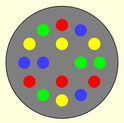


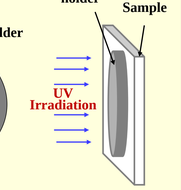
Large samples to avoid the edge effect on yellowing data

Exposure conditions

NIST 2-meter SPHERE*

Filters in filter holder



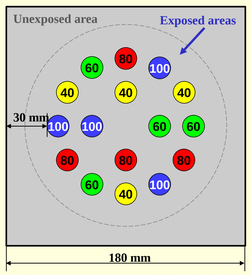


- T = 85 ± 5 °C
- RH = 0% with precision of 1 % (Dry)

* *Chin et al, Review of Scientific Instruments (2004), 75, 4951; Martin and Chin, U.S. Patent 6626053.*

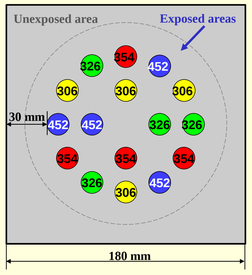
Experimental design

1) Reciprocity Study: Neutral Density (ND) filters



Various intensities of 40 %, 60 %, 80 % and 100 % (with no filter)

2) Wavelength Study: Band Pass (BP) filters



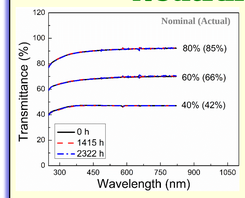
Various wavelength ranges centered at 306 nm, 326 nm, 354 nm and 452 nm

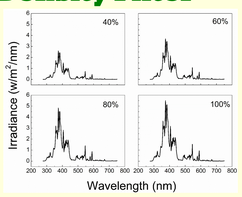
Characterizations

- Digital photos
- UV-Visible spectroscopy in reflection mode

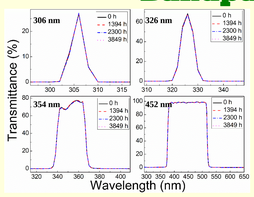
Stability of Filters and Spectral Distribution

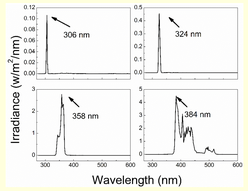
Neutral Density Filter





Bandpass Filter

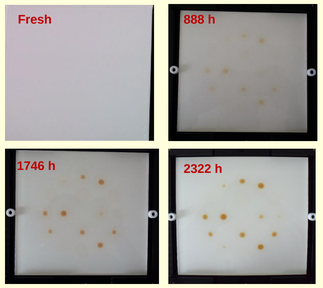




➢ Both neutral density filters and bandpass filters are stable during UV exposure at 85°C/Dry on the SPHERE.

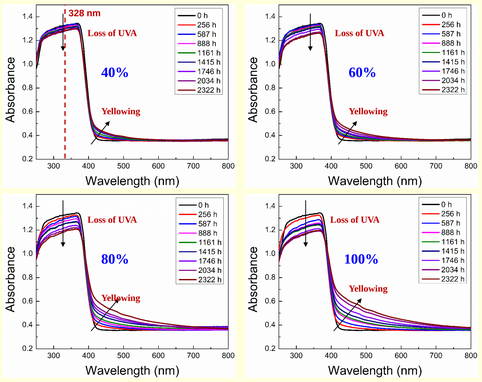
Effect of UV Light Intensity (Reciprocity study)

Digital Photos



➢ The exposure regions gradually became yellow, while yellowing areas basically kept constant.

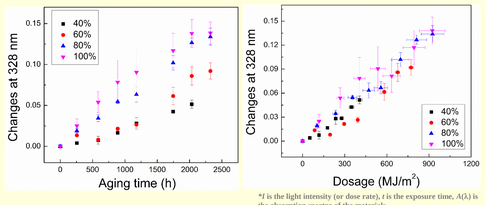
UV-Visible Spectra



➢ The loss of UV absorbers (UVA) correlated with the yellowing.
➢ Optical changes at different light intensities have a similar trend.

Evolution in UVA Loss at 328 nm

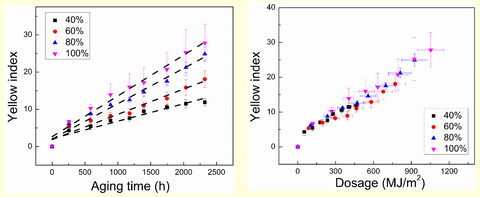
$$Dosage = It(1-e^{-A(\lambda)})$$



*I is the light intensity (or dose rate), t is the exposure time, $A(\lambda)$ is the absorption spectra of the materials.
* Error bars are one standard deviation of current measurement.

1) UVA loss increased with longer exposure time.
2) A higher light intensity led to a higher rate per time for the loss of UVA.
3) When plotting absorbance with dosage, deviations became smaller between different light intensities.

Evolution in Yellowing Index (YI)



* Error bars are one standard deviation of current measurement.

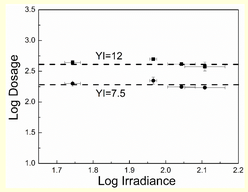
1) A higher light intensity led to a faster yellowing growth.
2) A quasi-linear relationship was observed for the YI-aging time plot.
3) The YI-dosage plots for different light intensities superimposed in to a single master curve.

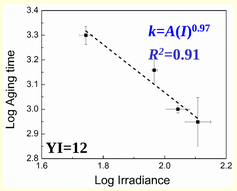
Validation of Reciprocity Law

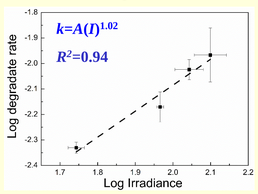
Schwarzschild Law: $t(I)^p$=constant or $k=A(I)^p$

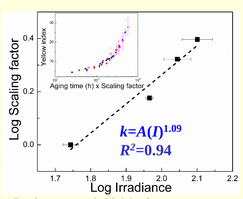
When Schwarzschild coefficient p=1, Schwarzschild Law reduced to Reciprocity Law.

➢ **For YI growth**





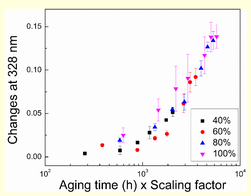


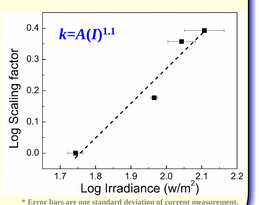


* Error bars are one standard deviation of current measurement.

➢ It appeared that the needed dosage at specific damage was independent of intensities and p value was close to 1.
➢ It was also found that growth of YI followed the same mechanism with different light intensity, as YI-aging time curves could be superimposed to a master curve based on scaling factors.
➢ Reciprocity Law appeared to be obeyed.

➢ **For UVA loss**



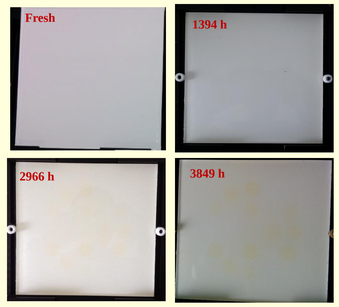


* Error bars are one standard deviation of current measurement.

➢ Reciprocity Law appeared to be obeyed.

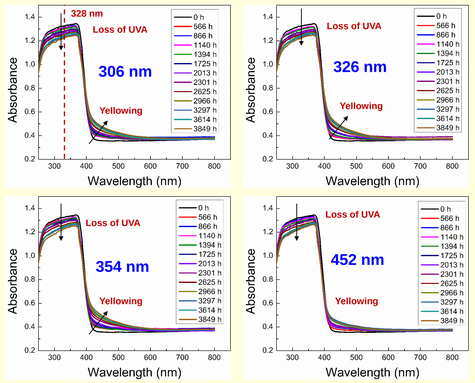
Effect of UV Wavelength

Digital Photos



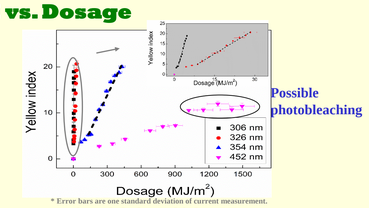
➢ Visible yellowing of regions under 306 nm, 326 nm and 354 nm filters was observed.

UV-Visible Spectra



➢ Both UVA loss and yellowing growth increased with exposure time under wavelengths of 306, 326 and 354 nm.
➢ The growth of yellowing under 452 nm slowed down at late stage, possibly due to competitions between yellowing and photobleaching.

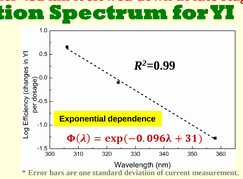
YI vs. Dosage



* Error bars are one standard deviation of current measurement.

➢ Shorter wavelength led to a higher YI.
➢ YI increased linearly under 306, 326 and 354 nm, while under 452 nm it slowed down at late stage.

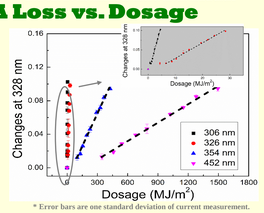
Action Spectrum for YI



Efficiency was calculated based on yellowing per dosage

* Error bars are one standard deviation of current measurement.

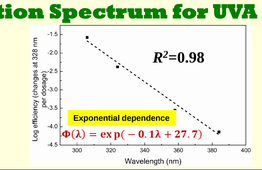
UVA Loss vs. Dosage



* Error bars are one standard deviation of current measurement.

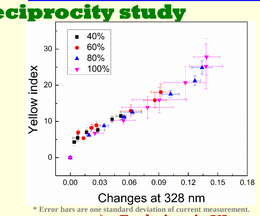
➢ UVA loss increased over UV exposure.
➢ The shorter wavelength, the higher loss rate per dosage.

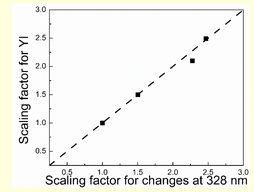
Action Spectrum for UVA Loss



Correlation between YI growth and UVA loss

Reciprocity study

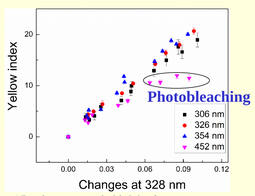




* Error bars are one standard deviation of current measurement.

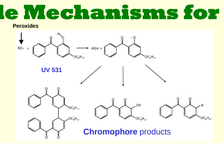
➢ Evolutions in YI correlated directly with UVA loss.

Wavelength study

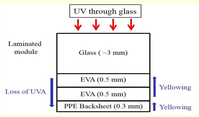


* Error bars are one standard deviation of current measurement.

Possible Mechanisms for UVA Loss and Yellowing



1) UVA loss might give rise to chromophore precursors.



2) UVA loss could permit UV light penetration to a greater extent.

**Klemchuk et al.. Polym degrad stabil. 1997; Fechine et al.. Polym degrad stabil. 2002.*

➢ A nearly linear relationship was found between YI and the loss of UV absorbers for the Glass/EVA/PPE system after UV exposure under 306, 326 and 354 nm, but not 452 nm.
➢ Visible light and oxygen, both could contribute to the photobleaching process under 452 nm.

**Decker, J Photochem,1981; Pern. IEEE Photovoltaic Specialists Conference. 1994; Hülsmann, P et al.. Prog Photovoltaics, 2014*

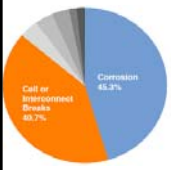
Summary

- Quantitative relationships between light intensity/wavelength and yellowing of Glass/EVA/PPE system have been established.
- The degradation rates for the growth of YI and the loss of UV absorbers are found to be proportional to the UV irradiance. Reciprocity law appears to be obeyed both for the growth of YI and the loss of UV absorbers in the studied UV irradiance range.
- Wavelength effect is clearly seen for growth of YI and the loss of UV absorbers. The action spectrum in exponential expression, is also obtained for these changes. Photobleaching effect is observed at longer wavelength under 452 nm.
- The yellowing of the glass/ EVA/PPE system can be resulting from degradation of encapsulant or/and backsheet. It is found that the growth of yellowing correlates well with the loss of UV absorbers.

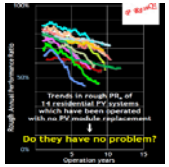
Title: Predictive Models and Novel Accelerated Tests for the Reliability of Front-Contact and Back-Contact Cell Metallization and Solder Joints in Photovoltaic Modules.

SunPower : Yu-Chen Shen (PI), John Lippiatt, Akira Terao, Kat Han and Jichao Li.
Future collaboration with NREL: Mike Kempe, Peter Hacke.
Funded by DOE Sunshot Predicts2

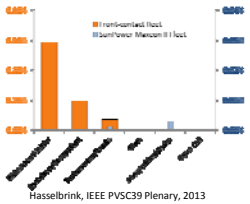
Motivation:



Wohlgemuth, 20th Eur. Photov. Solar Energy Conf. and Exhibition, 2005.



Kato, PV Module Reliability Workshop 2012, Golden, Colorado



Hasselbrink, IEEE PVSC39 Plenary, 2013

2005-2013: consistent reports that dominant failures are metallization/solder/interconnect fatigue and corrosion.

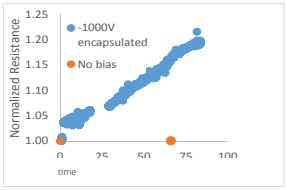
Research Strategy: Closed Loop Learning

- Incorporate physics of failure to understand the mechanism.
- Lifetime modeling.
- Design accelerated tests.
- Field data for confirmation.

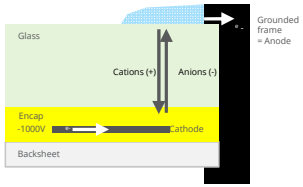
Key Outcomes of Research:

- Predictive models to determine degradation in 25 to 40 years.
- Accurate and fast accelerated tests useful for qualification, certification, and ongoing reliability.
- Shorten Qual+ TC500 cycle time.

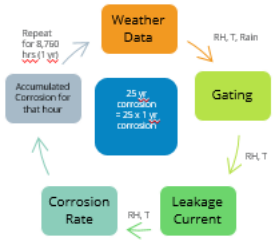
Corrosion Research: Preliminary Model



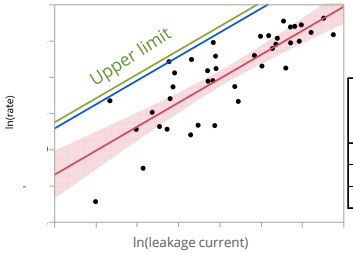
SunPower study of metal corrosion with and without bias. Leakage current is very important to corrosion.



Electrolytic corrosion. Variables: moisture, leakage current, temperature, ion migration,encapsulant by-products (acetic acid in EVA)



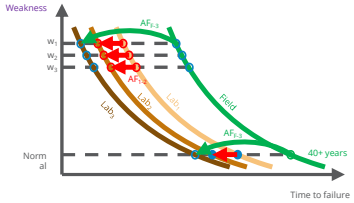
- Weather data: 1 year from Fort Myer, Florida; 1 hr intervals
  - Module temperature calculated from wind, illumination, and ambient T.
- Gating (Leakage Current when moisture is present on the module)
- Leakage Current vs RH,T at 1kV
- Corrosion Rate vs Leakage Current Case (Transport or Reaction limited?)
- Calculation for uniform corrosion



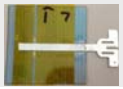
Estimate corrosion in 25 years

	Corrosion in 1 year (um)	Corrosion in 25 yrs (um)	dP% Absolute%/Rel%
Fit	x	xx	a
Threshold	y	yy	b
Upper Limit	z	zz	c

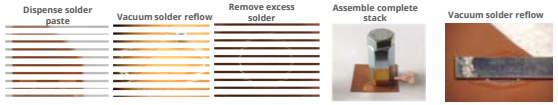
Solder Joint Fatigue Research:



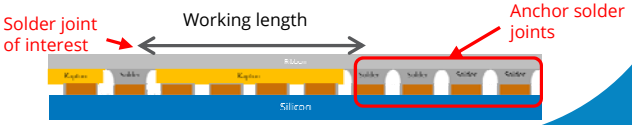
- Develop a test structure: controllably weakened solder joints:
  - Time zero characterization
  - Microstructure characterization
  - Microstructure evolution during aging
  - Finite Elements Analysis (FEA)
- Compare TC, RTC, Thermal Shock, and field conditions to determine acceleration factors

	Ring shaped joint	Bridge design
Mask type	Epoxy Mask	Kapton Tape on patterned metal
Picture		
Topology:	Copper layer on wafer is flat	Copper layer on wafer is patterned
Thickness:	Determined by screen print thickness	Determined by metal line thickness
Stress:	Around torus	From joint to anchor point
Parameters:	Outer diameter, width	Length, width
Issue:	Crack propagation reduces stress	Solder Filet

Ring shaped design



Bridge Design



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Research Center for Photovoltaics

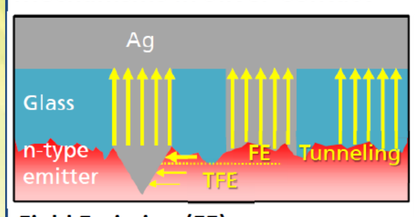
Electrical Detection of Gap Formation underneath Finger Electrodes on c-Si PV Cells Exposed to Acetic Acid Vapor under Hygrothermal Conditions

°Tadanori Tanahashi, Norihiko Sakamoto, Hajime Shibata, and Atsushi Masuda
National Institute of Advanced Industrial Science and Technology (AIST)

Introduction & Experimental Procedures

Background

Proposed Current Transport Mechanisms in Silver Contact[1)]



Field Emission (FE)
$N_D \geq 10^{20}\ cm^{-3}$

Thermionic Field Emission (TFE)
$10^{17}\ cm^{-3} < N_D < 10^{20}\ cm^{-3}$

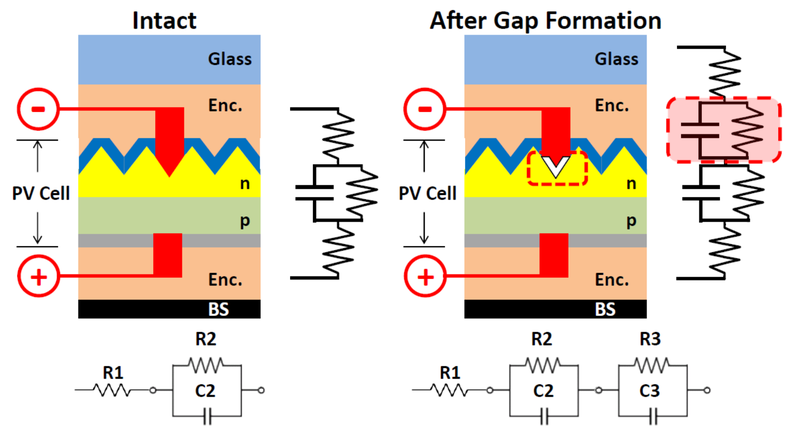
Electron Tunneling
through glass layer
(directly or *via* nano-Ag colloids)

Dissolution of Glass-Silver Boundary Layer by Acetic Acid[2)]

1) R. Hoenig et al., "Macroscopic and Microscopic Electrical Behavior of Screen Printed Silver Contacts to Phosphorus-Doped Emitters", presented at 5th Metallization Workshop, 2014.
2) A. Kraft et al., "Investigation of Acetic Acid Corrosion Impact on Printed Solar Cell Contacts", IEEE J. Photovolt. 5 (3): 736-743, 2015.

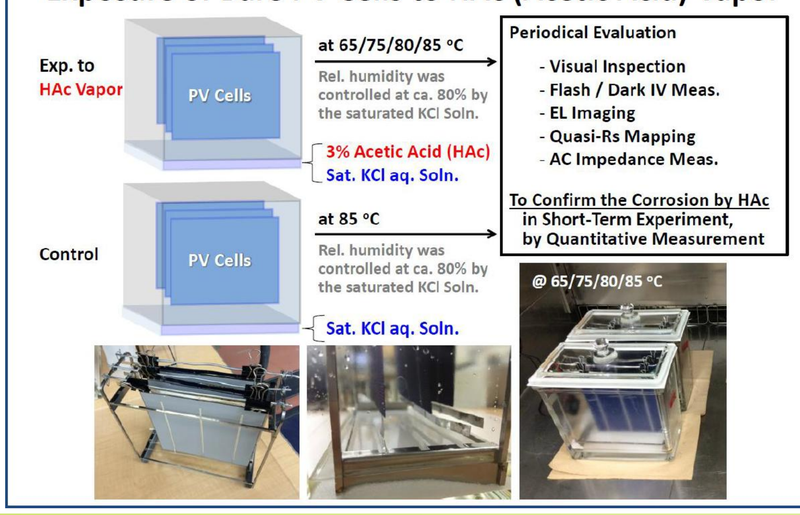
Objective

To Confirm the Formation of Gap underneath Finger Electrodes, by the Evolution of AC Equivalent Circuit



Experimental Procedures

Exposure of Bare PV Cells to HAc (Acetic Acid) Vapor



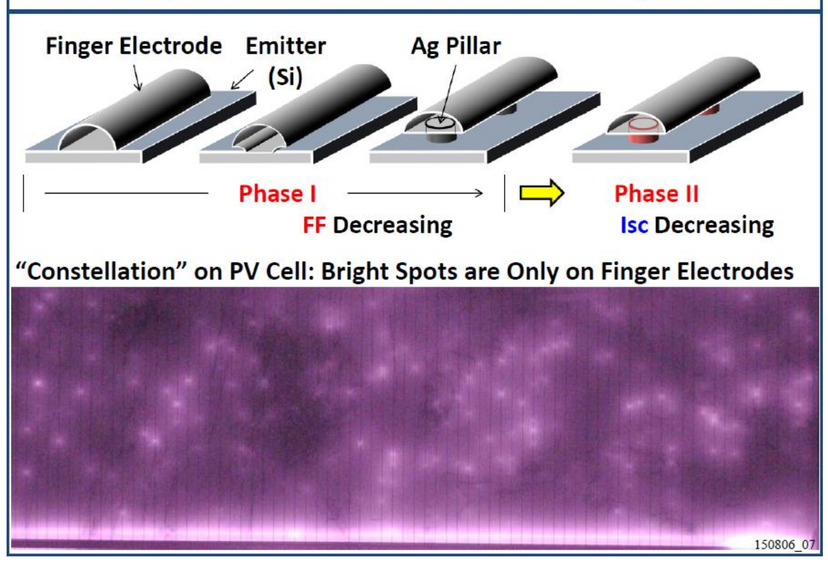
Summary

The current collection failure induced by the corrosion in finger electrodes on PV cells has been elucidated as a major degradation cause of c-Si PV modules. For the corroding mechanism, it has been recently proposed that acetic acid (HAc) would dissolve the glass layer, and the gaps underneath finger electrodes would be formed. Then, we tried to detect the electrical signal concerned in this gap formed by the exposure to HAc vapor, and obtained the results as follows;

- Bare c-Si PV cells were promptly degraded by the exposure to HAc vapor according to the exposed duration, and the formed gaps underneath finger electrode were confirmed by SEM/EPMA imaging (**Panels 1 - 4**).
- Since the synchronized increase in resistance (R3) with the intense decrease in FF was observed, we concluded that this R3 signal originates from the gap formed underneath finger electrodes (**Panels 5 - 9**).
- Interestingly, the degradation profiles were divided into 2 phases; firstly the generating power (P_{max}) was rapidly declined with decreasing in *FF* and increasing in R3 resistance (Phase I), and thereafter the gradual reduction of P_{max} with that of I_{sc} (Phase II) was observed (**Panel 8**) . The independence of each degradation phase was highly probable by the difference in their activation energies calculated by Arrhenius equation (**Panel 9**).
- The similar signals were observed also in c-Si PV modules exposed to damp heat stress in long-term.(**Panels 10 - 12**)

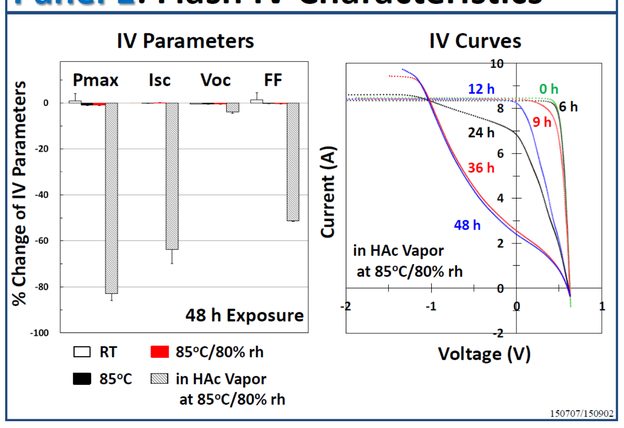
From these results, we propose a mechanism for 2-step degradation caused by HAc in PV modules (right figure). And, the electrical signal derived from the gaps would be a crucial "aging signature" in c-Si PV modules installed in fields.

Putative Degradation Process on c-Si PV Cells Exposed to HAc

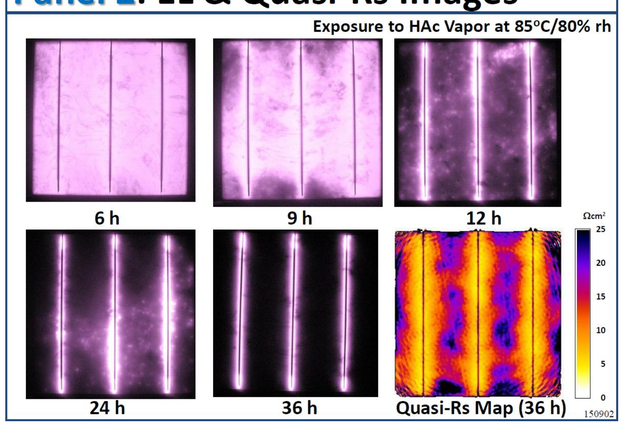


Results

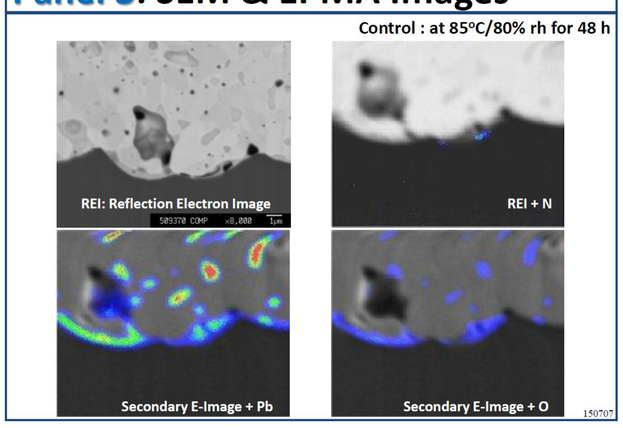
Panel 1: Flash IV Characteristics



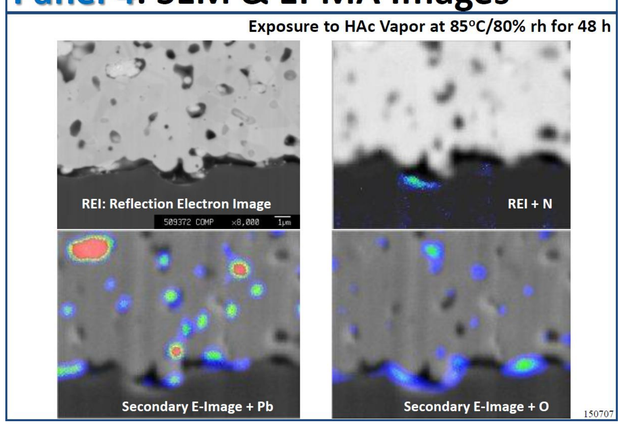
Panel 2: EL & Quasi-Rs Images



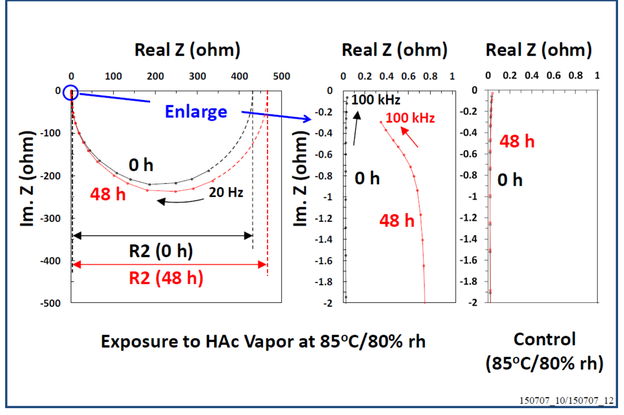
Panel 3: SEM & EPMA Images



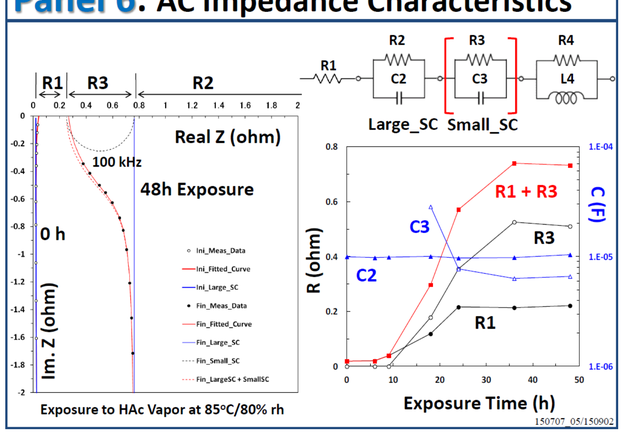
Panel 4: SEM & EPMA Images



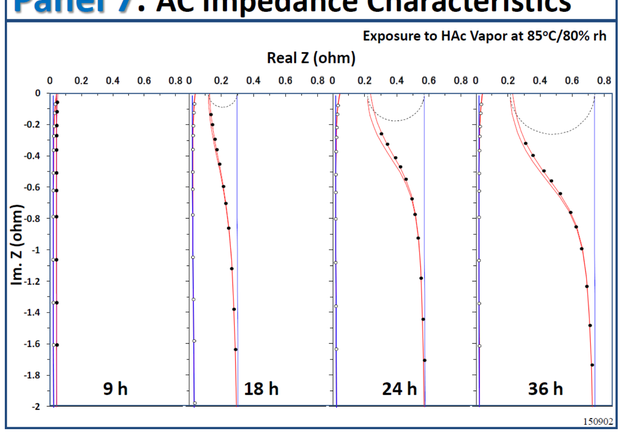
Panel 5: AC Impedance Characteristics



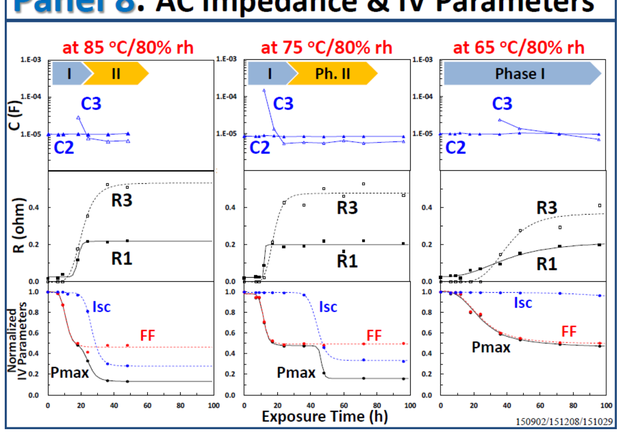
Panel 6: AC Impedance Characteristics



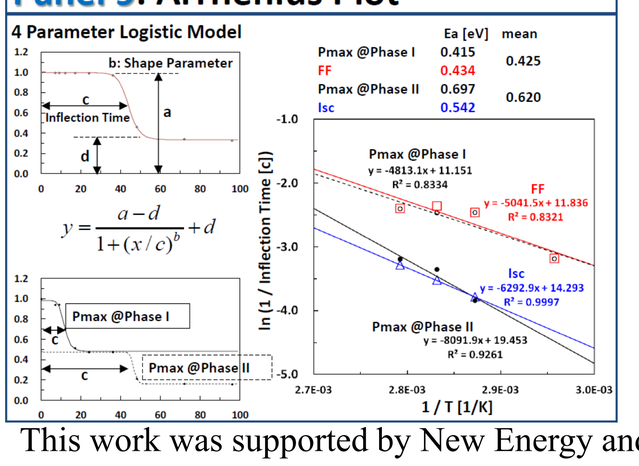
Panel 7: AC Impedance Characteristics



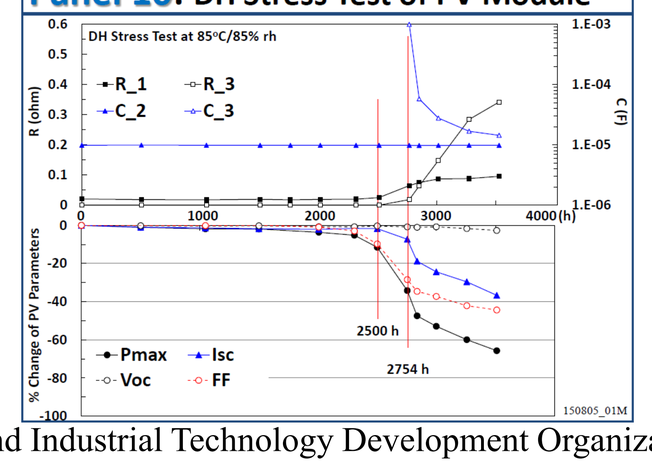
Panel 8: AC Impedance & IV Parameters



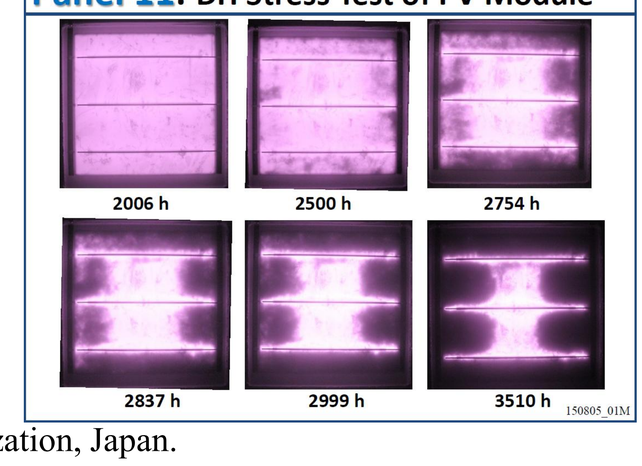
Panel 9: Arrhenius Plot



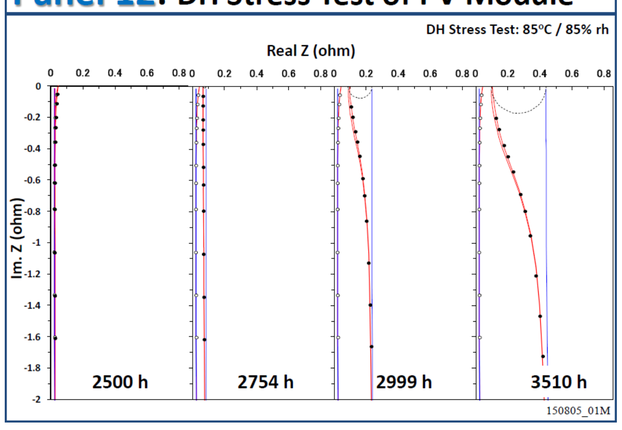
Panel 10: DH Stress Test of PV Module



Panel 11: DH Stress Test of PV Module



Panel 12: DH Stress Test of PV Module



This work was supported by New Energy and Industrial Technology Development Organization, Japan.
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Holistic Reliability: Accelerated Testing of Adhesion

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Introduction – Role of Metallization on Module Durability

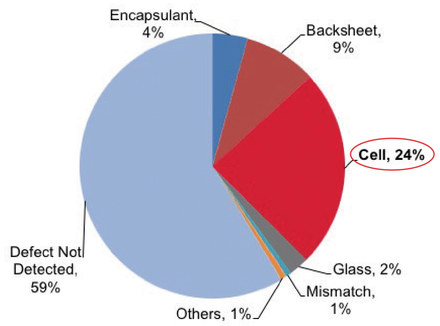
Motivation:

- 2/3rd of defects in inspected modules attributed to cell and metallization defects.
- Little past understanding of metallization related failures in the module.
- Metallization formulation changes every 1-2 years.
- Front metallization silver paste laydown decreased ~70% in last 5 years.
- Silver finger width reduced from 80µm to 35µm.

Goals:

- Understand mechanisms of adhesion and relevance for durability.
- Identify range for adhesion safe for reliability.
- Develop science based understanding of what modulates metallization failures.
- Develop accelerated tests to simulate metallization failures seen in the field.
- Design superior metallization pastes to ensure long term durability.

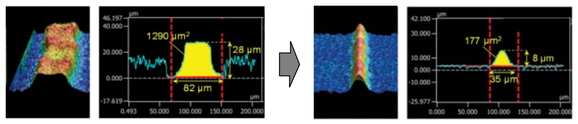
Module Defects

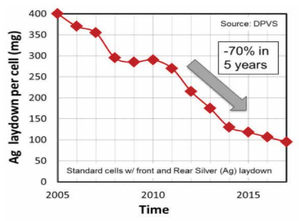


Subcomponent degradation mode pareto based on visual inspection

Bradley, J. Kopchick, B. Hamzavy. "Quantifying PV Module Defects" IEEE PVSC (New Orleans, 2015)"

Metallization Laydown Reduction



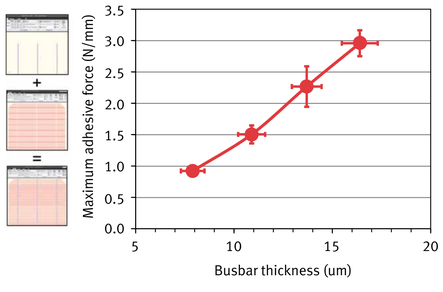


Variation of Paste-Driven Adhesion Component

Method:

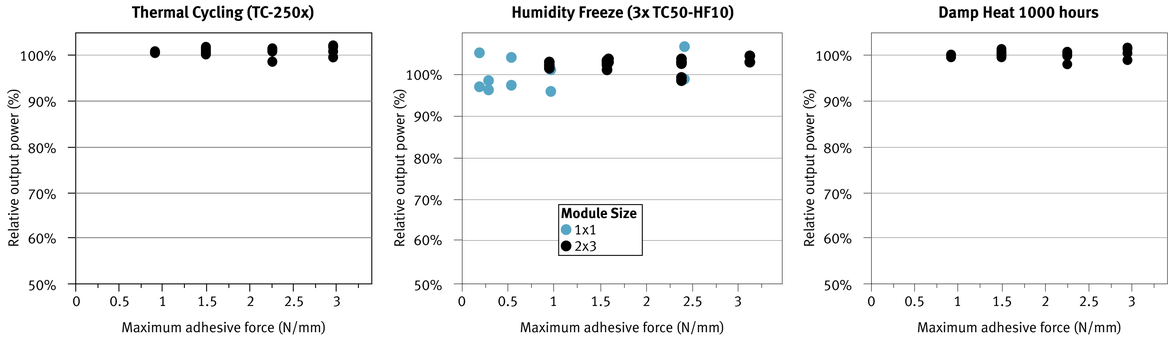
Vary busbar thickness; fingers constant

- Busbar thickness does not impact performance
- Wide adhesive force range: 0.9 – 3N/mm
- Is there an impact on module durability?



Paste-Driven Adhesion and Durability

IEC-Based Stress Testing



- Paste-driven adhesion does not affect module durability under Standard Tests
- Tests are currently extended (TC>500, Sequential testing, etc.)

The DuPont Difference

+110 Over the last 7 years, DuPont has introduced more than 110 new Solamet® pastes designed to boost solar panel power output.

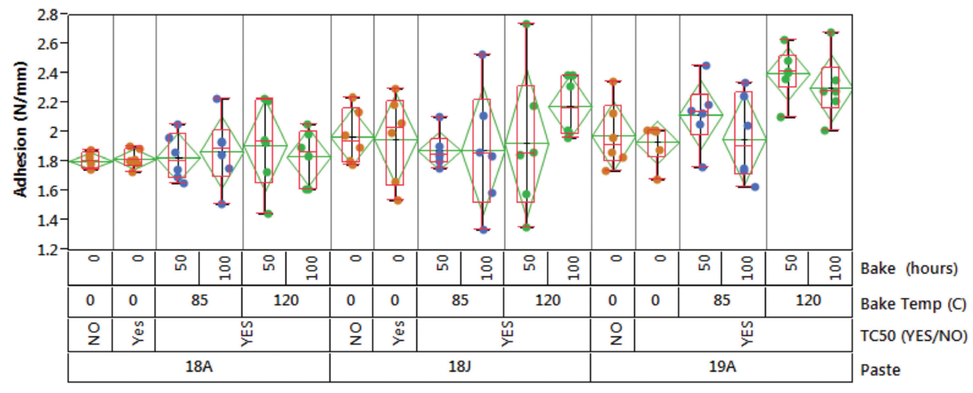
+30 YEARS Tedlar® film is the only backsheet material proven to protect solar panels for 30+ years in all weather conditions.

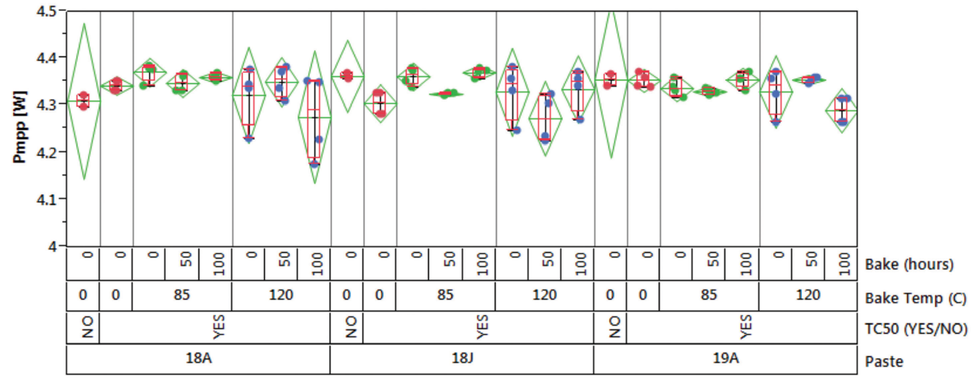
+50% More than half of the world's 400 million panels installed since 1975 have DuPont materials in them.

5 TRILLION DuPont PV materials have been time-tested in >5 trillion panel-hours of solar installations across the globe since 1975.

Adhesion: Aged Adhesion

- With the reduction in laydown by 70%, what is the impact on adhesion for long term module reliability?
- Borrowing from Microelectronics industry an accelerated test method with the intent of determining long term adhesion durability.
- Bake tabbed cells at 85°C and 120°C for 50 and 100 hours followed by temperature cycling from -40°C to 85°C for 50 cycles.
- Temperature cycling alone has negligible affect on adhesion and power output.
- Baking followed by temperature cycling has minimal affect on adhesion and power output.





Conclusions

- DuPont is studying role of metallization pastes for module durability.
- Paste-driven adhesion component does not affect module durability under IEC-Based Test Conditions.
- Adhesion and power output is not affected by temperature aging followed by temperature cycling under conditions tested.
- Further test development and validation with fielded modules that have been exposed to weathering is underway.

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Behavior of bypass diode during thermal runaway test

(J-TG 4 activities of QA Forum / QA Task Force 4 ; Diode, Shading & Reverse Bias)

This work was performed with the cooperation of Onamba, Sanken Electric, Nihon Inter Electronics, Kyocera and SHARP.

Feb. 23 - 24, 2016

2016 PVMRW @ Sheraton West, Lakewood, CO USA

Yasunori Uchida

JET (Japan Electrical Safety & Environment Technology Laboratories)

Introduction

QA Forum started in July 2011 in order to establish the criteria, guidelines and technical requirements for high reliability PV modules.
As one of the TG4 activities, I proposed a new work item for international standard of "Bypass diode thermal runaway test (future IEC 62979)" in October 2014 which is currently in the CD stage.
From the results of repeated experiments to establish the test method, the bypass diode (BD) behavior during thermal runaway test has become clear.

❶ Conditions of thermal runaway occurrence

❷ Influence of a switching time until applying of reverse bias voltage after shutting off forward current

❸ How to detect the thermal runaway occurrence

❹ The estimated junction temperature (Tj) during thermal runaway

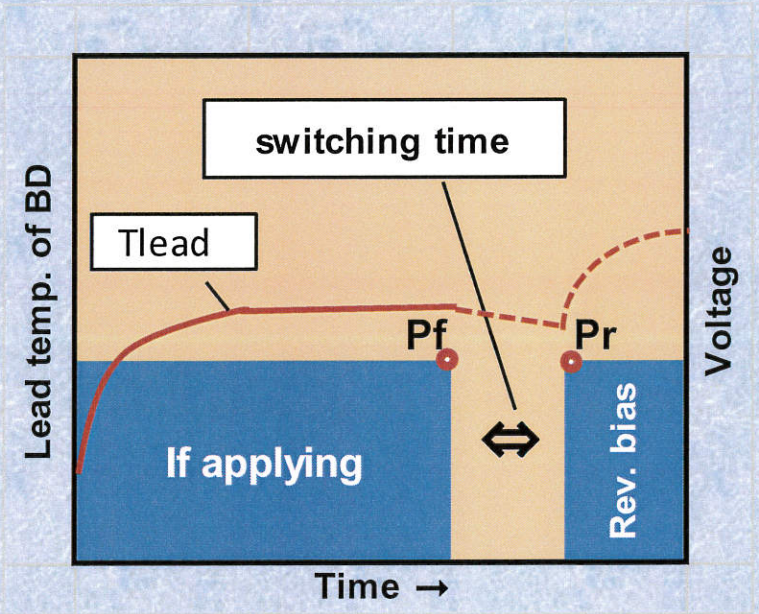
❶ Conditions of thermal runaway occurrence

The conditions of thermal runaway occurrence were studied.
The experimental results show that the ratio of Pf and Pr is a critical parameter for thermal runaway occurrence.

Pf ; Forward direction energy just before applying of Vr.

Pr ; Energy immediately after reverse bias voltage was applied.

The experimental results concerning the ratio of Pf and Pr are as follows.



❶-1 Cases that thermal runaway did not occur

Sample #	Pf Forward direction energy before Vr applying		Pr Reverse direction energy after Vr applying	Ratio Pr / Pf
◆J-box-A (If=13.5A/ Vr=15V)	3.9 W (Tlead=164.5℃/ Vf= 0.289V)	>	2.8 W (Tlead=164.5℃/ Ir= 0.189A)	0.72
◆J-box-B (If=13.5A/ Vr=15V)	4.2 W (Tlead=166.5℃/ Vf= 0.308V)	>	3.2 W (Tlead=166.5℃/ Ir= 0.227A)	0.76
◆Single SBD (If=11A/ Vr=15V)	3.2 W (Tlead= 147.3℃/ Vf=0.293V)	>	1.8 W (Tlead= 147.7℃/ Ir=0.120A)	0.56

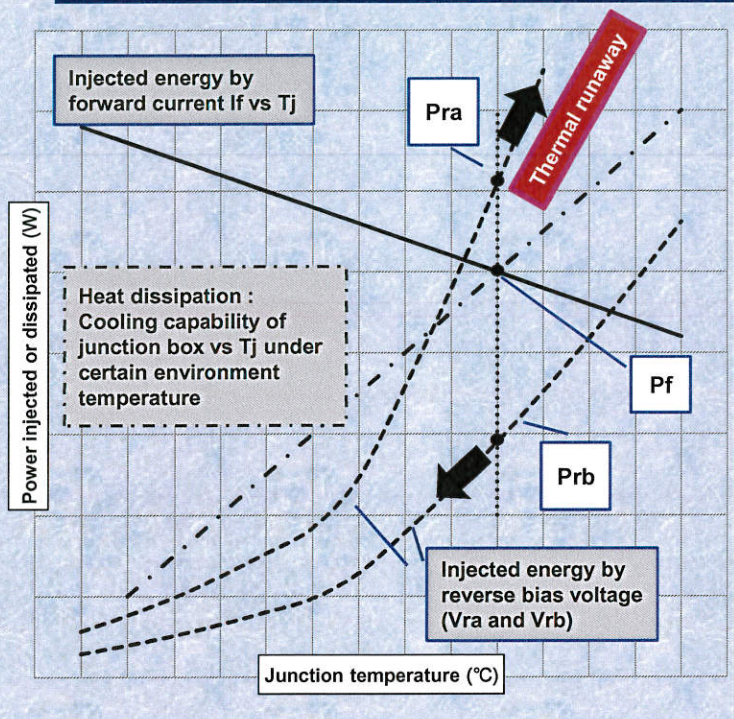
Ratio < 1 ➡ Thermal runaway does not occur !!!

❶-2 Cases that thermal runaway occurred

◆J-box-A (If=13.5A/ Vr=20V)	3.7 W (Tlead=163.6℃/ Vf= 0.274V)	<	5.8 W (Tlead=163.6℃/ Ir= 0.288A)	1.57
◆J-box-B (If=11A/ Vr=12V)	2.7 W (Tlead=180.8℃/ Vf= 0.251V)	<	8.3 W (Tlead=180.8℃/ Ir= 0.687A)	3.07
◆Single SBD (If=13.5A/ Vr=13V)	4.0 W (Tlead= 162.6℃/ Vf=0.295V)	<	4.1 W (Tlead= 162.6℃/ Ir=0.313A)	1.03

Rati > 1 ➡ Thermal runaway occurs !!!

How the thermal runaway occurs

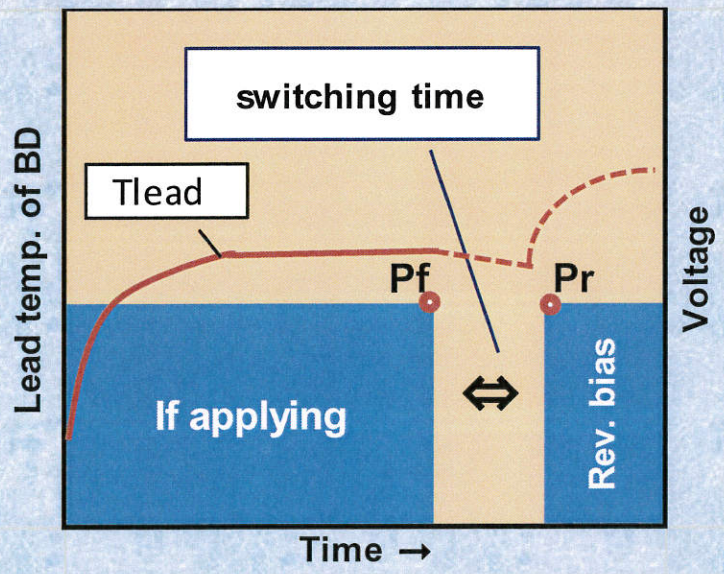


In the case of " Pra > Pf ", Pr increases along the injected energy curve of reverse voltage by the surplus energy "(Pra - Pf)" with increasing of the leakage current.

Tj of BD begin to rise and thermal runaway occurs.

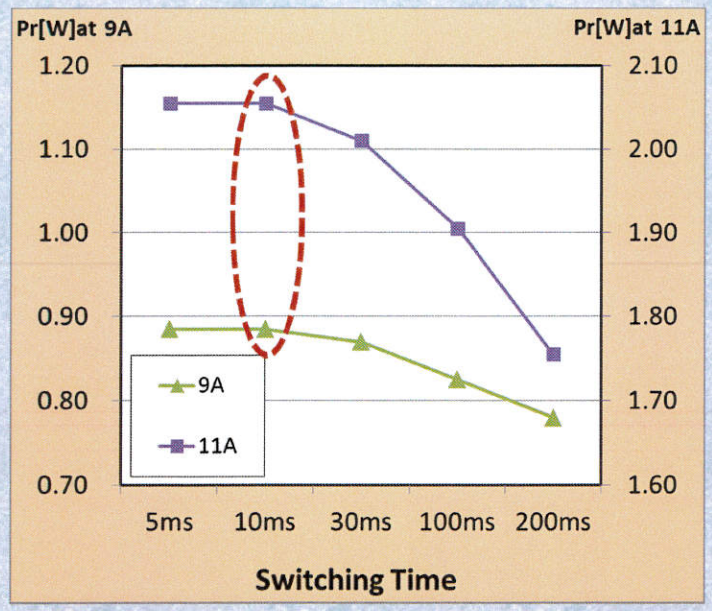
In the case of " Prb < Pf ", Tj decreases with time, because Prb is smaller than cooling capability.

❷ Influence of a switching time until application of reverse bias voltage after shutting off forward current



To verify the effect of the switching time, the energy immediately after the reverse bias voltage application was measured by changing of the switching time.

Pf (W) = Forward direction energy just before applying of reverse bias voltage.
Pr (W) = Energy immediately after reverse bias voltage was applied.



I.D. #	IF	Pr, W				
		5 ms	10 ms	30 ms	100 ms	200 ms
BD with potting	9A	0.89	0.89	0.87	0.83	0.78
	11A	2.05	2.05	2.01	1.90	1.75

Note: Pf = 2.61W at 9A
Pf = 3.21W at 11A

With the increase of the switching time (from 5ms to 200ms), the value of Pr becomes smaller.

This means, Tj will decrease if a longer switching time is applied.

The proposed 10ms is considered reasonable and is obtainable by PC controller.

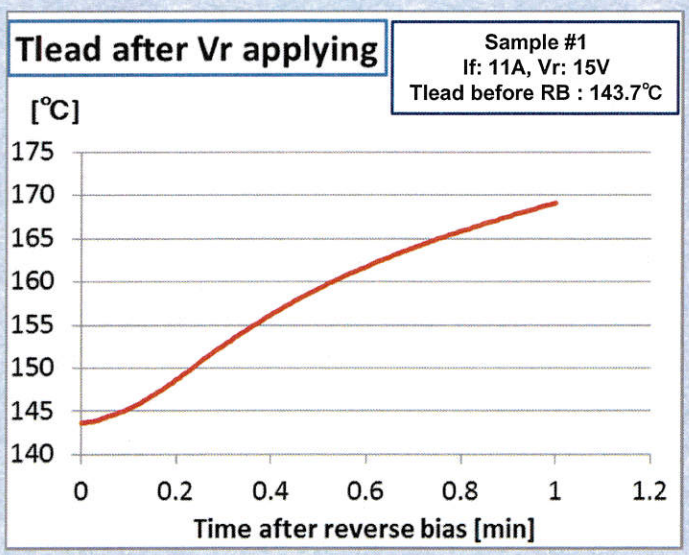
❸ How to detect the thermal runaway occurrence

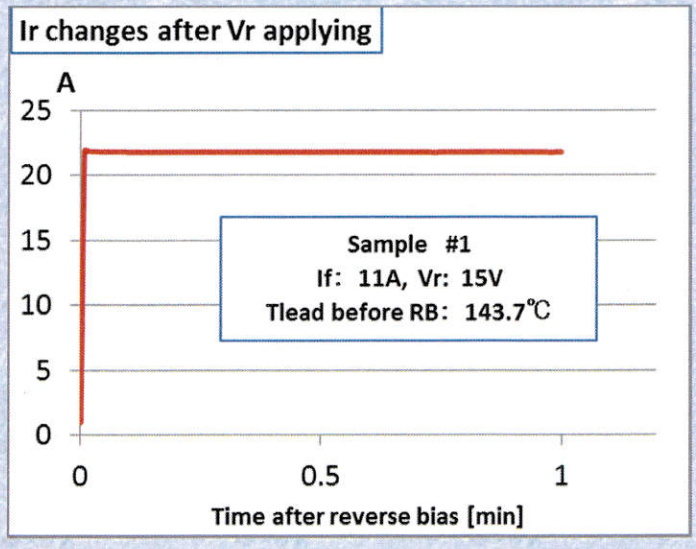
From our test experience, the changes of Tlead is gradual during thermal runaway.
In addition, Tlead becomes more than 200 ℃ during thermal runaway which is above the limitation of temperature to be measured by a thermocouple soldered on the diode lead.

Therefore, Tlead observation is not considered suitable for the evaluation of thermal runaway phenomenon.

To cope with these difficulties, the observation of leakage current is recommended as an effective method.
The leakage current respond sharply to thermal runaway.

Comparison of the observation of Tlead and Ir during thermal runaway





❹ The estimated temperature of Tj during thermal runaway

To know the junction temperature (Tj) of BD during thermal runaway, the measurement was tried.

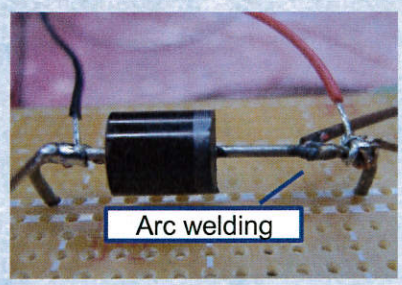
The Vf-Tj characteristics should be measured for the individual BD.

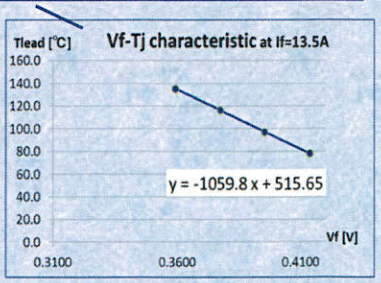
➜ Procedure and an example of the results

❹-1. To measure the lead temperature of more than 200℃, a thermocouple was arc welded to the diode lead.

❹-2. The measurement of the Vf-Tj characteristics of BD was made and the following formula was obtained.

Tj = -1059.8 X Vf + 515.65





❹-3 By using the value of If and Vf after 1 hour of the forward current application, Rth was calculated.

If=13.5A, Vf=0.2963、Tlead=163.7 ℃

Tj= -1059.8 × 0.2963+515.65=201.6 ℃

Rth = (Tj-Tlead)/(Vf × If)=(201.6 ℃ - 163.7 ℃) / (0.2963V X 13.5A) = 9.49 ℃/W

❹-4 Tj after 2 minutes of Vr application during which the thermal runaway occurred was calculated as follows.

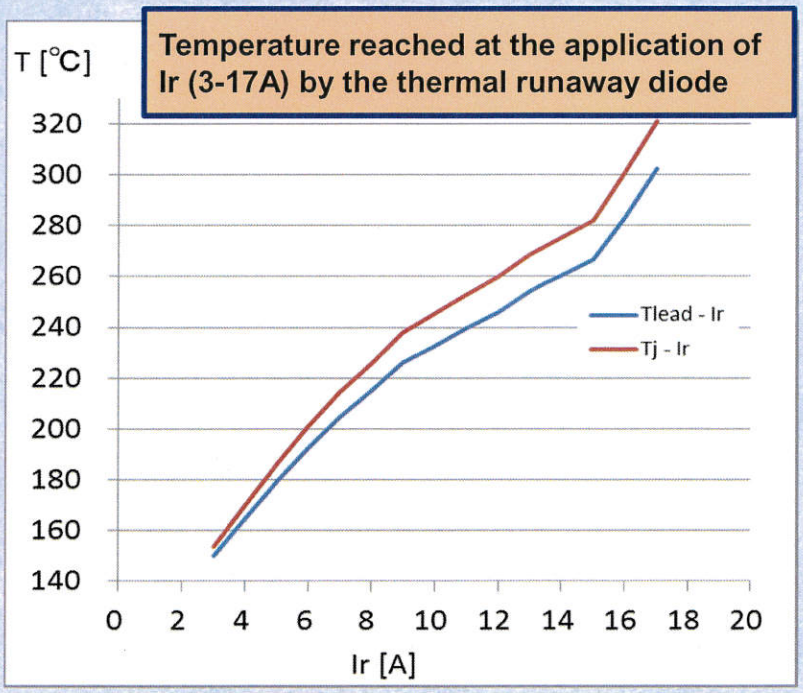
Vr=0.520V, Ir=20.02A, Tlead =255.2 ℃

Tj = Tlead + (Vr × Ir × Rth) = 255.2 ℃ + (0.520V X 20.02A X 9.49 ℃/W)

= 354 ℃

Tj and Tlead reached during the thermal runaway have a dependency on the upper limit current of the the constant-voltage power supply.

With increasing of limit value of the Ir, Tlead and Tj will increase.



Conclusions

❶ Conditions for thermal runaway occurs

In the case of "Pf < Pra", Pr increases along the injected energy curve of reverse voltage by the energy of "(Pra - Pf)".
Tj increases according to increase of leakage current.
Then, BD lead to thermal runaway.

❷ Influence of switching time for applying of reverse bias voltage after shutting off forward current

Pr becomes higher as the switching time becomes short.
The proposed 10 ms is considered reasonable and is obtainable by PC controller.

❸ How to detect the thermal runaway occurrence

To assess the phenomenon of thermal runaway, the leakage current observation is more effective than the lead temperature observation.

❹ The estimated junction temperature (Tj) during thermal runaway

Tj during thermal runaway is affected by the current limit of the power supply for applying a reverse bias voltage.
The junction temperature was estimated to be around **350 ℃** at the test condition of " If=13.5A and Vr=15V / current limit 20A ".

Backsheets: Correlation of Long-Term Field Reliability with Accelerated Laboratory Testing

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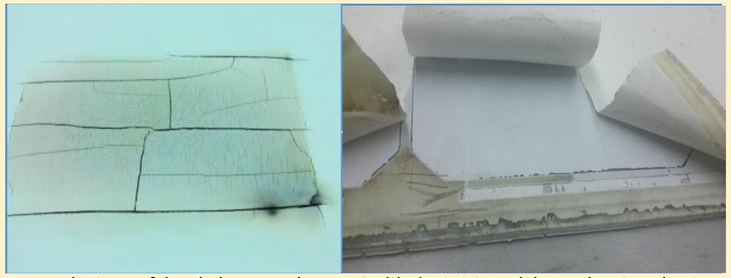
Department of [2]Material Science and Engineering

SDLE

SOLAR DURABILITY AND LIFETIME EXTENSION CENTER

- The backsheet of PV module is an indispensable part in providing environment and dielectric protection.
- The degradation of backsheet aggravates due to recent cost-reduction pressure and affects the PV module's performance over outdoor lifetime heavily.
- This research project was designed to develop predictive tests and a model based on point-in-time data from analytical techniques and data streams that are applicable to both outdoor and indoor PV module backsheet studies and are supplemented with meteorology data, climatic, and other accessible information.

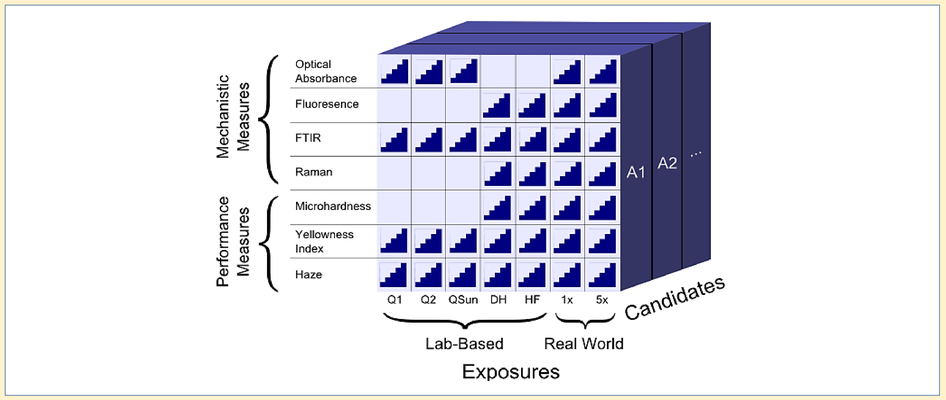


- Degradation of backsheet polymer is likely initiated by solar irradiation, which manifests itself in pitting, microcracking and discoloration. Mechanical stresses associated with thermal cycling or humidity/freeze/thaw exacerbate the degradation and leads to visible cracking and delamination.

- Data of different brand of PV modules both in the field and retrieved from the field will be collected and analyzed. The samples will be exposed in different climates and mounting configurations. The baseline evaluation will be established on retrieved samples.

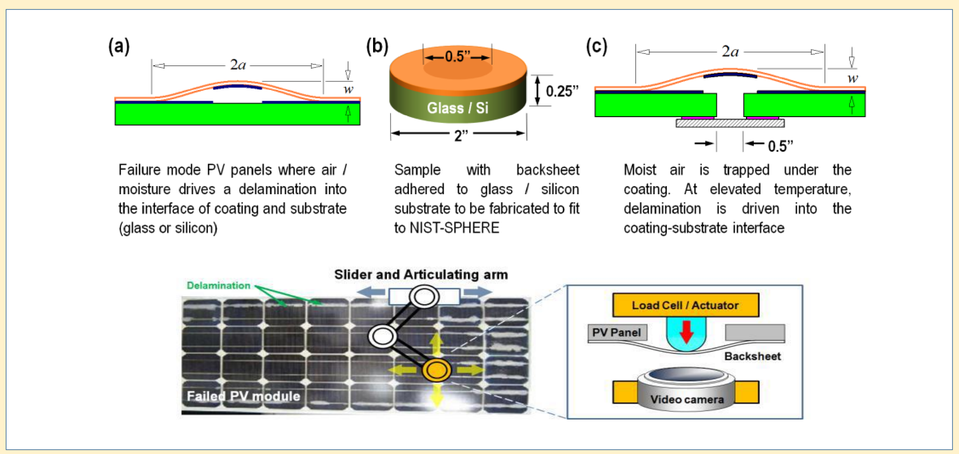
Accelerated exposure test detail	
Exposure type 1	Damp heat exposure (85C, 85% RH) for 1500 hours
Exposure type 2	ASTM D7869; Irr=0.8; Chamber T=65 C; BPT=90 C; RH=20% (4000 hrs)
Exposure type 3	ASTM D7869; Irr=0.8; Chamber T=65 C; BPT=90 C; RH=20% + water spray (4000 hrs)
Pull Scheduel	Non-destructive test at0, 500, 1000, 1500, 2000, 2500, 3000, 4000; Destructive testing at 0, 1000, 2500, 4000;

- With the performance of baseline exposure, indoor accelerated weathering tests will be carried out to explore backsheet degradation pathways, including thermal effects causing mechanical stress, e.g. water spray, thermal cycling or humidity/freeze/thaw.



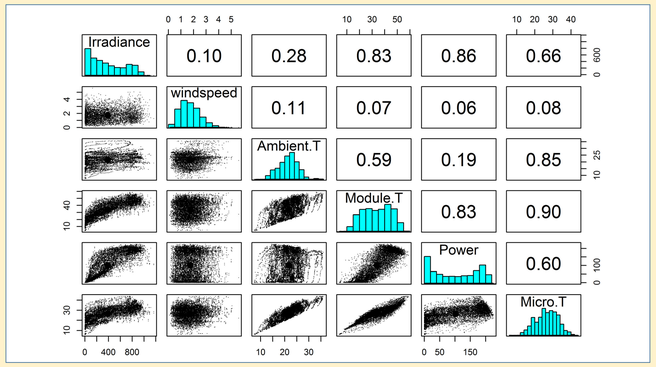
Evaluation: Data block for data analytics.

- Non-destructive surface measurements are key to probing chemical and physical degradation pathways, and can be particularly useful in providing mechanistic insights after very short exposure times. A set of non-destructive measurements including UV/Vis/NIR, FTIR, fluorescence, gloss, confocal Raman, colorimetry and microscopy of surface and cross-section will be carried out.

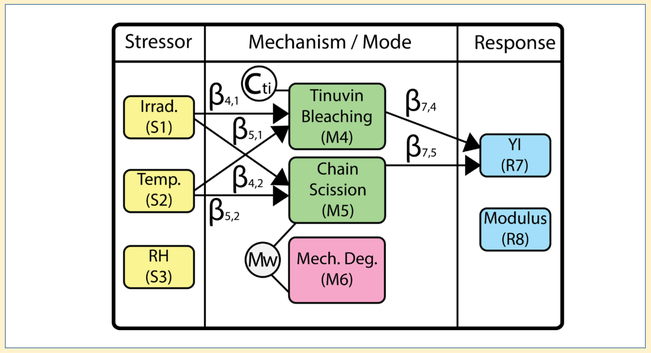


- Typical mechanical property measurement and interlayer adhesion measurements will be carried out and the ideal outcome is to identify how actual performance is affected by extended weathering exposure, and to correlate this with commonly measured properties.

- Stress / Response modeling of outdoor filed and retrieved modules and backsheet performance, degradation and failure.



- Stress / mechanism / Response modeling of indoor exposures and evaluations of retrieved coupon sample.



- Semi-gSEM identifies and quantifies relationships among many variables including stressors, mechanisms, and responses, which produces a multivariate predictive network model of the backsheet within a module

Goal of Objectives

- Based on the point-in-time data from analytical techniques and datastreams that are applicable to both outdoor and indoor PV module backsheet studies, the predictive models will be developed and the final version of predictive model will improve upon existing single stress linear degradation models.

References:

1. Roger H. French, Rudolf Podgornik, Timothy J. Peshek, Laura S. Bruckman, Yifan Xu, Nicholas R. Wheeler, Abdulkerim Gok, Yang Hu, Mohammad A. Hossain, Devin A. Gordon, Pei Zhao, Jiayang Sun, Guo-Qiang Zhang. "Degradation science: Mesoscopic evolution and temporal analytics of photovoltaic energy materilas," Current Opinion in Solid State and Materials Science, Vol. 19(August 2015) 212-226 doi: 10.1016/j.cossms.2014.112.008.
2. Mohammad Akram Hossain, Yifan Xu, Timothy J. Peshek, Liang Ji, Alexis R. Abramson, Roger H. French. "Microinverter Thermal Performance in the Real-World: Measurements and Modeling", Plos One, July 6, 2015, doi: 10.1371/journal.pone.0131279.

CORNING

Elimination of PID in PV Modules using Specialty Glasses

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Summary

Background

Potential induced degradation (PID) is a common problem affecting PV modules, significantly degrading their efficiencies over time. Sodium from the low iron soda lime glass typically used in PV modules in the presence of a negative bias has been generally accepted as the primary cause of PID. Economics are driving modules larger and strings longer, increasing voltage magnitude, making PID worse.

Objective

Evaluate the PID performance of modules fabricated with sodium free glasses.

Results

This study shows the elimination of PID performance in 85°C/85% r.h. with -1000V bias using sodium free specialty glasses. Electroluminescence (EL) images further support this work by separating the degradation patterns exhibited by water ingress and PID. Additional extreme PID acceleration tests at the single cell module level using aluminum electrodes on the external glass surfaces at 85°C and -1000V shows no evidence of PID with sodium free glass sheets on both sides of the cell.

Modules containing sodium free front glass with SLG back glass do show PID, but significantly outperform modules with SLG on both front and back.

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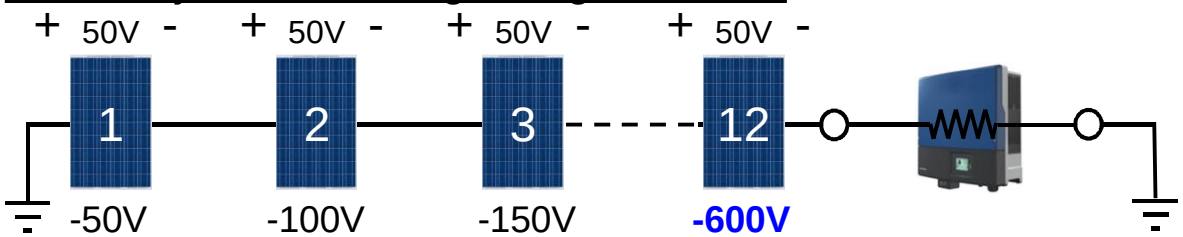
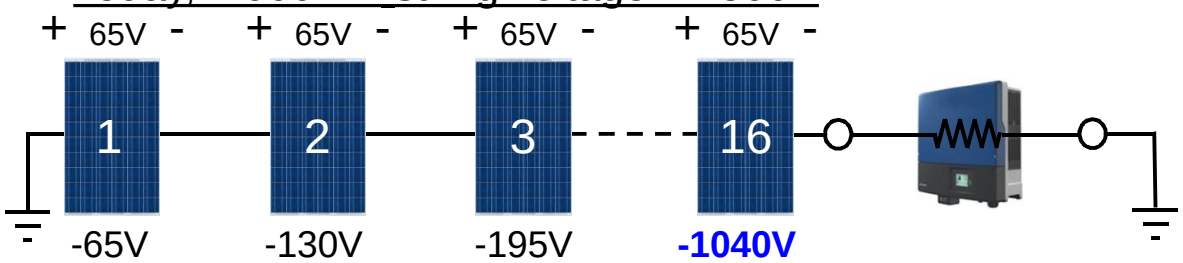
Economics are PV driving systems to larger panels, longer strings, and higher voltages

Yesterday, 600V ≤ string voltage < 1000V



Today, 1000V ≤ string voltage ≤ 1500V



Benefits:

- Lower system costs
  - Fewer support structures
  - Fewer combiners, inverters, etc.
  - Low cost grounding topologies
- Higher system efficiency

However…

- Higher voltages increase panel degradation

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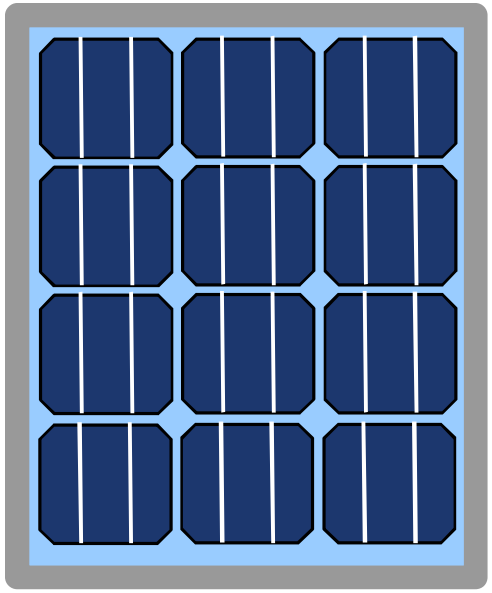
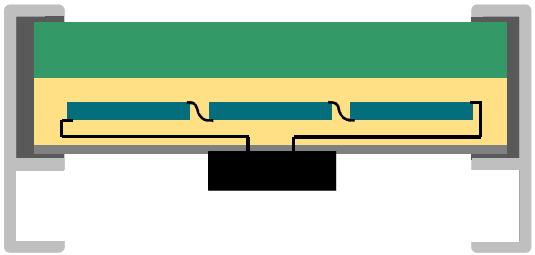
5 glass configurations were studied in 3 x 4 cell test modules

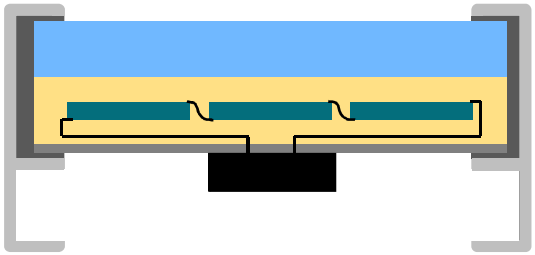
various combinations of soda lime (SLG) and sodium free (Na-free) glasses



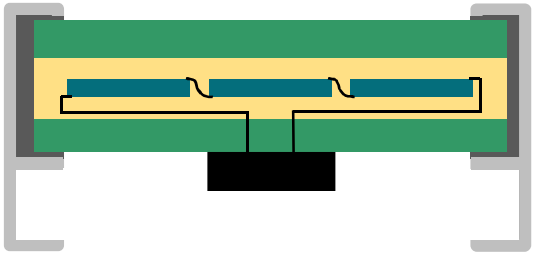
SLG / Backsheet



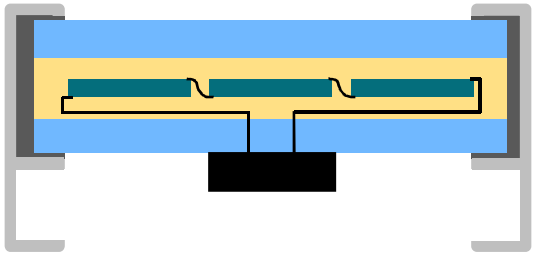
Na-free / Backsheet



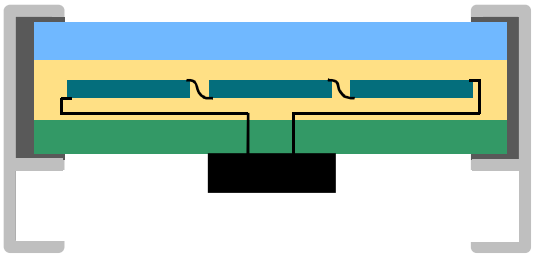
SLG / SLG



Na-free/ Na-free



Na-free / SLG



Polycrystalline cells
- Solartech cells prestrung by Spire Solar

STR EVA encapsulant
Laminated and framed at Corning
Corning Na-free glass

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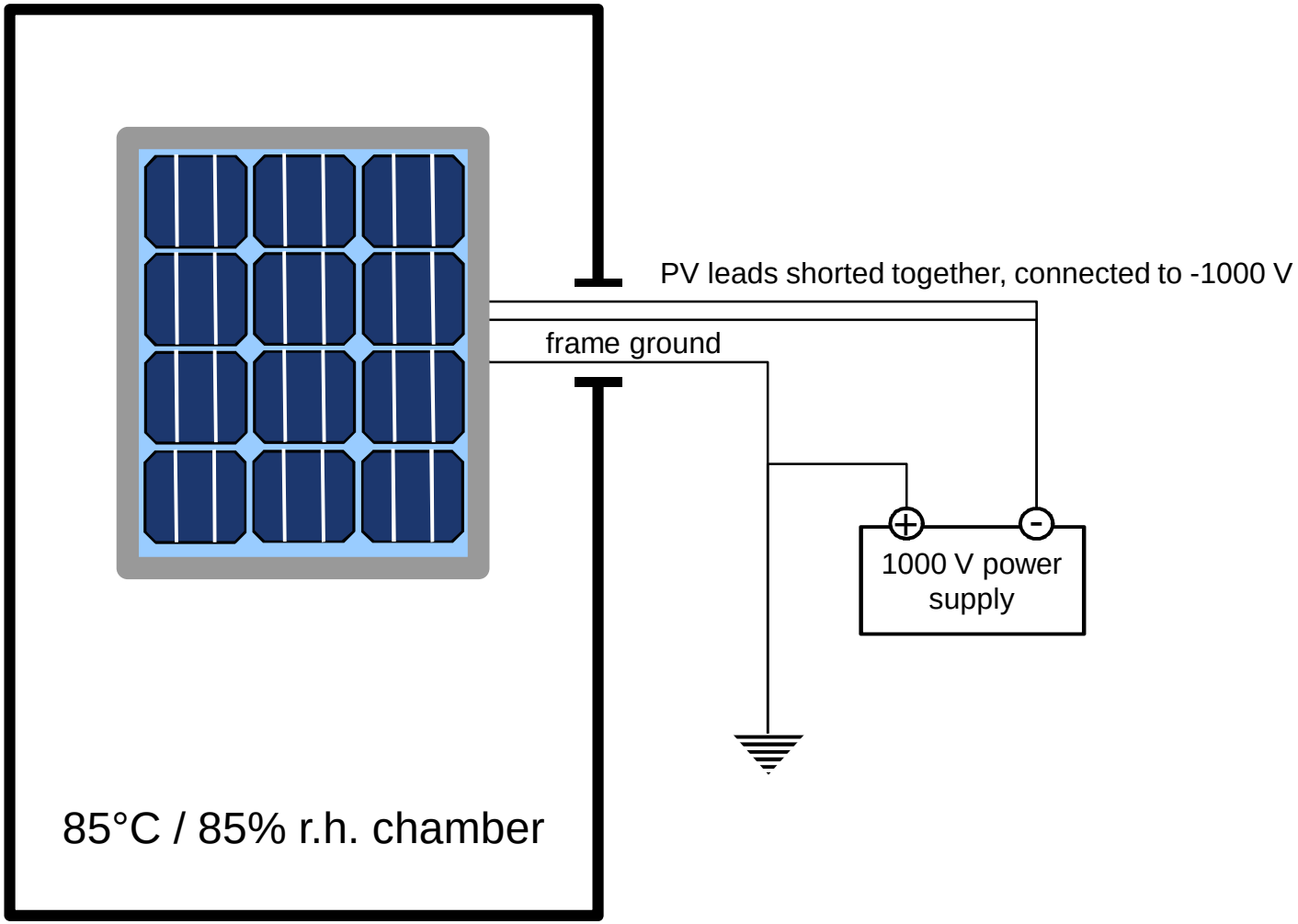
Setup for -1000 V bias testing at 85°C / 85% r.h.



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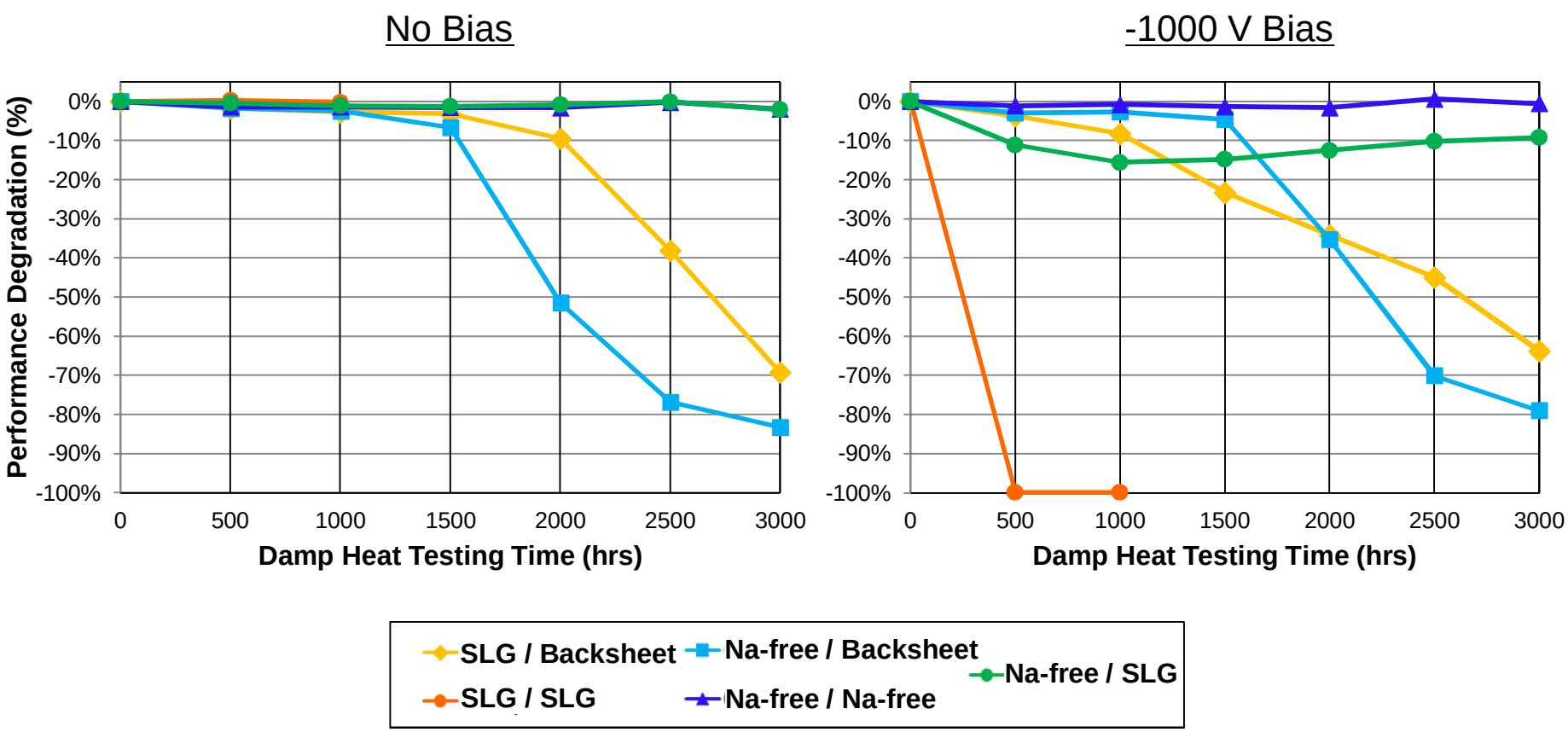
PID eliminated with 2 sheets of Na-free glass; significantly reduced with Na-free front / SLG back

- moisture degradation eliminated with glass-glass module
- PID degradation eliminated with elimination of sodium



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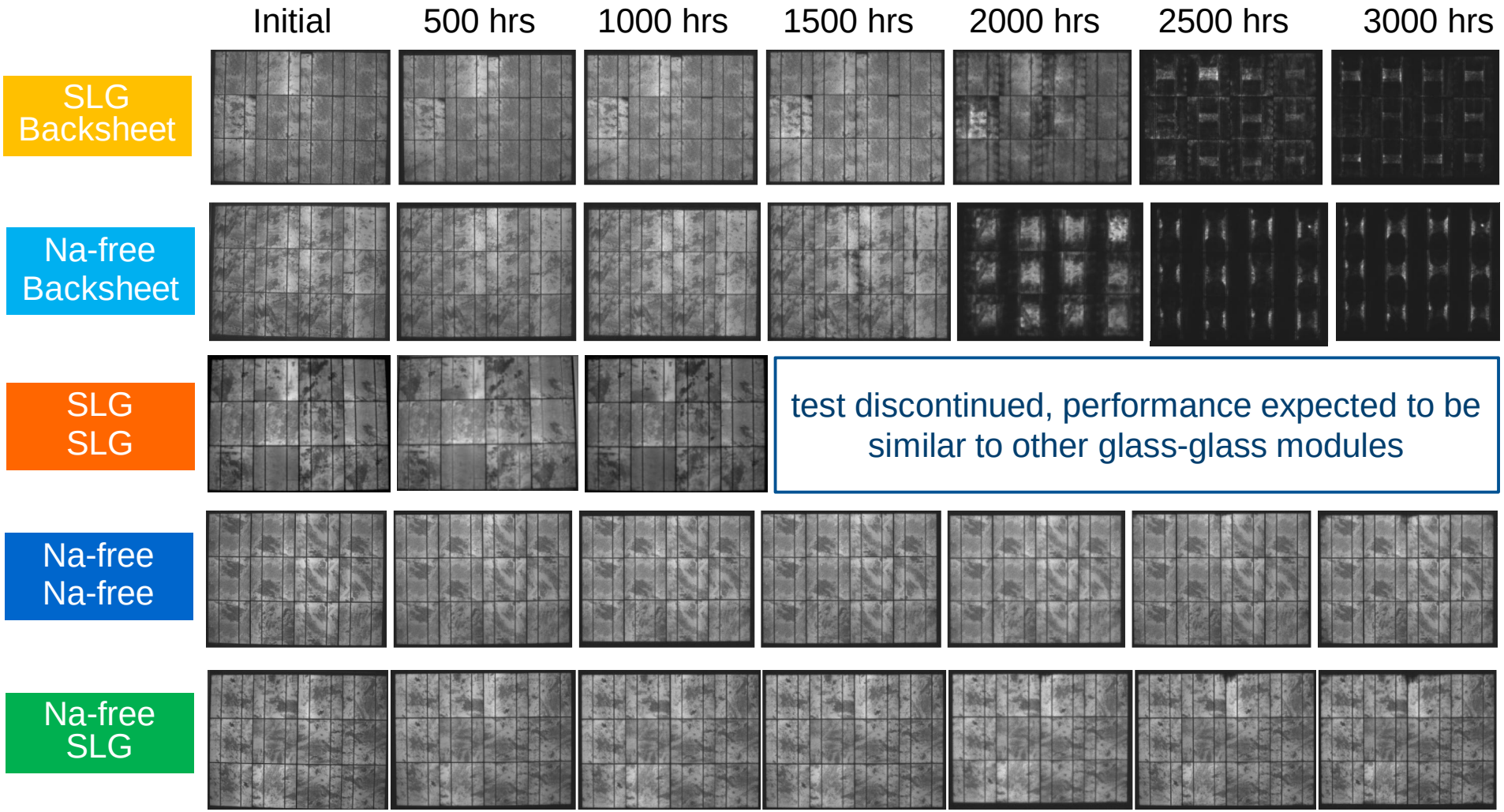
Damp heat with no bias

Electroluminescence images show moisture degradation initiating at cell perimeters in backsheet modules



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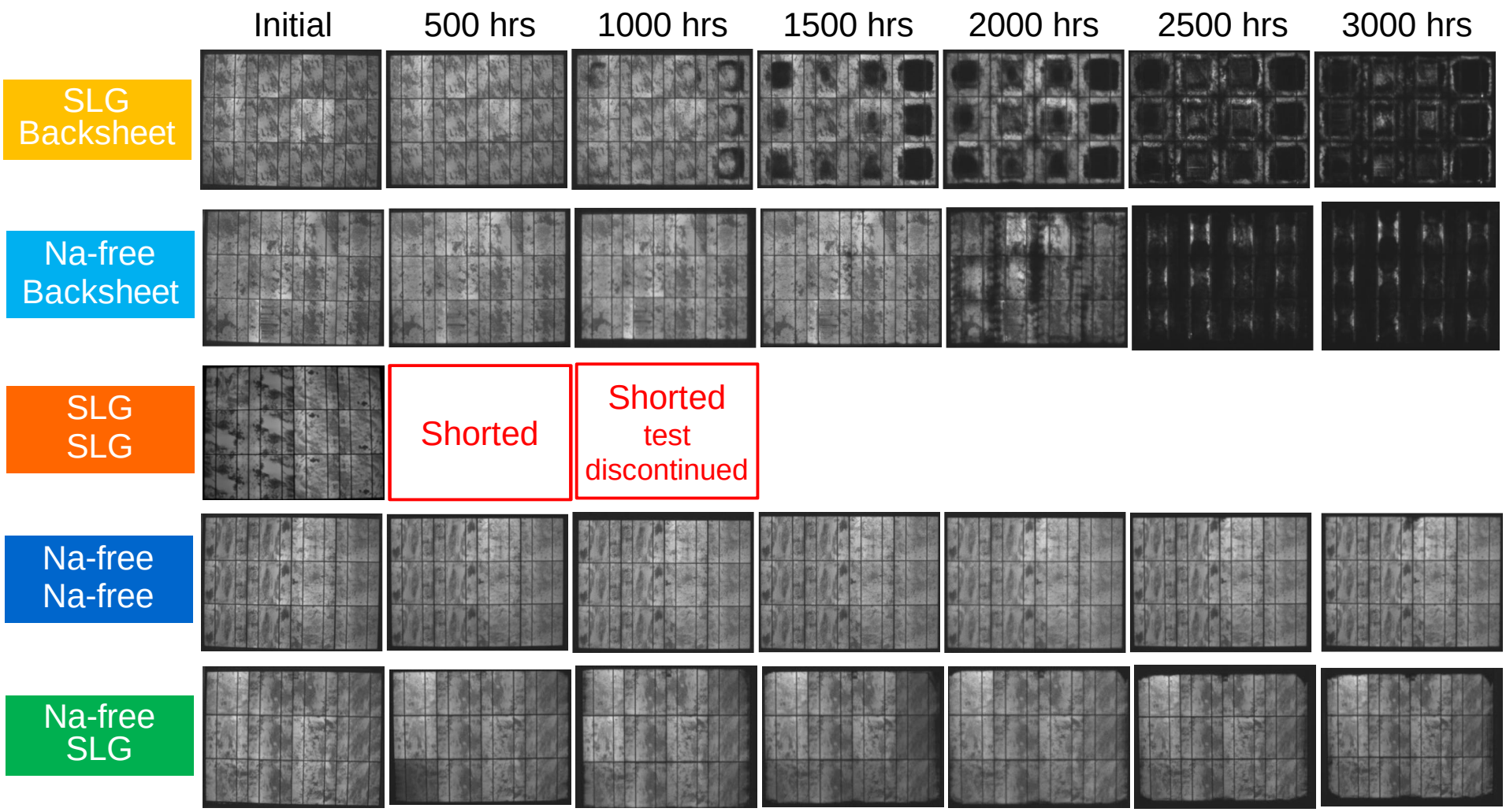
Damp heat with -1000 V bias

Electro-luminescence images show that non-sodium glass reduces both PID and water ingress



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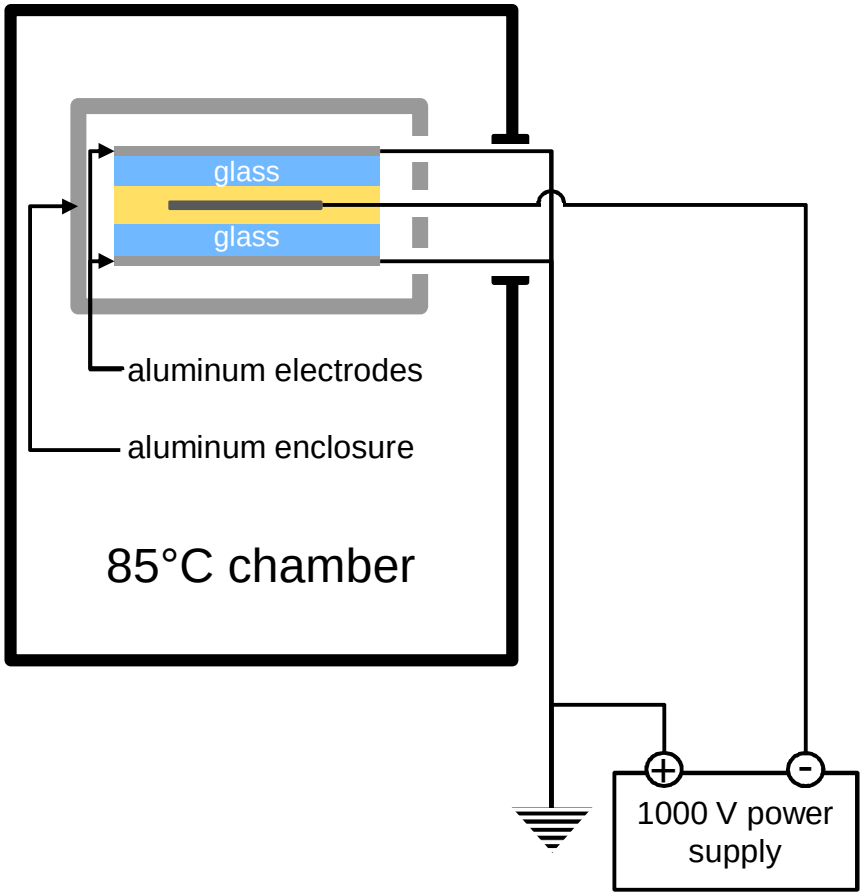
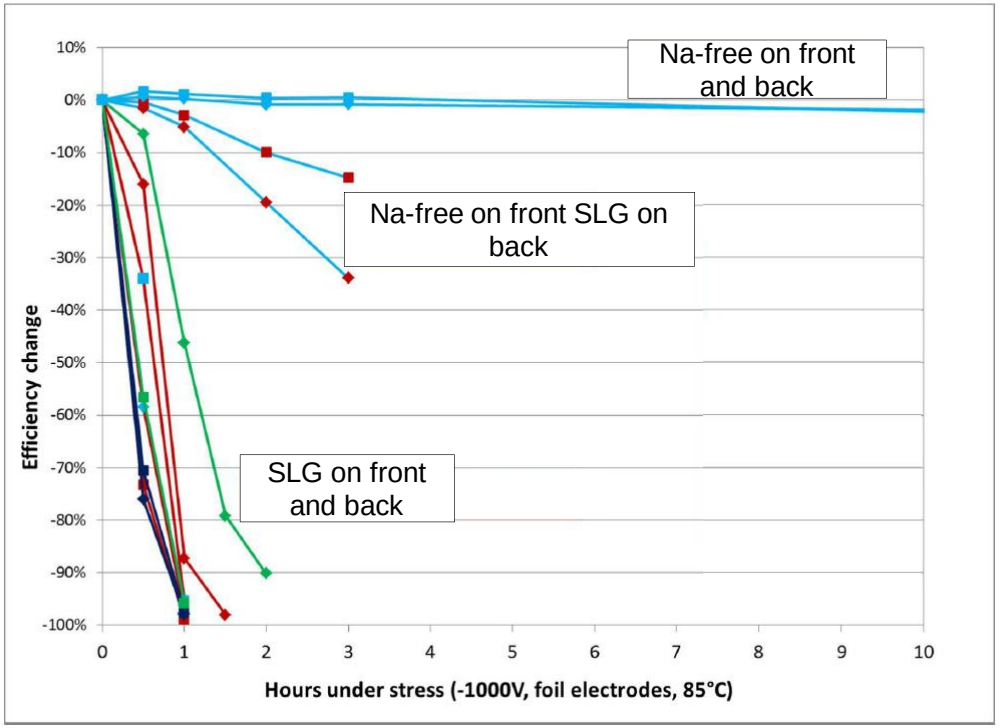
Highly accelerated single cell tests show no PID with Na-free glass on both sides; Na-free front with SLG back outperforms SLG on front and back



Highly accelerated PID testing with 3 glass configurations at cell level



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Understanding PV Backsheet Degradation under Different UV Light Intensities and Temperatures

Polymeric Materials Group

Li-Chieh Yu, Yadong Lyu, Chiao-Chi Lin, Jae Hyun Kim, Tinh Nguyen, and Xiaohong Gu

Introduction

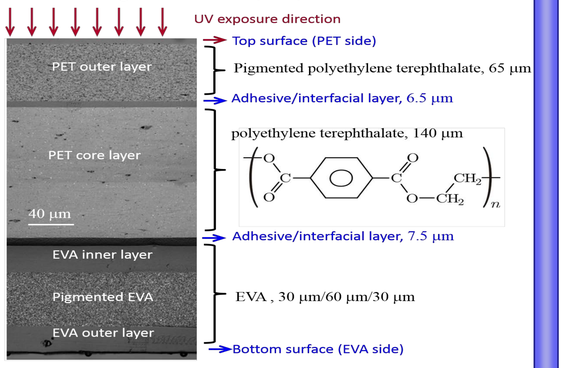
The solar cell backsheet is one of the outermost layers of a photovoltaic (PV) module, designed to ensure the long-term performance of the PV module under years of weathering. However, polymeric backsheets are susceptible to degradation (photo-, thermo-, hydrolysis, etc.) due to environmental stresses such as UV radiation, temperature and moisture.

In this work, accelerated laboratory testing was carried out on the NIST SPHERE *(Simulated Photodegradation via High Energy Radiant Exposure)* to study the effects of UV light intensity and temperature on a commercial PPE *(Polyethylene terephalate (PET)/PET/ethylene-vinyl acetate)* backsheet. Chemical, optical and morphological changes of the PPE films were followed by ATR-FTIR, UV-visible spectrometer and atomic force microscopy under different exposure conditions.

Experiment Set Up

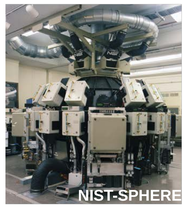
PET/PET/EVA Backsheet

Confocal images of fresh PET/PET/EVAs cross-section

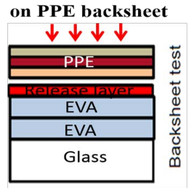


Accelerated Weathering

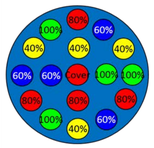
NIST Simulated Photodegradation via High Energy Radiant Exposure (SPHERE)



Direct UV radiation on PPE backsheet



Filter arrangement



- **UV Irradiance (300-400 nm):** 68, 102, 136, 170 W/m², controlled by neutral density filters (40%, 60%, 80%, 100%)
- **Temperature:** 45 °C , 65 °C , 85 °C
- **Relative Humidity** 0 ~ 5%

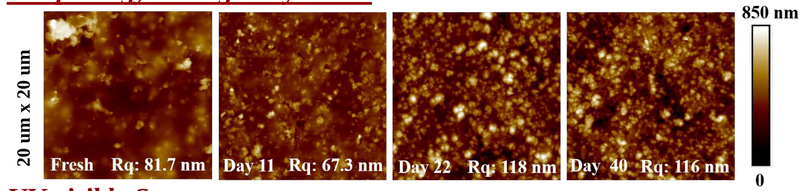
Characterization

- **Atomic force microscopy (AFM)** Morphological changes; Roughness
- **Ultraviolet-visible spectroscopy (UV-vis)** Yellowness index(YI), UV absorber loss
- **Attenuated total reflection (FTIR -ATR)** Chemical changes (Carboxylic acid formation, etc.)

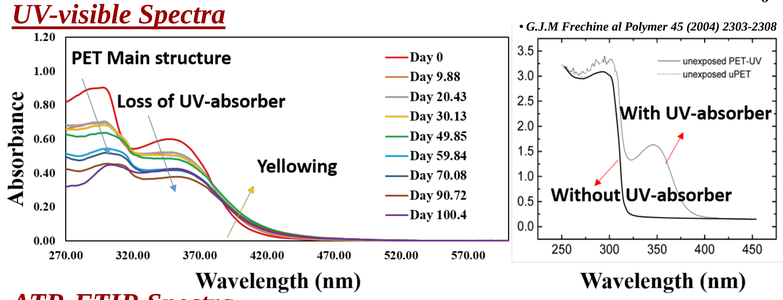
Results and Discussion

Surface Characterization

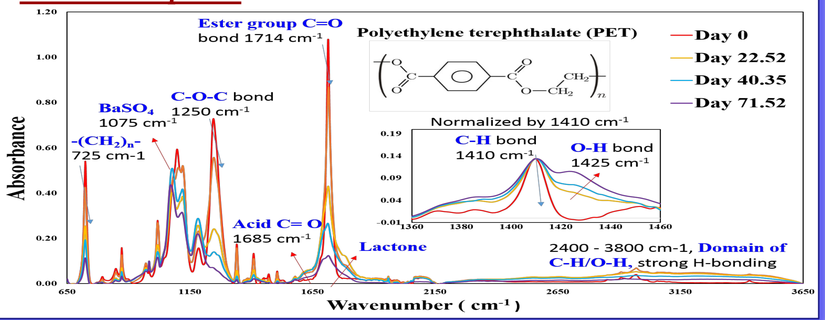
Morphology Changes by AFM



UV-visible Spectra



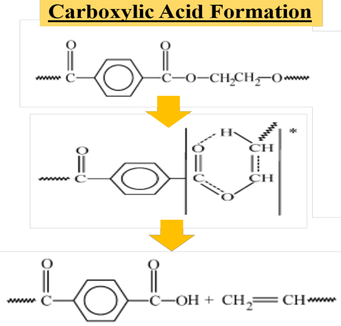
ATR-FTIR Spectra



Degradation Mechanism & Principle

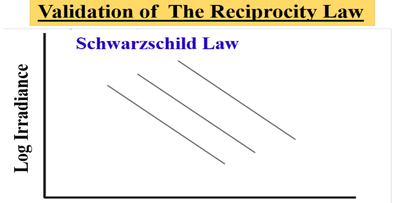
PET Chemical Degradation

Carboxylic Acid Formation



Reciprocity Law (UV Intensity Effect)

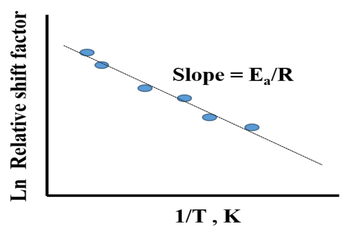
Validation of The Reciprocity Law



$$I t^{\text{p-coefficient}} = \text{constant}$$

I: Radiant intensity
t : Time to obtain given damage
Reciprocity law obeyed when P-coefficient =1

Temperature Effect and Activation Energy



Damage with Respect to Temperature :

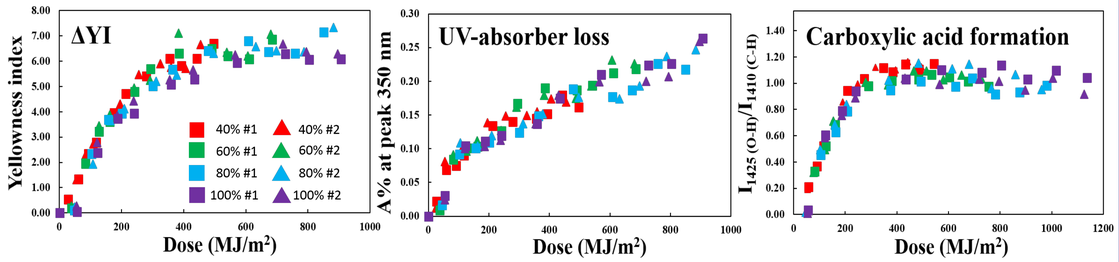
$$\ln a_T = \ln\left(\frac{t_{T_1}}{t_{T_2}}\right) = \frac{E_a}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

t_{T1} t_{T2}: Respect aging times
E_a : Activation Energy
R : Gas constant
T : Absolute temperature in K

- Mees et al./The Theory of the Photographic Process, MacMillan 1942
- S. Kahlen et al./ Solar Energy 84 (2010)
- Pickett et al., Polymer Degradation and Stability , 2008
- Haillant et al., Solar Energy Materials & Solar Cells, 2011

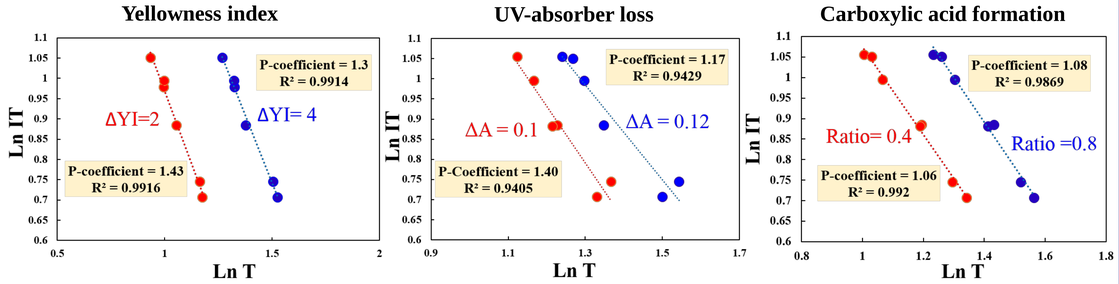
Effect of UV intensity (UV, 85 °C/0 % RH)

Damage Vs. Dose



- Reciprocity law appears to be obeyed until late stage of degradation, indicating that under different UV light intensities, the degradation mechanism and the required dose for a given damage is same for the studied PPE.

Validation of Reciprocity law

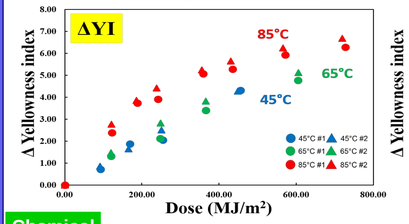


- The P-coefficients are close to be 1 for above optical and chemical changes, indicating that UV light intensity in the studied range doesn't change the degradation mechanism, and the reciprocity law is obeyed in this system.

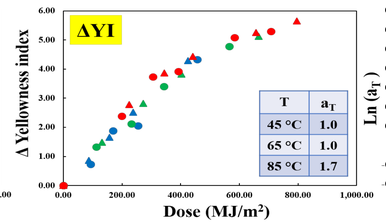
Effect of Temperature on Optical/ Chemical Changes (T/RH/UV)

Optical

Damage Vs. Dose

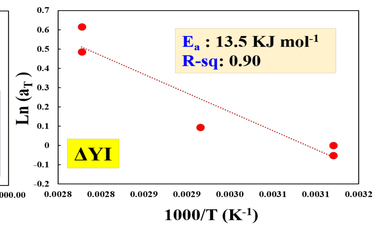


Superimposed

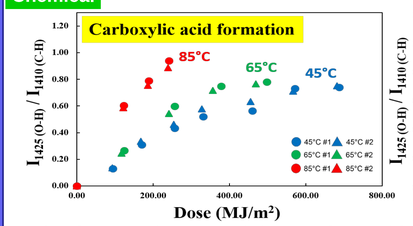


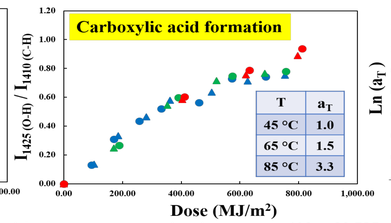
T	a_T
45 °C	1.0
65 °C	1.0
85 °C	1.7

Activation Energy

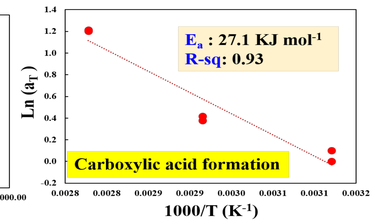


Chemical





T	a_T
45 °C	1.0
65 °C	1.5
85 °C	3.3



- The activation energy is in accordance with the apparent activation energy (10~60 KJ mol⁻¹) of polymers during photodegradation. However, chemical degradation appears to be more sensitive to temperature than the optical changes.
- More temperatures need to be investigated to further understand the temperature effect around the T_g. *(PET: T_g = 76 °C)*

Summary

- The results indicated that reciprocity law was obeyed for both optical and chemical changes of PPE during UV exposure. The degradation mechanism didn't change with different light intensities.
- The effect of temperature was observed on the photodegradation of PPE. The activation energy for yellowing and chemical changes has been calculated.
- This study has laid groundwork for developing mathematical models for service life prediction of PV backsheets based on accelerated laboratory exposure.

PID RESISTANCE OF PV MODULES OPERATING AT 1500V

Sergiu C. Pop[1], Ralf Schulze[1], Jane Kapur[2]

[1]Yingli Green Energy Americas, San Francisco, CA, USA
[2]E. I. DuPont de Nemours & Co., Inc., Wilmington, DE, USA

Introduction

Motivation

- Technological trend towards 1500V PV systems is combined with the shift towards transformerless inverters to reduce the system complexity and improve project economics – increase risk for PID
- The development of PID resistant modules rated at 1500Vdc requires investigations beyond current standards
- PID phenomenon in PV industry still remains one of the major technical challenges

PID Mechanism

- There are at least two important root causes which can trigger PID:
  1) Surface polarization: a non-destructive, partially reversible accumulation of static charges at the cell surface under positive bias - reverses under negative bias
  2) Ion migration [1] from glass to the cell due to leakage current - decrease of shunting resistance and it mainly occurs at stacking faults

Experimental

Cell Level

- Experimental concept: Si_Nx (ARC) can act as a barrier for Na^+ ions - particular ARC morphology is desired
- Four PECVD recipes were developed (2 factorial DoE)

Table 1

PECVD recipes	Gas Ratio (NH_3/SiH_4)	Pressure
1	High	Low
2	Low	Low
3	Low	High
4	High	High

- Parameters considered: NH_3/SiO_4 ratio and chamber pressure
- Upper and lower spec limits were included for both sets of parameters (Table 1)
- Random samples were selected from the line – optical characterization (thickness and refractive index) of ARC
- Resulted cells from each configuration were used for full size module built
- All samples were subjected to same PID testing conditions: 60°C/85%RH/ 1000Vdc
- During chamber test EL and I-V sweeps were taken every 24h up 96 hours

Module Level

- In this part of the study we focused on encapsulants with different properties subjected to 1500Vdc conditions
- For this purpose we have investigated several experimental groups (full-size modules) with same BoM except for the front encapsulant
- In first experimental stage we used a double encapsulant layer consisting of ionomer and standard EVA which was subjected to 60°C/85%RH/1500Vdc test conditions
- Second experiment was performed at elevated temperature (85°C) where we looked at several combinations of encapsulants

Results – Cell Level

The aim of screening DoE:

- Categorization of PECVD parameters in terms of impact on ARC morphology
- Evaluate the PID resistance of the experimental groups built with different ARC morphologies

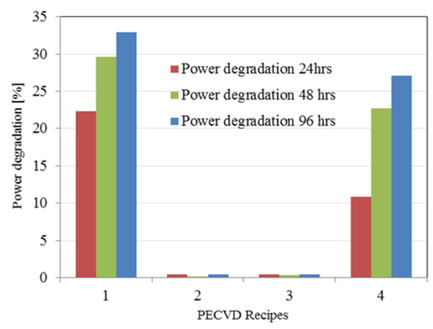


Figure 1

- As a result of a 2 factorial matrix calculations the parameter with highest impact on Si_Nx morphology was the gas ratio followed by the chamber pressure
- As observed in Fig. 1 the group of samples resulted from the PECVD recipes with higher gas ratio suffered the highest P_{max} loss (between 27 and 33%)
- An opposite result was recorded when the gas ratio was set at the lower spec. limit where the max. power loss was below 1%

Table 2

PECVD recipes	Thickness (nm)	R.I.	Isc (mA)
1	80.13	2.01	8.99
2	78.24	2.32	8.68
3	83.02	2.1	8.55
4	76.42	2.03	9.01

- The measured optical parameters at cell level (Table 2) show a strong correlation with the gas ratio - the higher the gas ratio, the lower the refractive index
- The highest values for Isc were recorded at the devices built with lower R.I. ARC films
- Further, the fine tuning optimization of PECVD parameters was performed to achieve the optimum ARC morphology for PID resistance without Isc loss

Results – Module Level

- In previous work [1] was demonstrated that the type of encapsulant can contribute to a significant reduction of Na^+ migration/PID
- We demonstrated that different types of encapsulants show large difference in reliability and PID at 1000Vdc
- Here we investigate the module degradation at 1500Vdc for two different chamber conditions
  - test duration: 110hrs at 60°C/85%RH
  - test duration: 144hrs at 85°C/85%RH

Test #1 (DuPont Lab)

Performed at 60°C/85%RH/1500Vdc for 110 hours

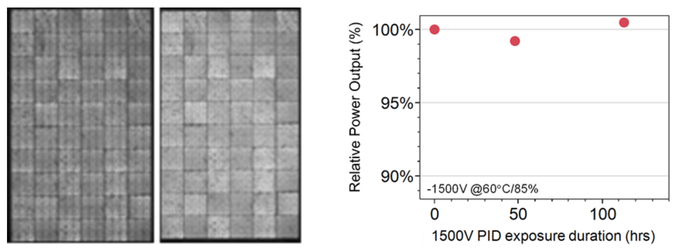


Figure 2: (left) EL images before and after chamber testing (right) I-V sweeps every 48hours

- EL images were taken before and after chamber testing and no significant difference was observed
- I-V sweeps were collected every 48 hours and a minimal current leakage was recorded

Test #2

Performed at 85°C/85%RH/1500Vdc for 144 hours

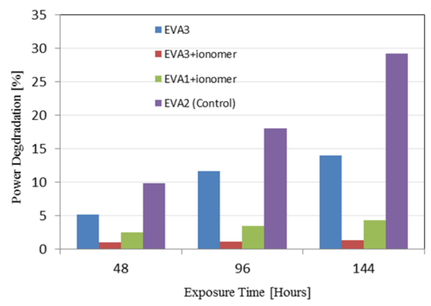


Figure 3

- This experiment was performed at Yingli Solar Lab [2] and four encapsulant configurations were considered: one type of EVA3, ionomer+EVA3, ionomer+Std.EVA1, EVA2 (control)
- All samples were prepared as full size modules and were subjected to the same testing conditions
- EL images and I-V sweeps were recorded every 48 hours (Fig. 3)
- The samples built with ionomer encapsulant show the best performance

Conclusions

- The optimized morphology of Si_Nx film does not provide a complete solution for PID at higher voltages
- New device architectures are explored to find ways to decrease the degradation under leakage current
- Yingli Solar is extending the standard PID resistance protocols aiming for a PID solution that is effective for voltages up to 1500Vdc
- The findings in this work will help evaluating the next module build configuration

References

[1] "Ionomer-Based PID-Resistant Encapsulant for PV Modules". S.C. Pop, R. Schulze, X. Wang, B. Yuan, J. Kapur, K.M. Stika, C. Westphal, H. Antoniadis, A. Meisel EU PVSEC Proceedings *29th European Photovoltaic Solar Energy Conference and Exhibition*, 152-157 (2014).

[2] "Pathways Towards Advanced PID Resistance of 1500V". S C. Pop, R. Schulze, X. Wang, H. Wang, B. Yuan, D. Inns, A. Meisel, J. Kapur, H. Antoniadis EU PVSEC Proceedings *30th European Photovoltaic Solar Energy Conference and Exhibition*, 15 – 19 (2015).

Spatial Non-Uniformity of Irradiance and Uncertainty in Power Rating for c-Si Modules

Harrison W. Wilterdink, Adrienne L. Blum, Cassidy L. Sainsbury, Ronald A. Sinton
Sinton Instruments, Boulder, CO, U.S.A.

ABSTRACT: We present experimental and simulated results regarding uncertainty in module power for solar simulators with varying degrees of non-uniformity. In particular, we show that *even in the worst-case, error in* reported *module power is ≤ 0.4 % for Class A solar simulators* (≤ 2 % non-uniformity). More typical scenarios for Class A solar simulators yield even smaller errors (≤ 0.2 %) in reported power.

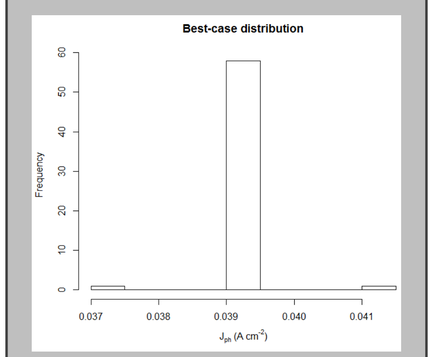
MODELING:

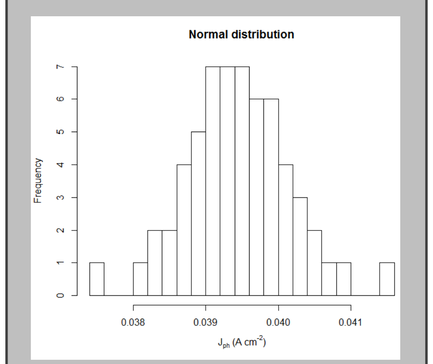
- Double-diode cell model using PERC values, as measured on Sinton Instruments' FCT-450
- Modeling of 60-cell modules (no bypass mechanisms) with varying severity and distribution of non-uniform irradiance

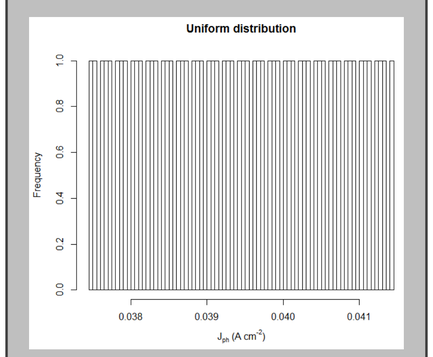
EXPERIMENT:

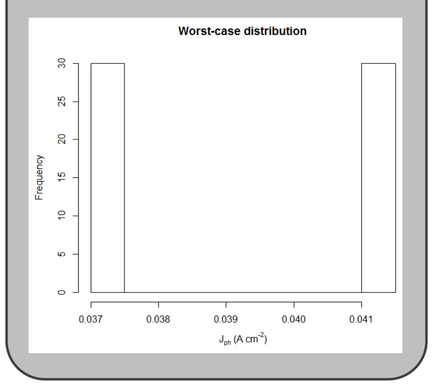
- 60-cell, mc-Si module measured on Sinton Instruments' FMT-350
  - Minimal non-uniformity (blue curve)
  - Deliberate non-uniformity (approx. ± 2.4 %), due to shadow (orange curve)

IRRADIANCE DISTRIBUTIONS (± 5 %)

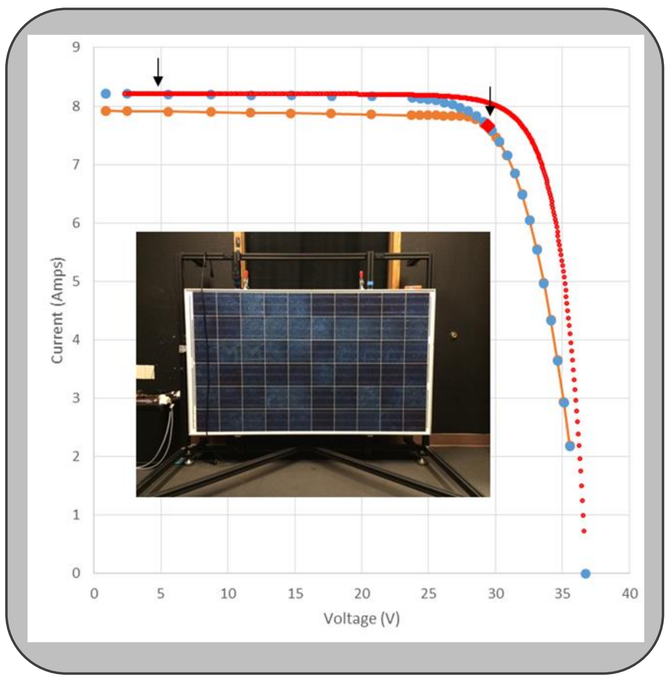




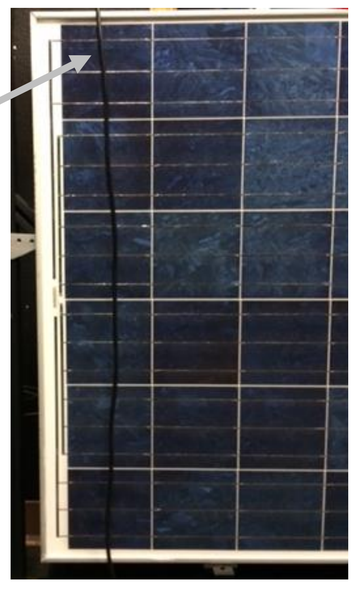




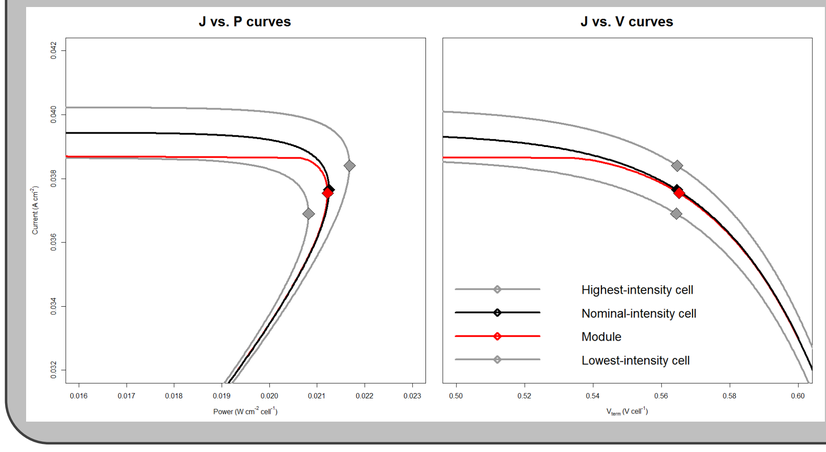
Non-uniformity (%)	Irradiance distribution	Error (%) in reported parameters (modeled) J_{sc}	V_{oc}	P_{mp}	J_{mp}	V_{mp}	Error (%) in reported parameters (measured) J_{sc}	V_{oc}	P_{mp}	J_{mp}	V_{mp}
1	Best-case	-0.43	0.00	0.00	0.00	0.00	–				
	Normal	-0.58	0.00	-0.01	-0.04	0.03					
	Uniform	-0.82	0.00	-0.04	-0.09	0.05					
	Worst-case	-0.99	0.01	-0.11	-0.23	0.12					
2	Best-case	-1.40	0.00	-0.02	0.00	-0.02	Class A				
	Normal	-1.41	0.03	-0.06	-0.11	0.05					
	Uniform	**-1.77**	0.03	**-0.15**	-0.27	0.12					
	Worst-case	**-2.01**	0.07	**-0.42**	-0.73	0.31	**-3.58**	0.02	**-0.23**	-1.03	0.80
3	Best-case	-2.40	0.00	-0.04	-0.12	0.08					
	Normal	-2.41	0.00	-0.13	-0.31	0.18					
	Uniform	-2.74	0.00	-0.34	-0.70	0.36					
	Worst-case	-3.04	0.01	-0.87	-1.54	0.67					
4	Best-case	-3.43	0.00	-0.10	-0.35	0.25	–				
	Normal	-3.42	-0.01	-0.25	-0.57	0.32					
	Uniform	-3.72	-0.01	-0.61	-1.18	0.57					
	Worst-case	-4.06	-0.01	-1.44	-2.35	0.91					
5	Best-case	-4.44	0.00	-0.23	-0.89	0.66	Class B				
	Normal	-4.45	0.00	-0.43	-1.06	0.63					
	Uniform	-4.73	0.00	-0.95	-1.78	0.83					
	Worst-case	-5.11	0.01	-2.09	-3.27	1.17					



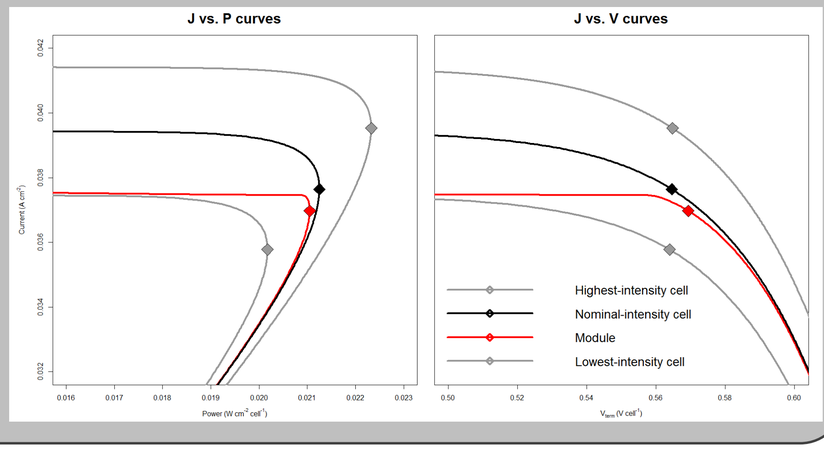
Power cord shadow (4.7 % of single-cell area)



NON-UNIFORMITY: ± 2 %



NON-UNIFORMITY: ± 5 %



CONCLUSIONS:

There is literature consensus [2] – [4] that module power is relatively insensitive to solar simulator non-uniformities ≤ 5 %. Moreover, *uncertainty in reported module power for Class A non-uniformity is ≤ 0.4 % in the worst-case, and more typically ≤ 0.2 %*. Two important implications follow:

1. When using reference modules to calibrate a module tester, matching *power* will be extremely accurate for a solar simulator with Class A non-uniformity [4].
2. Though non-uniformity is thought to introduce large errors for indoor flash-test measurement of primary calibrations [5], these errors in the power rating are actually quite negligible.

Sinton instruments

REFERENCES:

[1] IEC 60904-9:2007 "Photovoltaic devices - Part 9: Solar simulator performance requirements," 16 October, 2007.

[2] K. Wilson, D. De Ceuster and R. A. Sinton, "Measuring the Effect of Cell Mismatch on Module Output," in *IEEE 4th World Conference on Photovoltaic Energy Conversion*, 2006 (Waikoloa).

[3] W. Herrmann and W. Wiesner, "Modelling of PV Modules - The Effects of Non-Uniform Irradiance on Performance Measurements with Solar Simulators," EU PVSEC, 2000 (Glasgow).

[4] C. Monokroussos, D. Etienne, K. Morita, V. Fakhfouri, J. Bai, C. Dreire, U. Therhaag and W. Herrmann, "Impact of Calibration Methodology into the Power Rating of c-Si PV Modules Under Industrial Conditions," EU PVSEC, 2013 (Paris).

[5] V. Fakhfouri, W. Hermann, W. Zaaiman, C. Dreier, C. Droz, K. Morita and L. Johnson, "Uncertainty Assessment of PV Power Measurement in Industrial Environments," EU PVSEC, 2011 (Hamburg).

Sinton Instruments, 4720 Walnut Street, Suite 102, Boulder, CO 80301 U.S.A. www.sintoninstruments.com

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The power behind the panel.

PVST 光伏科学与技术国家重点实验室
State Key Laboratory of PV Science & Technology

The Reliability of Dual-Glass Module Designed for Harsh Climates

JianMei Xu, QiangZhong Zhu,
Pierre J.Verlinden, Yunhua Shu, Hui Shen,
Quan Sun, Jing Mao, Zhiqiang Feng, Yang Yang

NREL PV Module Reliability Workshop 2016

Feb. 24 2016

Outline

1 Introduction of Trinasolar

2 Application Challenge

3 Detailed design and advantages

4 Reliability test

5 Conclusion

1. Introduction of Trinasolar –The World Leading PV Manufacturer

- **Founded in 1997, Changzhou, China**
- **More than 20 Production and Sales centers around the world**
- **Listed on NYSE: TSL in 2006**
- **16.7 GW shipments since 2005.**
- **World leading PV manufacturer – approx. 13,000 employees**

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2. Application Challenge

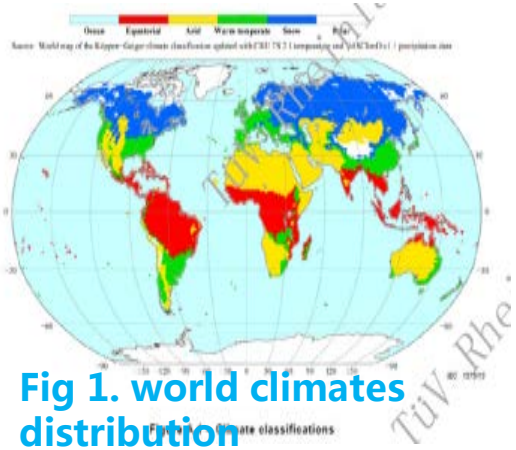


Fig 1. world climates distribution

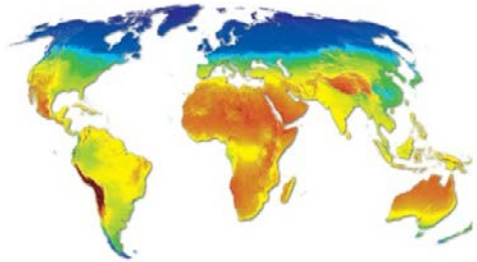
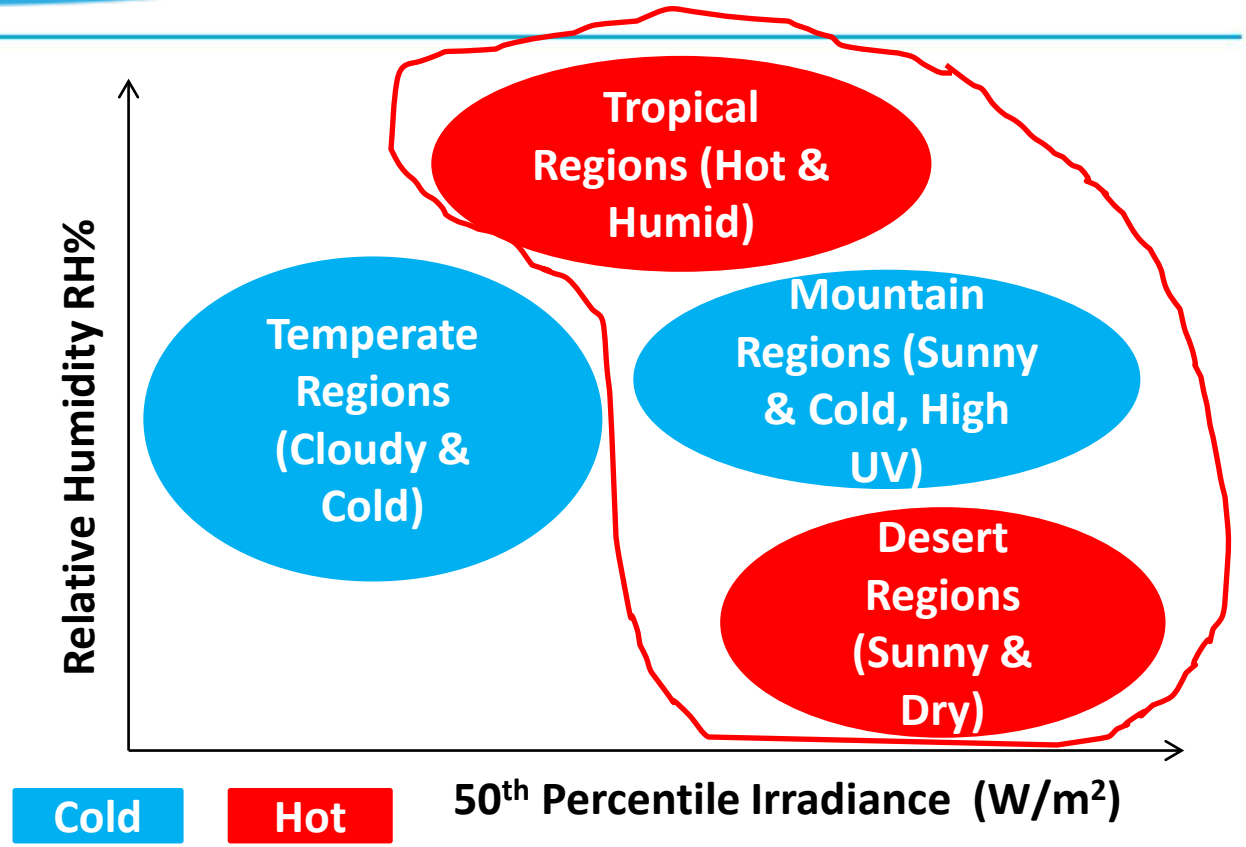


Fig 2. irradiance in the world



- PV modules have different durability under different climates
- Low-cost PV modules for temperate climates may not be suitable for tropical or desert climates
- Harsh climates require PV modules with an optimized design (performance and reliability)

How to develop it? Lower Cost & high reliability?

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3. Detailed Design and Advantages of Dual-Glass Module

3.1 Overview of Dual-Glass Module

3.2 DG Design

3.3 Back Glass vs. Back sheet: less permeability of moisture

3.4 Back Glass vs. Back sheet: Less stress to the cells

3.5 Back Glass vs. Back sheet: Less thermal mismatch

3.6 Advantages of Frame-less PV Modules

3.7 Other Advantages

Remark:

DG stands for "Dual-glass module"

TM stands for"Traditional module"

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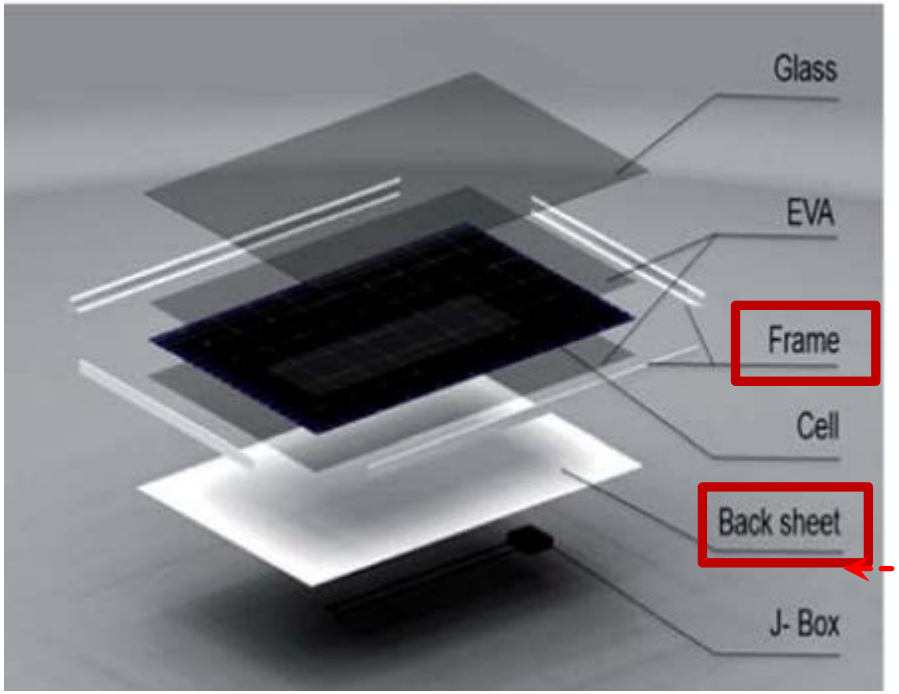
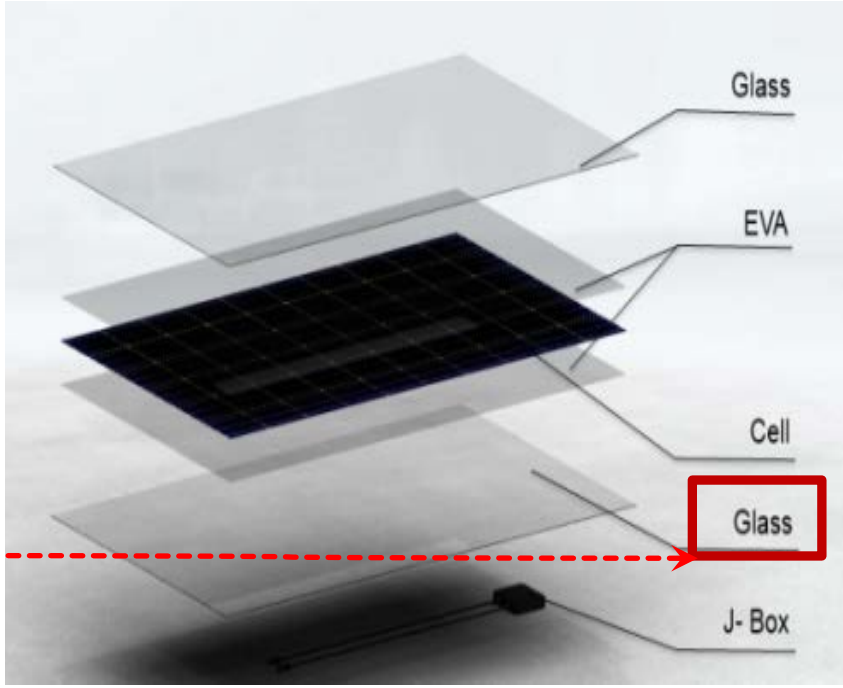
3.1 Overview of Dual-Glass Module



TM



DG

3.2 Dual-Glass Module Design

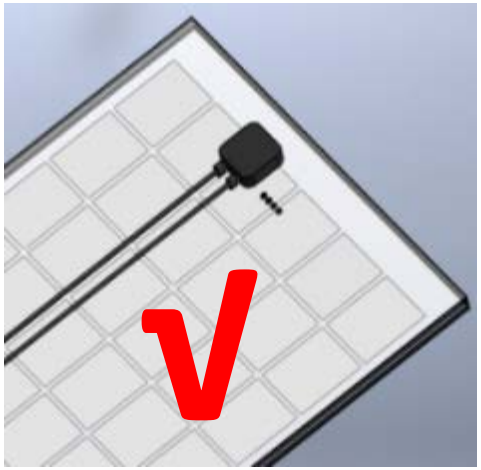
Trina Design: 2.5+2.5mm glass

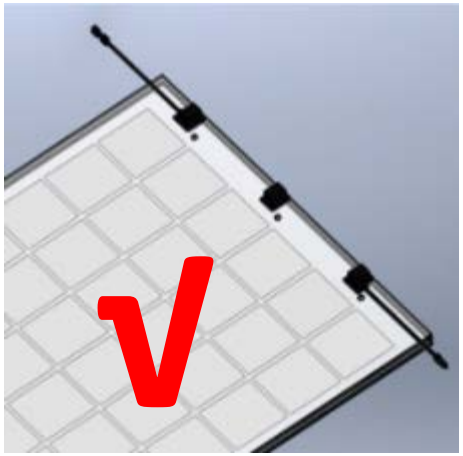
1. Thinner glass： 3.2mm reduced to 2.5mm, much lower weight compared to previous dual-glass designs

2. Both heat-strengthened glass, strong and stable

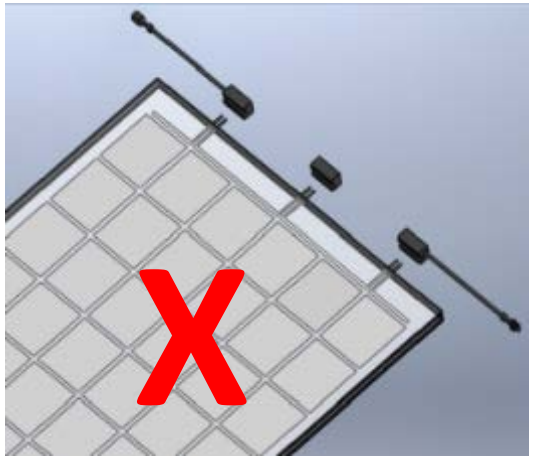
3. Front glass: low iron, patterned, ARC, high transmittance

4.Back glass: normal iron, flat, with 4 or 3 holes for wires go through and connected to J-box.





2.5mm + back holes + back J-box: Satisfied for all reliability
Industry innovation, Trina is leader.



No Holes + Edge J-box：
Insulation issue!
Difficult to pass UL30: Impact test at -35℃

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3. Detailed Design and Advantages of Dual-Glass Module

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3.2 DG Design

3.3 Back Glass vs. Back sheet: less permeability of moisture

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3.6 Advantages of Frame-less PV Modules

3.7 Other Advantages

3.3 Less permeability of moisture: Glass vs. Back sheet

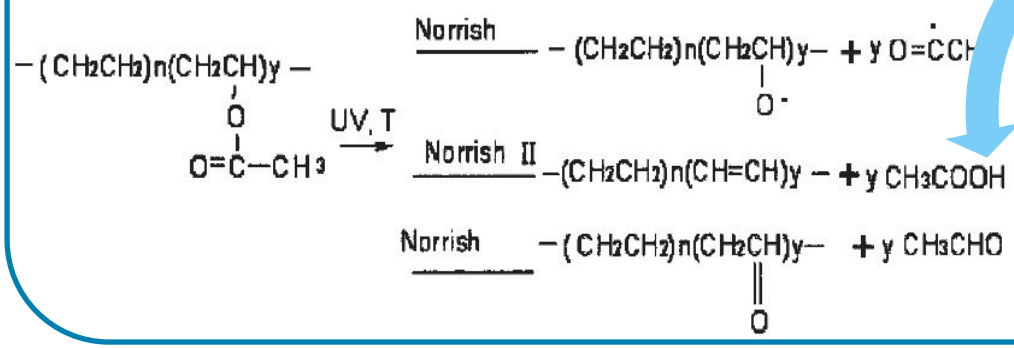
Permeability of moisture and oxygen is almost zero comparing polymer back sheet, leading to an excellent durability and resulting in:

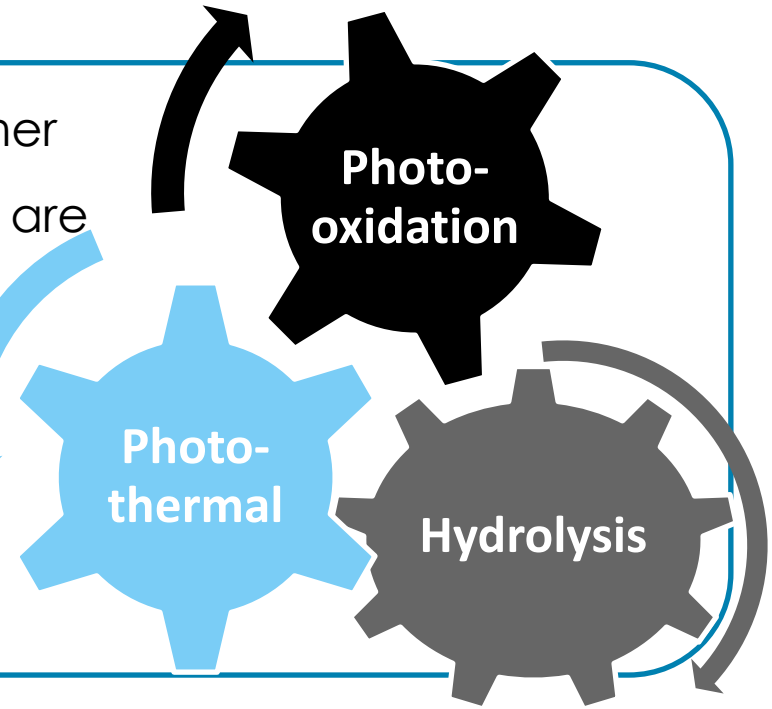
① **Anti-PID and No "snail-trail", excellent resistance to Hot Spot.**

② **Excellent anti-salt mist, anti-Alkali & Acid, anti-sand & dust**

③ **Reduced rate of degradation for polymer encapsulation materials (EVA, ….)**

The major degradation factors for polymer materials, such as backsheet and **EVA**, are **moisture**, **heat**, **O_2** and **UV**





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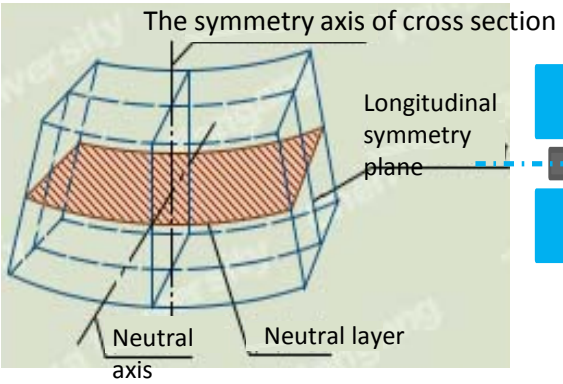
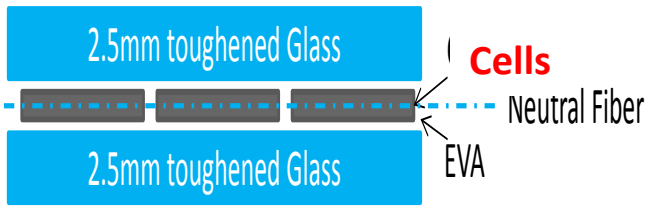
3.4 less stress to the cells: Glass vs. Back sheet

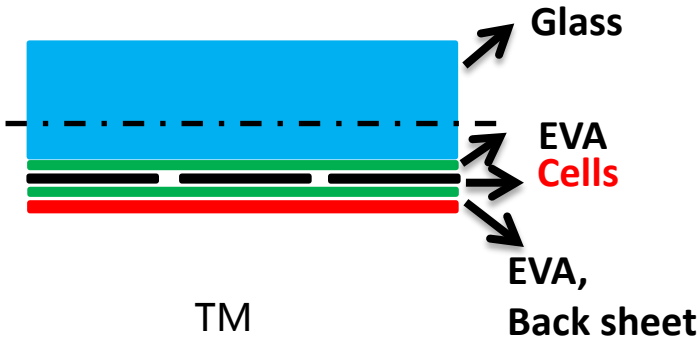
Dual-glass is a symmetrical "sandwich" structure, providing a better protection to cells



Stress analysis



DG



TM

- ✓ The middle layer of one structure is the "stress neutral layer" or "Neutral Fiber" according to structural mechanics theory.
- ✓ In a 2.5+2.5mm dual-glass structure, the cells are located at the "Stress neutral layer". During bending, the mechanical stress applied to the cells is negligible.
- ✓ In TM, the cells are located far from the "neutral layer" and the cells bear the maximum stress during bending.

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3.5 less thermal mismatch: Glass vs. Back sheet

Material	Coefficient of thermal expansion(CTE) α(10^-6/℃)	Thickness d (mm)	Young's modulus E0（Pa)	Poisson's ratio(v)
1 Si（cell）	3.5	0.18	1.31*10^11	
Cu（ribbon）	16.6	0.2		
2 glass	10	3.2	7.31*10^10	0.17
Polymer Back sheet (Typical)	800	0.3	9.5*10^7	0.33
EVA	150	0.8	7*10^6	0.33

Remark ：CTE of water α（10^{-6}/℃）： α=210(t>4℃); anomalous expansion(0℃<t<4℃); Ice=51

Maximum bending $\delta = \dfrac{3/4L^2(\alpha_{back} - \alpha_{glass})(T_f - T)(d_{back} + d_{glass})}{d_{back}^2\left(4 + 6\left(\frac{d_{glass}}{d_{back}}\right)^2 + \frac{E_{glass}}{E_{back}}\left(\frac{d_{glass}}{d_{back}}\right)^3 + \frac{E_{glass}}{E_{back}} \bullet \frac{d_{glass}}{d_{back}}\right)}$

Remark: Using a simple one dimensional model to calculate the bending of module [1];
L=1658 mm, Biaxial Young's modulus, E = E_0/(1-v), δ-Maximum bending of module

[1] Vear Popovich, Microstructure and Mechanical Aspects of Multicrystalline Silicon Solar Cells. Ph.D. Thesis,2013.

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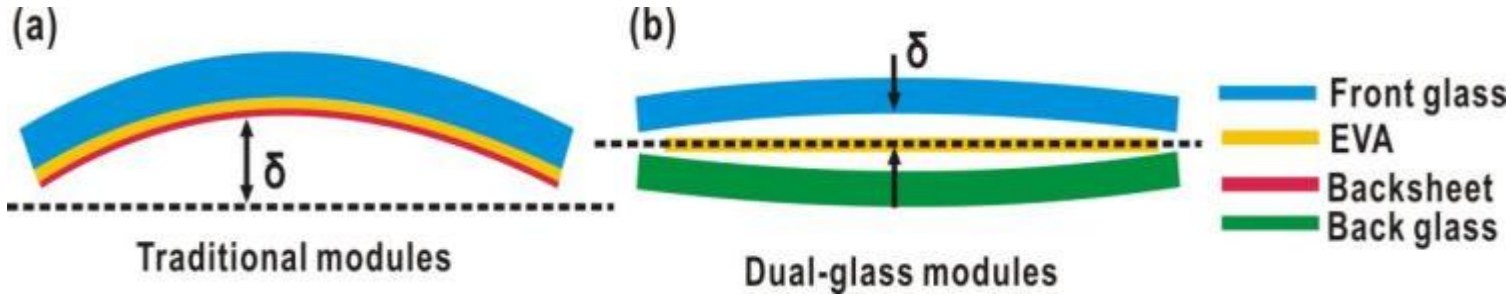
3.5 : less thermal mismatch: Glass vs. Back sheet



Condition	ΔT（℃）	$\delta_{T\ M}$ (mm)	$\delta_{DG\ M}$ (mm)
Out of laminator(about 140~ 25℃)	115	9.6	0.18
TC & HF(-40~+85℃)	125	10.4	0.20
In the field such as in desert	≈60	5.2（reference）	<0.2

Remark: In the actual conditions, the frame of TM limits the deformation of the module. This may cause higher thermal stress

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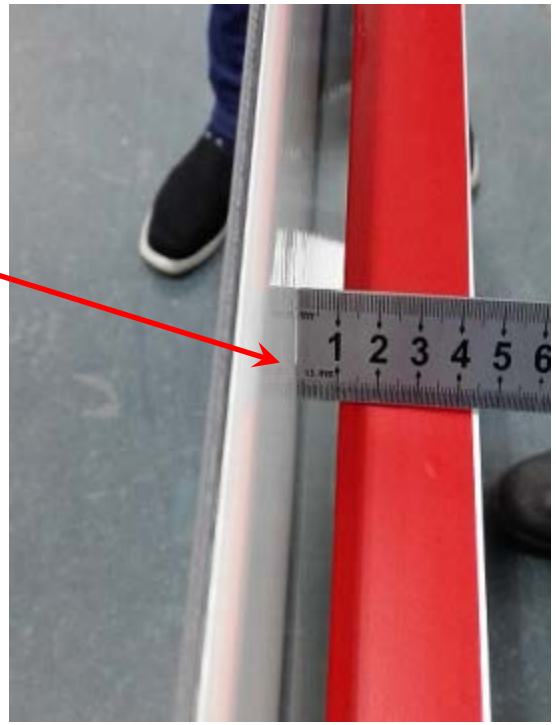
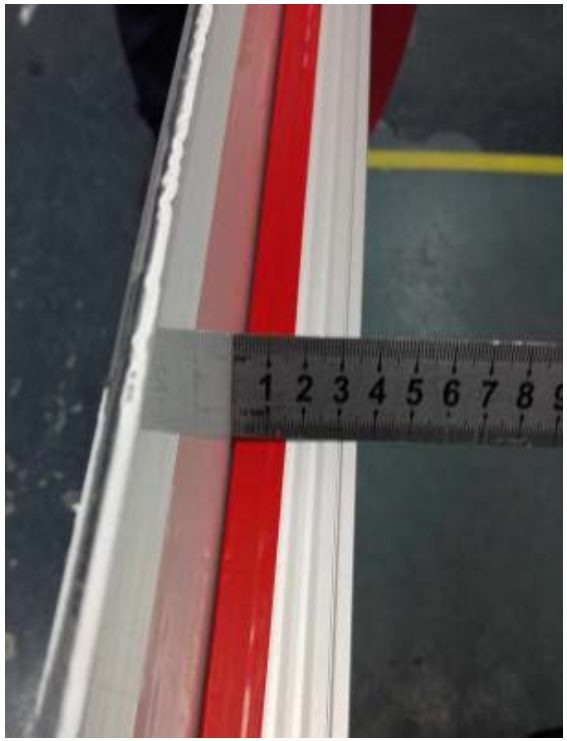
3.5 less thermal mismatch: Glass vs. Back sheet

The bending result when the modules come out from laminator in production progress



11mm for 60pcs cells TM



<1mm for 60pcs cells DG

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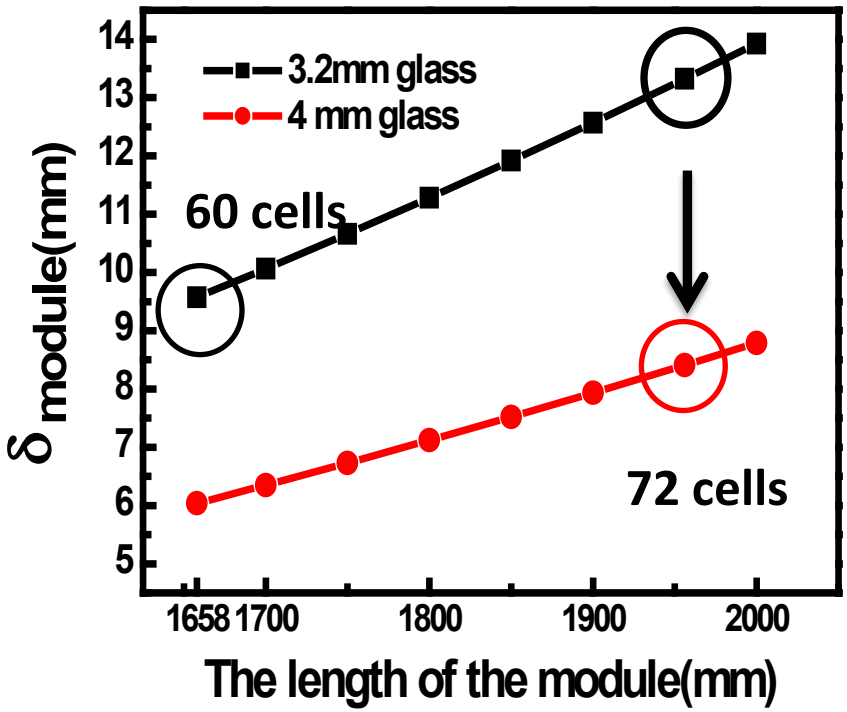
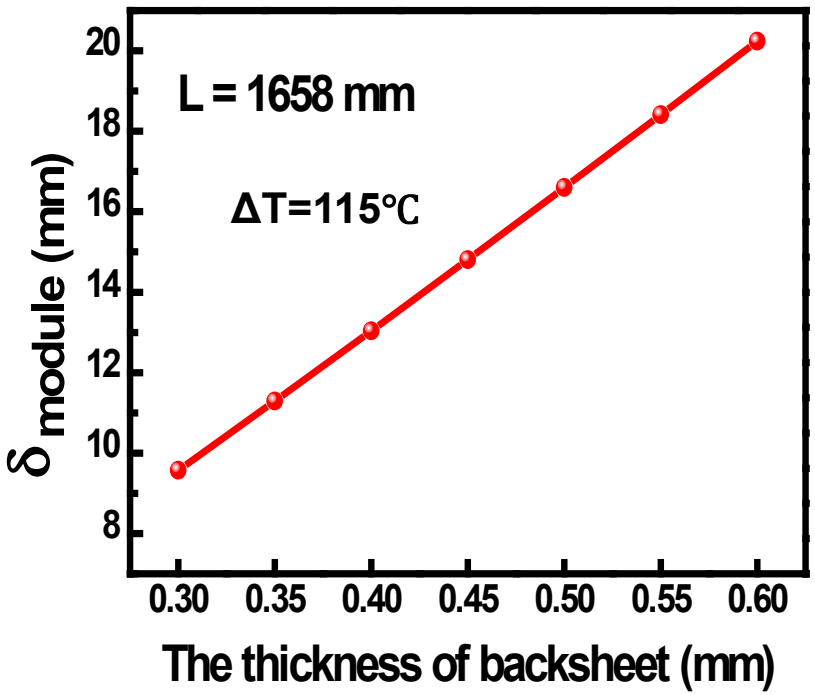
3.5 less thermal mismatch: Glass vs. Back sheet

Consider it Further： for TM

Increasing the module length (or amount of cells) and back sheet thickness: what will happen?





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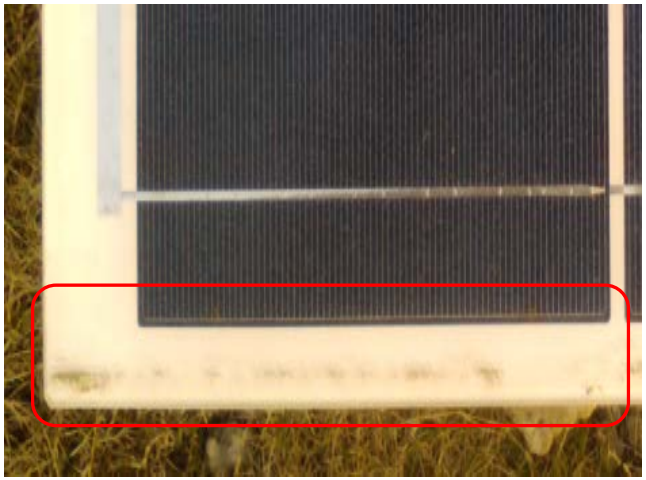
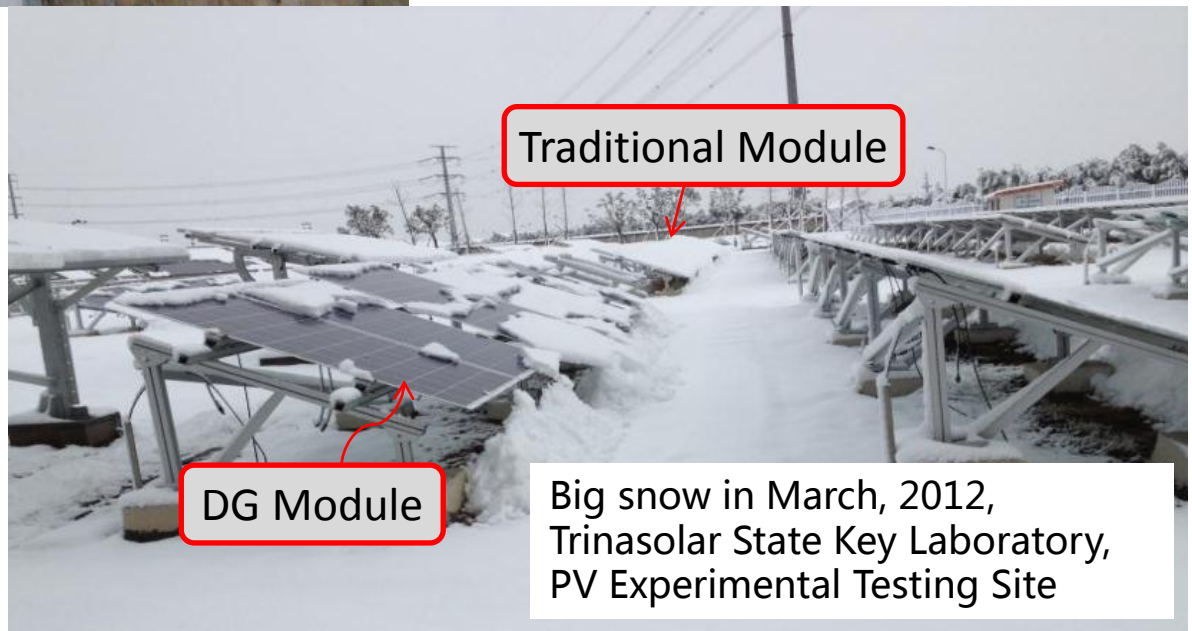
3.7 Other Advantages

3.6 Advantages of Frame-less PV Modules

✓ Framed modules suffer more from dust and snow accumulation than frame-less modules

vs.





Big snow in March, 2012,
Trinasolar State Key Laboratory,
PV Experimental Testing Site

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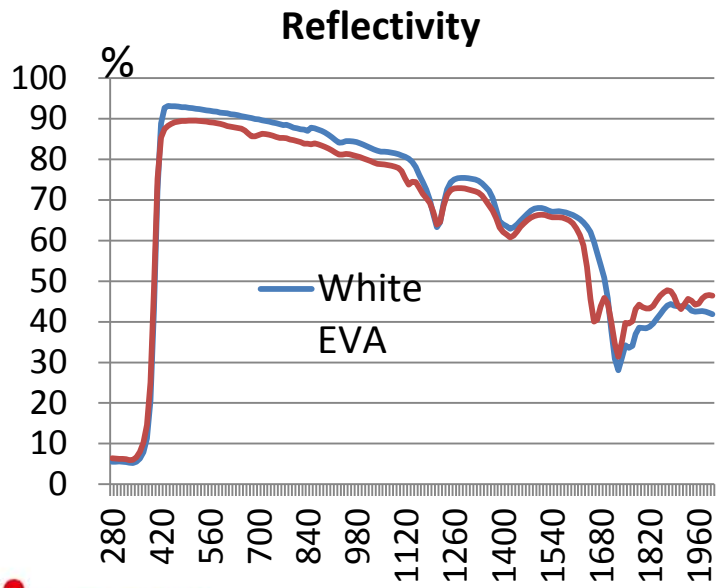
3.7 Other advantages

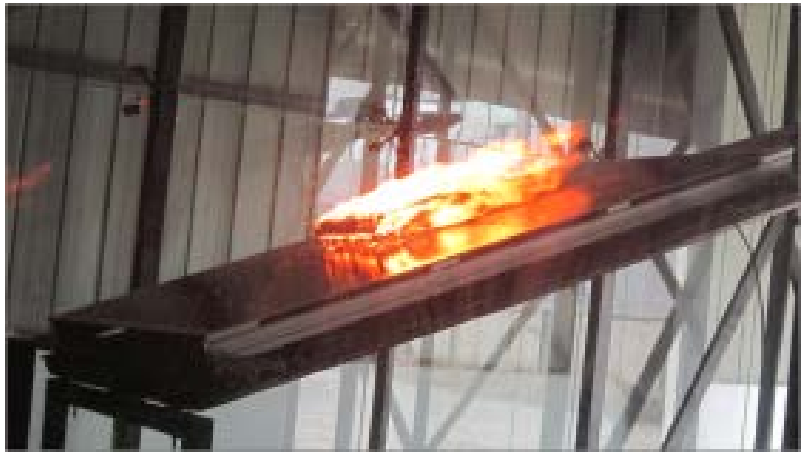
3.7 .1 Both white and transparent EVA can be used,

- ✓ White EVA leads to higher power output. White EVA is more reflective than backsheet (Fig.1)
- ✓ Transparent EVA is typically used for greenhouse, Bifacial or BIPV applications

3.7 .2 Complies with highest fire rating: Type 13/Class A of UL/TUV

3.7 .3 Complies with TUV1500V/UL1000V which reduce LCOE





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Outline

1 Introduction of Trinasolar

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4 Reliability test

5 Conclusion

4. Reliability tests

4.1 Overview

4.2 Mechanical Loading

4.3 Thermal cycling related tests —TS3000, TC600, HF50

4.4 Moisture related tests —DH3000, PID

4.5 Sequential Tests, more realistic and closer to field Conditions — DH2000+TC400+HF40

4.6 The “Breathing” issue

4.7 Abrasion Testing

4.1 Overview of Dual-Glass Module

- ✓ ＞150pcs modules tested based on 1.5times IEC standards, Pmax degradation: < 3%
- ✓ ＞22pcs finished extended reliability testing(3~5 times IEC & long term sequential test)

  14pcs in Trina, see Fig.1; 8pcs in RETC, see Fig.2

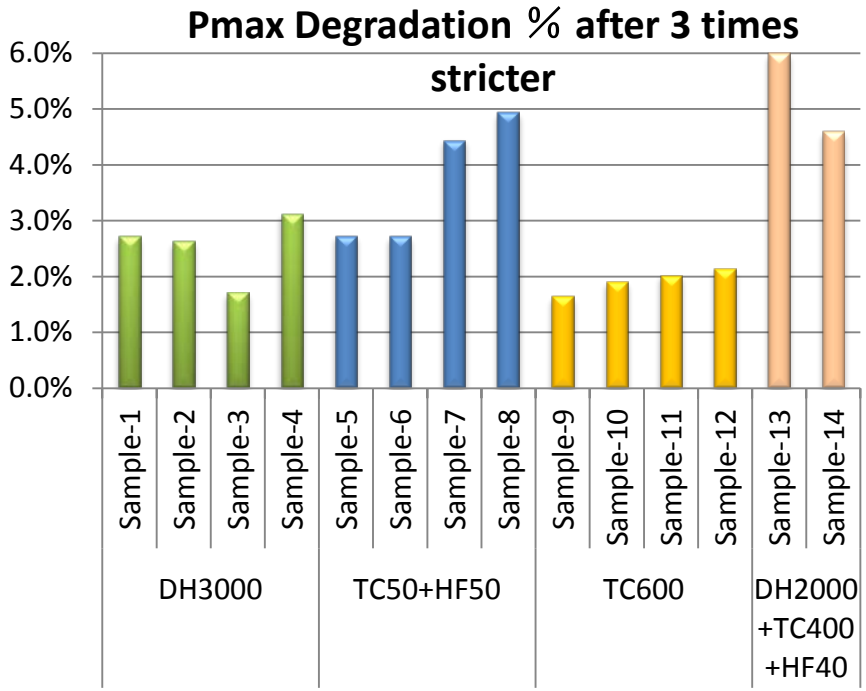

Fig.1

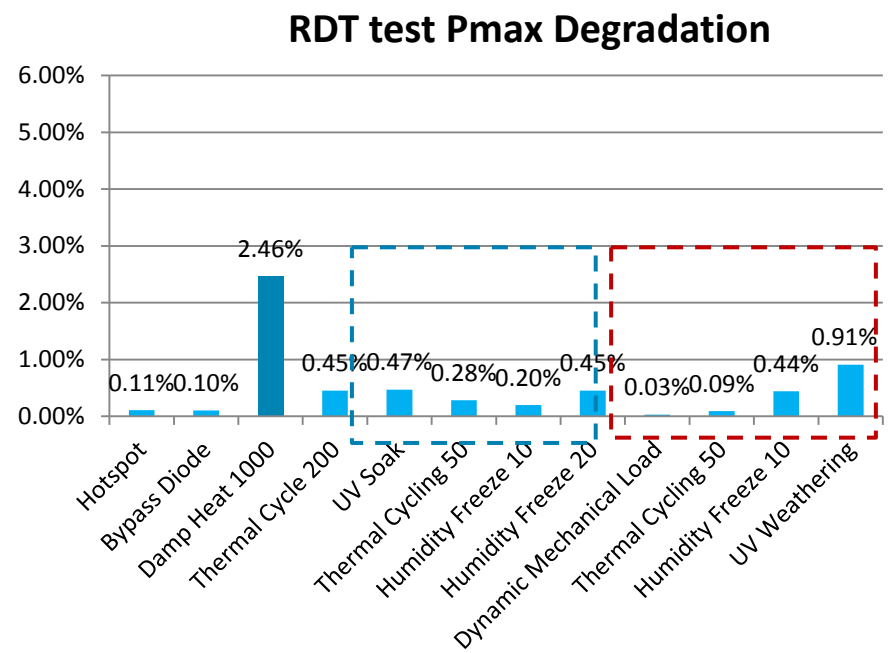

Fig.2

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4. Reliability tests

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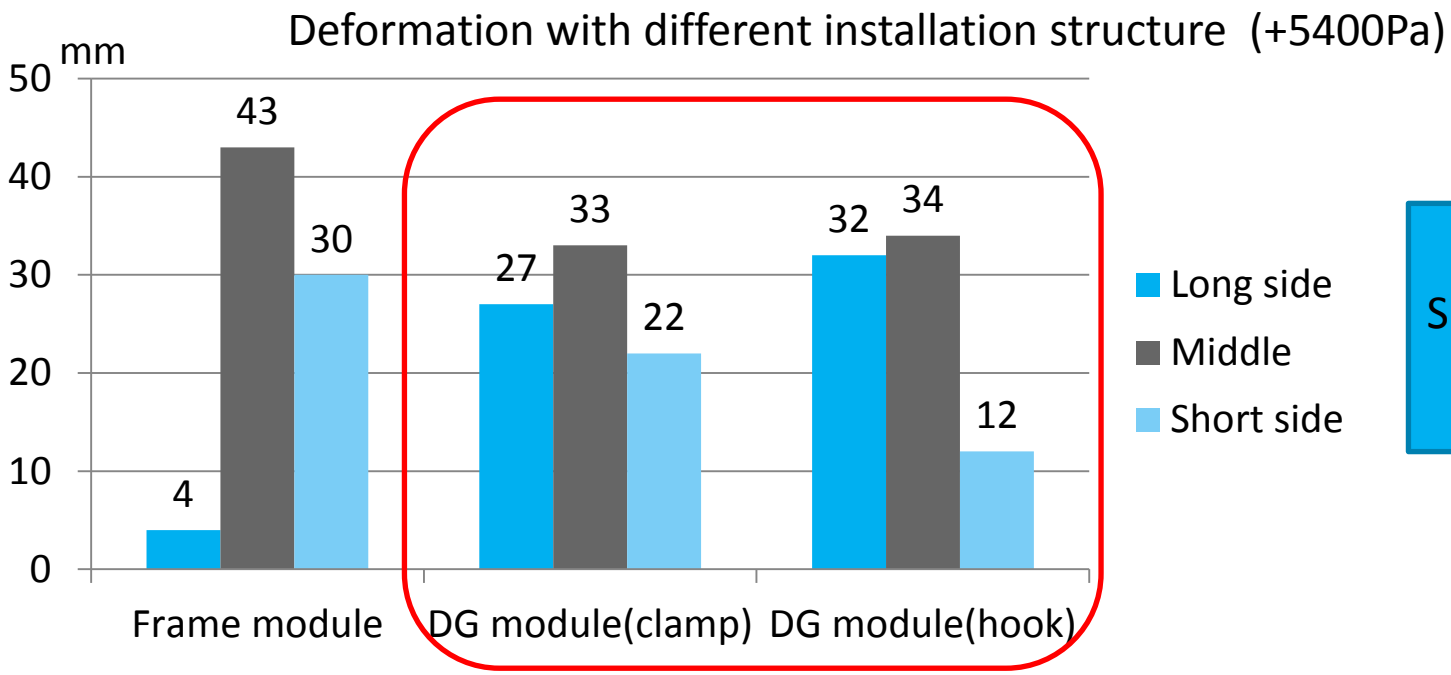
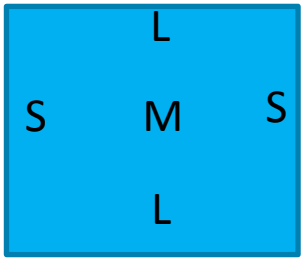
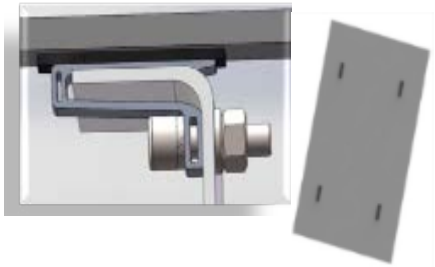
4.7 Abrasion Testing

4.2 Mechanical Loading (ML)

✓ Deformation under Static Mechanical Loading (ML)







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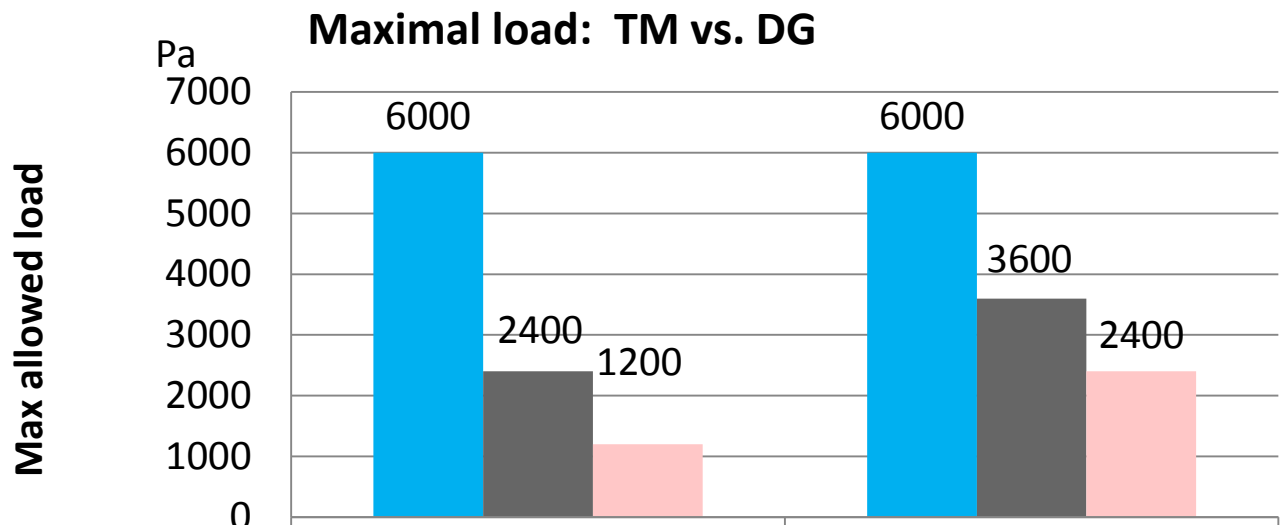
4.2 Mechanical Loading

✓ Max ML performance(with back hook installation)



	TM	DG
static postive load(Pa)	6000	6000
static negative load(Pa)	2400	3600
Dynamic load(pa)	1200	2400

Remark: Above is DH1500h + ML, TC300 + ML is on going

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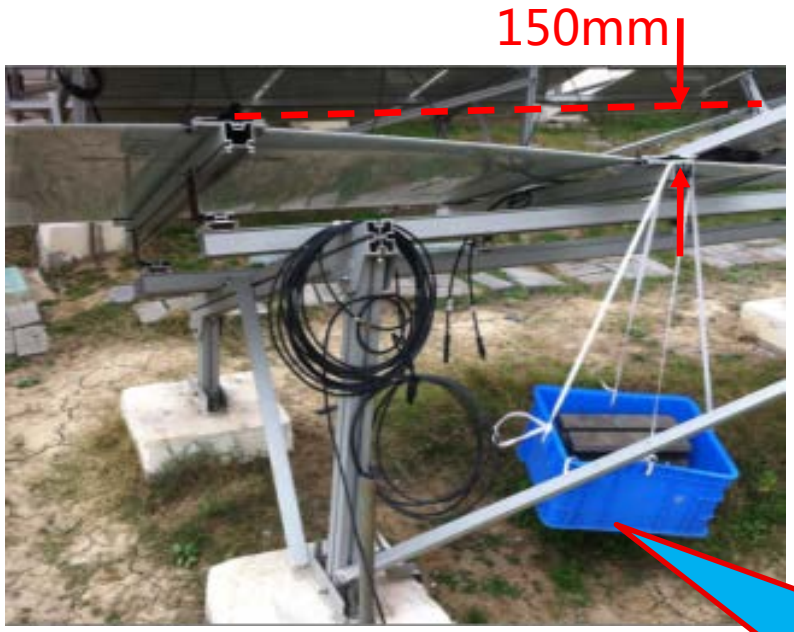
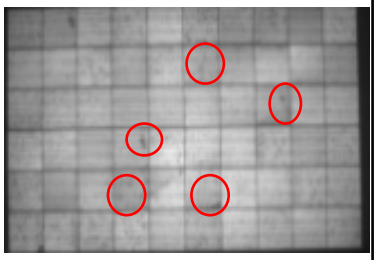
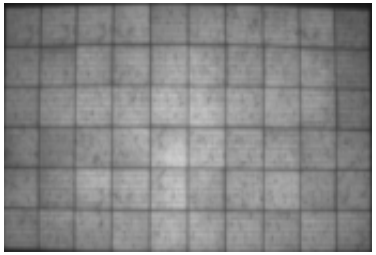
4.2 Mechanical Loading

✓ Simulation of land movement or rack deformation



	TM	DG
EL after for 3weeks		
Power char (%)	-1.8	-0.1

DG is virtually micro-crack free

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4.4 Moisture related tests —DH3000, PID

4.5 Sequential Tests, more realistic and closer to field conditions

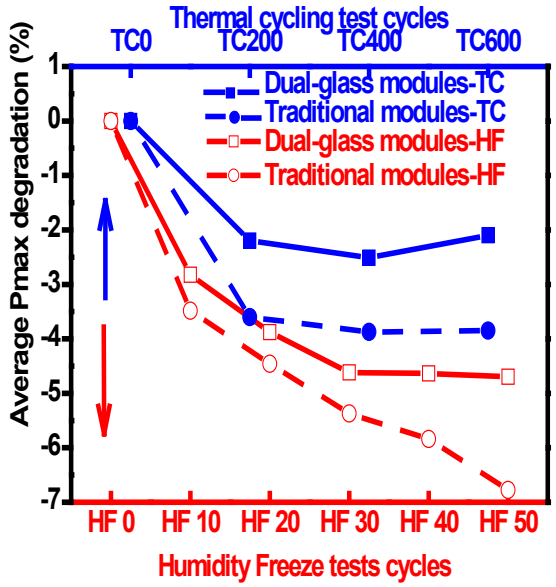
— DH2000+TC400+HF40

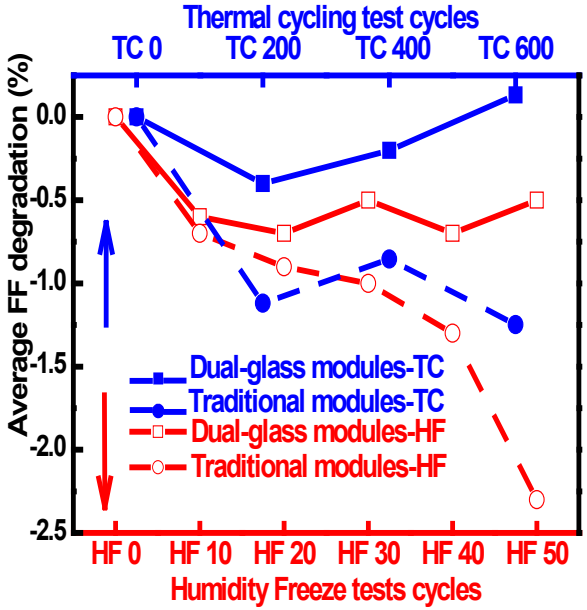
4.6 The “Breathing” issue

4.7 Abrasion Testing

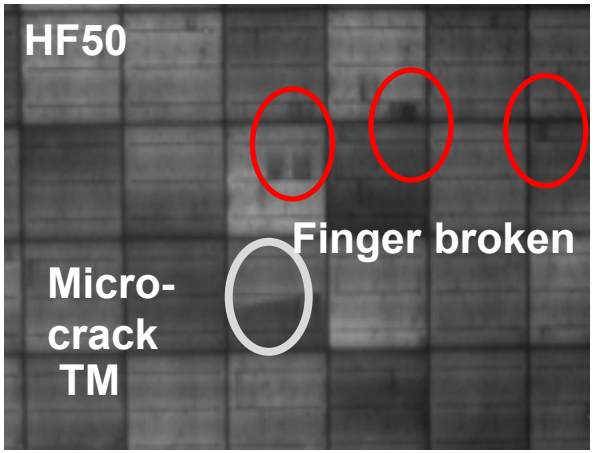
4.3 Thermal cycling and Humidity-Freeze related tests

1. TC600 & HF 50

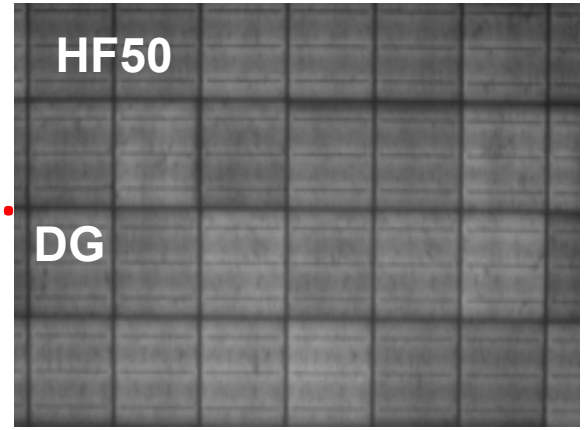




- Due to the CTE* of water in HF test, the FF degradation of TM is much higher than of dual-glass ones



VS.



*** Coefficient of thermal expansion(CTE)**

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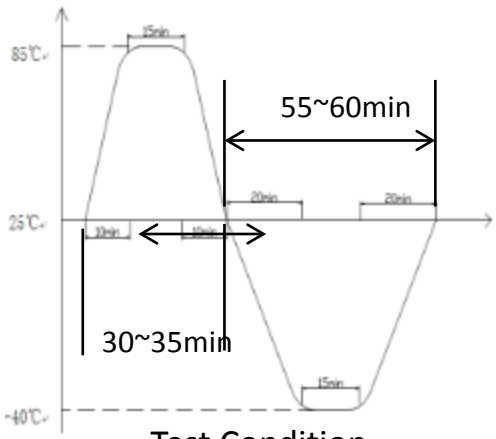
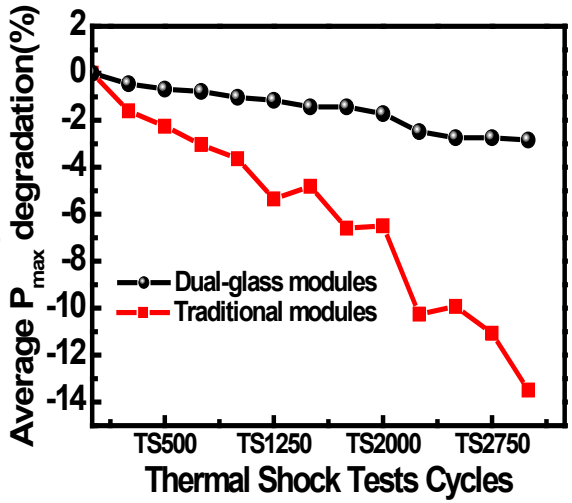
4.3 Thermal cycle related tests

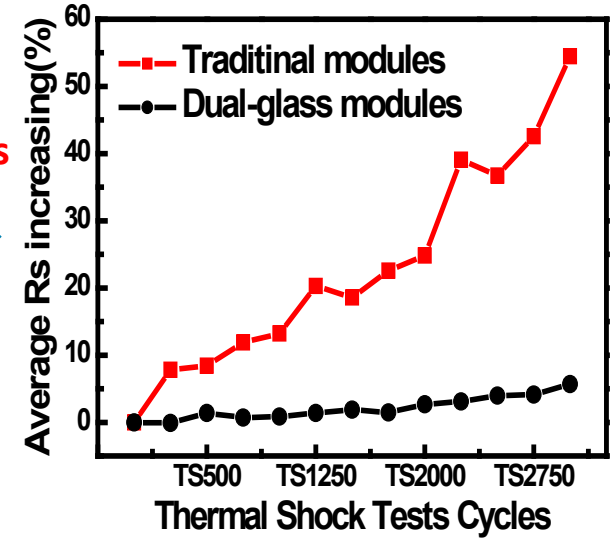
2. Thermal shock (TS3000)



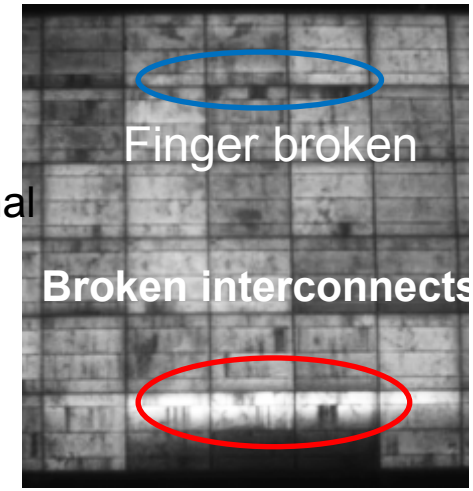
Test Condition



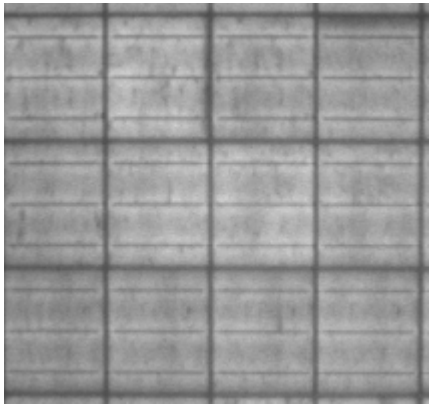
Due to Rs



Traditional module



VS.



Dual-glass module

Trinasolar
The power behind the panel.

4. Reliability tests

4.1 Overview

4.2 Mechanical Loading

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4.5 Sequential Tests, more realistic and closer to field conditions

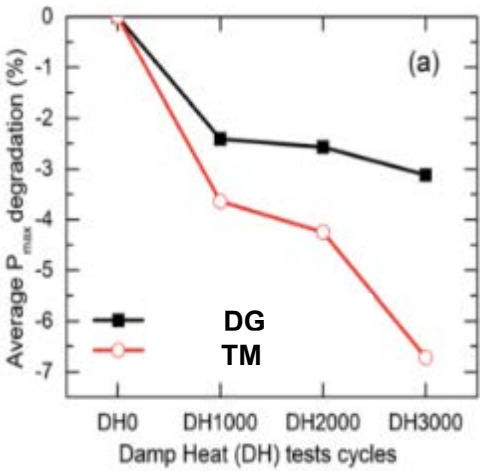
— DH2000+TC400+HF40

4.6 The “Breathing” issue

4.7 Abrasion Testing

4.4 Moisture related tests

1. Damp Heat 3000h



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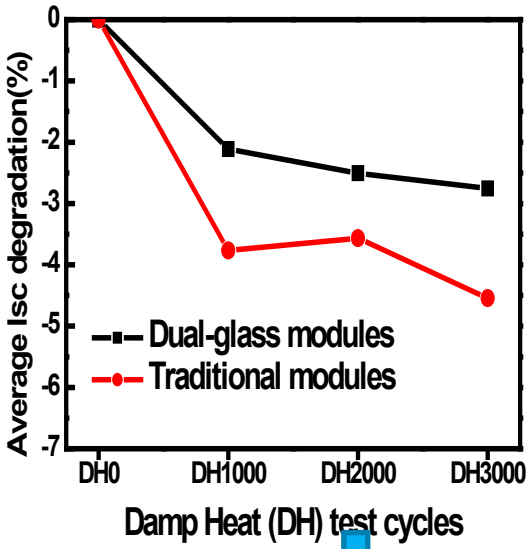
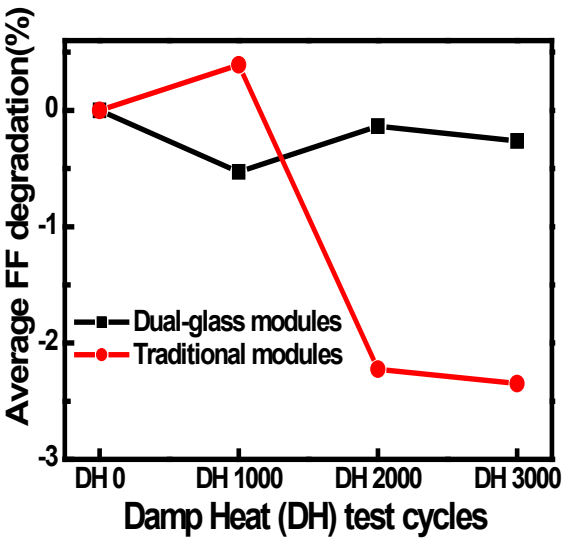
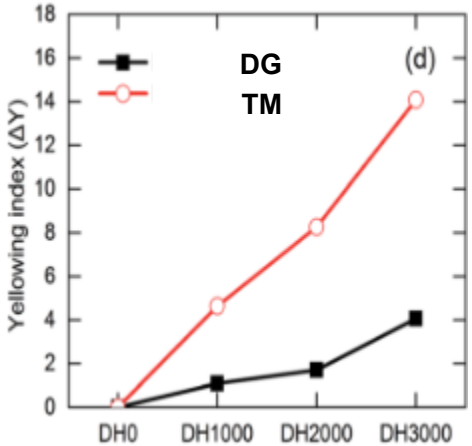
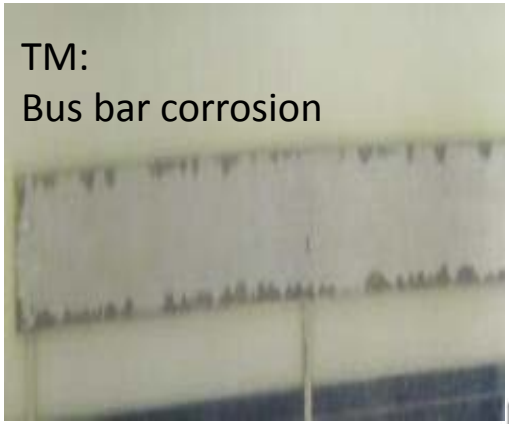


+



Penetration of $H_2O + O_2$





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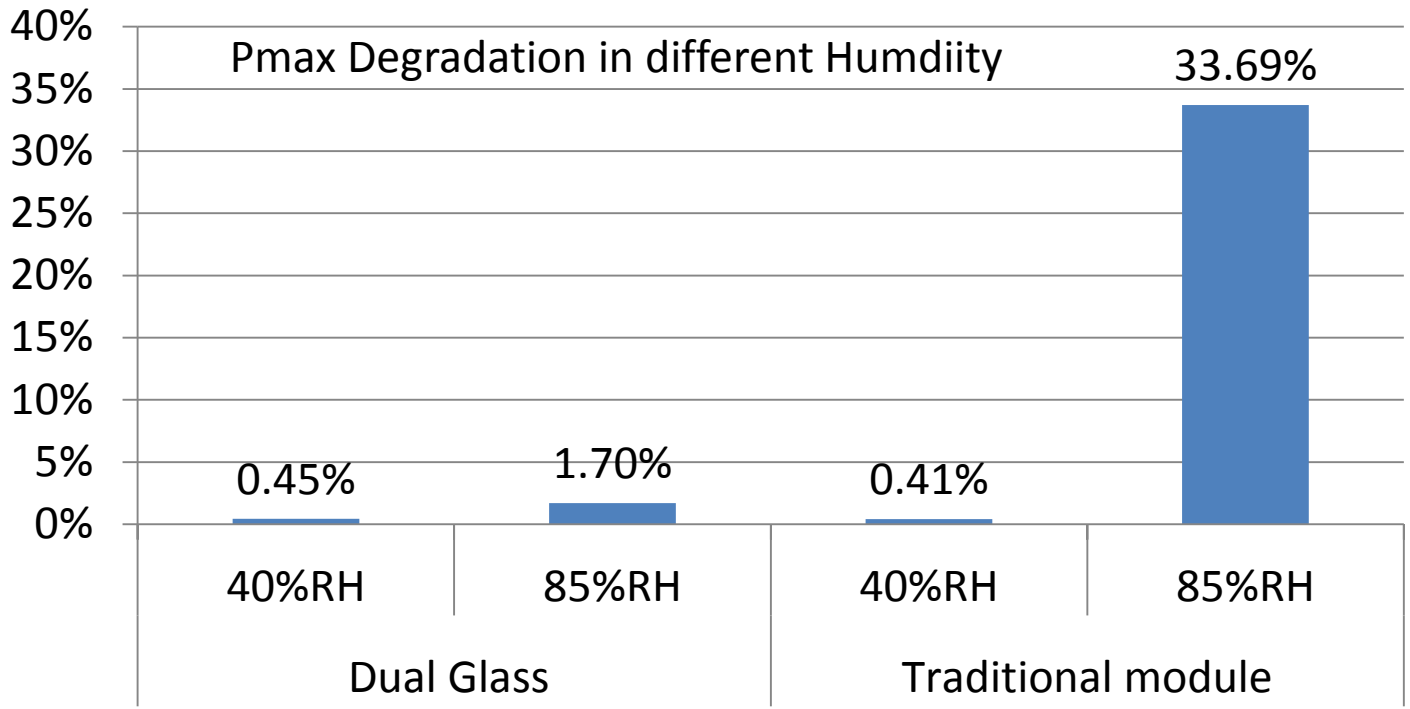
4.4 Moisture related tests

2. PID tests-1 (IEC 62804: System voltage durability test)

✓ **Test condition： Temperature：85℃； Time：96h； +1000V；**

Humidity：40%RH vs. 85%RH



With Normal cells

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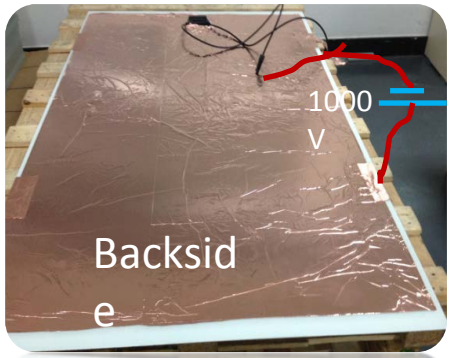
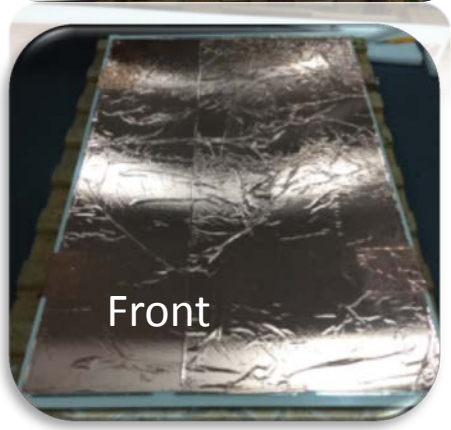
4.4 Moisture related tests

2. PID tests-2

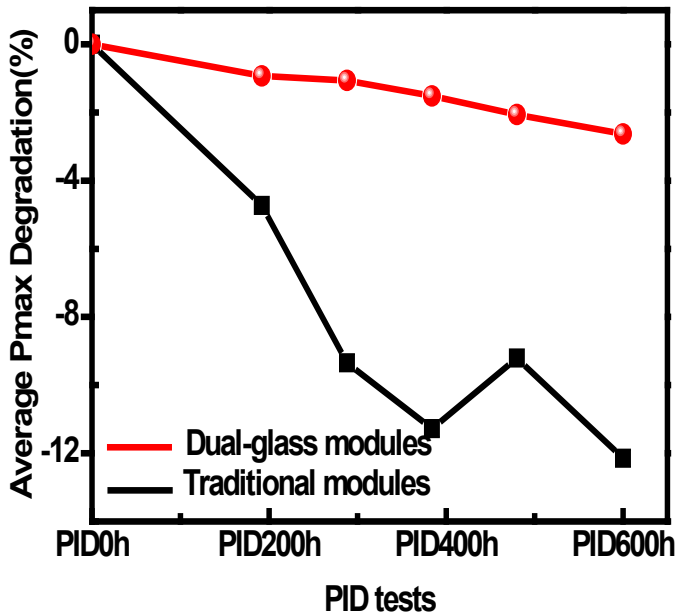
For Tropical and Mountain climates, the most difficult PID test must be considered.

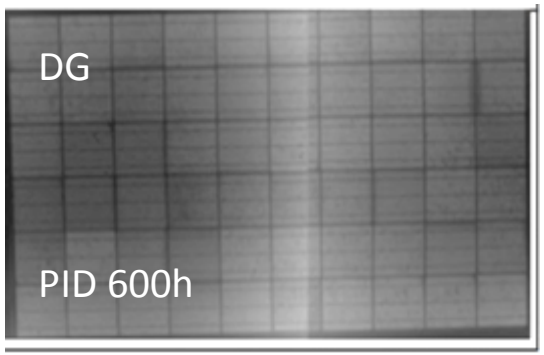
(a)

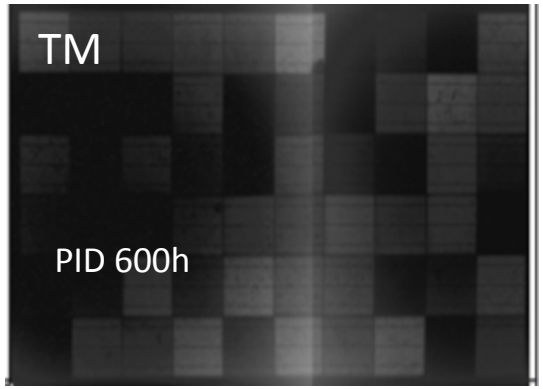




85% R.H., 85°C, 1000V, 600 hours
with Copper foil on both sides (Fig. a)







EL at 1A current

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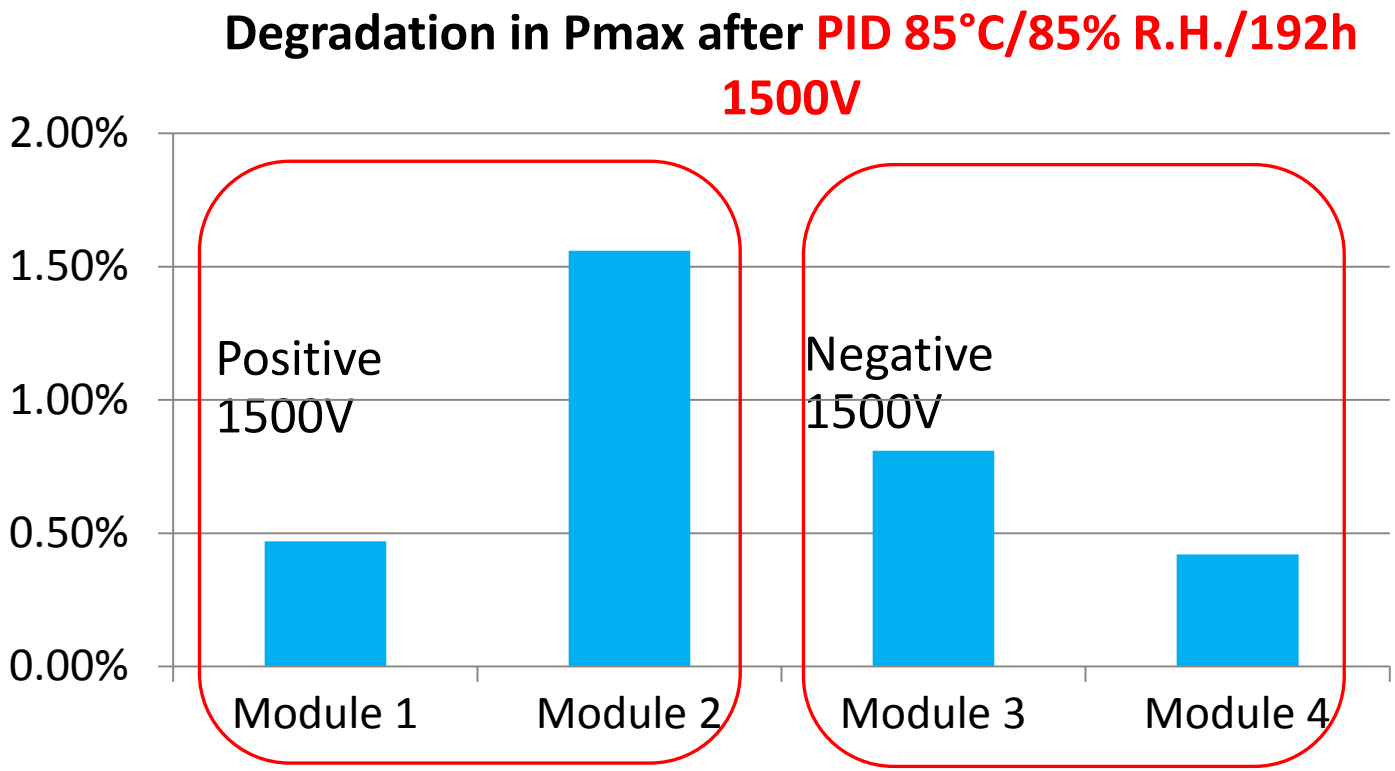
4.4 Moisture related tests

2. PID tests-3

✓ **Dual Glass Modules (72-cells) easily passed IEC 62804: System voltage durability test**



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4. Reliability tests

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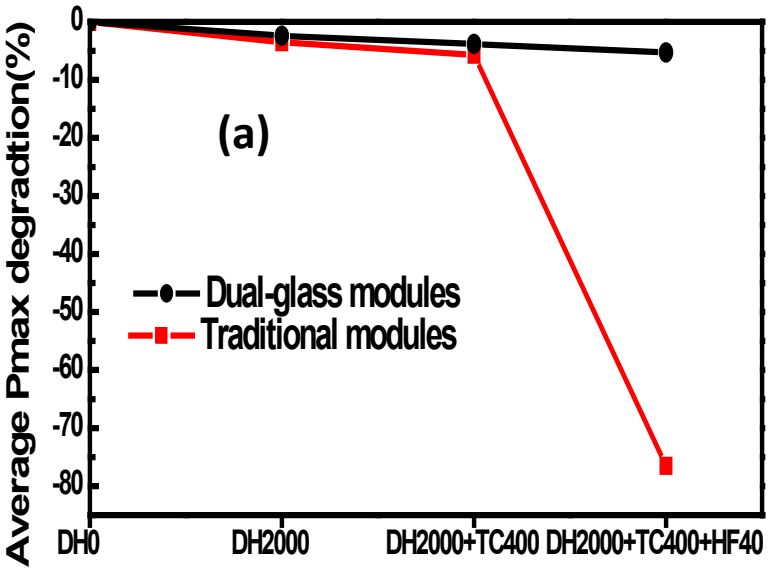
4.6 The "Breathing" issue

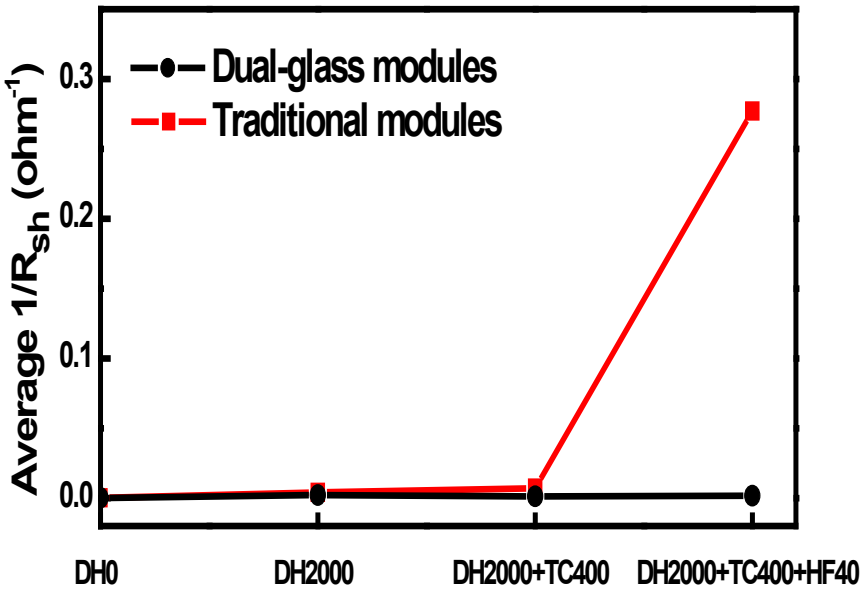
4.7 Abrasion Testing

4.5 Tests closer to field conditions

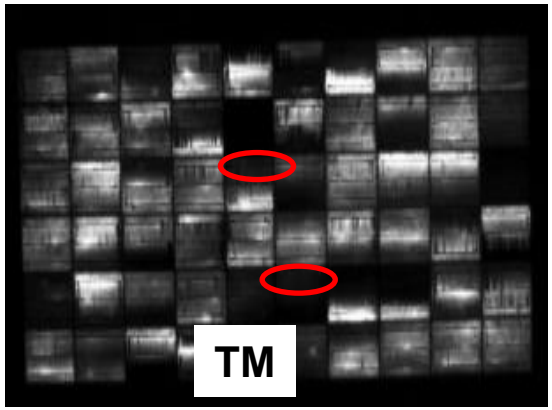
DH 2000+TC400+HF40

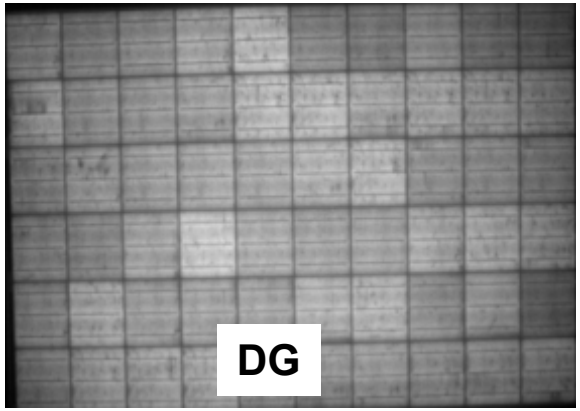


Due to



EL After DH2000 +TC400+HF40 test





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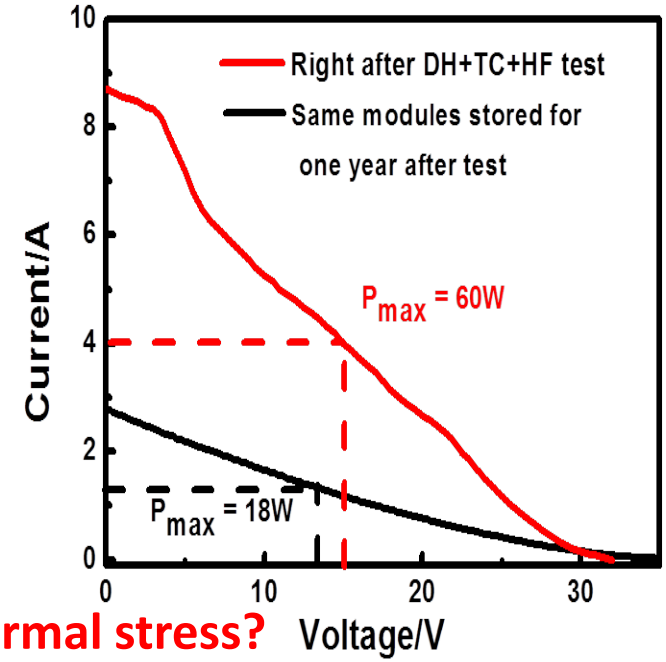
4.5 Tests closer to field conditions

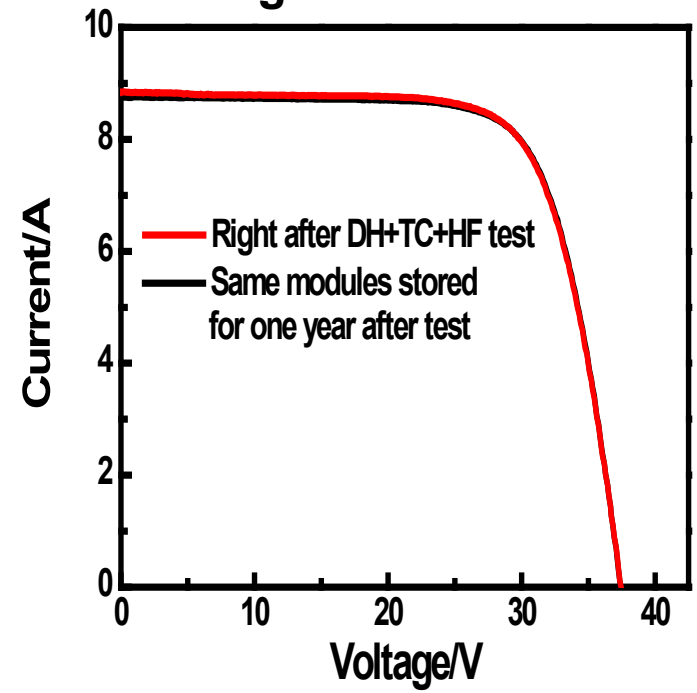
Traditional Module:

Dual-glass module

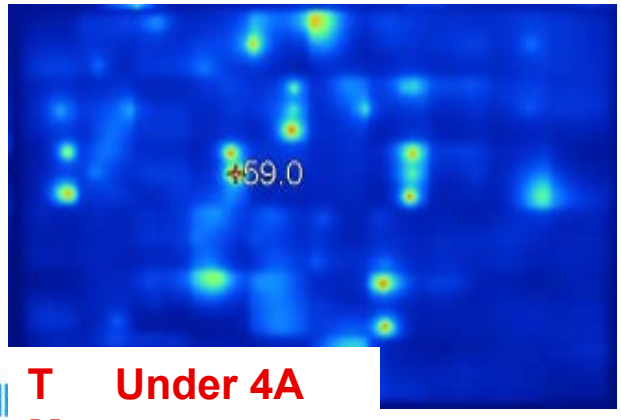
After One year storage



VS.

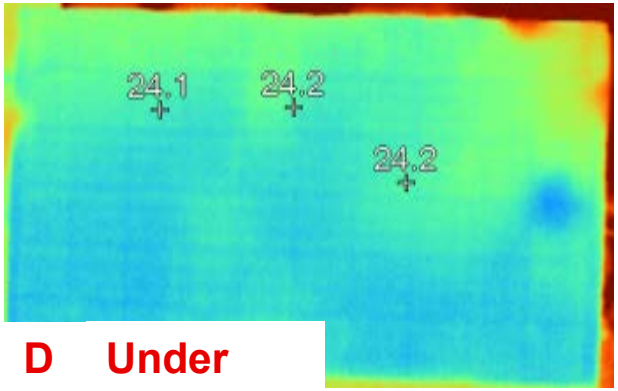


Continued thermal stress?



TM Under 4A

VS.



DG Under 4A

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4. Reliability tests

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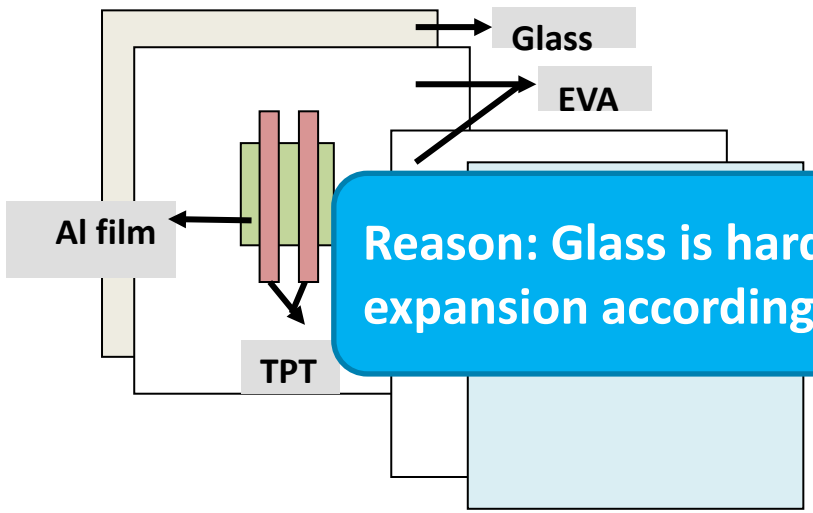
— DH2000+TC400+HF40

4.6 The "Breathing" issue

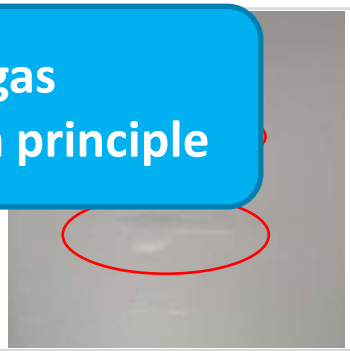
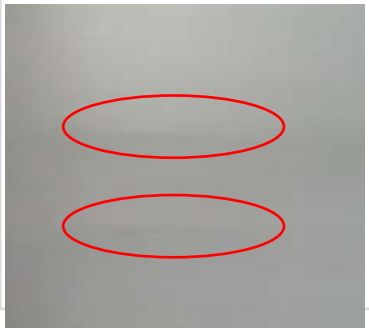
4.7 Abrasion Testing

4.6 The "Breathing" Issue

✓ **Experiment-1: about EVA outgassing**



Reason: Glass is hard and strong to prevent the gas expansion according to the chemical equilibrium principle

No.	Back Sheet	WVTR g/m²/day	155℃, 4h
1	GLASS	0	No change
	Al		
3	TPT	1.96	

Test Result

- Sample: No bonding between Al film and TPT
- Laminating parameters: 140℃-5min-19min
- Test Condition: 155℃, 4h in the oven

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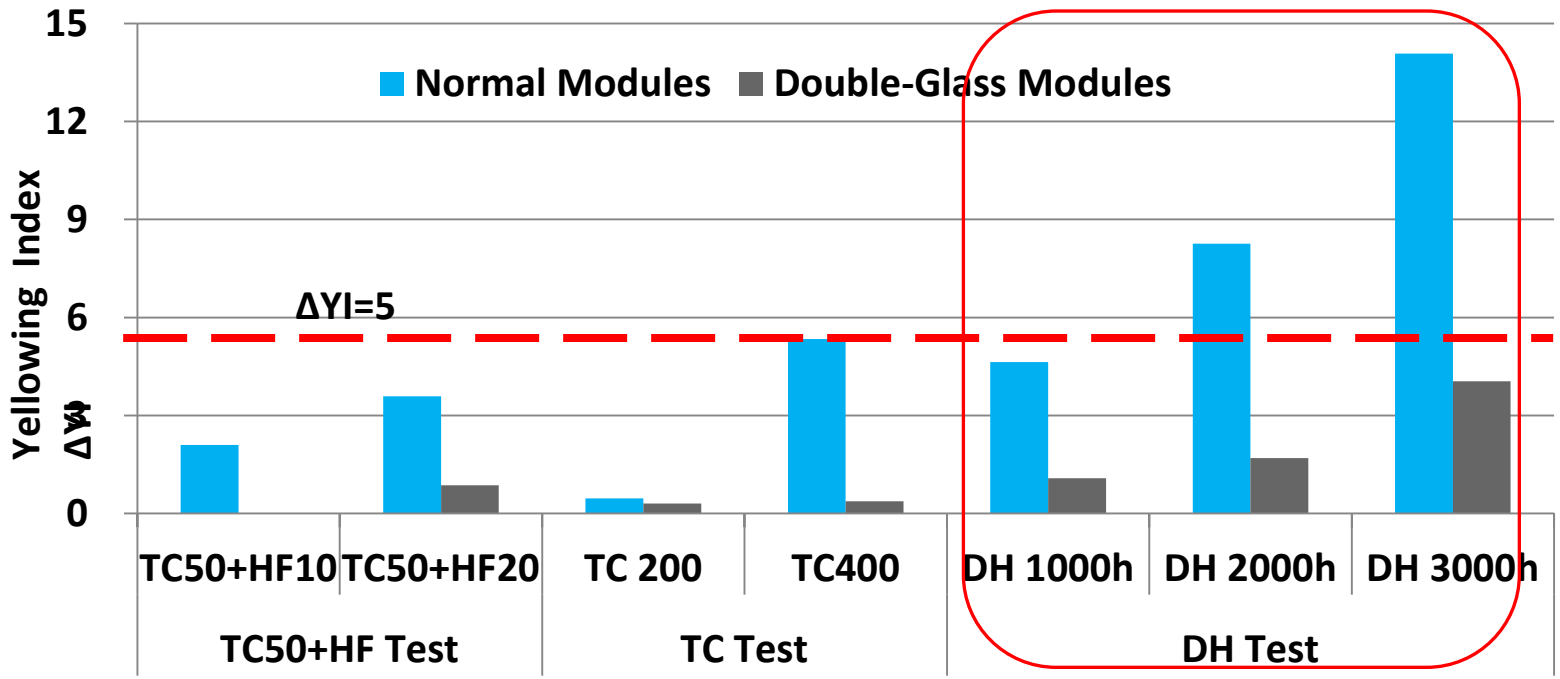
4.6 The "Breathing" Issue

✓ **Experiment-2: Regarding Yellowing**



- The Change in Yellow index of DG modules was less than 5
- The change in Yellow Index for TMs was higher , specially after DH tests

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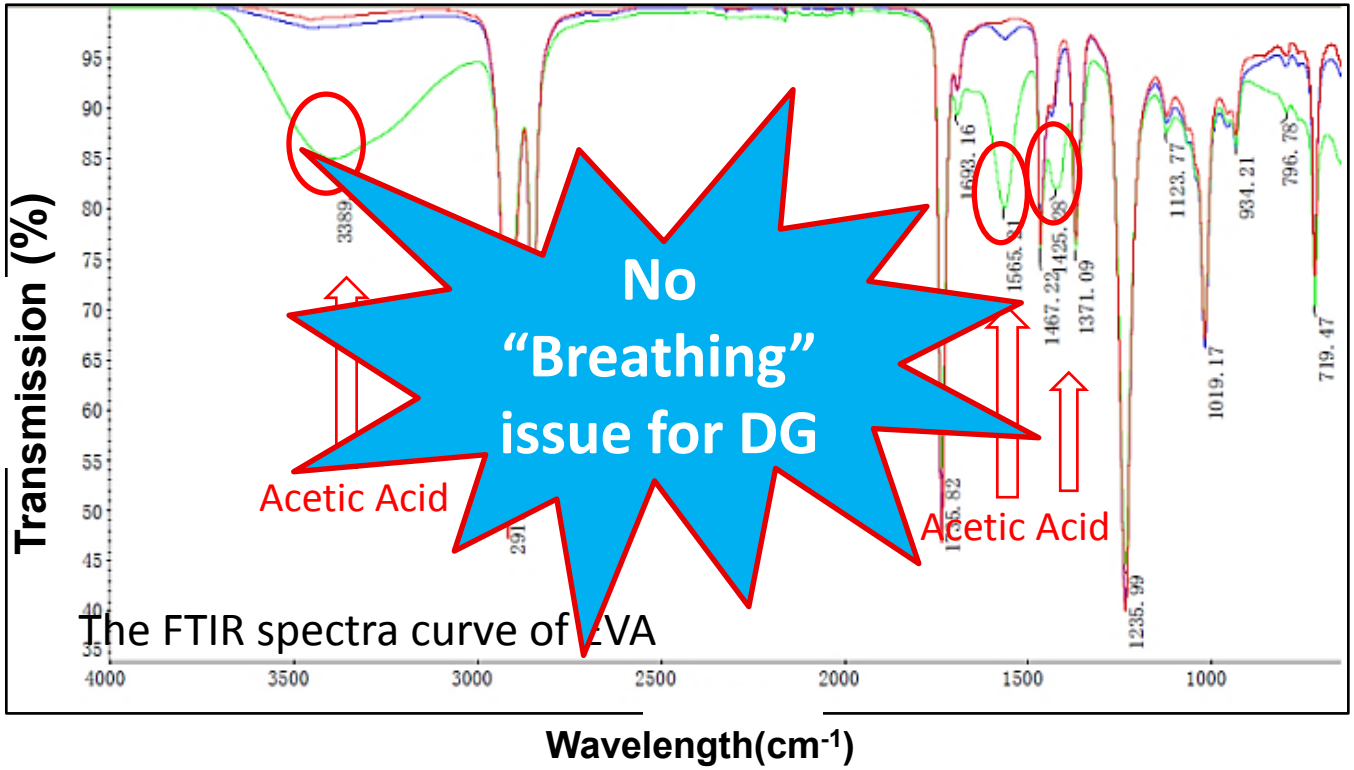
4.6 The "Breathing" Issue

✓ **Experiment-3: about EVA degradation after DH3000**



The peaks of acetic acid , in 3389 cm^{-1}, 1565cm^{-1} and 1425cm^{-1}

- **Big changes in TM**
- **Not in DG**

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4. Reliability tests

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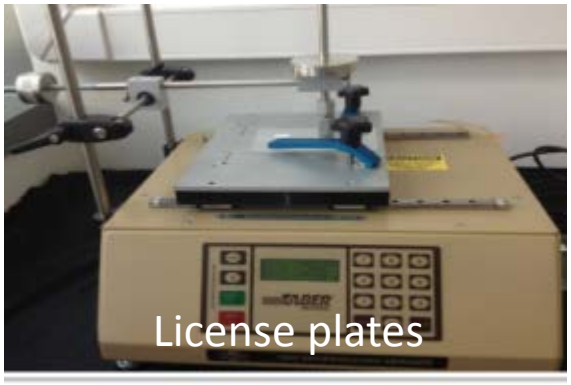
4.6 The "Breathing" issue

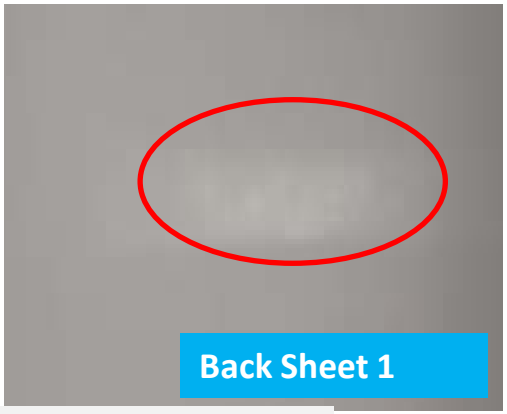
4.7 Abrasion Testing

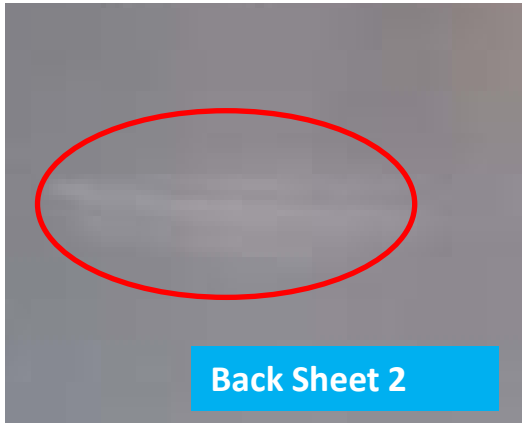
4.7 Abrasion Testing

Abrasion Testing：

After 250 cycles, Glass does not show any visual problem, whereas the back sheet surface is scratched







Instrument： Taber 5900

- Load: 4.5N
- The stroke rate :60 strokes/min
- The stroke length: 100mm
- Each test was done using a fresh felt pad.

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Outline

1 Introduction of Trinasolar

2 Application Challenge

3 Detailed design and advantages

4 Reliability test

5 Conclusion

5. Conclusion

Frameless Dual-Glass PV Modules:

- ✓ Passed more than 3 times IEC reliability
- ✓ Excellent PID performance (passed 1500V and 600h/85%/85C/1000V/Foil)
- ✓ No “snail trails”, no delamination
- ✓ Less sand accumulation, less snow retention
- ✓ No UV degradation of backsheet, Anti-alkali, sand, salt, most acids.
- ✓ Mechanically robust, almost micro-cracks free
- ✓ Rated UL Fire Class A/TUV Type13;
- ✓ IEC1500V & UL1000V Certificated;
- ✓ No grounding;
- ✓ 30years Warranty

TSM-PEG5： 60pcs cells, 250~265W

TSM-PEG14: 72pcs cells,

Further applications

- ✓ Bifacial cell, BIPV
- ✓ Water-sensitive cell

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Application of Trina Dual-Glass Module

Green house in Anhui province 25MW

Pu'er Tea Garden in Yunnan province 50MW

Fish Farm in Jiangsu province 50MW

Utility application in Anhui province 50MW

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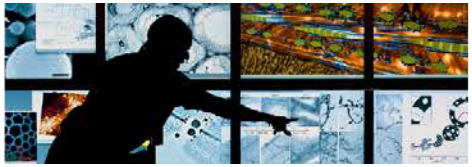
Trinasolar
天合光能
Thank You!

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Climate Specific Thermal Cycling- Is It Required For Reliability Testing?



Nick Bosco
National Renewable Energy Laboratory
Golden Colorado USA

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Motivation

Observations of higher rates of degradation due to series resistance increases in hotter climates

Climatic Zone	Pmax(%/year)	Isc(%/year)	Voc(%/year)	FF(%/year)
Hot and Humid	1.29	0.98	-0.34	0.89
Temperate	0.24	-0.34	0.04	0.46
Composite	0.56	0.45	-0.17	0.64
Hot and Dry	1.55	0.78	0.20	0.51
Cold and Dry	0.19	0.72	-0.11	0.21

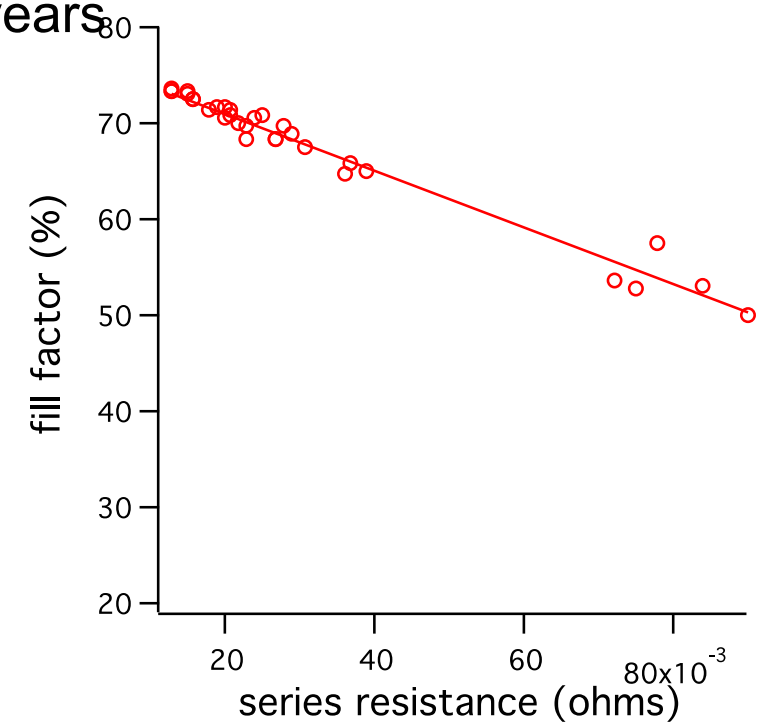
All-India Survey of Photovoltaic Module Degradation: 2013

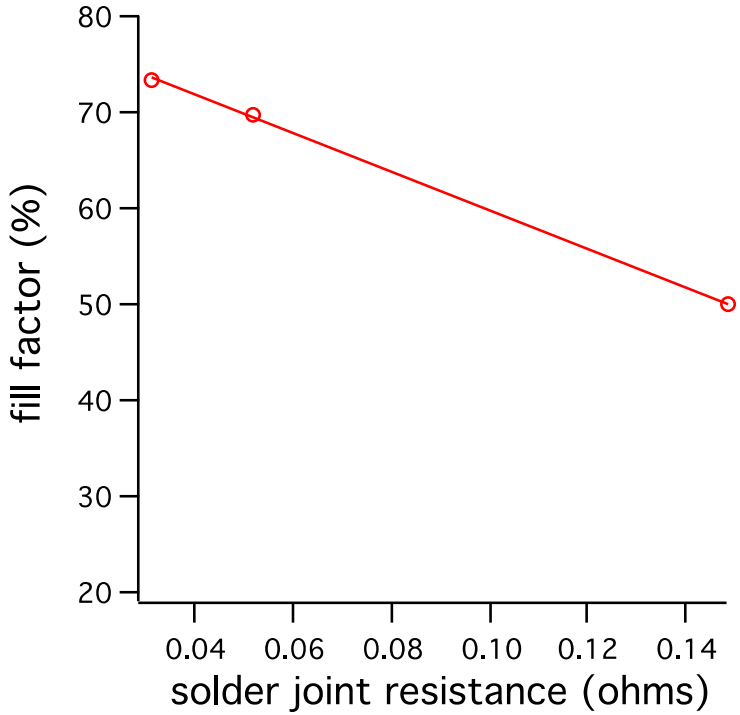
Rajiv Dubey, Shashwata Chattopadhyay, Vivek Kuthanazhi,
Jim Joseph John, B. M. Arora, Anil Kottantharayil, K. L. Narasimhan, Chetan S. Solanki, Vaman Kuber and Juzer Vasi
National Centre for Photovoltaic Research and Education Indian Institute of Technology Bombay
Powai, Mumbai 400076, India
and
Arun Kumar and O. S. Sastry
Solar Energy Centre
National Institute of Solar Energy Gwalpahari, Gurgaon, Haryana 122003, India

motivation

Observations of higher rates of degradation due to series resistance increases in hotter climates

Individual cell level measurements on module deployed in Phoenix for 18 years

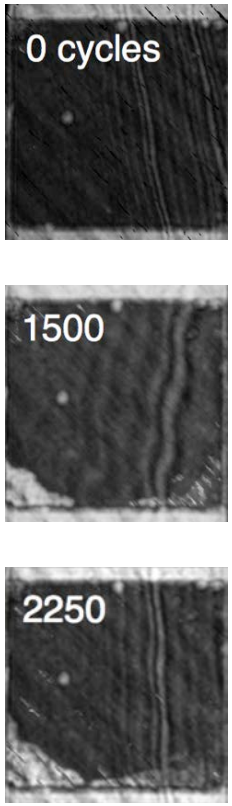


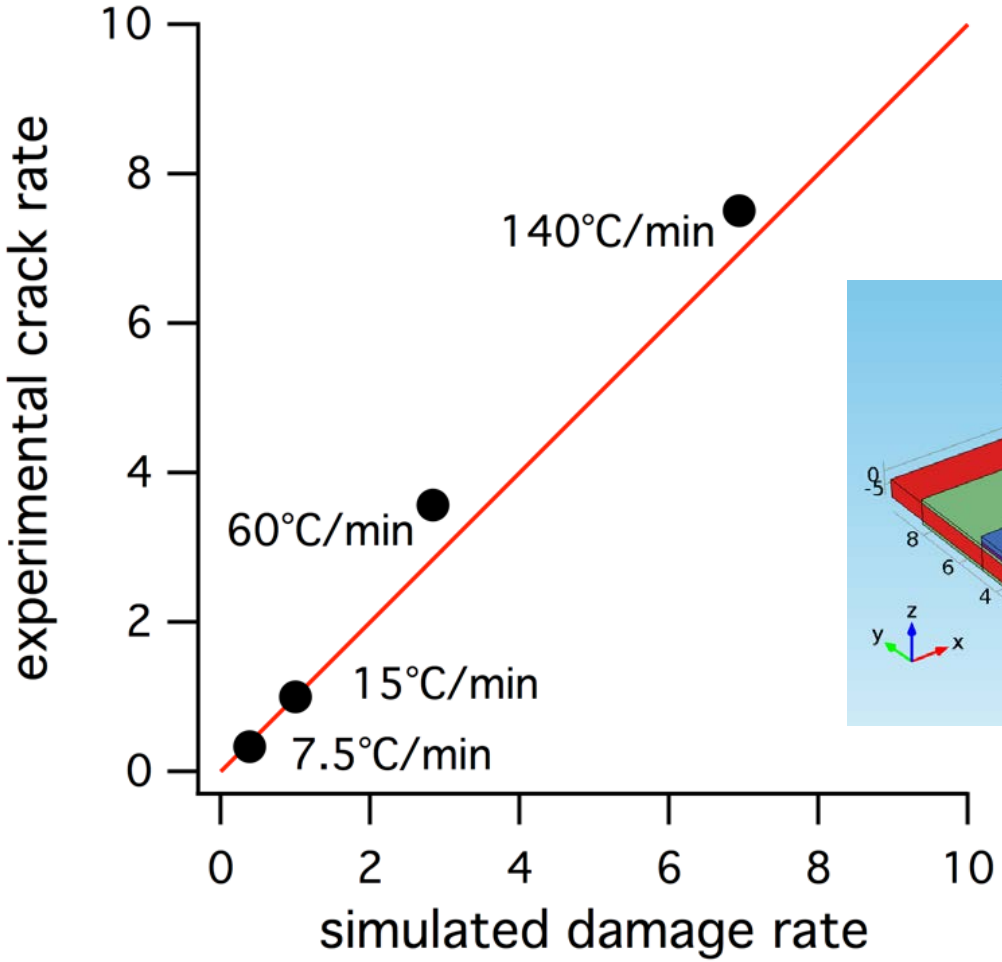


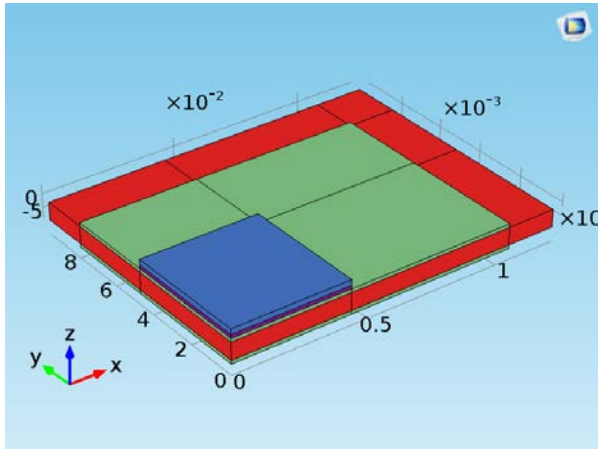
Data courtesy of:
Abhishiktha Tummala and Govindasamy Tamizhmani
Photovoltaic Reliability Laboratory
Arizona State University

Approach

FEM is in excellent agreement with thermal cycling experiments of PbSn solder bond fatigue.

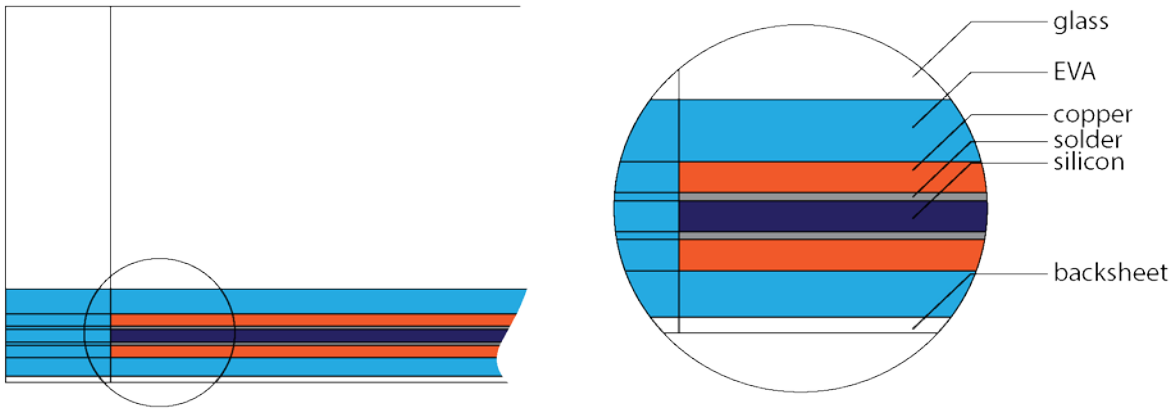






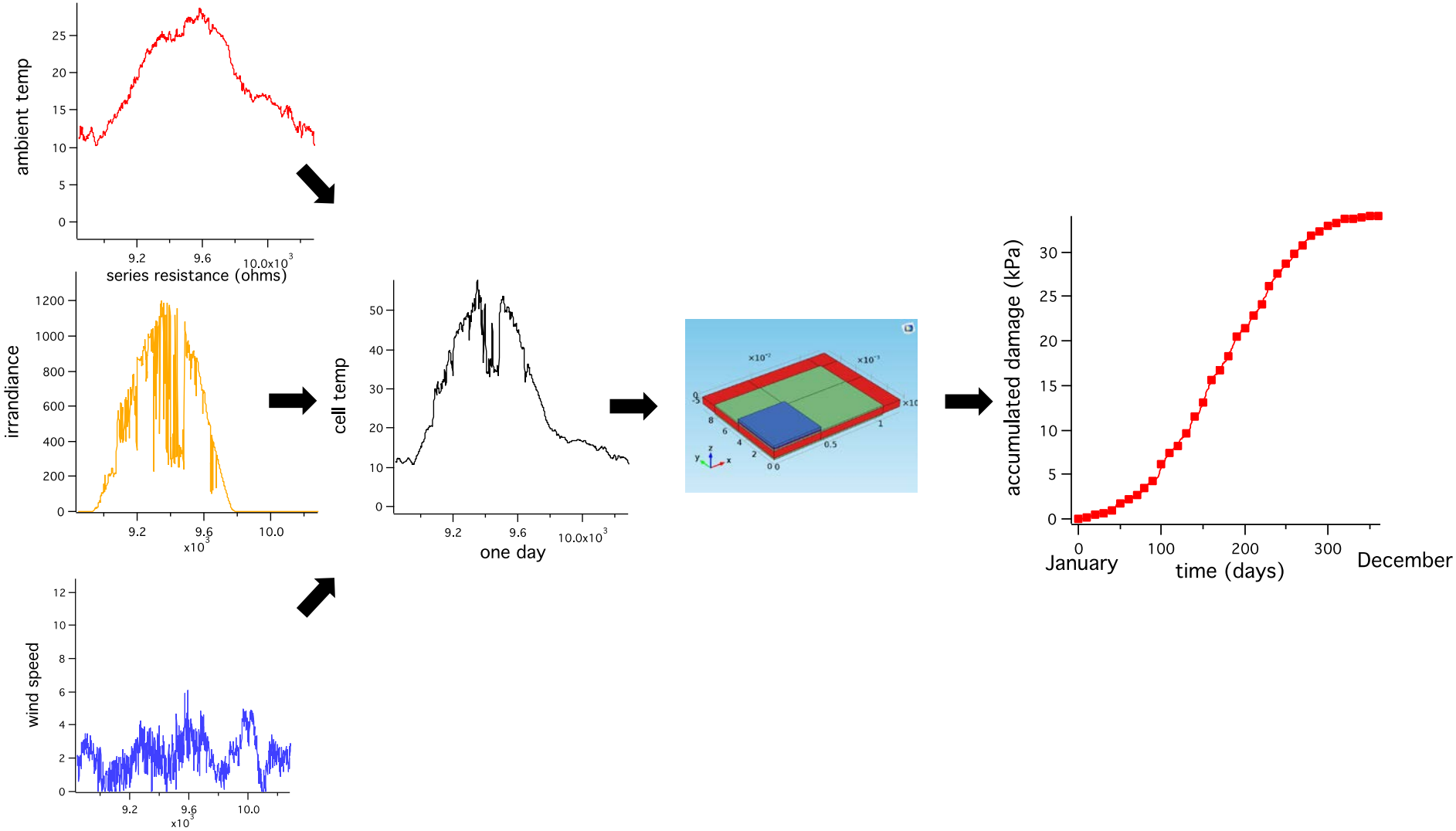
FEM

2D FEM of PbSn solder joint for flat plate PV module.



Approach

Flow of weather data through to accumulated solder damage



Cities

Seven cities examined

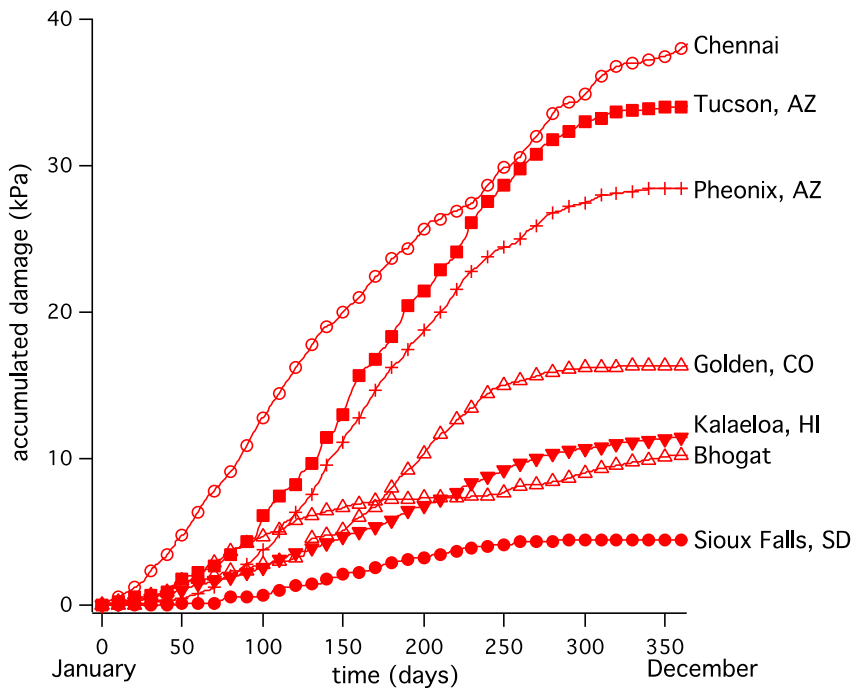
city	climate	mean monthly max temp (C)
Phoenix	Hot and Dry	38
Chennai	Hot and Humid	37
Tucson	Hot and Dry	36
Bhogat	Hot and Humid	35
Kalaeloa	Hot and Humid	31
Golden	Temperate	27
Sioux Falls	Cold	23

Definition of climates

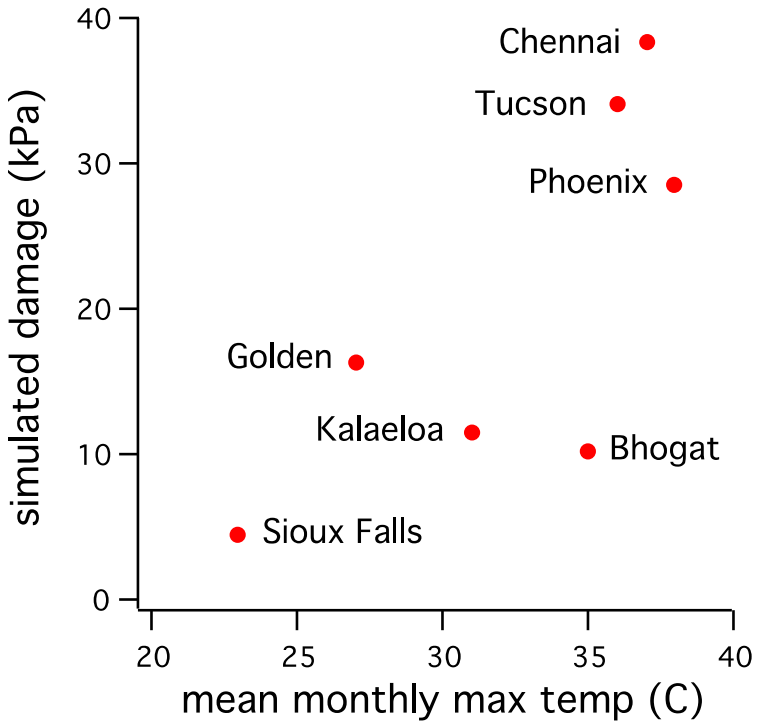
climate	mean monthly max temp (C)	mean relative humidity (%)
hot and Dry	>30	<55
hot and humid	>30 >25	>55 >75
temperate	25-30	<75
cold	<25	All values
composite	when 6 months or more do not fall within any of the above categories	

Results

Accumulated solder fatigue damage



FEM simulation of solder damage accumulation over one year's exposure



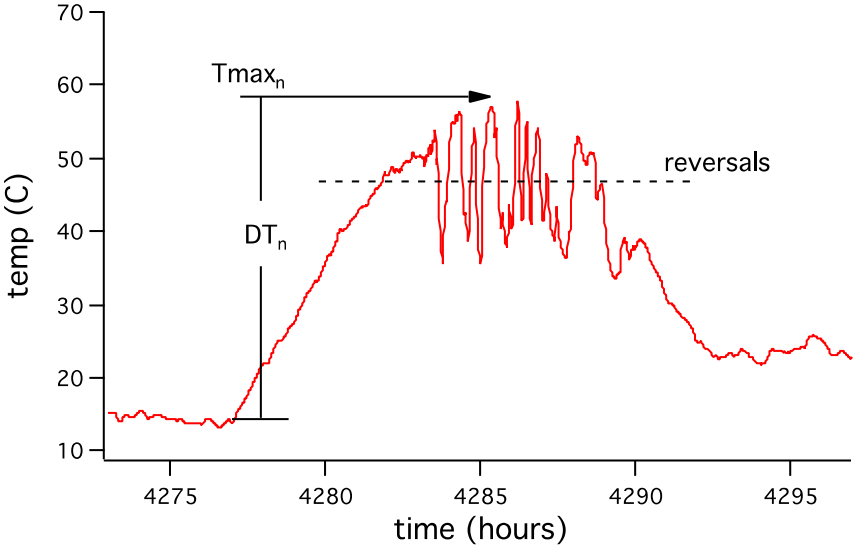
Comparison of solder damage with mean monthly max temp

Analysis

We wanted to create a simple equation that could predict the FEM calculated damage.

This equation also gives us an insight about which weather characteristics contribute to solder fatigue damage.

$$D = K \cdot rev(T_m)^a \cdot DT^n \cdot \exp\left(\frac{E_a}{kT_{\max}}\right)$$



city	T_{max}, mean daily max cell temp (C)	ΔT, mean daily max cell temp change (C)	$r(57)$, number of temp reversals across 57 ˚C
Chennai	59	35.5	2228
Phoenix	53.4	34.7	1264
Tucson	53.2	37	1474
Kalaeloa	51.2	30.7	142
Bhogat	49.7	27.9	174
Golden	37.6	33.4	466
Sioux Falls	25.8	23.5	0

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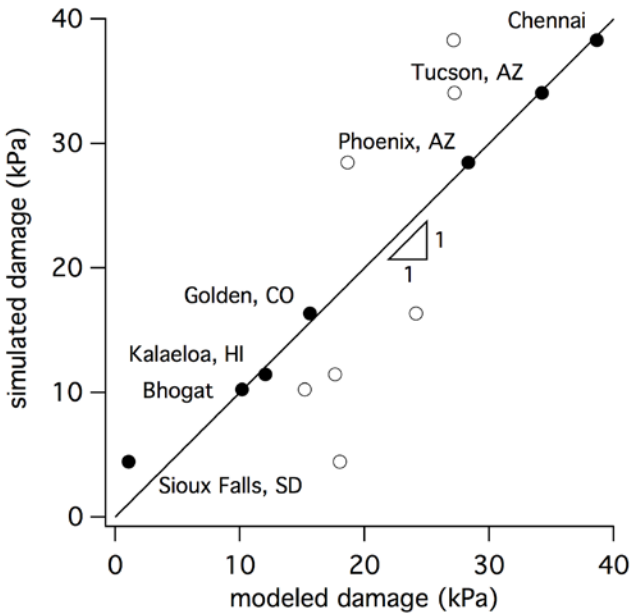

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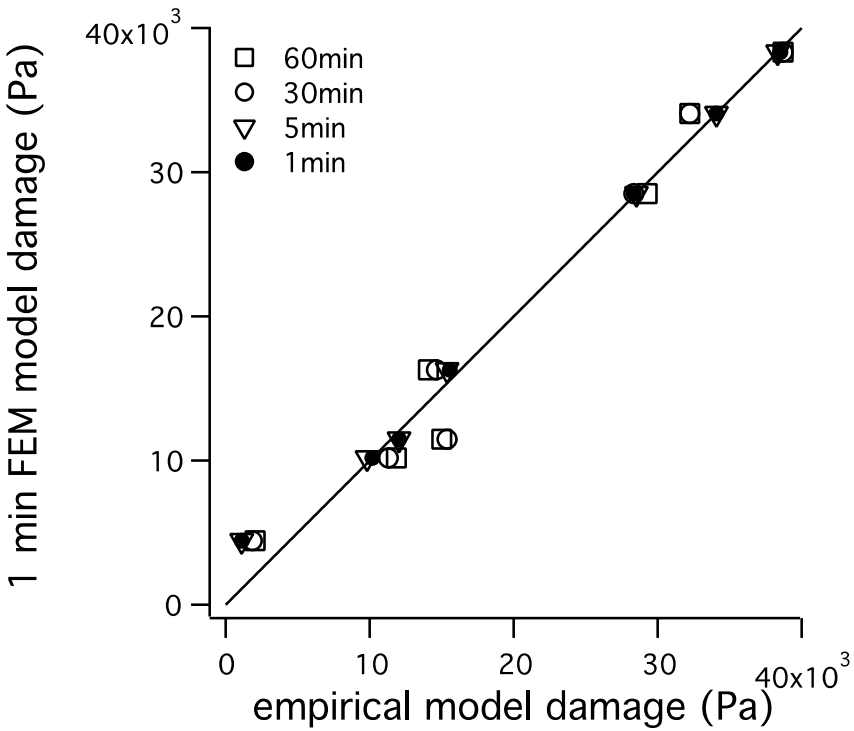
Sioux Falls	25.8	23.5	0

Analysis

- Weather data down to 30 minute resolution is still acceptable for empirical model input.

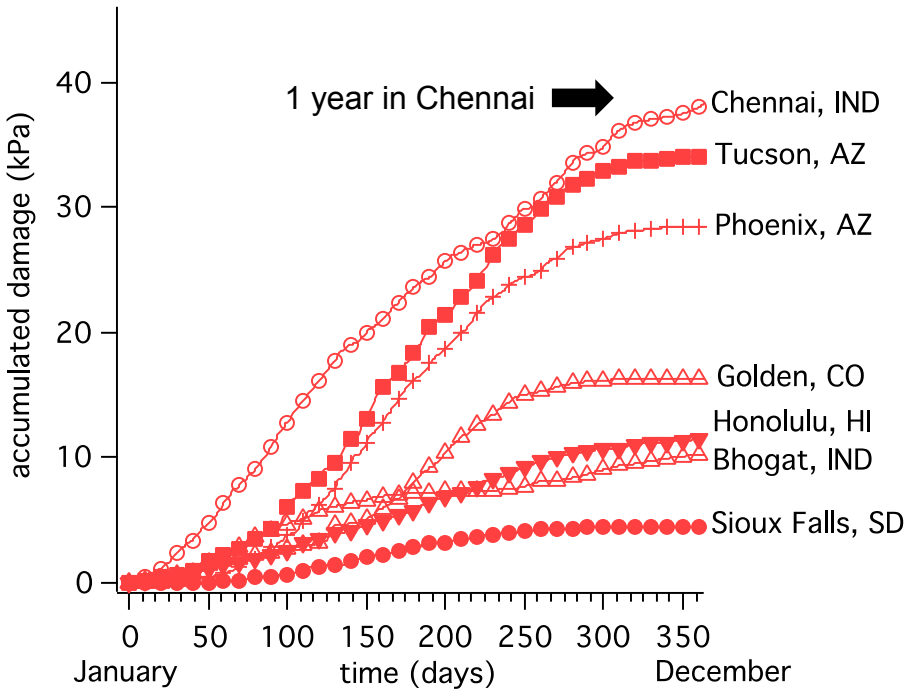


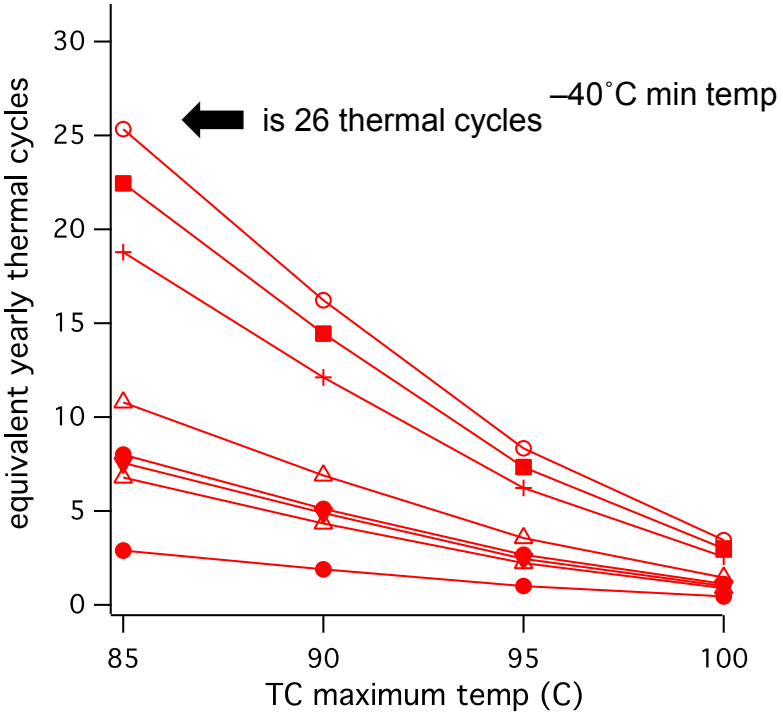
$$D = K \cdot rev(T_m)^a \cdot DT^n \cdot \exp\left(\frac{E_a}{kT_{\max}}\right)$$

interval (min)	K	T_m (C)	E_a (eV)	a	n
1	239.9	56.4	0.12	0.33	1.9
5	249.9	56.9	“	“	“
30	344.1	55.8	“	“	“
60	405.6	54.8	“	“	“

Analysis

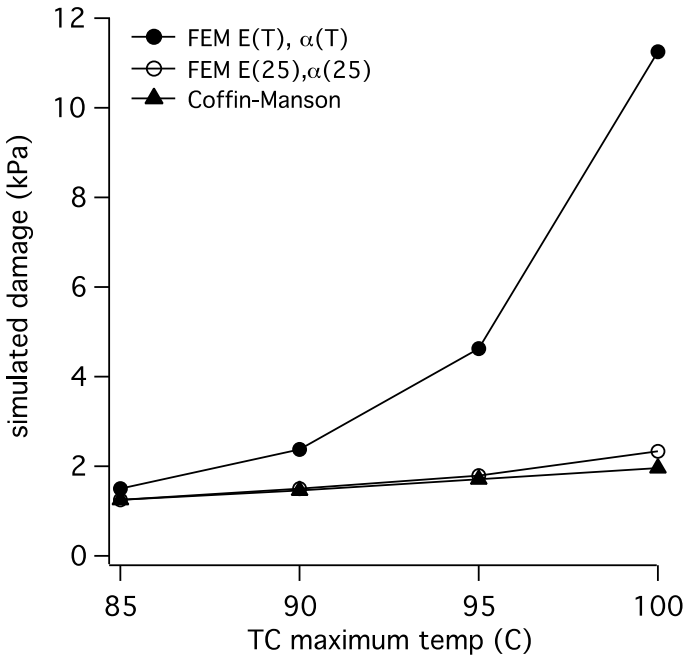
Thermal cycle equivalency to service conditions

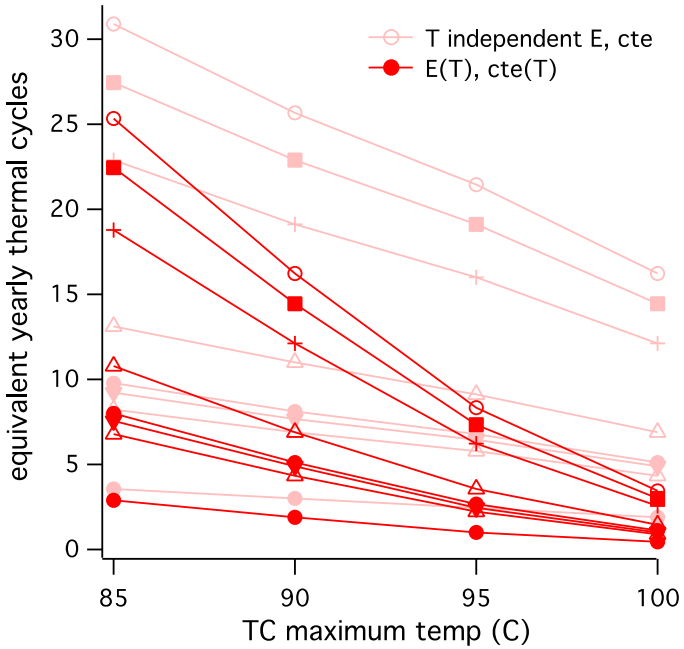




Analysis

Effect of encapsulant

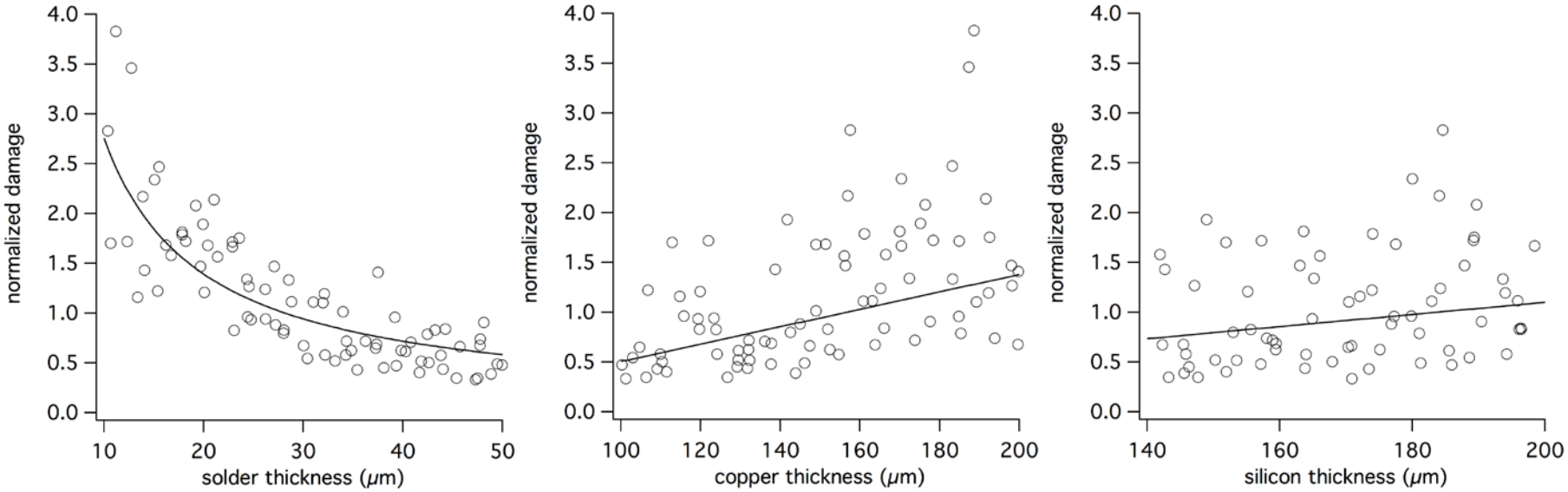




Analysis

The Influence of PV Module Materials and Design on Solder Joint Thermal Fatigue

Bosco, N., Silverman, T., Kurtz, S., Submitted to the Journal of Photovoltaics

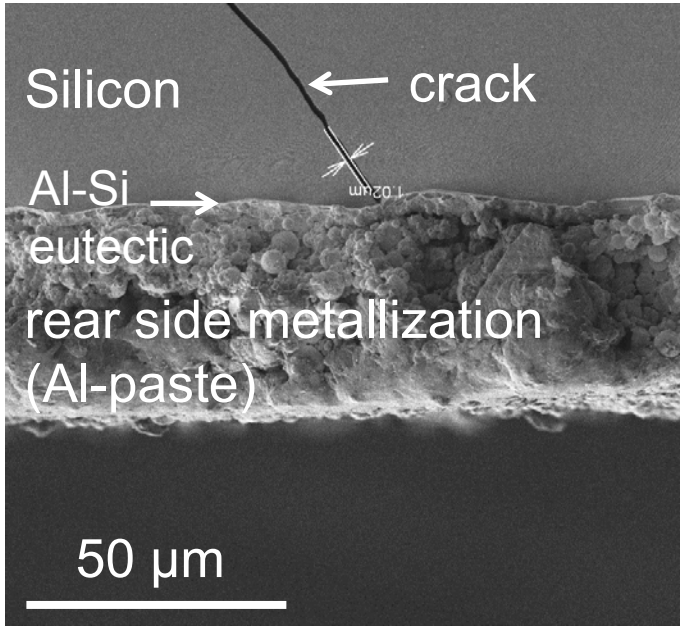


Conclusions

- Solder fatigue does accumulate faster in hotter climates.
- BUT, we must also know the daily temperature change and number of “reversals”.
- Climate zone alone does not tell the entire story.
- The developed empirical model should be used to compare the relative potential for solder fatigue damage in specific locations.

Acknowledgment

This research is based upon work supported in part under the Solar Energy Research Institute for India and the U.S. (SERIIUS) funded jointly by the U.S. Department of Energy subcontract DE AC36-08G028308 (Office of Science, Office of Basic Energy Sciences, and Energy Efficiency and Renewable Energy, Solar Energy Technology Program, with support from International Affairs) and the Government of India subcontract IUSSTF/JCERDC-SERIIUS/2012 dated 22nd Nov. 2012.

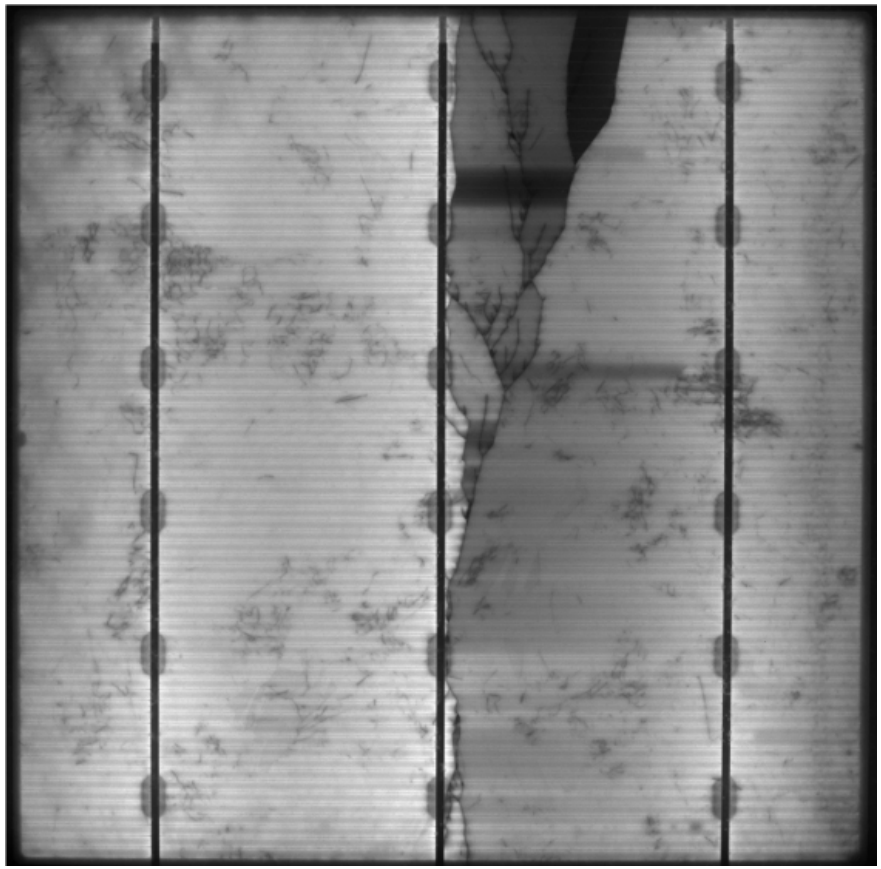


Properties of Cracks in Solar Cells and Their Impact on Long Term Module Power

F. Haase, J. Käsewieter, A. Morlier, M. Köntges

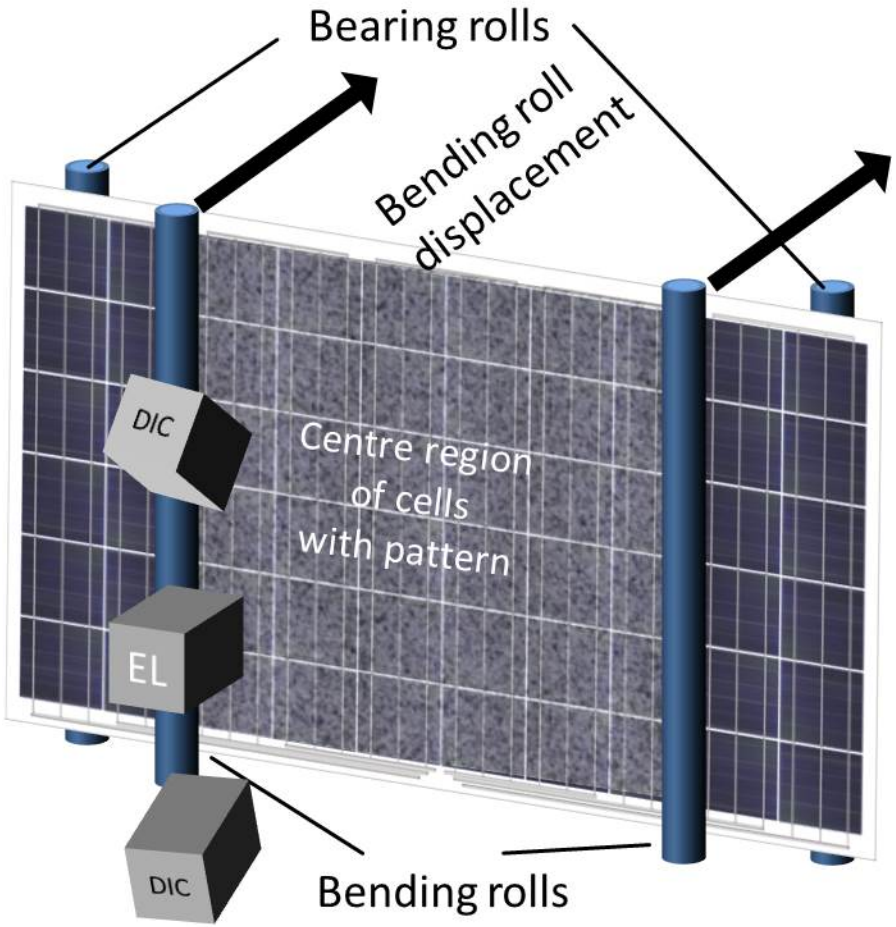
Institute for Solar Energy Research Hamelin (ISFH)

Motivation



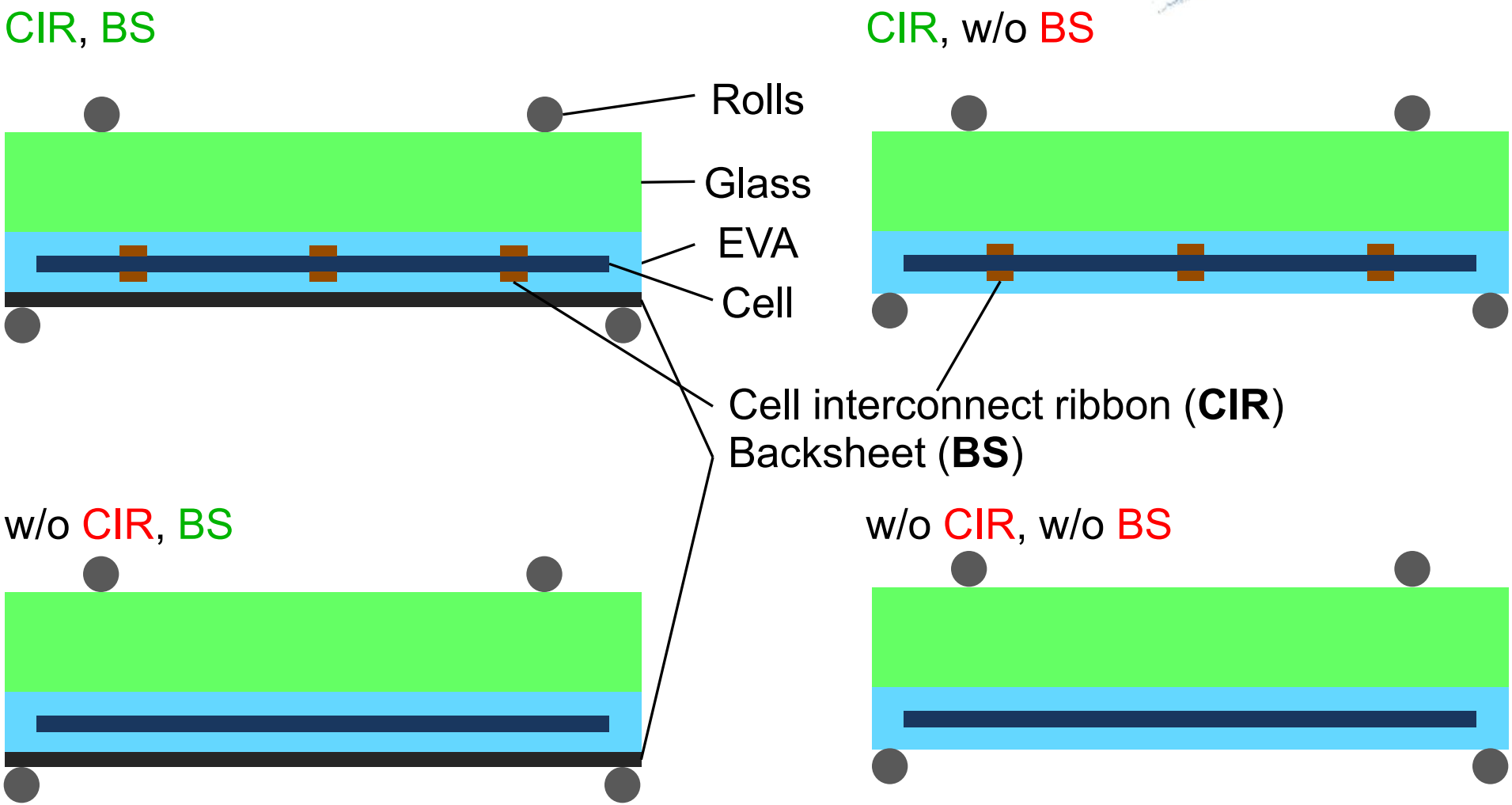
- Which parameter dominates the crack probability and pattern?
- Which parameter influences the crack width?
- Which are the mechanisms increasing the crack resistance?
- What is the impact of the cracks on the module power?

Crack positions and widths under mechanical load

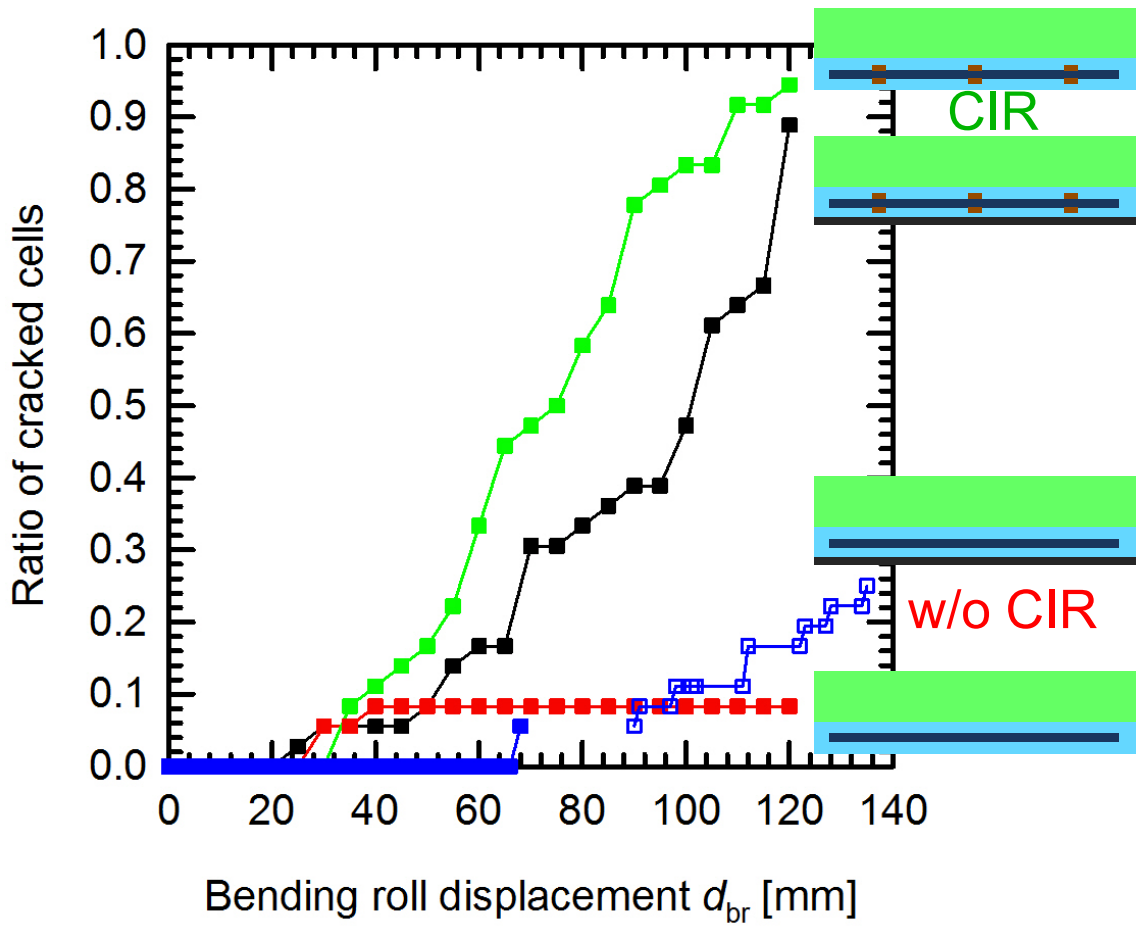


- 4-line bending test of full size laminates (60 cells)
- Homogeneous uniaxial load
- Electroluminescence for crack detection
- Digital image correlation for cell movement in the laminate

Impact of backsheet and cell interconnect ribbon on cell cracks

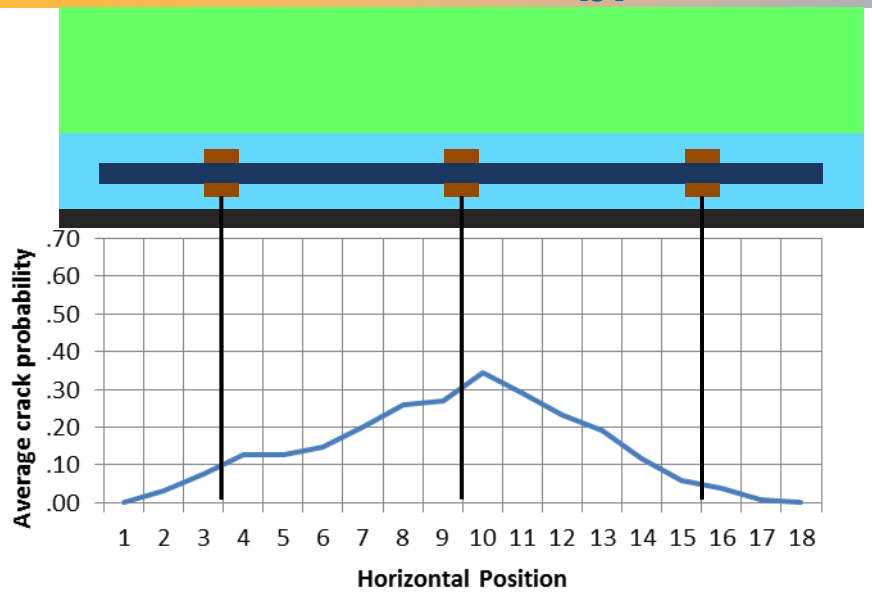


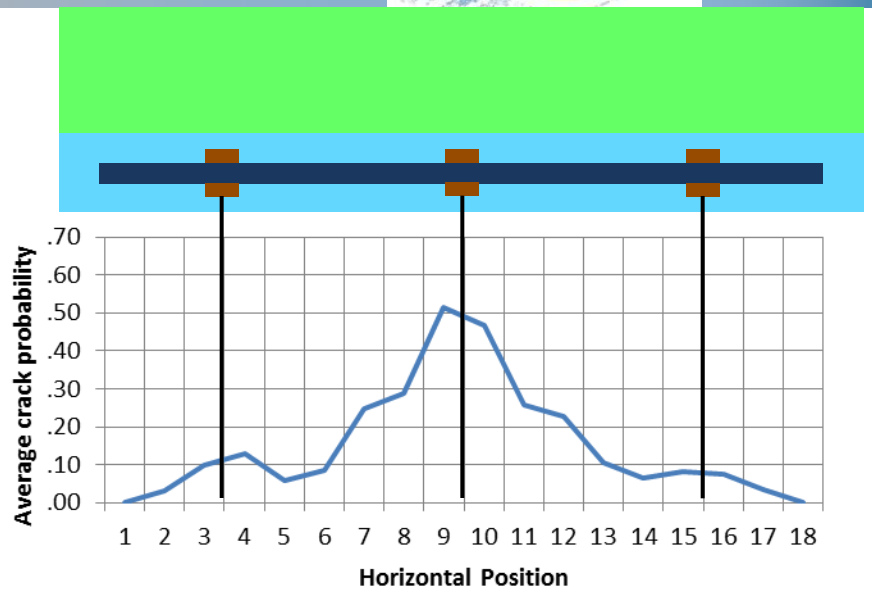
Cumulative crack probability

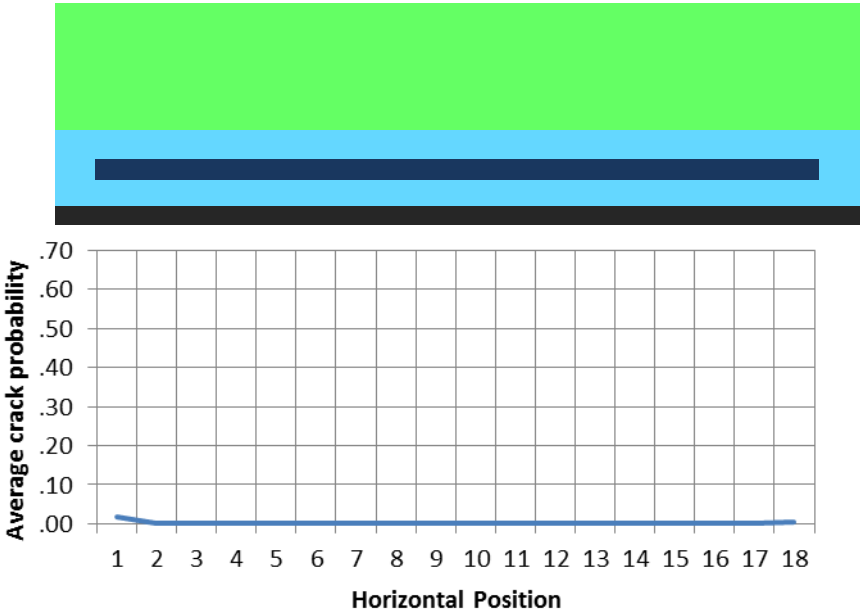


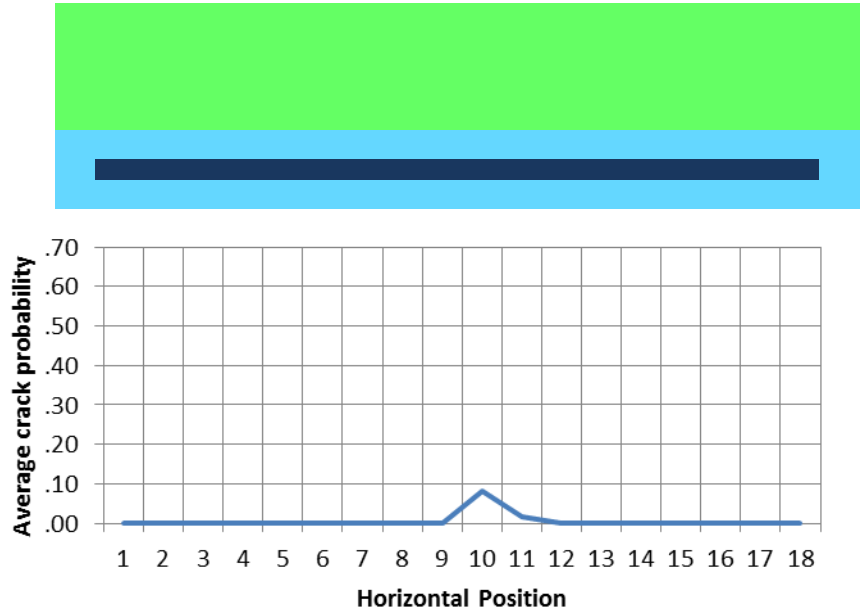
- Cell interconnect ribbons increase probability of cell cracks
- Backsheet small influence on probability of cell cracks

Local cumulative crack probability at d_{br} = 100mm









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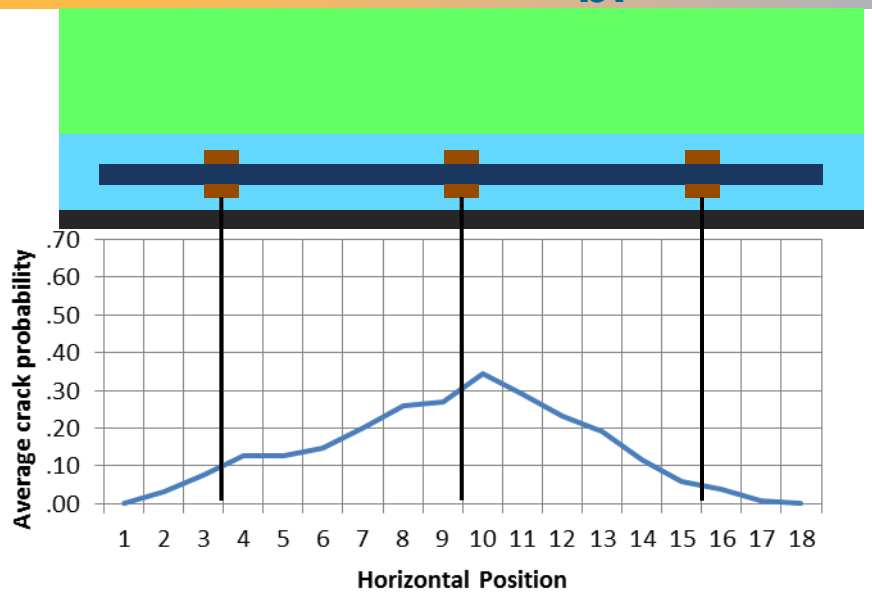
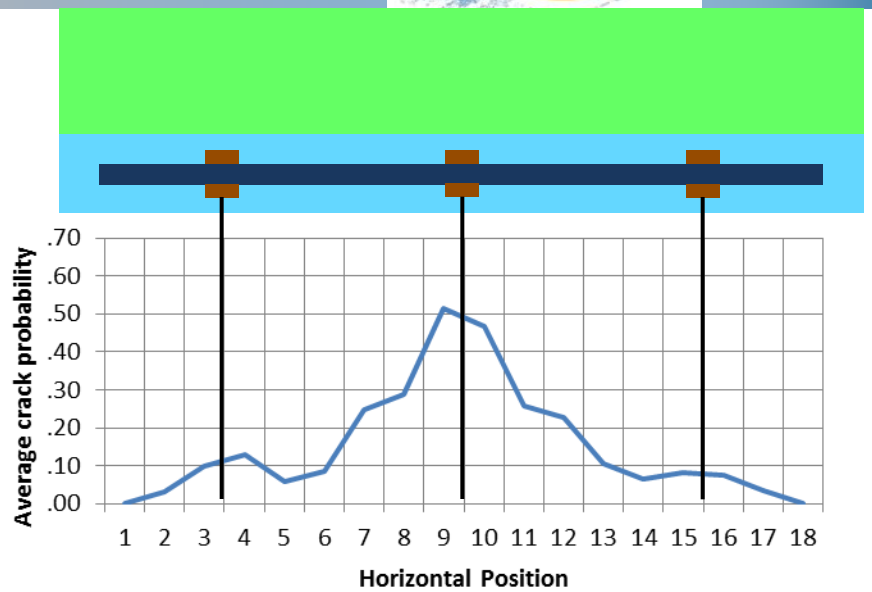
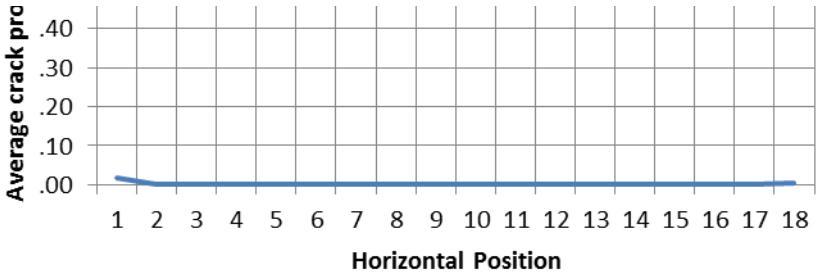
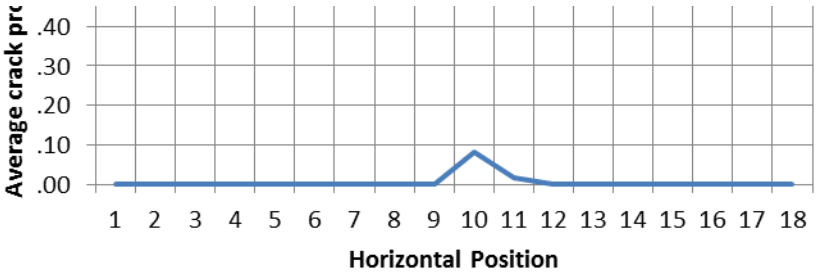




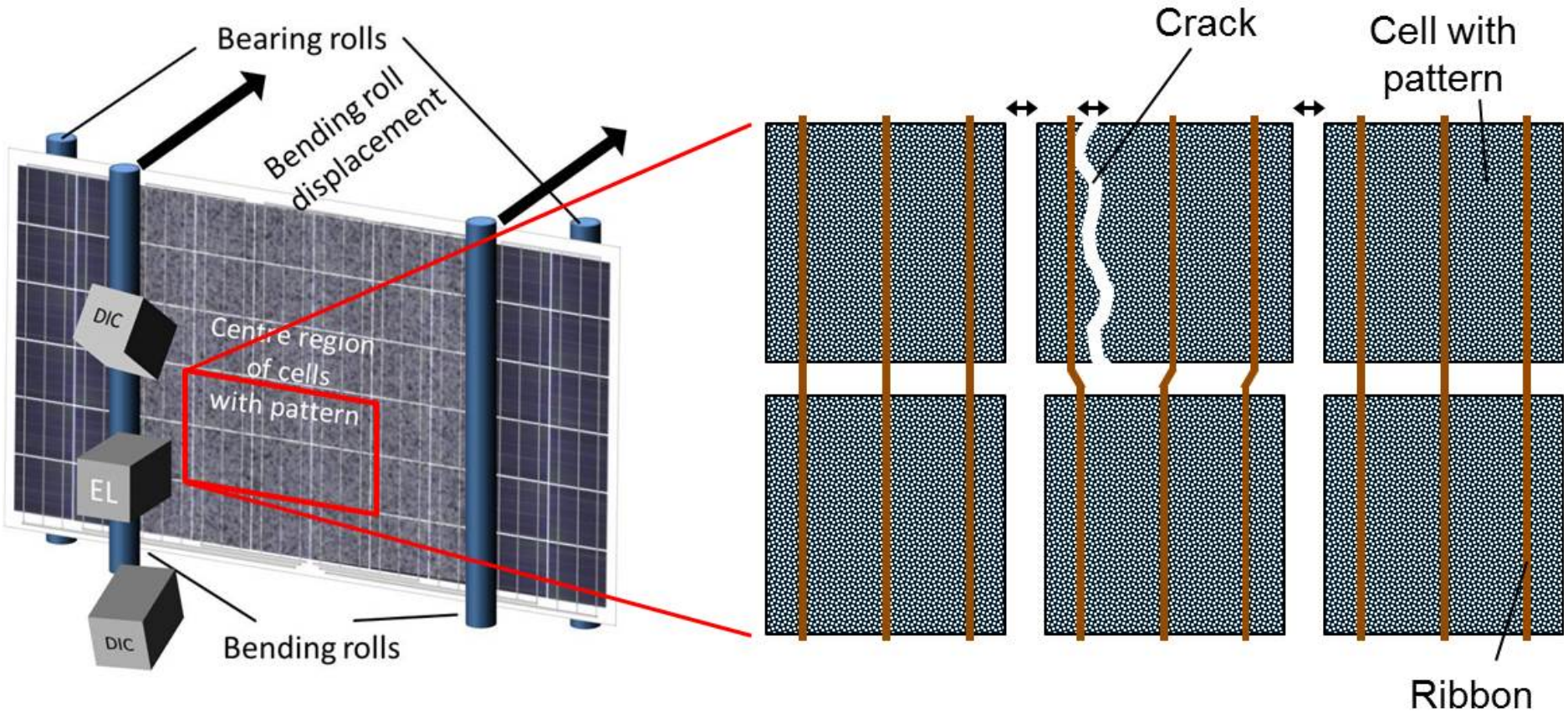
Which parameter influences the cracks?

- The probability is dominated by the cell interconnect ribbon
- The pattern is homogenized by the backsheet



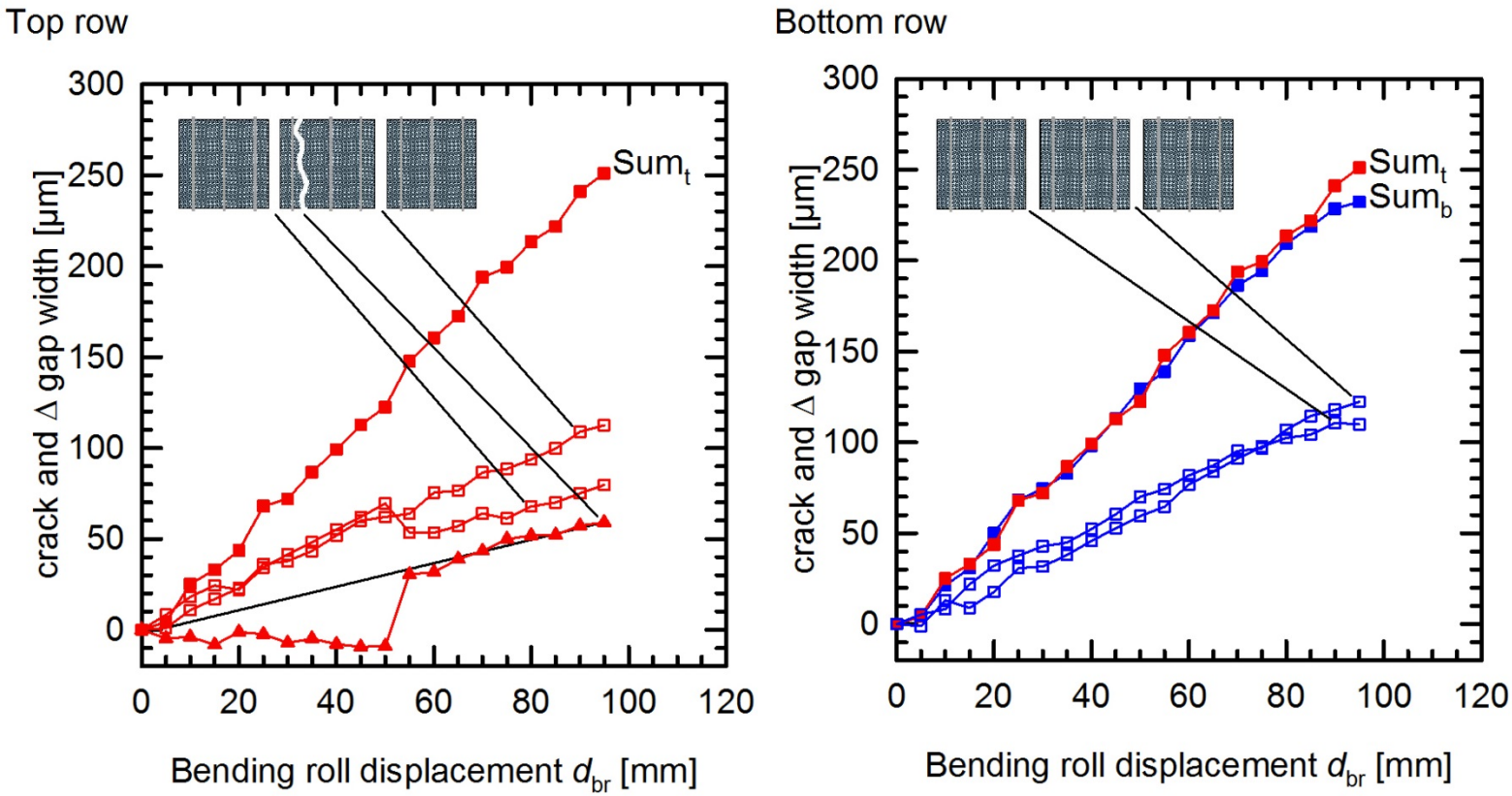


Gap and crack widths



- Measurement of cell movement during bending by digital image correlation
- Calculation of crack and gap widths based on movement of cells

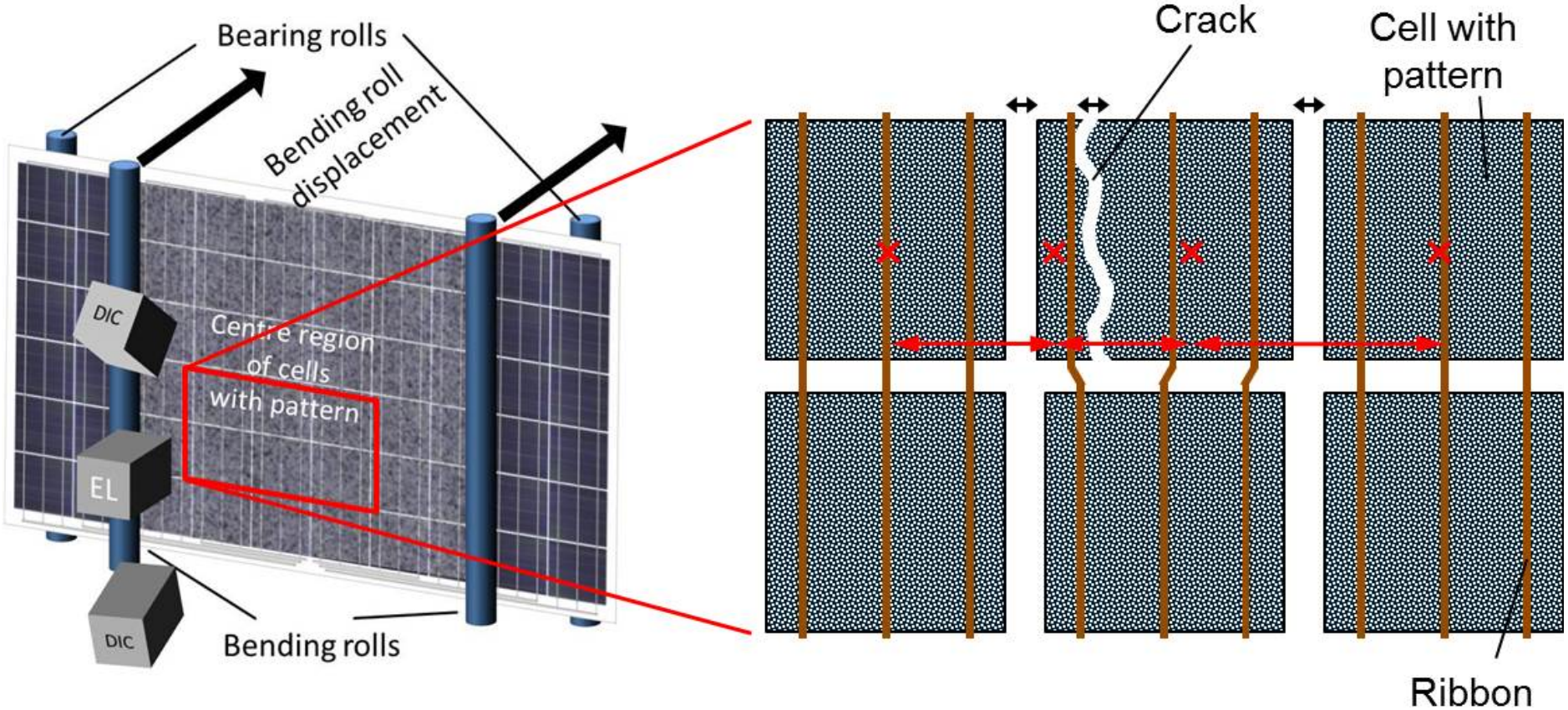
Measured gap and crack widths



- Linear increase of gap and crack widths with increasing displacement
- Abrupt opening of crack after cell breakage
- Sum of crack and gap widths is independent on cell cracks

F. Haase, J. Käsewieter and M. Köntges, "Understanding the movement of cracked solar cell parts in PV modules during mechanical loading", to be presented at Silicon PV 2016

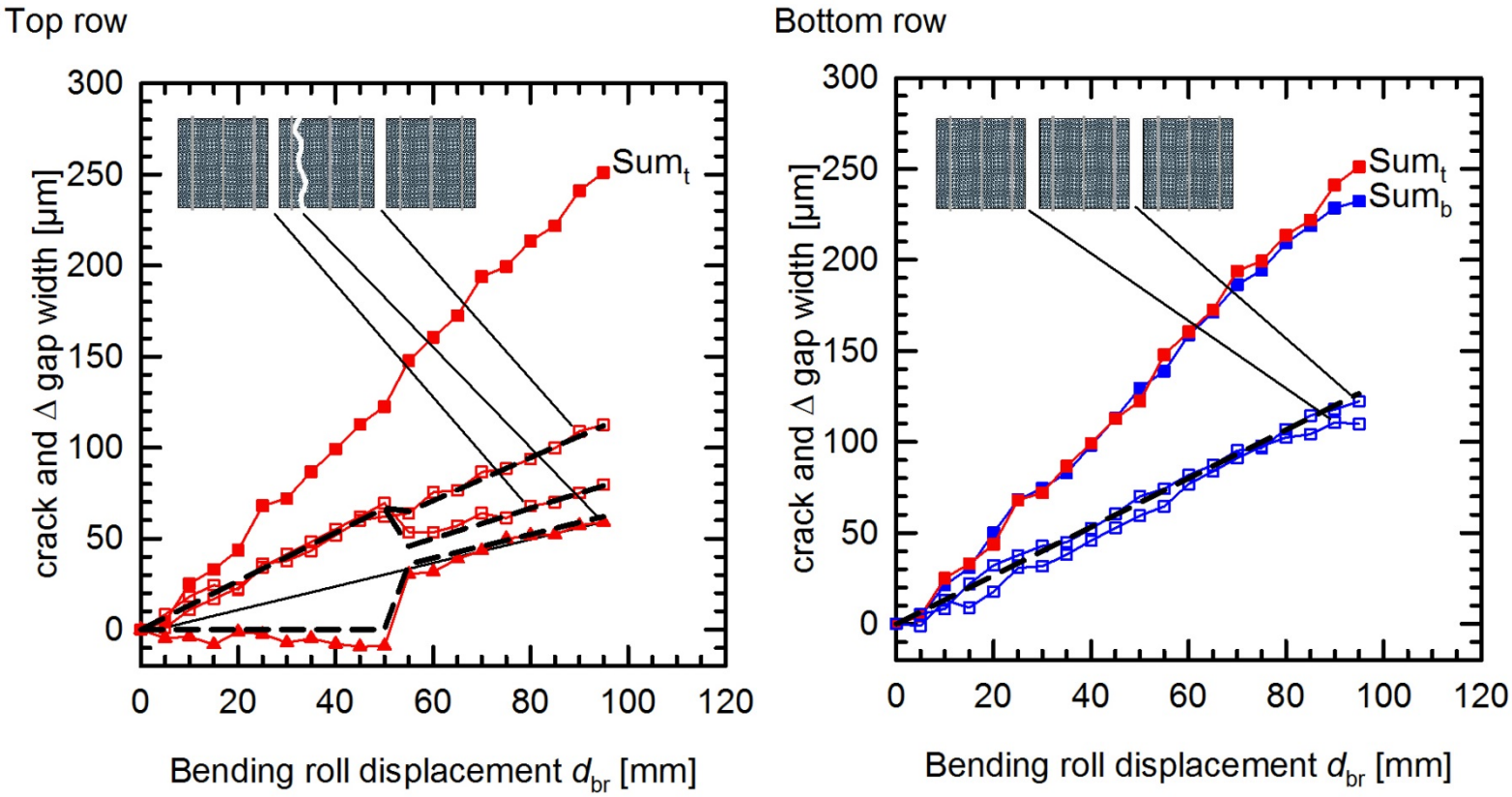
Model for cell movement



- Assumption: centers of mass (red crosses) of cells and cell parts are fixed to laminate glass during bending

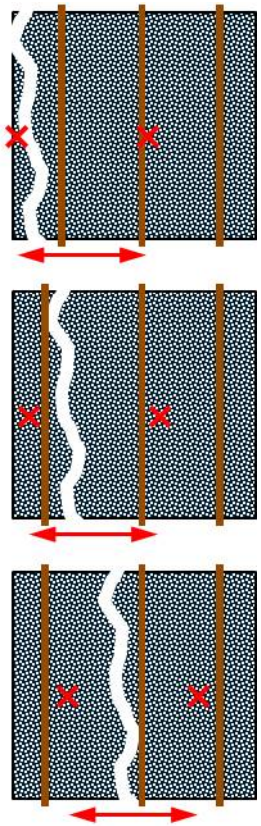
F. Haase, J. Käsewieter and M. Köntges, “Understanding the movement of cracked solar cell parts in PV modules during mechanical loading”, to be presented at Silicon PV 2016

Verification of model



- Calculated (dashed lines) and measured values of crack and gap widths at in agreement within max. 12 µm

Consequences of model



- Single crack width is independent on crack position since distance of center of masses is always half of cell width

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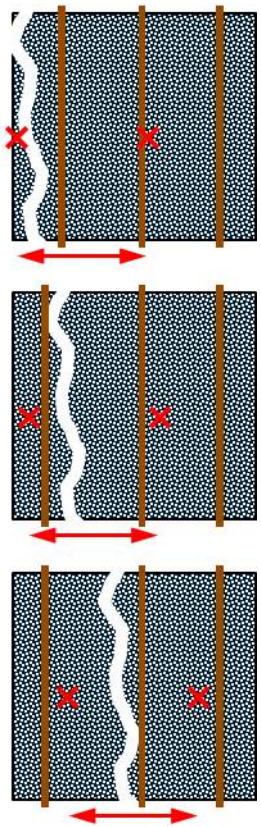
Consequences of model

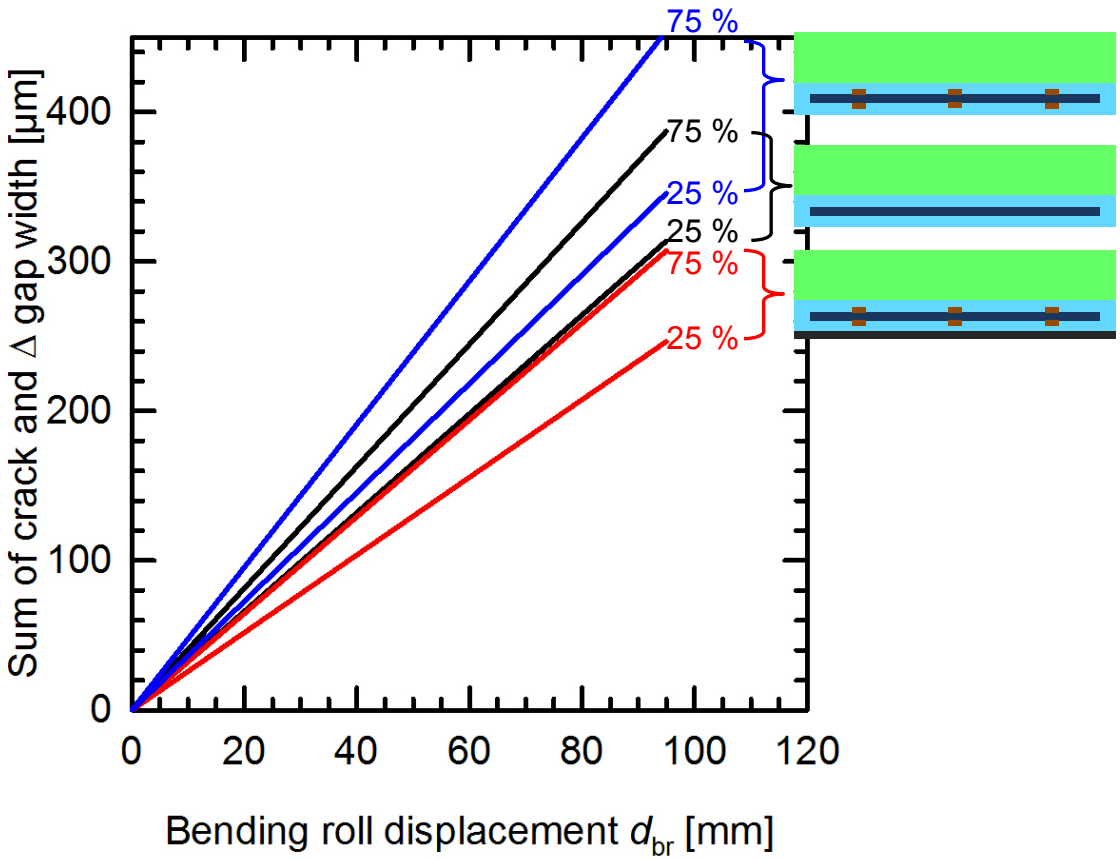


- Single crack width is independent on crack position since distance of center of masses is always half of cell width

- Multiple cracks cause smaller crack and gap widths since the sum is distributed over more cracks

F. Haase, J. Käsewieter and M. Köntges, “Understanding the movement of cracked solar cell parts in PV modules during mechanical loading”, to be presented at Silicon PV 2016

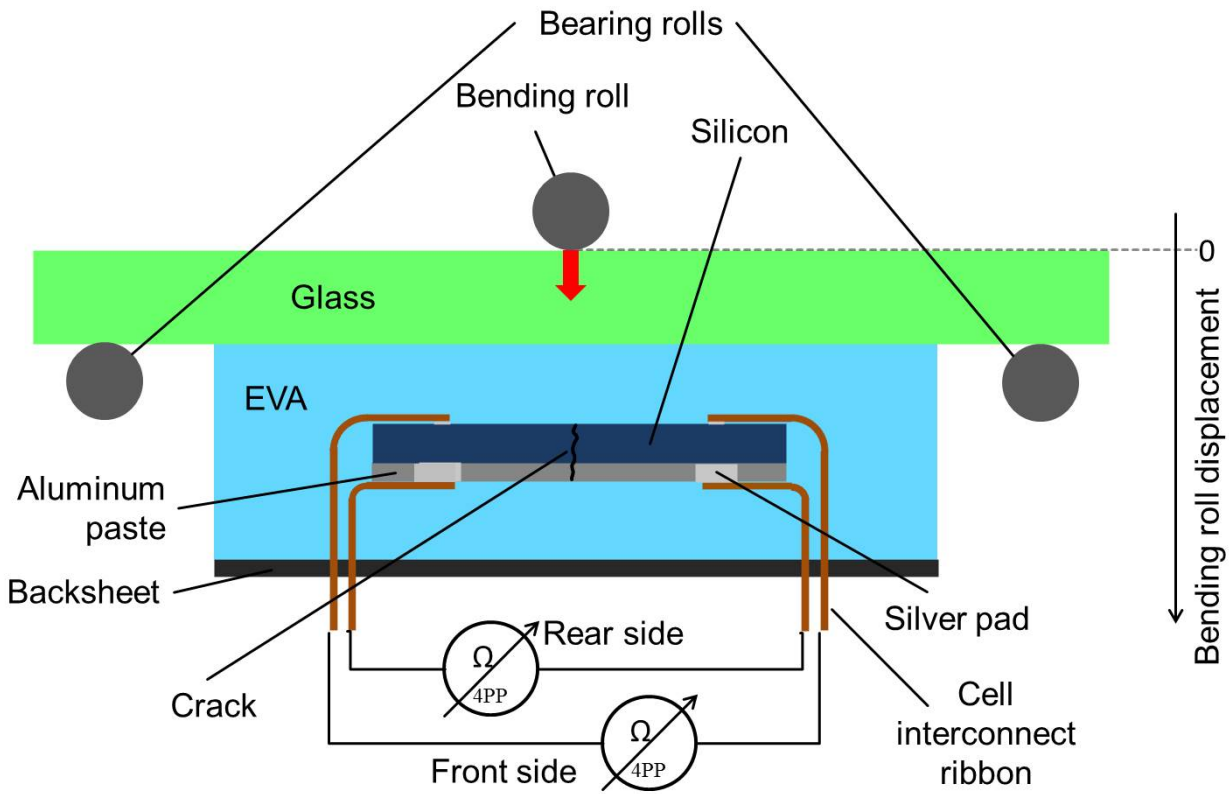
Dependence of BS on crack and gap widths



Which parameter influences the crack width?

- 9 to 16 measurements per laminate type
- Laminates without BS show higher change in crack and gap opening
- BS counteracts against the drifting apart of cell parts
- CIR has small influence

Resistance measurement setup



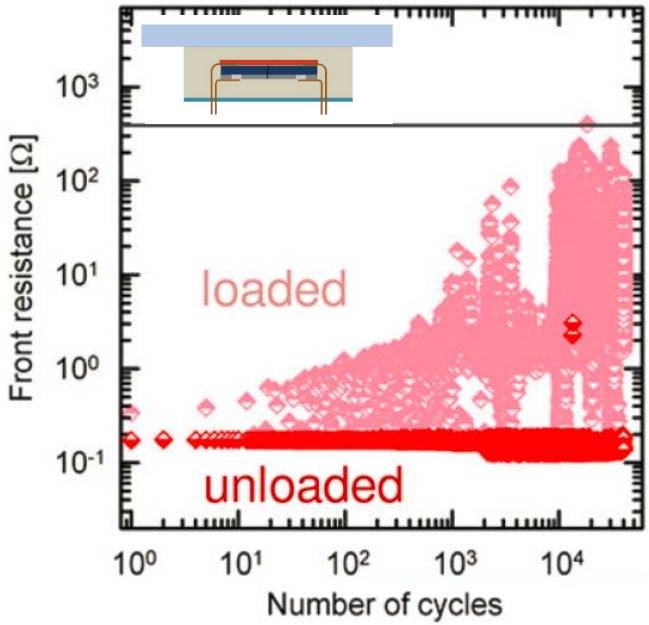
Resistance measurement

- during loading
- of front and rear side separately
- across cracked metallization

J. Käsewieter, F. Haase, and M. Köntges, “Model of cracked Solar Cell Metallization leading to permanent Module Power Loss”, IEEE Journal of Photovoltaics, vol.6, no.1, pp. 28-33, Jan. 2016, DOI: 10.1109/JPHOTOV.2015.2487829

Leibniz Universität Hannover

Front side resistance



- No fatigue of unloaded front side metallization

J. Käsewieter, F. Haase, and M. Köntges, “Model of cracked Solar Cell Metallization leading to permanent Module Power Loss”, IEEE Journal of Photovoltaics, vol.6, no.1, pp. 28-33, Jan. 2016, DOI: 10.1109/JPHOTOV.2015.2487829

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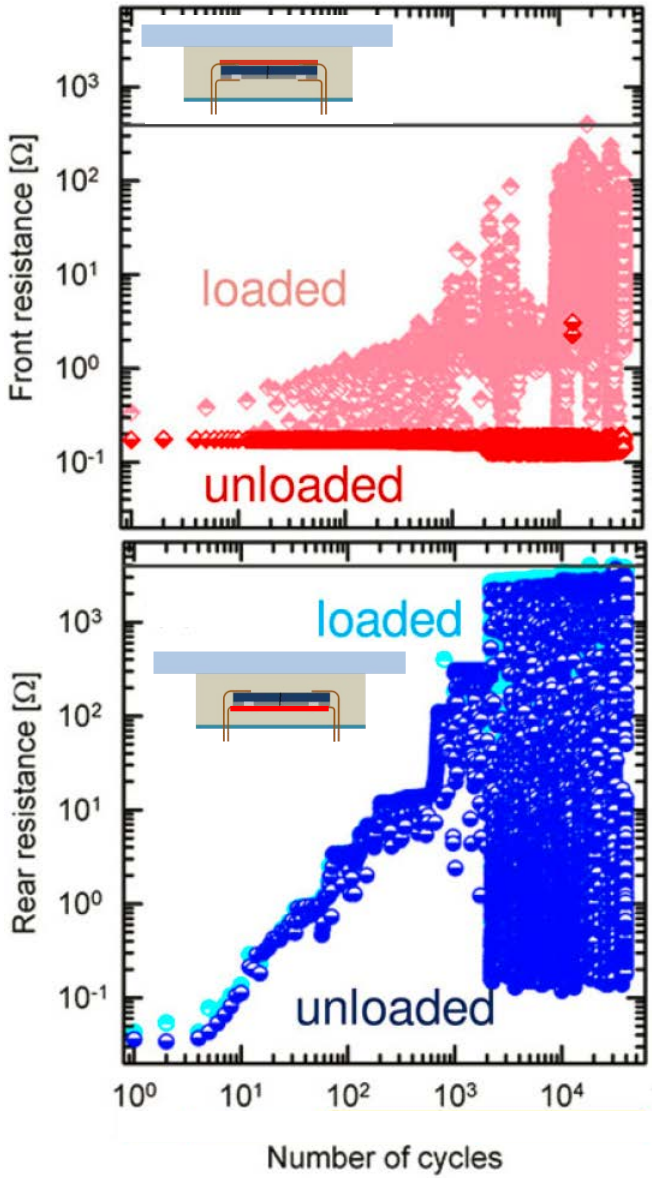
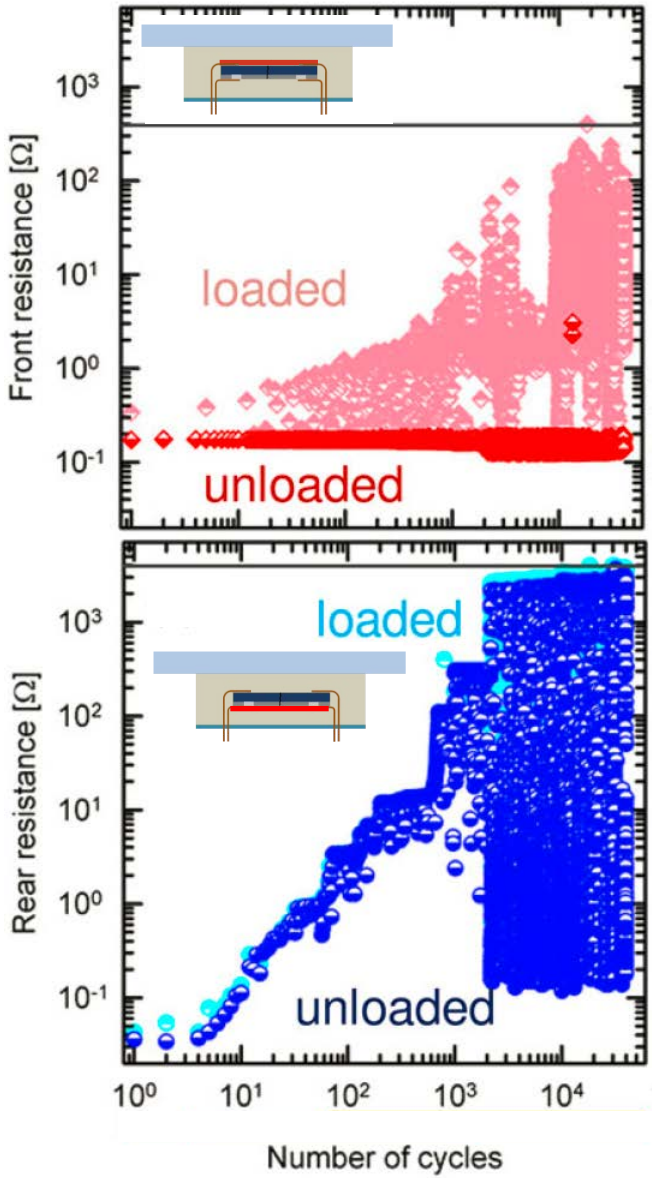
Rear side resistance



- No fatigue of unloaded front side metallization
- Fatigue of unloaded rear side metallization

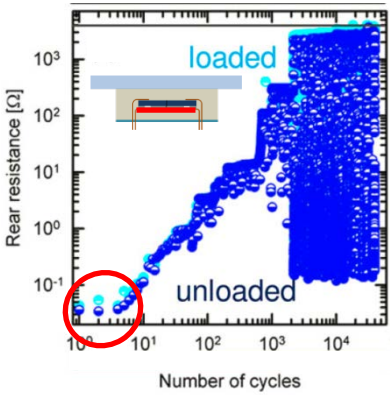
Rear side resistance



- No fatigue of unloaded front side metallization
- Fatigue of unloaded rear side metallization
- Modules most of the time in unloaded condition

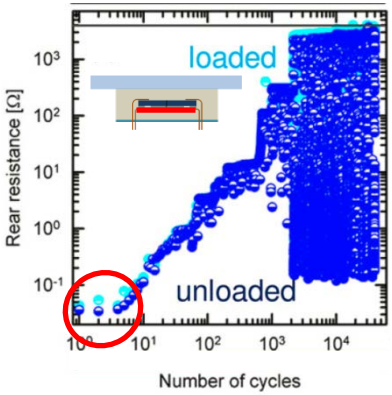
➡ Rear side dominates degradation

Fatigue state 1



- Silicon is broken
- Resistance increase during loading < 2

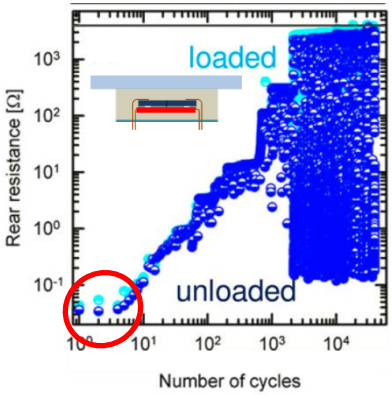
Fatigue state 1



- Silicon is broken
- Resistance increase during loading < 2
- Al-bridges mainly conduct the current

Visible in bottom view
by light microscope

Fatigue state 1



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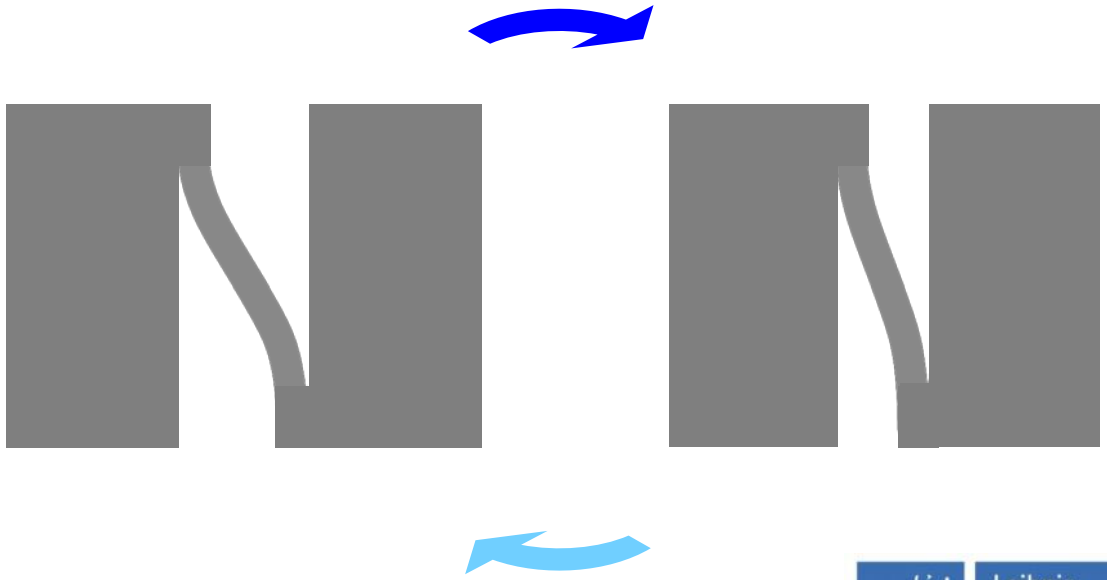

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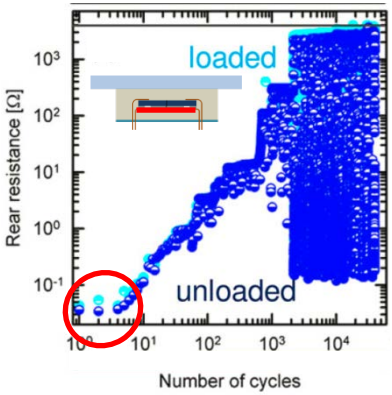
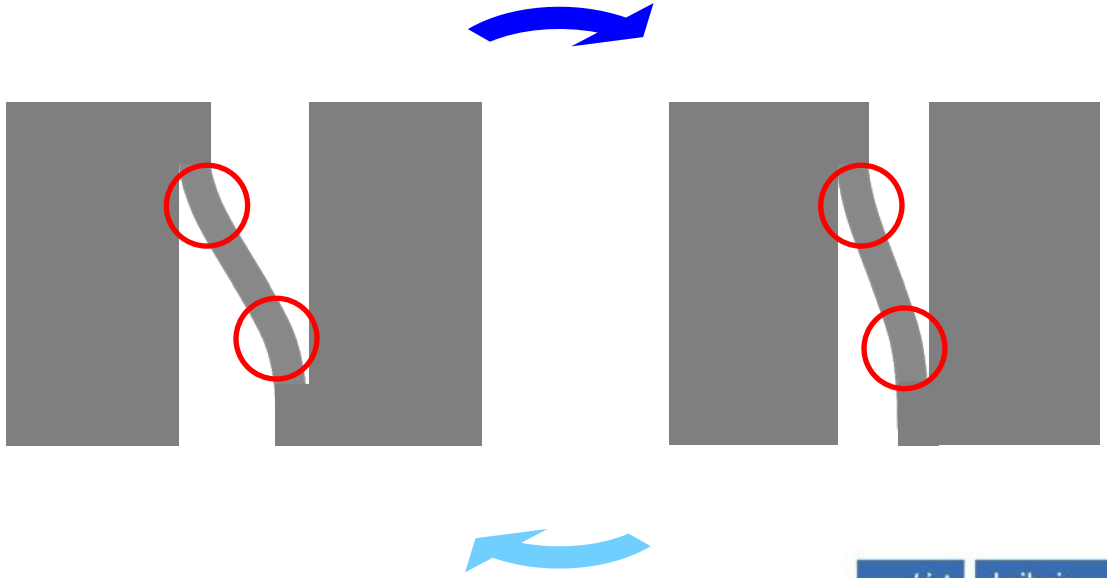
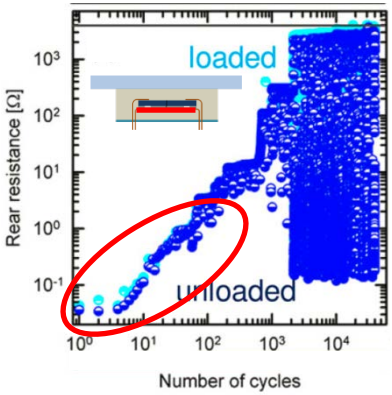


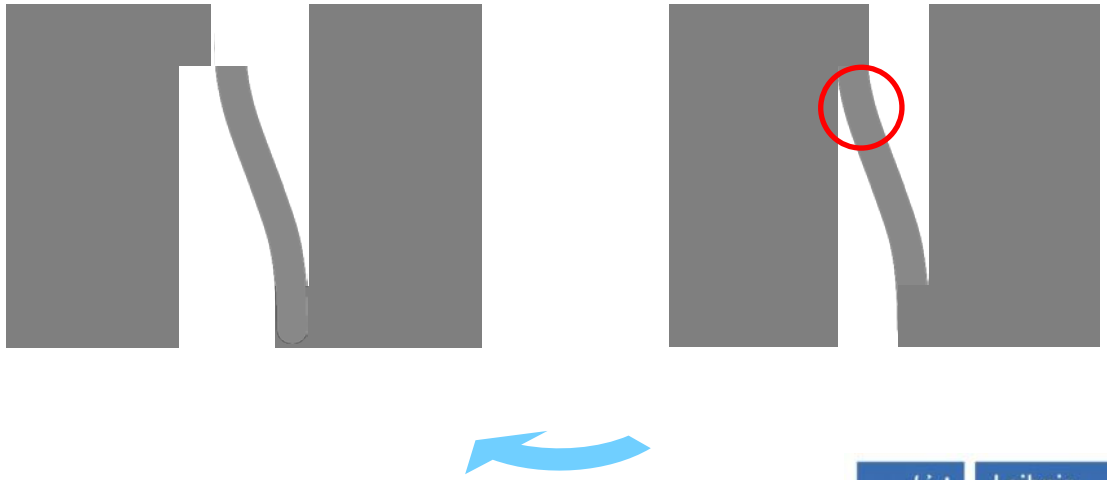
- Silicon is broken
- Resistance increase during loading < 2
- Al-bridges mainly conduct the current
- Deformation of Al-bridges during loading



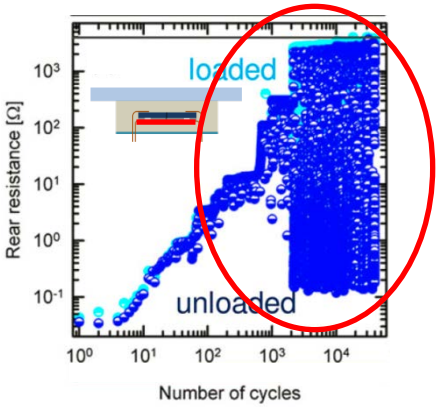
Fatigue state 2



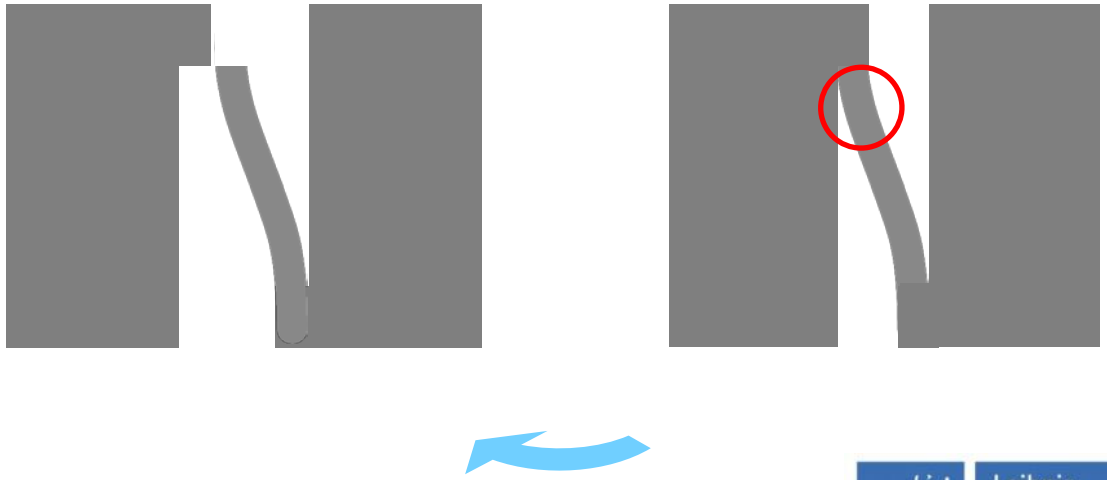
- Breakage of Al-bridges
- Resistance increases



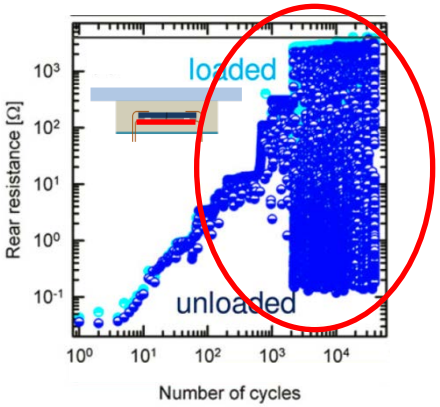
Fatigue state 3



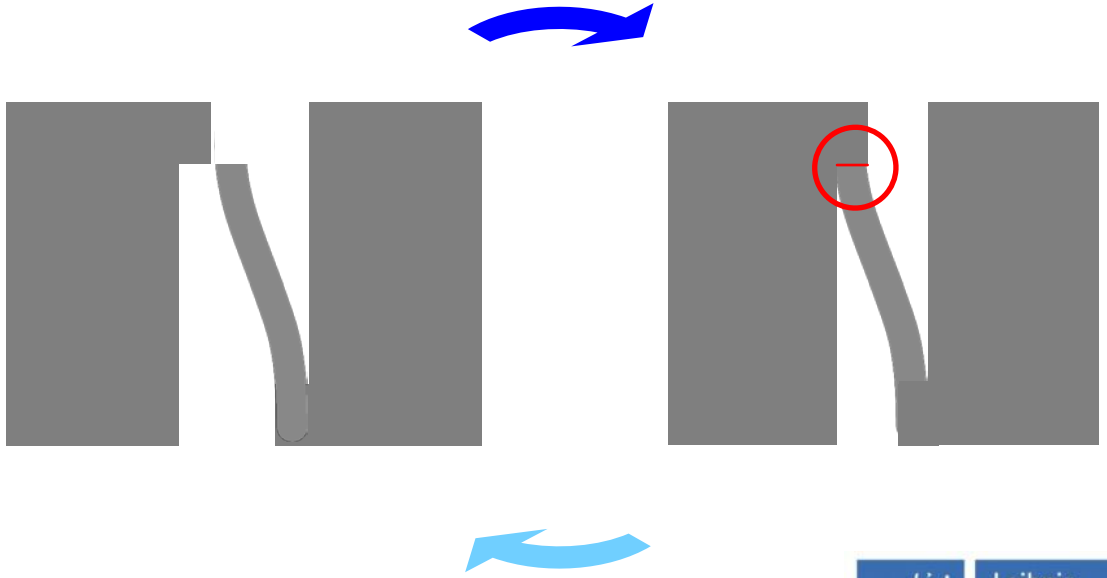
- More and more Al-bridges break



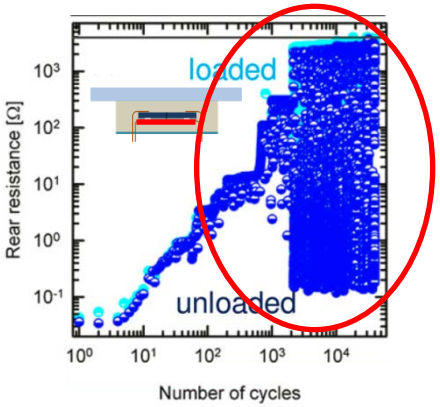
Fatigue state 3



- More and more Al-bridges break
- Al-bridges can electrically reconnect and disconnect randomly

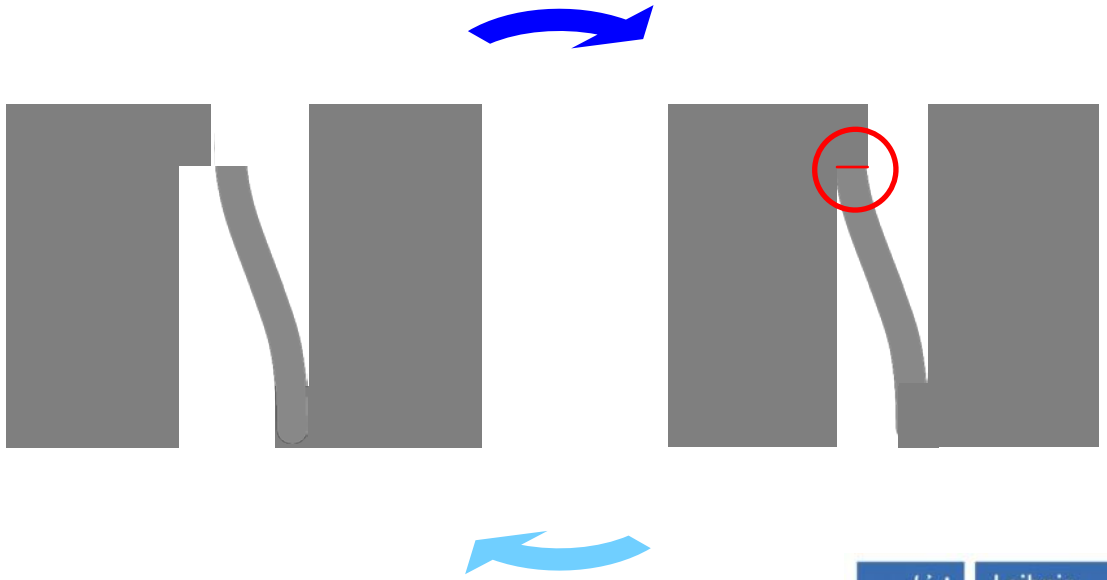


Fatigue state 3

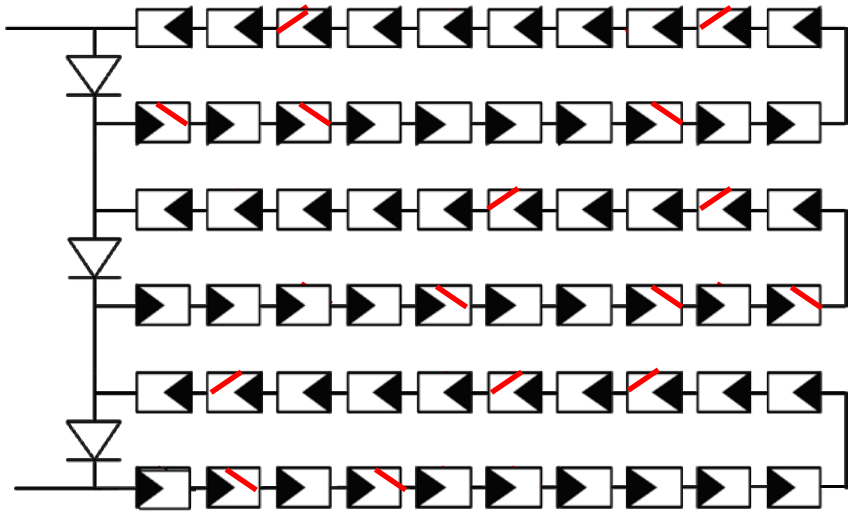


Which are the mechanisms increasing the crack resistance?

- Rear side metal degradation
- Fatigue of the Al-bridges in the Al-Paste during cycling



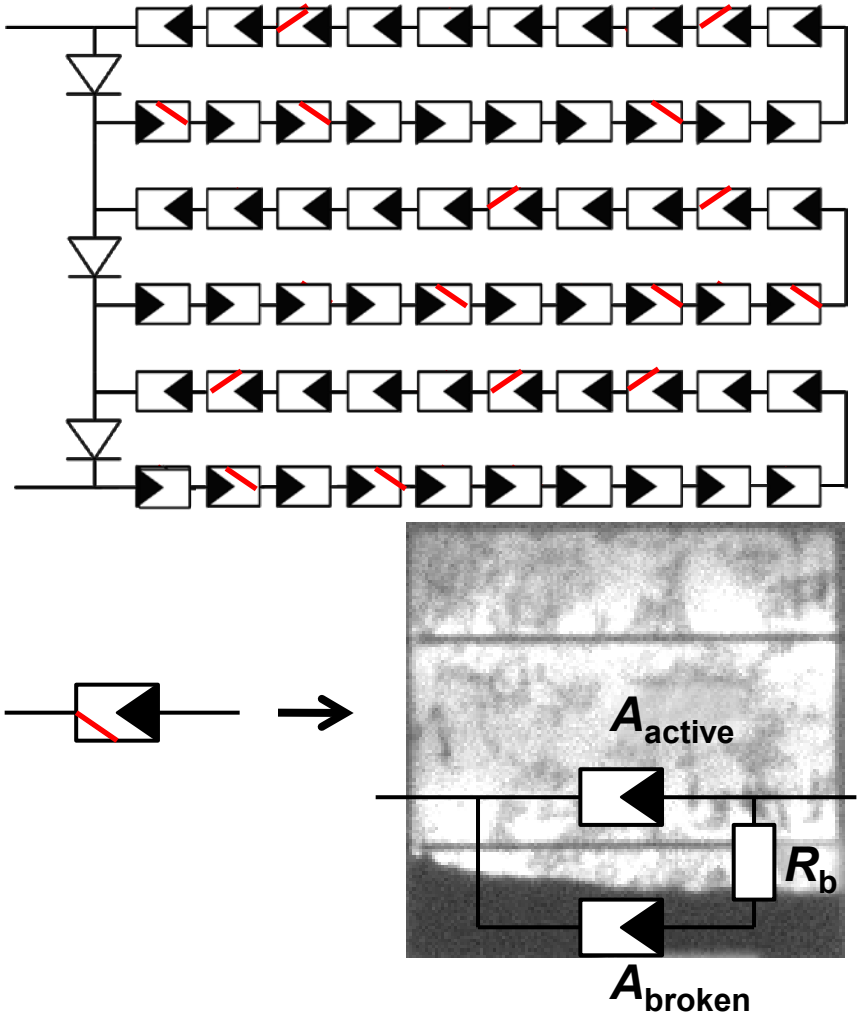
Power loss simulations



- Crack statistics from field of 574 modules

A. Morlier, F. Haase, and M. Köntges, “Impact of Cracks in Multicrystalline Silicon Solar Cells on PV Module Power - A Simulation Study Based on Field Data”, IEEE Journal of Photovoltaics, vol.5, no.6, pp.1735-1741, Nov. 2015, DOI: 10.1109/JPHOTOV.2015.2471076.

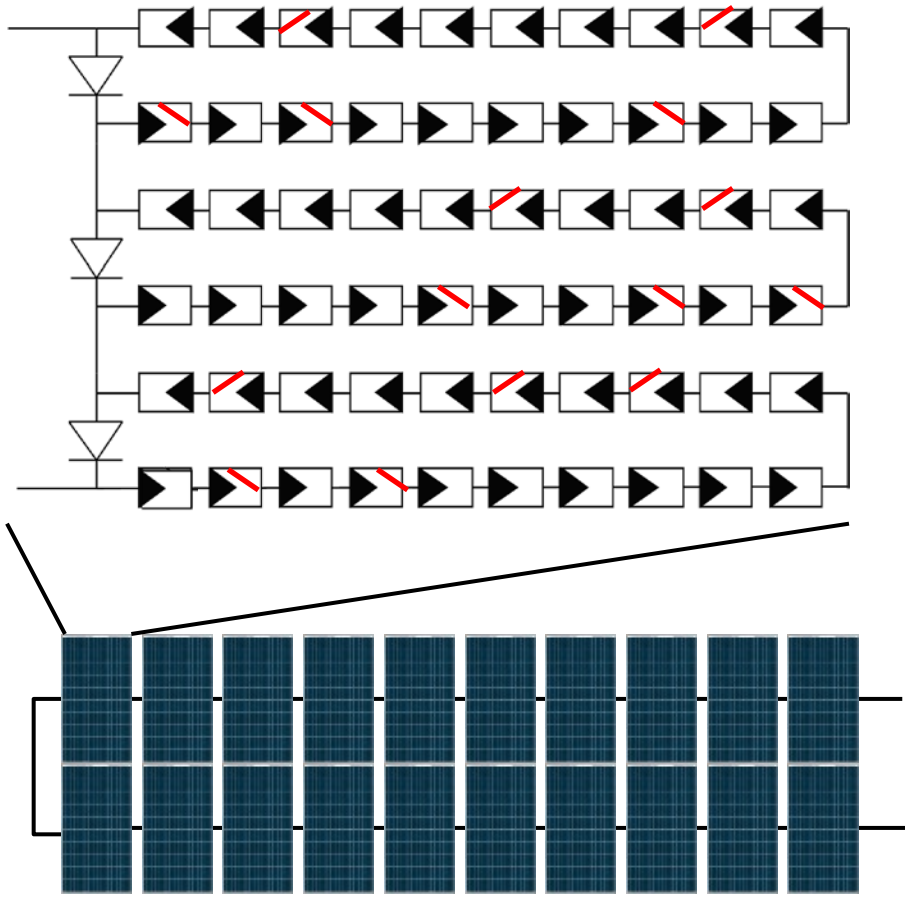
Power loss simulations



- Crack statistics from field of 574 modules
- Break resistance R_b links the broken cell area A_{broken} to the stringed part of the cell A_{active}

A. Morlier, F. Haase, and M. Köntges, “Impact of Cracks in Multicrystalline Silicon Solar Cells on PV Module Power - A Simulation Study Based on Field Data”, IEEE Journal of Photovoltaics, vol.5, no.6, pp.1735-1741, Nov. 2015, DOI: 10.1109/JPHOTOV.2015.2471076.

Power loss simulations



- Simulate 1000 modules with Monte Carlo using field statistics for different break resistances
- Connect the modules randomly in 1000 strings of 20 modules

A. Morlier, F. Haase, and M. Köntges, “Impact of Cracks in Multicrystalline Silicon Solar Cells on PV Module Power - A Simulation Study Based on Field Data”, IEEE Journal of Photovoltaics, vol.5, no.6, pp.1735-1741, Nov. 2015, DOI: 10.1109/JPHOTOV.2015.2471076.

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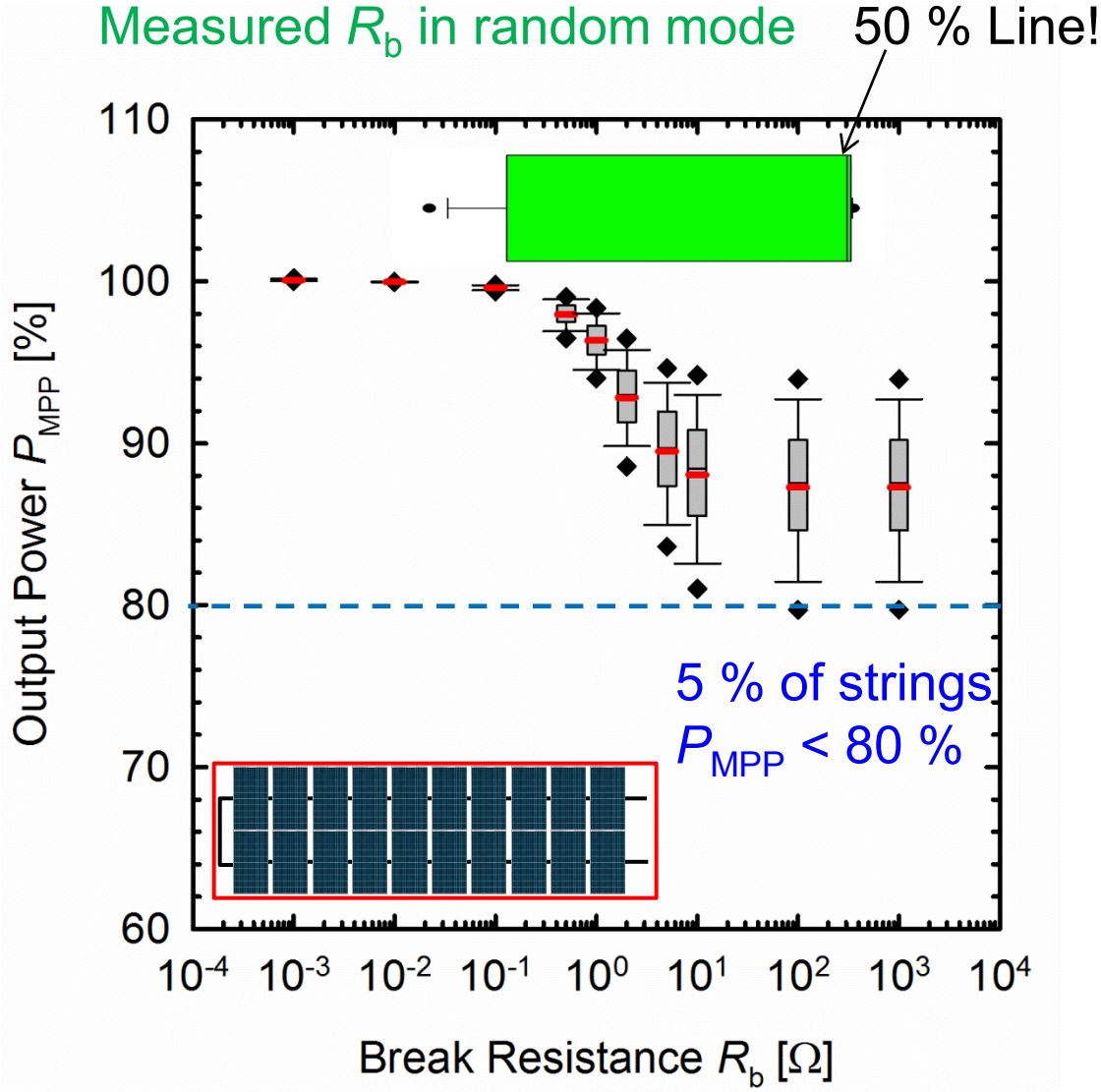
Power loss of module strings



What is the impact of the cracks on the module power?

- Decrease of the output power with R_b on the range [0.1;10] Ω
- R_b = 1000 Ω (>50 % of meas. R_b): 5 % of module strings under the warranty limit of 80 %

Summary

- Cell interconnect ribbons perpendicular to module bending cause the biggest increase in the crack probability of about 900 %, but have no influence on the crack width
- The backsheet decreases the growth of the crack width by about 25 %, but has small influence on the crack probability and on the crack pattern
- Main cause of power loss: Increased resistance by repeated crack opening and thus fatigue of the Al-bridges in the Al-paste 0.03 Ω to 4000 Ω
- Simulations based on crack statistics on field show significant power losses of modules for break resistances above 0.1 Ω
- Assuming the upper 50 % of the measured resistances, 5 % of strings are under the warranty limit of 80 %

Acknowledgment

- R. Winter, H. Fischer, S. Blankemeyer, S. Kajari-Schröder and I. Kunze
- The Federal Ministry of Education and Research for funding this work in the Innovationsallianz: MIKRO 03SF0419A

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Thank you for your attention

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Snail Tracks: Identification of Critical Environmental Stresses, Corrosion Products and Influences of Module Components

I. Duerr, J. Bierbaum, J. Metzger, D. Philipp

Fraunhofer Institute for Solar Energy Systems ISE

PVMRW 2016 NREL

Denver, 24.02.2016

www.ise.fraunhofer.de

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A SHORT INTRODUCTION

Fraunhofer
ISE

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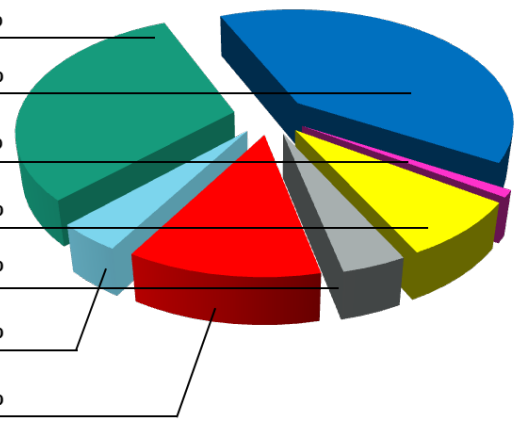
Introducing
Fraunhofer Institute for Solar Energy Systems ISE

- Established: 1981
- Director: Prof. Eicke R. Weber
- Key figures:
  - Staff: 1200
  - Budget with invest.: ~90 Mil. €

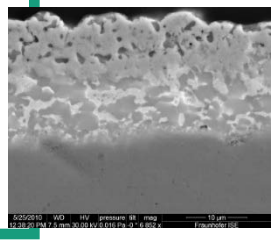
Industry	31 %
Federal Gov. Projects	40 %
Regional Gov. Projects	1 %
European Union	8 %
Others	4 %
Special Programs, FhG	4 %
Basic Funding*	12 %



* of which 90 % federal and 10 % state funds
** without building investment and economic program

Status : January 2014

Research
Materials,
Modeling,
Methods



Development
Components,
Prototypes,
Systems, Procedures

Services
Consulting, Testing,
Monitoring,
Quality Assurance

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Introducing
Division Photovoltaic Modules, Systems and Reliability

Module technology

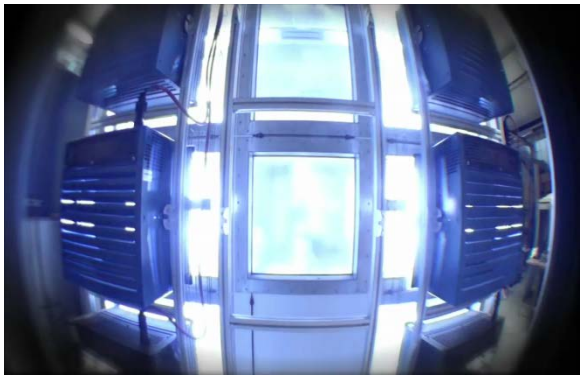
- Interconnection Technology
- Module Efficiency and new concepts
- Module Technology Center (MTC)

Module Testing and Failure Analysis

- Acc. Ageing Tests
- Certification TestLab PV Modules
- Module and Material Analytics
- Failure Detection

Quality Assurance PV Modules and Systems

- Yield Assessment
- Module Characterization CalLab PV Modules
- System Testing
- Quality Monitoring



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Certification Testing and Beyond

ISO 17025 accredited TestLab PV Modules

TestLab
PV Modules

Certification according to IEC, UL with partner VDE

VDE INSTITUT

Certification testing also of new technologies and module designs as bifacial PV or OPV

Pre-certification testing

Special module testing set-up as e.g. ML at low temperatures, DH/UV chamber

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Snail Tracks: Identification of Critical Environmental Stresses, Corrosion Products and Influences of Module Components

I. Duerr, J. Bierbaum, J. Metzger, D. Philipp

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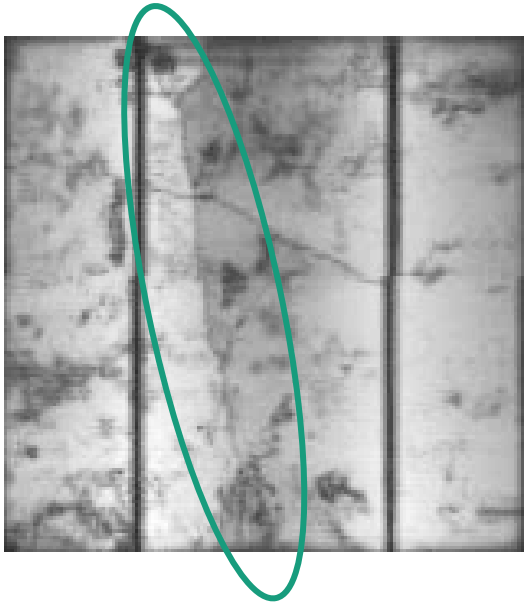
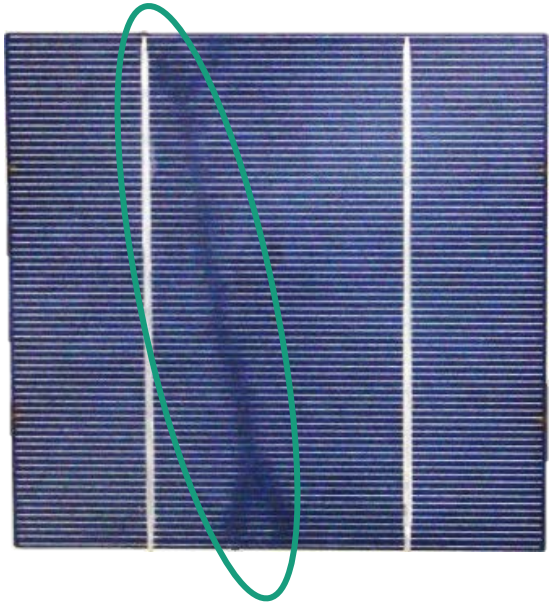
Introduction
What is a Snail Track Corrosion?

cell crack



EL picture

Grid finger discoloration



Picture of Snail Track

- Results from years of snail track study showed the existence of
  - different visual appearance of snail tracks
  - different behavior to artificial stress of snail tracks

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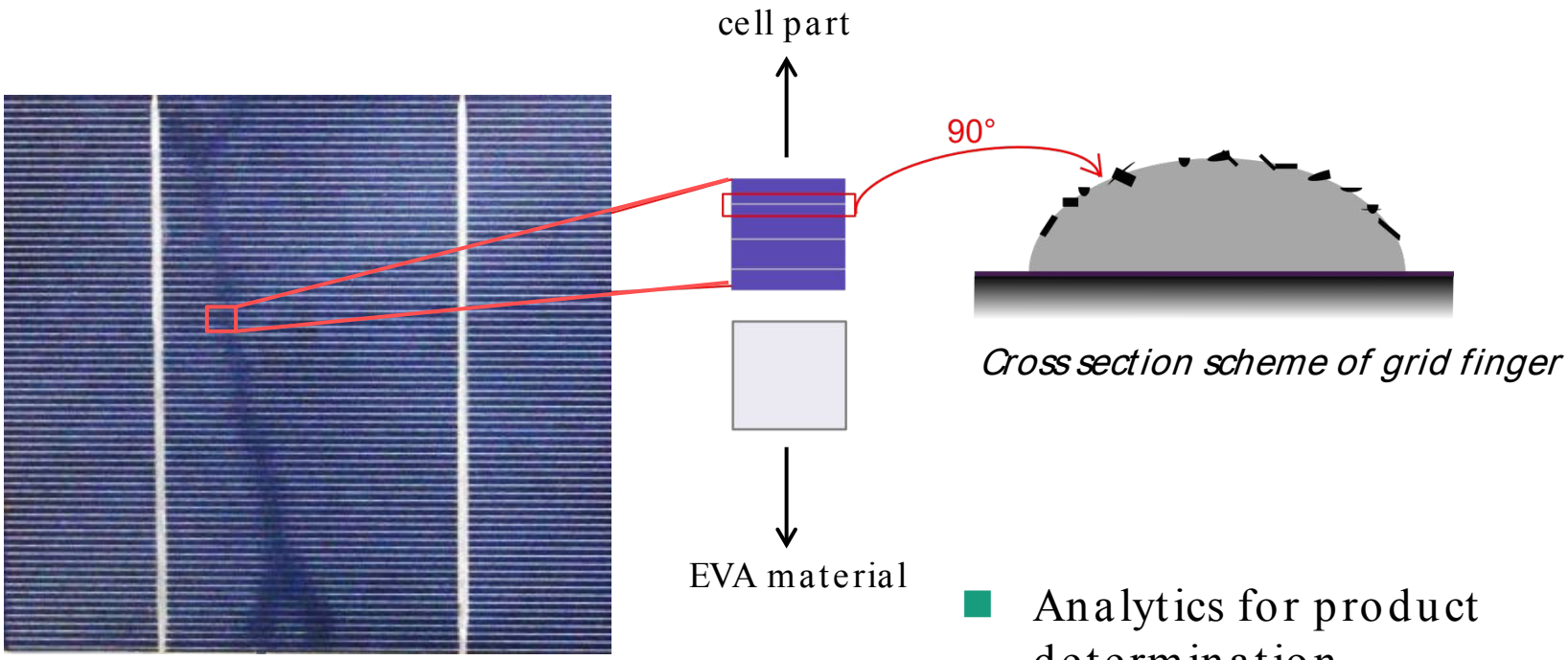
Experimental Set-up



- Snail Track affected c-Si PV module
- Preparation of cell part and corresp. encapsulation material out of the affected modules

- Analytics for product determination
  - Raman and
  - EDX spectroscopy
- Further stress tests for mechanism determination

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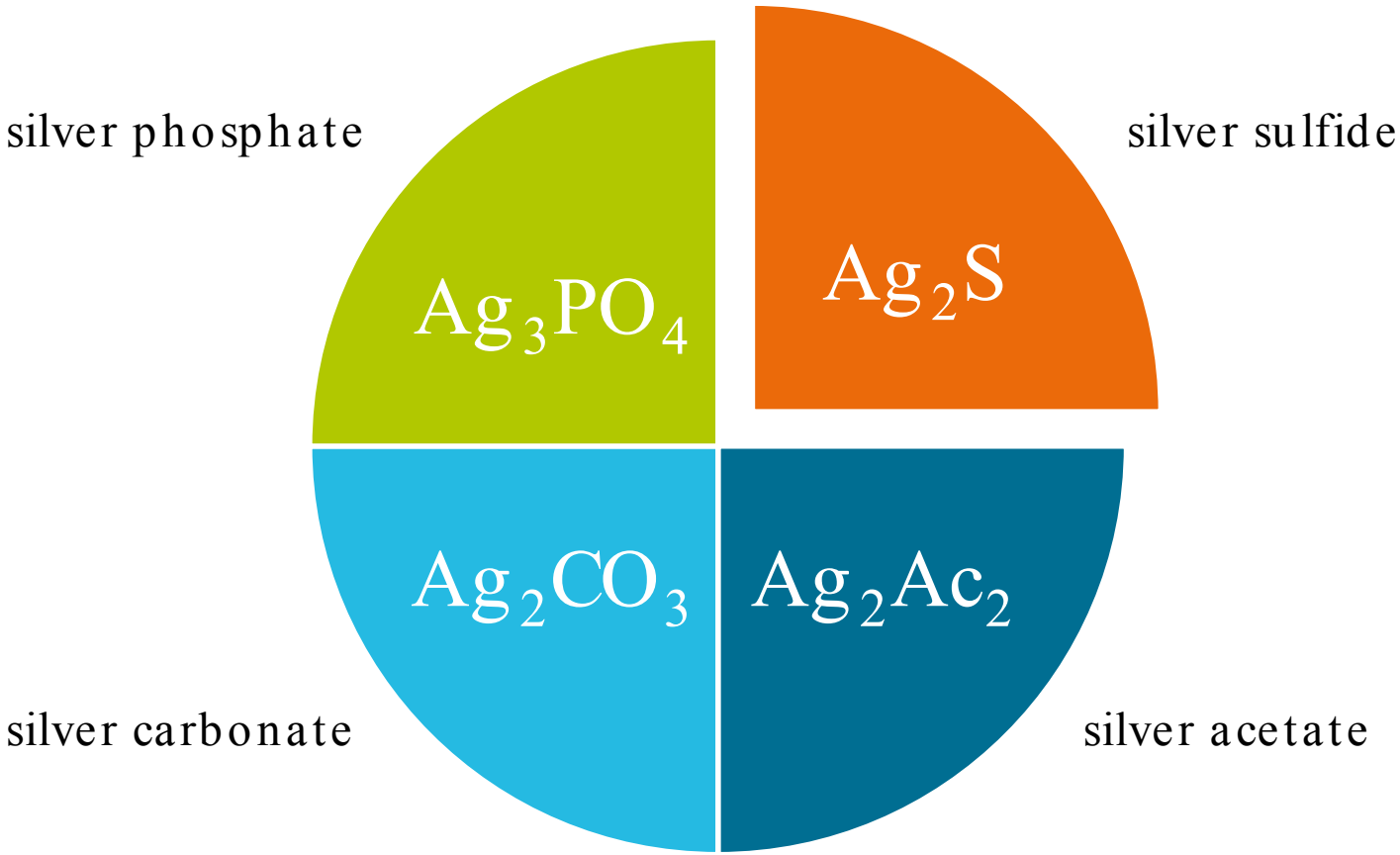
Results
Snail Track Products



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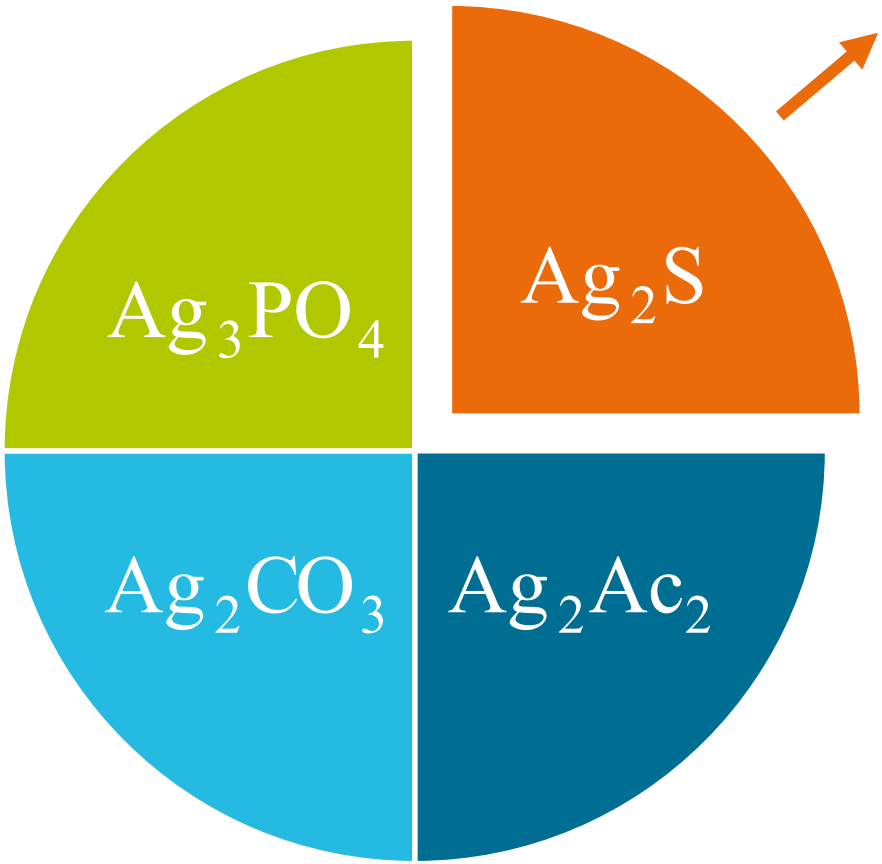
Results

Snail Track Products



Artificially induced !

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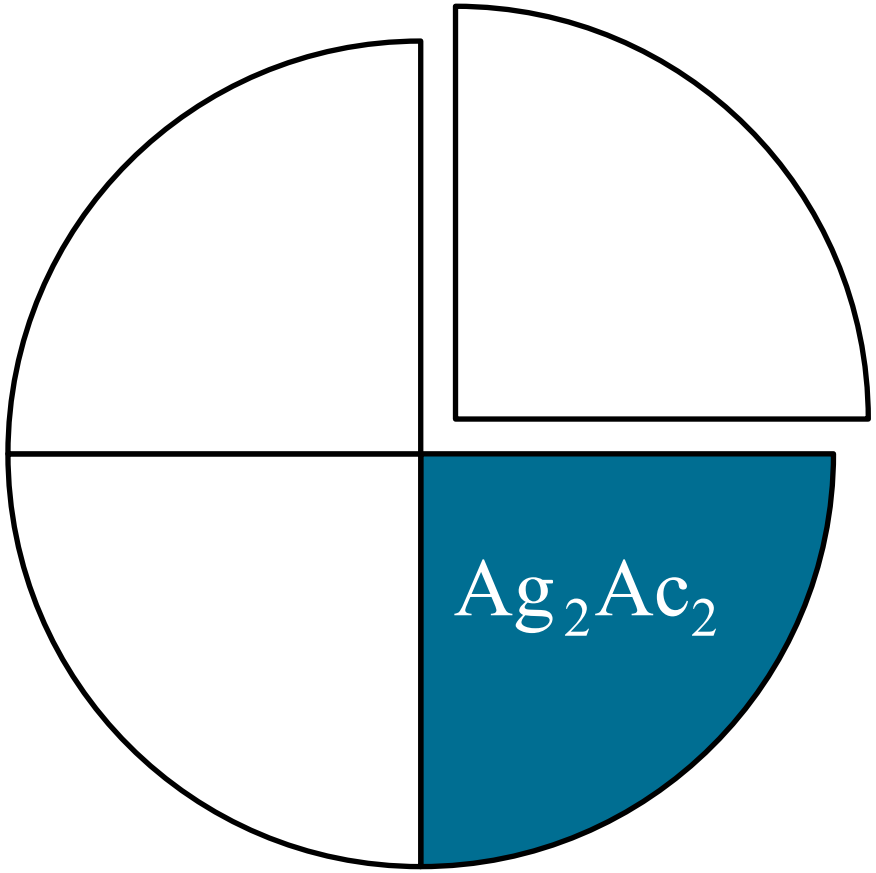
TestLab PV Modules

Fraunhofer ISE

1st Snail Track Product



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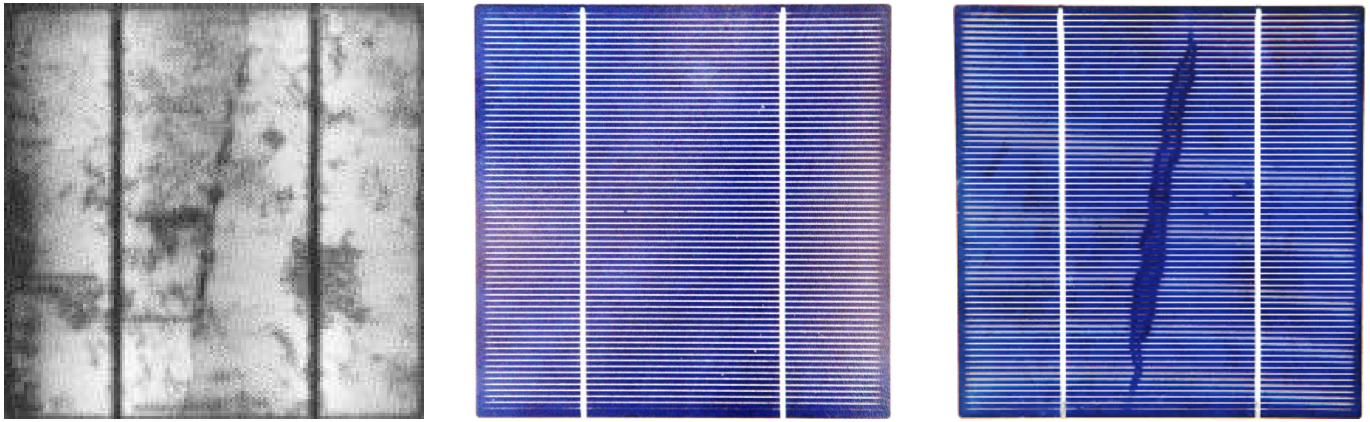
Silver Acetate $Ag_2(CH_3COO)_2$
Further Stress Tests



EL image (left) and photo images of cell from snail track affected module before (middle) and after (right) UV testing.

- Investigation on snail track affected module from field
- New cell crack induced
- UV irradiation testing induced new snail tracks

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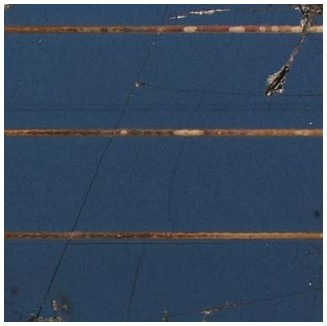
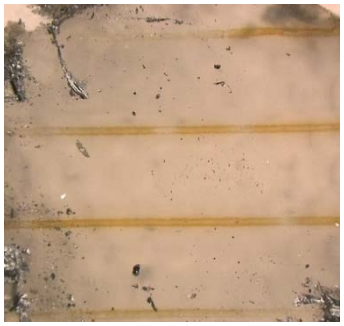
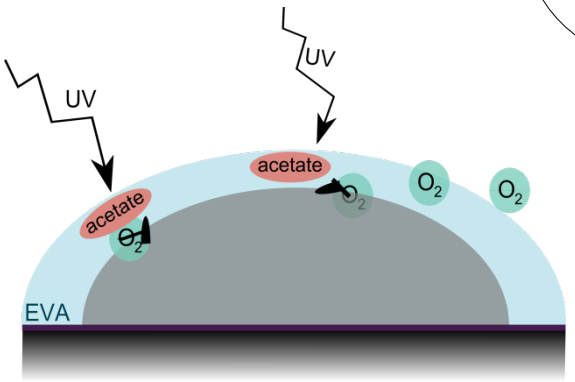
Silver Acetate $Ag_2(CH_3COO)_2$
Reaction





Extracted cell part and corresponding EVA material



$$2\ Ag + 2\ CH_3COOH \xrightarrow[-xH_2O]{UV,\ O_2} Ag_2(CH_3COO)_2$$

Cross section scheme and proposed mechanism for ST formation

- Snail track type formation further provoked by UV
- Photochemical degradation of EVA
- Often seen when back sheet with high OTR is used
- Occur after several years of field exposure
- ✓ **EVA as reaction partner, no limitation for evolution of these STs**

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Silver Acetate $Ag_2(CH_3COO)_2$
Material Involvement

	snail track formation depending on …				
component	WVTR	OTR	"CO_2"TR	processing	material
back sheet		✓			
encapsulation				✓	✓
metallization					

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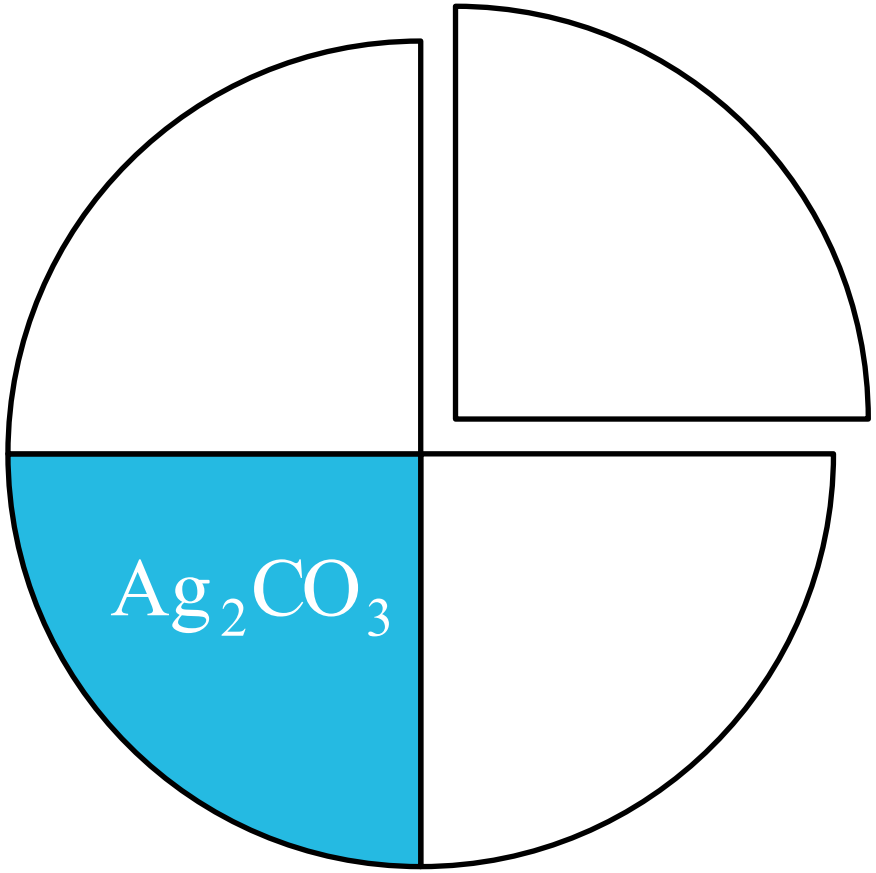
2nd Snail Track Product



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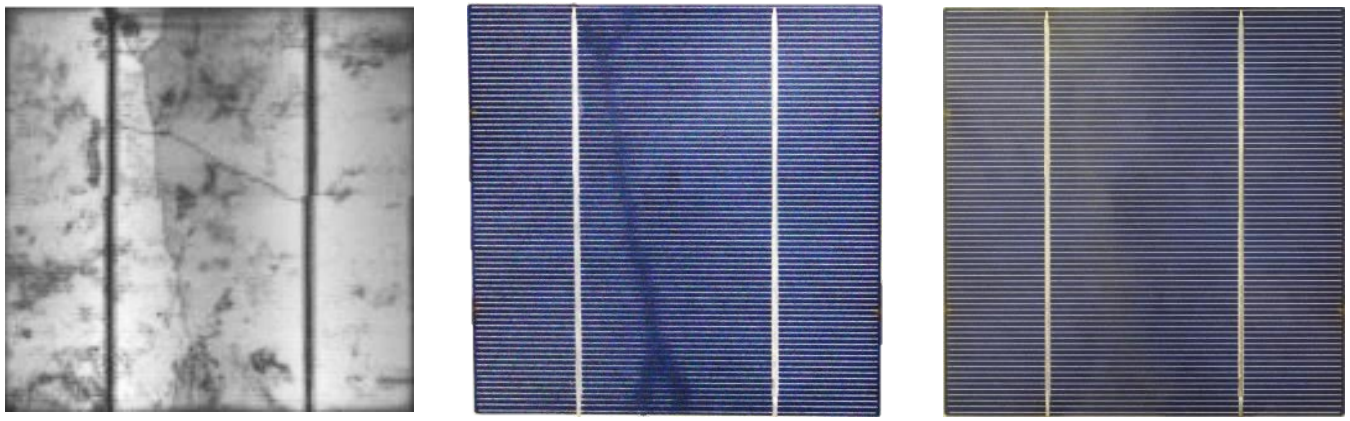
Silver Carbonate Ag_2CO_3
Further Stress Tests



EL image (left) and photo images of snail track cell before (middle) and after (right) DH testing.

- Investigation on snail track affected module from field
- Disappears in DH test conditions: Ag_2CO_3 moisture sensible in the dark
- No formation of new snail tracks

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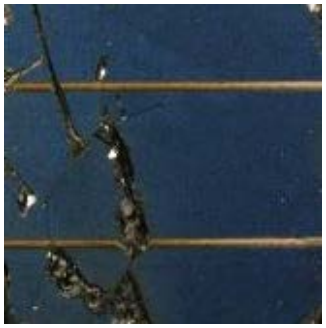
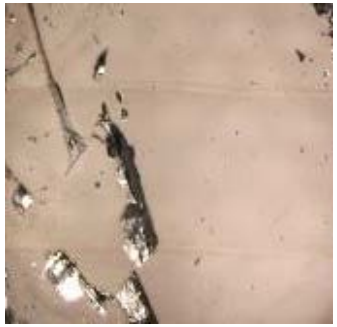
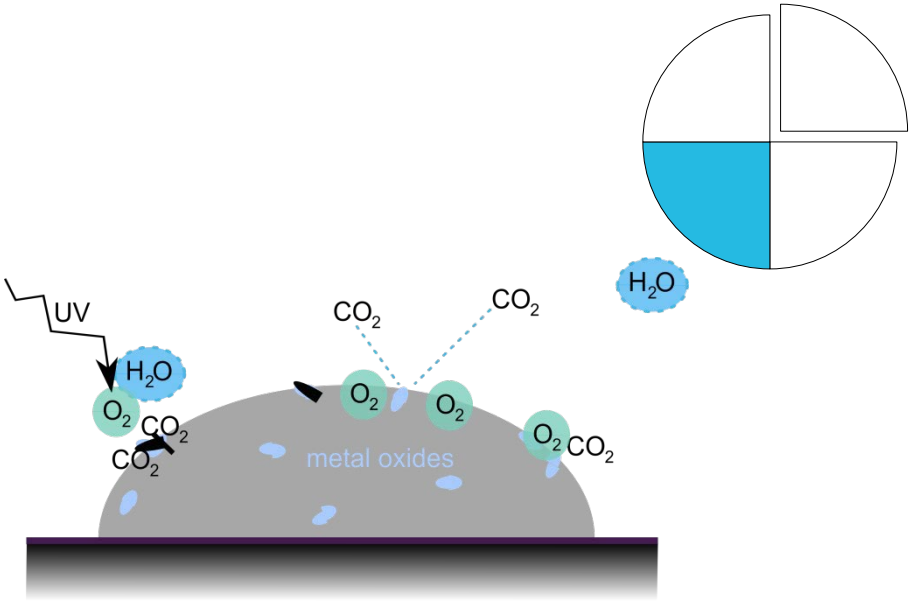
Silver Carbonate Ag_2CO_3
Reaction





Extracted cell part and corresponding EVA material



$$„ Ag + CO_{2(ads.)} + H_2O \xrightarrow[-xH_2O]{UV,\ O_2} (AgOH)Ag_2CO_3“$$

Cross section scheme and proposed mechanism for ST formation

- High amount ZnO on grid (glass additive) found for this type of ST
- CO_2 adsorption on silver surface needs metal oxides (literature)
- CO_2TR, WVTR and OTR of back sheet important for reaction
- Occur often after short installation time

✓ **Formation limited due to neutralization of oxides**

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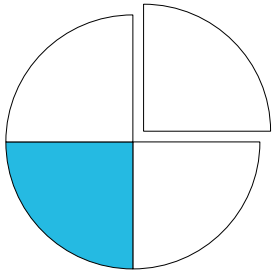
Silver Carbonate Ag_2CO_3
Material Involvement



	snail track formation depending on …				
component	WVTR	OTR	"CO_2"TR	processing	material
back sheet	✓	✓	✓		
encapsulation					
metallization				✓	✓

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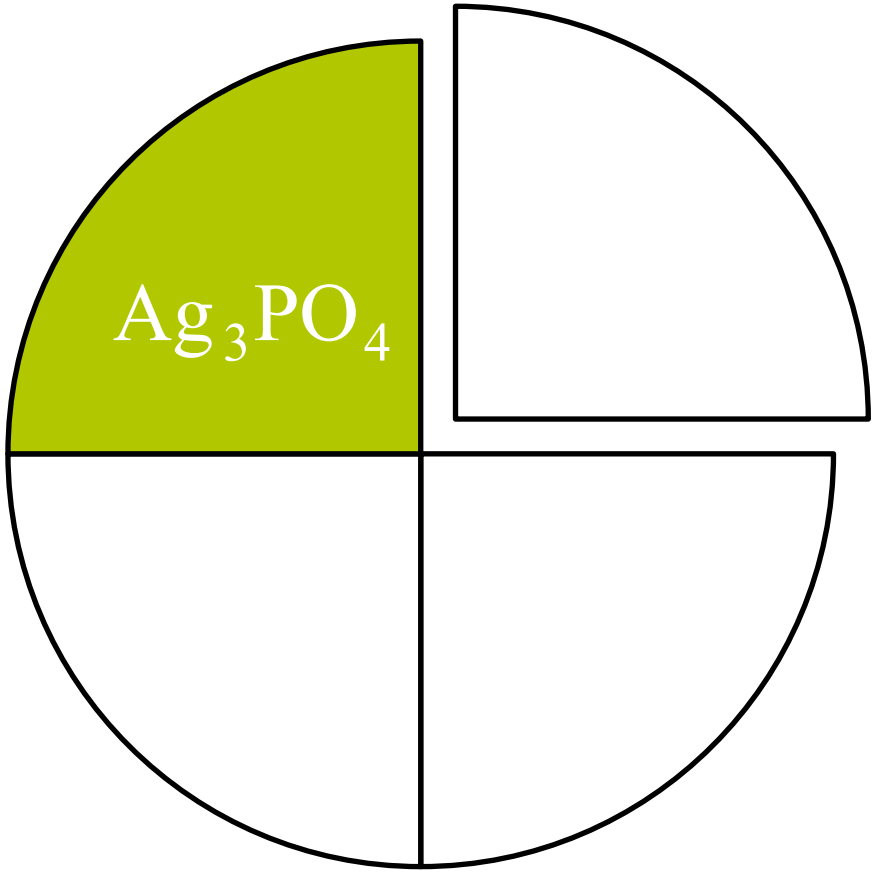
3rd Snail Track Product



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Silver Phosphate Ag_3PO_4
Further Stress Tests

EL image (left) and photo images of Snail Track I affected cell before (middle) and after (right) UV, DH and TC testing.

- Investigation on snail track affected module from field
- No further development/formation under UV, DH or TC

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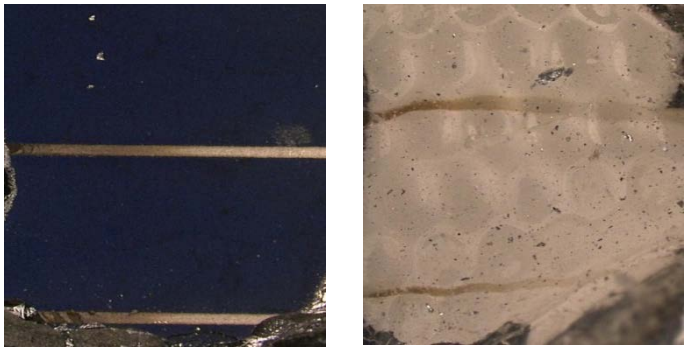
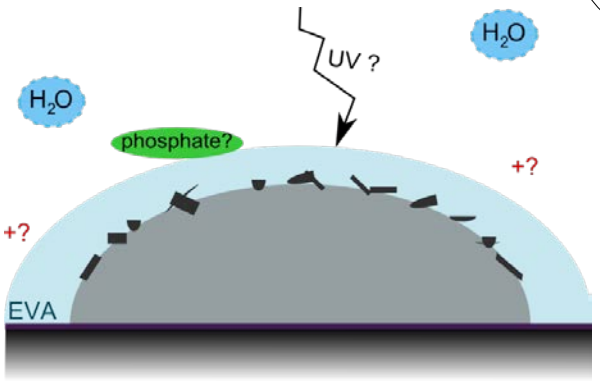
Silver Phosphate Ag_3PO_4
Reaction



Extracted cell part and corresponding EVA material



$$„\ 3\ Ag + PO4\text{-}X \xrightarrow{?,\ ?} Ag_3PO_4“$$

Cross section scheme and proposed mechanism for ST formation

- Reaction of phosphorous-containing antioxidants of EVA
- Affected module showed no further ST under (biased) DH or UV
- Most likely depending on microclimate conditions (humidity, ΔT,…)
- ✓ **Formation most likely limited due to consumption of additive**

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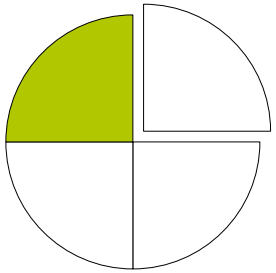
Silver Phosphate Ag_3PO_4
Material Involvement



	snail track formation depending on …				
component	WVTR	OTR	"CO_2"TR	processing	material
back sheet	✓	?			
encapsulation				?	✓
metallization					

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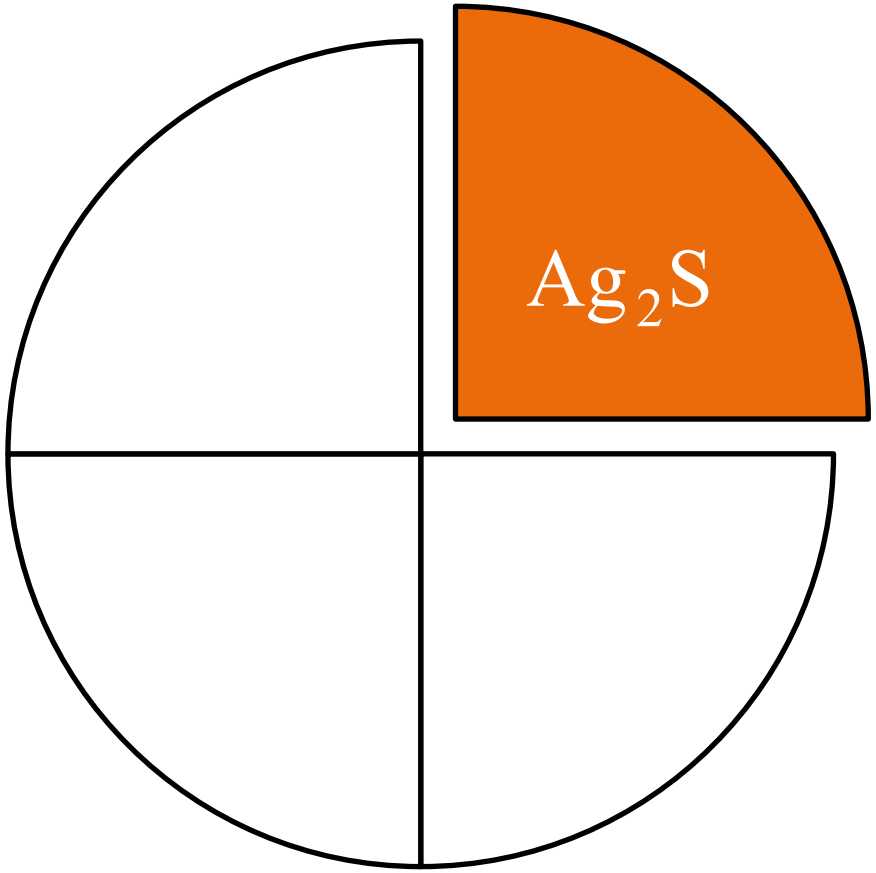
4th Snail Track Product



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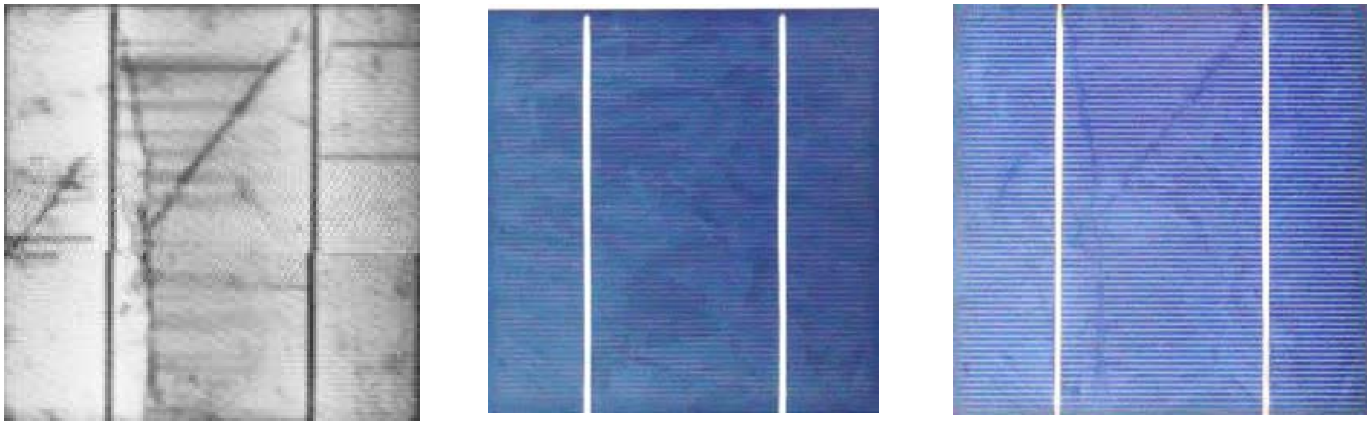
Silver Sulfide Ag_2S
Further Stress Tests



EL image (left) and photo images of Snail Track II affected cell before (middle) and after (right) DH testing.

- Investigation on new produced PV modules
- Cell crack introduction before testing
- Damp-Heat conditions induced new snail tracks

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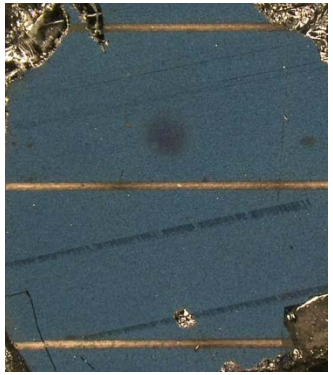
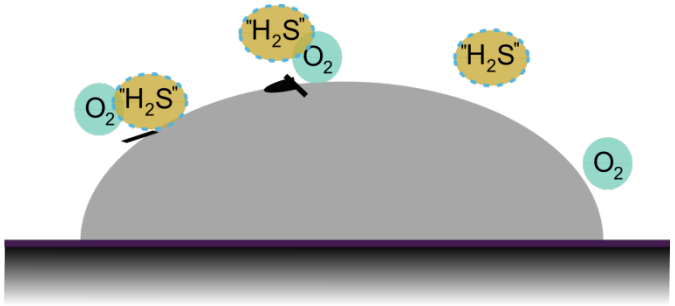
Silver Sulfide Ag_2S
Reaction



Extracted cell part and corresponding EVA material



$$2\ Ag + „H_2S“ + ½\ O_2 \longrightarrow Ag_2S + H_2O$$

Cross section scheme and proposed mechanism for ST formation

- Hydrolysis of sulphurous-containing antioxidant of back sheet
- Revealed by additive testing and experimental approach
- WVTR and OTR of back sheet essential for reaction
- Slower Ag_2S formation for back sheet with lower OTR
- ✓ **Relevance to field failure not given yet**

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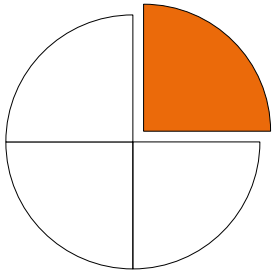
Silver Sulfide Ag_2S
Material Involvement



	snail track formation depending on …				
component	WVTR	OTR	"CO_2"TR	processing	material
back sheet	✓	✓			✓
encapsulation					
metallization					

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Summary and Conclusion

- **Four different kinds** of "snail tracks" found until now
- Formation dependent on **stress factors** (indoor/outdoor), but mainly …
- … on **material properties** and **combination**:
  - Quality and additives EVA (encapsulant) material (Ag_2Ac_2 and Ag_3PO_4)
  - Additives back sheet material (Ag_2S)
  - Gas permeability back sheet material (Ag_2CO_3, Ag_2S, Ag_2Ac_2 , Ag_3PO_4)
  - Cell metallization (Ag_2CO_3)
- Knowledge of ST products **helps you**…
  - … to optimize your materials
  - … to identify impact on module performance and reliability

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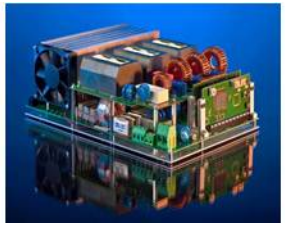
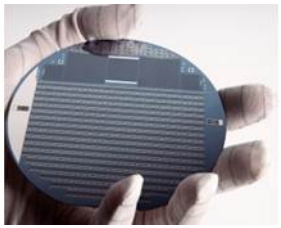
Thank you for your attention!

Fraunhofer Institute for Solar Energy Systems ISE

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Head of Team Failure Detection and Analytics

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TestLab PV Modules

Fraunhofer ISE

Potential Induced Degradation (PID):

A Physical Model Describing Degradation and Recovery in the Field

NREL PVMRW Feb 24th, 2016

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Hanwha Q CELLS

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INTRODUCTION:
PID = DEGRADATION FROM VOLTAGE STRESS

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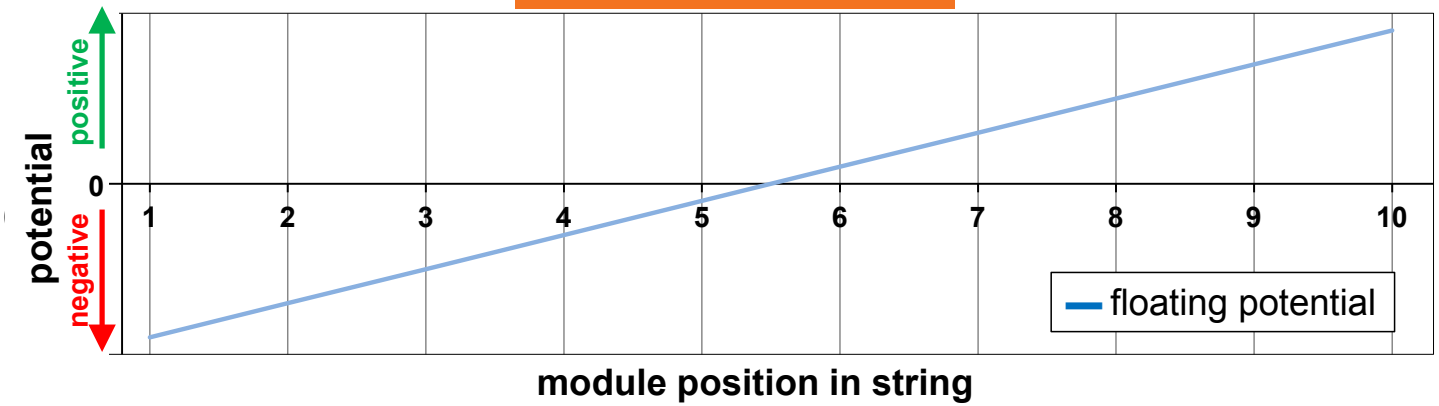
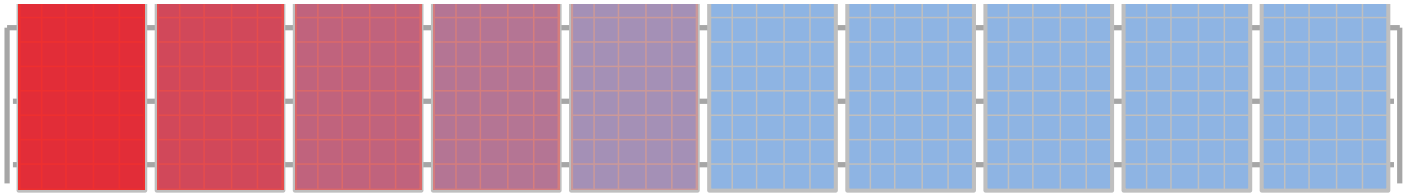
cell potential to ground

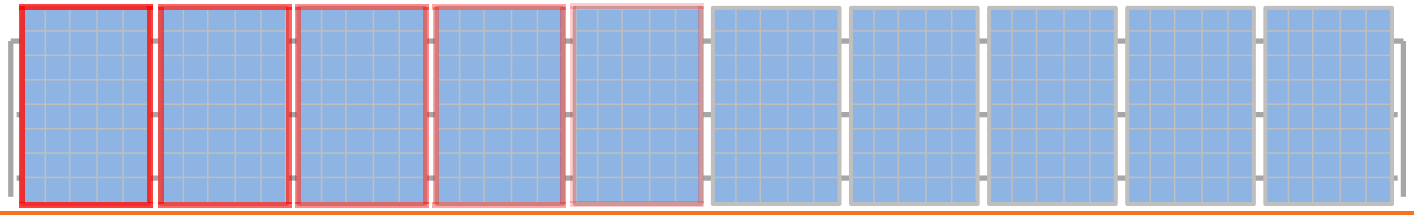


wet conditions



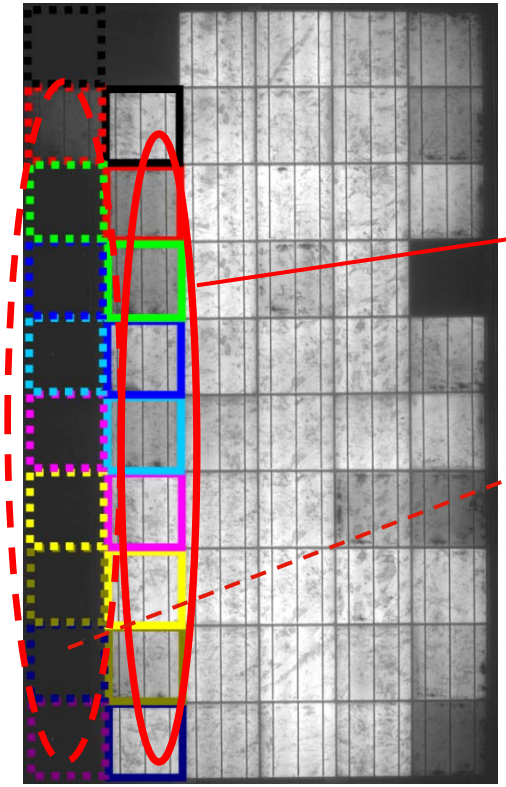
PID-s stress in module string with dry module front surface

dry conditions

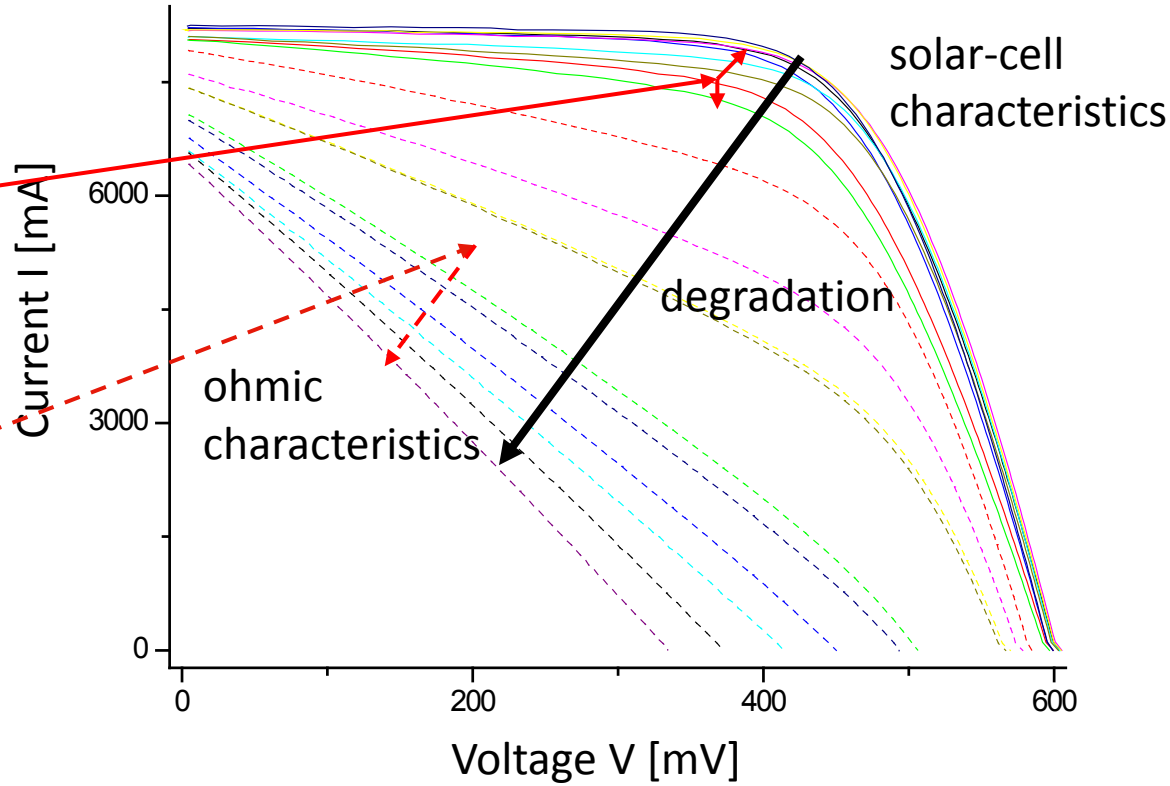


Serial interconnection leads to high voltage stress under wet conditions

INTRODUCTION
PID-s CHARACTERISTICS

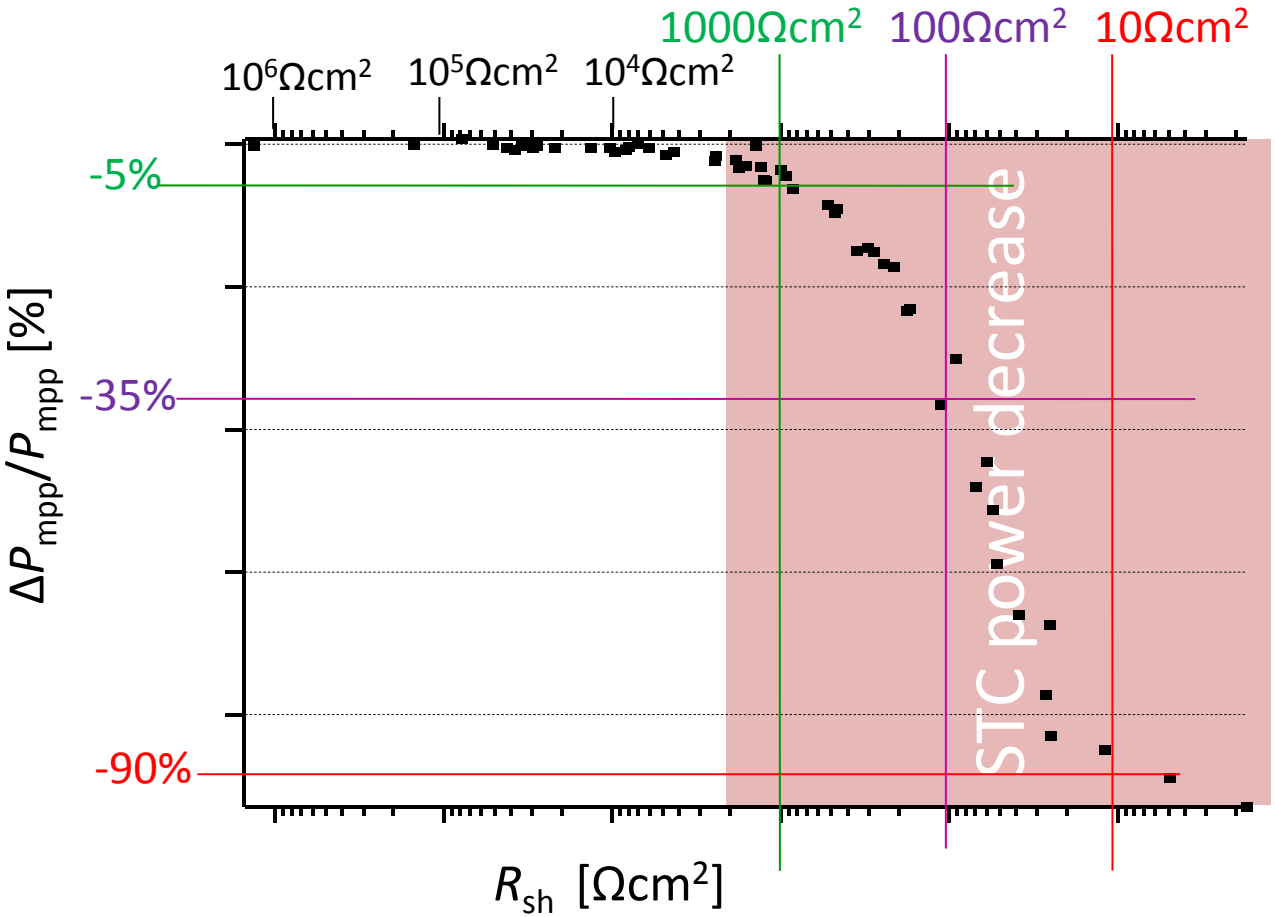


electroluminescence image



PID-s → Potential induced degradation by shunting of solar cell

KEY PARAMETER: SHUNT RESISTANCE R_{sh}



▪ 1-cell mini-module

significant power decrease below 1kΩcm²

Shunt-resistance R_{sh} reveals PID-s before module power decrease

LABORATORY PID TEST METHODS
IEC TS 62804:2015

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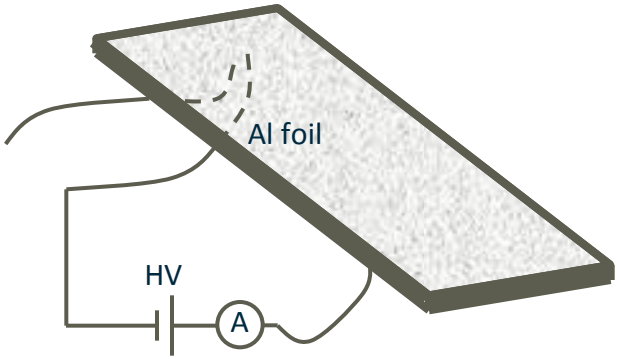
method A: chamber test (DH)

temperature: 60 °C ±2°C
voltage: system voltage (1 kV)
contacting: indirect via humidity
humidity: 85% ±3%
ramp-up procedure critical
time: 168h suggested, no pass fail

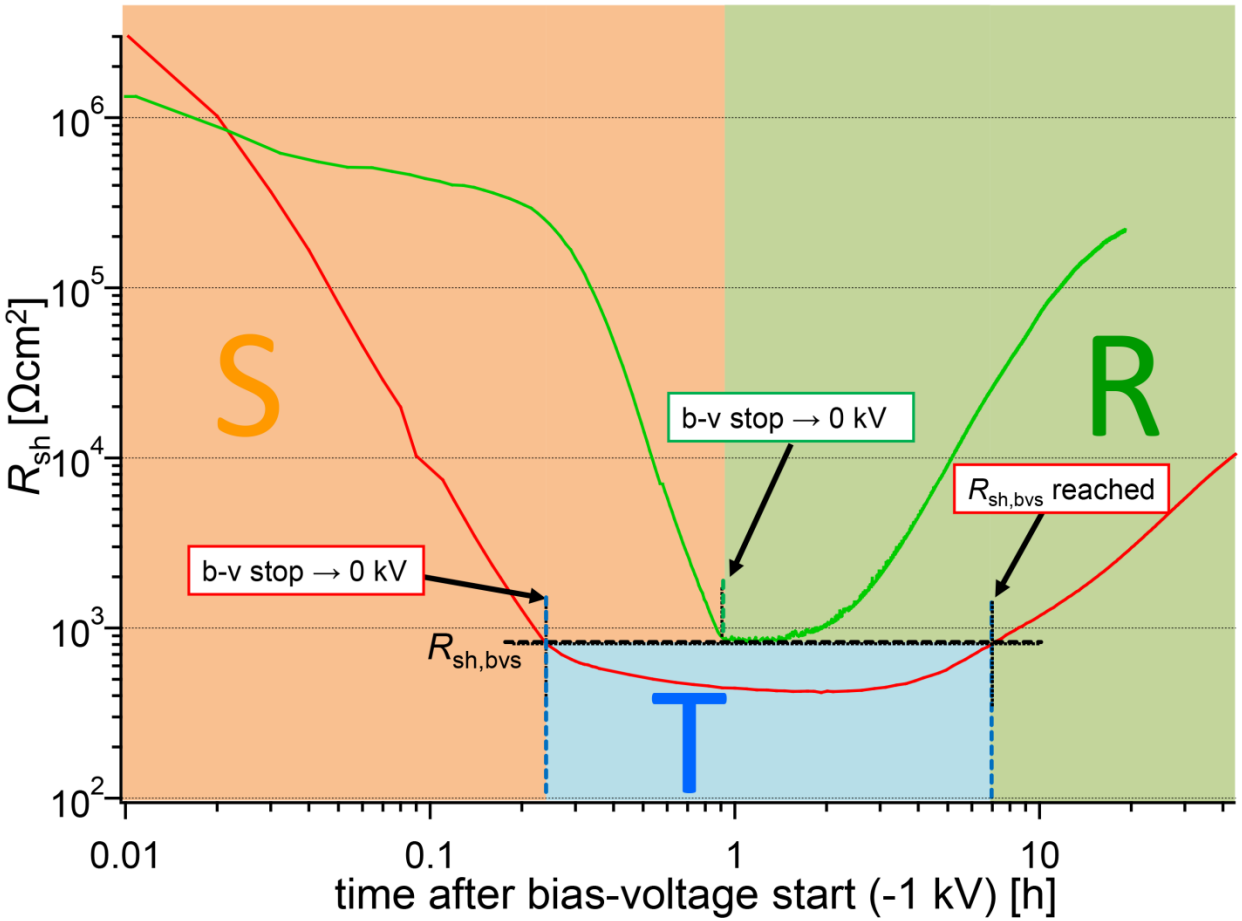
method B: Al foil test



temperature: 25 °C ± 1°C
voltage: 1 kV
contacting: Al-foil
ensure reliable contact of Al-foil
time: 168h suggested, no pass fail

→ reproducible but continuous PID stress

PID-s PROGRESSION:
DIFFERENT PHASES OF PID-s



→ shunting (S)-, transition (T)- and recovery (R)-phase

PROGRESSION OF PID-s LABORATORY ENVIRONMENT VS FIELD CONDITIONS

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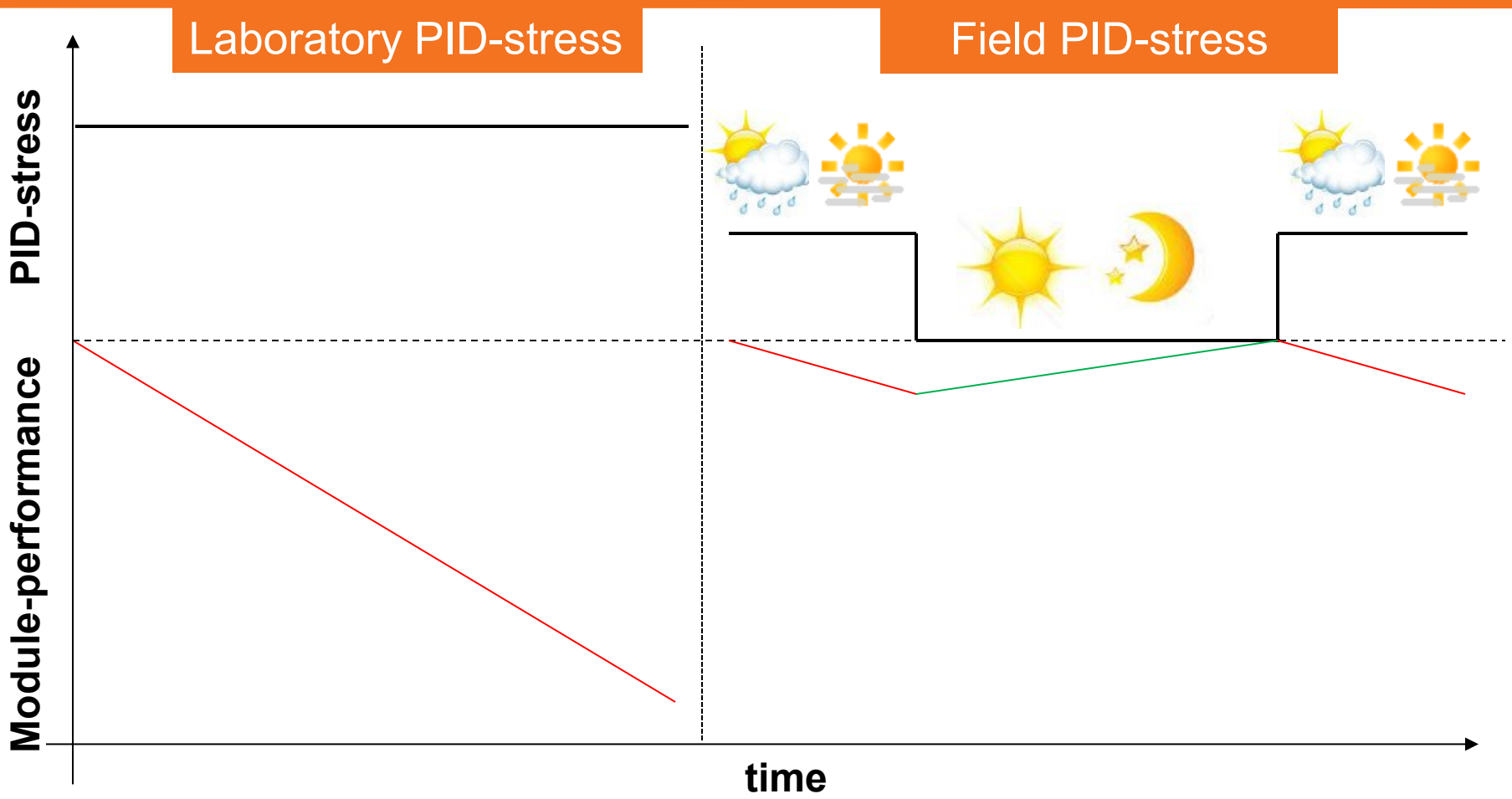

common PID-tests represent only one part of PID-s kinetics in the field

IEC TS 62804:
PID TEST SCOPE AND INFLUENCE FACTORS

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Precise control of test conditions essential

- light preconditioning speeds up PID-s degradation
- humidity control critical

reproducible results when protocols followed

IEC TS 620804 PID Test = constant stress levels

- **basic susceptibility test**
- no time of failure determination
- testing harder does not ensure better field performance
- **does not allow for comparative testing**

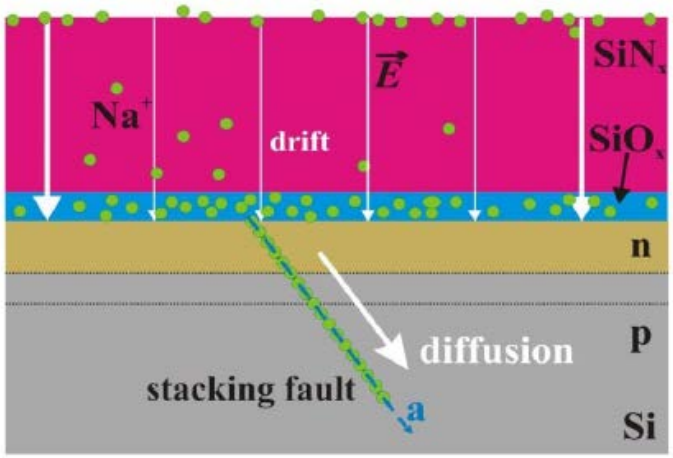
Requirements for a qualification test:

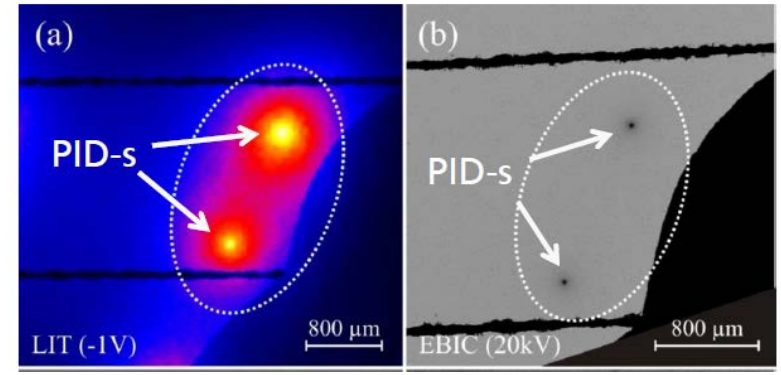
Outdoor progession is result of interplay between degradation and regeneration
A simple, single stress test will never allow to predict time of failure

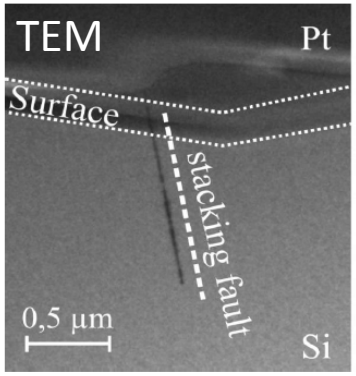
A detailed model is necessary to make service life prediction

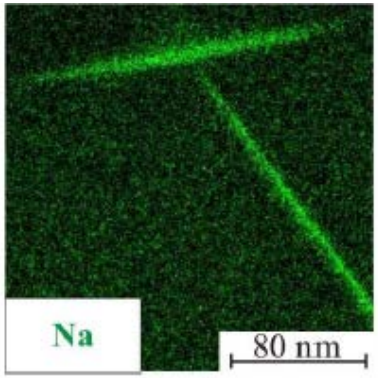
PHYSICAL PROCESS FOR DEGRADATION

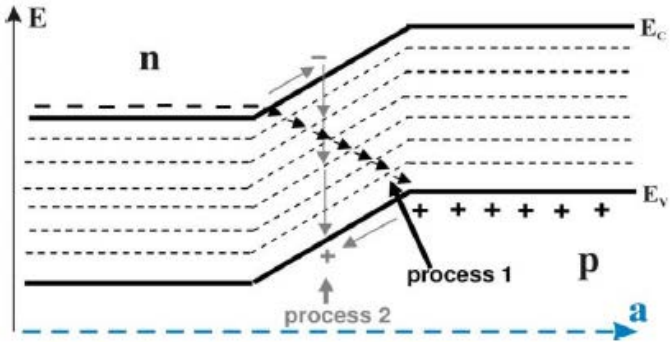
- Potential between (grounded) glass and cells
- Na ions migrate into cell
- Na ions accumulate in stacking faults present in Si
- pn junction is shunted locally











Naumann, V. et al.: *Energy Procedia* 33, pp 76-83 (2013)

Naumann, V. et al.: *Solar Energy Materials and Solar Cells* **120**, pp 383-389 (2014)

Naumann, V. et al.: *Phys. Stat. Solidi* **7(5)**, pp 315-318 (2013)

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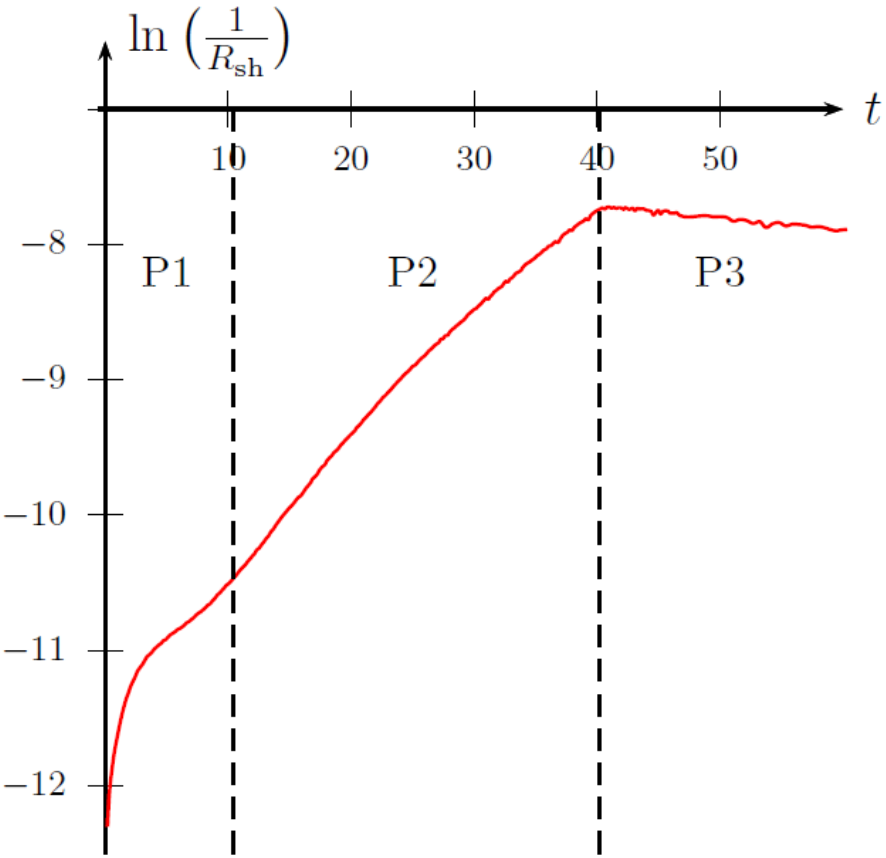
PID-s PROGRESSION



- **Slow shunting in P1**
- **Exponential shunt increase in P2**
- **Slowly beginning recovery in P3**

PHYSICAL MODEL FOR DEGRADATION AND RECOVERY: DRIFT DIFFUSION MODEL

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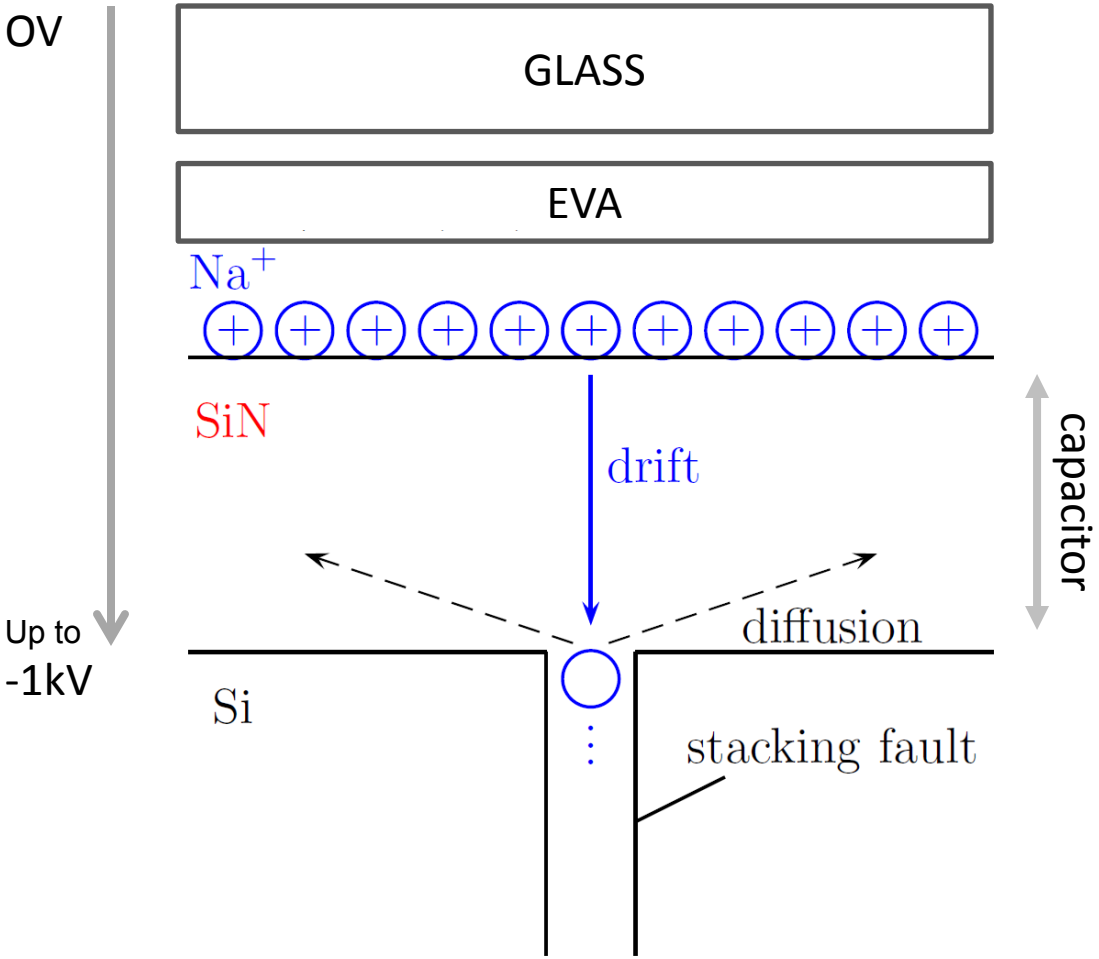
Drift-diffusion model



- ⇐ Source of Na+ ions
- ⇐ Conductive, ions can pass through it
- ⇐ Accumulation of Na+ over time
- ⇐ Voltage build-up over time
- ⇐ Drift in electric field caused by accumulated Na+ ions
- ⇐ Fast movement of Na atoms in stacking fault
- ⇐ outdiffusion of Na atoms during recovery

PHYSICAL MODEL FOR DEGRADATION AND RECOVERY: DRIFT DIFFUSION MODEL

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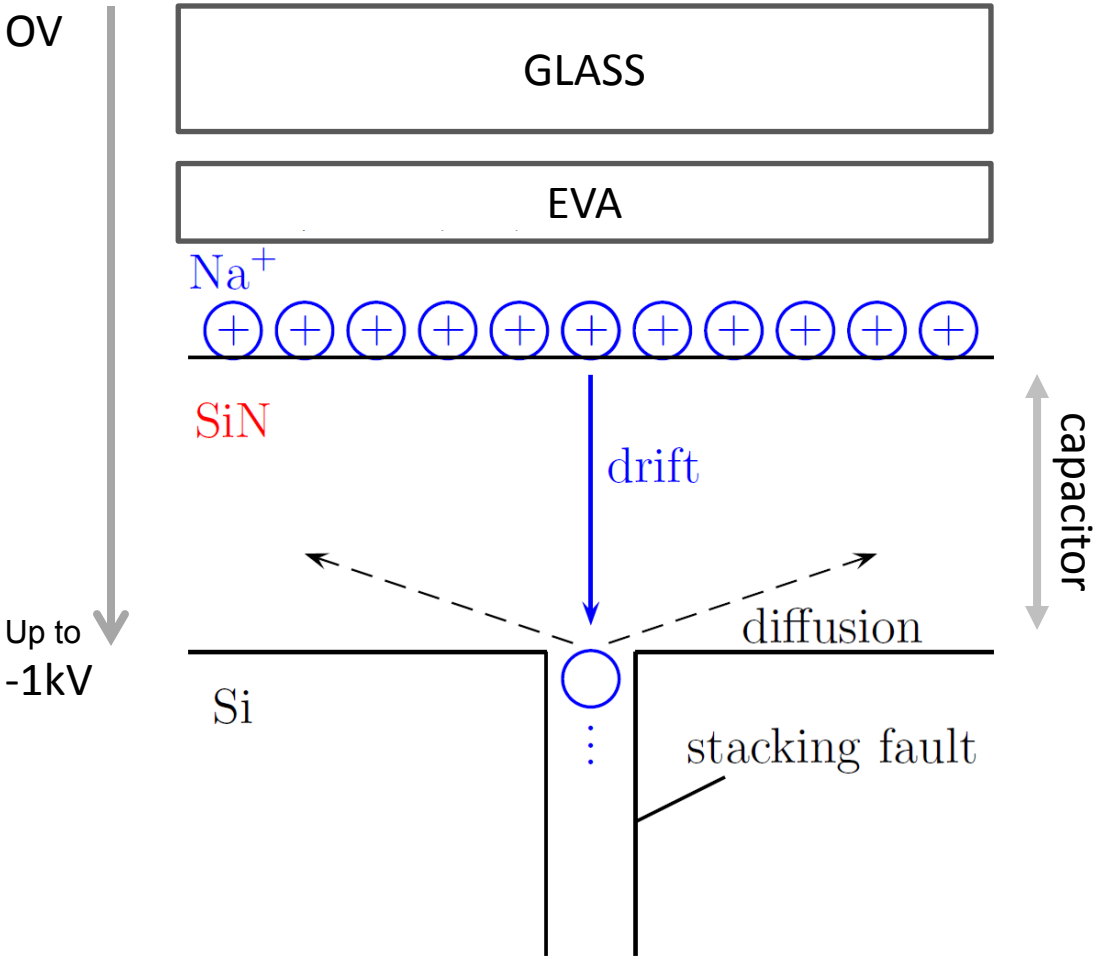

DEGRADATION

⇐ Linear Na+ build-up over time
⇐ Linear increase in voltage

⇐ Drift in electric field caused by accumulated Na+ ions
⇐ Drift speed increases over time

⇐ Aggregation of Na atoms in stacking fault
⇐ Increase of conductivity in stacking fault
⇐ PID shunt develops

PHYSICAL MODEL FOR DEGRADATION AND RECOVERY: DRIFT DIFFUSION MODEL

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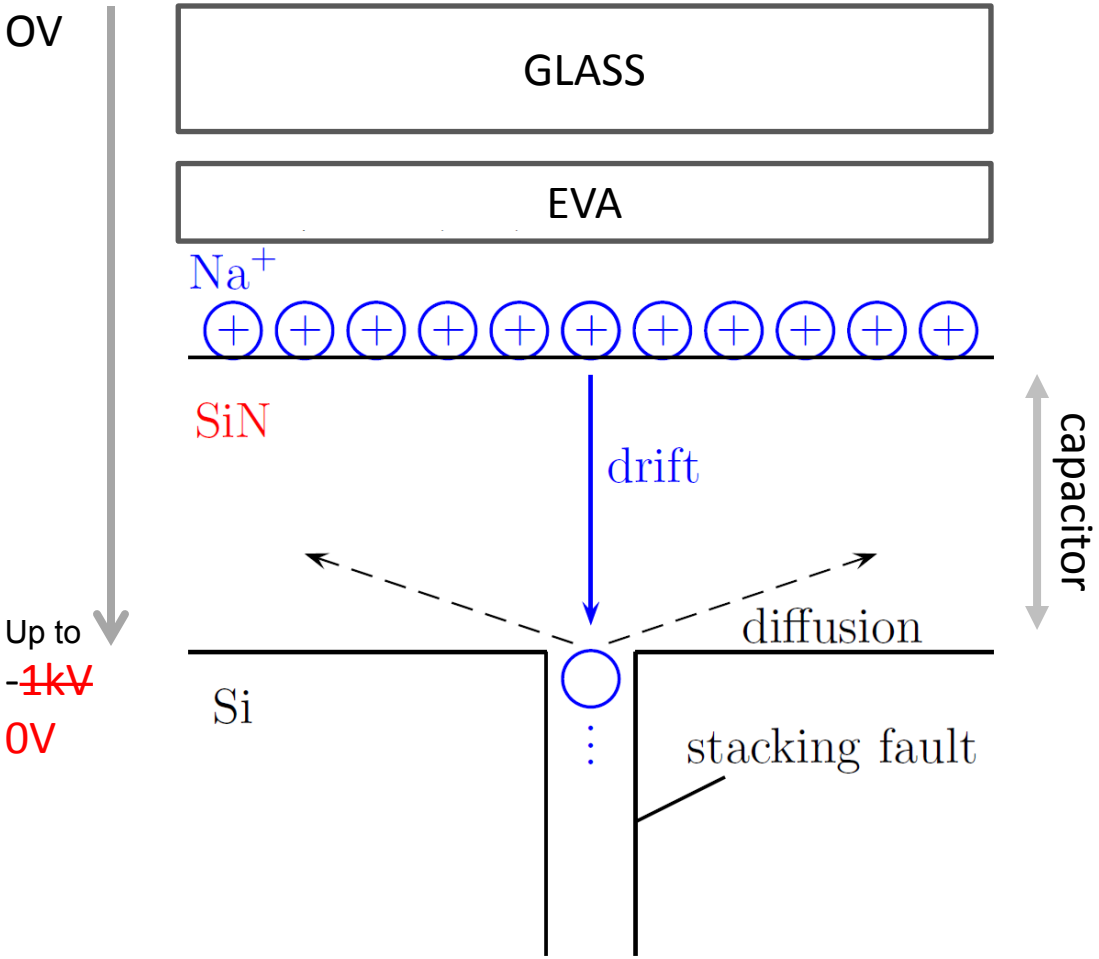

RECOVERY

- ⇐ Accumulated Na ions disperse by diffusion
- ⇐ Drift in electric field caused by remaining accumulated Na+ ions
- ⇐ Drift continues for limited time and decreases to zero
- ⇐ outdiffusion of Na atoms in stacking fault
- ⇐ Decrease of conductivity in stacking fault
- ⇐ PID shunt recovers

PHYSICAL MODEL FOR DEGRADATION AND RECOVERY

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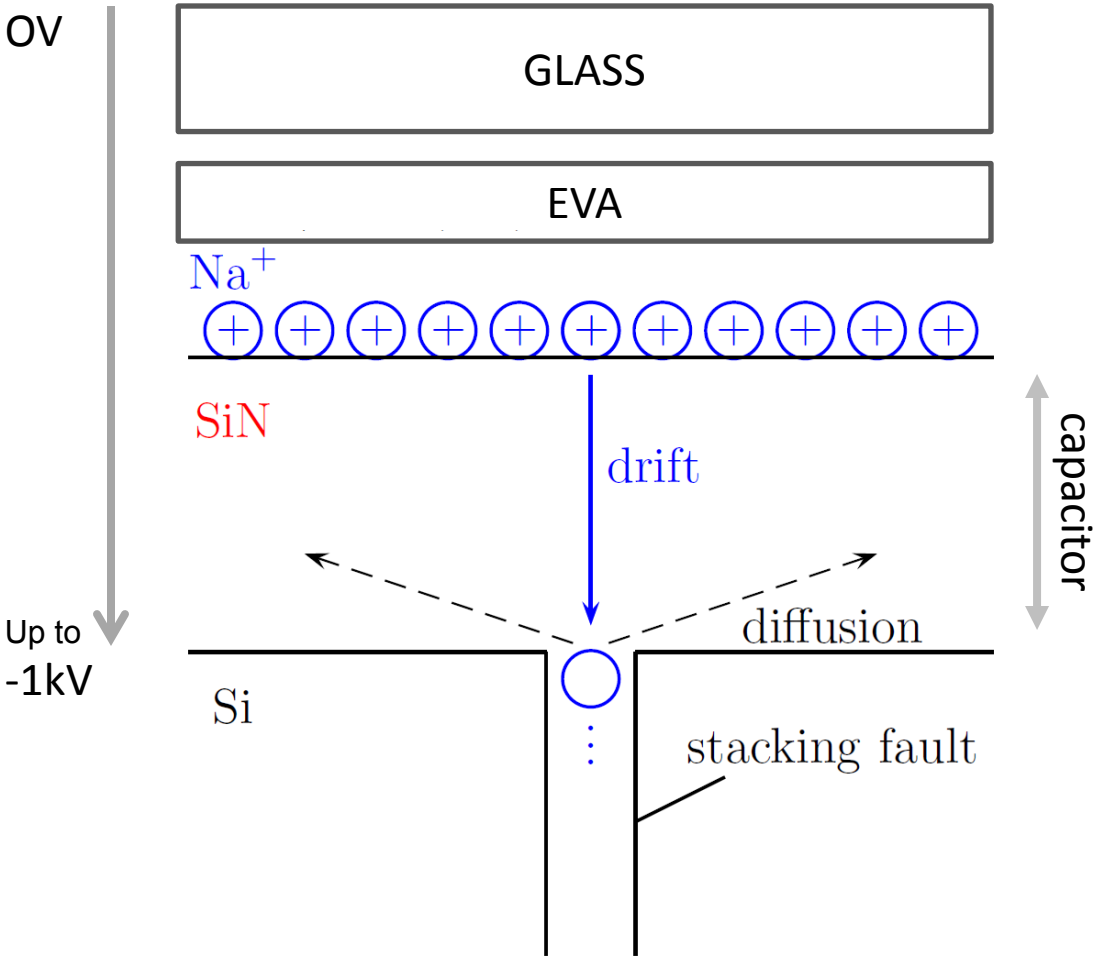


MODEL

DRIFT-DIFFUSION EQUATION

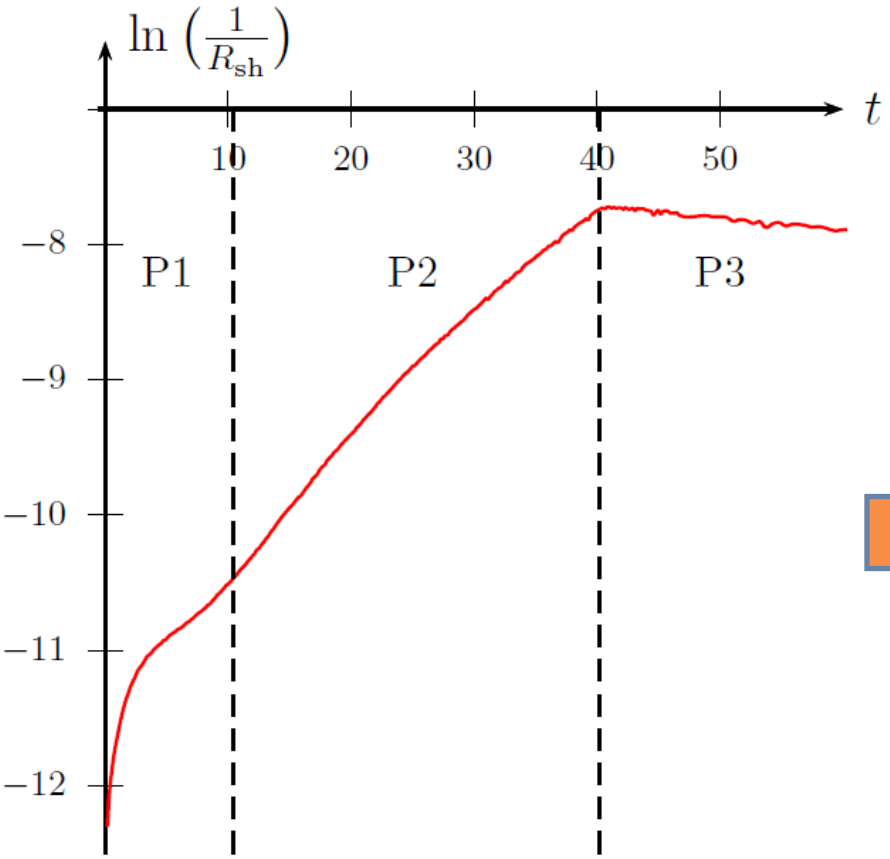
$$\begin{cases} \partial_t n(x,t) &= q(t) \cdot \mathbb{1}_{[-\epsilon;\epsilon]}(x) + D\partial_{xx} n(x,t) \\ n(x,0) &= 0 \end{cases}$$

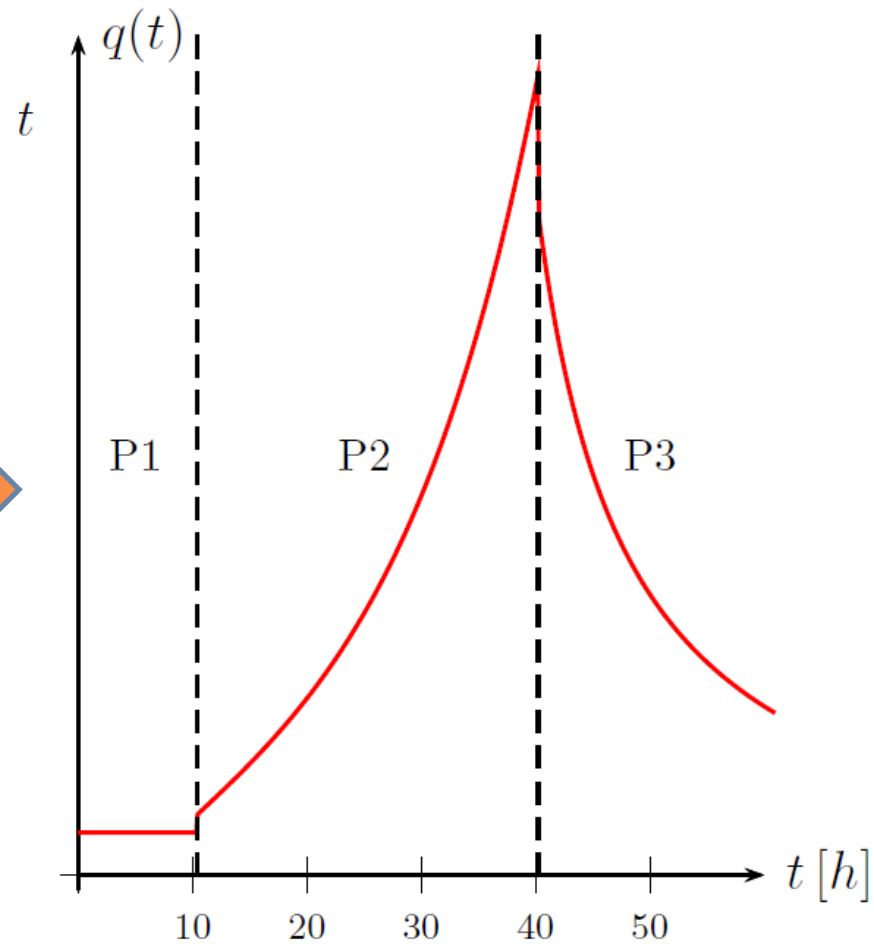
CONDUCTIVITY OF SHUNT

$$\sigma_{\mathrm{sf}}(t) \sim \int_{-\epsilon}^{\epsilon} n(x,t)\, dx$$

* Diss. V.Naumann, 2014

PID-s PROGRESSION





PHYSICAL MODEL FOR DEGRADATION AND RECOVERY

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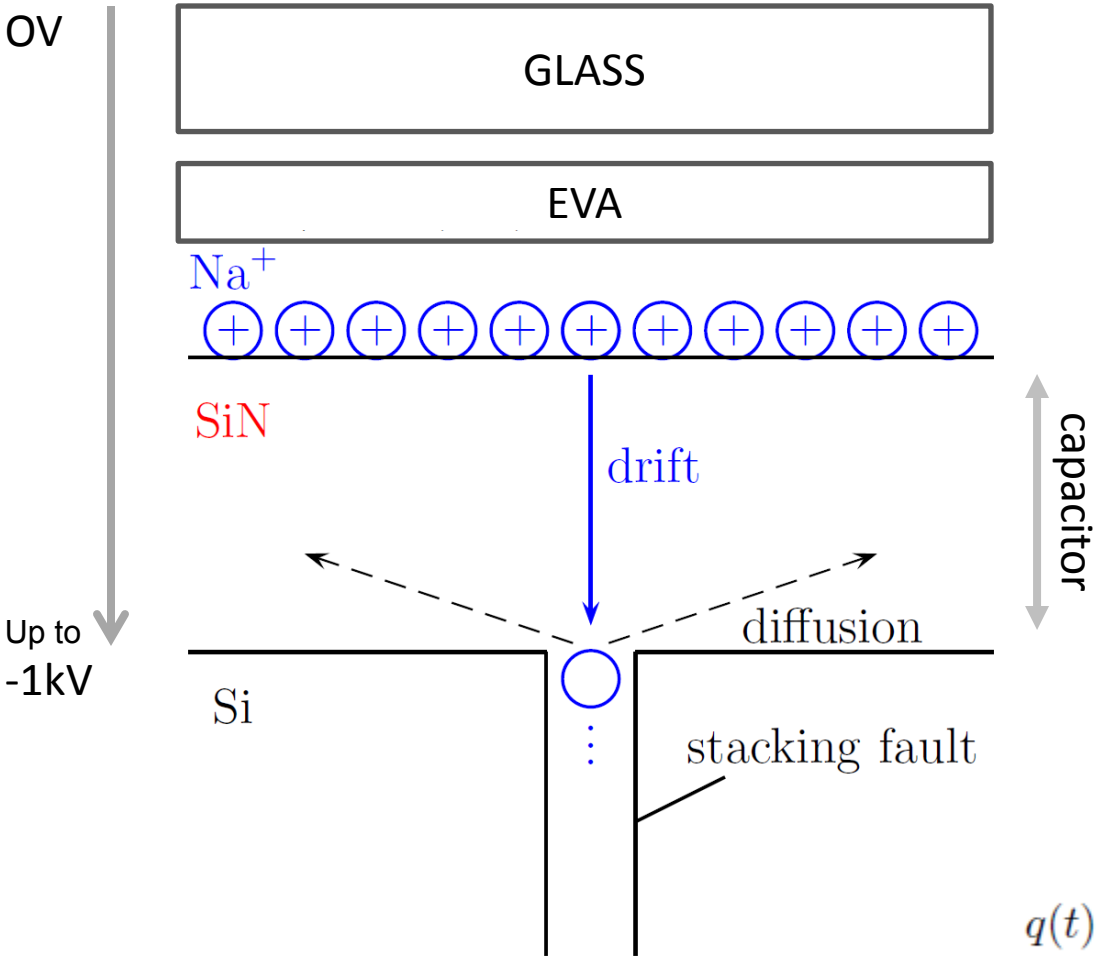

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CONDUCTIVITY OF SHUNT

$$\sigma_{\mathrm{sf}}(t) \sim \int_{-\epsilon}^{\epsilon} n(x,t)\, dx$$

DRIFT MODEL: STERN-EYRING RATE THEORY*

$$\mu_{\mathrm{Na}^+} = \frac{2D_{\mathrm{Na}^+}}{\lambda E} \sinh\left(\frac{q\lambda E}{2k_B T}\right)$$

SOURCE TERM

$$q(t) = c + \alpha_{\mathrm{se}} \sinh(\gamma_{\mathrm{se}}(t - t_0 + t_{\mathrm{ex}})) \cdot (t > t_0)$$

* Diss. V.Naumann, 2014

PROGRESSION OF PID-s
MODEL VS LABORATORY DATA

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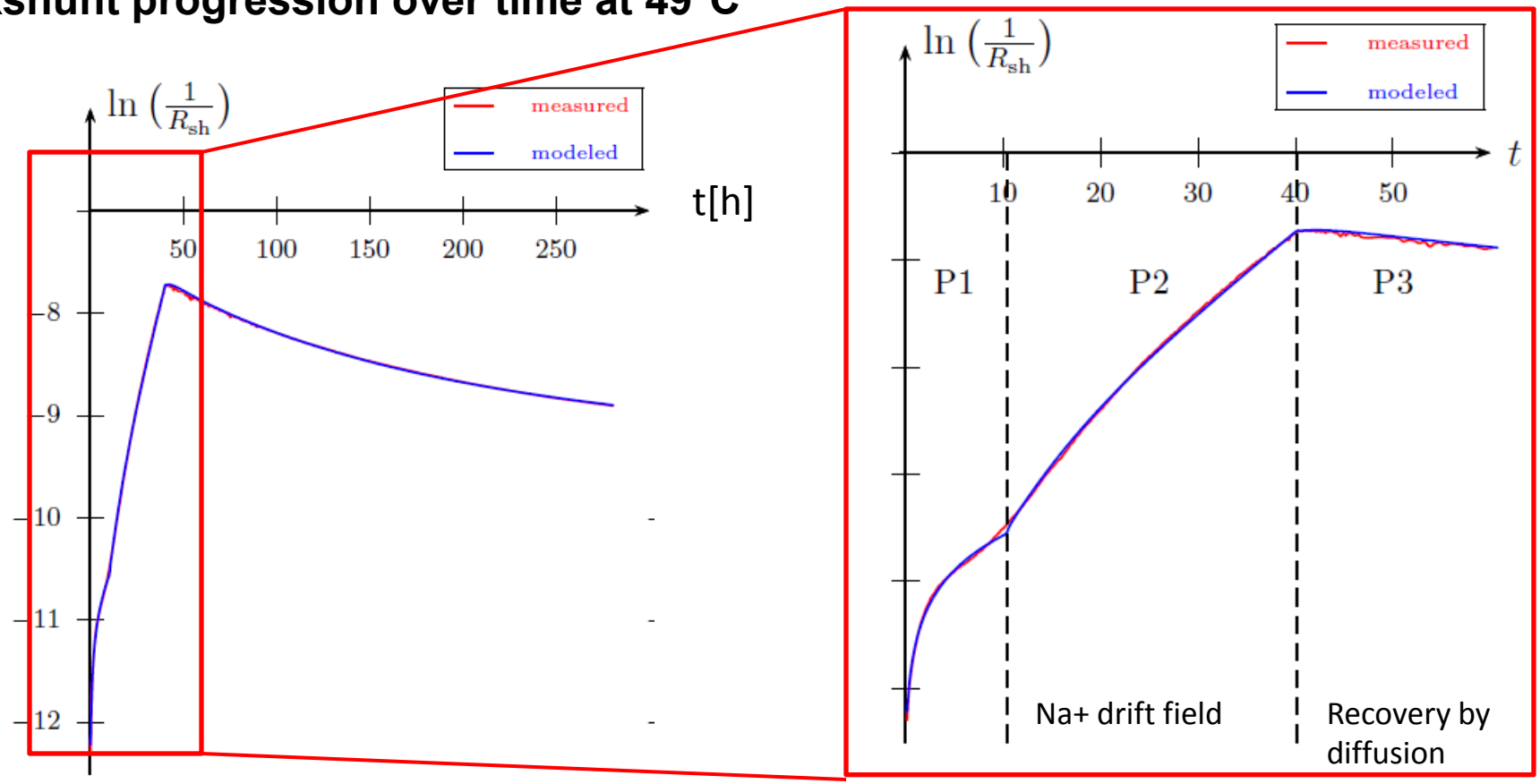
- **Rshunt progression over time at 49°C**



→ Excellent agreement between model and laboratory measurement

PROGRESSION OF PID-s
MODEL VS LABORATORY DATA

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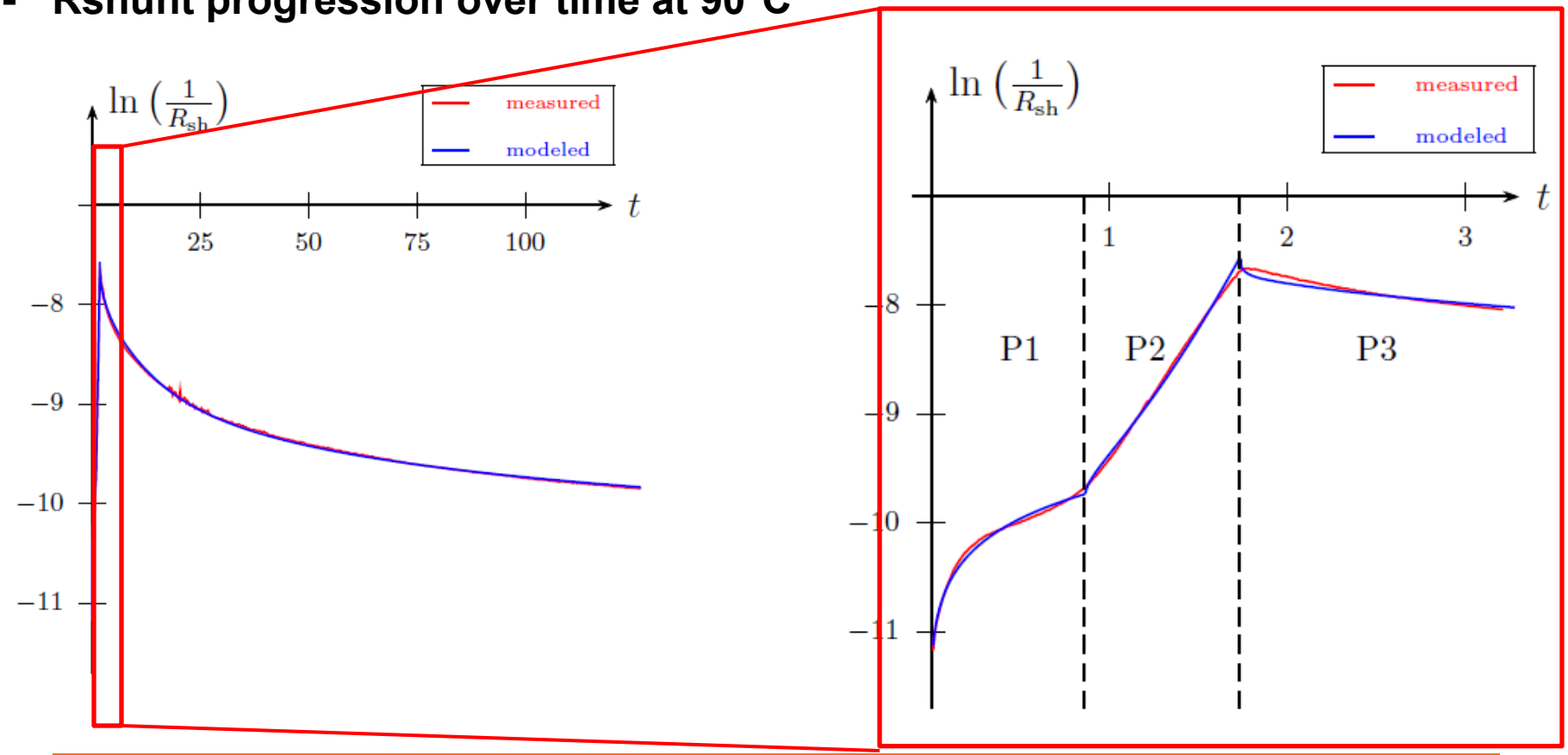
- **Rshunt progression over time at 90°C**



→ Excellent agreement between model and laboratory measurement
→ Different phases described correctly with one single model

MODELING FIELD PROGRESSION: STEPS FOR A LIFETIME MODEL

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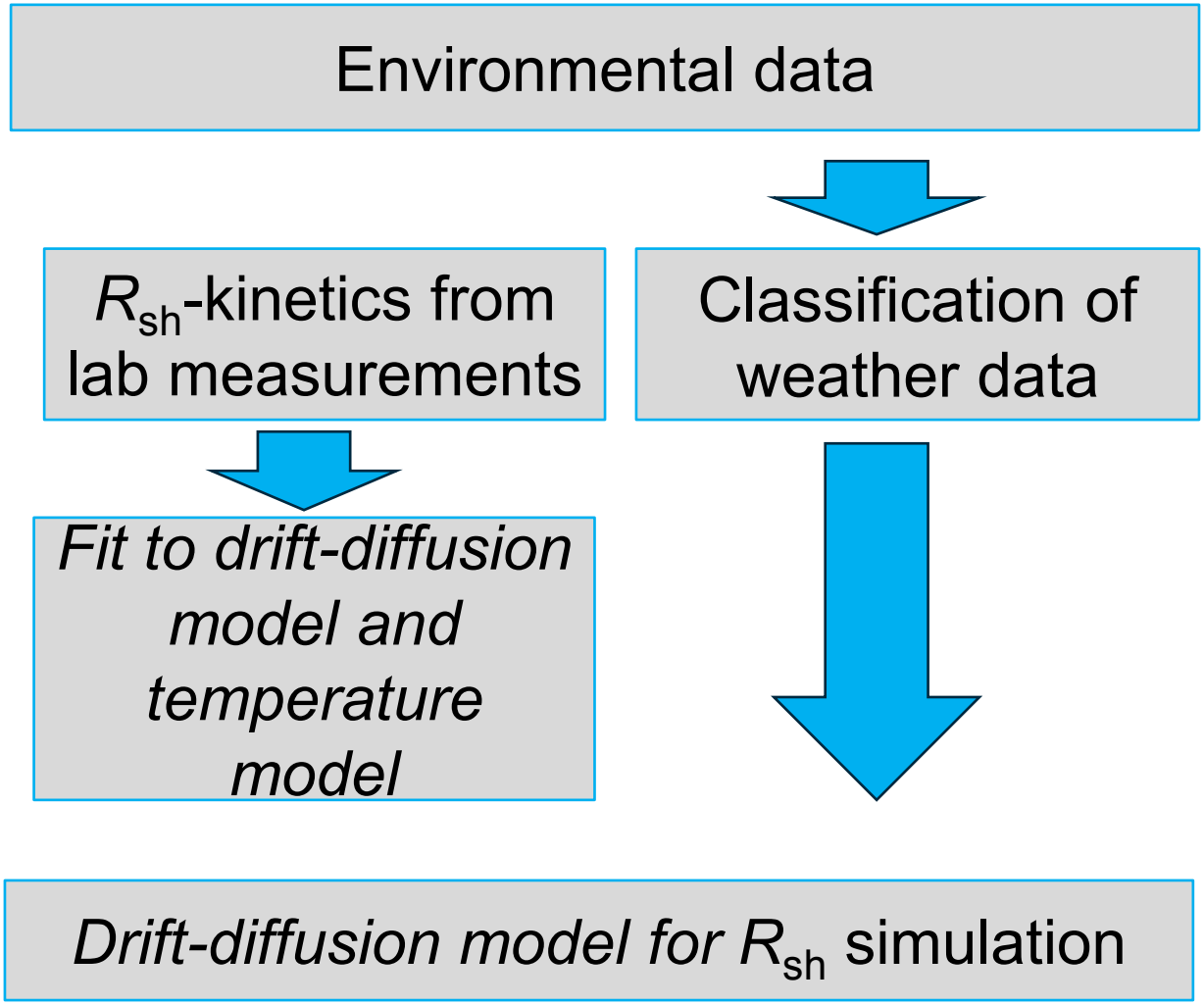

COMPARISON TO OUTDOOR MEASUREMENTS: THALHEIM GERMANY TEST SITE

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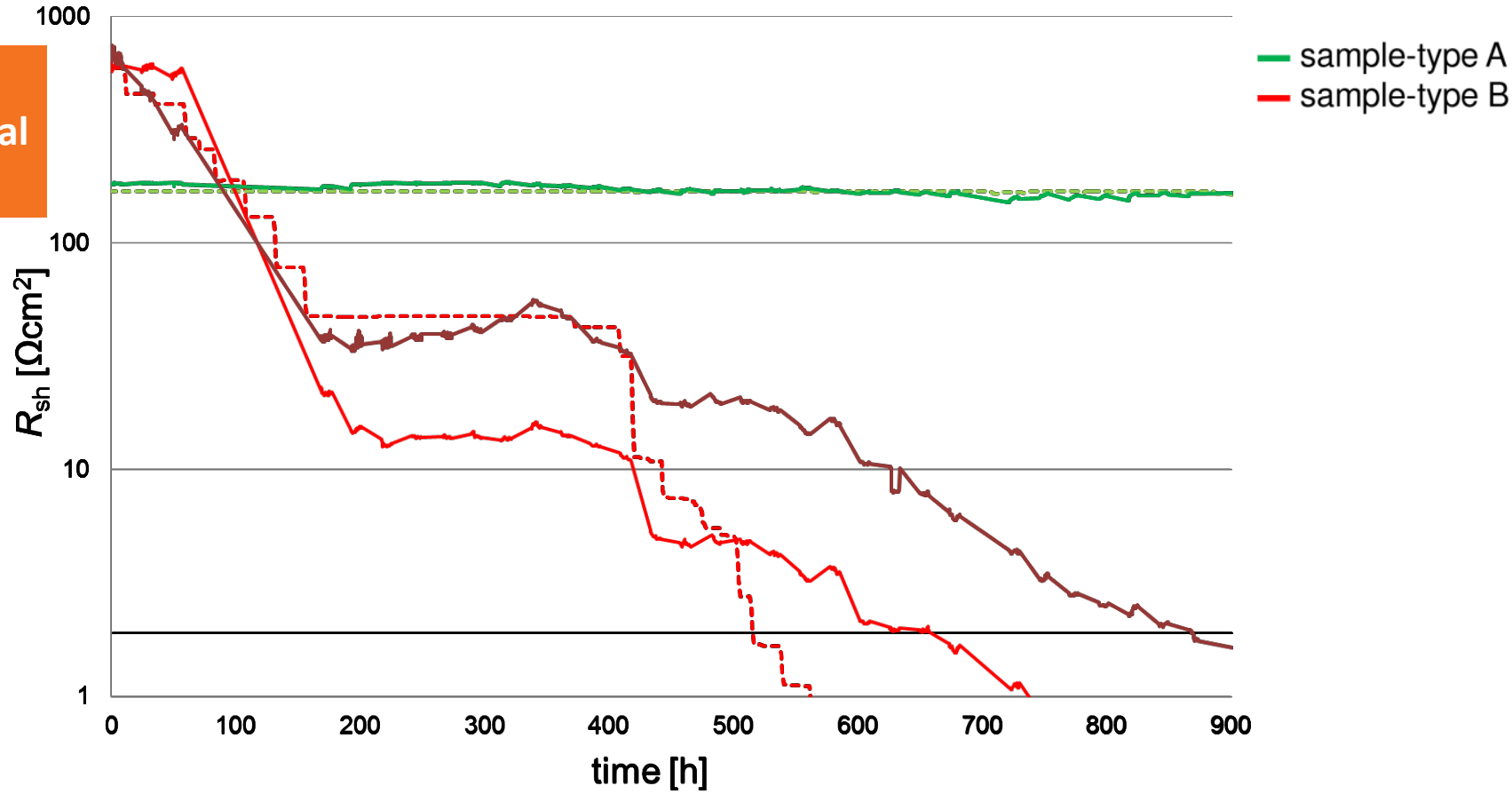
old empirical model



→ Good agreement with outdoor test data
→ Model can estimate time of onset in a specific location

CONCLUSION AND OUTLOOK

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- **reproducible PID tests are available** (Al-foil, climate chamber)
  - following protocol is essential in order to have reproducible results
  - tests apply constant stress
  - studying recovery properties is essential
  - IEC 62804 is basic susceptibility test
- **physical model based on drift and diffusion can describe degradation and recovery**
- **lifetime model based on laboratory tests and meteorological data can describe long term progression**
  - allows for prediction of time of PID-s onset in specific location

- **NEXT STEPS:**
  - **build temperature model**
  - **update of lifetime model with unified physical model**

Thank you

Denver, Feb 24th, 2016

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February 24, 2016. NREL PV Module Reliability Workshop

Alternate DH Test Methods To Mitigate Test-Specific Degradation in CIGS Modules

H. Tomita[1], D. Schmitz[1], S. Tokuda[1], K. Sakurai[2], K. Ogawa[2] and A. Masuda[2]

1. Solar Frontier KK
2. National Institute of Advanced Industrial Science and Technology (AIST)

Outline

Part 1. Introduction

Current DH test method
Module at high temperature in the field
Purpose of the study

Part 2. Experimental setup

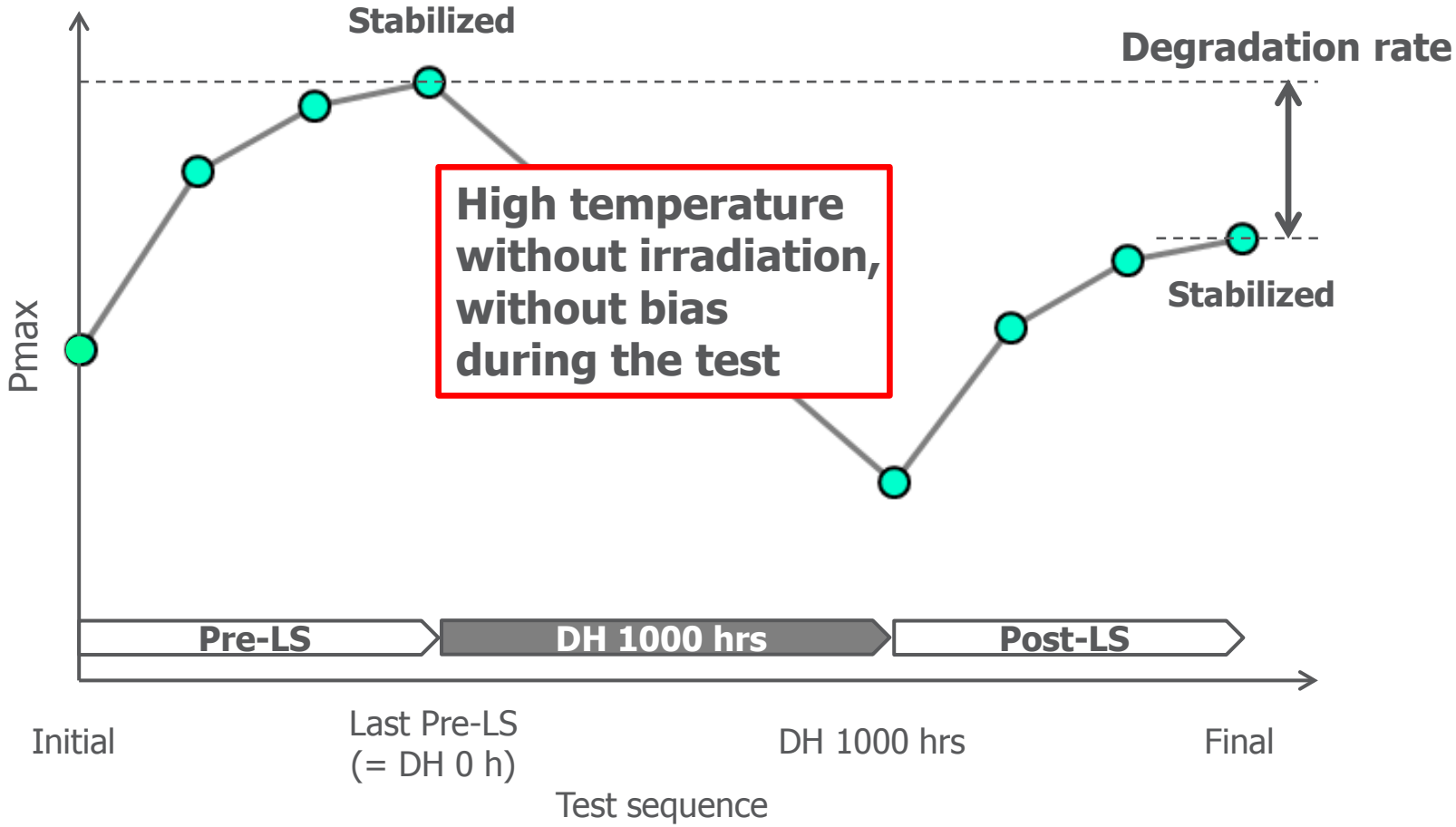
Types of tests, Test sequence
Experimental setup

Part 3. Experimental result

DH with/without light irradiation
DH with/without with forward bias
Dry heat test with/without forward bias
Can sufficient post-LS recover test-specific degradation ?

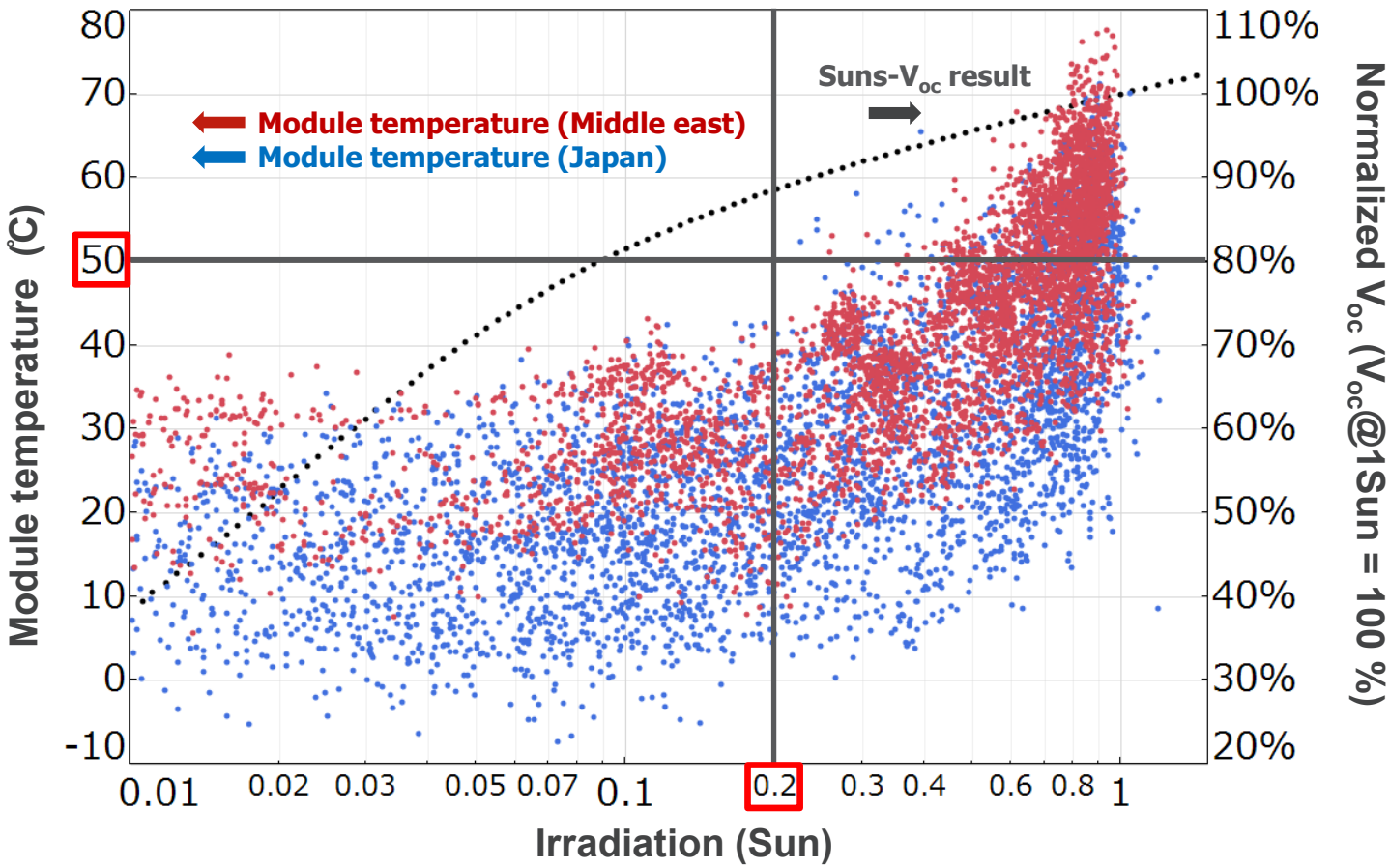
Part 4. Summary & Future work

Current DH test method



- Degradation rate is calculated from two stabilized Pmax values.
- **No bias application nor light irradiation during the current test.**

Module at high temperature in field



- In the real field, module temperature seldom exceeds 50 ℃ without > 0.2 Sun irradiation.
  ⇒ **High temperature & dark condition is unnatural state.**
- With 0.2 Sun irradiation, our CIGS shows 88 % of V_{oc} compared with 1Sun-V_{oc}.
  ⇒ **At high temperature, module is soaked in light and generating bias voltage.**

Purpose of the study

We suppose, in case of CIGS modules, **light irradiation** and **forward bias** may play an important role in reliability testing. To clarify this point, we tried various types of tests in this study.

Types of tests

5 types of tests below were performed with SF 170W-class CIGS modules.

	Test type	Irradiation	Bias
Wet	Normal DH	—	—
	DH with irradiation	0.2 Sun*	—
	DH with forward bias	—	NMOT-V_{pm}** STC-V_{pm}*
Dry	Normal dry heat test	—	—
	Dry heat test with forward bias	—	NMOT-V_{pm}** STC-V_{pm}*

* Performed at AIST. Others were performed at SF.
**NMOT : Nominal Module Operating Temperature.

Test sequence

1st Pre-LS → 2nd Pre-LS → **Test 1000hrs** → 1st Post-LS → 2nd Post-LS

- Open-circuit state
- LS chamber for 21 hrs (SF) or Outdoor for one week (AIST)

- Open-circuit state
- LS chamber for 21 hrs (SF) or Outdoor for one week (AIST)

With some modules, we performed additional post-LS with **Pmpp-state** (LS with resistor-loaded state).

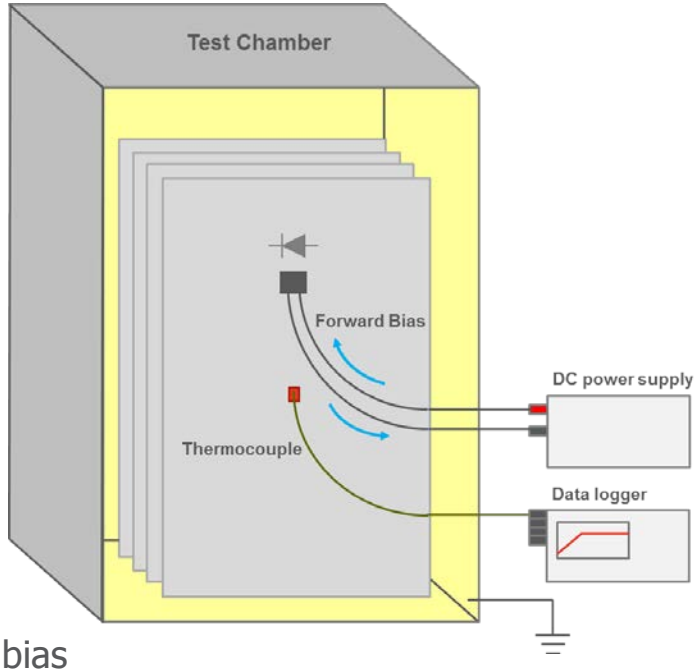
Additional Post-LS

Experimental setup

Test with light irradiation

Chamber with white LED light

Test with forward bias

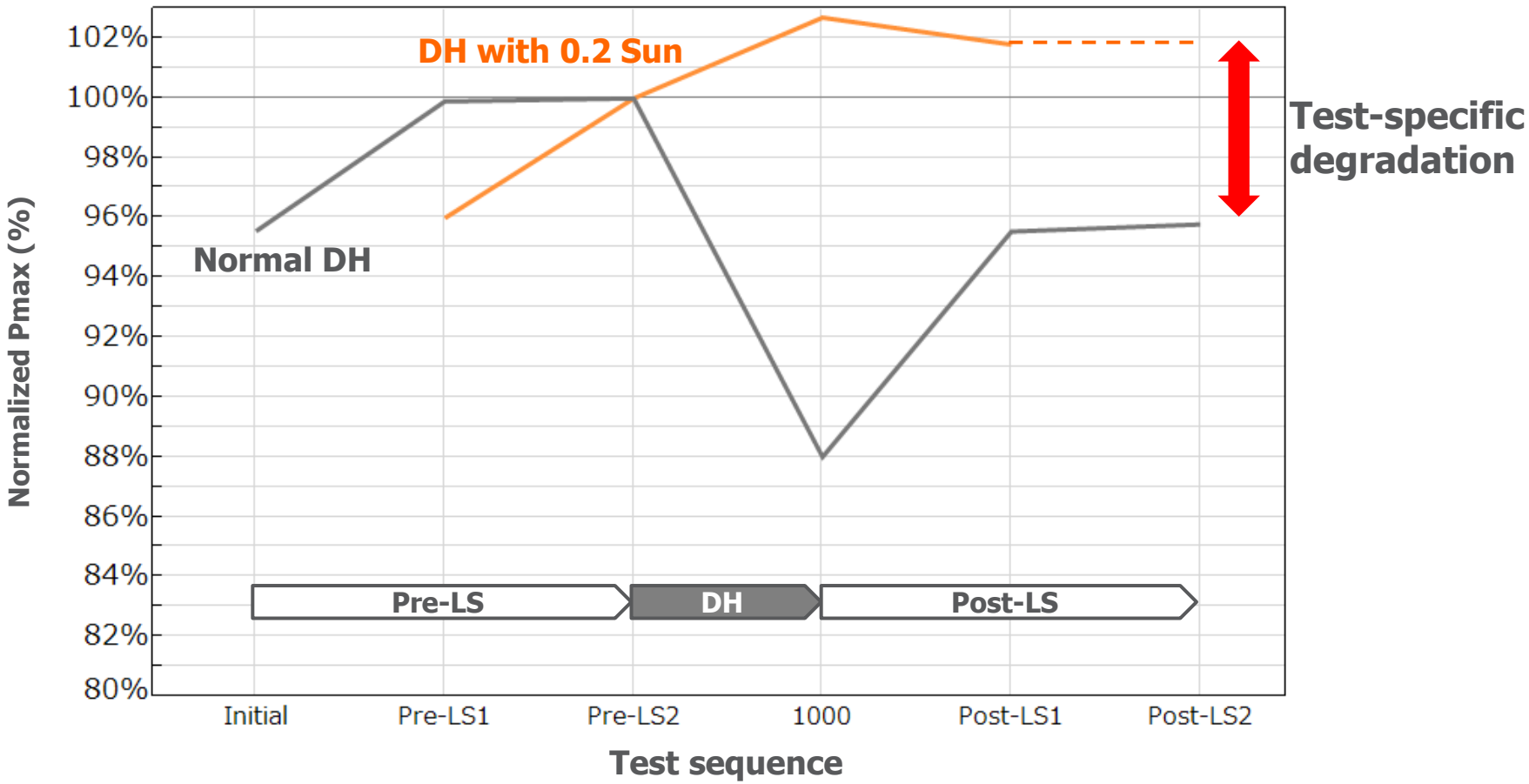


Chamber for test with forward bias

Module current : ~ 0.2 A
(with NMOT-V_{pm}, T_{mod} 85 ℃)

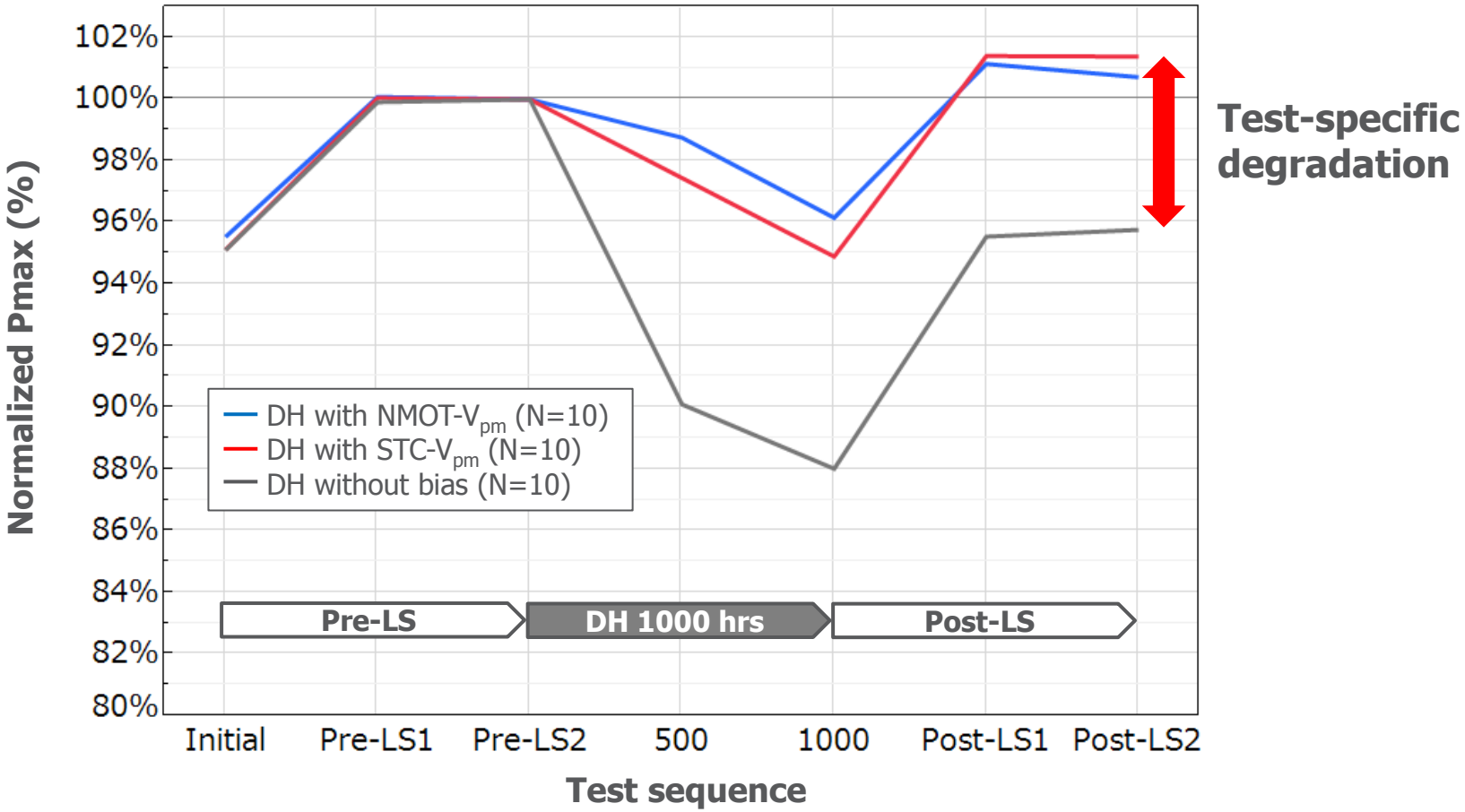
In case of test with bias application, chamber condition (temp. & hum.) was set to stabilize the module surface 85℃ & 85 %RH.

DH with/without light irradiation



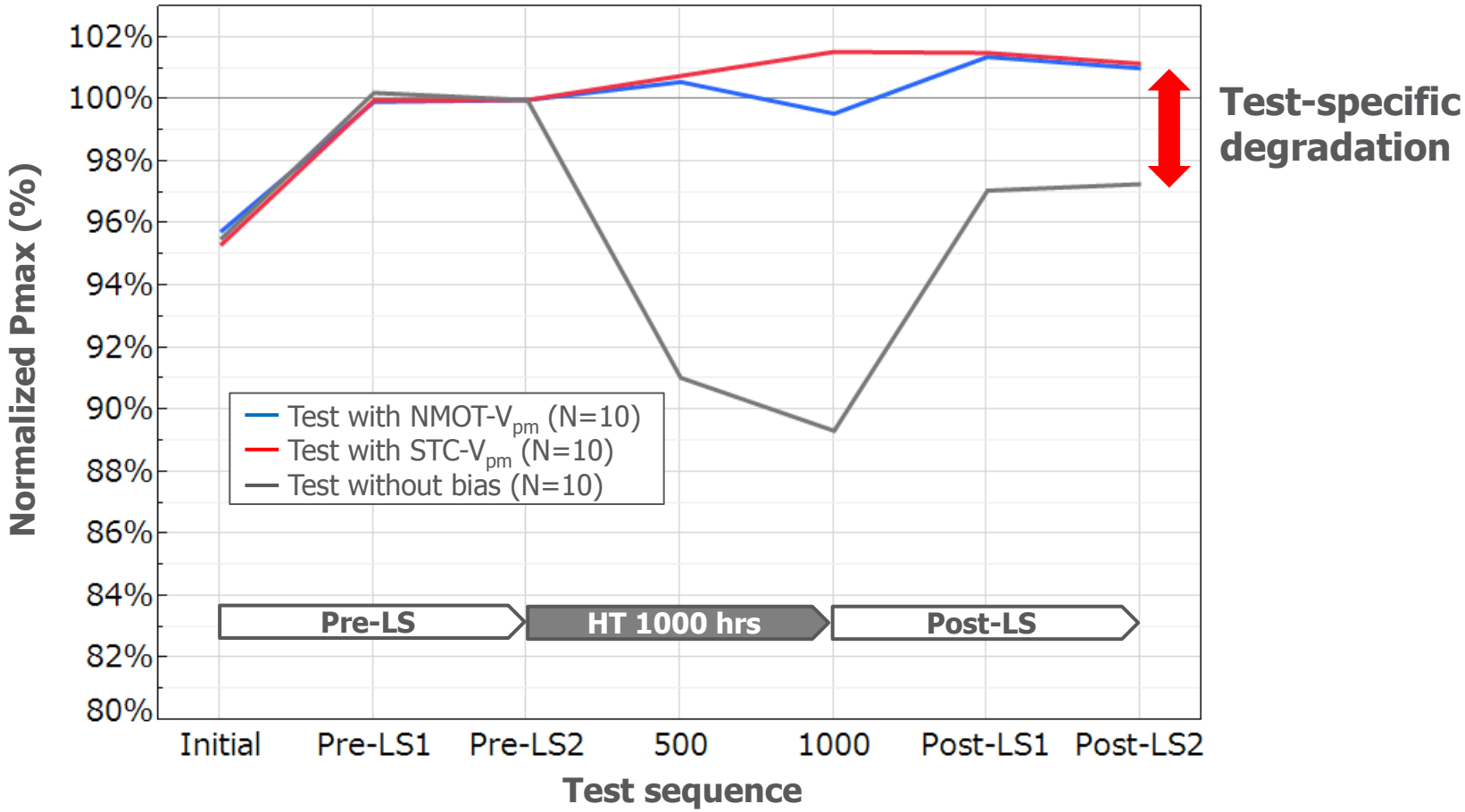
- The modules after DH with light irradiation showed good reliability. Meanwhile, the modules after normal DH showed significant drop.
- Even after post LS, the gap between DH with light irradiation and normal DH still remained.
  ⇒ **Dark DH test triggers "test-specific degradation".**

DH with/without forward bias



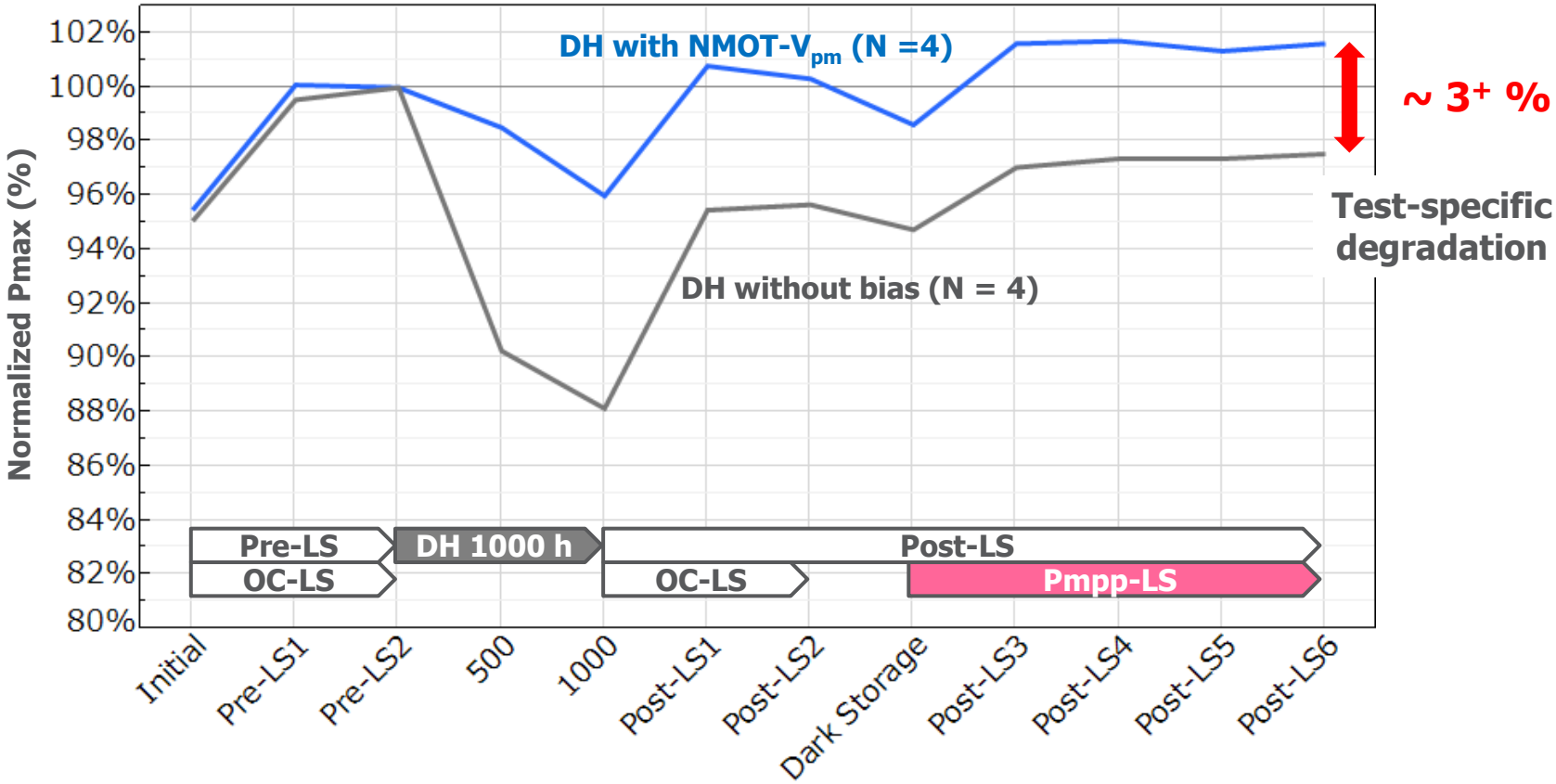
➢ The modules after DH with forward bias also showed similar behavior to those observed in the field.
⇒**Forward bias application shows similar effect to light irradiation.**

Dry heat test with/without forward bias



➢ Even in the dry condition, test without bias showed test-specific degradation.
⇒ **There's no relation between humidity and test-specific degradation.**
"Dark heat state" creates it.

Can sufficient Post-LS recover test-specific degradation? ⇒ No.



➢ We tried 4 times of Pmpp-LS (resistor-loaded LS) as additional post LS, but test-specific degradation (3+ % in this study) still remained.
⇒**Test-specific degradation is irreversible and cannot be recovered with post LS conditioning.**

Summary

- In the real field, high temperature with sun irradiation is the natural state. And even 0.2 Sun irradiation generates adequate forward bias.
- The modules after DH with light irradiation or forward bias showed similar behavior to real field. Meanwhile, normal DH brought "Test-specific degradation", which is not observed in field.
- Test-specific degradation is irreversible.

Take-home message :

DH with bias application or DH with light irradiation is more suitable test to evaluate the reliability of CIGS modules.

Future work

- DH with 0.1 Sun irradiation.
- DH with/without bias (Pmpp Pre-LS version).
- Understanding of mechanism of test-specific degradation.

☺ Thank you for your attention !

Contact : h.tomita@solar-frontier.com

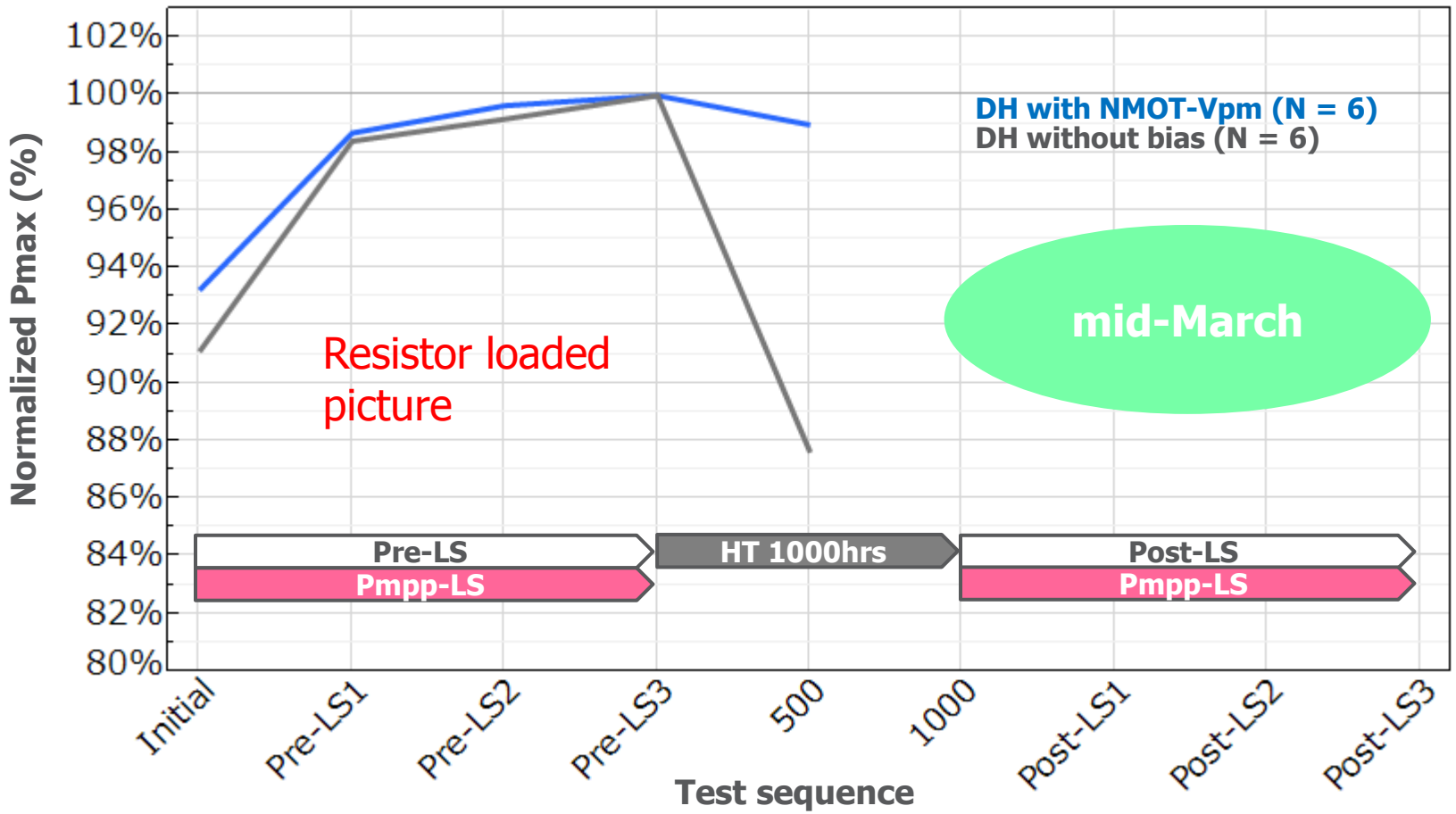
February 24, 2016. NREL PV Module Reliability Workshop

Backup

Backup

Current work : DH with / without forward bias

(Pmpp Pre-LS version)



➢ DH with NMOT-Vpm (6 modules) & DH without bias (6 modules) are under testing in SF.

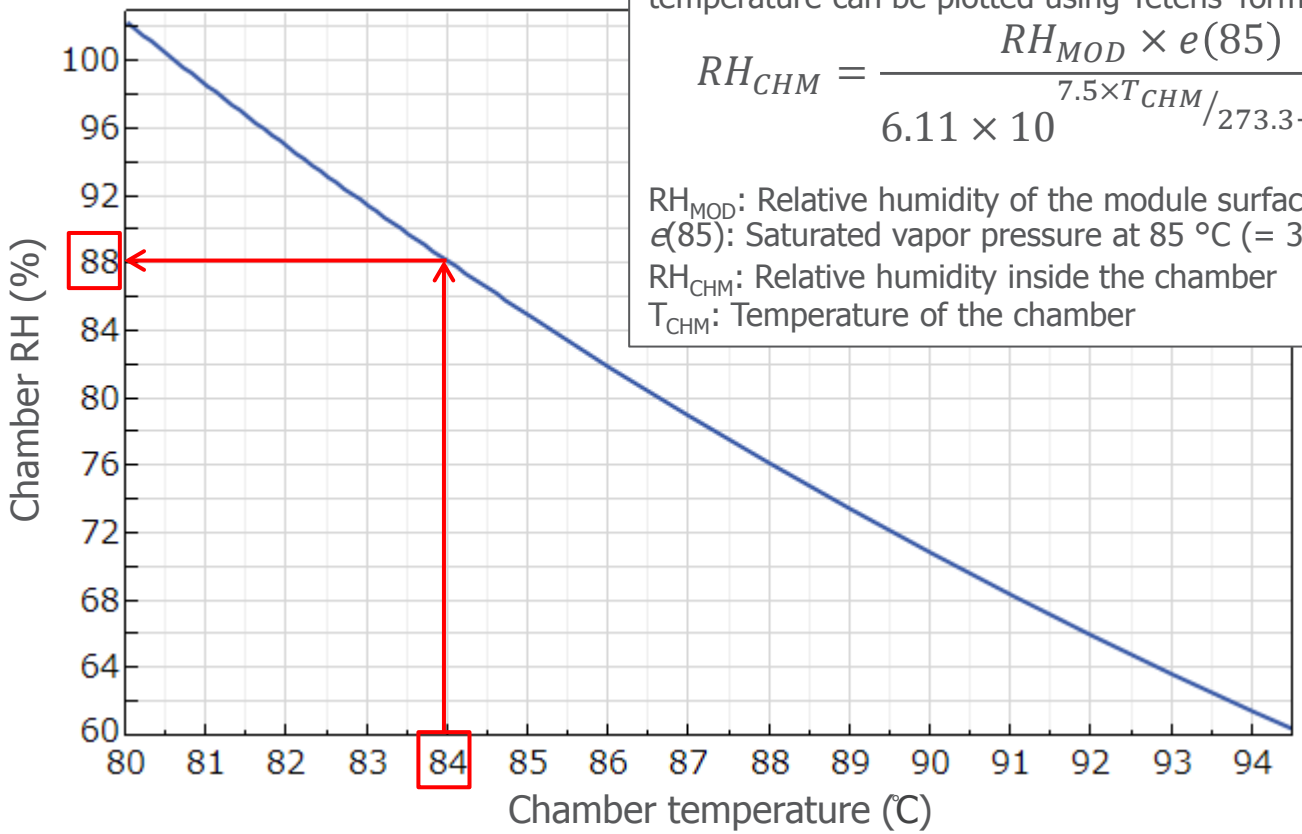
Backup

How to determine the chamber RH value

The curve of chamber relative humidity as a function of chamber temperature can be plotted using Tetens' formula:

$$RH_{CHM} = \frac{RH_{MOD} \times e(85)}{6.11 \times 10^{7.5 \times T_{CHM} / 273.3 + T_{CHM}}} \times \frac{1}{100}$$

RH_{MOD}: Relative humidity of the module surface (= 85 %)
$e(85)$: Saturated vapor pressure at 85 °C (= 367 hPa)
RH_{CHM}: Relative humidity inside the chamber
T_{CHM}: Temperature of the chamber

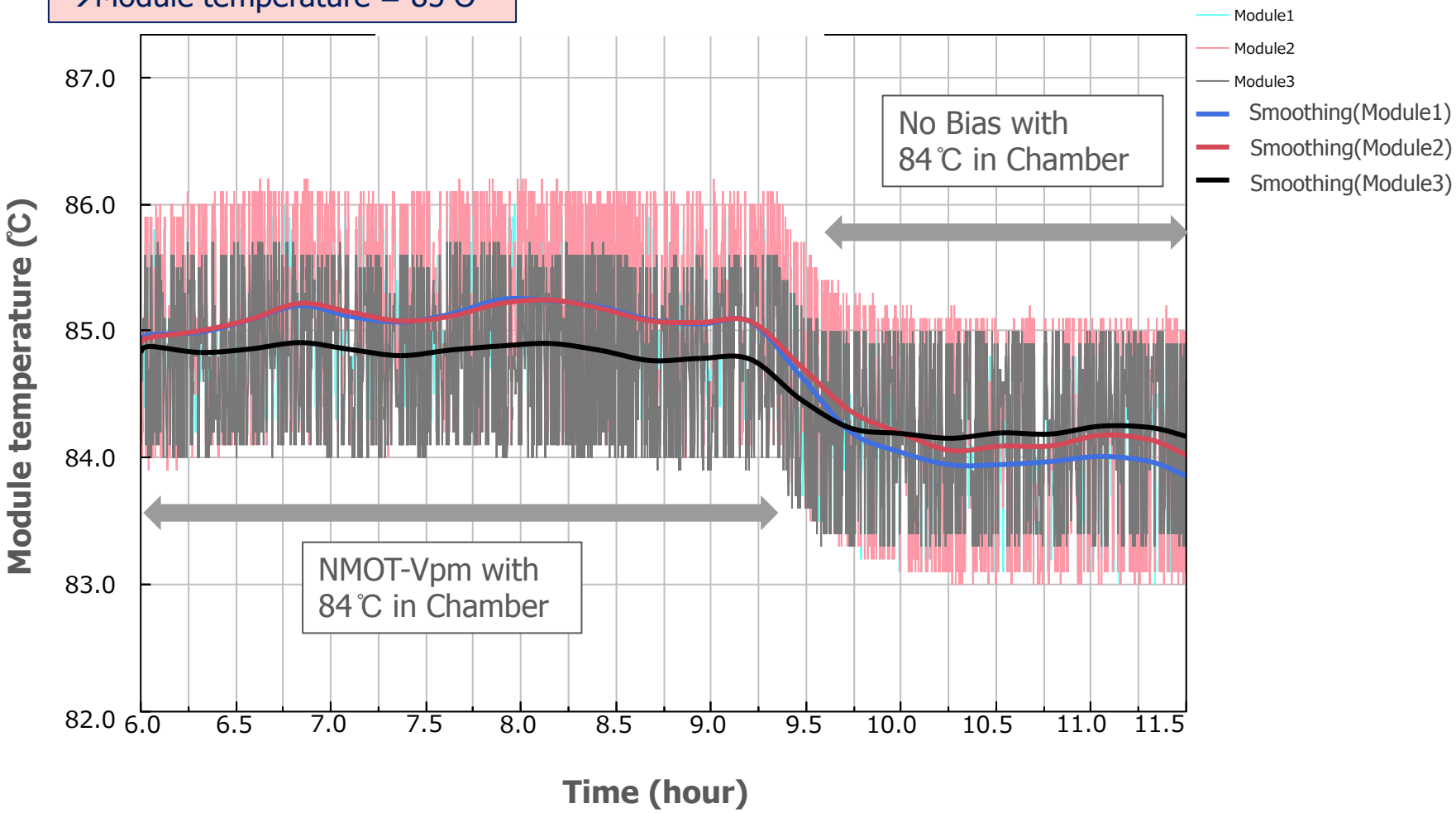


➢ Chamber RH should be set to realize the module surface RH 85%.
In case of our study, chamber temperature was set 84 ℃ to realize the module temperature 85 ℃.
Then, according to this graph, we set chamber RH 88 %.

Backup

Preliminary Testing of Module Temperature

With Vpm (at NMOT) bias,
Chamber temperature = 84℃
→Module temperature = 85℃



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Partial-shade endurance testing for monolithic thin-film photovoltaic modules

Timothy J Silverman
Michael G. Deceglie
Chris Deline
Sarah Kurtz

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory.

Agenda

Why partial shade matters

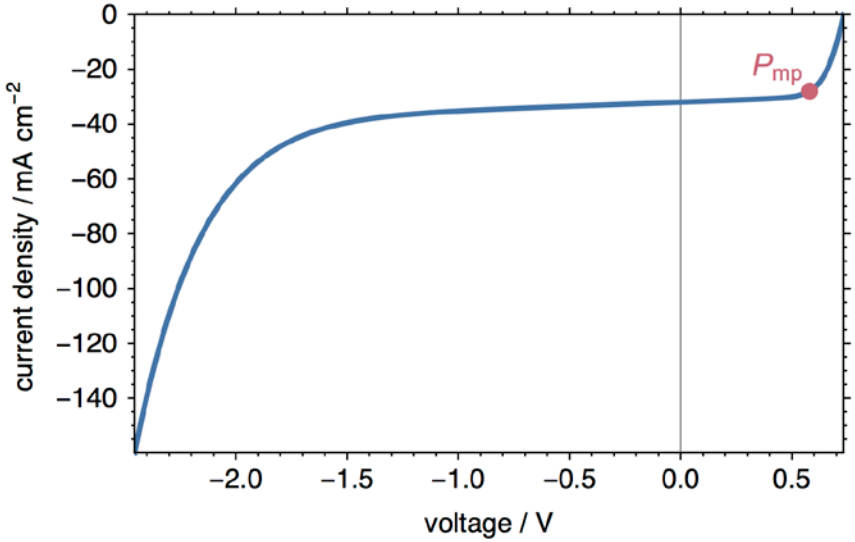
Designing a quantitative test

- Preliminary testing
- Computer simulations

Results from trial testing

Reverse bias in cells

Reverse bias can damage PV cells



Large voltage

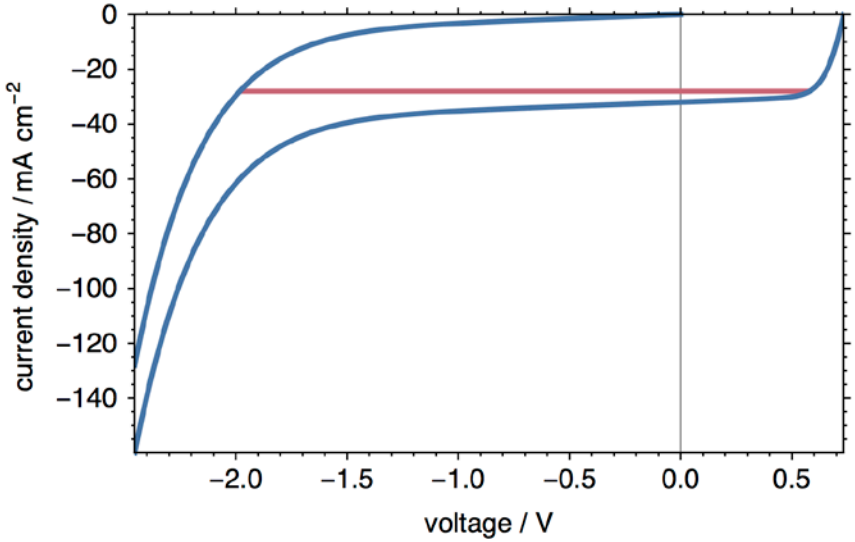
High current density

High temperature

Stress can be worse at local flaws

Reverse bias in modules

Reverse bias occurs in modules when they are in partial shade

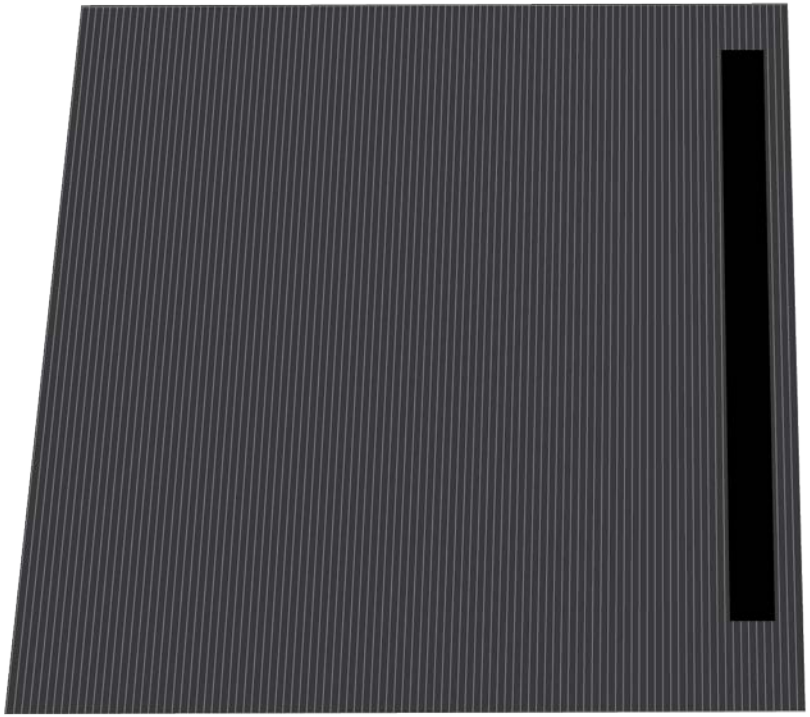


Most thin-film modules are series connected

The current-matching requirement drives shaded cells into reverse bias

Reverse bias in service

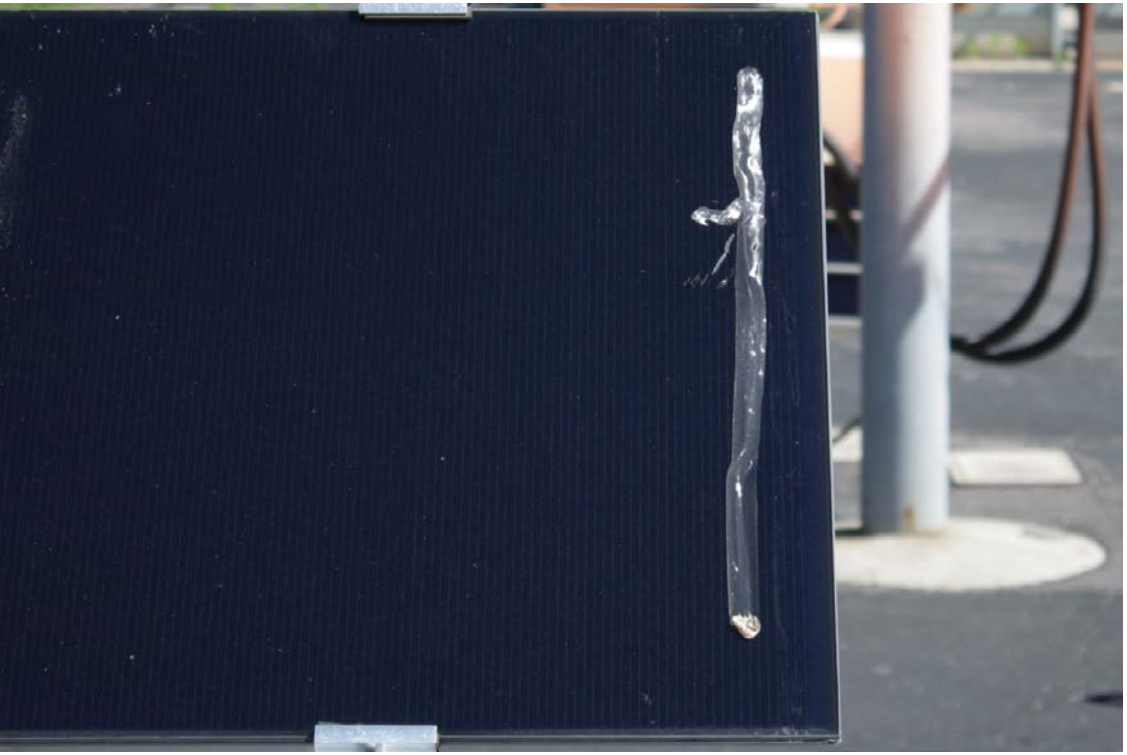
Partial shade happens in service



It is realistic for several cells to be mostly or completely covered with a mask

Reverse bias in service

Partial shade happens in service



It is realistic for several cells to be mostly or completely covered with a mask

Reverse bias in service

Partial shade happens in service

It is realistic for several cells to be mostly or completely covered with a mask

Testing for durability to partial shade

The standard hot spot endurance test and our test consist of two stages

Determine the size of the “worst-case” shadow

Apply the “worst-case” shadow to drive failures due to voltage, current density, temperature

Designing a quantitative test

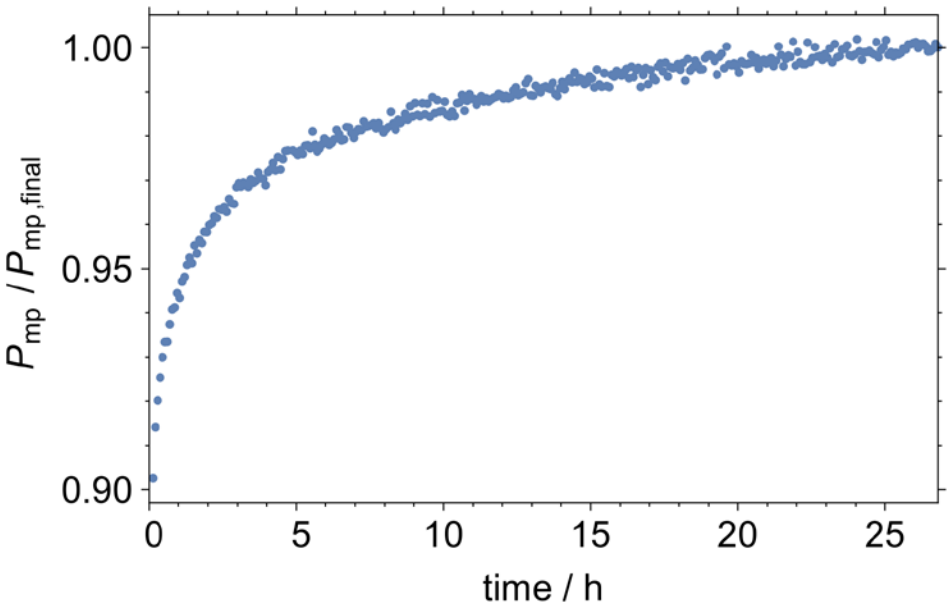
The standard hot-spot durability test does not quantify performance loss

A test that quantifies loss of performance must consider

- Light exposure effects (metastability)
- Damage done when mask size is being decided
- Light-enhanced reverse breakdown
- Realistic illumination and electrical conditions

Problem

Light exposure effects



Changing P_{mp} under constant illumination at 1000 Wm^{-2} at 50°C

Thin-film modules show reversible changes in performance with light exposure

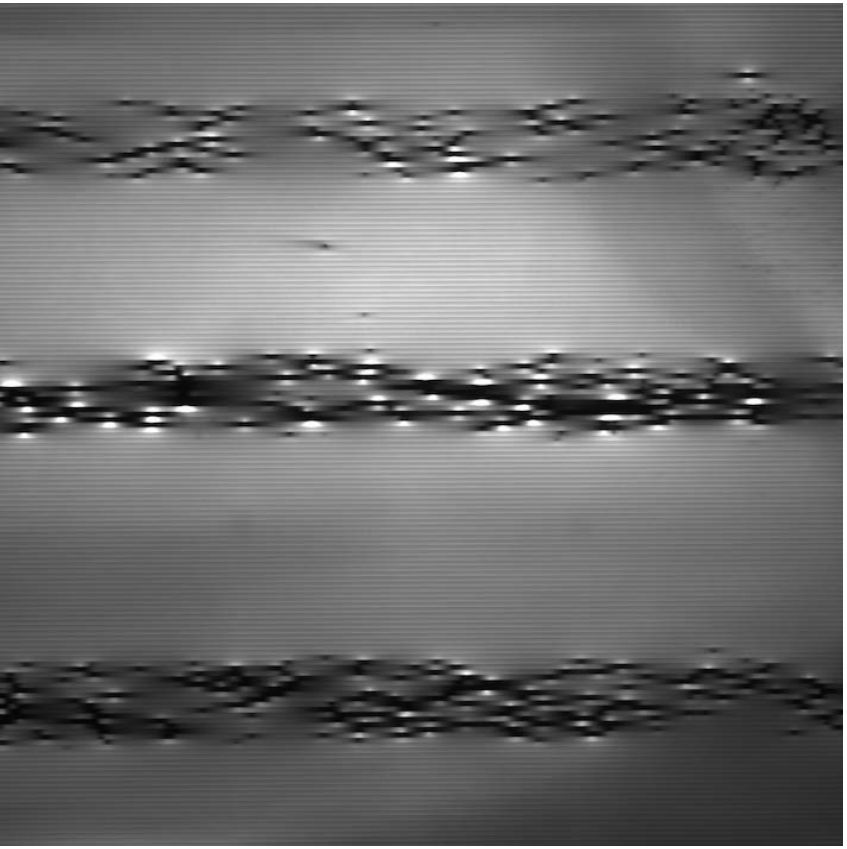
These can mask or masquerade as permanent changes resulting from stress

We follow the practices recommended by Deceglie, et al.

Deceglie et al., *SPIE Optics+ Photonics for Sustainable Energy* (2015)

Problem

Damage when determining mask size



EL image showing widespread shunting after flash testing with an opaque mask in three locations

Flash testing a module (~100 ms) with a mask causes permanent damage

This damage can affect subsequent steps

Solution:

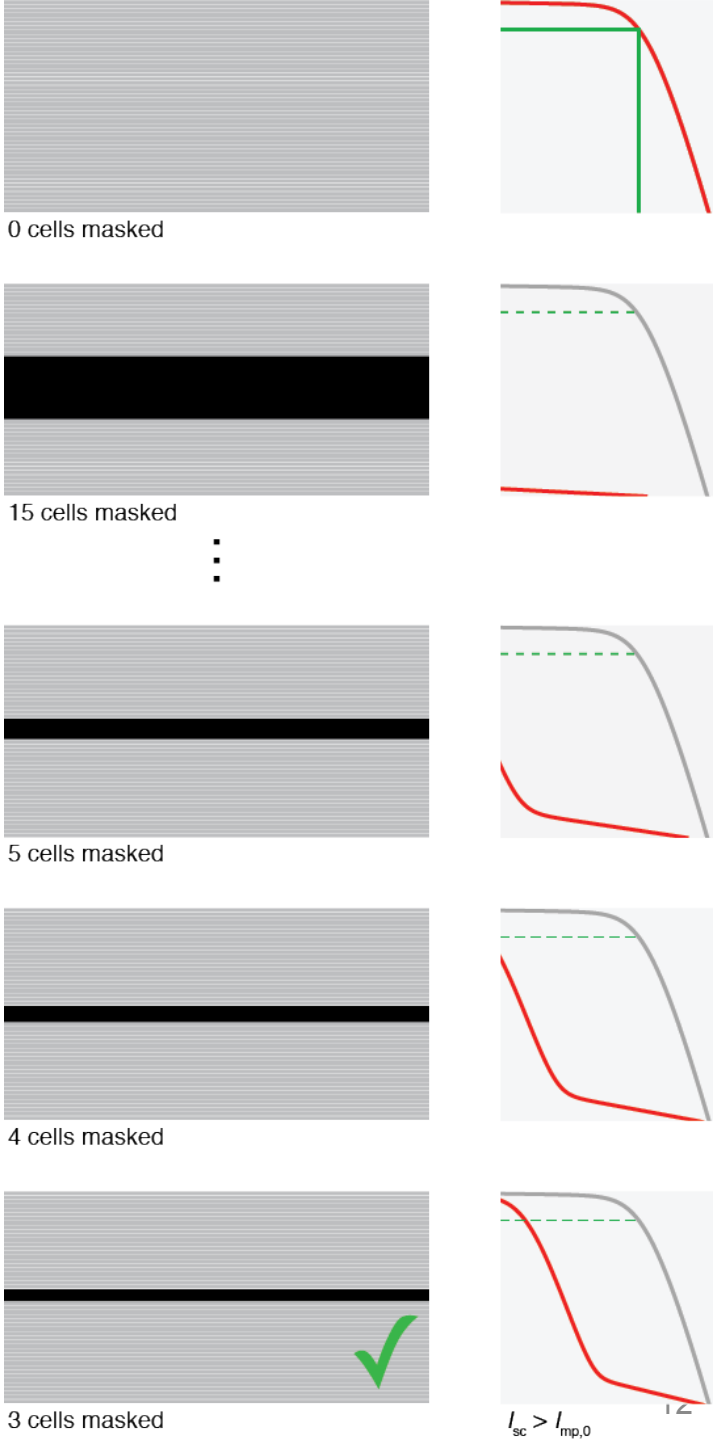
Decreasing-size procedure

We start with a large mask and decrease its size

- This reduces the likelihood that damage will affect later results

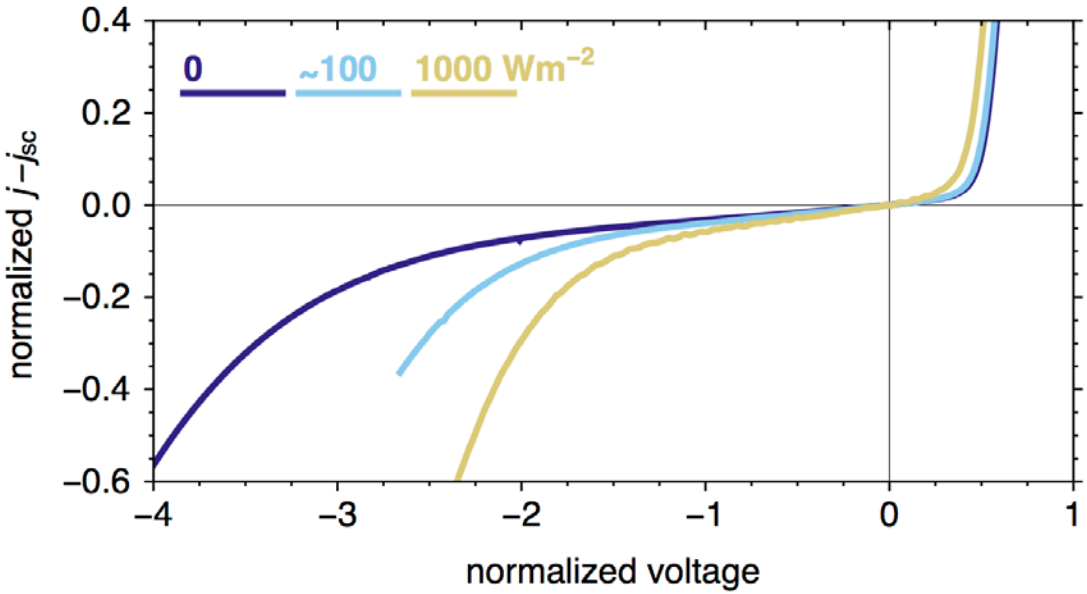
We use the largest mask where I_{sc} exceeds $I_{mp,0}$

- This is the largest mask with nearly the highest power dissipation per cell



Problem

CIGS has light-enhanced reverse breakdown



Light-dependent JV curves from an unencapsulated commercial CIGS coupon

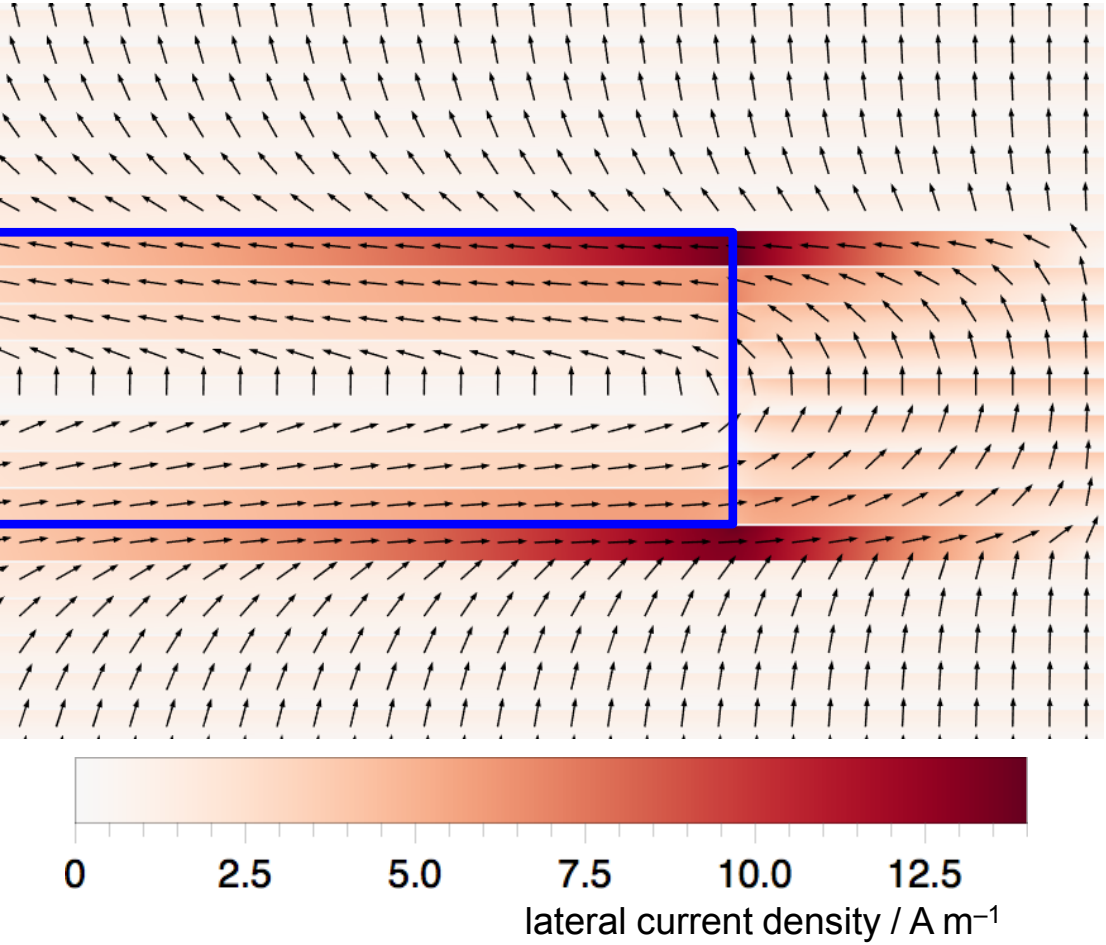
Curves are shifted to pass through the origin

The reverse breakdown voltage of commercial CIGS cells is sensitive to illumination, especially at low irradiance

This light-enhanced reverse breakdown (LERB) effect has consequences for the stress that occurs during partial shade

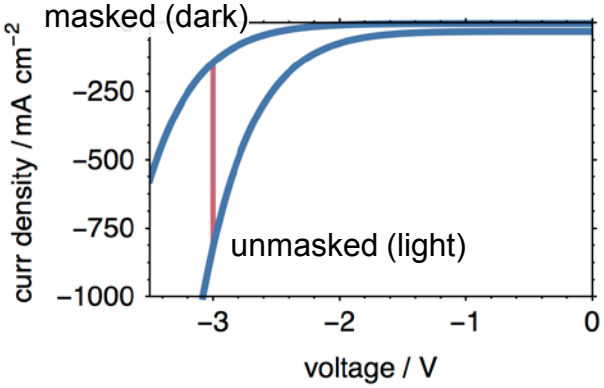
Silverman, et al., J-PV 5: 6 (2015)

Crowded current in a module with LERB



Near the edge of a shadow, cells pass high current density and reach high temperature

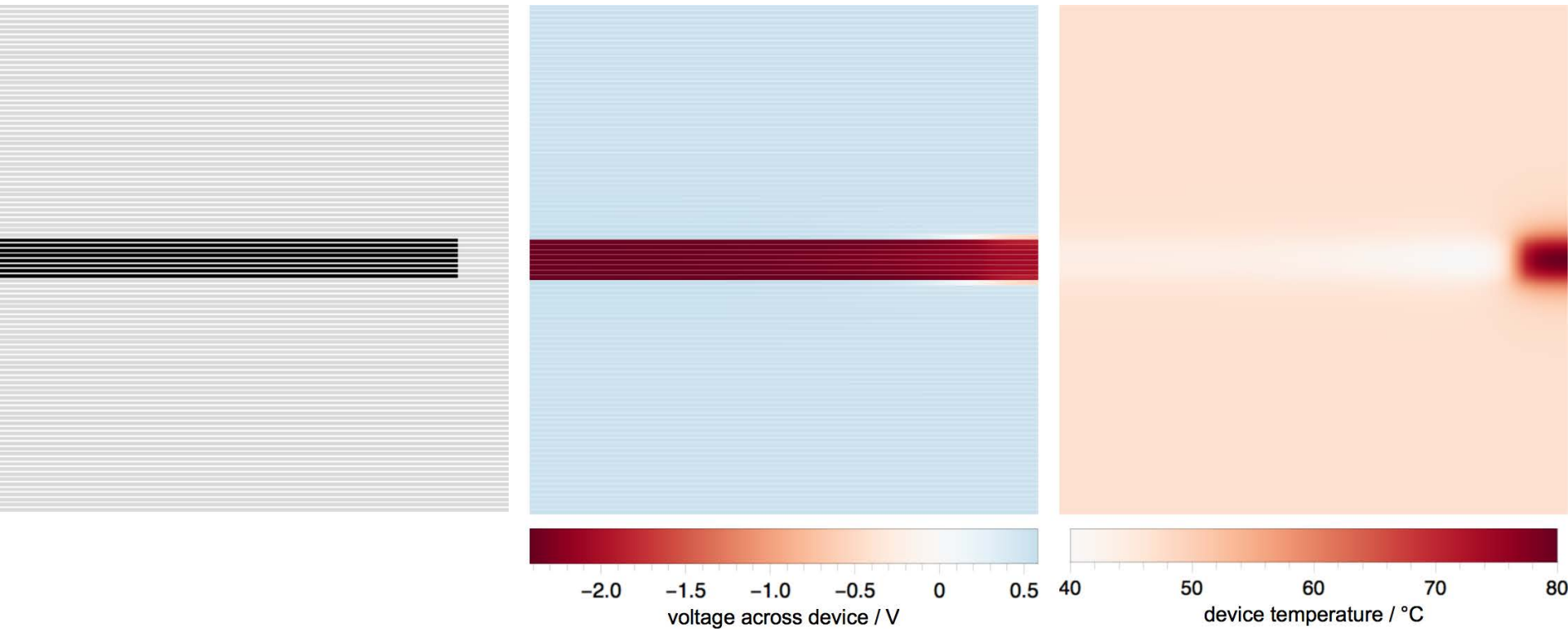
The image shows a crop of the full module area; the blue rectangle shows the masked area



Silverman, et al., J-PV 5: 6 (2015)

Solution

Partial-extent, partially opaque mask



We use a 90% extent, 90% opaque mask for stress

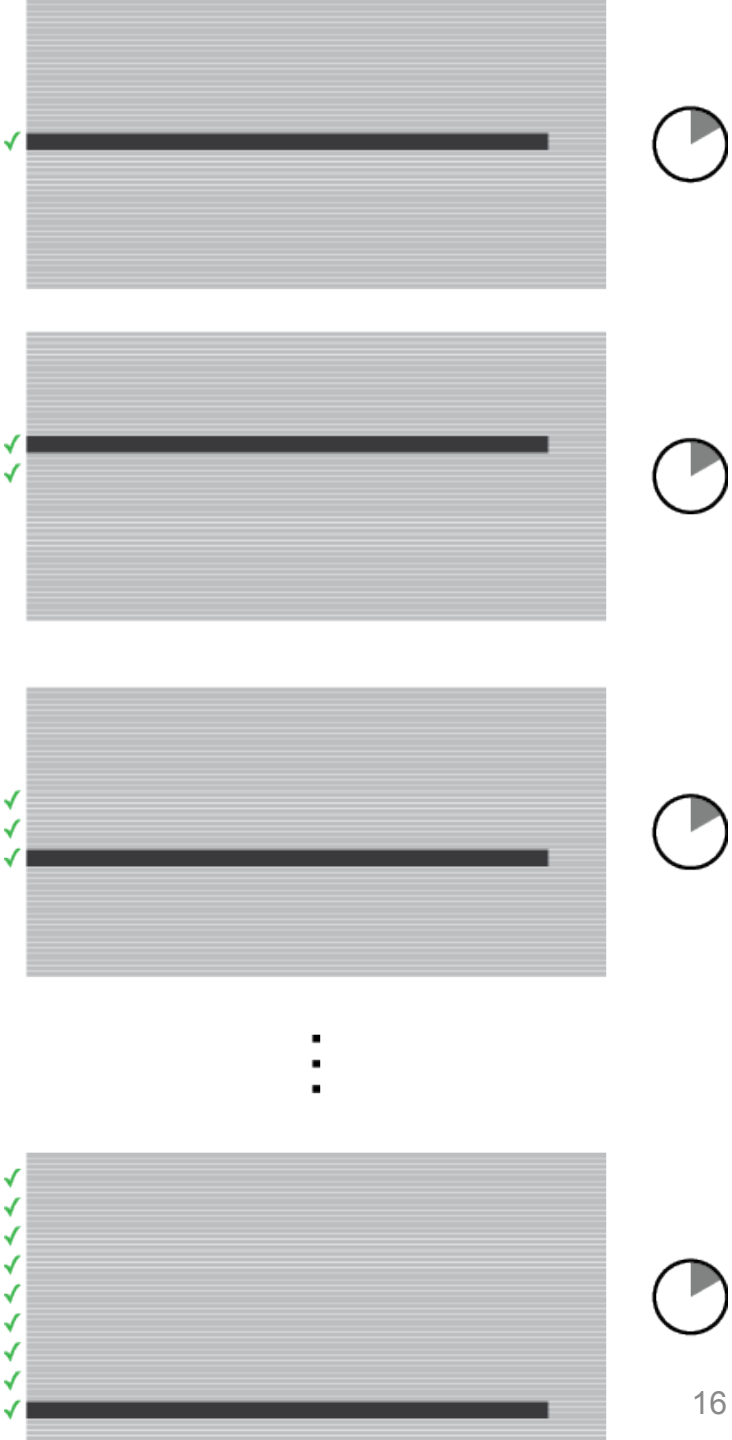
- Enables current crowding in the unmasked area
- Reduces sensitivity to exact mask opacity

Silverman, et al., J-PV 5: 6 (2015)

Multiple mask applications

Real shadows move across the module

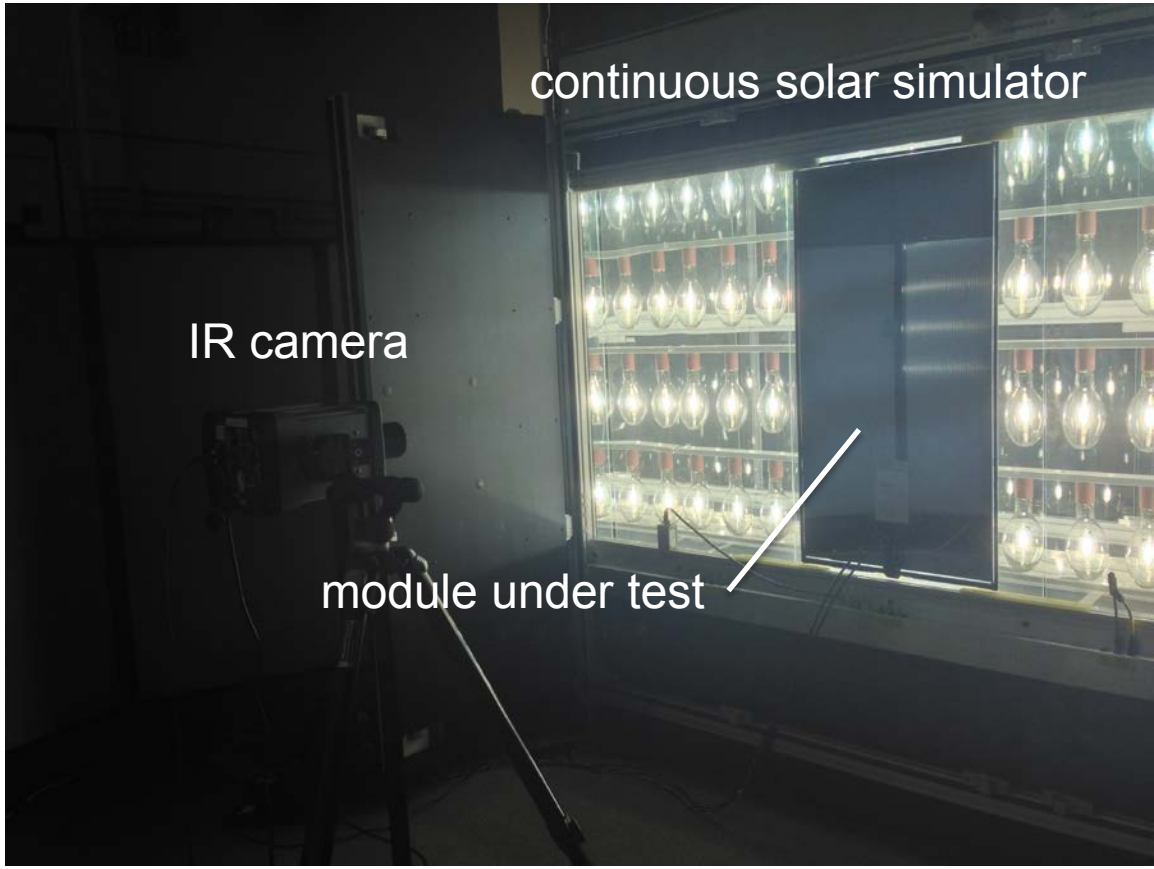
We apply the mask repeatedly until ≥50% of cells have been stressed for 10 min



Realistic electrical loading

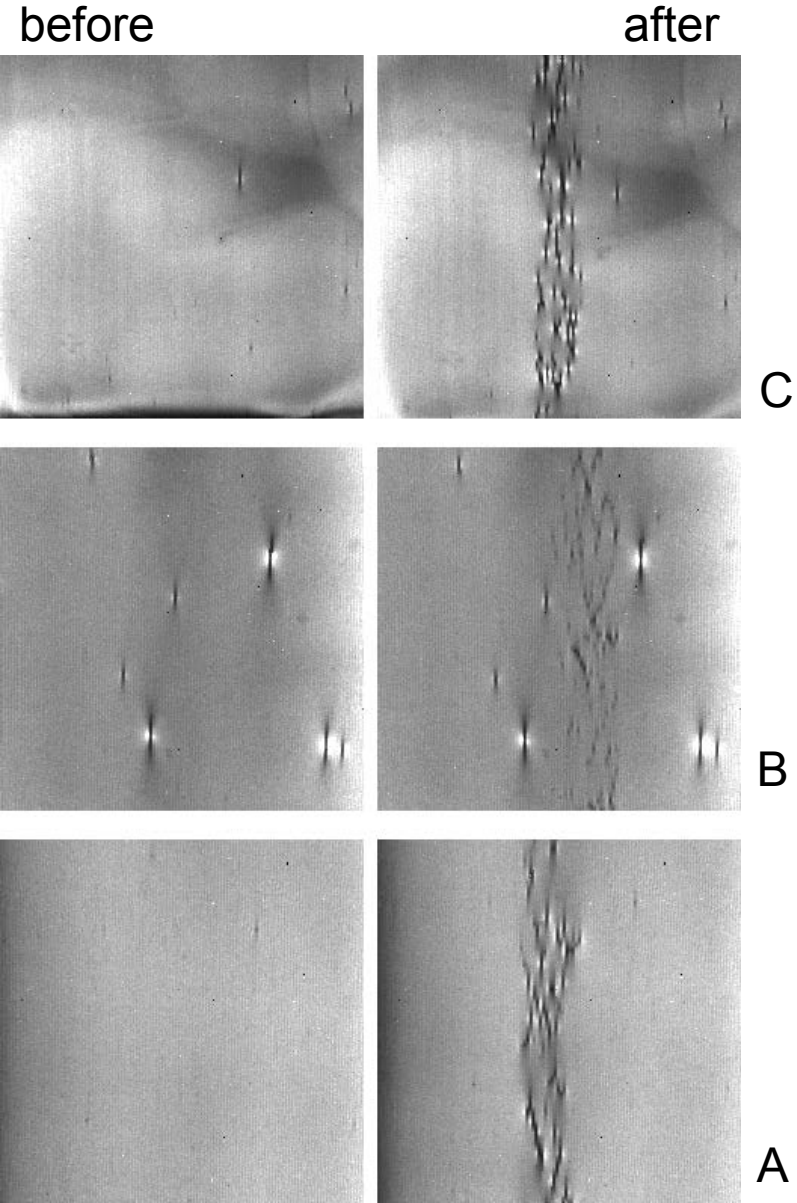
The module is loaded at unshaded I_{mp} to represent serial interconnection of modules

We perform the testing in a continuous solar simulator



Results

Damage from mask sizing



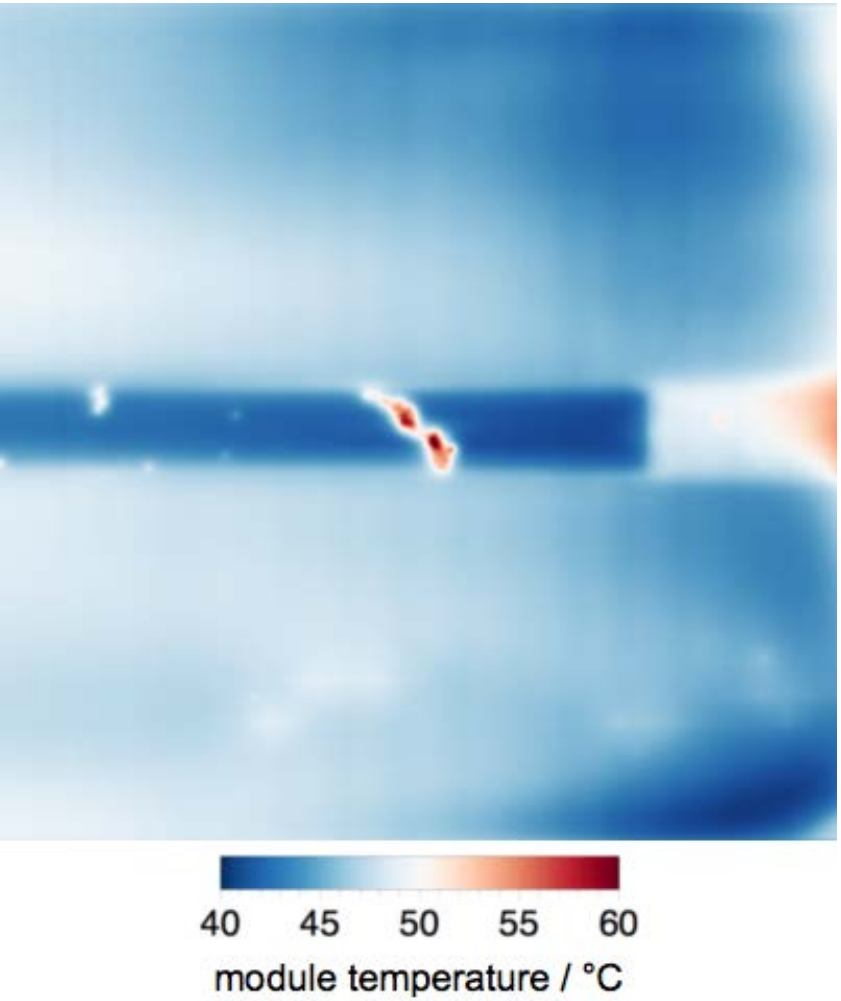
Masked flash tests still cause permanent damage

In our tests, we used a new module for subsequent steps

Cropped EL images for three module types before and after mask sizing

Results

Temperature during stress



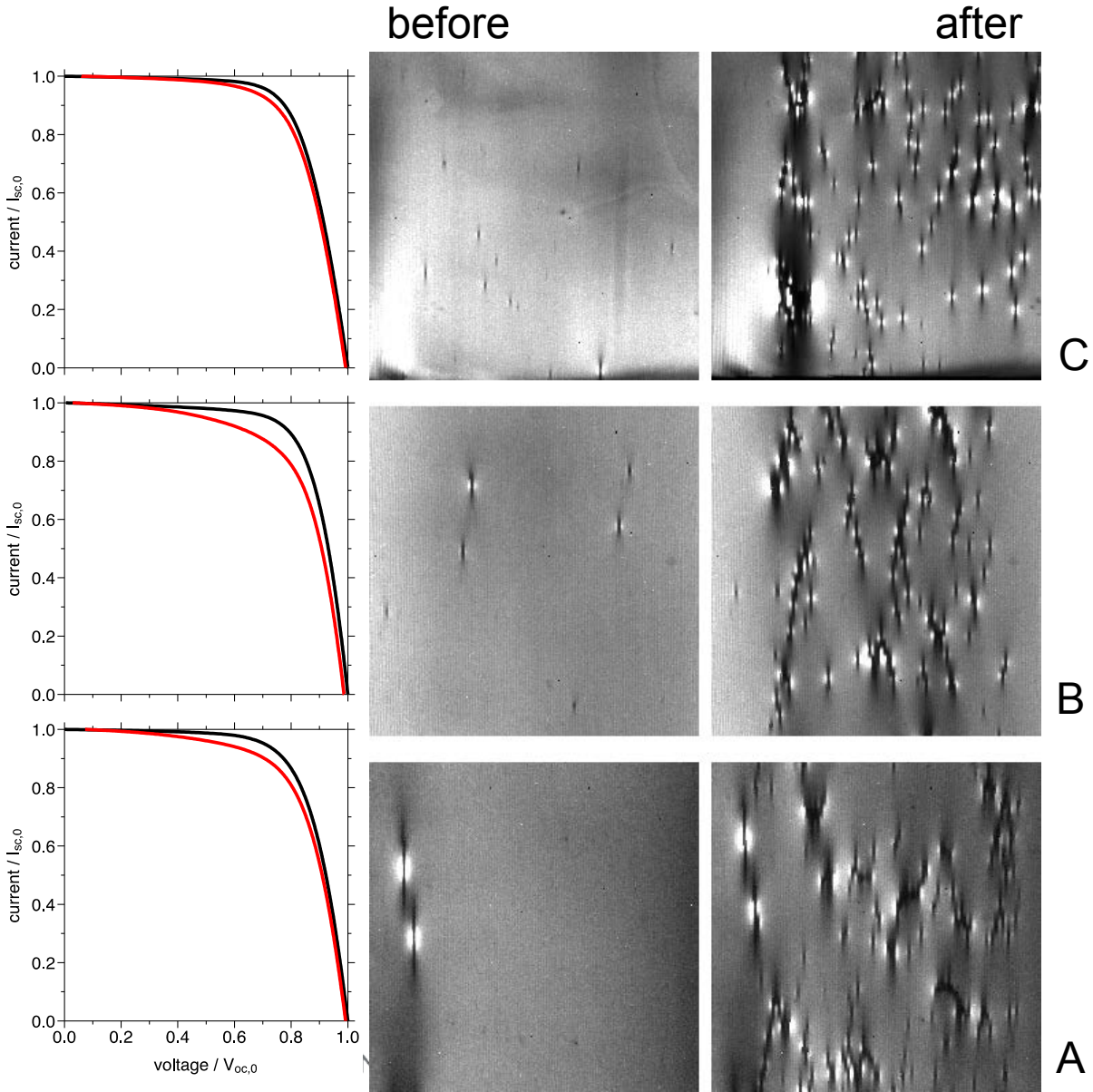
Cropped IR temperature map

Temperature map shows current crowding

Localized defects are more pronounced

Results

Damage from partial shade stress



Widespread shunting occurs after stress

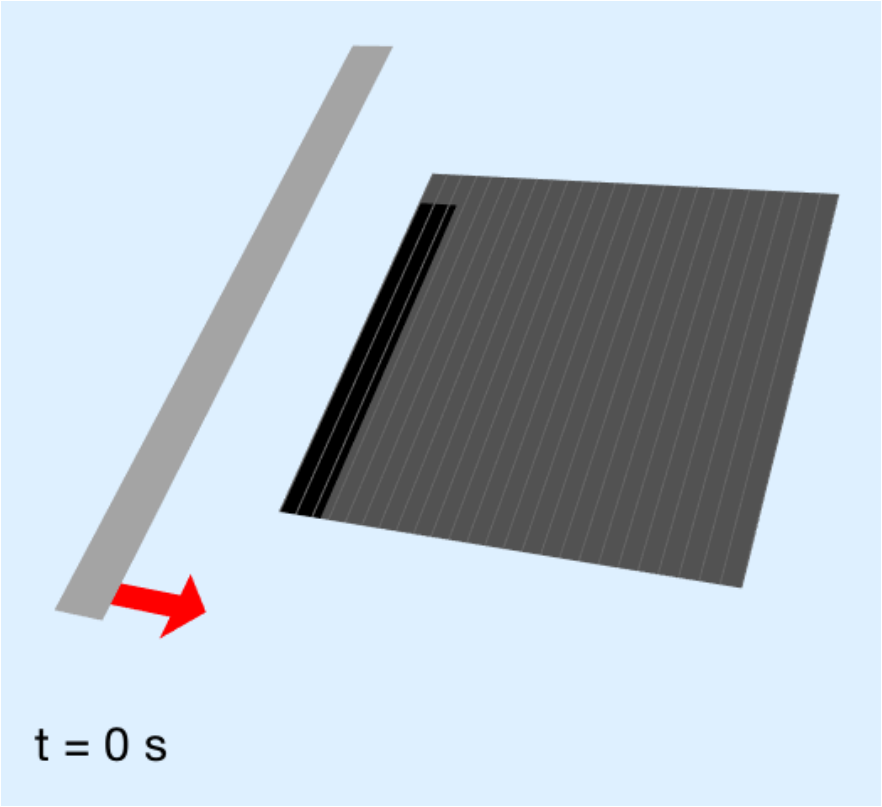
Immediate P_{mp} loss up to 8%; up to 11% after light exposure

I-V curves and cropped EL images for three module types before and after masked stress

Outdoor shade test

We placed a module outdoors in sunny conditions at midday

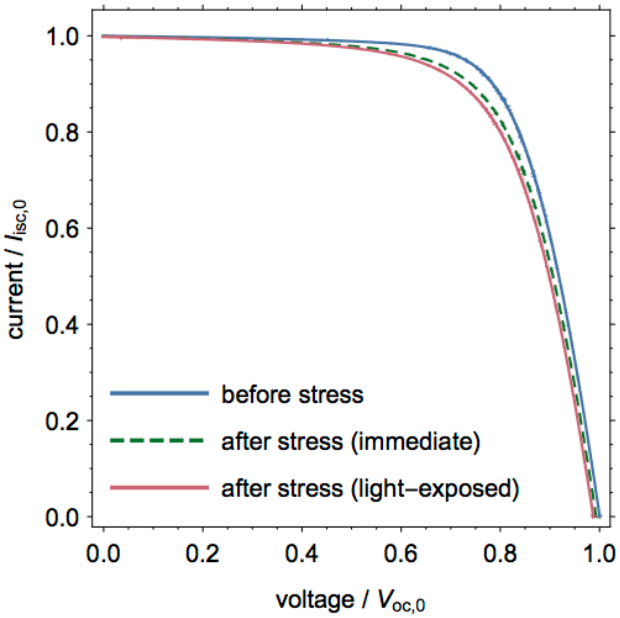
We passed a distant, opaque mask in front of a module in 20 s

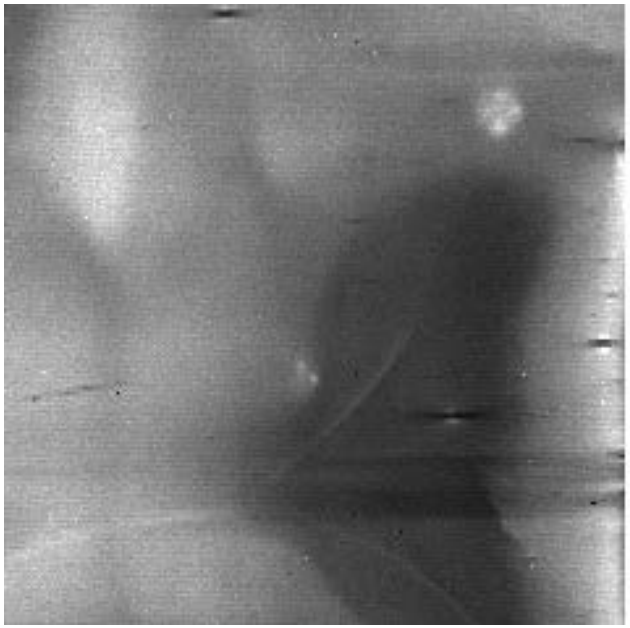


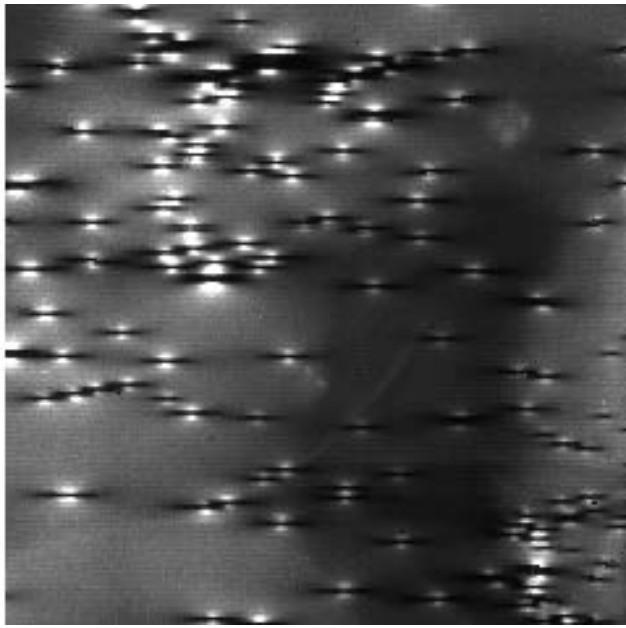
Outdoor shade results

The 20-s shade event led to decreased shunt resistance and >7% of loss in P_{mp}

EL image shows similar effects as the indoor test







Test conditions summary

Quantifying performance change

- Precondition prior to each I-V measurement

Choosing mask size

- Pulsed simulator
- Shrinking mask

Applying stress

- 90% extent mask
- 90% opaque mask
- Continuous solar simulator
- Loaded at unmasked I_{mp}
- Thermal equilibrium near 50°C
- 10 minutes per application
- ≥50% of cells stressed

Conclusion

We have introduced a partial-shade durability test that is quantitative and realistic

The test addresses:

- Light exposure effects (metastability)
- Damage done when mask size is being decided
- Light-enhanced reverse breakdown
- Realistic illumination and electrical conditions

We will add a pass/fail criterion to this procedure and propose it as a NWIP for amendment to IEC 61215

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory.

Some of the data in this report were obtained using equipment at the Energy Systems Integration Facility (a national user facility sponsored by the U.S. DOE Office of Energy Efficiency and Renewable Energy) located at the National Renewable Energy Laboratory.

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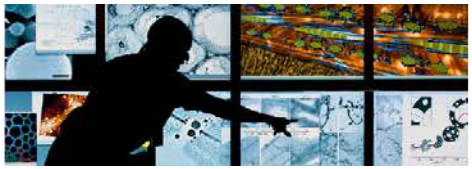
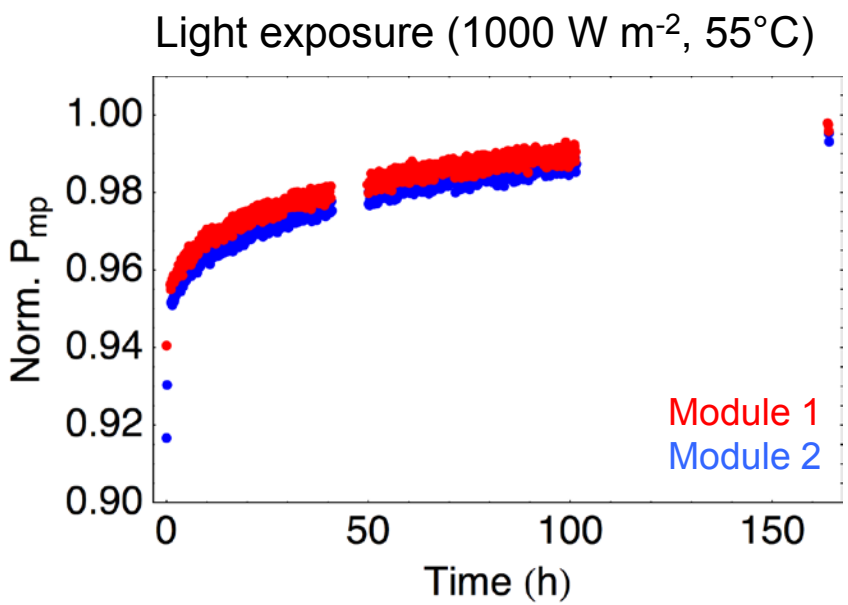
Achieving Relevant and Reproducible Power Measurements for Thin-Film Modules

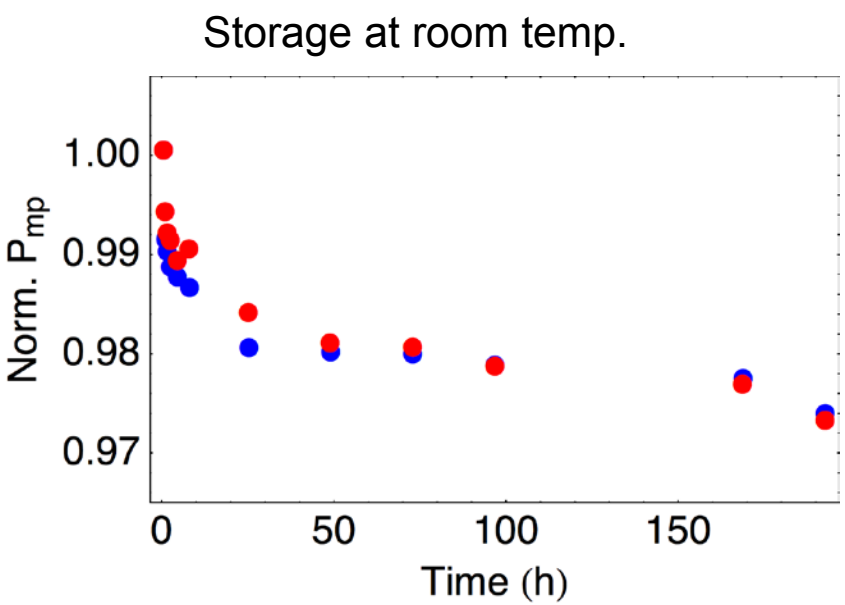
Michael G. Deceglie
Timothy J Silverman
Bill Marion
Sarah R. Kurtz



NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

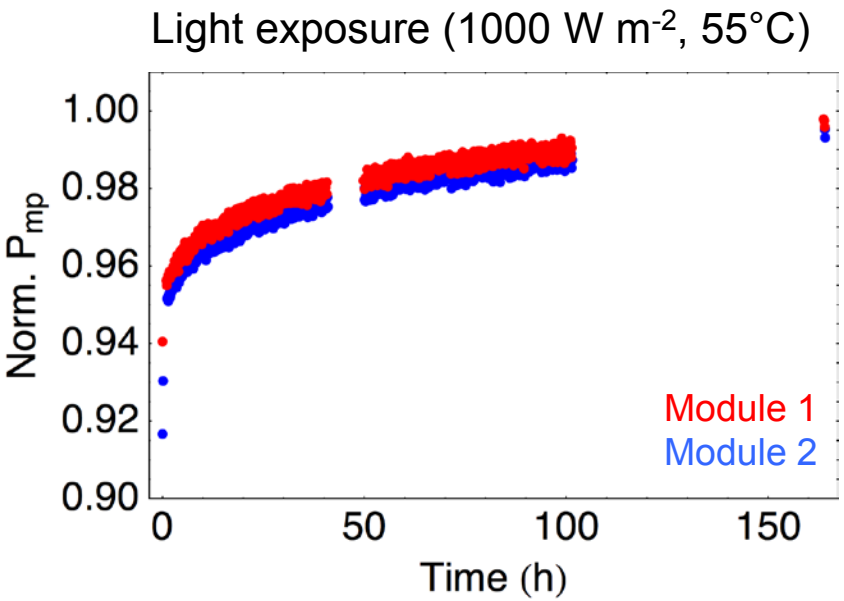
Metastable performance in thin-films

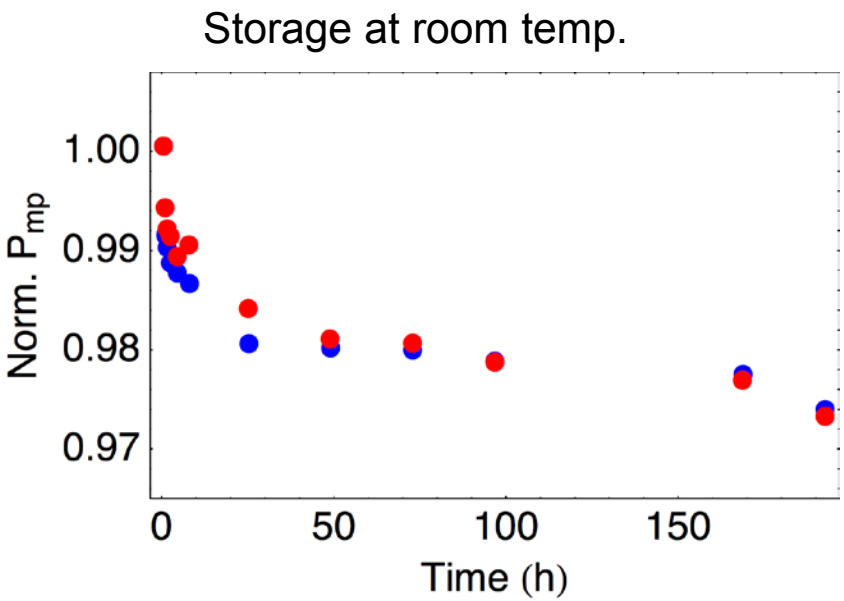




Thin-film modules change performance upon exposure to light and storage in the dark

Metastable performance in thin-films

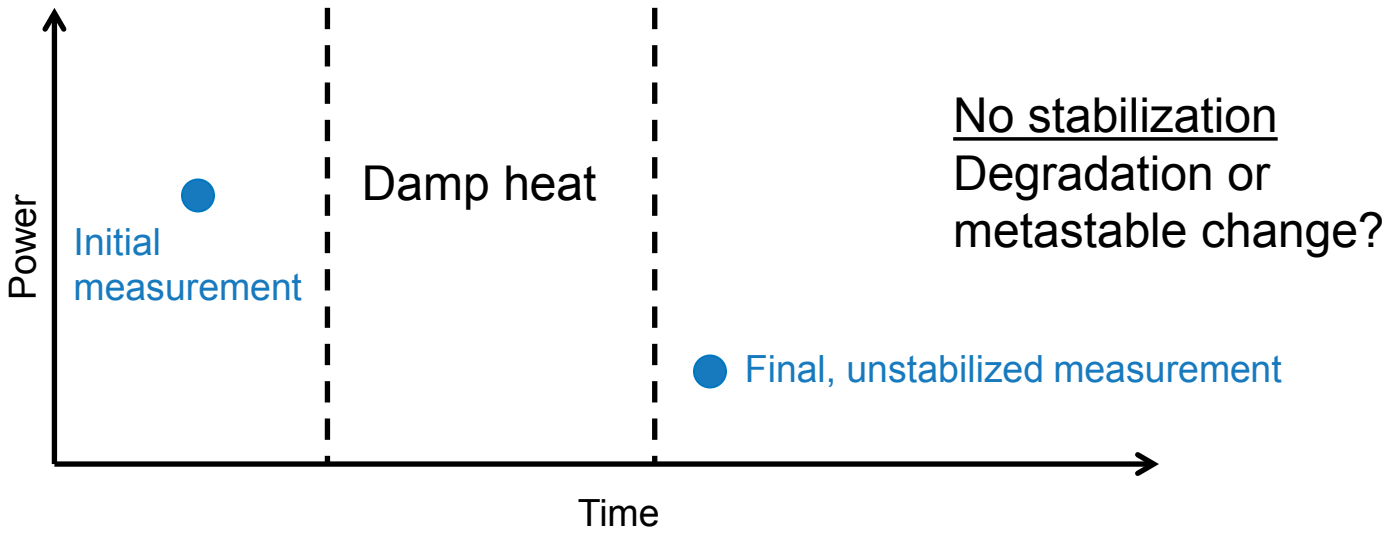




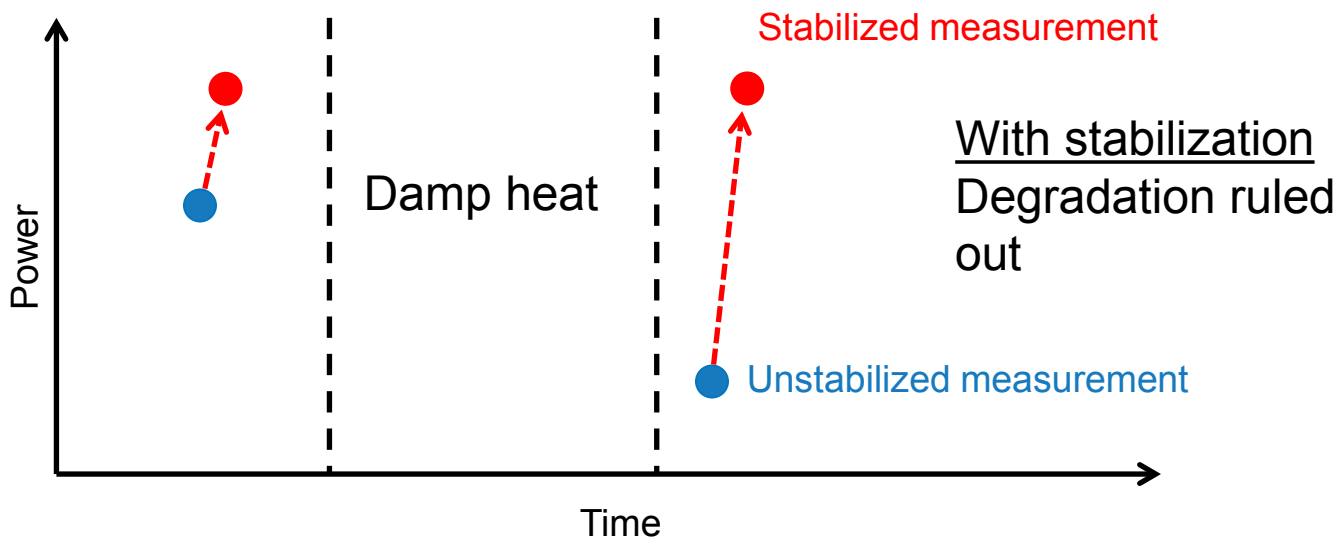
Thin-film modules change performance upon exposure to light and storage in the dark

Metastabilities: reversible changes
Stabilization: Repeatedly achieving metastable state

Differentiating degradation

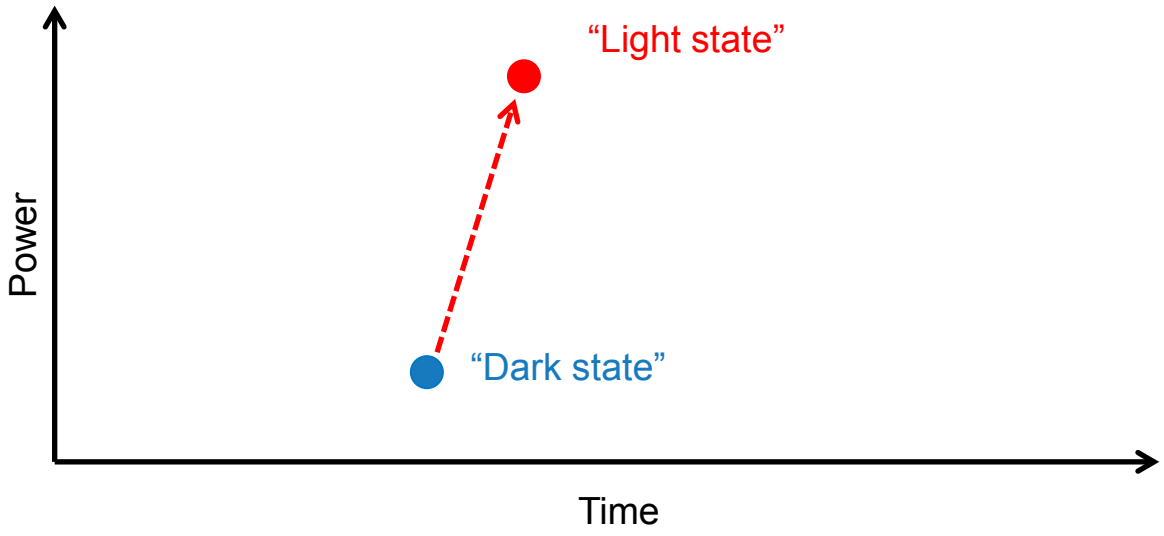


Differentiating degradation

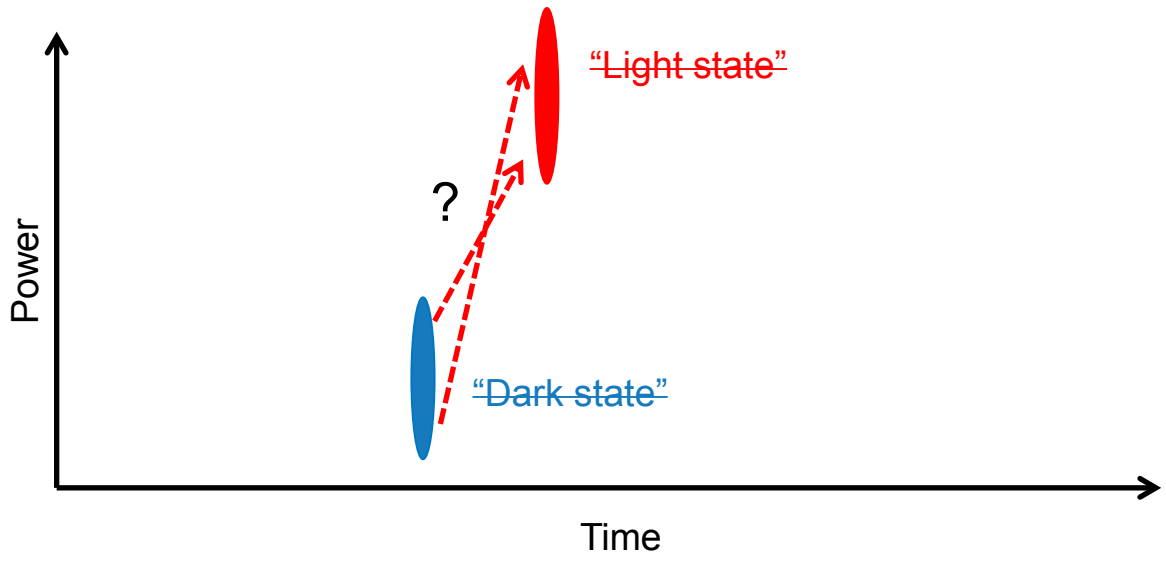


Repeatable stabilization procedure needed before and after reliability test

“The light state”

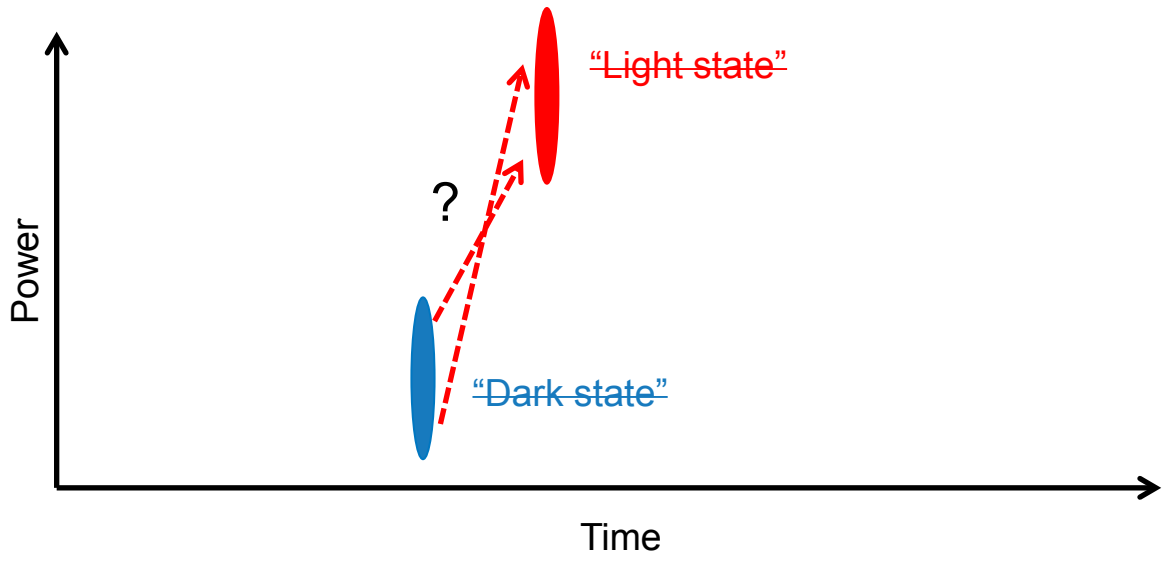


The challenge



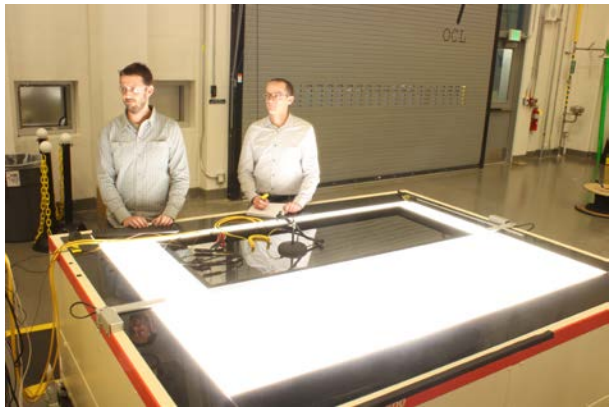
There is not a single well-defined light state

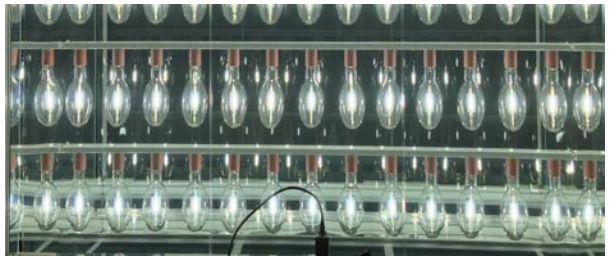
The challenge



- Rich body of literature on physics of metastabilities
  - Characteristics are process/product specific
- Status quo: stabilization carried out in loosely defined conditions → poor reproducibility
- Goal: Meaningful and reproducible power measurements

Module characterization tools

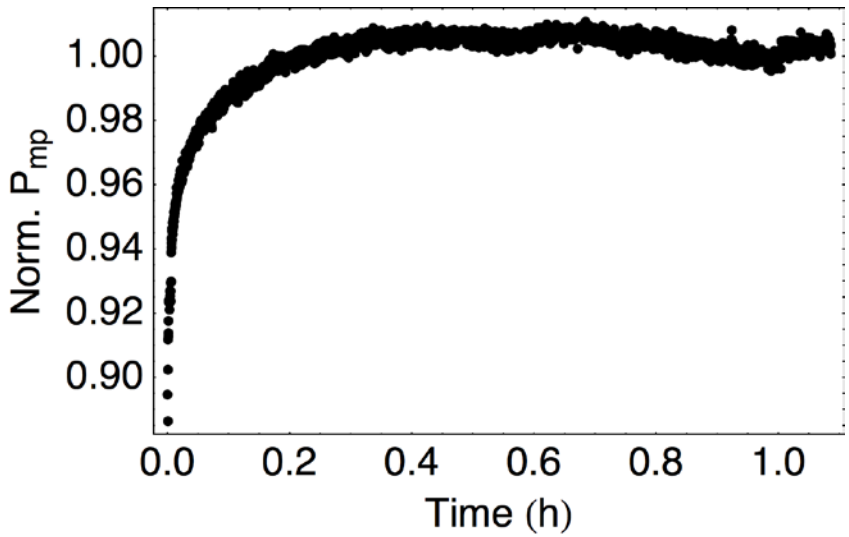


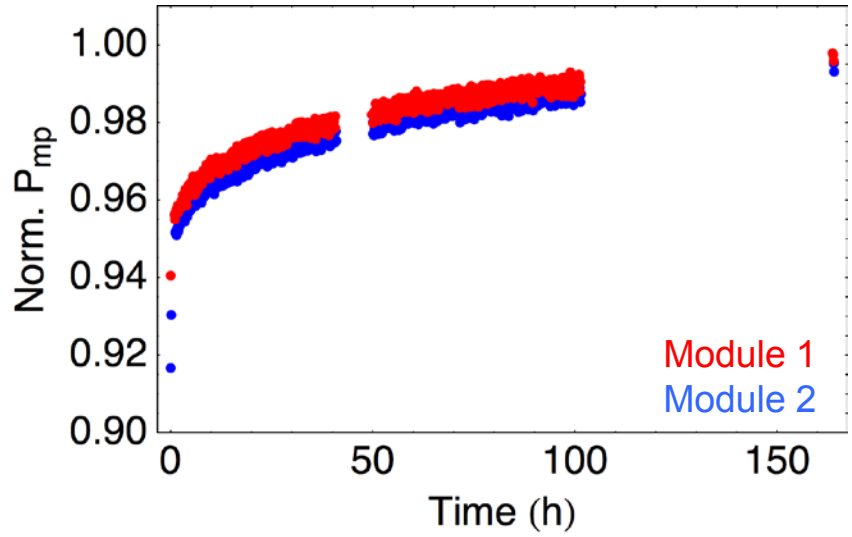


- **Module flash tester**
  - Room temperature current voltage (IV) curves
- **Light soaking chamber**
  - Continuous exposure in controlled conditions
  - In situ IV curves and max power tracking
- **Performance and energy rating test bed**
  - Modules deployed outdoors
  - Automated 15 minute IV curves
  - Meteorological data

Timescales of change

Transient changes in performance of two different types of CIGS modules

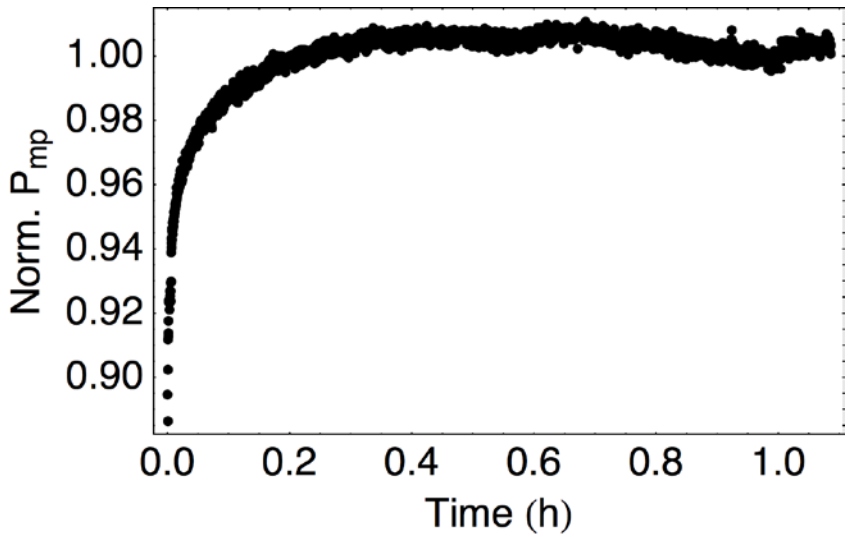


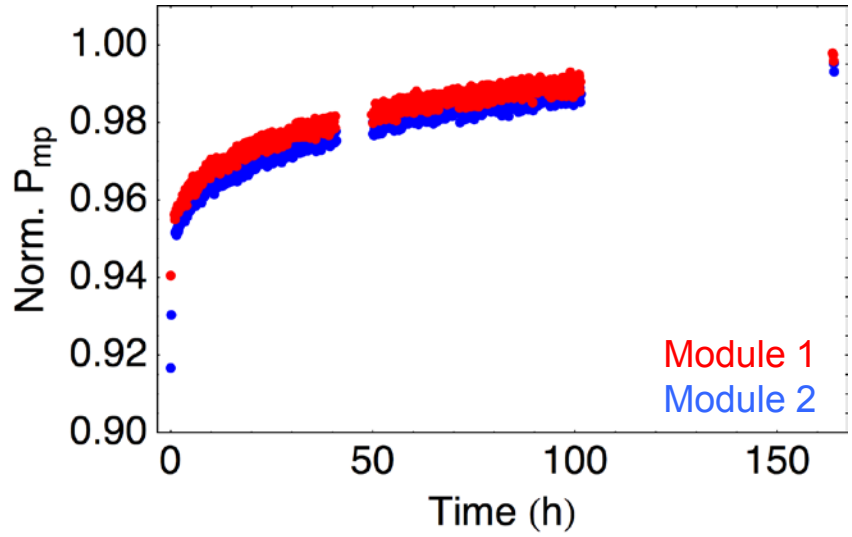


- Changes have different timescales in different products
- Must define the timescale of interest

Timescales of change

Transient changes in performance of two different types of CIGS modules

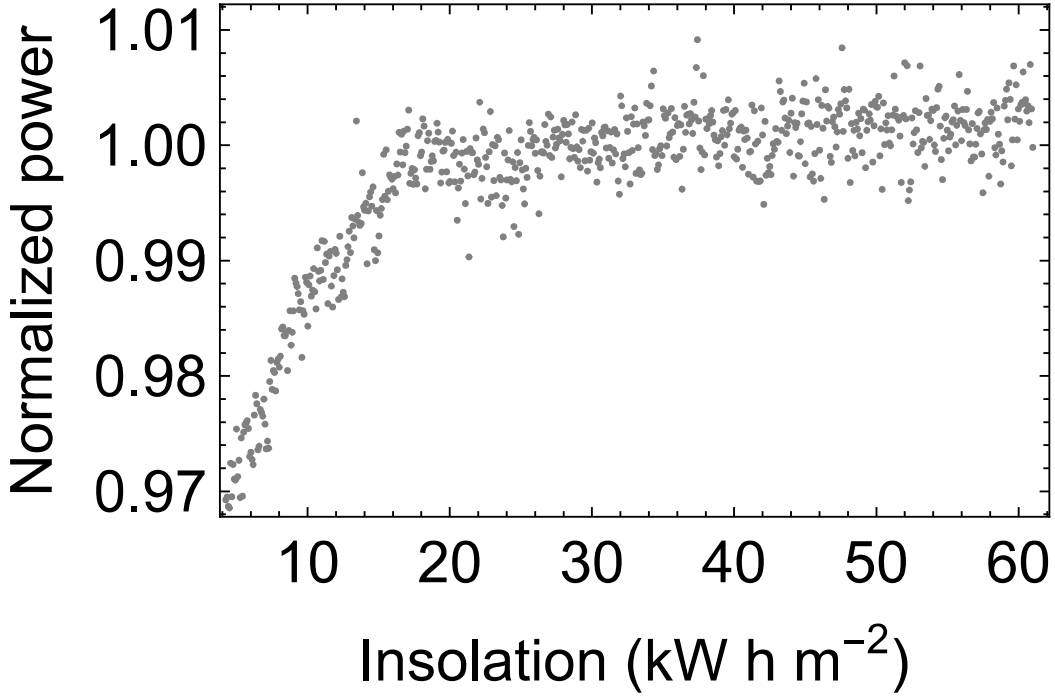




- Changes have different timescales in different products
- Must define the timescale of interest
- Community gravitating toward: <1% per 20 kW h m^{-2}

Determining stability

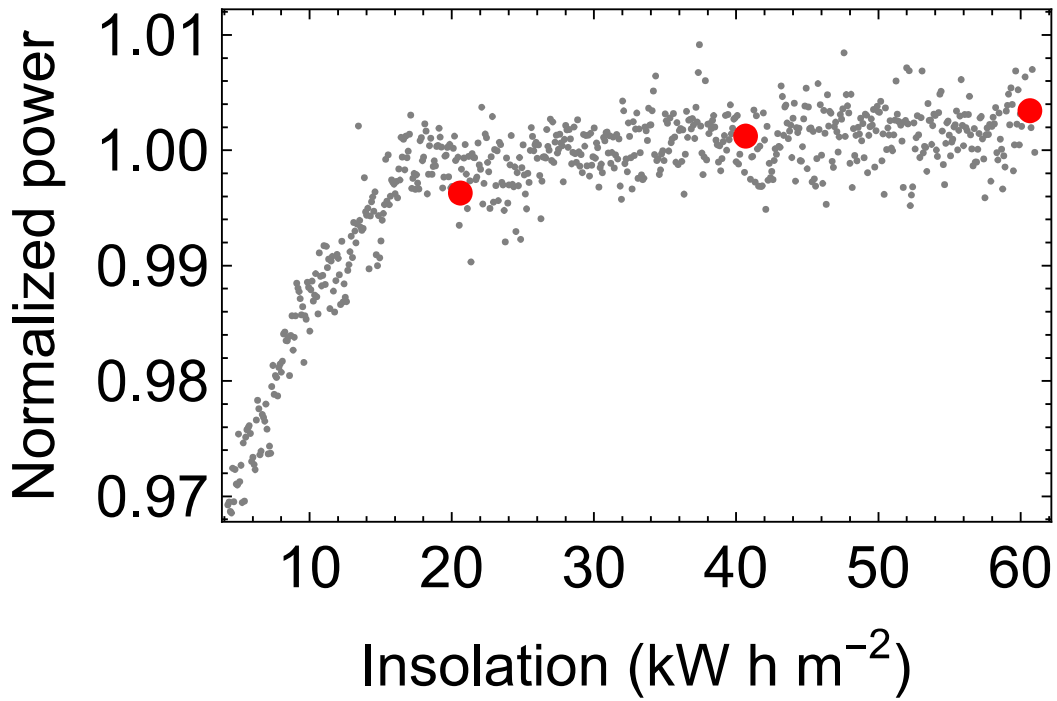
Transient change in CdTe module exposed at 1000 W m^{-2}, constant temperature



Deceglie et al., SPIE Optics + Photonics , 2015 (DOI: 10.1117/12.2188827)

Determining stability

Transient change in CdTe module exposed at 1000 W m^{-2}, constant temperature

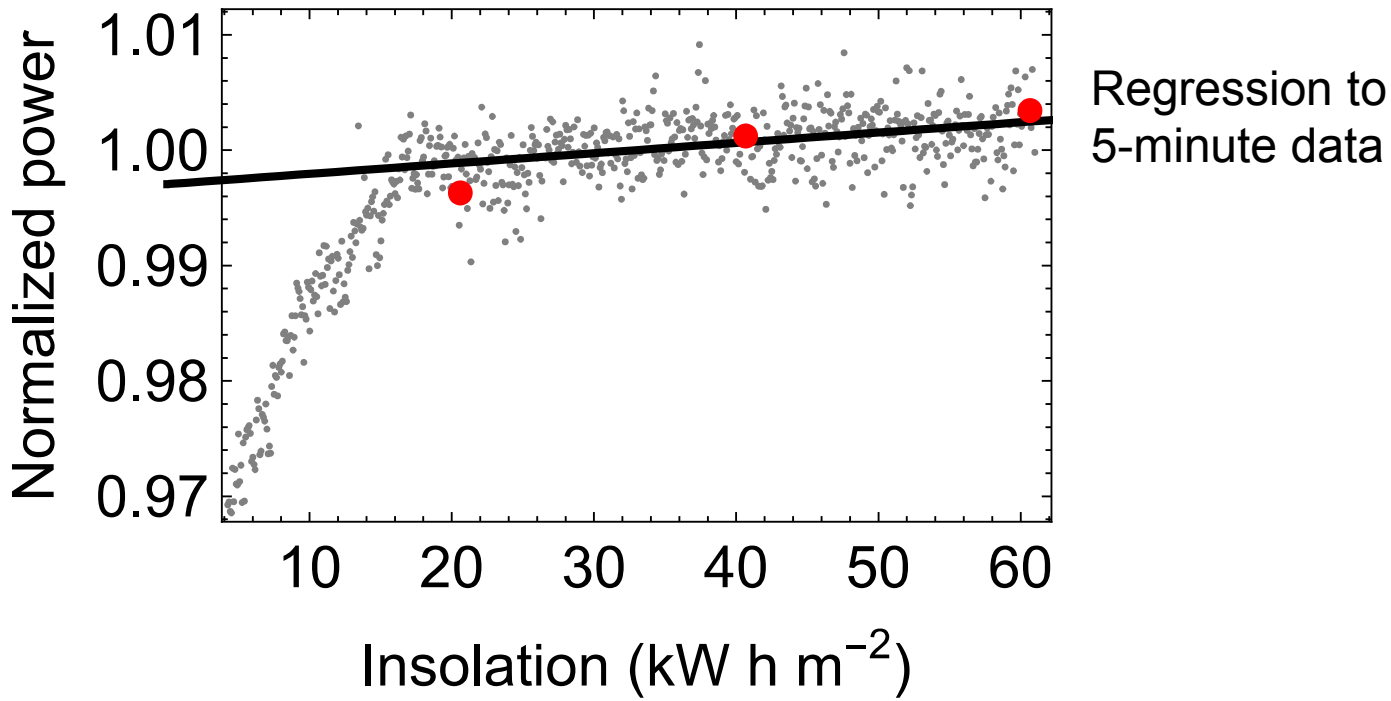


Current practice: use 3 discrete measurements

Deceglie et al., SPIE Optics + Photonics , 2015 (DOI: 10.1117/12.2188827)

Determining stability

Transient change in CdTe module exposed at 1000 W m^{-2}, constant temperature



Frequent measurements increase certainty

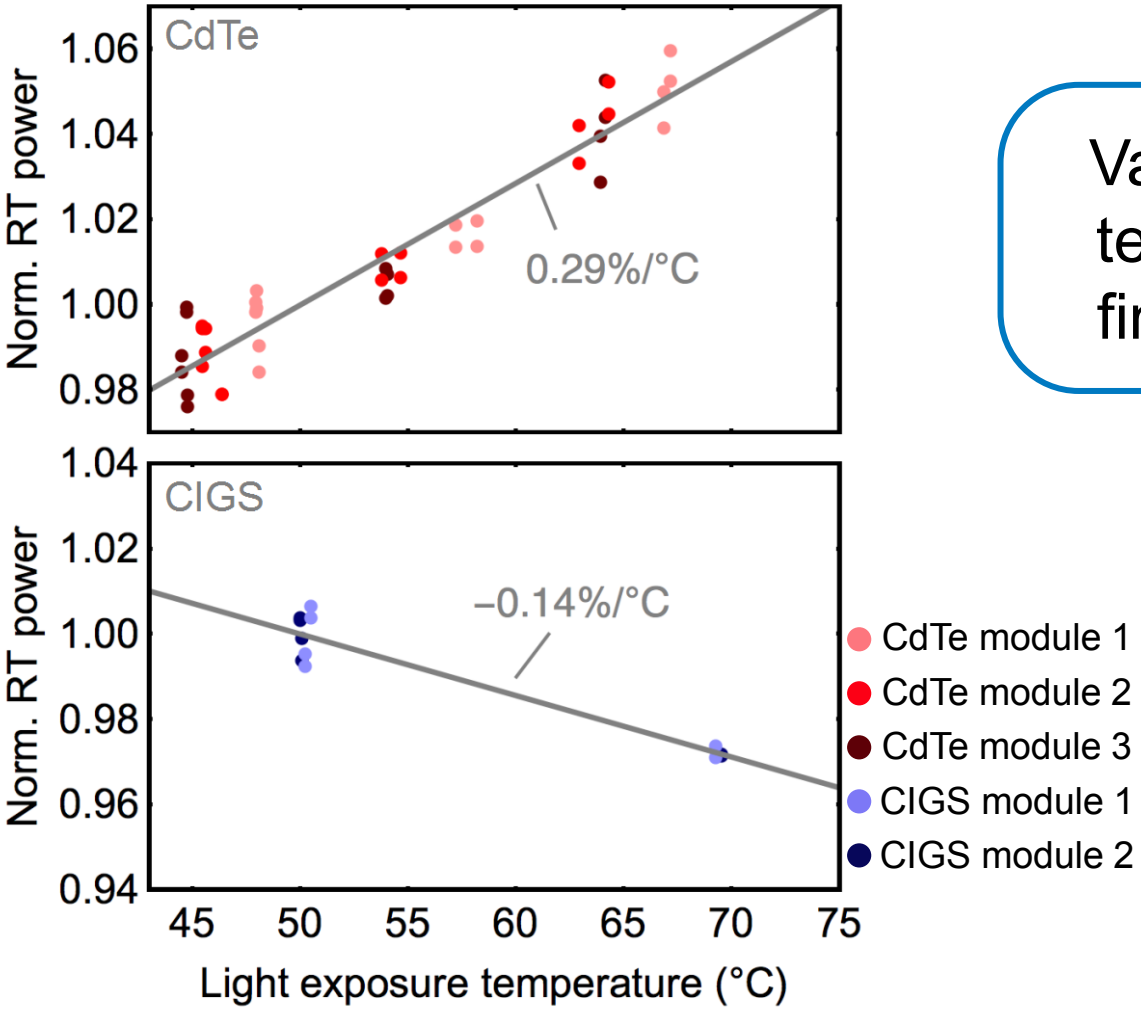
Deceglie et al., SPIE Optics + Photonics , 2015 (DOI: 10.1117/12.2188827)

Effect of temperature during light exposure

- Light soak in chamber until stable
- Measure IV at room temperature
- Repeat light soak at different back-of-module temperature
- Example:
  - Light soak at 50°C
  - Measure RT IVs
  - Light soak at 70°C
  - Measure RT IVs
  - Light soak at 50°C
  - Measure RT IVs

Discriminates permanent vs. reversible changes

Temperature-dependent "light states"



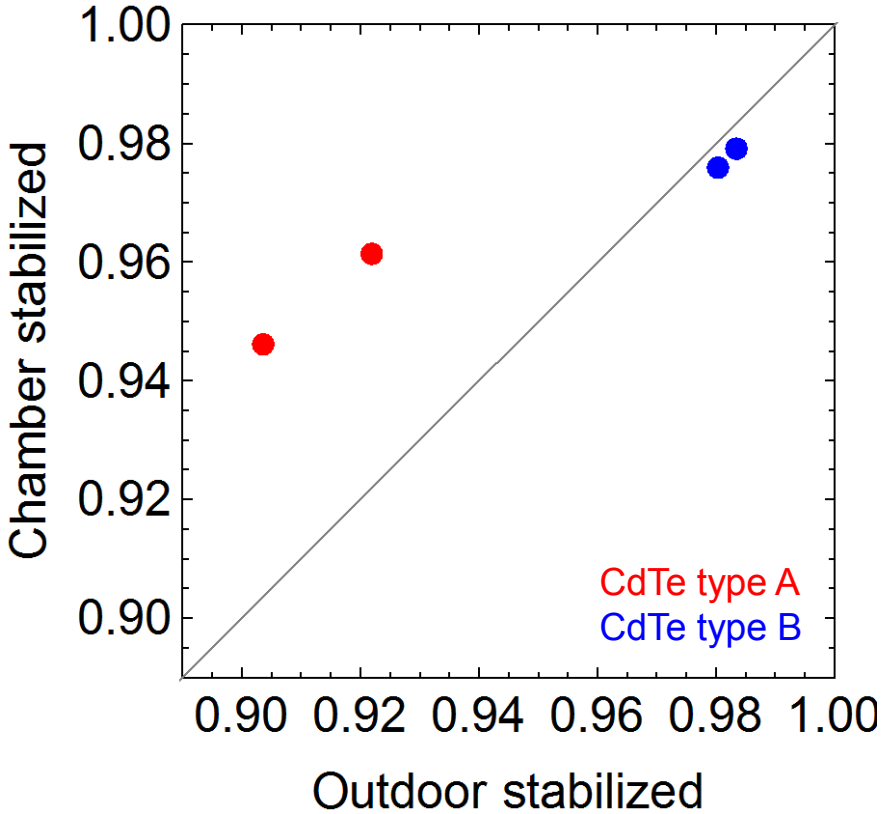
Variations in light-soak temperature affect the final metastable state.

For a +20°C change:
–2.8% change in CIGS
+5.8% change in CdTe

(Effects not universal)

Deceglie et al., PVSC, 2015 (DOI: 10.1109/PVSC.2015.7355854)

Chamber vs. outdoor stabilization

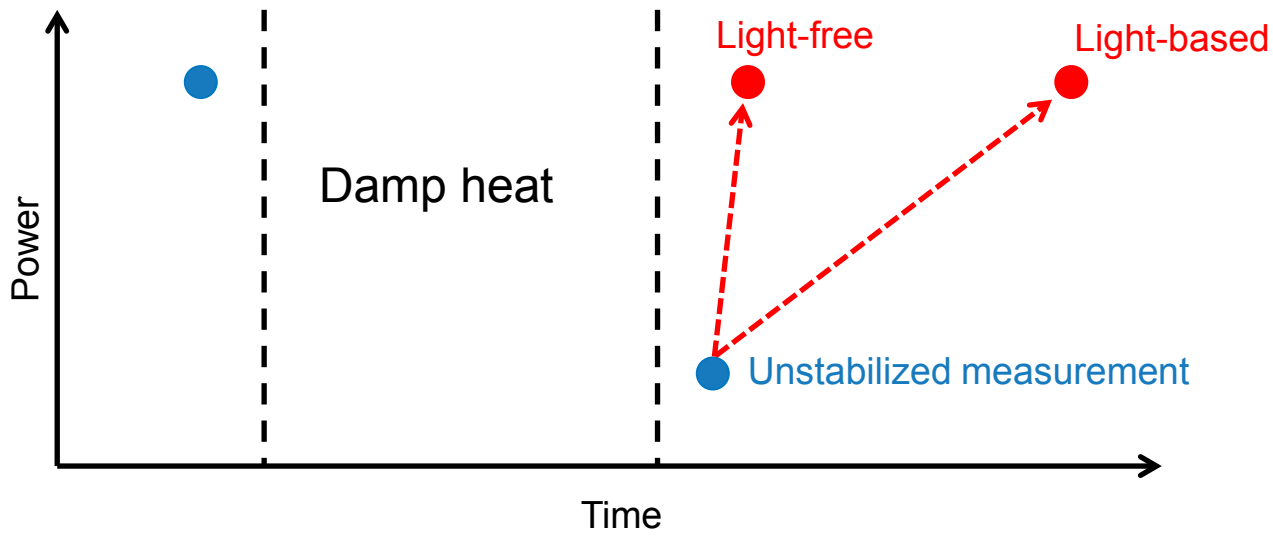


Normalized STC power for two types of CdTe module stabilized indoors and outdoors

Repeatable measurements require controlled exposure temperature

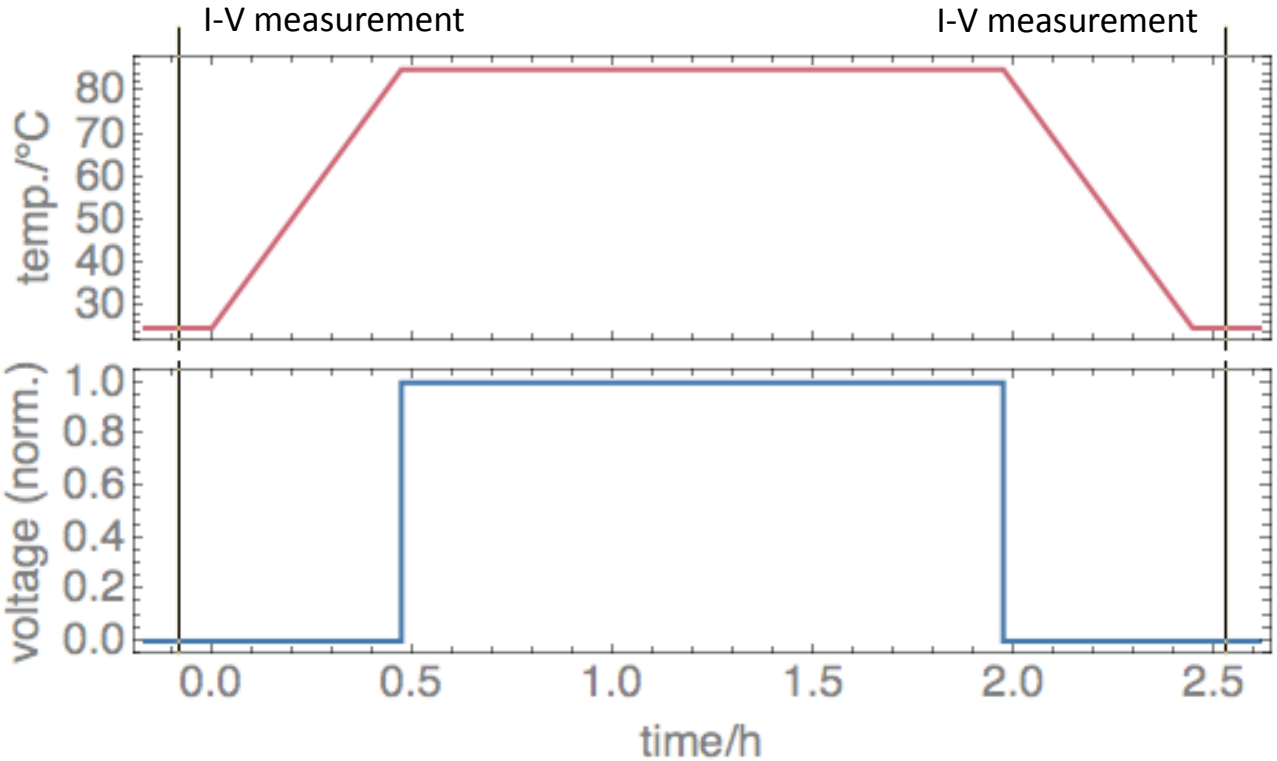
Deceglie et al., SPIE Optics + Photonics , 2015 (DOI: 10.1117/12.2188827)

Light-free stabilization



- Can be **quicker** and **cheaper**
- Must produce **relevant state**

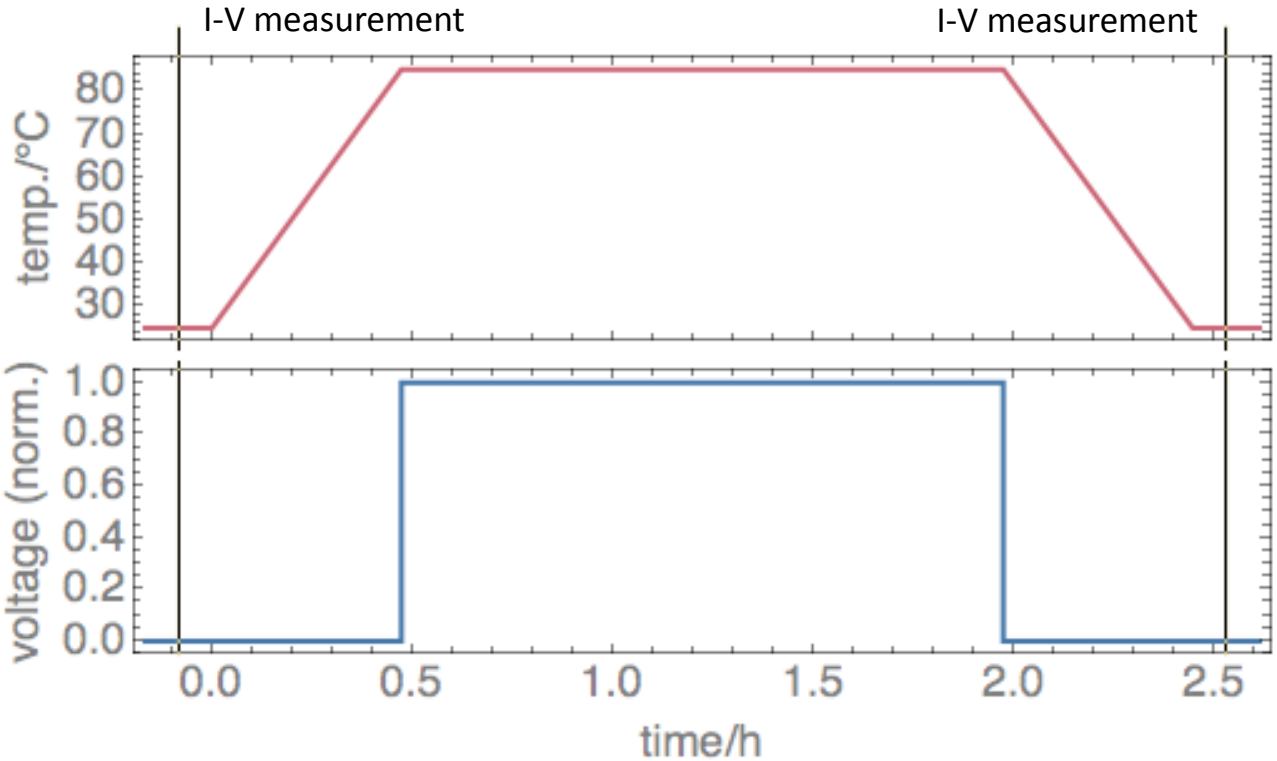
Bias at elevated temperature (BET)



Method based on proposal in draft IEC 61215 update:

- Collect light I-V curve
- Heat to 85°C
- Apply forward bias (0.6 to 0.7) × V_{oc}
- Cool to room temperature
- Collect light I-V curve
- Repeat until power is stable

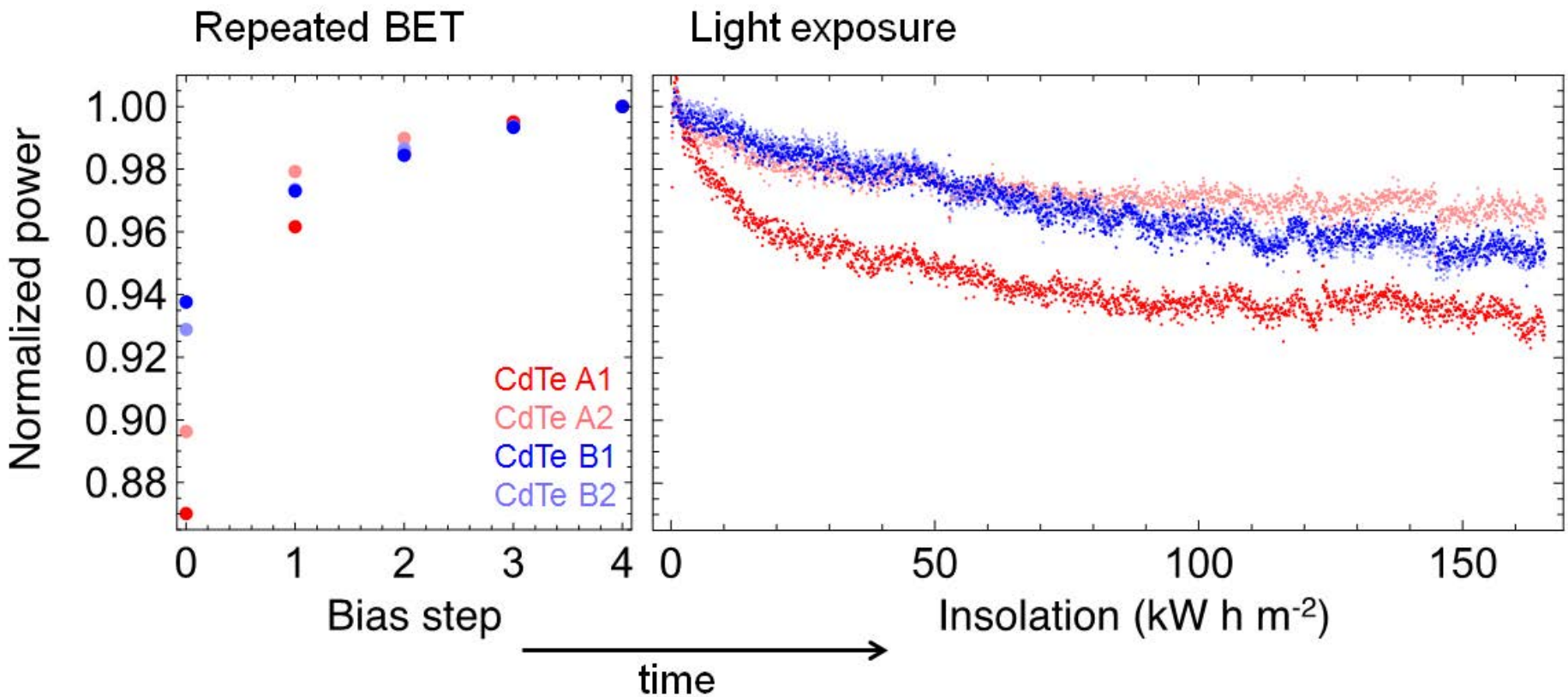
Bias at elevated temperature (BET)



Does this produce a **relevant** state?

Does hot bias produce a relevant state?

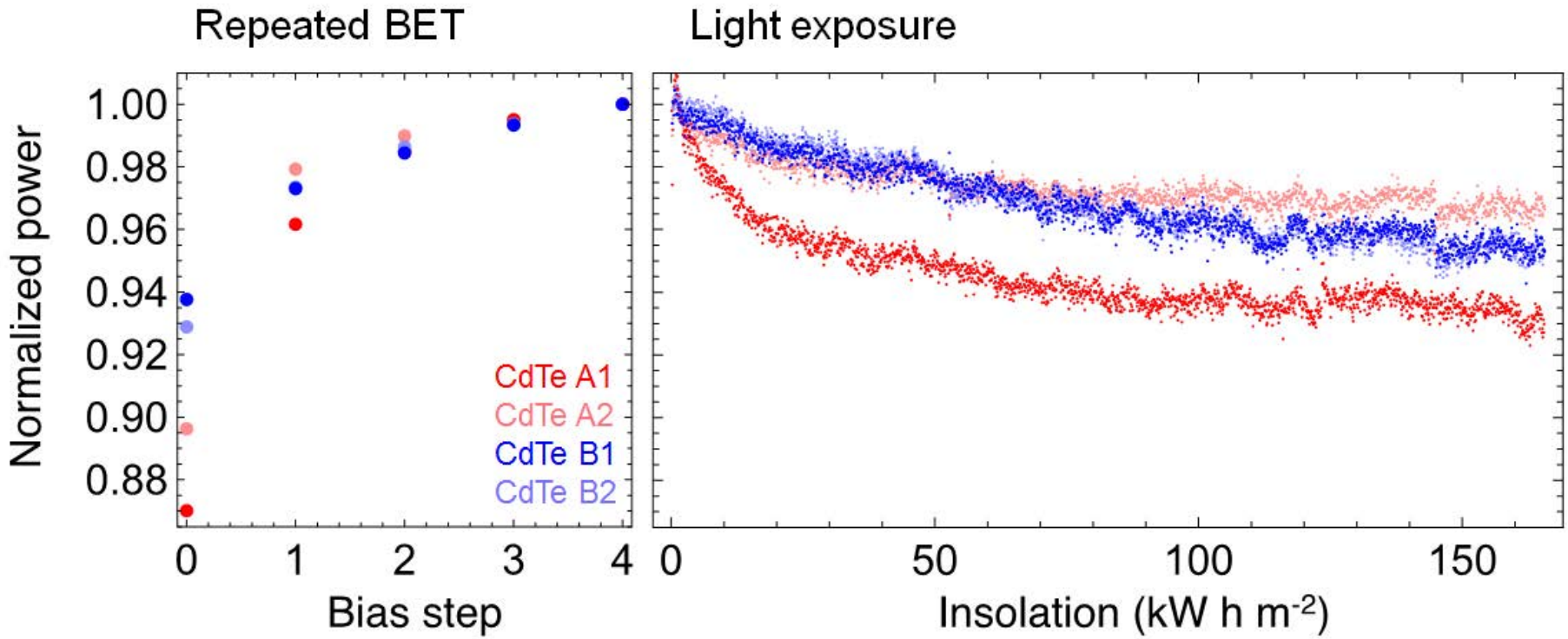
Two types of CdTe module were stabilized with the bias at elevated temperature (BET), then placed in light-soak chamber



BET does not always produce a light-stable state

Deceglie et al., SPIE Optics + Photonics , 2015 (DOI: 10.1117/12.2188827)

Does hot bias produce a relevant state?



Any alternate procedure should be validated for each module/cell type

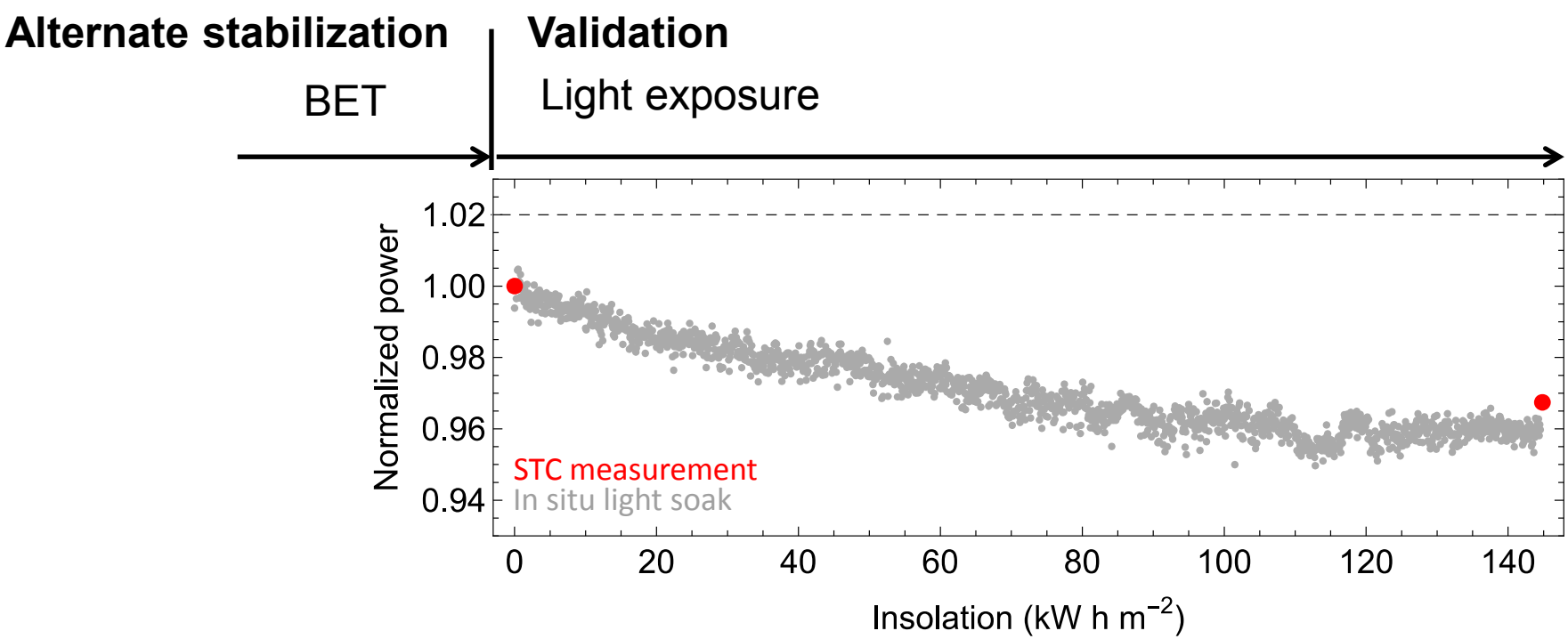
Deceglie et al., SPIE Optics + Photonics , 2015 (DOI: 10.1117/12.2188827)

Screening alternate procedures

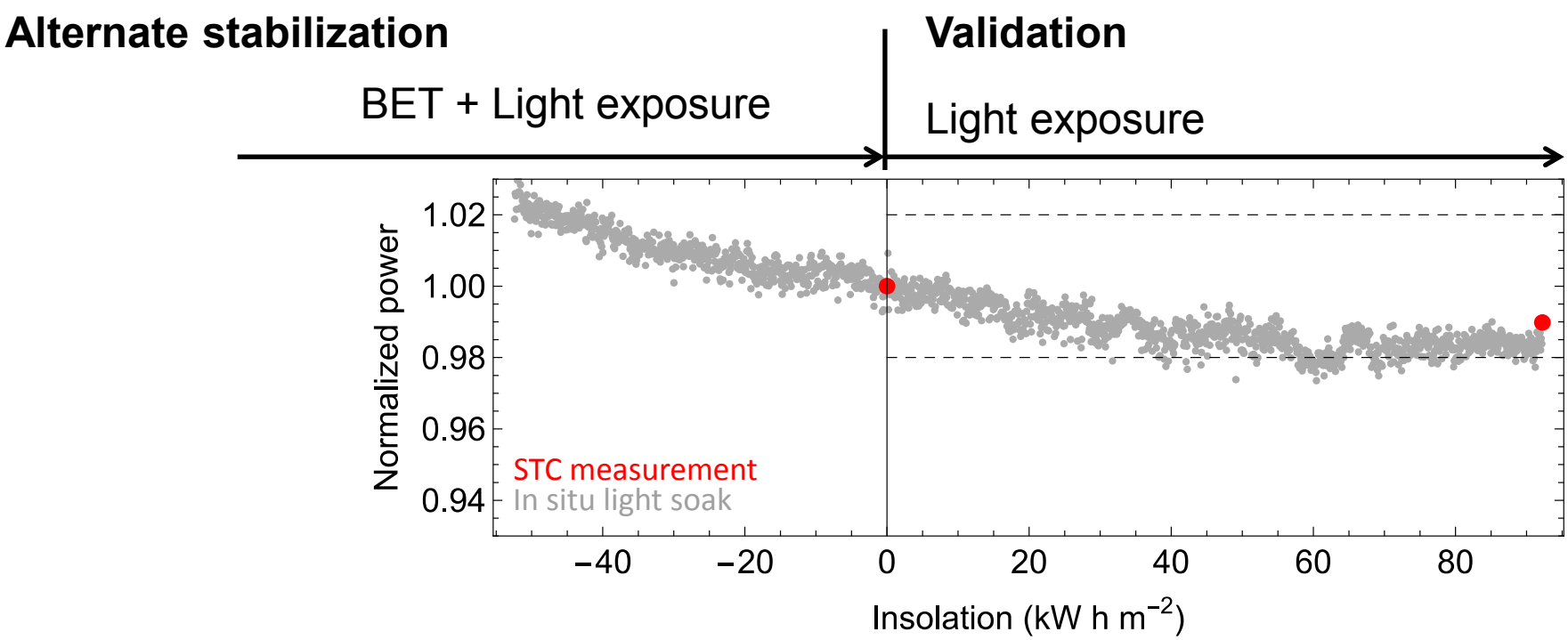
- **Goal: Demonstrate that such alternate stabilizations can be effectively screened**

- Proposed validation technique:
  - Perform alternate stabilization
  - Measure STC performance
  - Perform light-based stabilization
  - Measure STC performance

Effective screening of alternate procedures



Effective screening of alternate procedures



With careful screening, some alternative procedures can be validated

Relevant and repeatable measurements

- Light-based stabilization
  - **Use repeatable conditions**
    - Expose to light 800–1000 W m^{-2}
    - Control module/cell temperature to 50±2°C
    - At maximum power point
  - **Determine stability**
    - Criteria: < 2% per 40 kw h m^{-2}
    - Preferred: regress frequent measurements
    - Alternative: 3 infrequent measurements
- Alternative procedures:
  - **Validate that result is light-stable**
    - Product-specific procedures should not be standardized

Deceglie et al., SPIE Optics + Photonics , 2015 (DOI: 10.1117/12.2188827)

Acknowledgments

- Steve Rummel
- Allan Anderberg
- Jose Rodriguez
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- Keith Emery

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Seven Useful Things We Can Learn from the Physics of Metastability in Thin-Film Modules

Ingrid Repins[1], Steven Glynn[1], Stephan Lany[1], Jian V. Li[1,2], Michael Deceglie[1], Tim Silverman[1]

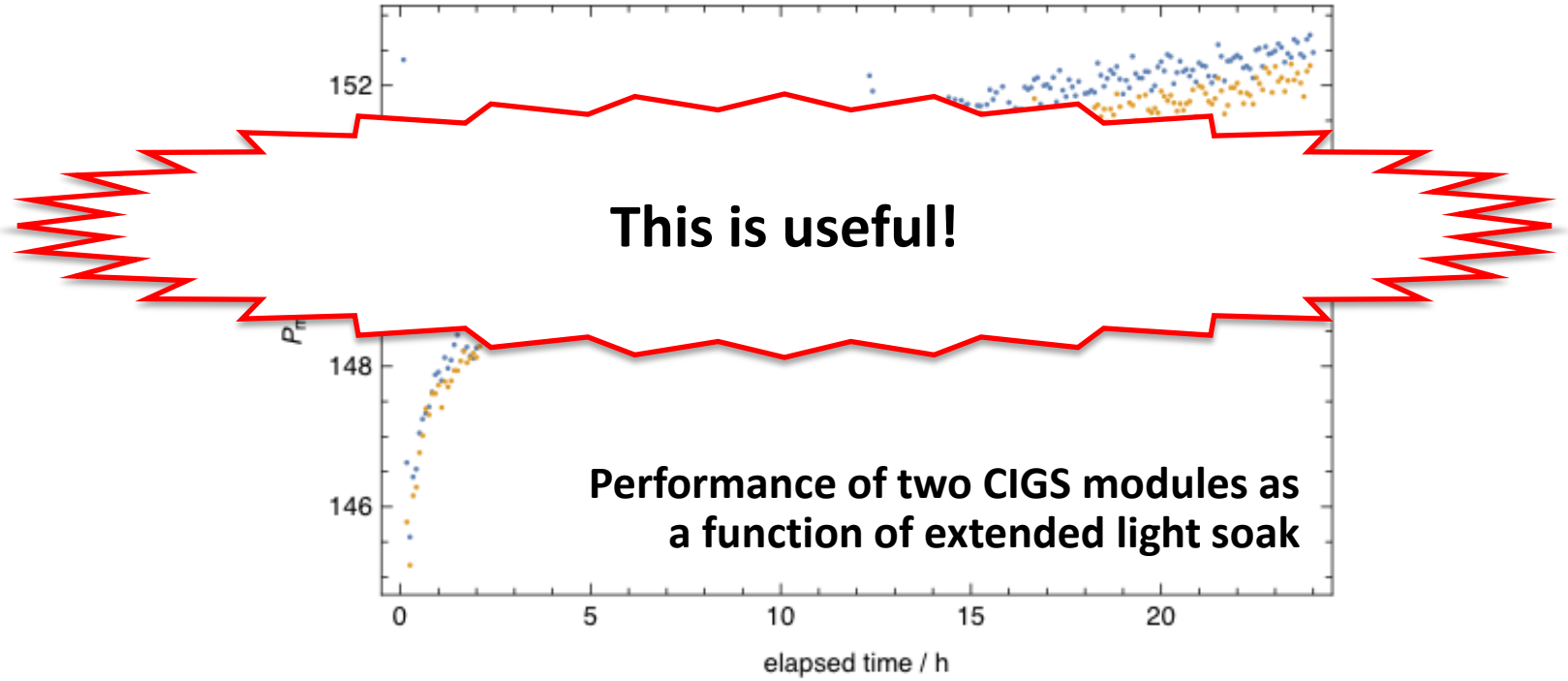
[1] National Renewable Energy Laboratory, [2] Texas State University

NREL PV Module Reliability Workshop
Golden, CO
February 23-25, 2016

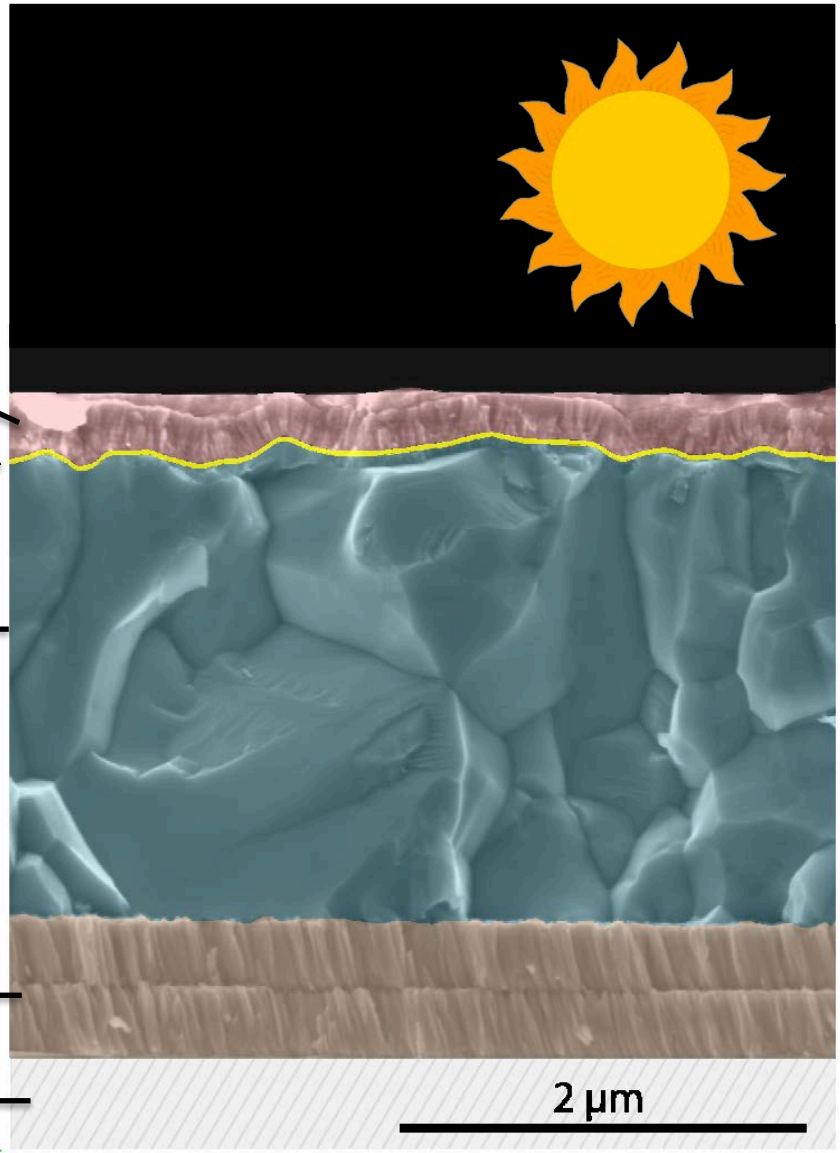
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

“Metastability”

Thin-film modules can undergo reversible changes in performance upon exposure to light and storage in the dark



Terminology - Layers in a CIGS cell



Transparent Conductor: Zinc Oxide or Indium Tin Oxide

Buffer: Cadmium Sulfide or Zinc Oxysulfide

$Cu(In,Ga)Se_2$ absorber ("CIGS")

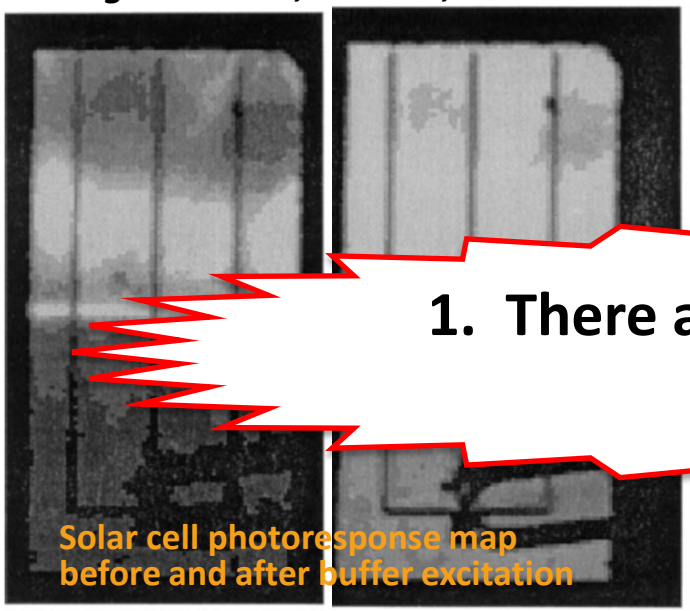
Molybdenum back contact

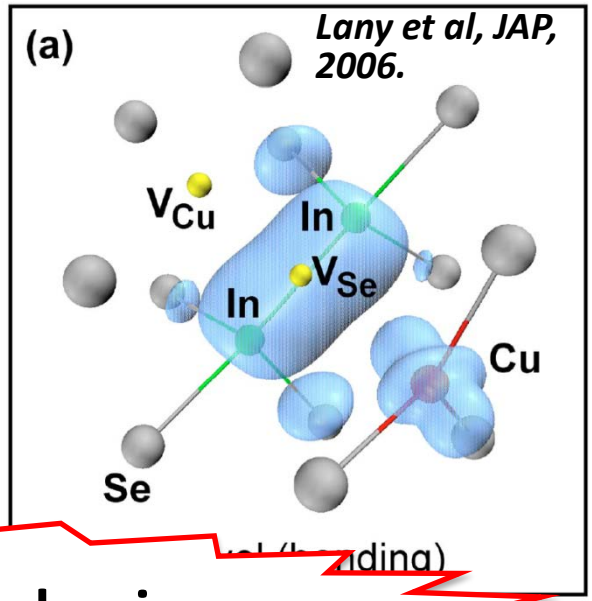
Substrate: Glass, plastic, steel…

Known and Suspected Sources of Metastability in CIGS

1. Defects involving a missing Se atom + a missing Cu atom.

Eisgruber et al, Sol Mat, 1998.

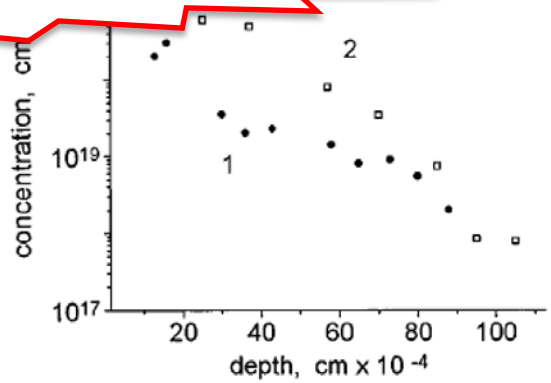




Lany et al, JAP, 2006.

2. Buffer

1. There are likely multiple mechanisms acting in parallel.

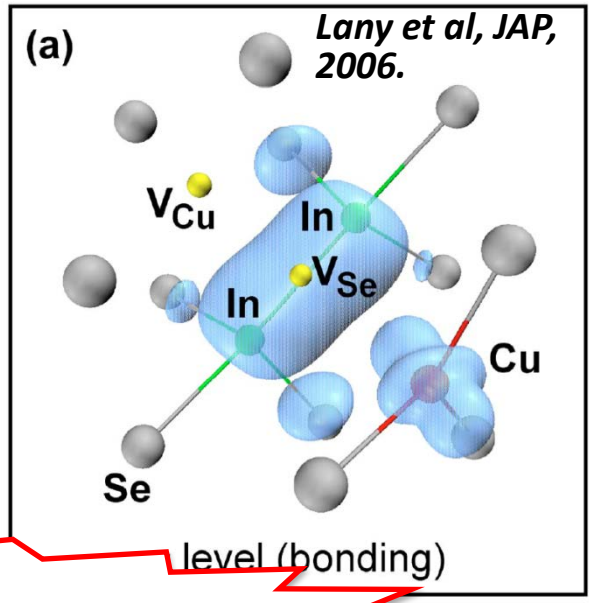


Gartsman et al, JAP, 1997.

3. Ion diffusion (Na or Cu)

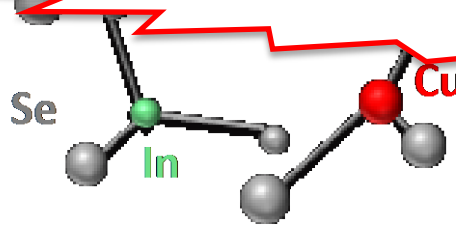
Defects involving Se vacancy (V_{Se})

1. Defects involving a missing Se atom + a missing Cu atom.

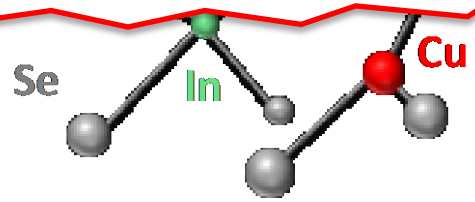


Thermally-activated relaxation

2. Rates toward steady-state in light versus relaxation in dark are different.



Normally, Cu or In atoms bond only to Se

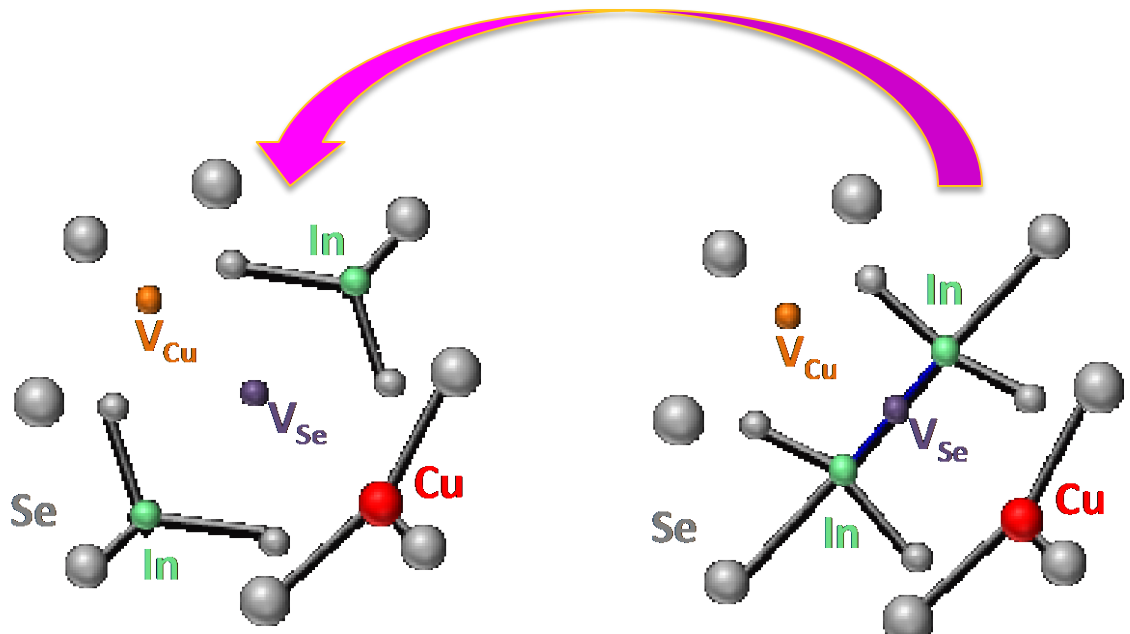


Absorb a photo-excited electron

Defects involving Se vacancy (V_{Se})

- Numerous characterization studies support this picture.
- See, for example, Igalson, *Thin Solid Films*, 2007; Urbaniak, *JAP*, 2009; Siebentritt, *APL*, 2008; Serhan, *Thin Solid Films*, 2011; Erslev, *APL*, 2011….

Thermally-activated relaxation



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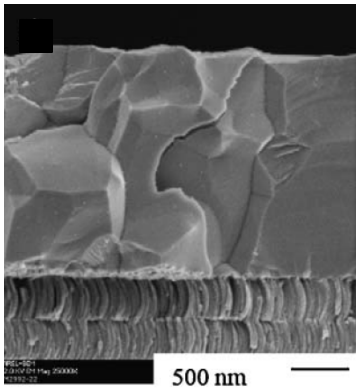
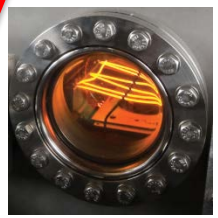
- Cl… …ncies.
- …

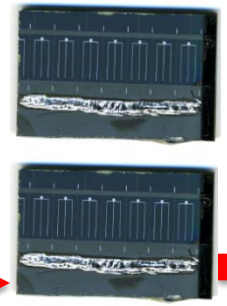
3. Understanding of metastability is increasing, and it can be manipulated by process variations.

Make a piece of standard CIGS

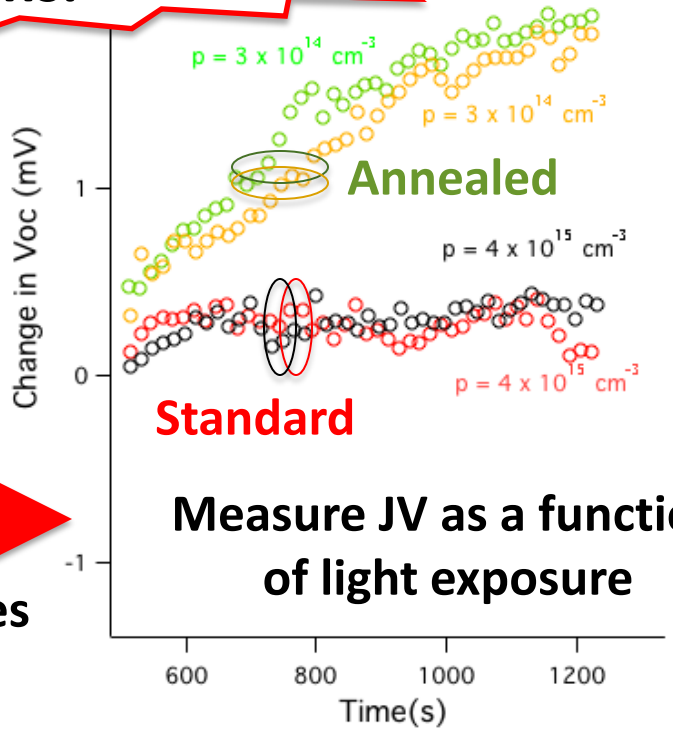


drive out Se



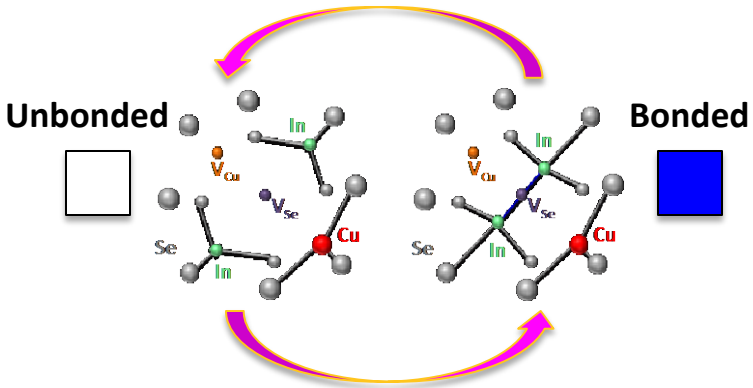


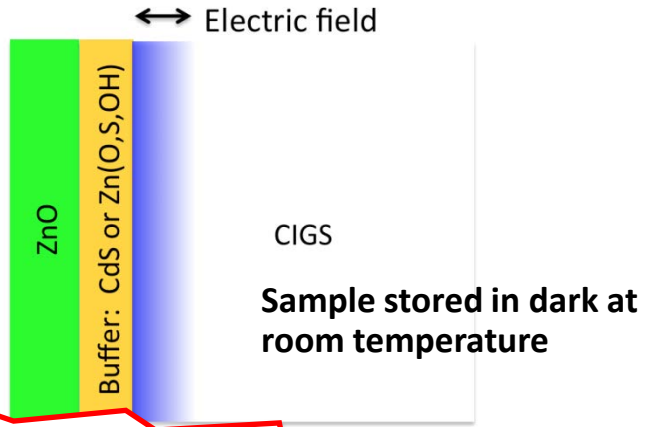
Make devices



Measure JV as a function of light exposure

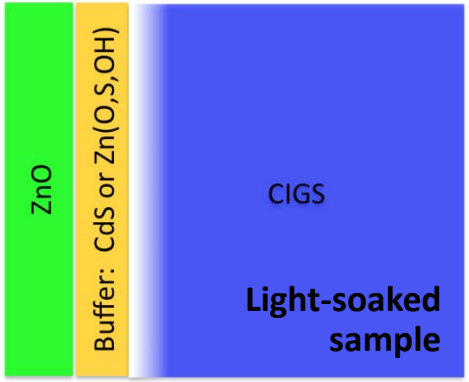
Distribution of defects contributes to device effects

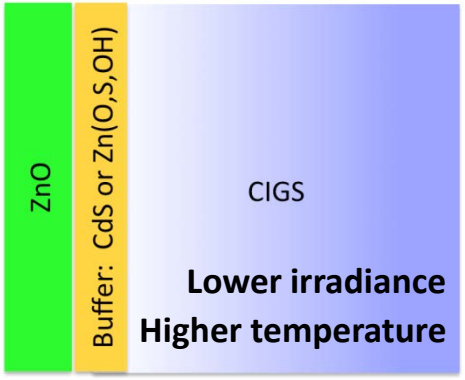




4. There is no such thing as a single "light" or "dark" state for a device or module.

Population profile is changed by temperature, irradiance, voltage, and where photons are absorbed.





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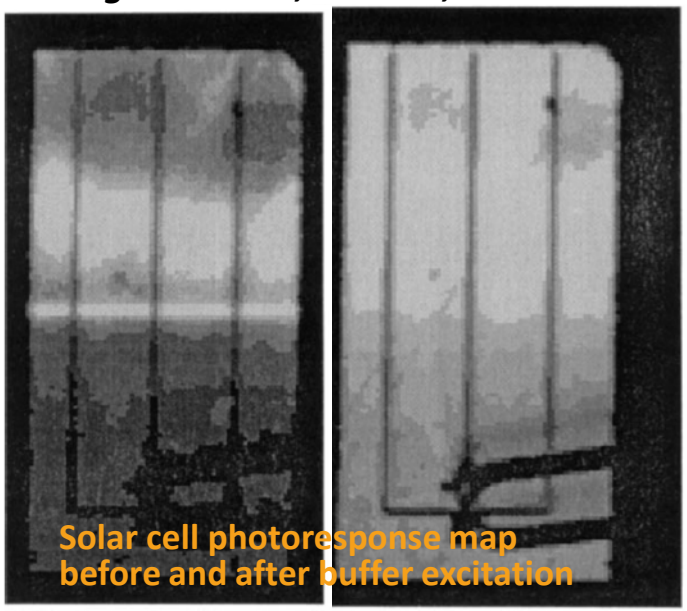
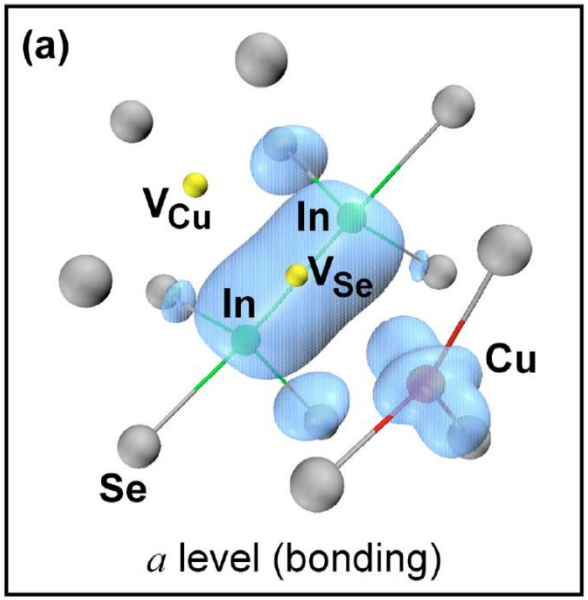
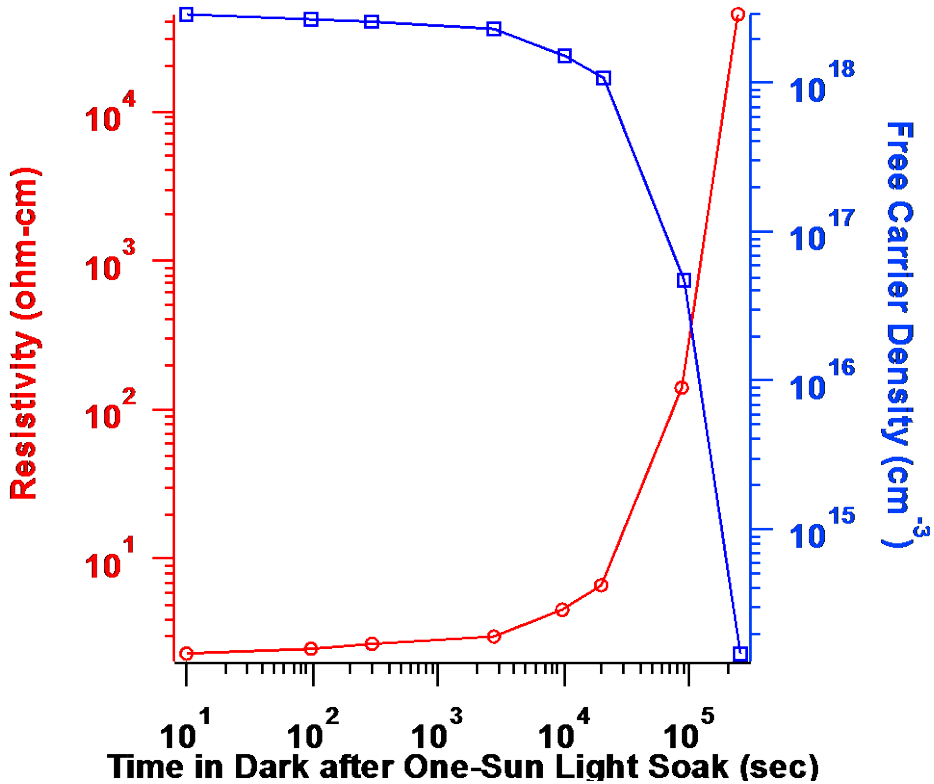




2. Buffer photodoping (traps in CdS or Zn(O,S))

What is buffer "photo-doping" ?

Resistivity and carrier density of CdS on glass after two hours of light exposure

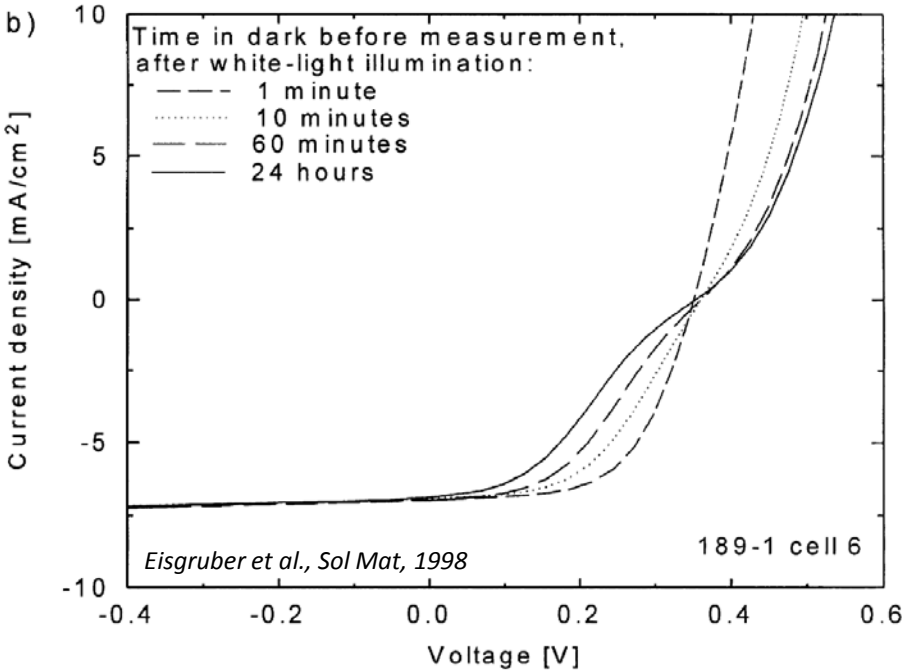


- Buffer becomes much more conductive after exposure to light
- Long-lived "photo-doping" of CdS (10^5 sec ~ 1 day)
- Attributed to "traps" – defects with imbalance in capture cross-section for electrons vs. holes

What is buffer "photo-doping" ?

Effect on JV curve considered well-understood.

Several studies measure and model this phenomenon in the CIGS device.



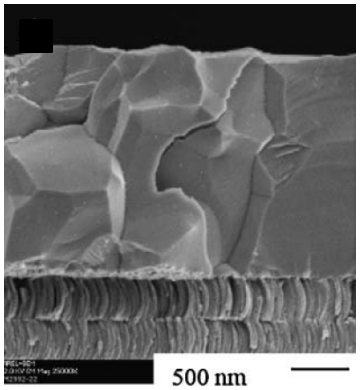
Eisgruber et al., Sol Mat, 1998

Buffer photo-doping

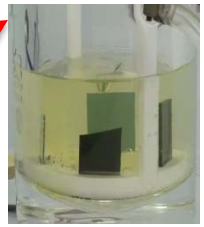
Current work at NREL examines implications of buffer photo-doping for device metastab

5. "Thin Film" metastability is not all the same, even within one absorber type.

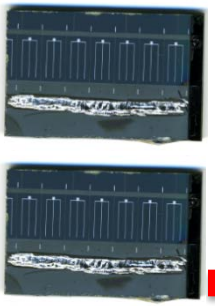
Make a piece of standard CIGS



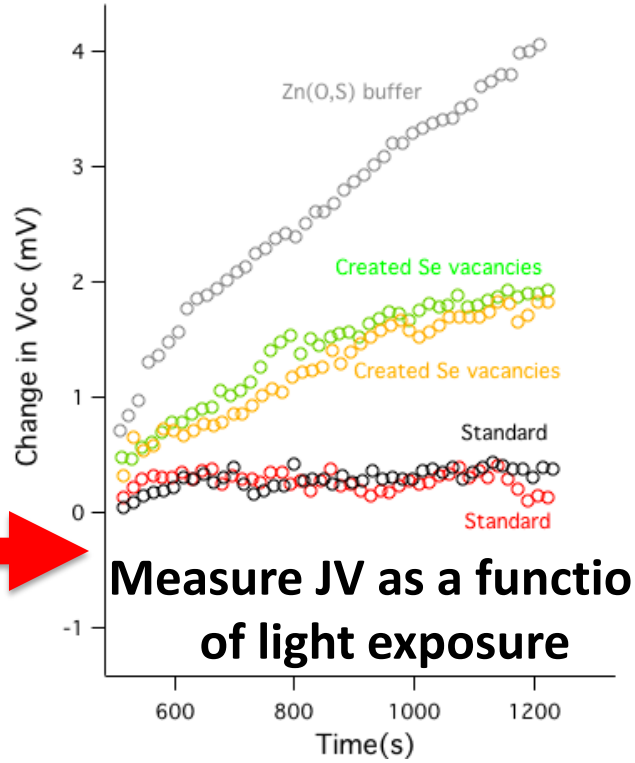
Deposit CdS buffer



Deposit Zn(O,S) buffer

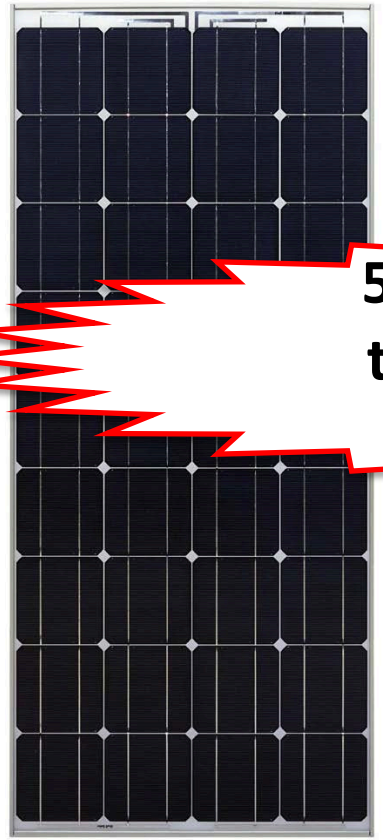


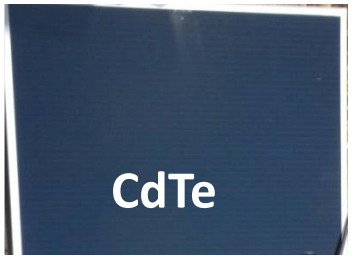
Complete devices



Measure JV as a function of light exposure

“Thin film” metastability





5. “Thin Film” metastability is not all the same, even within one absorber type.

Silicon

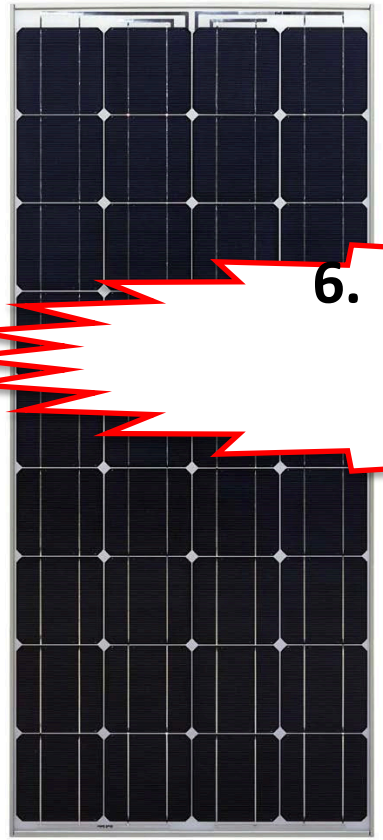
Relatively small metastabilities

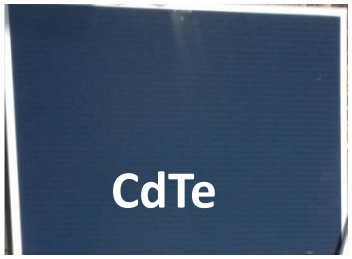
Not Silicon = “thin film”?

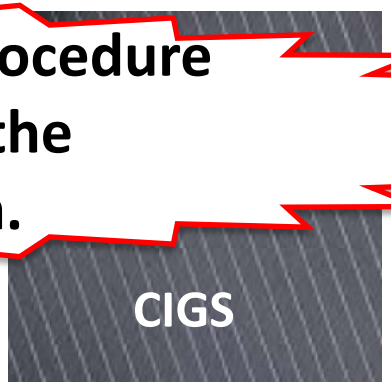
Same metastable behavior?

No.

“Thin film” metastability







6. A well-written standard or procedure should be independent of the metastability mechanism.

Silicon

Relatively small metastabilities

Not Silicon = “thin film”?

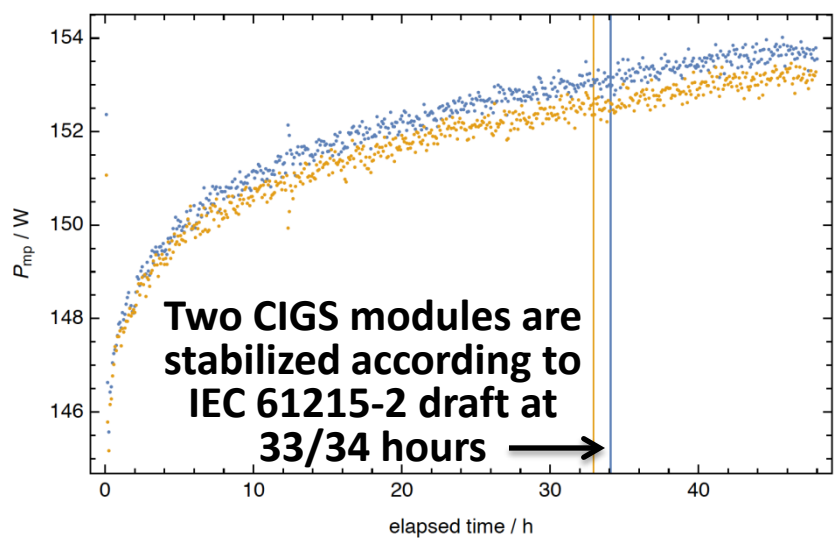
Same metastable behavior?

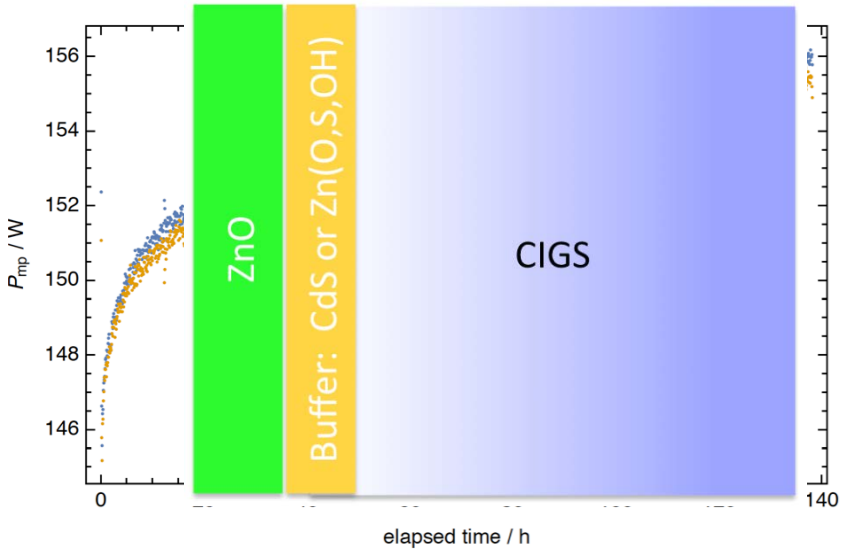
No.

Defect distribution throughout absorber and buffer

- Defects switch states based on probability (of thermal excitation, carrier capture, etc.)
- Performance approaches steady-state asymptotically, not abruptly

7. There is no such thing as "completely stabilized".





Conclusions

1. There are likely multiple mechanisms acting in parallel.
2. Rates toward stabilization in light versus relaxation in dark are different.
3. Understanding of metastability is increasing, and it can be manipulated by processing changes.
4. There is no such thing as a single “light” or “dark” state for a device or module.
5. “Thin Film” metastability is not all the same, even within one absorber type.
6. A well-written standard or procedure should be independent of the metastability mechanism.
7. There is no such thing as “completely stabilized.”

On prediction of moisture induced degradation in the field for flexible PV modules

Kedar Hardikar, Todd Krajewski, Kris Toivola.
PVMRW Feb 2016

Background

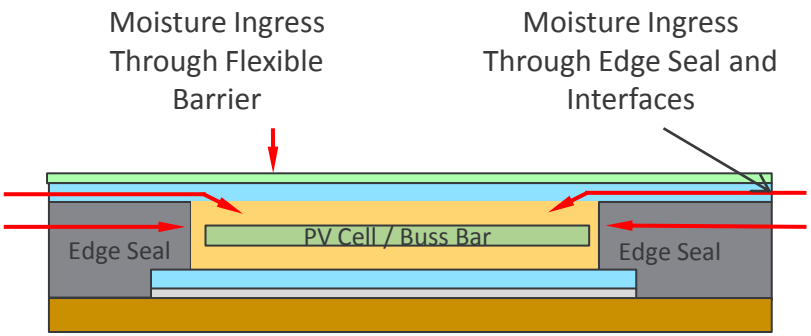
- MiaSolé is a leading manufacturer of high efficiency low cost CIGS thin film solar cells and modules
- MiaSolé has demonstrated a record efficiency of >16.5% for its CIGS thin film flexible solar panels.
- For flexible PV modules using new technology relevant field data is not yet available over extensive periods since the product is recently introduced.
- Rigorous techniques to assess field performance from accelerated testing results are critical to enable adapting products using newer technologies.
  - It is important that these techniques are built upon an appropriate scientific foundation.

A representative MiaSolé flexible panel

Outline

- Semi-Analytical model for accelerated testing and lifetime prediction based on moisture ingress.
- Candidate empirical models for moisture induced degradation.
- Acceleration factor model development and lifetime prediction.
- Module lifetime prediction for moisture induced degradation based on framework for rate processes.
- Conclusions

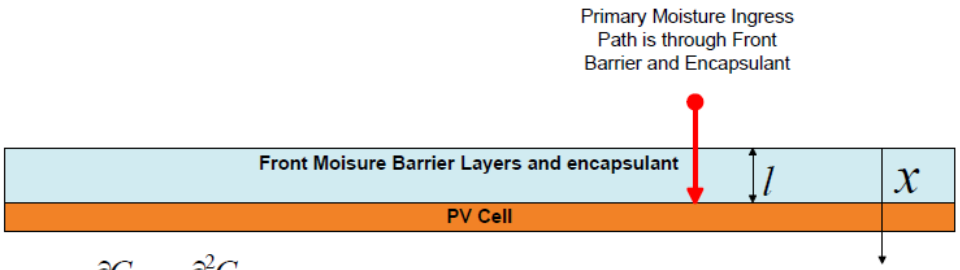
Potential moisture ingress through multiple paths in a flexible module



When edge seal width is sufficiently large the primary moisture ingress path is through the front barrier. This can be tested based on methods developed earlier at MHT for obtaining acceleration factors for the edge seal.

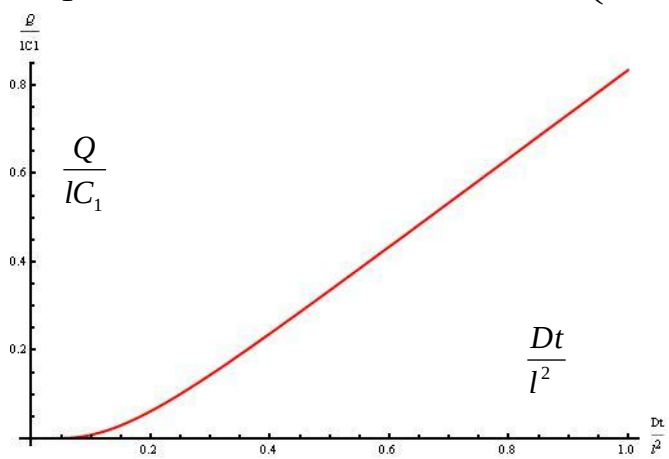
Diffusion-based model

- Moisture ingress and associated cell degradation can first be modeled using 1-D diffusion equation



$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2};\ C(x=0,t)=C_1;\ C(x=l,t)=0;\ C(x,t=0)=C_0$$

$$\frac{Q}{lC_1} = \frac{Dt}{l^2} - \frac{1}{6} - \frac{2}{\pi^2}\sum_{1}^{\infty}\frac{(-1)^n}{n^2}\exp\left(-\frac{Dn^2\pi^2 t}{l^2}\right)$$



Implications :

- If the degradation of cell is assumed to be proportional to the amount of moisture arriving at the cell,

$$\left(\frac{\Delta P}{P}\right) \propto t$$

- Degradation is proportional to external concentration C_1 and implies that time to failure as defined by critical degradation can be expected to be inversely proportional to RH

$$\left(\frac{\Delta P}{P}\right) \propto (RH)$$

- Combining the above with expected Arrhenius behavior of diffusion coefficient provides a semi-analytical model for time to failure -

$$TTF \propto (RH)^{-1}\exp\left(\frac{\varepsilon_a}{kT}\right)$$

Candidate Empirical Acceleration Factor Model

- In consumer electronics industry Hallberg-Peck model [1] is used to predict performance against moisture induced failures.

$$AF = \frac{TTF(field)}{TTF(test)} = \left(\frac{RH_{field}}{RH_{test}}\right)^n \exp\left(\frac{\varepsilon_a}{k}\left[\frac{1}{T_{field}} - \frac{1}{T_{test}}\right]\right)$$

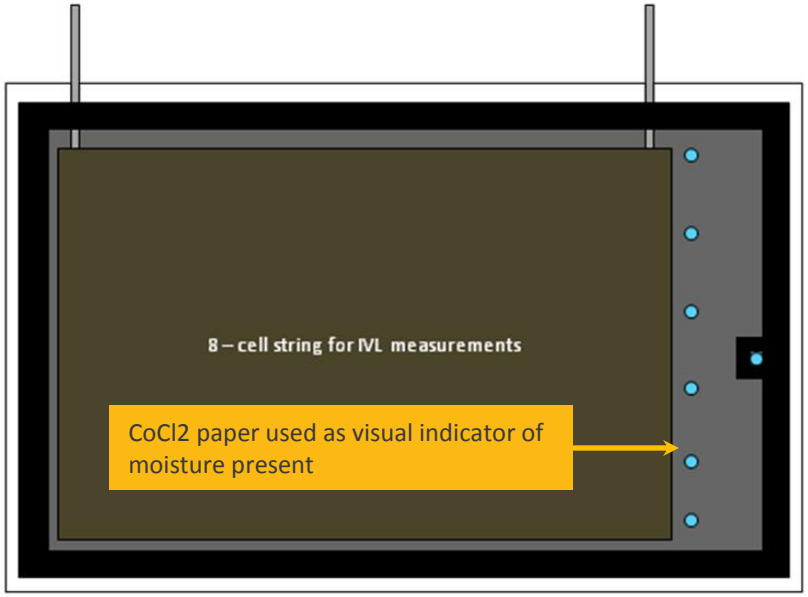
TTF: Time to failure
RH: Relative humidity
ε_a : Activation energy
n: Humidity exponent
AF : Acceleration factor

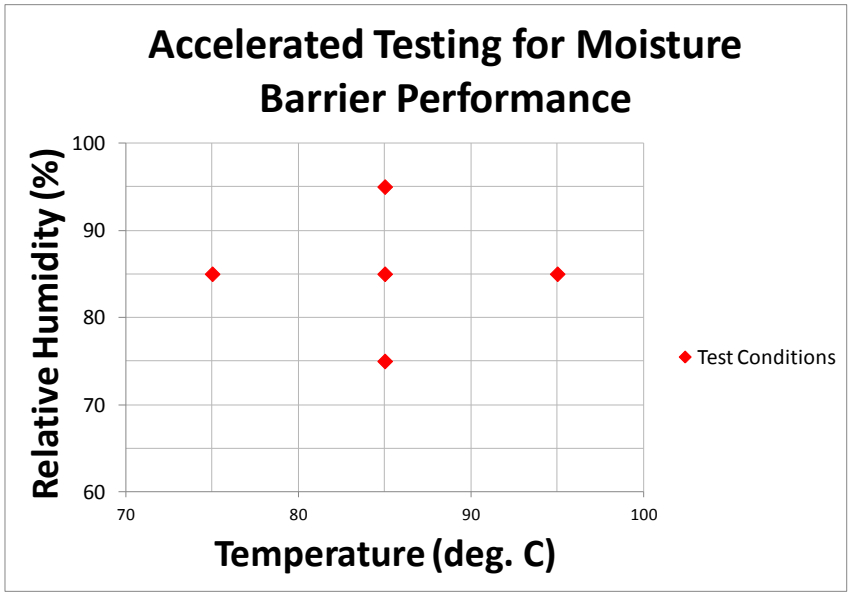
- This corrosion rate model and its validity is not established for PV applications.
  - Originally proposed for corrosion failures of encapsulated metallization in electronic devices.
- Hallberg-Peck model may be a suitable candidate for prediction of flexible PV module performance for moisture induced degradation but further scrutiny is warranted due to possible differences.
  - Details of mechanism by which CIGS cell degrades due to moisture can be different from corrosion of encapsulated metallization
  - CIGS cells can have temperature dependent degradation significantly different from the degradation of encapsulated metallization

Accelerated testing plan

- Barrier materials independently characterized by Mocon testing for diffusivity at different temperatures.
- Module-level testing carried out at different temperature and RH conditions with 5 samples per barrier type.
- Test conditions chosen include conditions beyond typical 85C/85% RH based on desire to highly accelerate certain failures. Results require scrutiny in case of unrealistic failures.

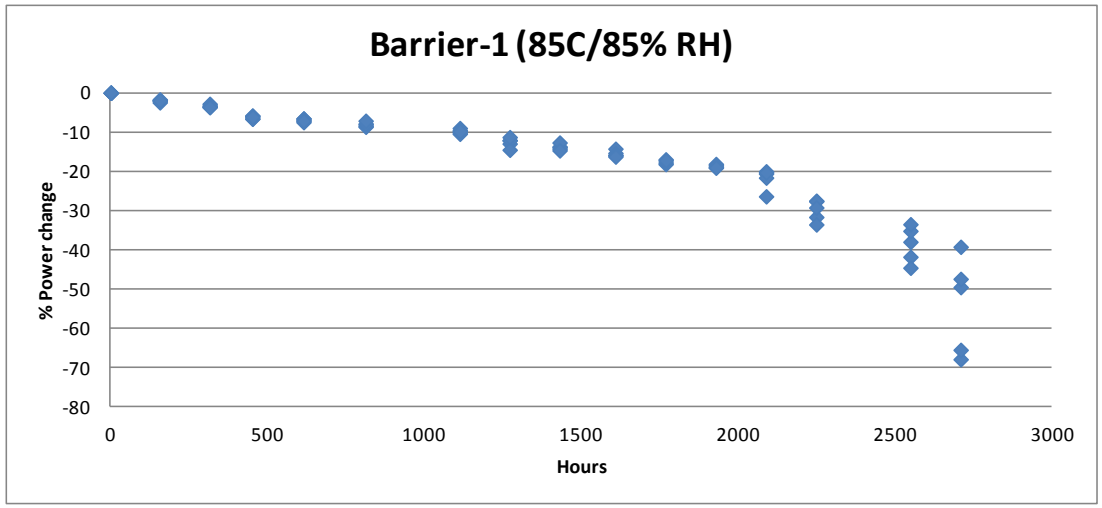
Name	WVTR
Barrier-1	0.0071 g/sq.m/d @37C/100%RH
Barrier-2	<0.0022 g/sq.m/d @37C/100% RH
Barrier -3	<5e-4 g/sq.m/d @50C/100%RH (Not amenable to MOCON testing)

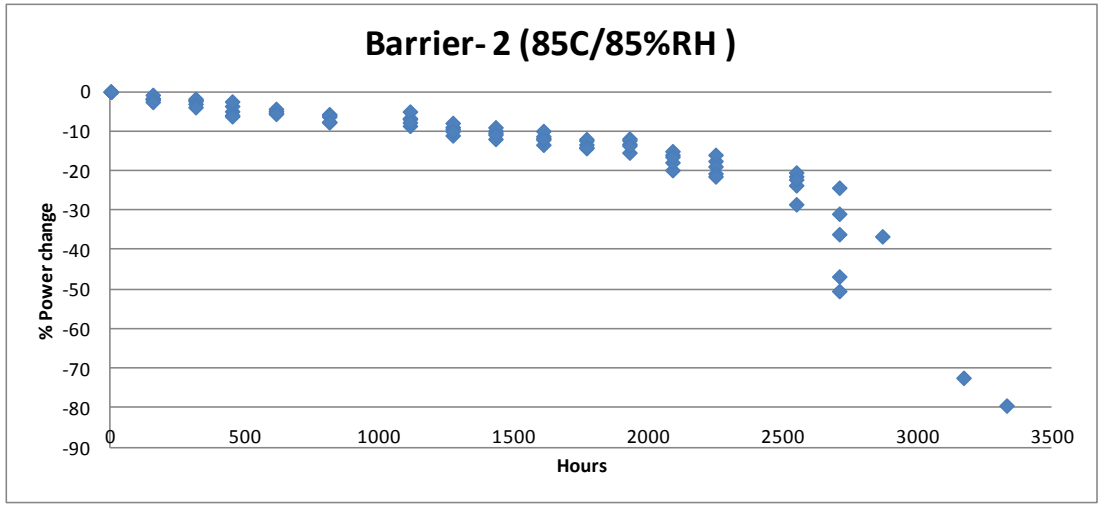




Representative results for degradation

- Data exhibits two different regimes in degradation.
- Approximate linear degradation is seen up to ~20% drop in Pmax beyond which a "crash behavior" is seen.
- Two regimes are seen to be different even on log-log scale.
- Scatter in data is higher in post-crash behavior.
- Barrier-3 samples were not amenable to MOCON testing and did not exhibit dP<-20% after ~7000 hrs at 85C/85% RH

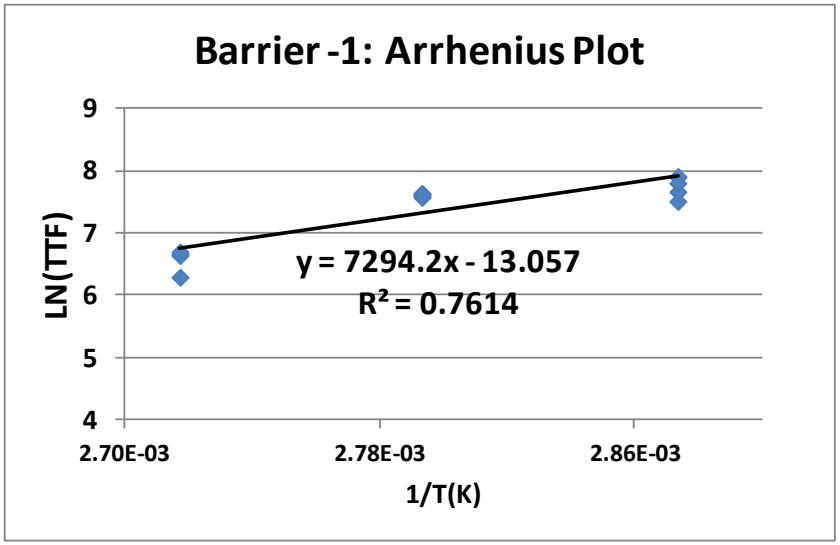


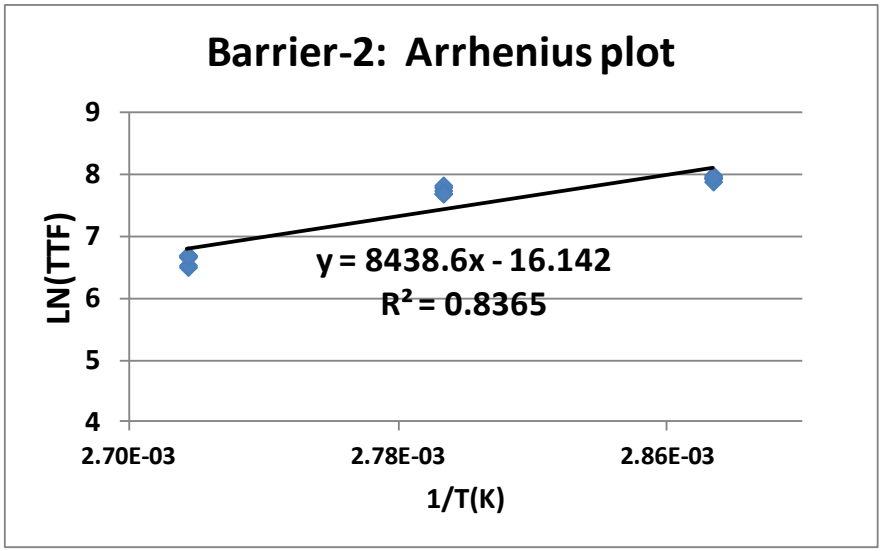


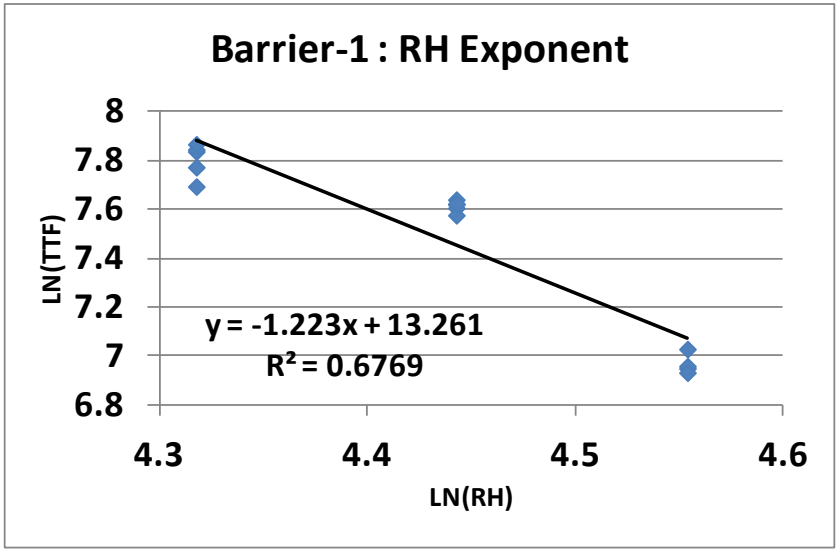
H-P Fit for Module Tests (ΔP=-20%)

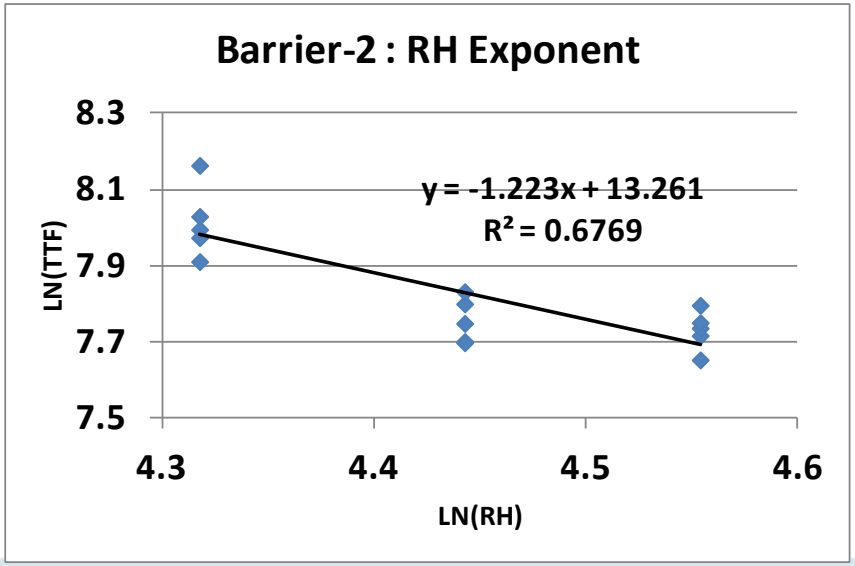
Barrier - 1 $\varepsilon_a = 0.63eV;\ n = -3.41$

Barrier-2 $\varepsilon_a = 0.73eV;\ n = -1.21$









Data Summary

Barrier	Activation energy from Mocon (barrier only)	Activation Energy from module level test (includes cell degradation)	RH Exponent from module level tests
Barrier-1	0.58 eV	0.63 eV	-3.41
Barrier-2	0.51 eV	0.73 eV	-1.22
Hallberg-Peck Recommendation (for encapsulated metallization)	NA	0.7 eV	-2.66

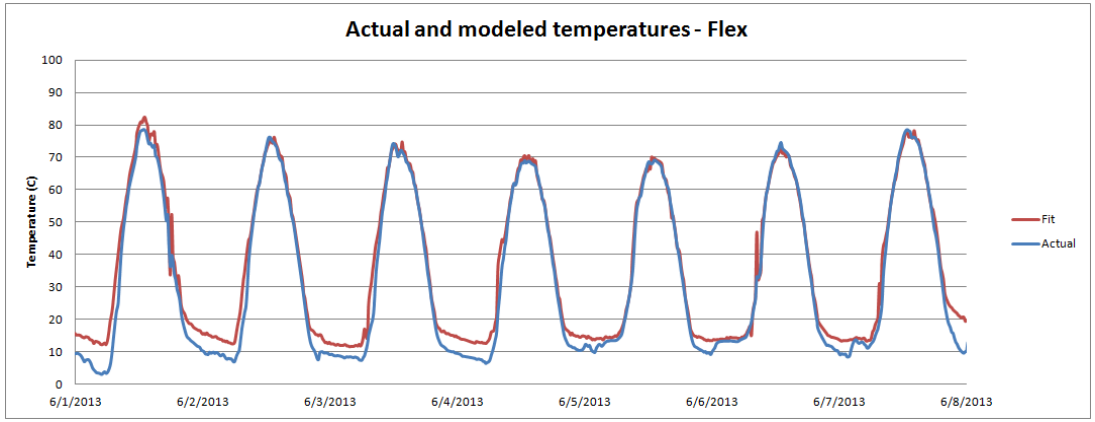
- Activation energy obtained by module level tests is not entirely consistent with the activation energy obtained from Mocon tests.
- Scatter in the data could be addressed with the following –
  - Increasing the sample size.
  - Using larger modules in test to account for potential variations in the cells and localized non-uniformities of barrier surface.
  - Improving consistency of electrical contacts through the test.

Method for assessment of field performance

- Acceleration factor for a given location can be found using hourly TMY data and Hallberg-Peck relation

$$< AF_{1yr} >= \frac{1}{t_{1yr}} \int_0^{t_{1yr}} \left(\frac{RH_{field}(t)}{RH_{test}} \right)^n \exp\left(\frac{\varepsilon_a}{k} \left[\frac{1}{T_{field}(t)} - \frac{1}{T_{test}} \right] \right) dt$$

- For a good module performance prediction, the to predict module temperature in the field is critical.
- Relative humidity used for these calculations is the ambient relative humidity and is believed to provide a conservative estimate.
- In this approach field conditions over a period of one hour are assumed approximately constant (the interval used for TMY data).



Sandia Model for predicting Module Temperature

$$T_{mod}(\deg.C) = T_{amb}(\deg.C) + \Delta T$$

$$\Delta T = (DNI) * Exp\ (-a - b\ V_{wind})$$

$$a = -2.96,\ \ b = 0.0178 \quad (by\ \ fit)$$

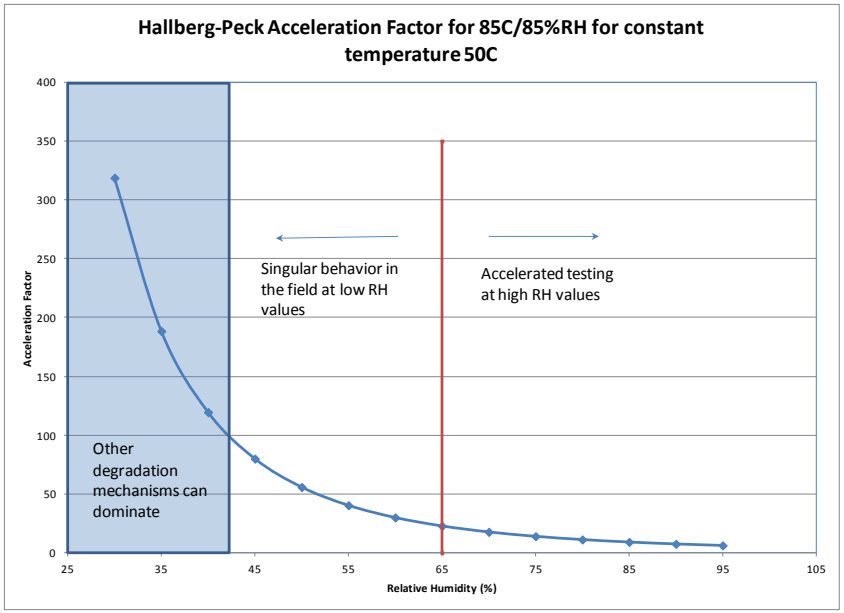
Deviations from predictions are seen to correspond to night time

Initial Assessment for Moisture Induced failures

Time to failure (yrs) for barriers based on H-P model and accelerated testing results considering moisture induced degradation only

Location	Criteria	Barrier-2 (n=-3.41)	Barrier -2 (n=-1)	Barrier-1 (n=-3.41)	Barrier-1 (n=-1)
Bangkok	dP=-20%	26.9 yrs	21.1 yrs	13.1 yrs	10.1 yrs
San Jose, CA	dP=-20%	175.4 yrs	84.8 yrs	71.5 yrs	33.1 yrs

- Predictions are based on TTF obtained at 85C/85%RH and Pmax change of 20% as failure criteria.
- Additional considerations are necessary.
  - Singular behavior of RH term in H-P model dominates predictions at locations with dry environments.
  - Other mechanisms can dominate in dry conditions. The model merely indicates *unavailability* of moisture over typical warranty period to drive degradation



Singular Behavior of H-P model for n=-3.41

Generalized Eyring Model (1941)

- Acceleration factor models based on theory of rate processes are considered to be better candidates.
- Appropriate functional form for rate processes (rate R) including thermal (T) and non-thermal (S) effects is

$$R = \gamma_0 T^m \exp\left(-\frac{\varepsilon_a}{kT}\right)\exp\left(\gamma_2 S + \frac{\gamma_3 S}{kT}\right)$$

- For most practical applications where the temperature range (on absolute scale) is small Generalized Eyring Model can be used as a basis for acceleration factor calculations

$$m = 0, \gamma_3 = 0 \ \ as\, it\, is\, absorbed\ \ in\, Arrhenius\ \ \ term$$

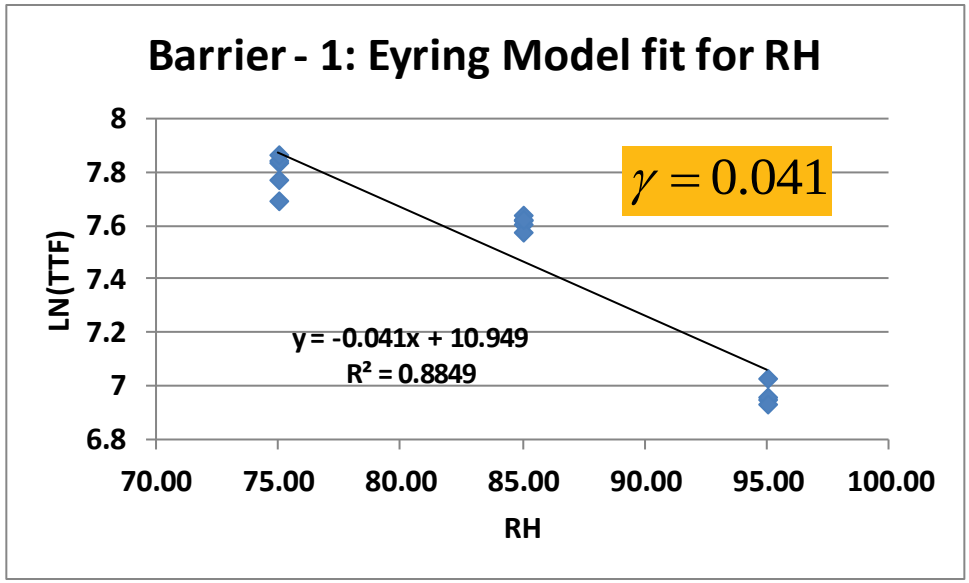
- For degradation driven by temperature and humidity, RH can be taken as a non-thermal stress driving degradation and thus leading to

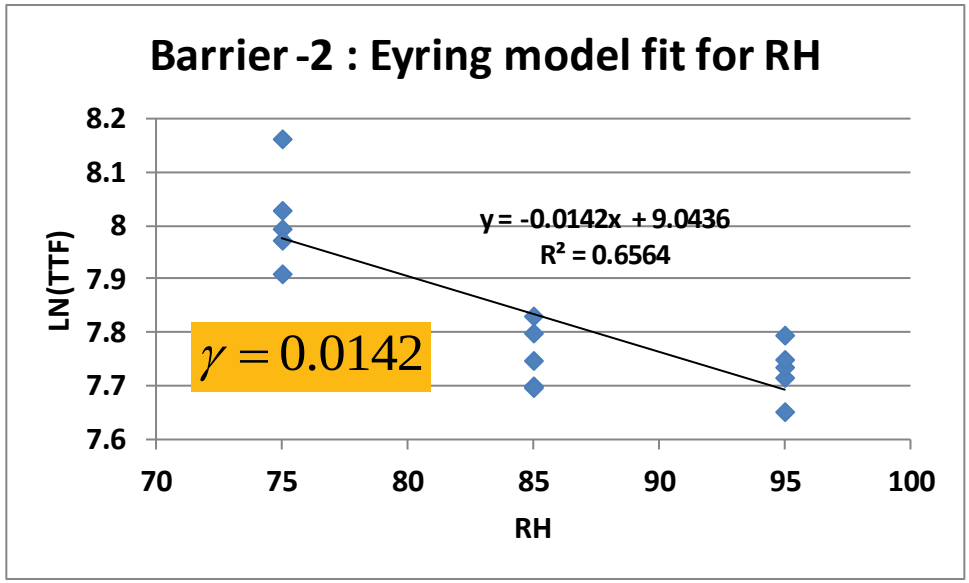
$$TTF \propto \exp\left(\frac{\varepsilon_a}{kT}\right)\exp\left(-\gamma_2 RH\right)$$

- As RH (non thermal) stress goes to zero, the Arrhenius behavior is recovered. This model does not have the singular behavior of H-P model and is seen to provide a bounding estimate for dry environments.

Eyring model for RH

- Eyring model captures RH dependence and eliminated singular behavior in H-P model.
- Improving the quality of fit will require
  - larger sample sizes
  - larger modules as test samples
  - testing with wider range of conditions including at low RH.
  - The associated test times can be prohibitive





Revised Lifetime predictions (Eyring Model)

- Singular behavior of H-P model and analytical model are eliminated using Eyring Model.
- These estimates address degradation driven by temperature and humidity only.
- Due to limited data available, these estimates should be taken as best estimates dictated by available data.
  - The quality of prediction can be improved by obtaining more test data over larger range of conditions.

Estimated Field performance (yrs) for moisture induced degradation only

Location:	Power change:	Barrier-2 (n = -3.41)	Barrier-2 (n = -1)	Barrier-1 (n = -3.41)	Barrier-1 (n = -1)	Barrier-2 (Eyring model, gamma=-0.0142)	Barrier-1 (Eyring Model, gamma=-0.041)
Denver	20%	45664	487	16489	163	363	455
Arizona	20%	3332	86	1649	36	69	100
Bangkok	20%	27	21	13	10	**21**	**12**
San Jose	20%	175	85	72	33	84	48

Singular behavior of H-P model dominates predictions in dry environments

Barrier-1 and Barrier-2 are found to be inadequate for aggressive environments like that in Bangkok

Conclusions

- Hallberg-Peck model was shown to be a candidate empirical model for assessment of field performance of flexible PV modules with regard to moisture induced degradation in high humidity conditions. H-P model was shown to give a singular behavior in dry environments, which is not desirable.
- Eyring Model was shown to be a better candidate for predicting moisture induced degradation in the field for flexible modules and does not have singular behavior in dry environments.
- Based on accelerated testing and subsequent analysis Barrier-1 and Barrier-2 are shown to not likely meet typical warranty requirements of 25 years in aggressive environments like Bangkok while Barrier-3 is considered adequate.
- Refinement of the analysis and prediction will require testing at low RH values, larger temperature ranges and with larger sample sizes and larger modules. Test times can become prohibitive at low RH values for high barrier systems, particularly for Barrier-3.

References

1. Hallberg, O., and Peck, D.S., “Recent humidity accelerations, a base for testing conditions”, Qual. Reliab. Eng., Vol 7, pp 169-180, 1991
2. J. Crank, “The Mathematics of Diffusion”, Oxford Science Publications, 1975
3. Glasstone S., Laider, K. J., Eyring H., Theory of Rate Processes, McGraw-Hill Book Company, London, 1941.
4. Luis A. E. and Meeker W. Q., A Review of Accelerated Test Models, Statistical Science, 2006, vol 21, No 4, 552-577.
5. Hardikar, K., Vitkavage D., Saproo A., Krajewski T., “ A methodology for testing, characterization and prediction of edge seal performance in PV modules”, PV International v22, December 2013.
6. Hardikar, K., Krajewski T., Toivola, K. “Predicting moisture-induced degradation of flexible PV modules in the field”, *Photovoltaics International*, 30th edn, pp. 72–83, December 2015.

National Renewable Energy Laboratory
Innovation for Our Energy Future

National Center for Photovoltaics

Factors in the Development of a PID Test Method for Thin Film Modules

Peter Hacke
John Wohlgemuth
Ingrid Repins
Steve Johnston

NREL PV Module Reliability Workshop

Feb. 23-25, 2016

NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC

Factors

- Status Review
- Factors
  - Degradation mechanisms of interest
- Recovery
- Reporting
  - Separating PID from other effects

62804-1 PHOTOVOLTAIC (PV) MODULES – TEST METHODS FOR THE DETECTION OF POTENTIAL-INDUCED DEGRADATION Part 1: **Crystalline Silicon**

Kyoto WG2 meeting poll Fall, 2013

Make this a test method with no pass/fail: 12
Qualification test with pass/fail: 4
~70 abstentions

Because there were no strong opinions to keep a pass/fail, the decision was to re-write the scope and title, making this a test method with no pass/fail requirements. The goal is to give the industry a standard method for performing the PID test. Both methods proposed will be included.

Published Sept. 2015

Procedures to test and evaluate the durability of crystalline silicon photovoltaic (PV) modules to the effects of short-term high-voltage stress including potential-induced degradation (PID)

Test methods

a) testing in damp heat using an environmental chamber

severities represent the minimal stress levels for detection of PID

- **60°C / 85% RH / + & – V_{sys} 96 h**
- **65°C and 85°C for further acceleration**

b) testing in dry using Al foil in the dry

severities represent the minimal stress levels for detection of PID

- **25°C / <60% RH / + & – V_{sys} 168 h**
- **50°C and 60°C for further acceleration**

"give community a chance to try it out before rolling it into IEC 61215 with pass/fail" – J. Wohlgemuth

What we do for c-Si may not be plug and play for TF

Photovoltaic Module Reliability Workshop 2010

February 18–19, 2010

Common Failure Modes for Thin-Film Modules and Considerations Toward Hardening CIGS Cells to Moisture

Kent Whitfield, Dir. Reliability

MiaSolé Thin-film solar

Qualification Testing

- **UL 1703, IEC 61646, IEC 61730**
  - **Don't be fooled…these are really standards built around crystalline PV failure modes with a dash of thin-film specific conditioning tests thrown in.**

Some differences

- Moisture ingress in TF takes longer (sealed glass/glass)
- Relatively quick PID recovery in c-Si

62804-2 PHOTOVOLTAIC (PV) MODULES – TEST METHODS FOR THE DETECTION OF POTENTIAL-INDUCED DEGRADATION Part 2: **Thin Film**

82/1082B/RVN

RESULT OF VOTING ON NEW WORK ITEM PROPOSAL

IEC/TC or SC	Date of circulation
TC82	
Allocated project number **PNW 82-1042 Ed. 1.0**	

Reference number of the proposal	Title of the TC or SC concerned
82/1042/NP	Solar photovoltaic energy systems

Title of proposal:
Photovoltaic (PV) modules - Test methods for the detection of potential-induced degradation - Part 2: Thin-film (proposed IEC 62804-2 TS)

Voting results

see printout attached

Number of P-members approving the new work item proposal	Number of P-members not approving the new work item proposal	Number of P-members having nominated or confirmed an expert and approving the new work item proposal
23	0	5

NWIP
Circulation Oct. 9, 2015
Approved Feb. 12, 2015

Experts: Document 82/1042/NP		
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First name	Last name	Email
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Peter	Seidel	peter.seidel@firstsolar.com
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Country: JP		
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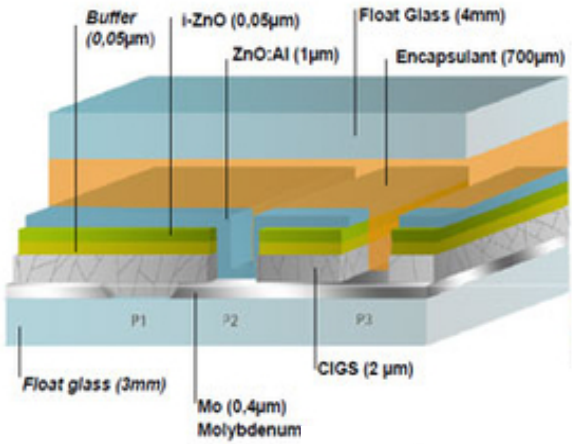
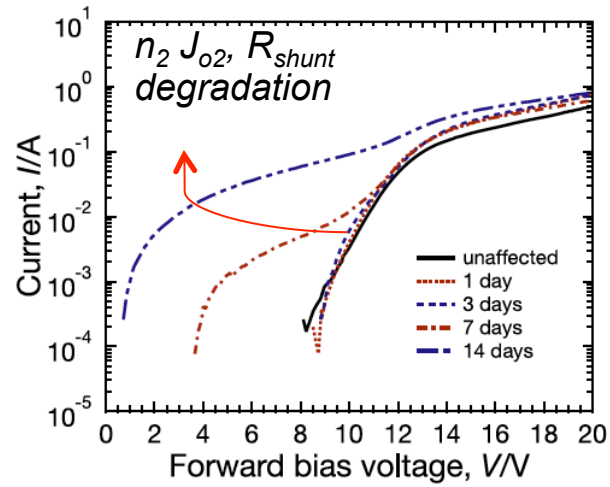
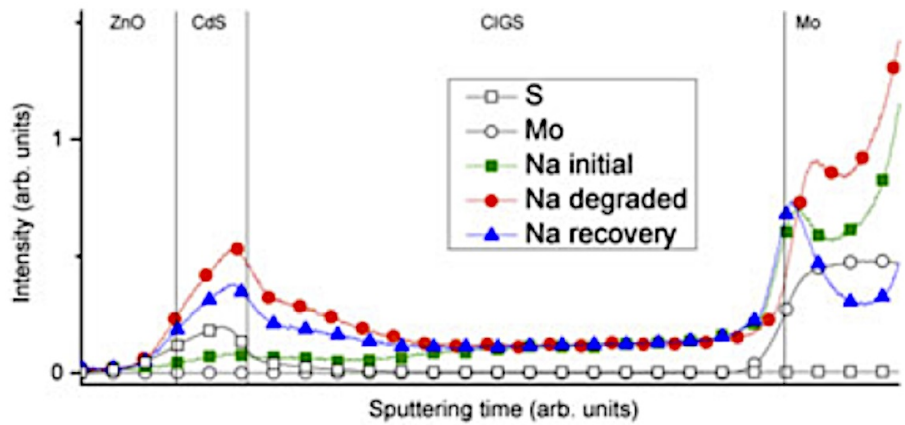
Country: US		
First name	Last name	Email
Sumanth	Lokanath	sumanth.lokanath@firstsolar.com

Shunting - CIGS

Shunting and junction degradation whereby elevated concentrations of Na impurity at the p-n junction (around the CdS layer and into the CIGS layer)







(a)

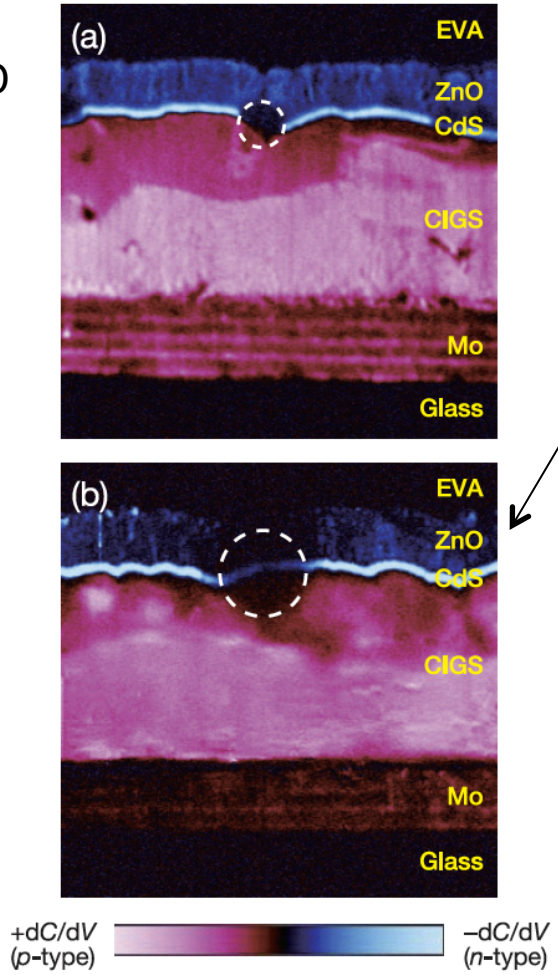
Lechner, and coworkers, 28th European Photovoltaic Solar Energy Conference and Exhibition, p. 2810, 2013.
Fjällström and coworkers, IEEE Journal of Photovoltaics, **5** (2), p. 664, 2015
Yamaguchi and coworkers, Japanese Journal of Applied Physics **54**, 08KC13, 2015.

Series resistance - CIGS

Increased series resistance, i.e, in the ZnO

Before PID

With PID



- 85°C /dry/ foil
- Scanning capacitance microscopy images of CIGS.
- A decrease in the signal intensity of the ZnO layer means a decrease in carrier concentration.
- Series resistance increases –
  - Substitutional Na (Na_{Zn}) which can produce deep acceptor levels in ZnO semiconductor.
  - Impurity scattering
  - The space charge region width may also increase through carrier compensation

Yamaguchi, S., Jonai, S., Hara., K., Komaki, H., Shimizu-Kamikawa, Y., Shibata, H., Niki, S., Kawakami, Y., and Masuda., A., "Potential-Induced Degradation of Cu(In,Ga)Se_2 Photovoltaic Modules," Japanese Journal of Applied Physics **54**, 08KC13, 2015.

CIGS Electrochemical TCO delamination

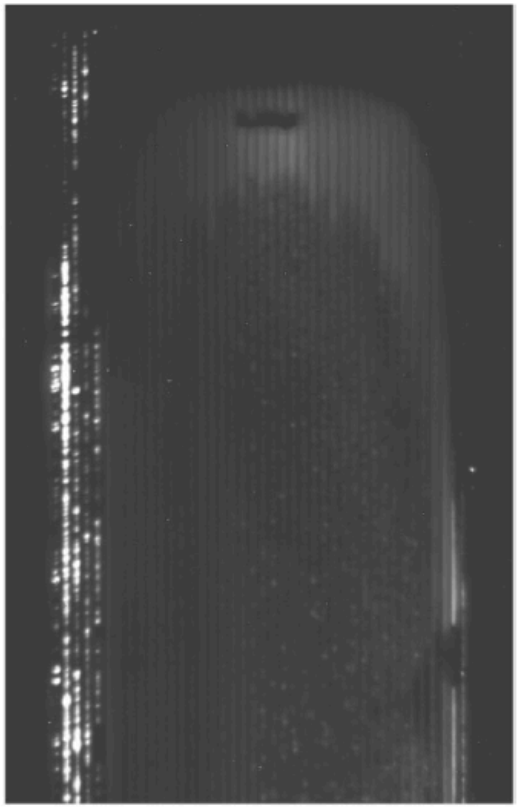
Initial

Optical

After 1043 h stressed in chamber at 85°C, 85% RH, and −1000 V

Optical

Electroluminescence

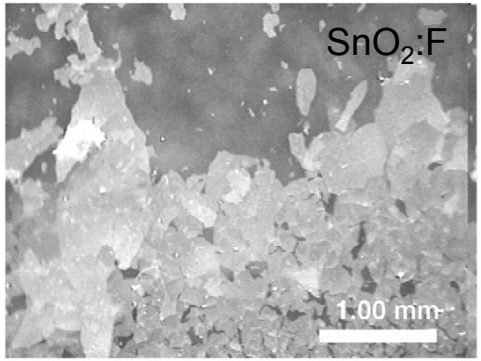


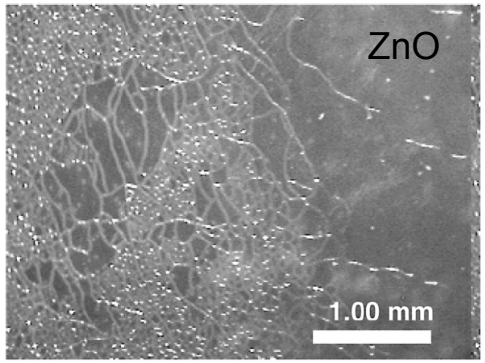
- Bar-graphing near at points near the frame and junction box penetration: moisture ingress

Hacke, P., and coworkers "Survey of potential-induced degradation in thin-film modules," J. Photon. Energy. **5**(1) 053083, 2015.

electrochemical TCO cracking/delamination process

- Well studied in a-Si (glass/TCO interface)
  - CIGS typically has a glass/encapsulant/TCO structure)
- Mobility of Na^+ increases with T
- Voltage across the glass drives Na^+ toward the cathode, (–) biased surface
- Na^+ reduction to Na (this is seen with both SnO_2:F and ZnO samples as a darkening of the TCO films)
  (so far this is reversible with reverse bias, the biasing treatment are able to lie dormant in the TCO in dry environment)
- With moisture ingress, non-reversible corrosion:
  - $H_2O + Na \rightarrow NaOH + H$
  - $4H + SnO_2 \rightarrow Sn + 2H_2O$
  - Other reactions leading to Sn reduction, HF from SnO_2:F
  - Stress in films lead to cracking and/or delamination





K.W. Jansen*, A.E. Delahoy, "A laboratory technique for the evaluation of electrochemical transparent conductive oxide delamination from glass substrates, Thin Solid Films 423 (2003) 153–160.

Confirming lack of moisture ingress

Degradation = Voltage potential + Moisture ingress
(take one away, you may not see PID)

			Modeled K	Modeled 25 years required width	Modeled 25 years equivalent time at 85°C/85% RH	Modeled 25 years equivalent time at 45°C/85% RH	T_{eq} using Ea_D
$D_{eff} = D_o e^{\left(\frac{Ea_D}{kT}\right)}$	D_o (cm^2/s)=	17.00					
	Ea_D (kJ/mol)=	54.8					
$S = S_o e^{\left(\frac{Ea_S}{kT}\right)} \frac{RH\%}{100\%}$	S_o (g/cm^3)=	0.0326					
	Ea_S (kJ/mol)=	5.00					
Reactive Ca absorption (g/cm^3)=		0.0320	(cm/h$^{1/2}$)	(cm)	(h)	(years)	(°C)
Miami, Florida	Open Rack, Glass/Polymer		0.00179	0.84	3,700	5.3	32.2
	Open Rack, Glass/Glass		0.00181	0.85	3,800	5.4	33.6
	Close Roof, Glass/Glass		0.00188	0.88	4,100	5.8	40.2
	Insulated Back, Glass/Polymer		0.00192	0.90	4,300	6.1	43.6

M. Kempe and coworkers, Prog. Photovolt: Res. Appl. (2014)

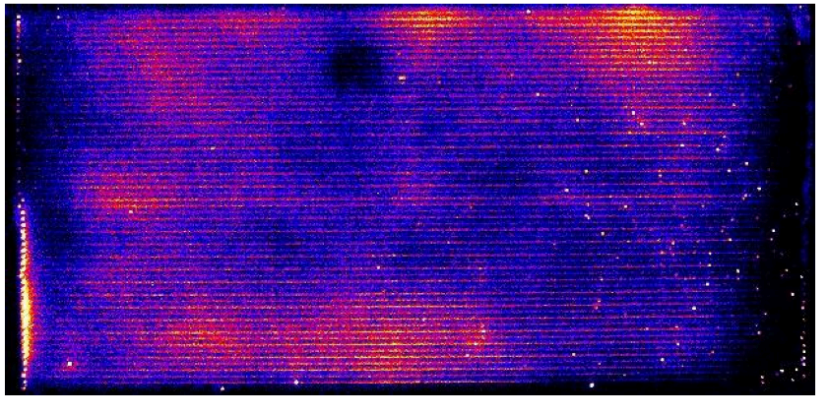
$$A = \frac{L_u}{L_a} = \exp\left(\frac{E_{a,\deg} + E_{a,perm} - E_{a,S}}{2R}\left(\frac{1}{T_u} - \frac{1}{T_a}\right)\right)\left(\frac{RH_a}{RH_u}\right)^{\frac{1}{2}}$$

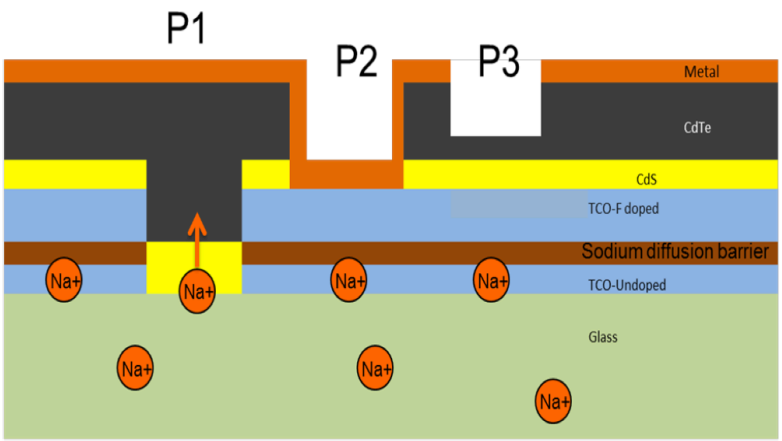
Acceleration factor has E_a for degradation, permeability, and solubility. D. Coyle, IEEE PVSC (2009)

- Moisture participating in corrosion
- Conductivity of encapsulants increase with moisture content

NWIP Conditions therefore put at 85°C/85%RH/1000 h/ + Vsys

CdTe Shunting

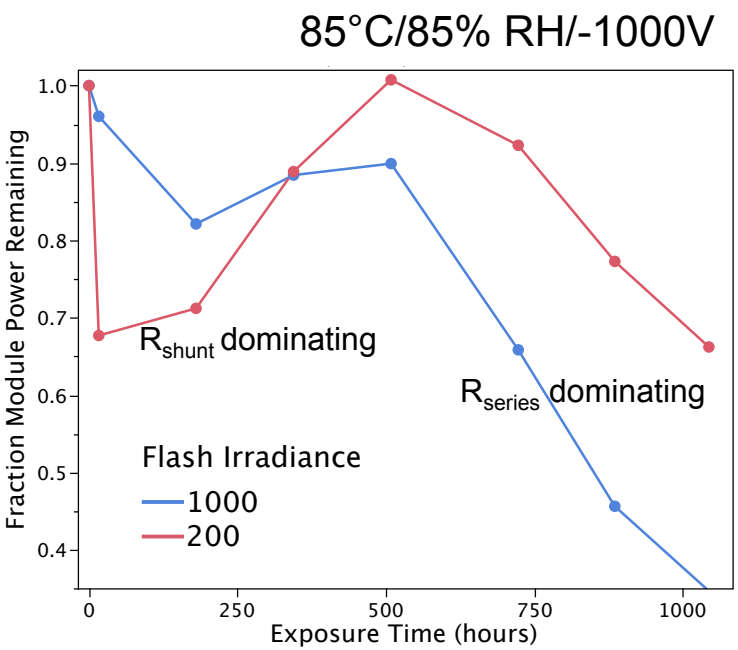


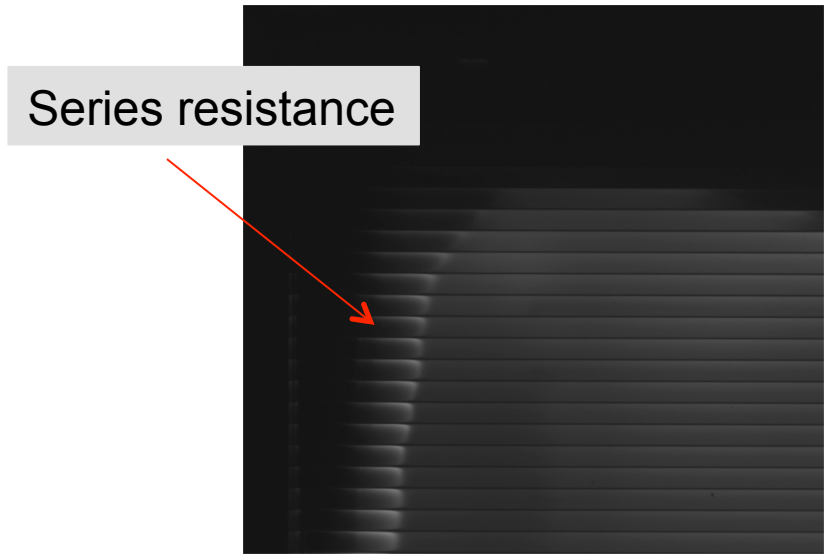


- Lock in thermography showing shunts at P1 Scribe

N. A. Olsson, M. Propst, C Richardson, and J. Hevelone, Thin Film PID Field Failures Root Cause Determination, 2014 PVMRW

CdTe series resistance





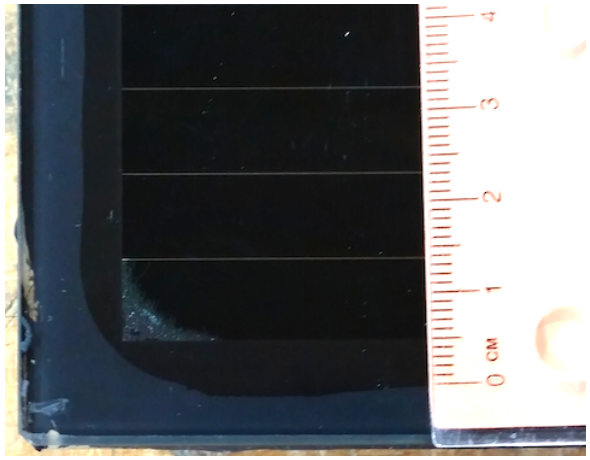
Electroluminescence
(more in S. Johnston poster, this workshop)

Degradation of the SnO_2:F TCO suggested
(possibly formation of NaF, Na_2SnO_3 and SnO, corrosion)

Hacke, P., and coworkers "Survey of potential-induced degradation in thin-film modules," J. Photon. Energy. **5**(1) 053083, 2015.

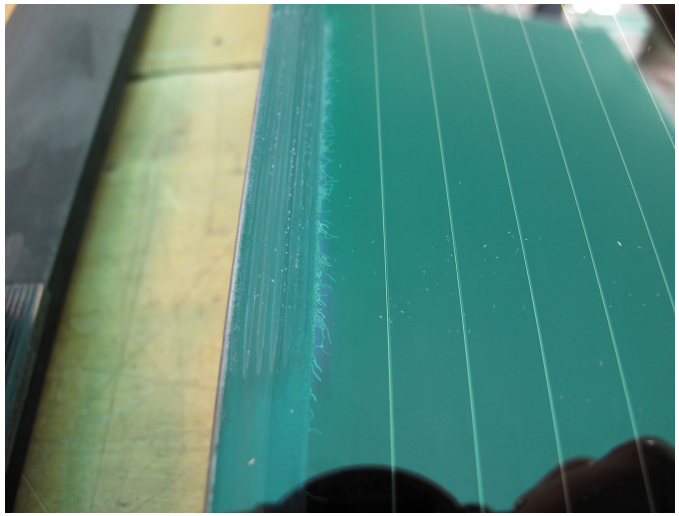
CdTe TCO corrosion

Foil = uniform field



25°C/95%RH/Foil/~1000 h
Corrosion at corner, area of highest moisture ingress

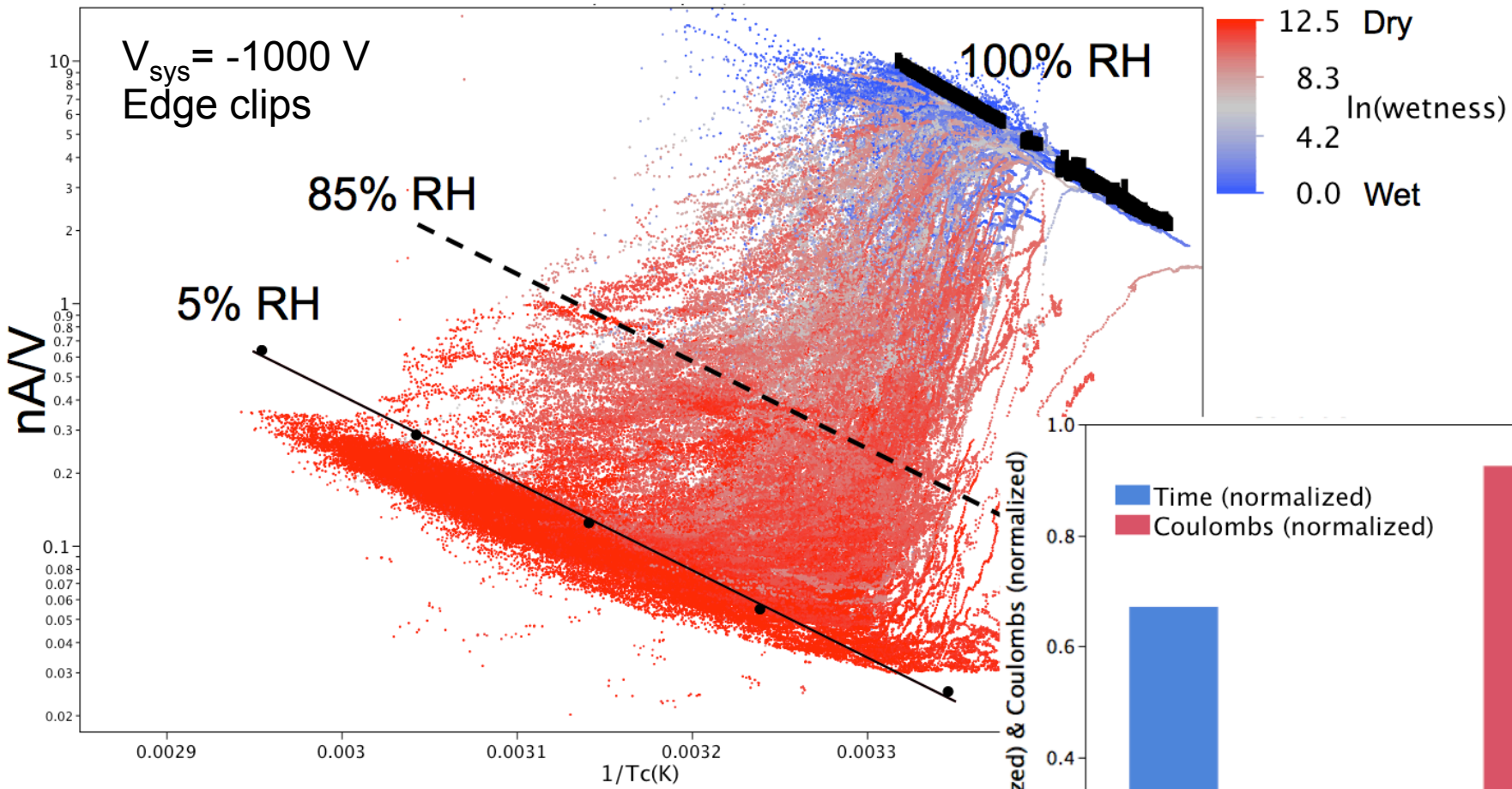
Edge clips/ damp heat

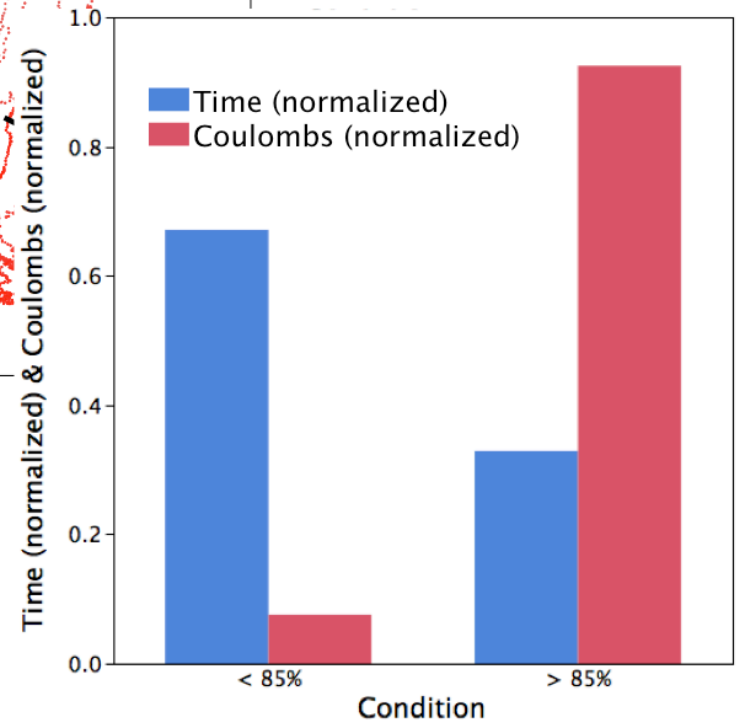


60°C/85%/-1000 V/ 550 h
Corrosion at edge clip (ground), area of electric field – not corners
moisture ingress still fastest at corners

Field + moisture = maximum acceleration of PID-corrosion type

Distribution of current transfer, CdTe, FL

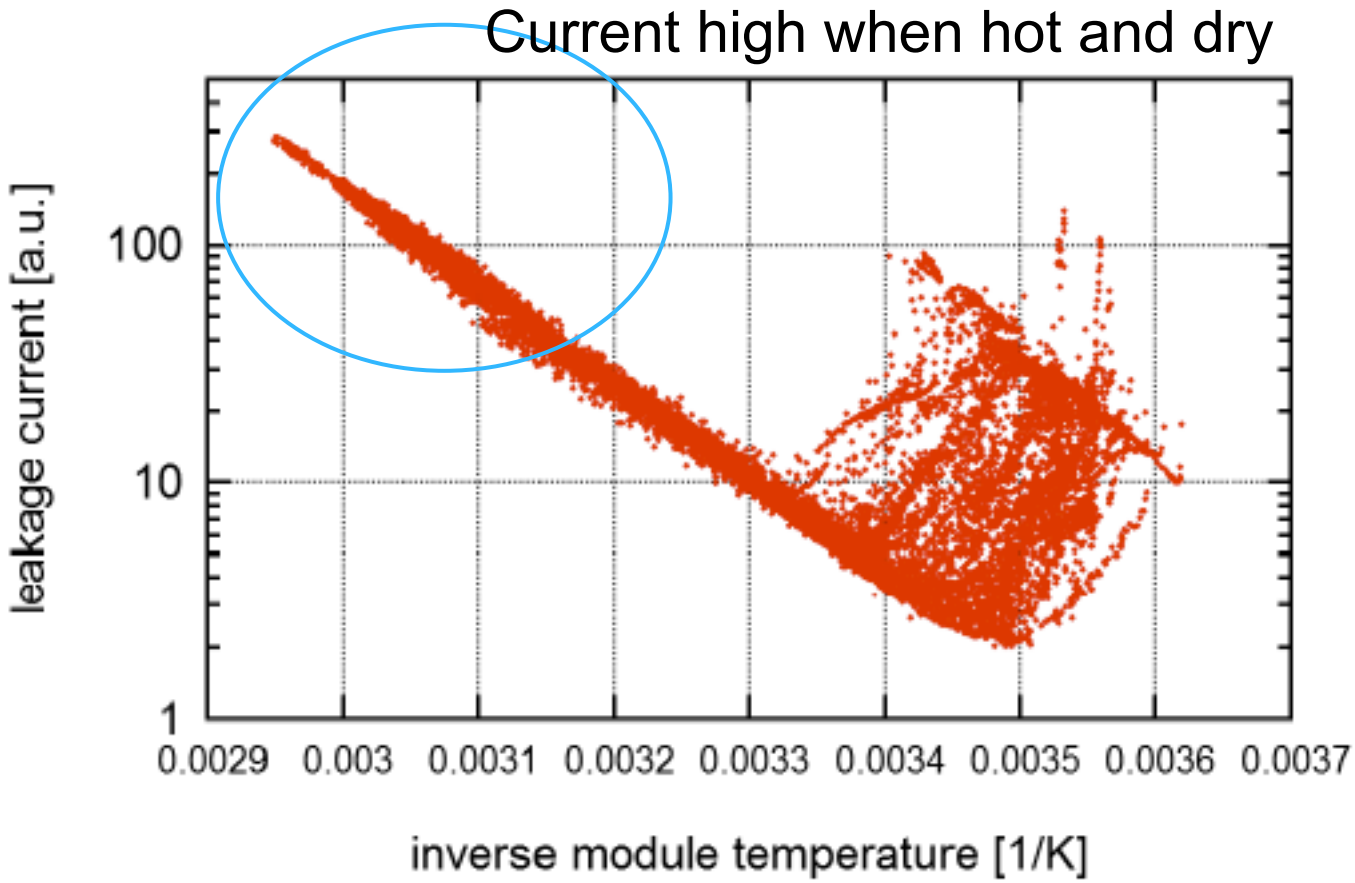




Condensed water **can** defeat electrical resistance provided by from edge clips

- Do we use Al foil ?.....

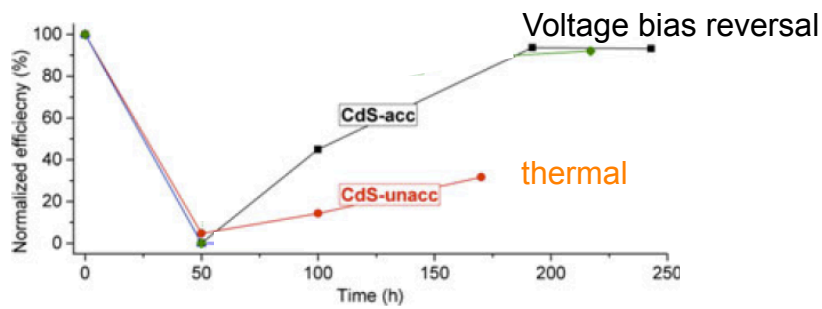
But statistics differ for type and location, CIGS, DE



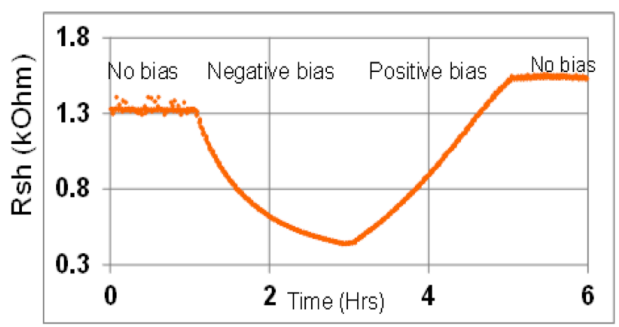
Borowski, P., and Karg, F., "PID-Free CIGS Thin-Film Modules,"
Proceedings 29th European Photovoltaic Solar Energy Conference and Exhibition, p. 2356, 2014.

Recovery

CIGS: Bias reversal ($-V_{sys} \rightarrow +V_{sys}$) or thermally activated recovery



CdTe: Bias reversal ($-V_{sys} \rightarrow +V_{sys}$) recovery



Fjällström and coworkers, IEEE Journal of Photovoltaics, **5** (2), p. 664, 2015
Yamaguchi and coworkers, Japanese Journal of Applied Physics **54**, 08KC13, 2015.

Pre-conditioning/post-conditioning

Recovery precludes post-conditioning light soak because PID may recover during that time

Alternatives for PID test conditions –

- Test in a dark repeatable state
  - Place module at stress temperature until there is no change in power
- Test in dark forward bias to achieve band offset as it would be under light
- Test under light
- Test PID vs an unbiased in-chamber reference module

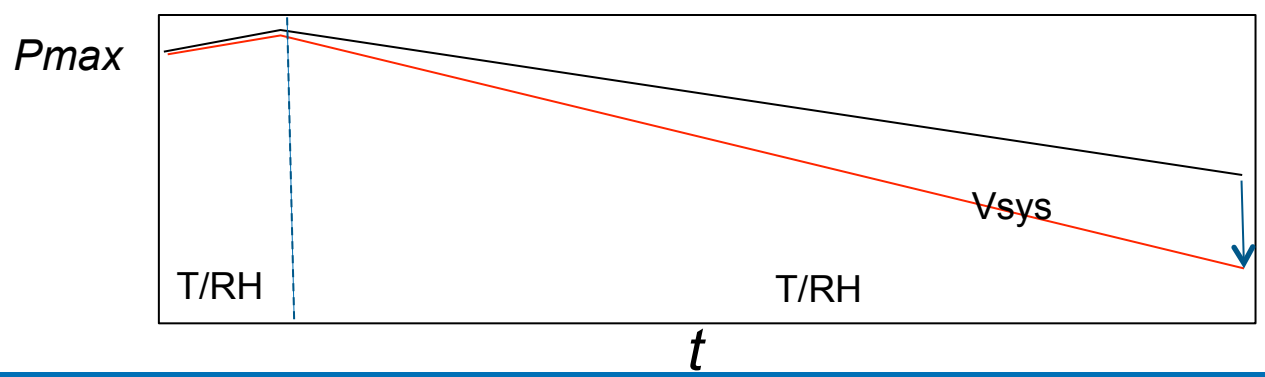
PID you get under these various states might be different, to be determined, but it seems reasonable to allow the choice.

To measure PID, measure against an in-chamber reference without V bias

To separate PID from any other effects during the PID test

- Metastabilities
- Contact annealing (migration of Cu in CdTe)
- Other degradation mechanisms

	Condition	Initial (W)	Final (W)	Change (W), relative to initial measurement	Change (%) relative to initial measurement	Change (%), relative to initial measurement, adusted for change in reference module
1	Reference	200	220	20	10.0	–
2	- 1000 V	200	180	-20	-10.0	-20.0
3	- 1000 V	200	180	-20	-10.0	-20.0
4	+ 1000 V	200	240	40	20.0	10.0
5	+ 1000 V	200	240	40	20.0	10.0



Stress conditions

Ahead of discussing stress conditions, we must determine

- What mechanisms do we want to test for
  - Proposal to omit bar-graphing
- Some PID mechanisms accelerated by moisture ingress, so how long do we want to simulate?
  1. Test over the duration of damp heat with voltage stress
  2. Test with voltage stress for a shorter period after damp heat alone.

Thank you for your attention

-- questions, comments

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Thin film session, Wednesday 8 -10 AM

Questions to Solar Frontier talk

Q1: (Solibro) We do not see this behavior [test-specific degradation], because there is no water ingression. Where does this behavior happen? Perhaps interface states are being changed?

A1-a: (Neelkanth Dhere) Metallic precursors might be contributing to this effect

A1-b: (Markus Beck) The behavior will vary with different device production processes

A1-c: (Solar Frontier) [The presentation noted that this test-specific degradation is not related to water ingression because it was found in both damp heat and dry heat tests. This effect happens in dark + high temperature conditions, which does not represent real field conditions.]

Q2: (Unknown) Are the effects of applying forward bias and light irradiation during the DH test equivalent?

A2: (Solar Frontier) Yes. [The presentation slides 8 and 9 noted that the P_{max} recovered by the post-test light soaking after DH test was the same level as that for both DH with forward bias and DH with light irradiation.]

Q3: (Unknown) Do you see similar behavior [test-specific degradation] in the field?

A3: (Solar Frontier) No, we do not see such behavior in the field and there is no reason to find this behavior in the field. [The presentation noted that test-specific degradation occurs in dark + high temperature conditions, which does not represent real field conditions. Refer to slide 4 regarding behavior in the field and slide 10 regarding behavior in dark heat conditions.]

Questions to Tim Silverman's talk

Q1: (Angus Rockett) Need to test modules under reverse bias, fit with exponential function, determine ideality factor.

A1: We have several papers where such analysis was applied to cells, explanation is related to tunneling effects.

Q2: (Jim Sites) If mechanism is shunts, then effect would saturate. Would this be a good metric to analyze the mechanism?

A2: Probably true, but there are time constrains in qualification test.

Q3: (Markus Beck) Could this apply to all technologies?

A3: Only for monolithically integrated modules

Questions to Michael Deceglie's talk:

Q1: (Keith Emery) Dark bias in at high-T data - why you choose 55 deg. C?

A1: Based on earlier suggestions

Q2: (Keith Emery) For short transient temperature changes time scale, but not the final state

A2: We did not test short transients.

Q3: (Unknown) Will this change the standards?
A3: (Unknown) Discussion is in progress.

Questions to Ingrid Repins' talk

Q1: (Jim Sites) Can we extrapolate to infinite time?
A1: Simple exponential can't be applied to metastability, stretched exponential was used, but it is only empirical model.

Q2: (John Previtali, Wells Fargo) How do we know that product is stable? How long does it take to evaluate metastability?
A2: All modules are different. For Solar Frontier's modules 1-2 weeks is recommended for field verification of stabilized P_{max}, for Solibro there is no metastable effect.
[In Solar Frontier's presentation, stabilization of P_{max} can be confirmed in slide 11. Data shows a high level of stabilization after 21 kWhrs, with no significant fluctuation between 21 kWhrs (equivalent to roughly 5 days) and 126 kWhrs (equivalent to roughly 1 month).]

Q3: (Marko Topic) What would be a perfect precondition?
A3: Conditions where module needs to work, such as STC.

Discussion questions:

From moderator Markus Beck: What does community need to do to assure financial organizations of the good reliability of thin film PV?

Comment 1: Neelkanth Dhere: Need more data – how do we get access to it?
Answer, Solar Frontier: Currently, Solar Frontier does not have wide access to accurately monitored field data, which prevents relevant data sharing.

Comment 2: Larry Pratt, in response to moderator: Name-plate ratings are needed to show actual output from the day one. Send modules to independent test labs.
Reply to comment 2: Markus Beck: this is no longer allowable, thin film modules are now rated the same as silicon.
Reply to comment 2: Solar Frontier: For Solar Frontier's modules 1-2 weeks is recommended for field verification of stabilized P_{max}.
[This will vary with actual irradiation level at site. In Solar Frontier's presentation, stabilization of P_{max} can be confirmed in slide 11 with data showing a high level of stabilization after 21 kWhrs, with no significant fluctuation between 21 kWhrs (equivalent to roughly 5 days) and 126 kWhrs (equivalent to roughly 1 month).]

Comment 3: long question/comment from John Previtali, Wells Fargo, in regard of perceived financial risk of thin film modules: In the future, we would like to do a test after the system stabilizes, a "final acceptance test". Is this done

currently?

Summary of this discussion - need more public information about metastability.

Comment 4: James (did not get the last name?) From installer's perspective, LCOE for thin films is currently lower than for Si. Also characterization for low light performance, metastability, etc. is lacking.

Reply to comment 4: Darshan Schmitz, Solar Frontier

We have shipped 4GW of CIGS modules worldwide and we have numerous case studies on our website showing a performance ratio that is better than c-Si, so we feel progress for thin film PV is substantial.

[Regarding characterization, PVSyst allows for modeling of both low light performance and metastability from the light soaking effect. Solar Frontier also offers measurement guidelines of module power output to customers and test labs to address potential variability from preconditioning procedures, solar simulator specifications, calibration methods, etc.]

Comment 5: Jeff Brad, JPMorgan

There is more variability in thin film, this creates apparent risk.

BAPVC

Overcoming perovskite degradation by eliminating free volume and gas diffusion

Stanford | ENGINEERING

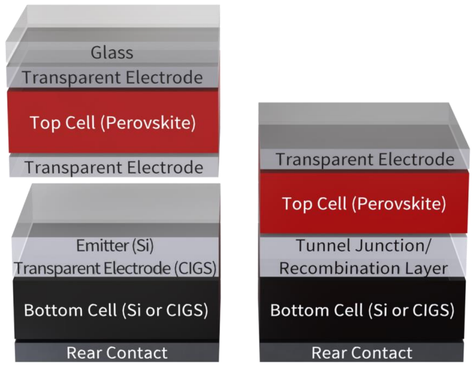
SunPreme SmartSilicon for Solar

COLIN D. BAILIE[1], KEVIN BUSH[1], YE CHEN[2], ANDREA R. BOWRING[1], WEI WANG[2], WEN MA[2], TOMAS LEIJTENS[1], FARHAD MOGHADAM[2], AND MICHAEL D. MCGEHEE[1]

[1] Department of Materials Science and Engineering, Stanford University, [2]SunPreme, Palomar Avenue, Sunnyvale CA

Perovskites enable low-cost tandems

Why perovskites and perovskite tandems?



- Efficiency breakthroughs needed to reach 6 ¢/kWh Sunshot target and 3 ¢/kWh stretch goal.
- Single-junction silicon has limited efficiency projections. Mutlicrystalline silicon is limited to ~21% and advanced silicon cells to ~25%.
- Perovskite tandems can boost the performance of silicon by 30-50% depending on the quality of silicon used.

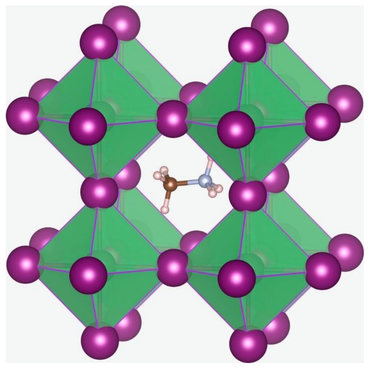
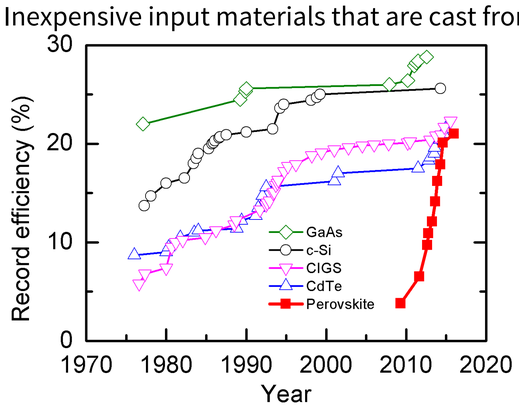


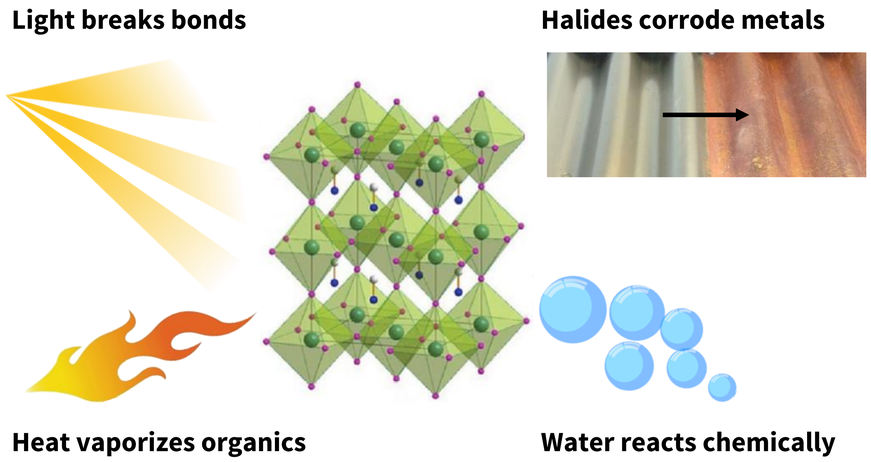
Image credit: Eames, C., et al. (2015) Ionic transport in hybrid lead iodide perovskite solar cells. Nature Comm.

- Metal-halide perovskite stoichiometry: ABX_3. Most commonly methylammonium(A)-lead(B)-iodide(X).
- Variants possible on the A site (formamidinium or Cs), on the B site (Sn), and on the X site (Br). These variants tune the bandgap from 1.2eV to 2.3eV
- Inexpensive input materials that are cast from solution.



- The perovskite operates efficiently as a polycrystalline material.
- Record efficiency increase from 4% in 2009 to 21% in 2016. Fastest-improving photovoltaic technology in history.

Environmental stability prevents commercialization



Weak bonds – susceptible to light and heat

Schottky formation energy in metal-halide perovskite is **0.14eV per defect**[1]
Schottky formation energy for BaTiO3 is **2.29eV** per defect[1]
Enthalpy of formation for Si-Si bond is **3.4eV**

Hygroscopic – moisture causes structural degradation[2]

Iodization is similar to oxidation and corrodes metal electrodes

AgI Enthalpy of formation is -62 kJ/mol
Ag_2O Enthalpy of formation is -31 kJ/mol

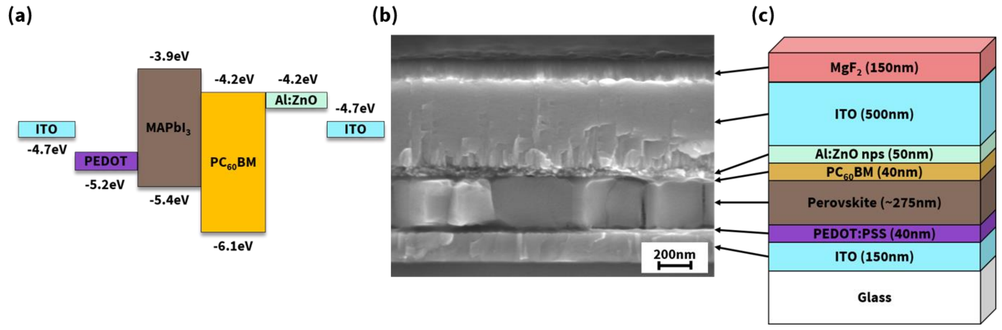
[1] Walsh, A., et al. (2015). Self-Regulation Mechanism for Charged Point Defects in Hybrid Halide Perovskites. *Angewandte Chemie.*
[2] Leijtens, T., et al. (2015). Stability of Metal Halide Perovskite Solar Cells. *Advanced Energy Materials.*

The following results are from Bailie, C., et. al. (2016). **Thermal and Environmental Stability of Semi-Transparent Perovskite Solar Cells for Tandems Enabled by a Solution-Processed Nanoparticle Buffer Layer and Sputtered ITO Electrode.** *Advanced Materials.*

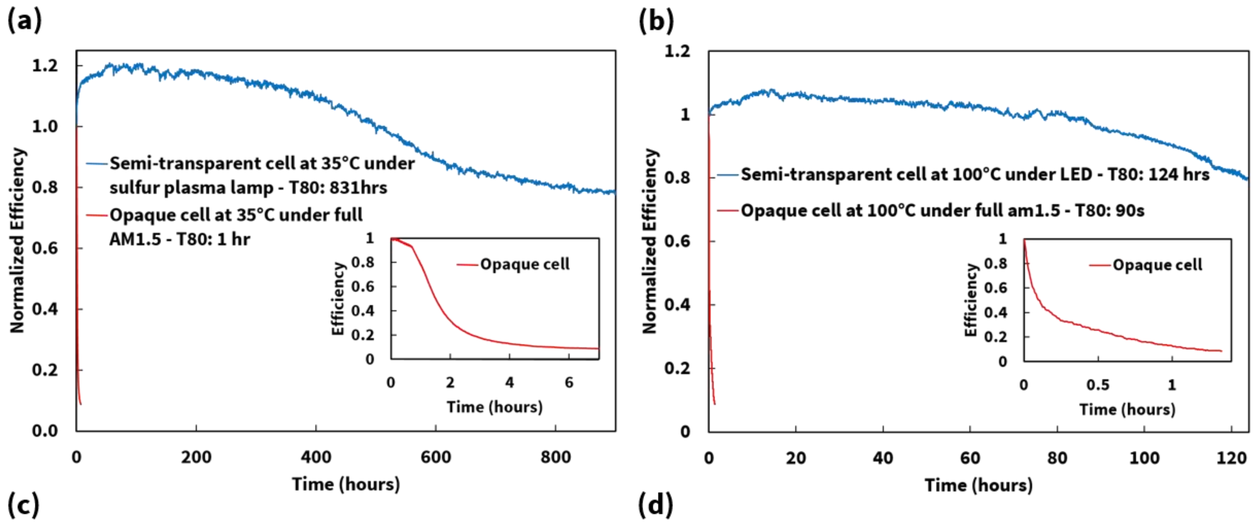
Stabilize the perovskite with an oxide capping layer

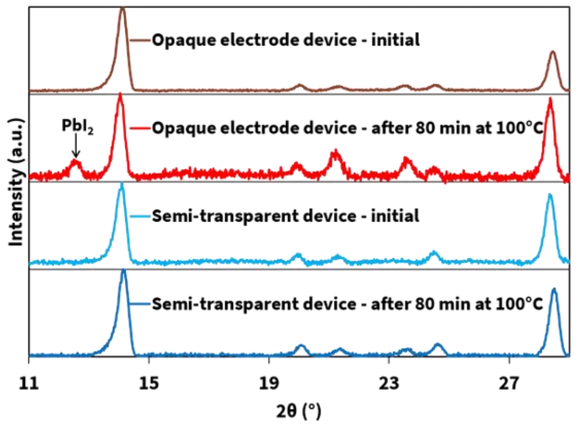
Double the functionality of the transparent electrode (TE) with a TCO

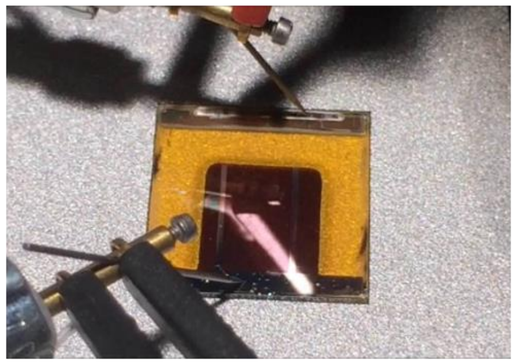
A TE deposited onto the perovskite is required for both mechanically-stacked and monolithic tandems. ITO is known for being a good moisture barrier and may serve the dual functionality of TE and stabilize the perovskite.



Above. Sputtering ITO onto the soft perovskite and organic heterojunction layers causes damage. An inorganic buffer layer of AZO nanoparticles is introduced via solution to act as a buffer layer.







Above. (a,b) The ITO capping layer improves operational lifetime ~1000X. The likely cause of eventual degradation is slow gas diffusion laterally to the edges and through pinholes in the ITO layer. Further packaging may arrest these degradation pathways. **(c)** XRD shows the degradation is due to loss of methylammonium iodide when no capping layer is present, leaving behind lead iodide. **(d)** Photo taken after 90s at 150°C. The remaining brown area is underneath the ITO. Lead iodide is yellow in color.

IEC 61646 is not enough for predicting perovskite field stability

- Unlike other photovoltaic technologies, light is a strong accelerant for main perovskite degradation pathways in addition to heat and moisture.
- IEC 61646 test protocols, which stress the module under temperature and/or moisture in the dark, miss an important stressor for predicting the field robustness of the perovskite.
- A new testing protocol that includes illumination during thermal tests should be developed.
- Weathering chambers, such as the Q-lab Q-sun, can perform such tests with full spectrum illumination using Xe arc lamps.

Alternate Damp Heat Test for CIGS to Mitigate Pseudo Degradation

Kannan Ramanathan, Fred Mikulec, Richard Bunte
Stion Corporation, San Jose CA

Introduction

The proposed IEC 61215 standard for Damp Heat test subjects CIGS modules to stress conditions that cause “pseudo degradation” not observed under normal operation. In fact, CIGS module output increases in outdoor sun exposure. The degradation observed during DH is purely a thermal effect, occurs when heated in the dark, and fully reversed by light soaking. To mitigate against the ‘artificial’ degradation’, the modules should be tested under constant light soaking or an equivalent condition, forward bias to mimic the actual operating conditions. This experiment compares two groups of modules tested with and without applied bias.

Procedure: 1000 hr DH with and w/o Bias

- Modules were soaked in outdoor sunlight for a few days under open circuit. JV curves were measured.
- 8 modules were held under no bias during DH, and 8 modules were biased at STC Vpm of 60V.
  - Biased modules were connected in parallel.
    - Total current: 5.8 A, or 0.725 A per module (about 27% of typical Isc @ 2.7 A).
  - Module temperature under bias was measured prior to DH and found not to increase by more than 1 degree due to the biasing.
- JV of all modules was measured after 1000 hrs of DH
- JV of all modules was remeasured after 1h of outdoor sun soak
- JV of all modules was remeasured after another 5 hrs of partial sun (cloudy), then again at 14 and 26 hours.
- Graphs at right illustrate recovery of Pmax, fill factor, Voc and Isc relative to initial values (before DH).

Results

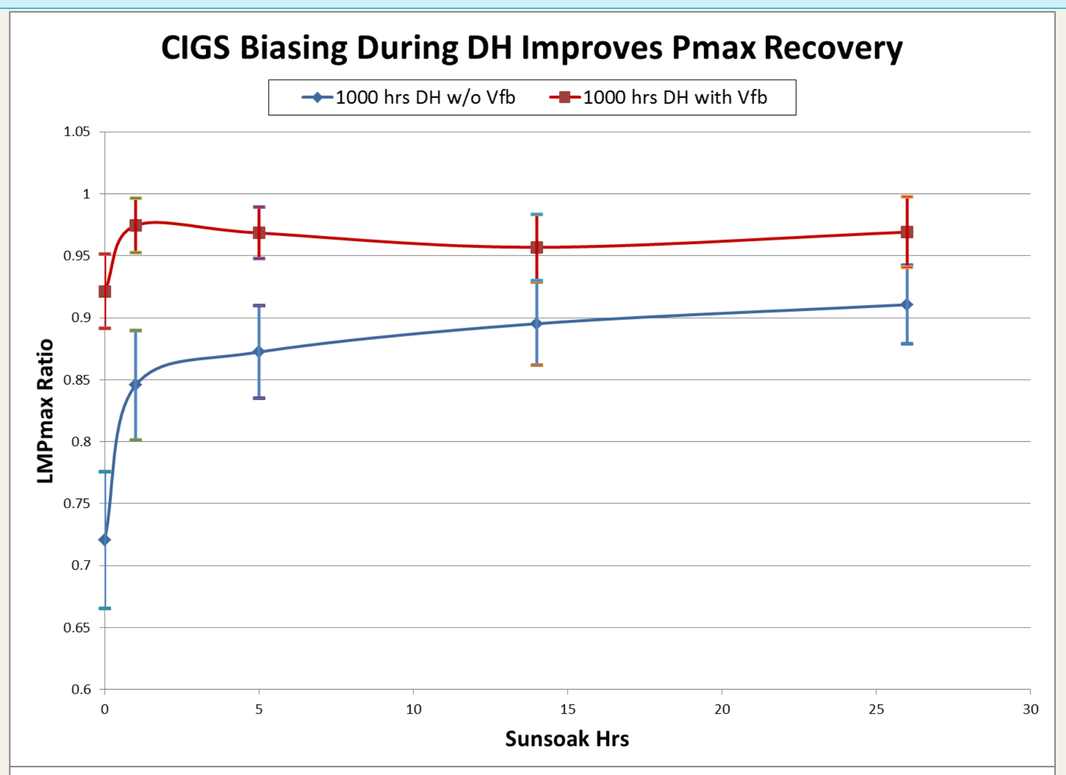
The data show forward biased modules recovered almost fully (with Pmax average = 0.97) after only 1 h of sun soak. This was not true for the unbiased modules, which showed a leveling off of Pmax ratio – still short of saturation – even at 26 hrs of sun soak.

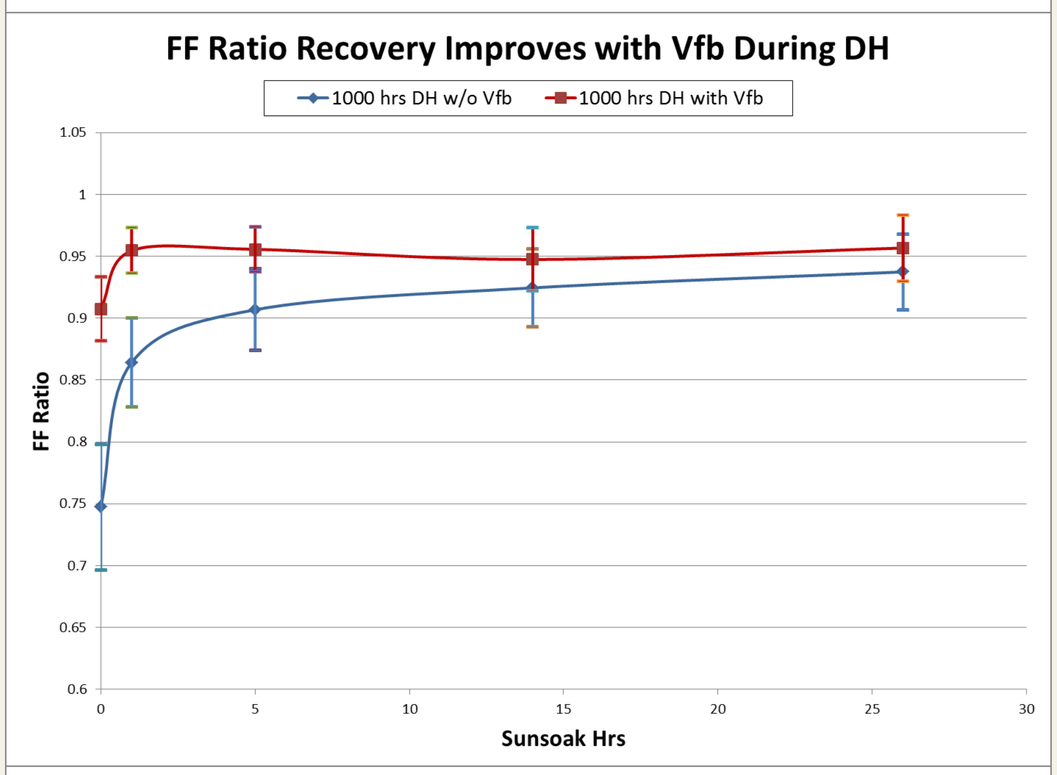
A

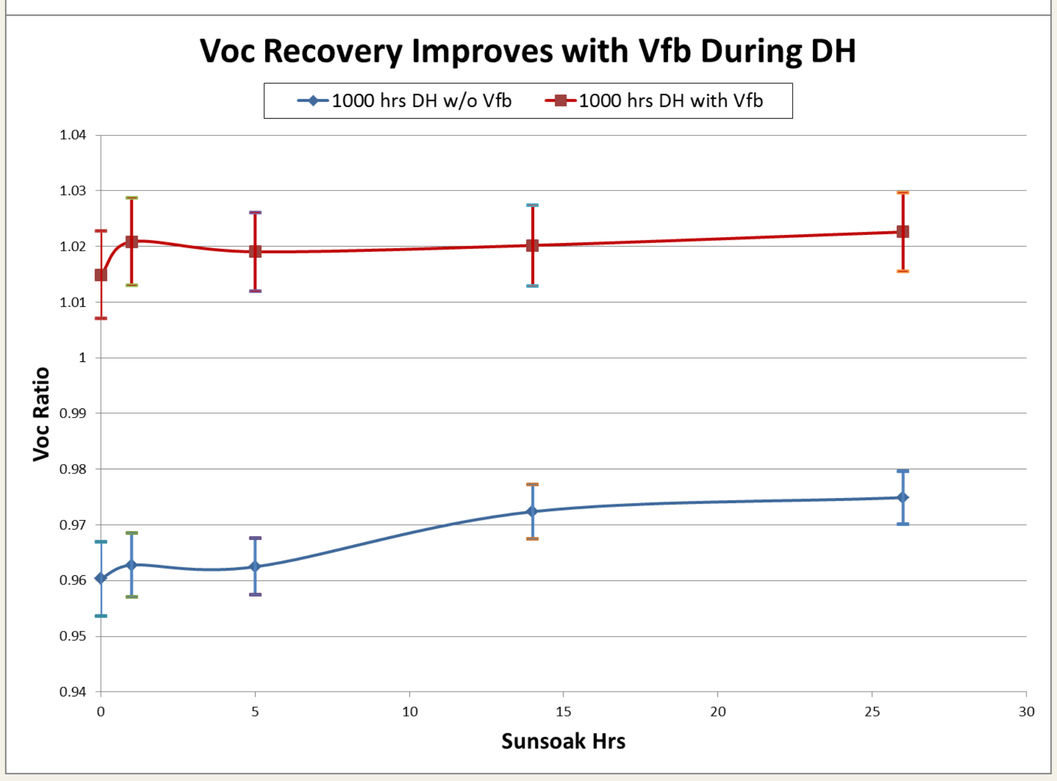
B

Conclusions

- The regular DH process shows high variability in recovery rate with a lower overall recovery than usual. Typical Pmax ratio recovery for production is 1.00 within 26 hour sun soak.
- For the next round of tests, pre- and post- conditioning will be done under load.
- Voltage bias corresponding to 85C or NMOT will be applied rather than STC because the higher temperature during DH puts the module under much higher forward bias and causes a high dark current flow.







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PARAMETERIZATION OF THIN FILM MODULES

M. Görig, C. Ulbrich, B.E. Pieters, A. Gerber, U. Rau
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JÜLICH FORSCHUNGSZENTRUM

Motivation

- Increasing photovoltaic capacity → greater demand *on* and *for* energy yield prediction
- Many performance models need physical parameters (R_{sc}, R_{oc}, J_{sc}, V_{oc}) determined from measured *JV* curves
- Common parameter determination methods: linear fits → parameters depend on fitting range
- Karmalkar-Haneefa (KH) fit offer physical parameters directly

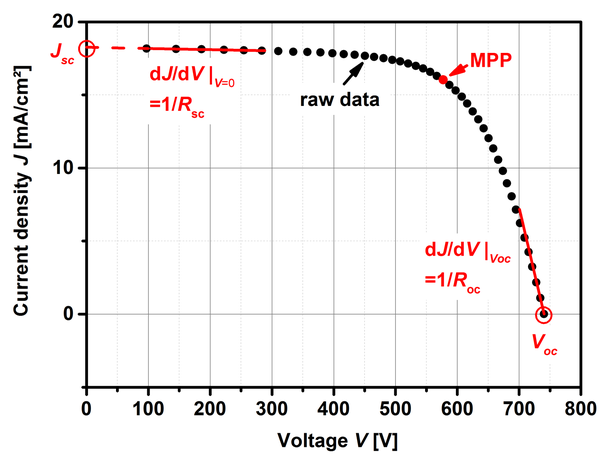
→ **Comparison between the two fitting methods**

Field Data

- investigated technologies: amorphous Silicon (a-Si), Cadmium-Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS)
- Testing site: Cologne, Germany
- Testing duration: 1 year
- Tested by TÜV Rheinland
- Frequency of measured JV curves: every 10 minutes

Analysis

Linear Fitting Method



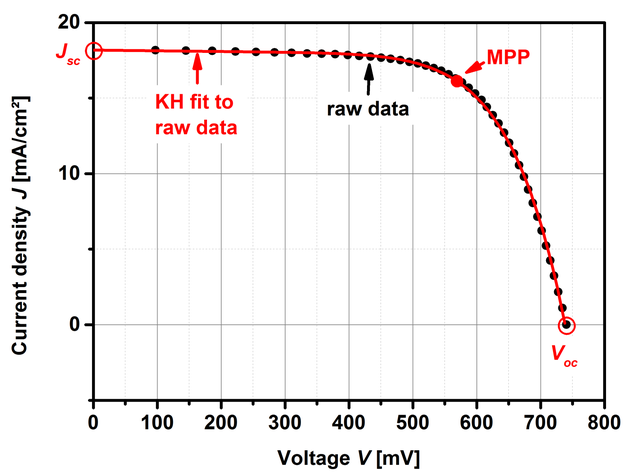
Fitting range for J_{sc} and R_{sc}:

$$[V_{min}, x \cdot V_{mpp}],$$
x =[1/4, 1/3, 1/2, 5/8]

Fitting range for V_{oc} and R_{oc}:

$$[J_{min}, y \cdot J_{mpp}],$$
y =[1/7, 1/4, 1/2, 5/8]

KH Fitting Method

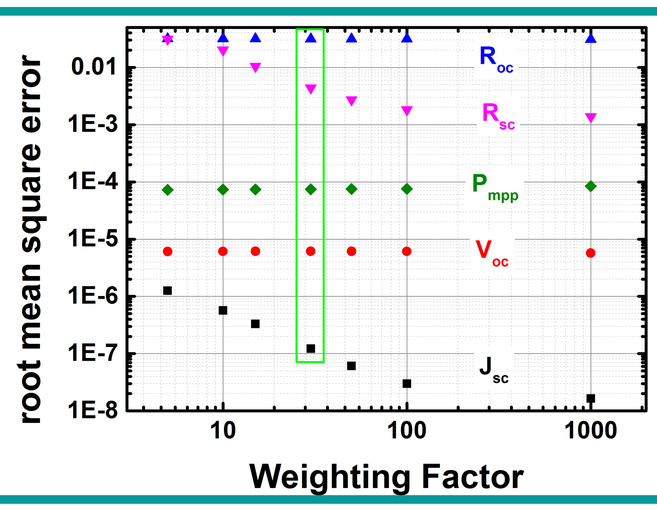


$$J(V) = J_{sc}\left[(1-\gamma)\frac{V}{V_{oc}} + \gamma\left(\frac{V}{V_{oc}}\right)^m - 1\right]$$

Results

Comparison between Parametrization from KH and linear fit – exemplary for CdTe

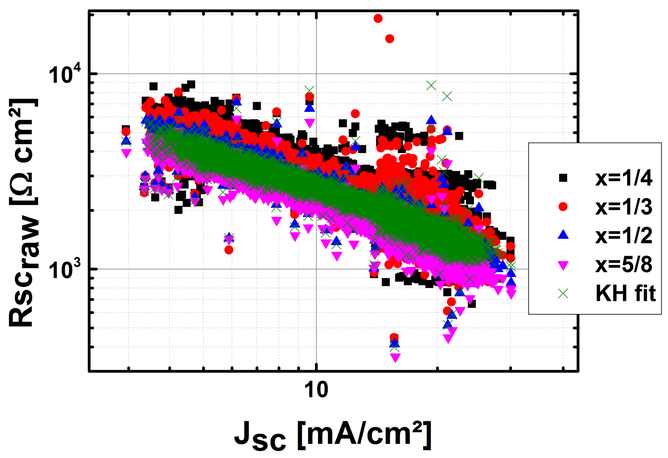
Weighting the KH fit in the same range using for the linear fit
→ smallest deviation between the parameters from the KH equation and those of the linear fit

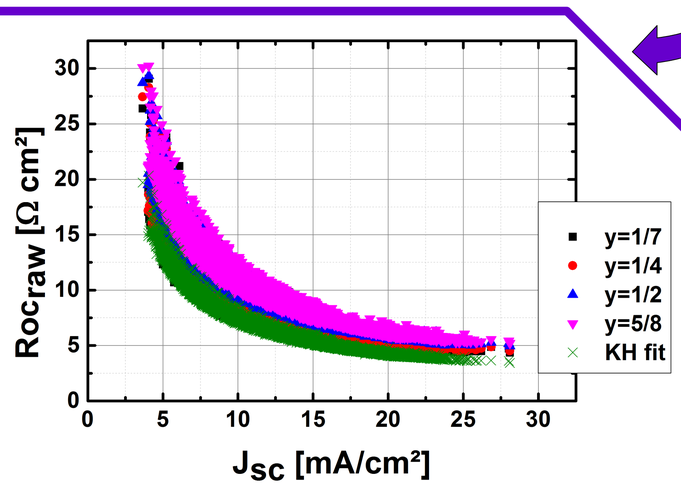


rmse between the parameters obtained from a linear fit in the range [V_{min}, 1/2·V_{mpp}] and the KH fit; weighting factor for the KH fit in the range [V_{min}, 1/2·V_{mpp}]

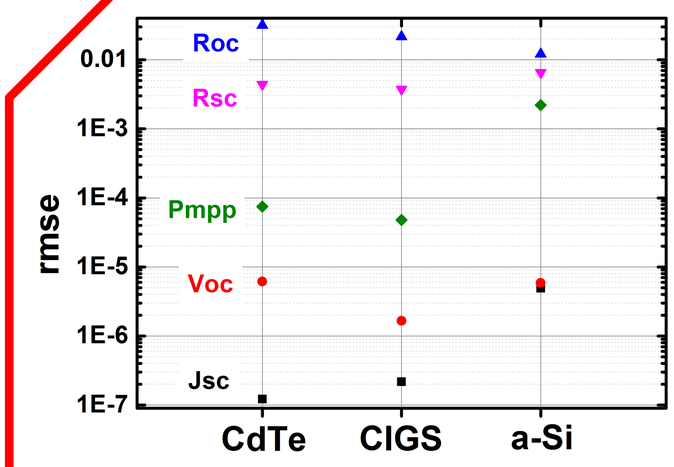
The lowest error between all four parameters for all three technologies from the two linear fits and those from only one KH fit, is obtained by weighting the KH fit with a factor of 30 in the range of *V*=[V_{min}, 1/2·V_{mpp}].

- J_{sc} and V_{oc}: only slightly affected by the linear fitting range
- R_{sc} and R_{oc}: strongly affected by the linear fitting range
- Parameters from KH fit: less spread compared to the linear fits





All technologies



rmse for all technologies between the linear fits with x=1/2 and y=1/7 and the KH fit with a weighting factor of 30 in the range V=[V_{min}, 1/2·V_{mpp}]

Conclusion

- Weighting factor of 30 for KH fit in the same range than the linear fit is recommended to obtain similar values compare to linear fit, especially for R_{sc} values
- Values obtained from the linear fits spread more than the parameters from the KH fit
- KH equation is a suitable method for determining physical parameters from measured *JV* curves of thin film modules

- **Outlook:** Using KH parameters as input parameters for other performance models like the LFM enables a better comparison between the KH model as a fitting model and the LFM as a factorization model

Acknowledgement: This work was carried out in the framework of the project „PV-Klima“, project number 0325517C, funded by the Bundesministerium für Wirtschaft und Energie (BMWi)

Mitglied der Helmholtz-Gemeinschaft

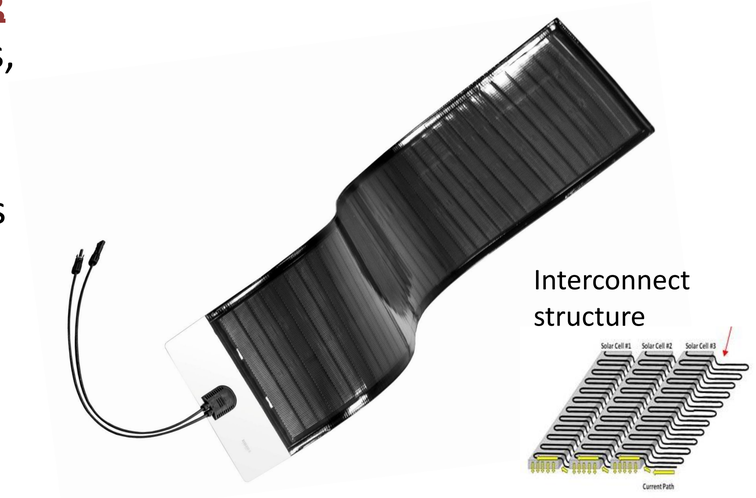
Implications of Thermal Cycling Test Results on Field Performance of Flexible PV Module

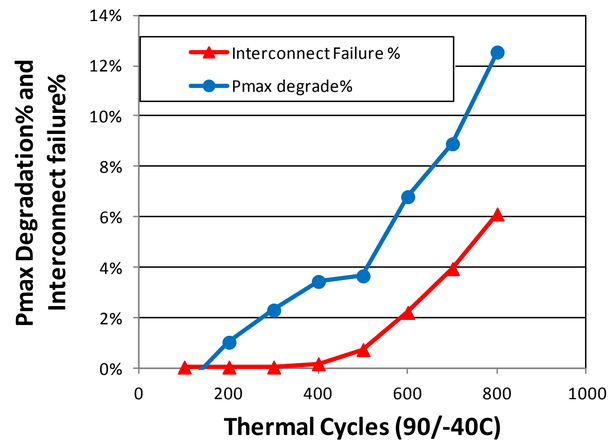
Authors: Kedar Hardikar, Bill J. J. Liu.

MiaSolé
A Hanergy Company

Identifying Failure Mode in Extensive Thermal Cycling

- For newer technologies and product configurations, implications of standard tests such as TC200 are unclear with regard to field performance.
- Extensive thermal cycling (TC600 and beyond) tests identify weak links in the design.
- Potential interconnect failure mode identified for one product design during development.



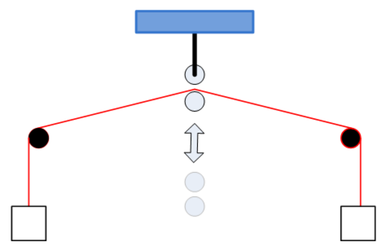


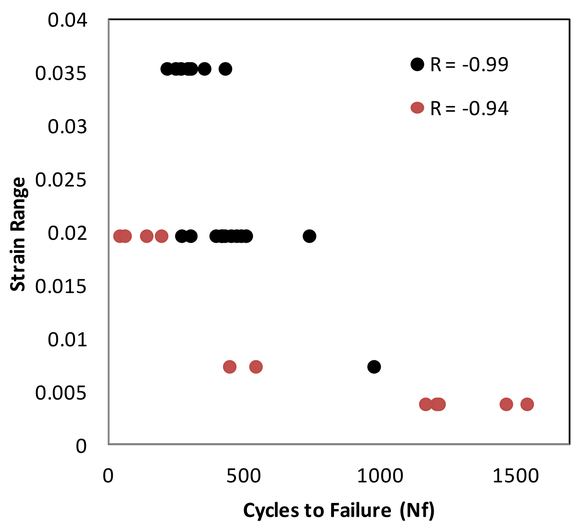
Component Fatigue Test dictates the Form of Acceleration Factor (AF)

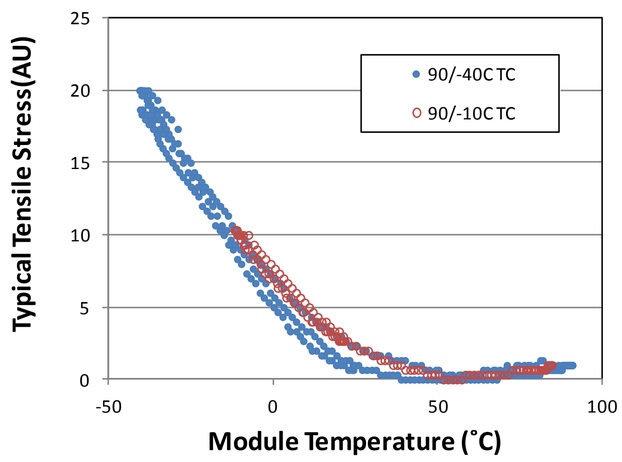
- Coffin-Manson relation with Walker Mean Stress Correction describes component fatigue life

$$N_f = C_1(\Delta\varepsilon)^{\alpha}\left(\frac{1-R}{2}\right)^{\beta}$$

Nf: cycles to failure, Δε : Strain range,
R: stress ratio = σmin / σmax







Component fatigue model suggests acceleration factor model for the module in TC

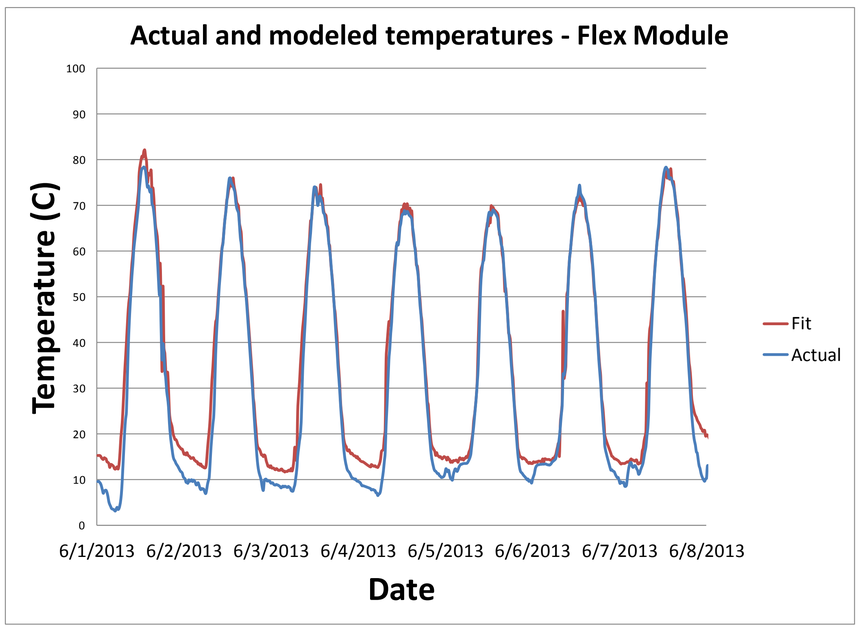
$$N_f \propto (\Delta T)^{\alpha}(T - T_{\min})^{\gamma}$$

T_{max}(C)	T_{min}(C)	Measured 5% breakage cycles	Model estimated 5% breakage cycles
90	-40	910	891
90	-15	2180	2106
90	-10	2545	2589
70	-10	3454	3200

Alternate TC Test results Validate the AF Model

$$AF = \frac{TTF_{field}}{TTF_{test}} = \left(\frac{\Delta T_{field}}{\Delta T_{test}}\right)^{\alpha}\left(\frac{(T_c - T_{\min})_{field}}{(T_c - T_{\min})_{test}}\right)^{\gamma}$$

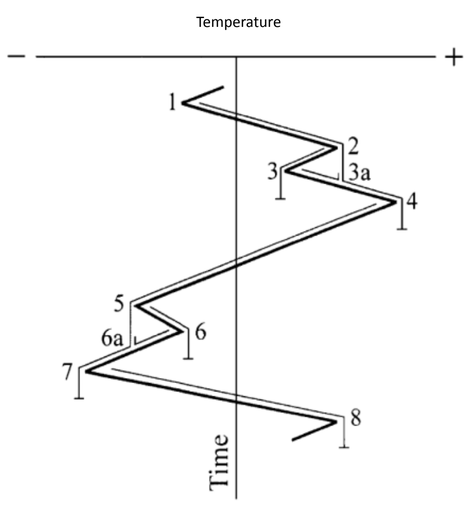
Location Specific Module Temperature can be satisfactorily predicted using Sandia Model and TMY Data



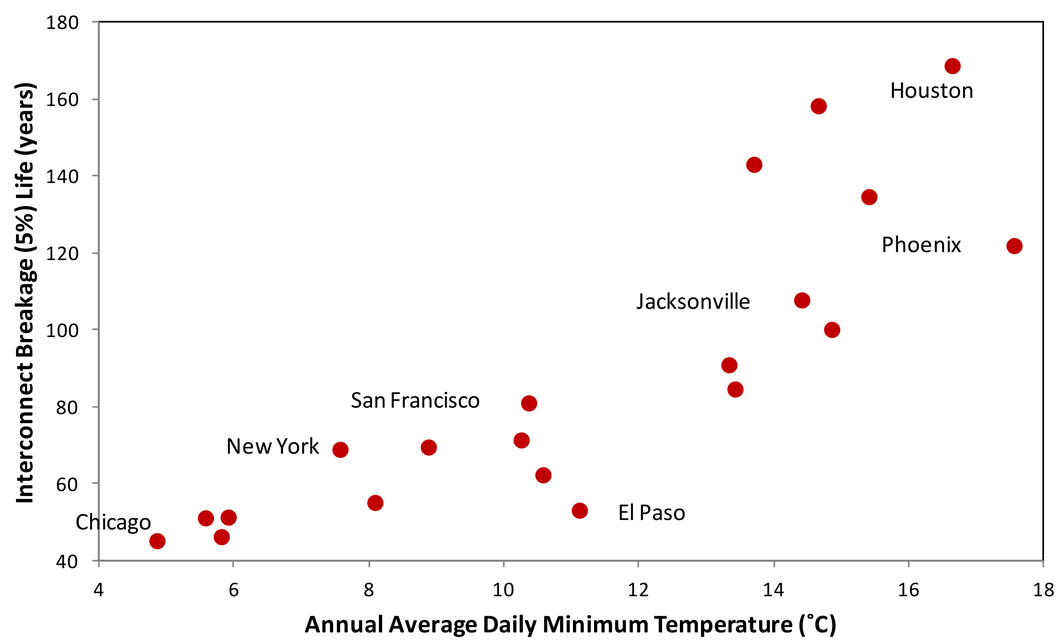
$$T_{mod}(\deg C) = T_{amb}(\deg C) + (DNI\ W/m^2)Exp(-2.96 - 0.0178V_{wind}(m/s))$$

Rainflow Cycle Counting applied to predicted module temperatures over a TMY data

ASTM E1049-85 based Rainflow Cycle Counting Enables Using Fatigue Methodology for predicting field life for the failure mode of interest



Validated Acceleration factor model enables field performance prediction from TC results



Conclusions:

- Using the validated acceleration factor model from alternate TC testing combined with rainflow cycle counting for TMY data enables location specific prediction of field life for the failure mode of interest.
- For particular failure mode of interst the predicted service life exceeds typical warranty period by ~2x.

Testing Procedures for Highly Reliable Photovoltaic Modules

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Sheraton West, Lakewood, CO

23-25 February 2016

Japan Electrical Safety & Environment Technology Laboratories

Introduction

- Most commercial modules are required to be certification model based on IEC standards. However, these standards are considered to be insufficient to assure long term reliability. To obtain information of highly reliable module designs, NREL proposed a test-to-failure (TTF) protocol [1]. In this protocol two stress tests are selected, damp heat (DH) test and thermal cycle (TC) test.
- We have studied testing procedures for higher reliability using commercial modules, 15 models (13 c-Si types, 2 a-Si types). Testing procedures was extension and/or repetition of DH and TC. Although all models passed environment tests in accordance with IEC 61215 or 61646, some models did not pass extension tests and/or repetition test. We will discuss information of testing procedures to assure long term reliability and to screen higher reliability modules.

[1] C. Osterwald, “Terrestrial Photovoltaic Module Accelerated Test-to-Failure Protocol”, Technical Report NREL/TP-520-42893 March 2008.

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Samples, tests, and assessment

- Commercial PV modules (mono-Si, mc-Si, thin-film Si): 15 module designs
- Extension tests and repetition test:
  - Damp heat (DH) test:
    85˚C / 85%RH 1000, 2000 and 3000 h
  - Thermal cycle (TC) test:
    −40˚C ↔ +85˚C 200, 400 and 600 cycles
    Crystalline Si models with Ipm applied above 25˚C
    Thin-film Si models without current applied
  - Repetition (RE) test:
    DH 1000 h → TC 200 cyc → DH 1000 h → TC 200 cyc
    (Steps are DH1000, TC200, DH2000, TC400, respectively.)
- Assessment:
  Power, visual defects and insulation resistance (no data in this poster)

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The number of sample modules

Models	Cell types	DH	TC	RE
A	mc-Si	10	5	5
B	mc-Si	10	10	5
C	mc-Si	10	10	5
D	thin-film Si	10	10	10
E	mc-Si	5	5	5
F	mono-Si	5	5	5
G	mc-Si	5	5	5
H	mono-Si	5	5	5
I	mc-Si	5	5	5
J	mc-Si	5	5	5
K	mc-Si	5	5	5
L	thin-film Si	5	5	10
M	mc-Si	5	5	5
N	mc-Si	5	5	5
O	mc-Si	5	5	5

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Timing of the appearance of critical defects

	Cracking in Si cells (by EL image)			Cracking in backsheets		
Models	DH	TC	RE	DH	TC	RE
A	–	–	TC200	3000 h	–	TC400
B	2000 h	–	TC200	–	–	DH2000
C	–	–	TC200	–	–	–
D	–	–	–	–	–	–
E	–	–	TC200	–	–	TC400
F	–	–	TC200	–	–	TC400
G	–	–	DH1000	3000 h	–	TC200
H	–	–	DH2000	3000 h	–	–
I	–	–	–	3000 h	–	DH2000
J	–	–	TC200	3000 h	–	DH2000
K	–	–	TC200	–	–	TC400
L	–	–	–	–	–	–
M	–	–	TC200	–	–	–
N	–	–	TC200	–	–	TC400
O	–	–	DH1000	–	–	TC400

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Timing of the appearance of cable defects

	Shrinking of cable sheath			Hardening of cable		
Models	DH	TC	RE	DH	TC	RE
A	–	–	DH 2000	–	400 cycles	–
B	–	–	–	–	200 cycles	–
C	–	–	–	–	–	DH 2000
D	–	–	–	3000 h	–	–
E	–	–	–	3000 h	–	–
F	–	–	–	–	200 cycles	–
G	–	–	–	1000 h	–	–
H	3000 h	–	DH 2000	2000 h	–	DH 2000
I	–	–	–	–	–	–
J	–	–	–	–	–	–
K	–	–	–	1000 h	–	–
L	–	–	–	1000 h	–	–
M	–	–	–	2000 h	–	–
N	–	–	–	2000 h	–	–
O	–	–	–	3000 h	200 cycles	DH 2000

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Summary about visual defects

- After TC for long term, almost no significant defects were observed. In contrast, various defects were observed after DH or RE.
- RE is a test which is likely to induce cracking in backsheets and cells.
- Delamination of encapsulants was not observed in this work.
- It is implied that some defects, for example, cracking in backsheets and cells, are important indicators to associate with failure of wet insulation test or snail trail.

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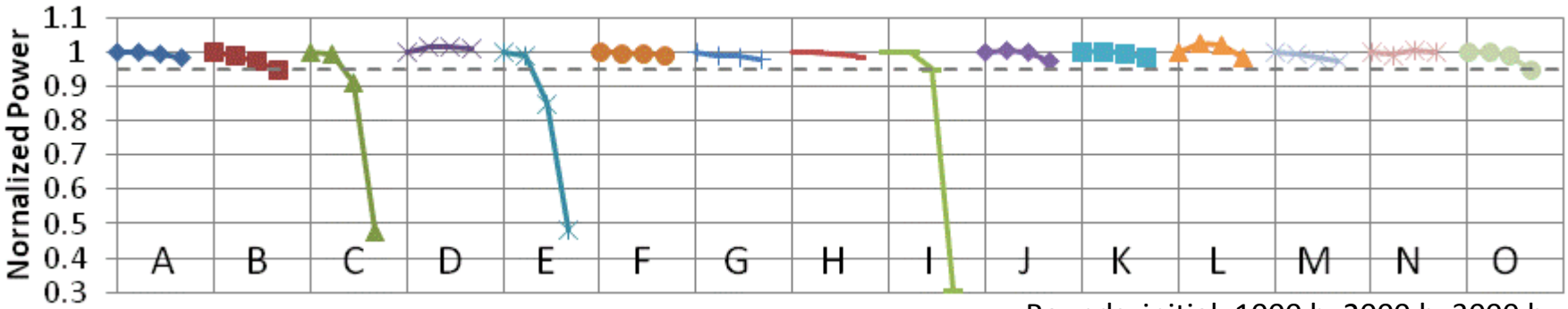
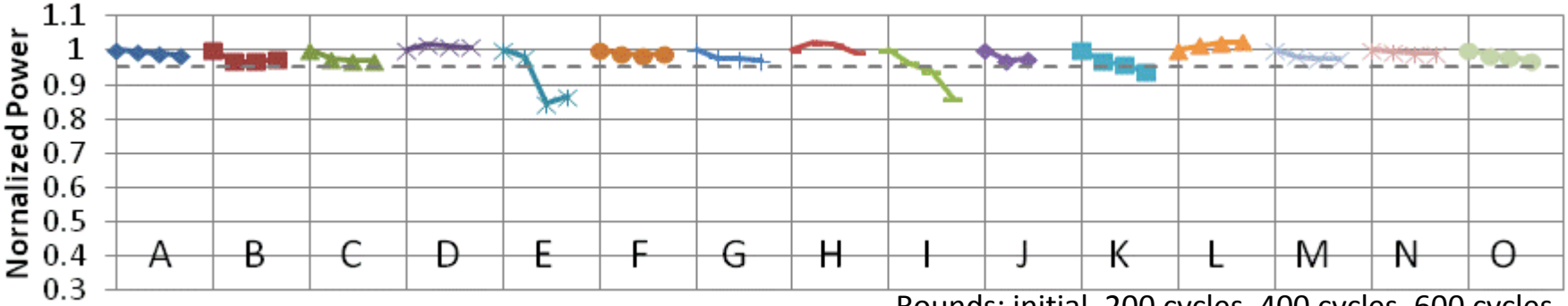
Power change after extension and repetition of DH and TC

DH



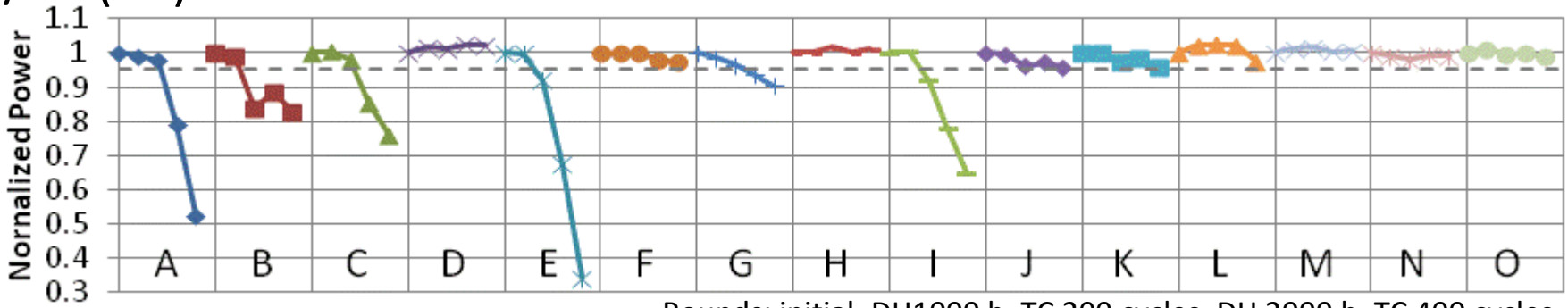
Rounds: initial, 1000 h, 2000 h, 3000 h

TC



Rounds: initial, 200 cycles, 400 cycles, 600 cycles

DH/TC (RE)



Rounds: initial, DH1000 h, TC 200 cycles, DH 2000 h, TC 400 cycles

All symbols show average values.

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Reproduce of degradation in fields in this work

Degradation in fields	Supposed factors	DH	TC	RE
Snail trail	Cracks in cells	△	×	○
Disconnection	Peeling of interconnectors	×	○	○
Rust of inner wiring	Corrosion	×	×	×
Expansion of dark area in EL image	Increase in resistance at finger grid	○	×	○
Yellowing of active plane	Degradation of encapsulants	○	×	○
Delamination along grid line	Decrease in adhesion	×	×	×
Cracking in backsheets	Degradation of materials	○	×	○

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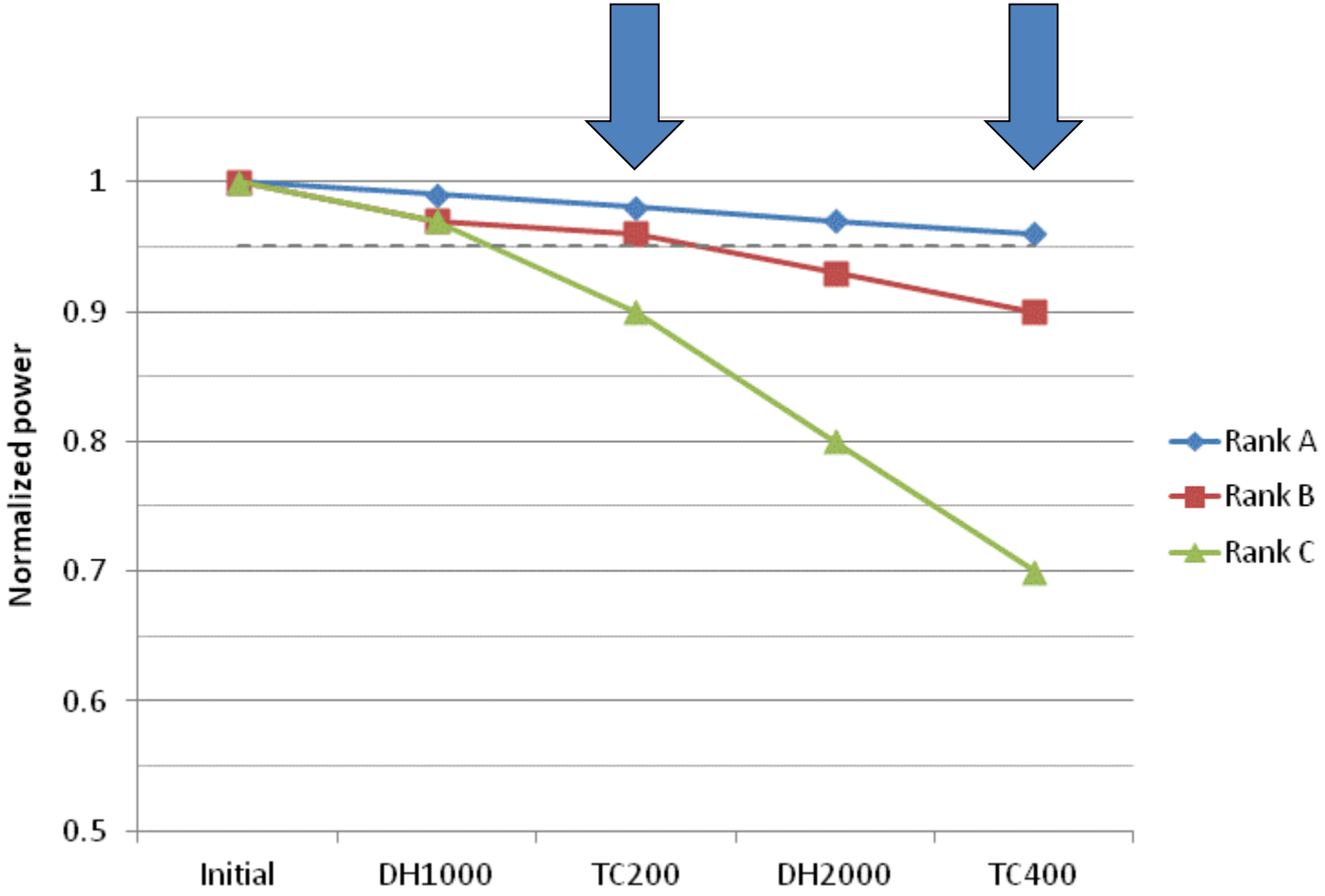
Screening by result of power change after RE test



For example,

Rank A → D, F, H, L, M, N, O

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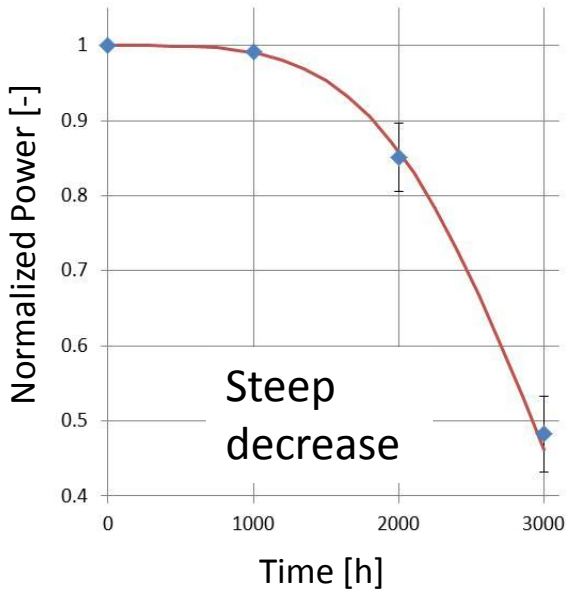
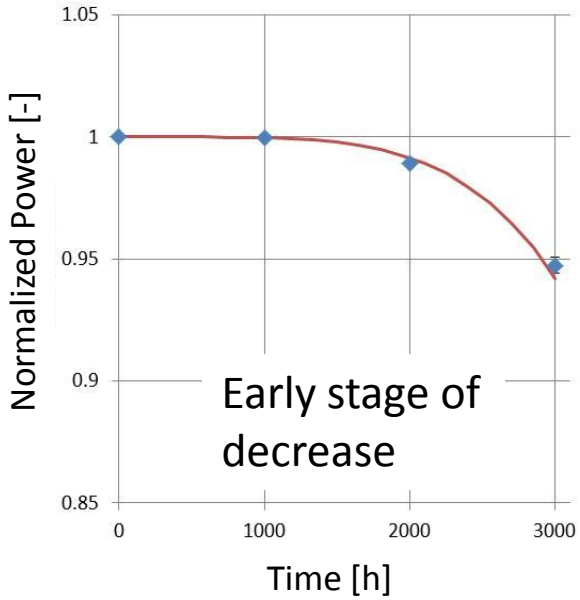
[Future work] Approach of modeling power change

Model E after DH



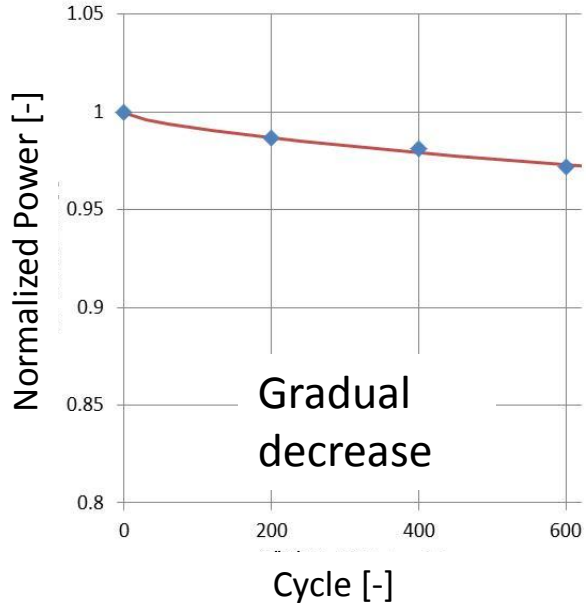
α = 4.0
β = 3200 h

Model O after DH



α = 4.8
β = 5400 h

Model O after TC



α = 0.65
β = 100000 cycle

Power change is not linear
→ modeling the change by non-linear function (Weibull distribution)

$$P = exp\left\{-\left(\frac{t}{\beta}\right)^{\alpha}\right\}$$

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Conclusions

We conducted 3 kinds of tests, DH, TC, and RE to commercial modules of 15 module designs. Almost no significant defects were observed after TC 600 cycles in most models. In contrast, various defects were observed after DH and RE. Additionally, RE is likely to reproduce defects of cracking in backsheets and cells which can be indicators to failure of wet insulation test and snail trail.

Regarding power change, 3 models decreased highly after DH 3000 h. Result after RE test was similar to that after DH, and 5 models decreased highly. Therefore, it is suggested that RE test is a useful test for screening highly reliable models among many candidates.

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Dependence of Stability of CdTe Solar Cells

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Powered by SunShot U.S. Department of Energy

Difficulties Contacting CdTe

Forming true ohmic contact is nearly impossible [1]
- High electron affinity of CdTe
- No metal has large enough work function

Back surface doping used to help contact
- Cu is typical dopant

Buffer layers also incorporated
- High work function material
- Material with band structure that mitigates barrier
- Te or C used in this study

Stability in CdTe Solar Cells

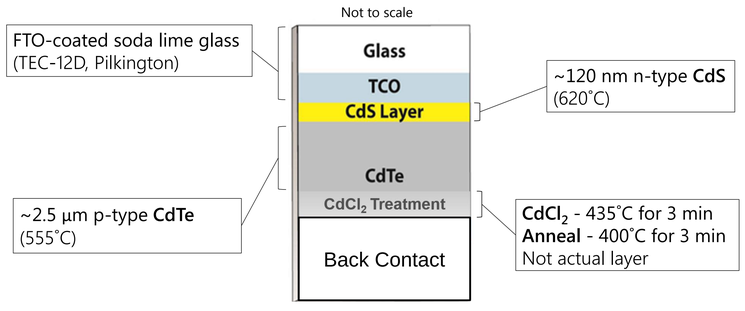
Typically attributed to Cu diffusion [1]
- Cu added at back surface of CdTe
- Cu_{Cd} acts as p-type dopant
  - Can decay into Cu_i+V_{Cd} (acceptor defects)[2]
- Cu_i acts as an n-type dopant
  - Highly mobile in CdTe

Diffusion of other atomic species [1]
- S, O, Cl

Degradation of back contact materials [1]
- Oxidation
- Moisture intrusion

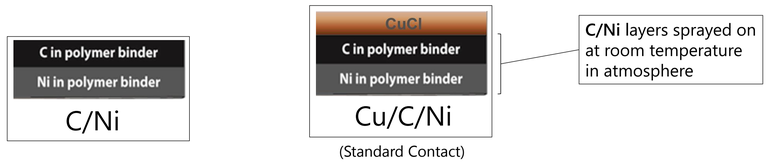
Device Fabrication

Fabricated in CSU's PV Manufacturing Lab [3]
In-line close-space sublimation process

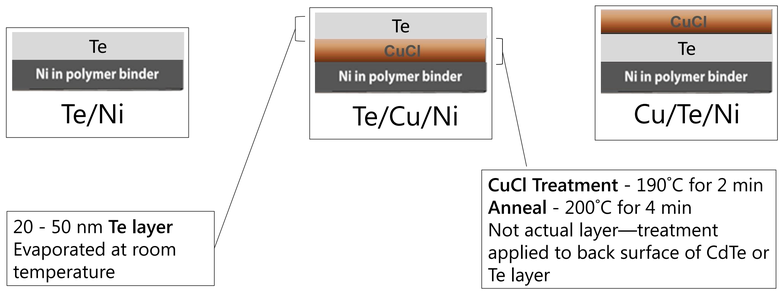


5 Different Back Contact Methods

Carbon Contacts



Tellurium Contacts



NREL PV Module Reliability Workshop, February 23-25, 2016, Lakewood, CO

Device Characterization

Current-Voltage (J-V)
Measurement of current with applied voltage bias
Light (AM 1.5) and Dark

Quantum Efficiency (QE)
Number of electrons collected per incident photon
Provides understanding of current recombination

Capacitance-Voltage (C-V)
Measure of capacitance due to small change in voltage
Ability to calculate carrier density throughout device

All measurements performed at room temperature

Device Storage

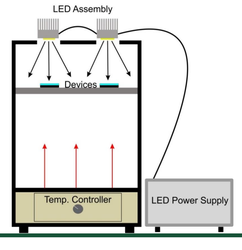
Standard
Plastic container with tight-fitting silicon-seal lid at room temperature (~22˚C)
Sealed
Vacuum sealed at room temperature (~22˚C)
Cold
Vacuum sealed at lower temperature (~8˚C)
Low Oxygen
Vacuum sealed at room temperature (~22˚C) with oxygen absorber packets

All contained desiccant pellets
All stored in dark

Device Stressing

Elevated Temperature and Light Stress [4]
~1 sun illumination (~1 kW/m²)
Temperature: 80°C
Duration: ~1000 hours
Open-circuit

Left: Diagram of elevated temperature and light stressing apparatus.
Right: Actual experimental set-up.



Acknowledgements

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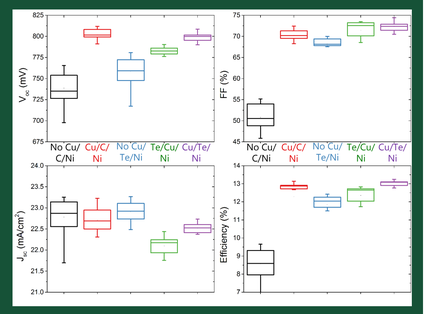
[1] K. Dobson, I. Visoly-Fisher, G. Hodes, D. Cahen, "Stability of CdTe/CdS thin-film solar cells," *Solar Energy Materials and Solar Cells*, Volume 62, Pages 295-325, 2000.
[2] Gretener, C., Perrenoud, J., Kranz, L., Cheah, E., Dietrich, M., Buecheler, S., & Tiwari, A. N. (2016). New perspective on the performance stability of CdTe solar cells. *Solar Energy Materials and Solar Cells*, *146*, 51-57
[3] D. Swanson, et al., "A Single Vacuum Chamber with Multiple Close Space Sublimation Sources to Fabricate CdTe Solar Cells," under review.
[4] J. Raguse, R. Geisthardt, J. Drayton, J. R. Sites, "Compact accelerated life testing with expanded measurement suite," *in IEEE Photovoltaic Specialist Conference*, 2014, p. 2644

Results

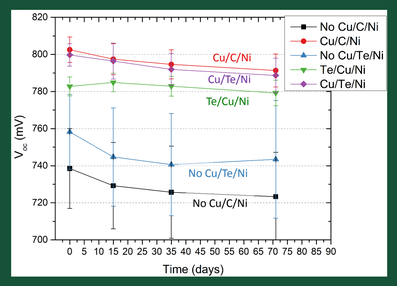
Changes in performance of cells with 5 different back contacts

Initial Device Performance

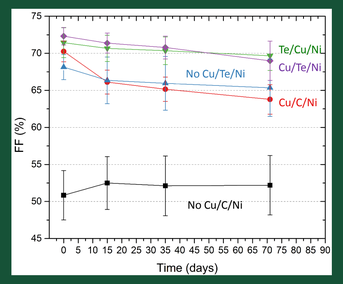
Variation is in 9 cells delaminated from same substrate
- Cu treatment needed for high V_{oc}
  - Cu directly on surface of CdTe produces best values
- Cells with Te exhibit good FF
  - Even without Cu treatment
- J_{sc} is consistent for all devices
  - QE measurements in agreement



Changes in Storage

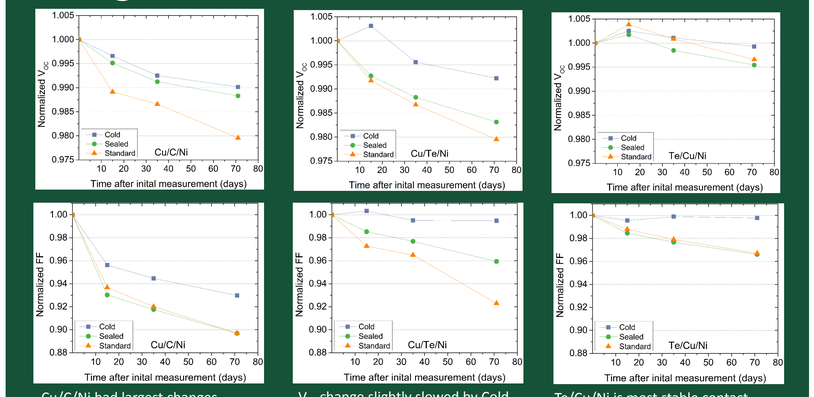


- Devices with Cu treatment directly on CdTe show similar changes
- No Cu devices also trend similarly
- Cu after Te has most stable V_{oc}



- All devices show changes in FF over time
- Cu/C/Ni show highest losses
- Cu/Te and Te/Cu devices are best-performing and most stable

Storage Method Differences



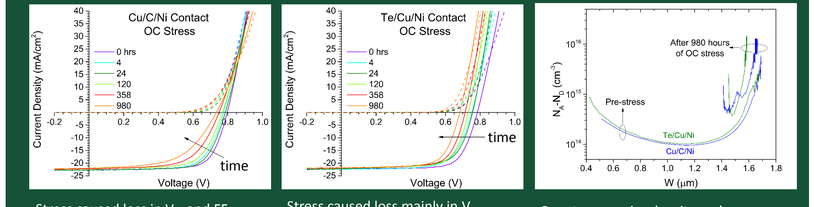
Cu/C/Ni had largest changes
Low dependence of V_{oc} on storage
Cold storage slightly slowed FF

V_{oc} change slightly slowed by Cold
Cold storage slowed FF
FF more stable than Cu/C/Ni

Te/Cu/Ni is most stable contact
Low dependence of V_{oc} on storage
Most stable FF, regardless of storage

Cells sealed with oxygen absorbers show same degradation as sealed or standard storage

Changes after Stress



Stress caused loss in V_{oc} and FF
FF loss greatly impacted efficiency
Lost 4.1% in efficiency

Stress caused loss mainly in V_{oc}
FF loss was minimal
Lost 2.4% in efficiency

Pre-stress carrier density and depletion width nearly same
Post-stress depletion widths have greatly narrowed, apparent carrier density increased

Conclusions

- Initial performance of Te-containing contacts with Cu treatment on par with standard Cu/C/Ni contacts
- Cu/C/Ni contact most unstable after initial measurement
- Te/Cu/Ni contact stable after initial measurement and stress
- Moisture intrusion not problem with current storage methods
- Cold storage improved stability of devices
  - Especially those containing Te layer

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SOLIBRO A COMPANY OF Hanergy

PID prevention in CIGS modules

Introduction

Solibro has analyzed the basic mechanism of PID, Potential Induced Degradation, in CIGS thin film PV modules. Appropriate test procedures and a climate-specific PID prediction model have been developed. Applying this model and test procedures, the PID prevention of the Solibro CIGS PV modules was demonstrated.

Background

It is well known that sodium is a mobile ion in glass. Test of CIGS PV devices of ordinary soda-lime glass biased with negative voltage at elevated temperatures and humidity cause a degradation, PID. The same tests on sodium free glass, or glass with less mobile sodium, show little or no degradation[1)].
To confirm sodium is the cause, two groups of CIGS cells were examined with SIMS, one reference group and one exposed to PID, Figure 1. The cells exposed to PID show a significantly higher sodium concentration in the CIGS/Cds/ZnO interface which could be related to deteriorated electric properties.

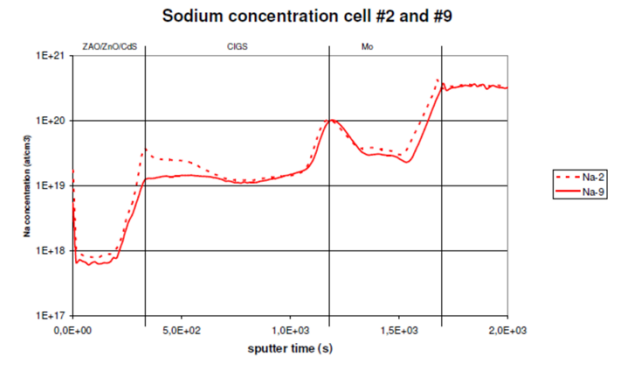

Figure 1, cell 2 is exposed to PID, cell 9 not.

To verify that the performance decreasing properties were located to the CIGS/CdS/ZnO layer, one group of cells was exposed to PID and one not. After measurement the CdS/ZnO layer of both groups were etched off and replaced by new. As seen in Figure 2, the exposed group recovered almost completely with a new CdS/ZnO layer. Our conclusion is that PID degradation is caused by sodium migration into the CIGS/CdS/Zno interface.

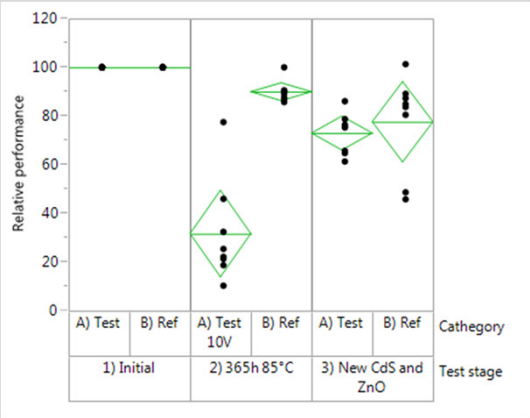

Figure 2, with new CdS and ZnO the severely degraded cells are almost completely recovered.

Defining the PID test criteria

The overall goal is to make sure the modules are resilient to PID in all climates. A critical charge, $Q_{PID\ 10\%}$, was defined as the time × the PID current causing 10 percent degradation of the CIGS module. The bulk and surface resistivity of the substrate glass was measured at different temperatures and humidity. The bulk resistivity, ϱ_{bulk}, is only temperature dependent while the surface resistivity, ϱ_{surf}, is both temperature and humidity dependent.
The charge was calculated by applying a voltages across the module, figure 3. With the resistivity and the time to 10 percent degradation known, the PID current and the critical charge could be calculated. A matrix showing the dependence of the PID current on temperature and RH is shown in Figure 4.

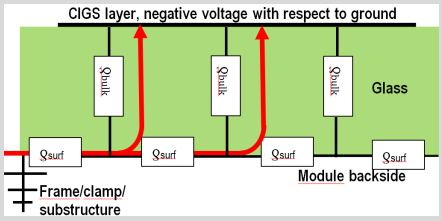

Figure 3, PID current, the leakage current between the solar cell and the module surface.

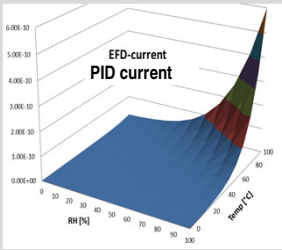

Figure 4, PID-current vs temp and RH.

Two concerns were that the degradation would not scale linearly with voltage and that the day/night and summer/winter variation causing voltage variations and interruptions would not be as simple as adding charges.
It was confirmed that the degradation depends on the dose, voltage × time. Neither frequency nor the relation between voltage and time changed the degradation rate, Figure 5 and 6.

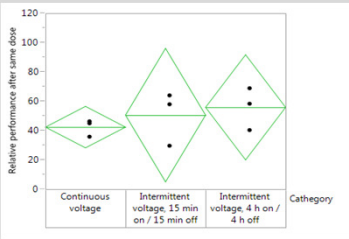

Figure 5, PID at different stress conditions with the same same dose, Volt × hours.

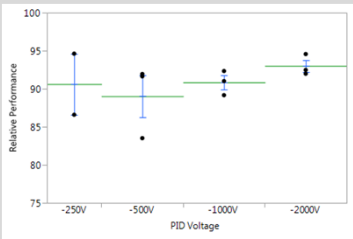

Figure 6, voltage variation, same dose, Volt × hours.

1) V.Fjällström et. al. IEEE Journal of Photovoltaics

With the critical charge as well as the temperature and humidity dependent properties of glass and voltage known, the time to 10 percent degradation could be calculated for different climates.
Hourly data; temperature, humidity and irradiation, for an average year were taken from Meteonorm. By dividing the critical charge with the sum of hourly charges over a year, the number of years to maximum allowed PID degradation for the most exposed module in the string could be calculated. For non grounded systems the string voltage was divided by two since the plus and minus potential is assumed to be symmetric around zero.

$$\frac{Q_{PID\ 10\ \%}}{\sum_{n=1}^{8760} \frac{Stringvoltage(irr_n)\ /2}{f(\varrho_{surf}(T_n, RH_n), \varrho_{bulk}(T_n))}} = \text{years to } PID_{10\%}$$

Equation 1

Solutions

Solibro has investigated three solutions to prevent PID degradation:

1. A PV module backsheet, on the backside of the module increases surface resistivity and decreases the PID current due to lower RH.
2. A diffusion barrier between glass and molybdenum decreases the transport of sodium ions from the glass into the CIGS/CdS/ZnO.
3. Grounding the negative pole. By not allowing negative potential, the transport of sodium ions into the CIGS is not possible.

Equation 1 was used to calculate the time to 10 percent degradation due to PID for an 800 Volt system comparing our current results of barrier and back sheet. The time was calculated for one temperate and, from a PID point, the most extreme climate we have found, Accra in Ghana.

Site	Years to 10 % PID degradation for most exposed module		
Site/technology	Backsheet	Barrier	Grounding
Bremen, Germany	54	46	No PID
Accra, Ghana	29	25	No PID

Figure 7, years to 10 percent degradation for an 800 V system. The time applies to the module in the string with the highest potential difference to ground.

Understanding and Elimination of Module-level Light/Voltage-induced Instabilities and Thermal Cycle Based Failures in CIGS Photovoltaicsovel Contact Materials for Improved Performance CdTe Solar Cells

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PREDICTS 2 Project 1195-1565

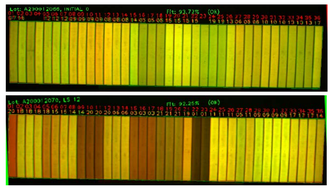
Overview

We are working with several major CIGS manufacturers to understand and control two critical module failure mechanisms: light/voltage induced instabilities and adhesion/moisture-related failures. This project is preparing to use several unique characterization techniques to identify physics-based models to explain the failure mechanism, apply these models to understand the degradation pathways, and identify the most appropriate accelerated lifetime testing methods to simulate degradation in the field. Similar to the "multiscale modeling" approach that has proven essential to simulating materials performance, we are preparing a multiscale characterization approach that will include large-area diagnosis of failure in full modules coupled downward to ultimately identifying the physical cause of the failure due to nanoscale defects. The results will be used to refine processes based on in-situ diagnosis and control methods that we will develop and transfer to our industrial partners. The project is just getting underway. We welcome samples and data for analysis and modeling as well as collaborations in the study.

Module Analysis

Commercial CIGS modules are under test. We have complete modules made from individual cells that show variability in the individual cells. The current task is to establish variability across the individual cells vs from cell to cell. Connected to cell manufacturing conditions or to microscopic defects or phenomena.

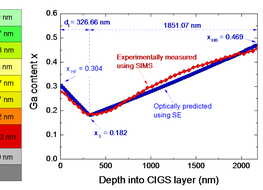
Light Soak	Efficiency (%)	PMAX (W)	Voc (V)	Isc (A)	FF (%)	Rs (ohm)	Rp (ohm)
None	16.3	80	24.7	4.47	0.72	0.54	107
12 hours	16.0	78	24.5	4.47	0.71	0.55	121
None	16.3	80	24.6	4.49	0.72	0.54	184
12 hours	15.9	78	24.3	4.48	0.71	0.59	93



Ellipsometry

Sample analysis by ellipsometry can permit determination of complete stack optical properties including grading. Can narrow down areas to analyze.

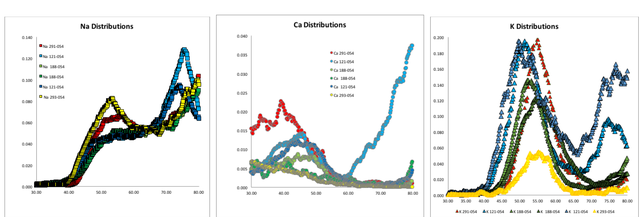
Surface roughness (f_1=30.6%)	34.29 nm
ZnO:Al (f_1=2.9%)	111.97 nm
ZnO:Al / i-ZnO ($f_{1,ZnO}$=21.8%, f_1=2.9%)	140.08 nm
i-ZnO (f_1=0.0%)	36.23 nm
i-ZnO / CdS ($f_{1,ZnO}$=48.6%, f_1=0.0%)	44.47 nm
CdS (f_1=0.0%)	48.67 nm
CdS / CIGS ($f_{1,CdS}$=77.5%, f_1=0.7%)	59.12 nm
CIGS (Graded Layer, f_1=0.0%) (x_{Ga} = 0.304, x_{In} = 0.182, x_{Se} = 0.469)	2177.73 nm
CIGS / Mo ($f_{1,Mo}$=62.0%)	19.89 nm
Mo (Opaque)	

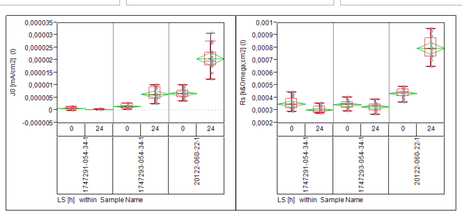


Nanochemical analysis

SIMS analysis of samples showing different light soaking behaviors shows preliminary differences in some alkali metals for light sensitive materials.

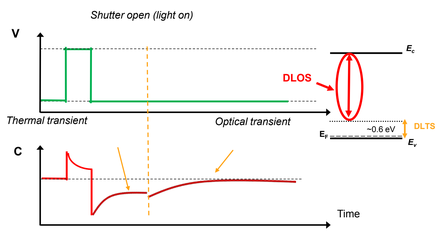
Sample	CdS (nm)	CIGS (µm)	Cu (at%)	In (at%)	Ga (at%)	Se (%)
Sample 1a	60	2	21	15	12	52
Sample 1b	60	2	22	15	11	52
Sample 2a	70	1.6	22	15	11	52
Sample 2b	70	2	22	15	11	52



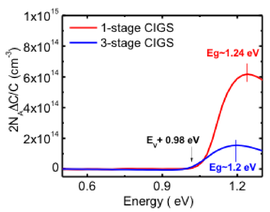


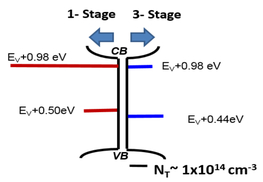
Nano DLTS & DLOS

Nano DLTS in the electron microscope and with added optical excitation accesses the entire energy gap and with submicron resolution permits mapping of local defects and comparison of materials.

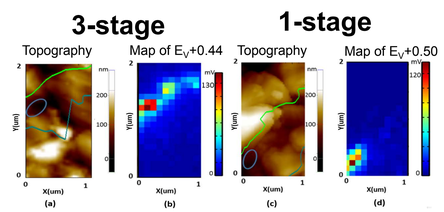


Analysis of materials underway shows changes in trap density with light soak



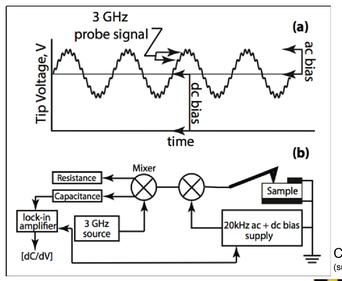


- Large increase in E_V+0.98 eV level for 1-stage sample
- Little change in concentration of E_V+0.44/0.50 level
- E_V+0.44/0.50 eV level distributed non-uniformly in intergrain regions
- Scanning-DLTS of E_V+0.98 in progress (appears intergrain related as well)



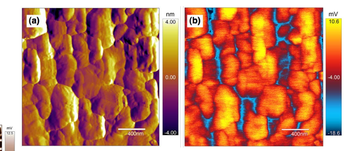
Scanning Microwave Impedance Microscopy

SMIM is a scanning probe method that permits local (50 nm resolution) determination of mobile charge density and dielectric constant. We are using this to study grain boundaries locally. Can also add light bias to probe local carrier lifetime.



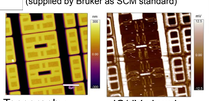
Development of this method for the current study is in progress.

Data shown here for CdTe devices from Toledo.

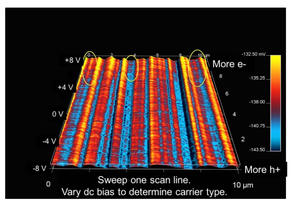


Topography dC/dV signal

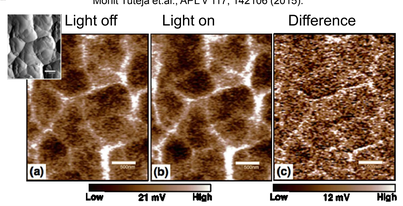
Calibration - SRAM sample (supplied by Bruker as SCM standard)



Topography dC/dV signal

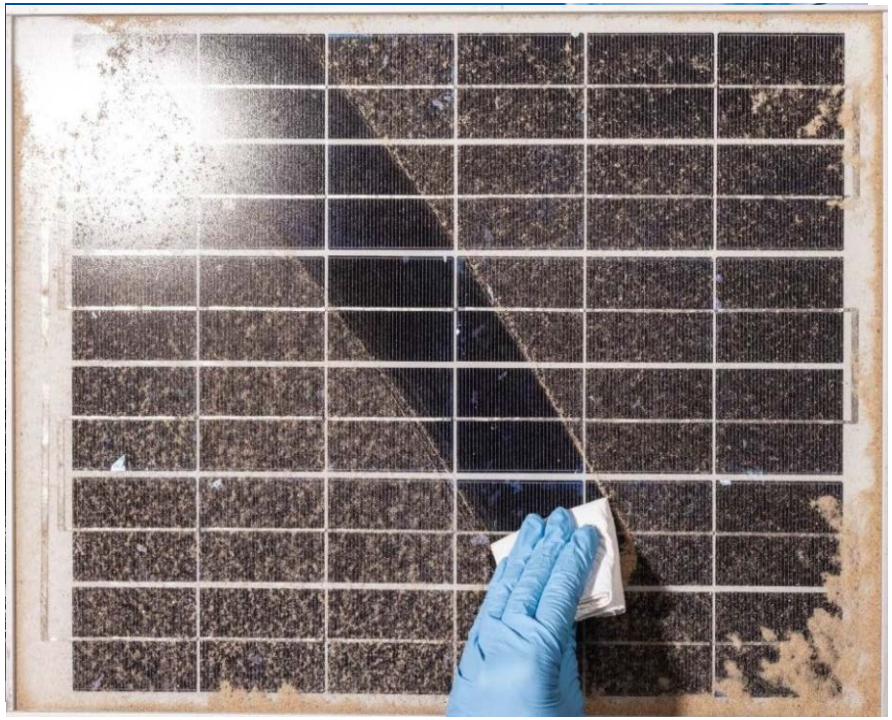


Mohit Tuteja et.al., APL v 117, 142106 (2015).



DUST TO STAY – OR DUST TO GO

Soiling and Abrasion Testing of Surfaces for Solar Energy Systems Adapted to Extreme Climatic Conditions



Elisabeth Klimm, Laura Ost, Michael Köhl, **Karl-Anders Weiß**

Fraunhofer-Institut for Solar Energy Systems ISE

Service Life Analysis

www.ise.fraunhofer.de

PVMRW 2016

Denver, February 24th 2016

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Group Service Life Analysis

Outdoor Performance → **Accelerated Testing** → **Analytics** → **Service Life Analysis**

- Outdoor facilities with **diff. climates**
  - Moderate
  - Alpine
  - Arid
  - Maritime
- High-resolution climate monitoring and recording

- Based on data from outdoor exposure
- Development of procedures
- **Simulation of** degradation mechanisms in **accelerated aging** tests

- Identification of degradation indicators
  - Materials
  - Components
- Development of non-destructive test methods
- Efficient, flexible test procedures

- Investigation of
  - **Quality** and
  - **Durability**

  of PV-modules, solar thermal collectors and components
- **Simulated durability testing**
- Standardization

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Degradation of performance

Soiling Overview: Influences and measures

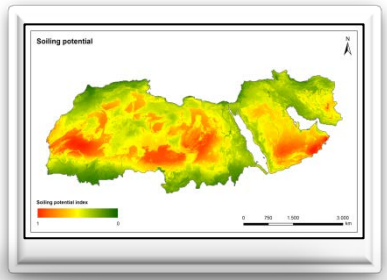
Dirt / Effects

Type of soiling

- Origin
- Composition

Consequences

- Soiling
- Abrasion
- Performance loss



Climate / Location

Modelling the degree of soiling

- Environment
- Climate

Glass / Coating

Surfaces

- Structure
- Functionality
- Economic efficiency

Testing / Simulation

Functionality

- Characterization
- Reproducible soiling method

Durability

- UV, Temperature, Humidity
- Pollutants (e.g. Salt)

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Degradation of performance: OUTDOOR

Material qualification

1. Pre-preparation of sample
   - Characterization (optical, gravimetric)
   - (cleaning)
2. Dusting
   - Different material and coatings
   - Inclination angle and installation
3. Material qualification
4. Weathering
   - Different climatic loads

Soiling testing

- **Outdoor**

Solar glass with visible dust coverage
- after 1 year
- at the Canary Islands and
- angle dependent positioning a) at 60° and b) at 23°

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SpeedColl

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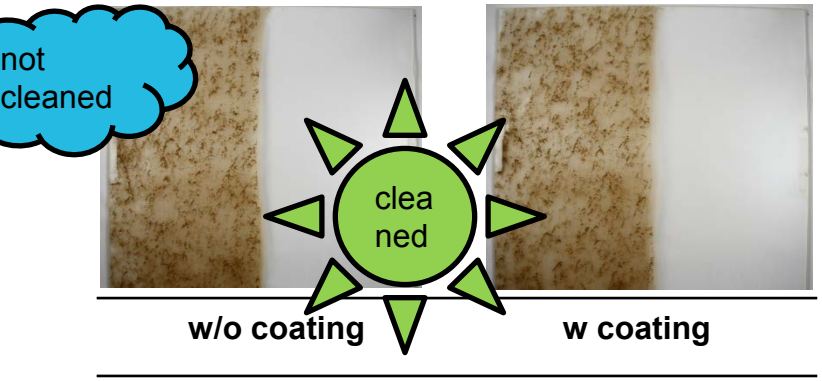
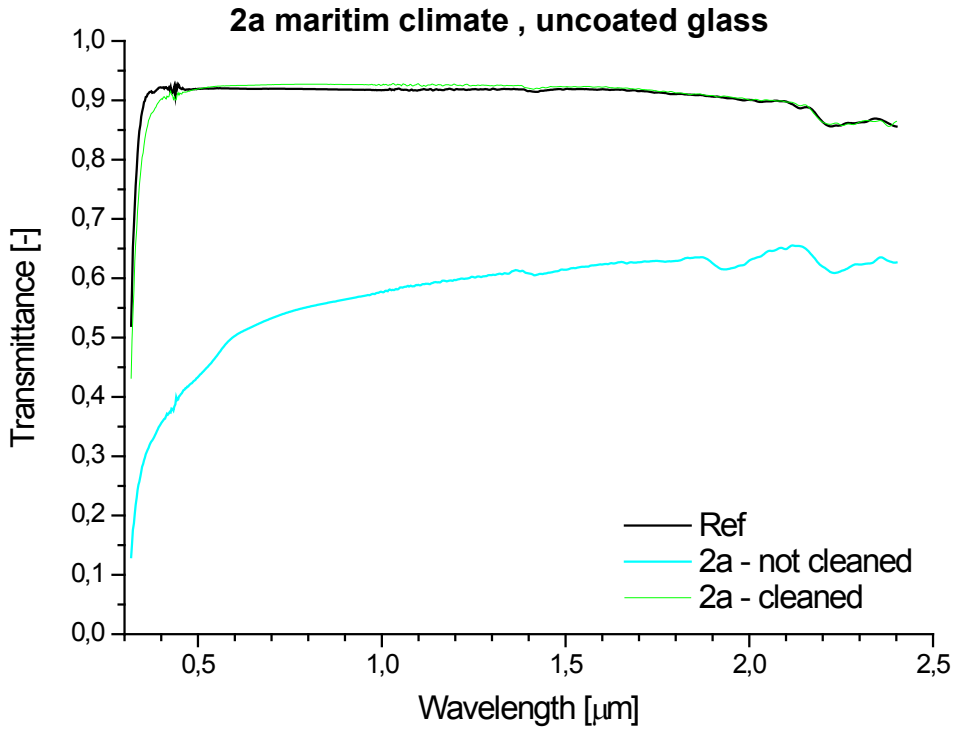
Degradation of performance: OUTDOOR

Material qualification

Glass exposed 2a in maritim climate (Canary Islands)



- 2a exposed and cleaned, 2a exposed and not cleaned and reference differences due to soiling effects



No irreversible soiling detected

Example for all measured samples valid

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Degradation of performance: OUTDOOR

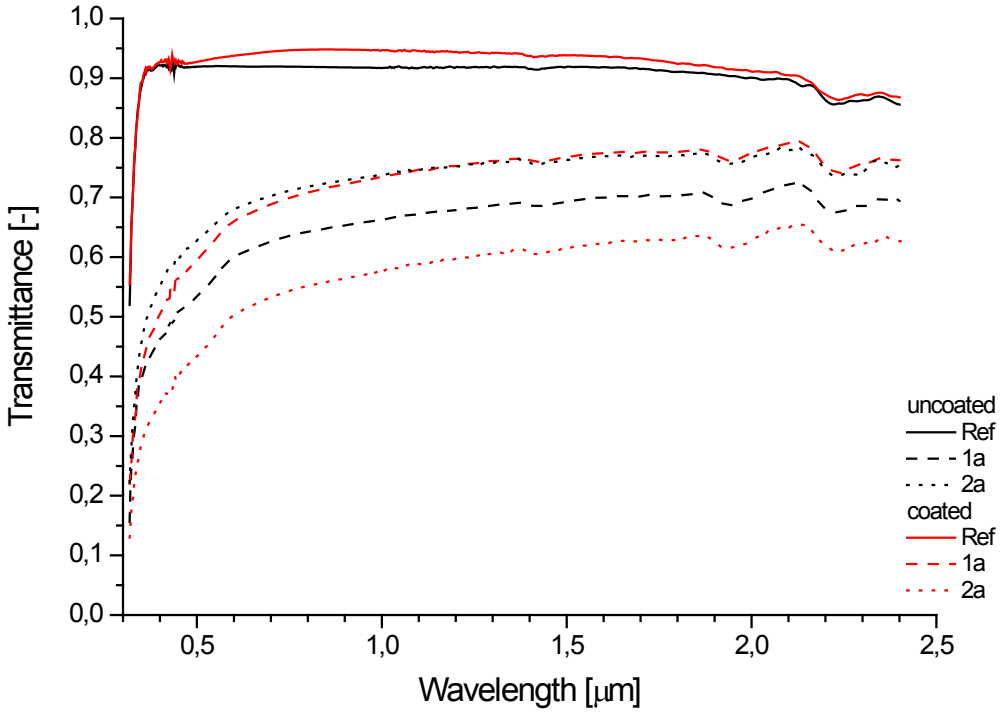
Material qualification

Glass exposed 2a in maritim climate (Canary Islands)

w/o coating

w coating

- Compare dashed (1a exposed), dotted (2a exposed) and solid graphs (reference) to see differences due to soiling



Possible time dependency

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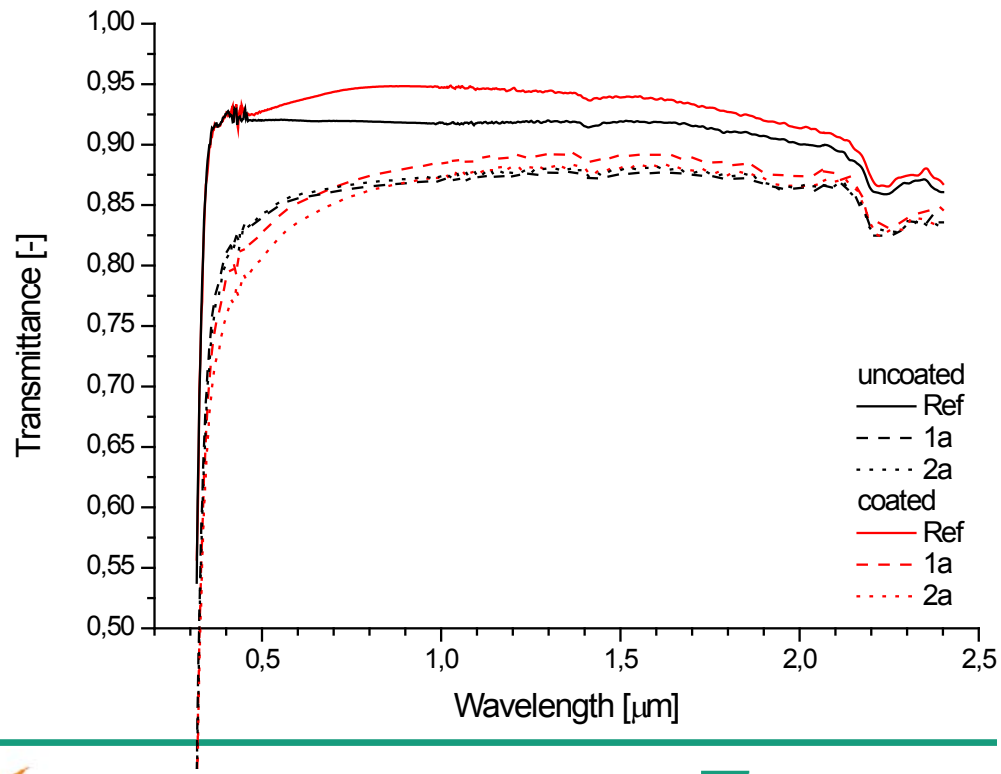
Degradation of performance: OUTDOOR

Material qualification

Glass exposed 2a in arid climate (Negev Desert)

w/o coating	w coating

- Compare dashed (1a exposed), dotted (2a exposed) and solid graphs (reference) to see differences due to soiling



Possible „soiling saturation“ of surface already before 1a

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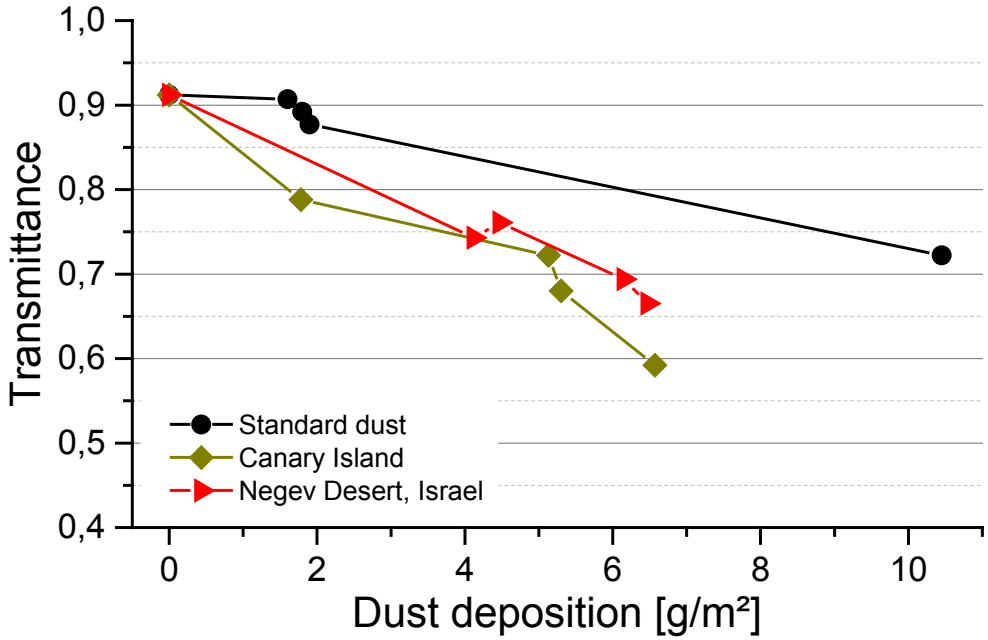
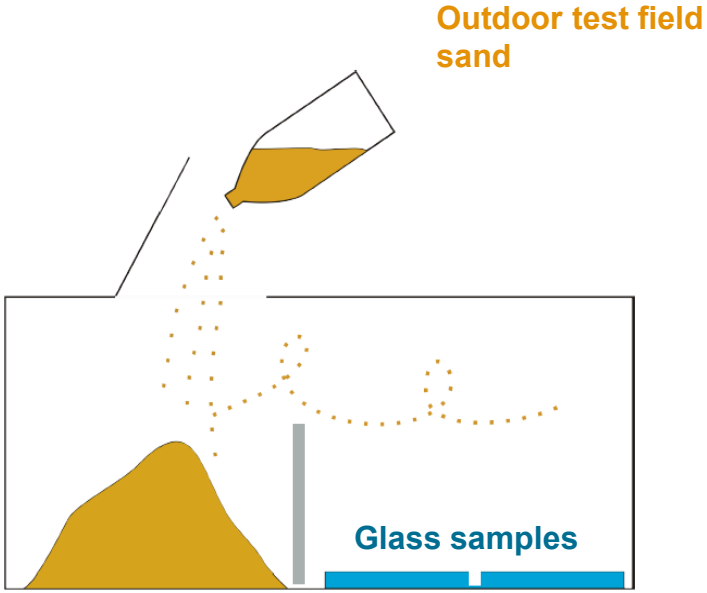
Degradation of performance: INDOOR

Artificial Soiling: PRESTUDY with “tons” of sand





- Very large amounts of accumulated dust achieved, but maybe due to larger particles

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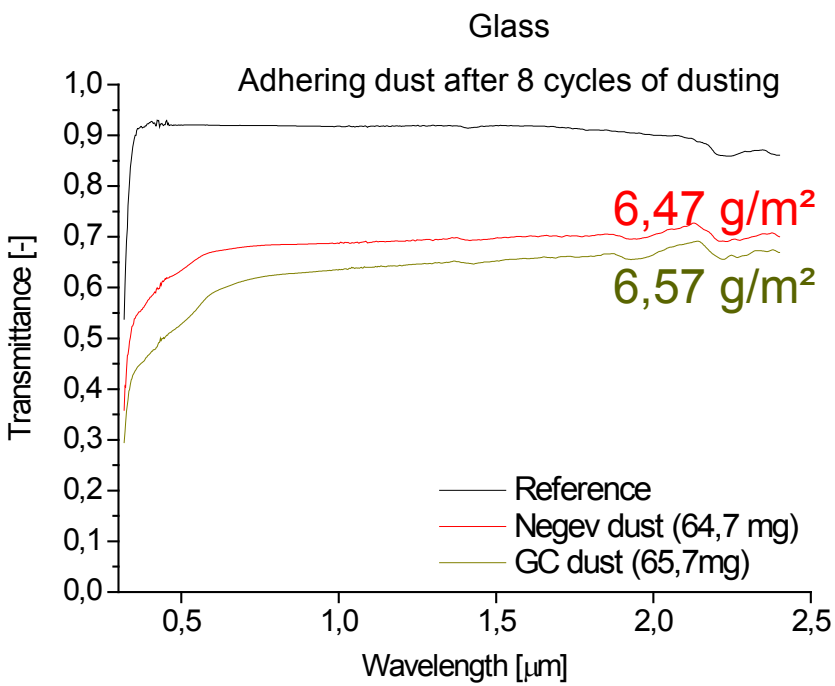
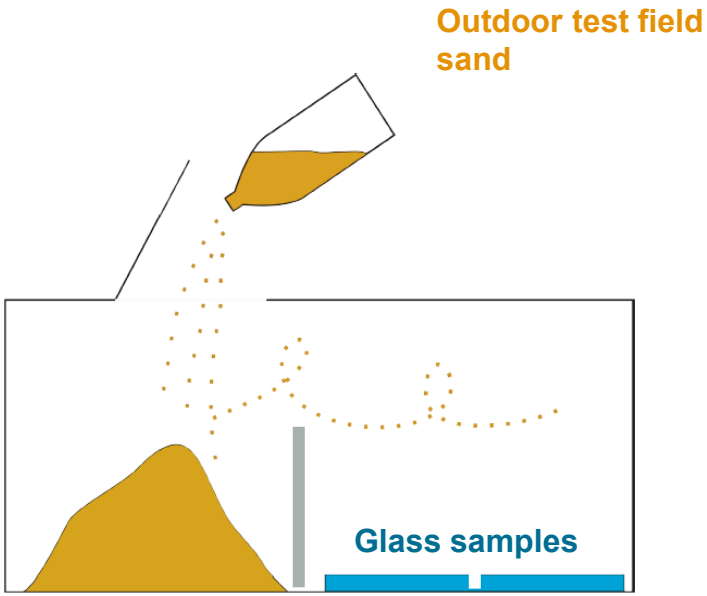
Degradation of performance: INDOOR

Artificial Soiling: PRESTUDY with “tons” of sand





- Nearly identical amount of „arid“ and „maritim“ dust results in differences on solar transmittance

→ Homogeneous, reproductive soiling test had to be developed to confirm results

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Degradation of performance: INDOOR

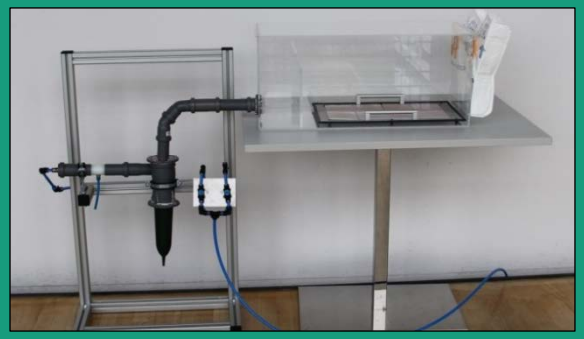
Soiling procedure

1. Pre-preparation of sample
   - Characterization (optical, gravimetric)
   - (cleaning)
2. Dusting
   - Dry dust (standard or real) distribution
   - (cyclic dusting)
   - Condensation if applicable
   - Wet dust deposition
3. Material qualification

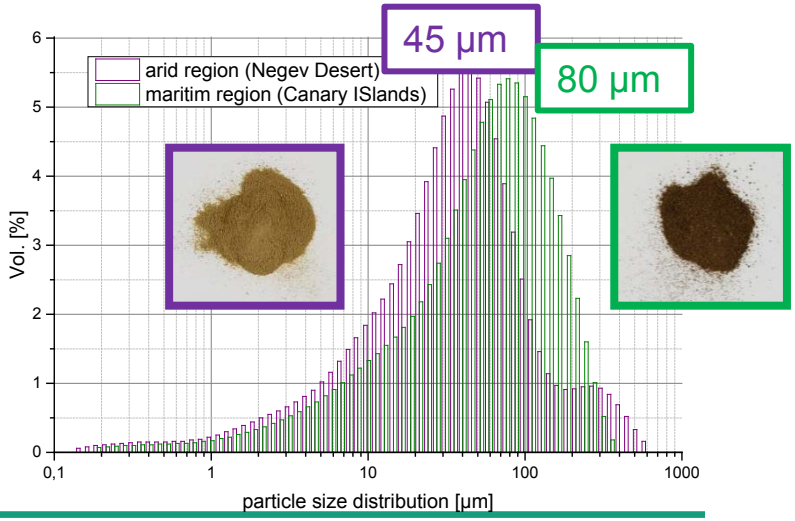
1. Material characterisation	2. Material qualification
• Soiling test	• Analysis of the soiling behavior of material by spectral measurement • Weathering

Soiling testing

❖ **Indoor**



In-house developed dusting device



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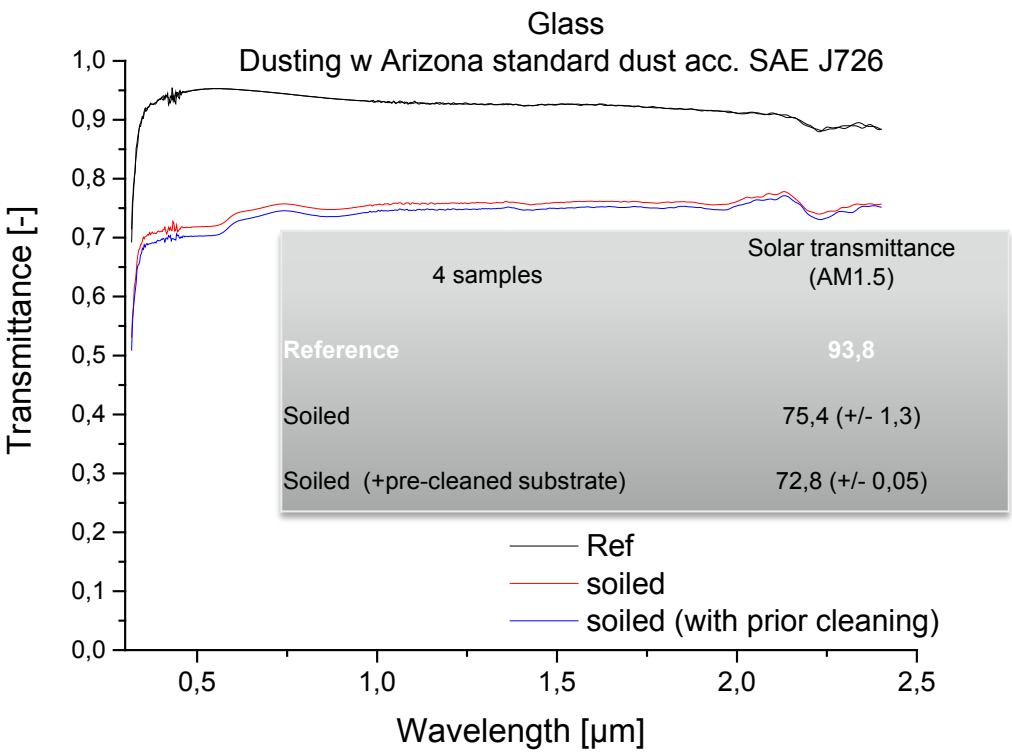
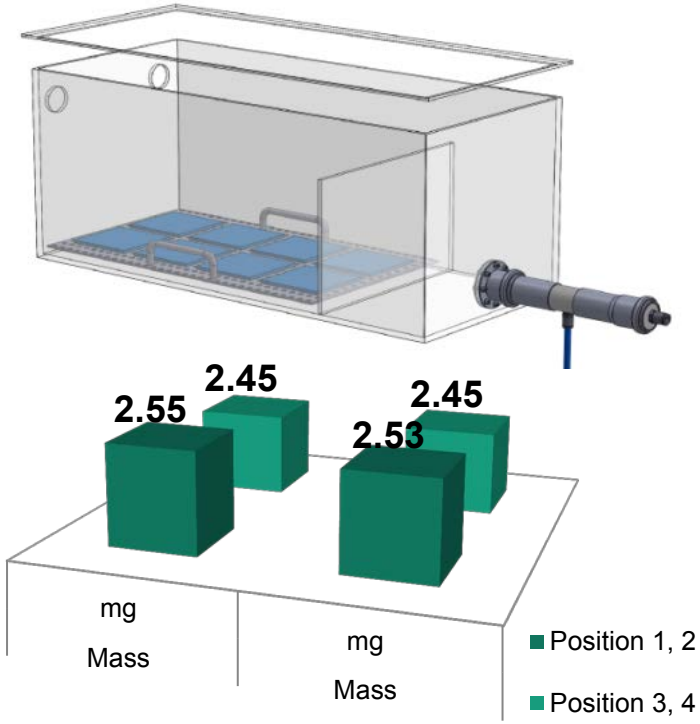
Degradation of performance: INDOOR

Validation of new in-house developed soiling test



4 samples	Solar transmittance (AM1.5)
Reference	93,8
Soiled	75,4 (+/- 1,3)
Soiled (+pre-cleaned substrate)	72,8 (+/- 0,05)



Weighted dust deposition in [mg] adhering to glass surface (5 cm x 5 cm)

Significant loss of spectral transmittance, due to 1 g/m² homogeneous distributed Arizona standard dust

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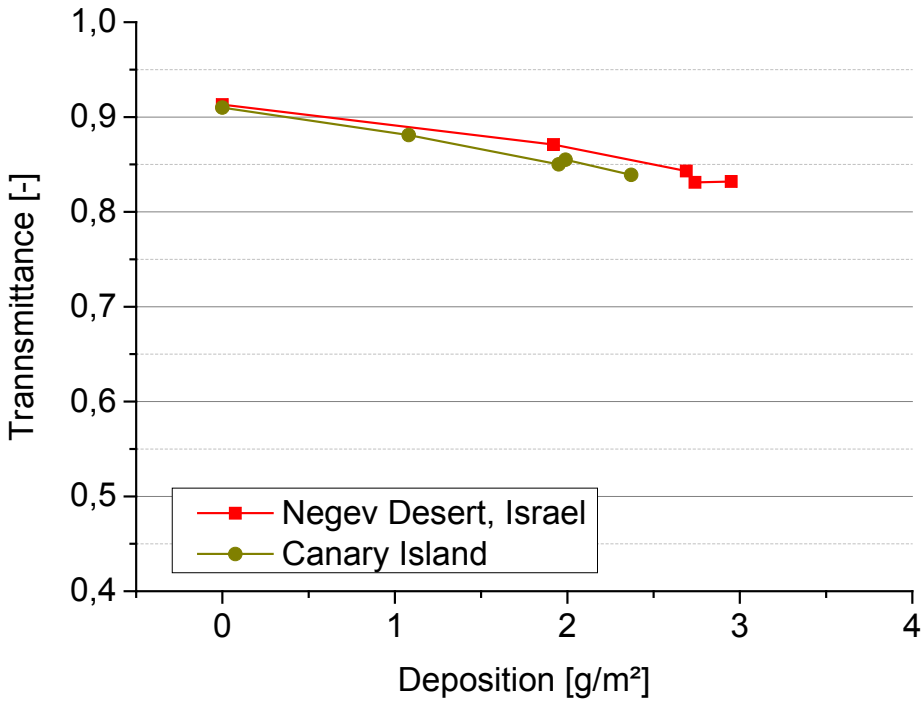
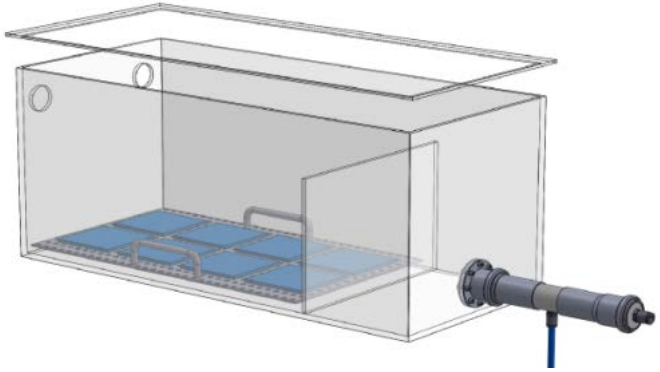
Degradation of performance: INDOOR

Validation of new in-house developed soiling test





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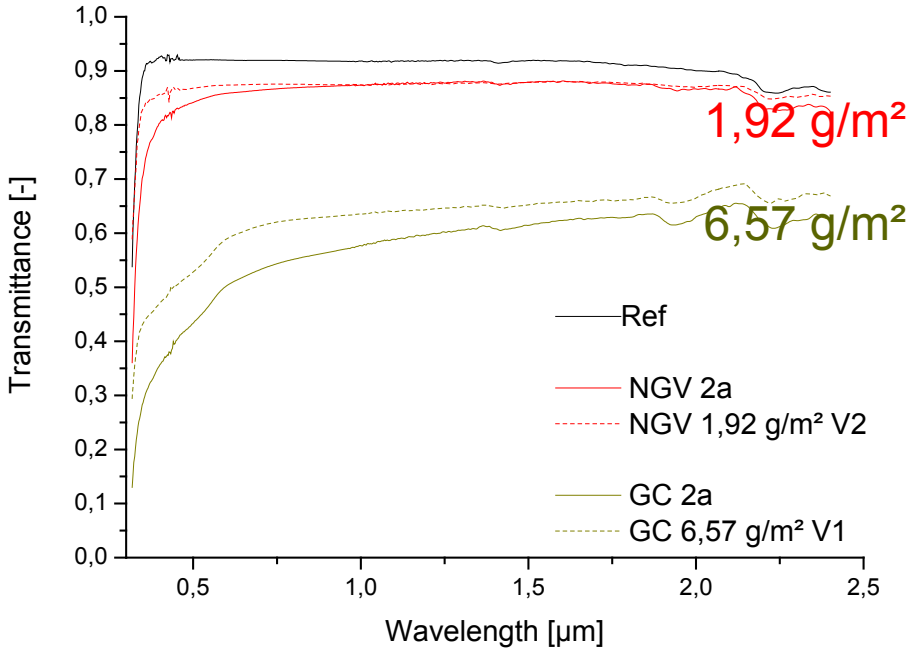
Comparison INDOOR & OUTDOOR
Results



- Dust deposition modelled for outdoor exposure
- Soiling tests so far with uncoated glass
- Maritime region shows far worse soiling effects, then our arid region (Negev Desert), in terms of transmittance loss

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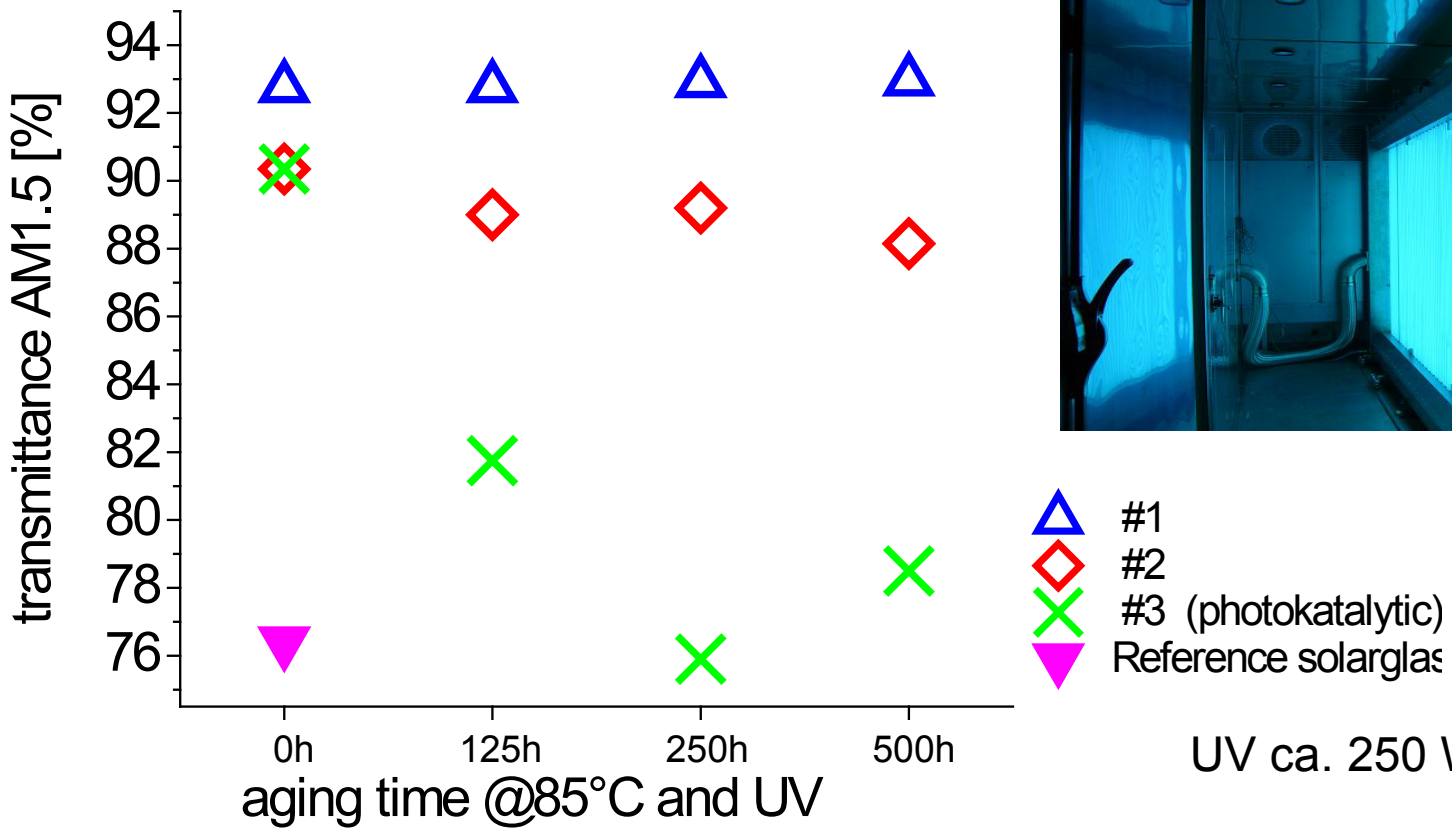
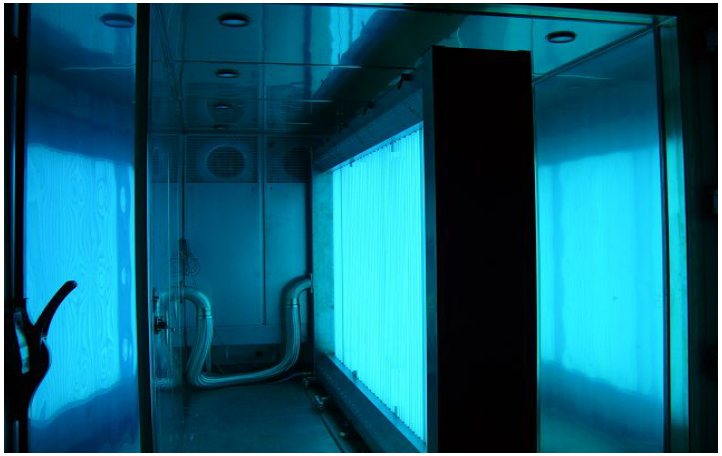
Degradation of performance: INDOOR
Weathering





UV ca. 250 W/m² ~ 5X

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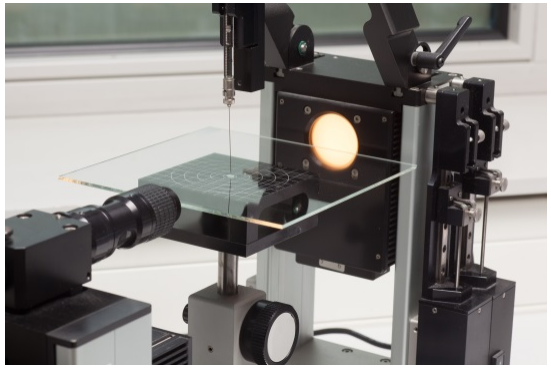
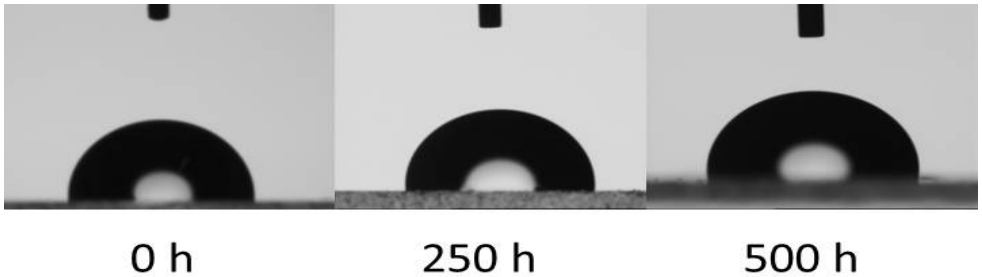
Degradation of performance: INDOOR
Weathering



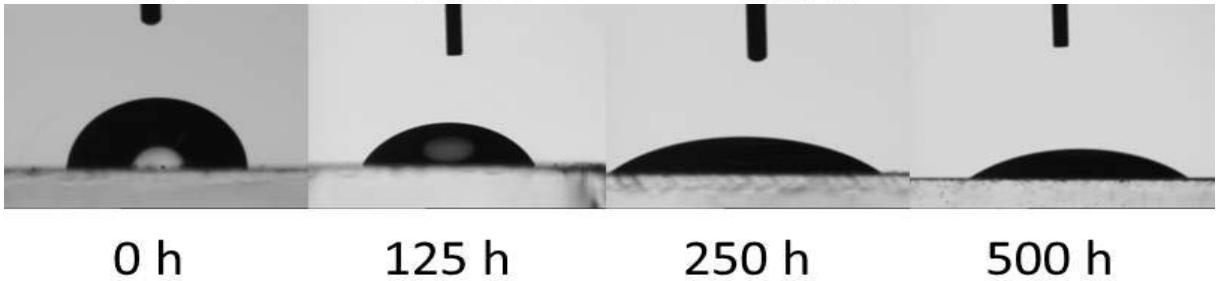
Measurement of contact angles

After weathering at 85°C with UV

solar glass sample #1



solar glass sample #2



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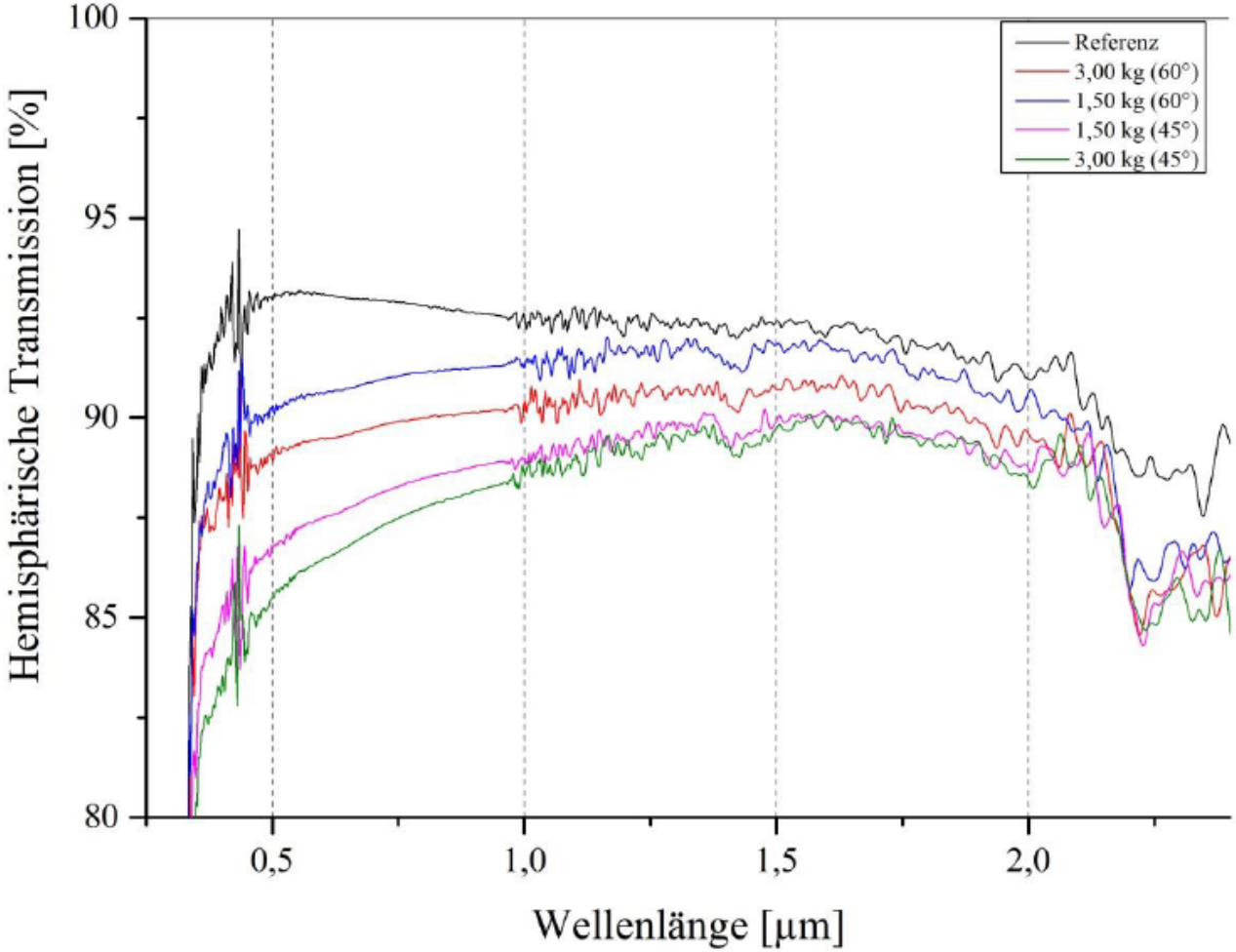
Degradation of performance: INDOOR
Abrasion

- Sand trickling test with standard test sand
- Different abrasion tests address different effects



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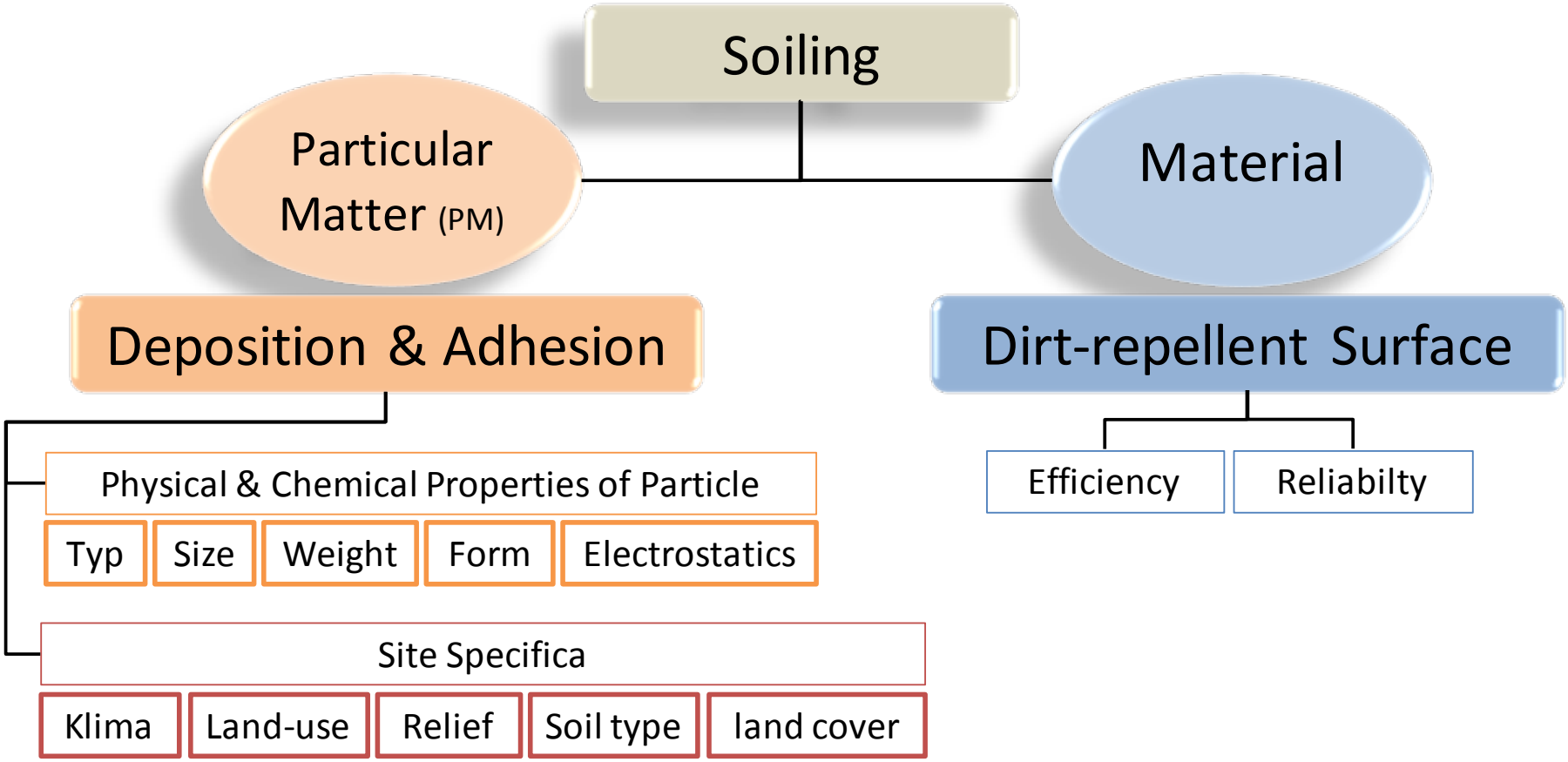
Degradation of performance
Abrasion



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Conclusion

- Different dust types have different “soiling efficiency”
- Correlation of dust deposition and spectral transmittance is possible
- Outdoor soiling effects can be reproduced in the lab
- Soiling method influences the deposition rate and the soiling effect
- Testing of functionality and reliability is necessary
- Tests have to be adapted to operational and local conditions / requirements

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Thank you for your attention!

The work was partly funded by the German Federal Ministry for Economic Affairs and Energy and industrial partners in the project *Speed*Coll.

Thanks to all my colleagues for their contribution

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Field Performance of Anti-Soiling Coatings on Photovoltaic Glass

NREL PVMRW 2016

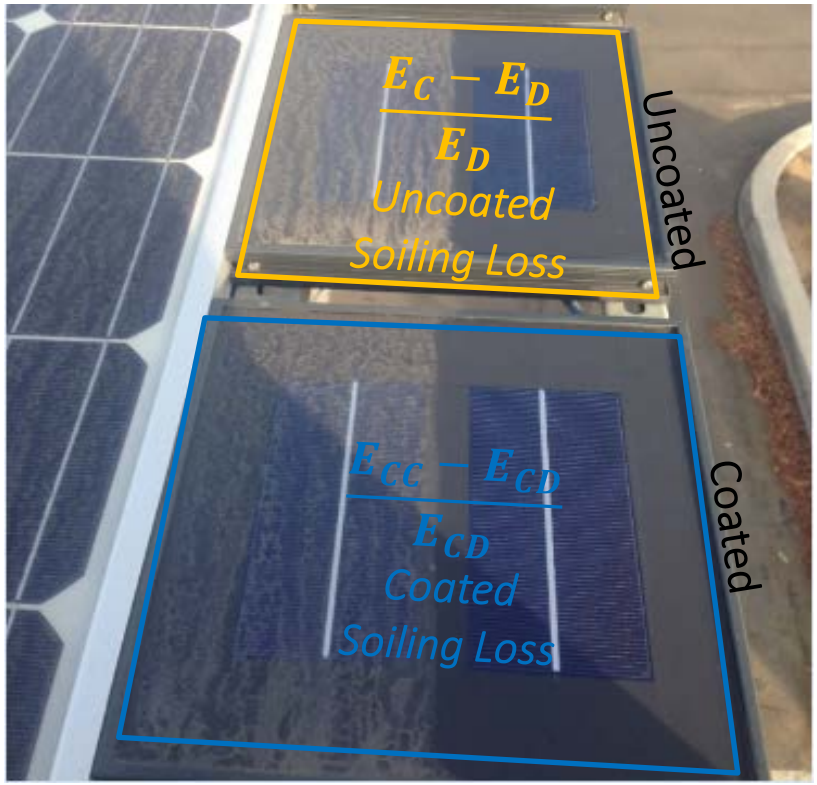
enkitech.com

Introduction

- Soiling test has been running for 2+ years
  - 14 stations in CA, NV, AZ, NM, TX, and MD
    - 9 active as of 10/31/2015
  - Each station consists of two Atersa reference cell sensors, each of which has two reference cells
    - One sensor is coated with Enki hydrophobic anti-soiling ARC
    - Sensors were flow-coated and cured at low temp which is not optimal for AR property.
- Atersa sensor outputs irradiance for each reference cell, logged by array weather station.
  - 1 minute measured data is logged. This analysis uses averaged 15 minute data.
- Does a hydrophobic coating show an anti-soiling effect?

Experimental Method

	Dirty	Cleaned
Uncoated	E_D	E_C
coated	E_{CD}	E_{CC}



Test Station just after cleaning procedure

$(E_C - E_D)/E_D$ = Uncoated Soiling Loss (U_{SL})

$(E_{CC} - E_{CD})/E_{CD}$ = Coated Soiling Loss (C_{SL})

$U_{SL} - C_{SL}$ = Anti-Soiling Gain

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Experimental Method

- The ‘clean’ side of both sensors is washed manually about twice a month
  - Soiling measurement is only valid immediately after cleaning, thereafter measurement accuracy decreases as ‘clean’ cell becomes soiled
  - The ‘clean’ cell is not consistent over time, some cleaning events clean the wrong side of the sensor so ‘clean’ and ‘dirty’ cells are reversed
    - Use $|U_{SL}|$ and $|C_{SL}|$ to eliminate this error
- The two reference cells within each sensor exhibit an varying offset error over time
  - At times when cells should experience identical irradiance (i.e. both cells are clean), different irradiance values are output for each cell

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Reference Cell Offset Errors

- 169 Key dates were manually identified over the 14 sites
  - Days on which there was a rain event and a observed response in the dataset
  - Assume that the rain event cleans both cells and returns the sensor to a 'baselined' state
    - Measured Irradiance should be equal so difference between cells is the offset error
- Offset errors (normalized for POA irradiance) for all key dates and all sensors (n=333)
  - Mean 0.00%; Std Dev 0.83%
- A correction coefficient for each sensor and each key date is calculated based upon the irradiance measurements from 7 succeeding days after a key date.
  - $C_U = \frac{\sum_{kd}^{kd+7} E_D}{\sum_{kd}^{kd+7} E_C}$ … correction coefficient for uncoated sensor
  - $U_{SL} = \frac{C_U E_C - E_D}{E_D}$ … calculation of uncoated soiling loss with C_U
  - Correction coefficients are linearly interpolated between key dates

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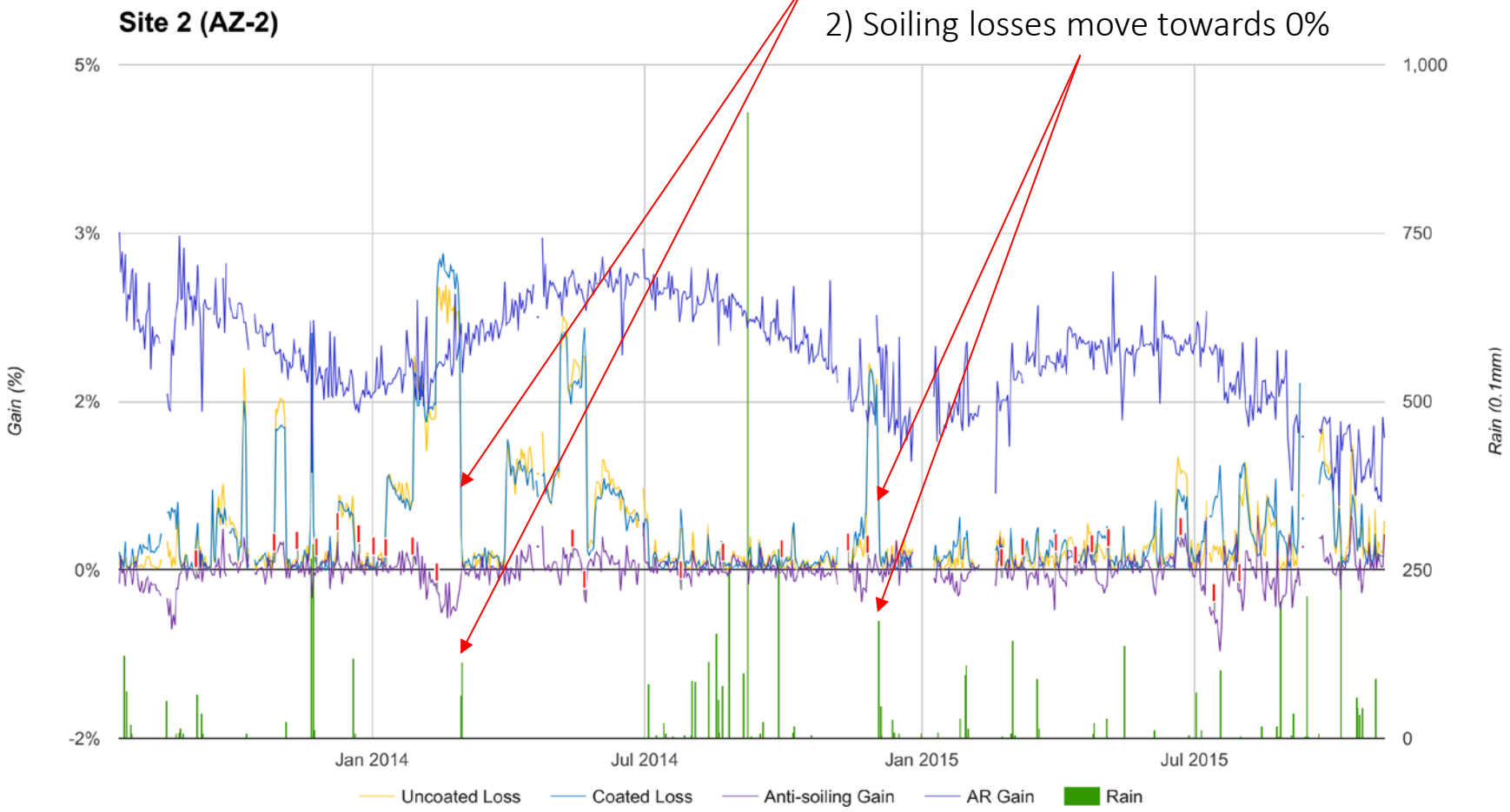
Key Date Identification Example

Key Date:
1) Rain recorded
2) Soiling losses move towards 0%



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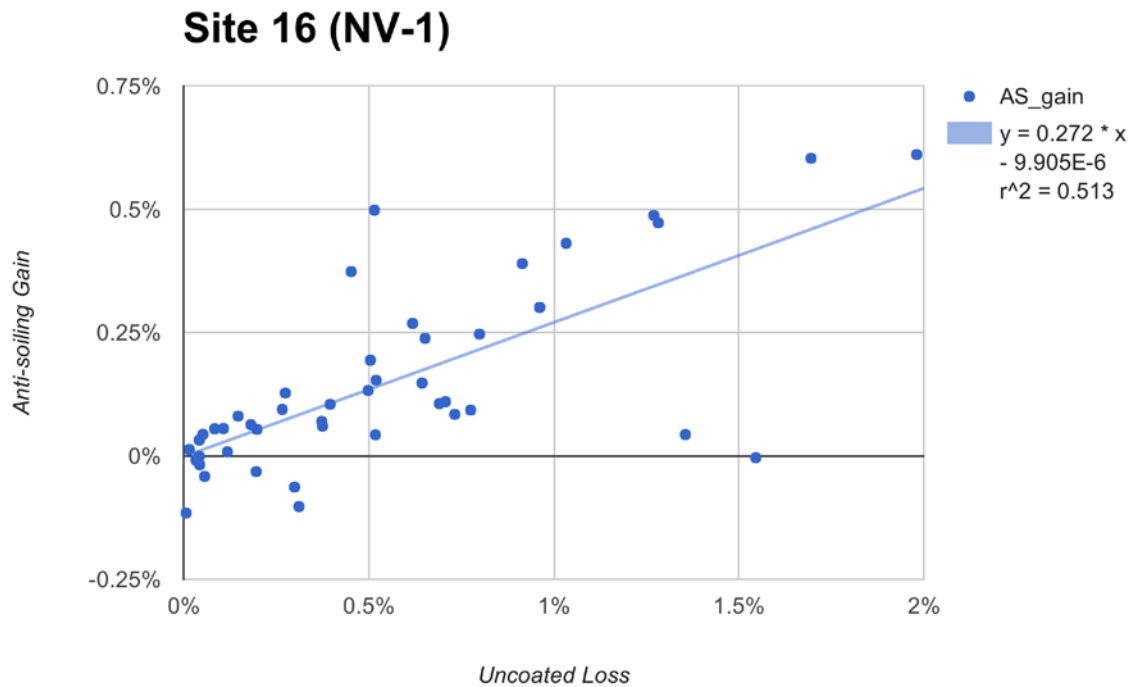
Anti-Soiling Performance



- Taking just the days after a cleaning event
  - Because the time of cleaning on the day is not known
  - negligible soiling of 'clean' cell – so accurate measure of soiling
- Plot Anti-Soiling Gain vs Uncoated Loss
  - Slope of a fitted line is the recover rate: % of energy generation lost to soiling recovered by coating

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Soiling Losses

- Experiment DOES NOT measure total soiling loss at a site over time
  - Losses between cleanings are unknown
    - As 'clean' cell becomes soiled, actual soiling loss is masked
    - Measured soiling loss is an underestimate
- Best possible is lower bound to soiling loss
  - Sum over full period: $\frac{\sum(E_C - E_D)}{\sum E_D}$
- There are no cleaning events logged for site 14 (NM-2) so it is excluded from the analysis

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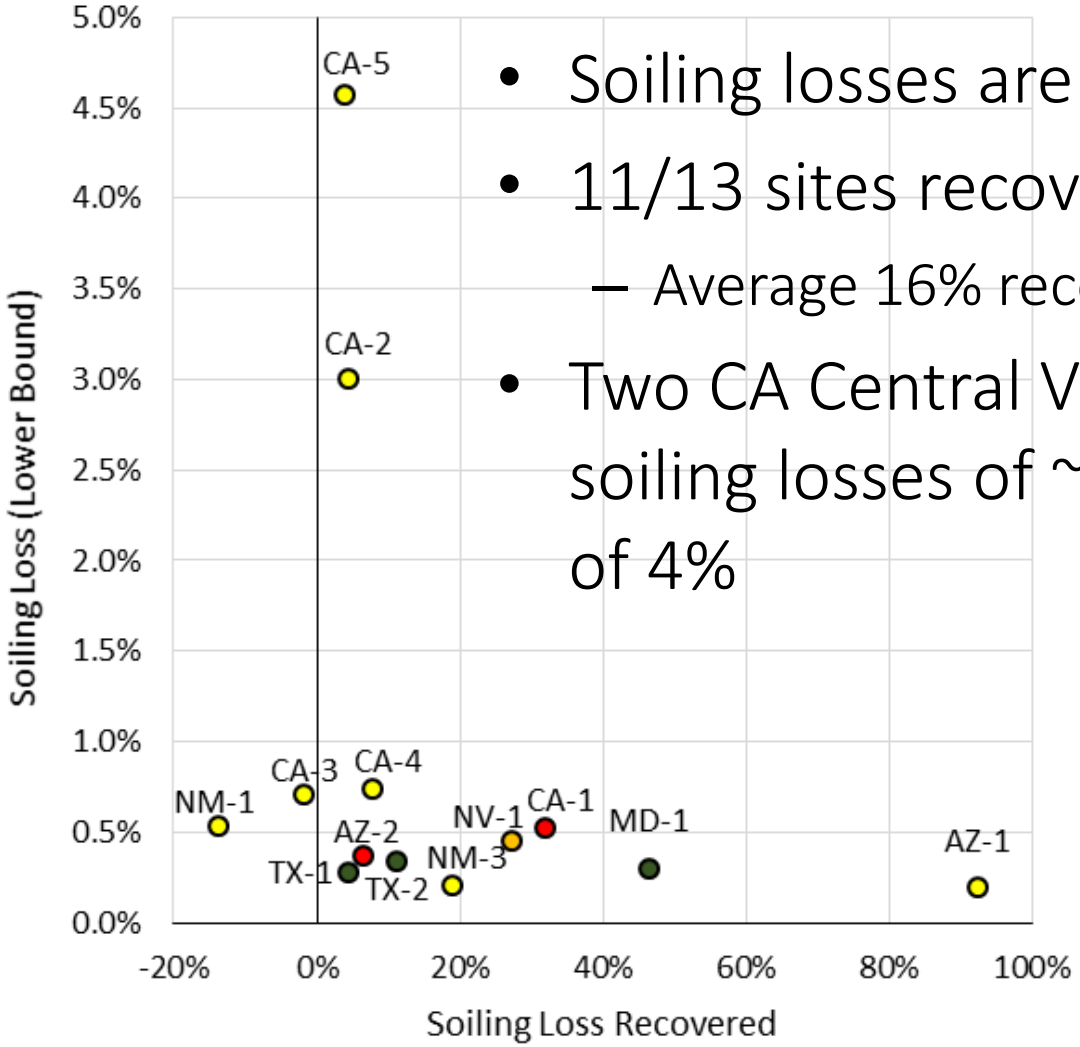
Soiling Performance Summary



- Soiling losses are low ~0.5% at most sites
- 11/13 sites recovery some soiling loss
  - Average 16% recovery
- Two CA Central Valley locations have soiling losses of ~4% with a recovery rate of 4%

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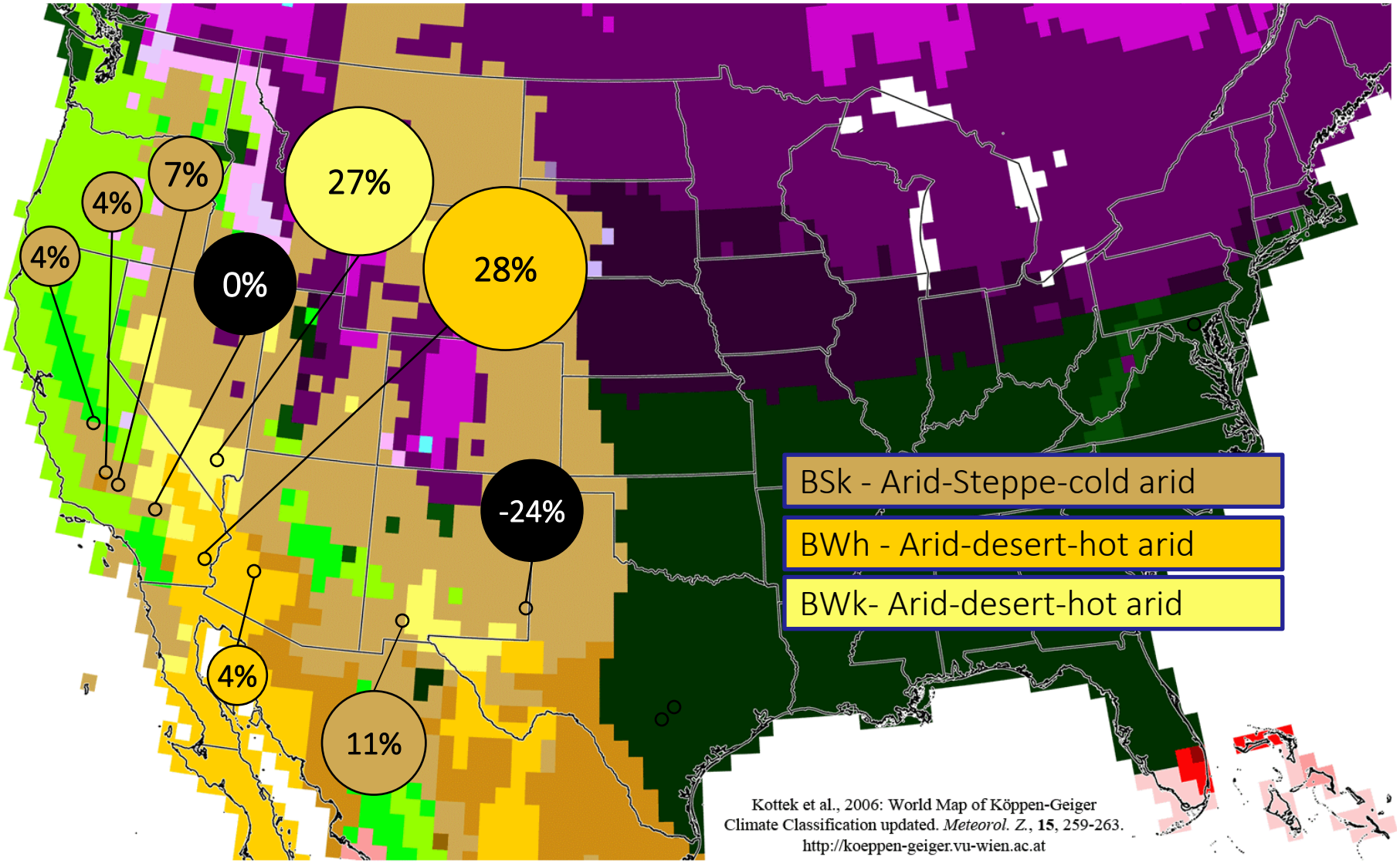
Soiling Recovery in Arid Climates



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Anti-Soiling Performance

- 8/10 test locations in arid climates show soiling recovery
  - 3 Arid Koppen Climate Classifications Tested
    - BWh - Arid-desert-hot arid
    - BWk - Arid-desert-hot arid
    - BSk - Arid-Steppe-cold arid
- 2 sites had no or negative recovery
  - Due to location very close to sources of petrochemical pollution or soot
    - Within an active oil-field
    - Next to warehouse/distribution center

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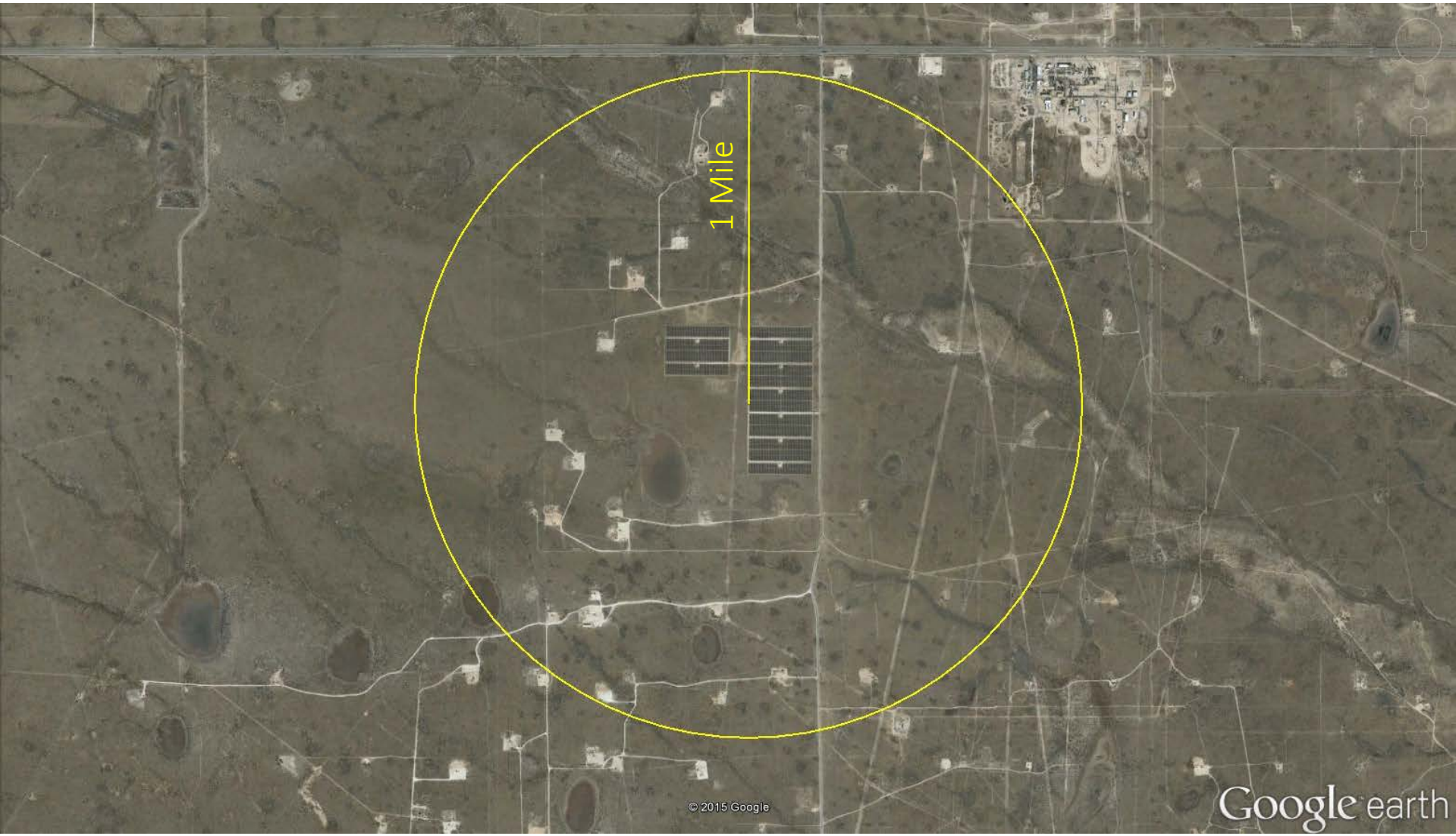
Oil Field Location (NM-1)



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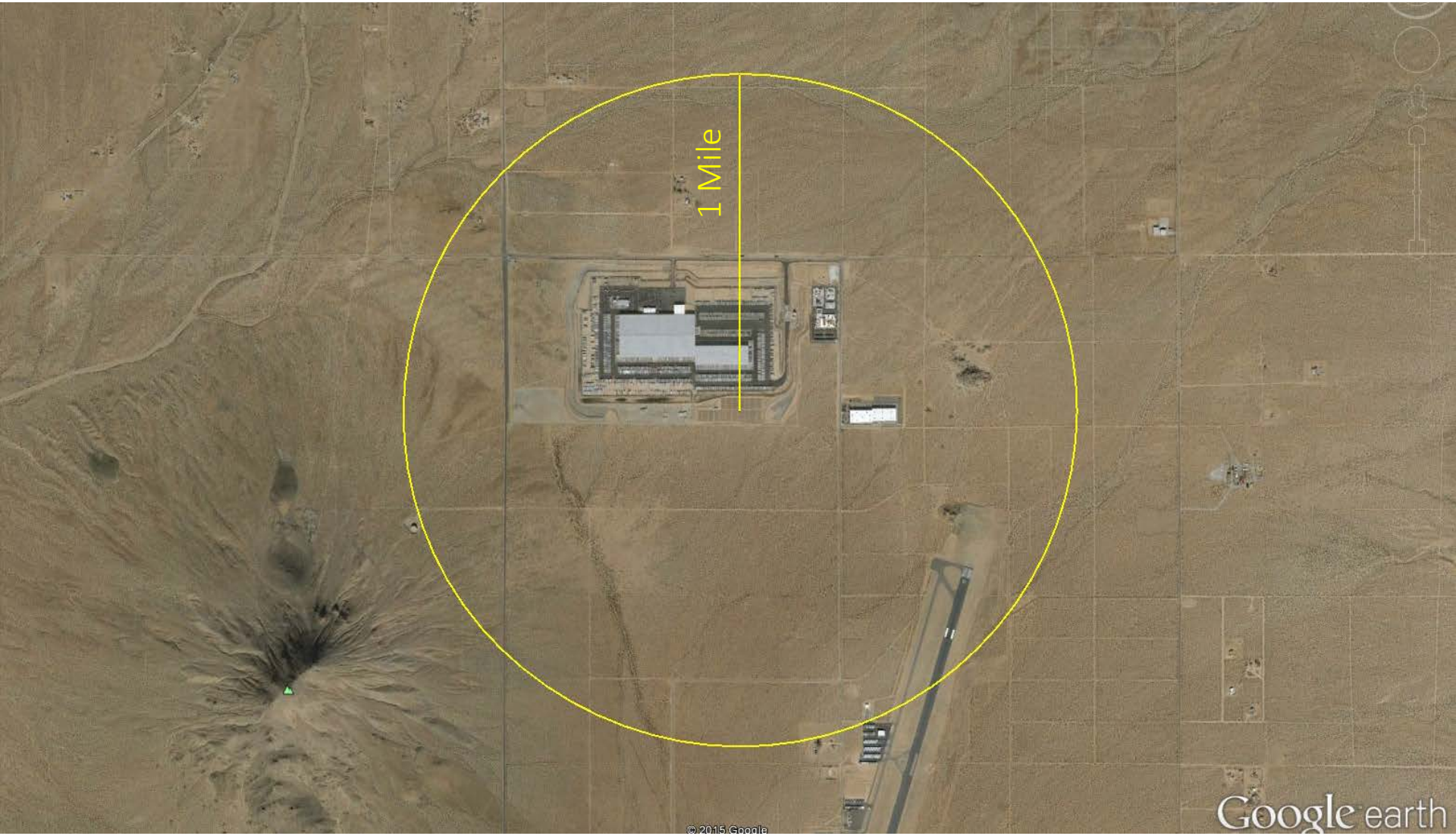
Warehouse Location (CA-3)



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Soiling Test Conclusions & Lessons

- Data for 2.25 years at 14 test locations was analyzed
- Soiling losses at most locations generally low
- Anti-soiling effect is demonstrated at 11/13 test locations
  - Average recover of soiling losses is 16%
- Hydrophobic coatings perform worse than glass at locations with hydrocarbon soiling
- Manual cleaning is not optimal for this type of experiment
- Select sites with measurable soiling losses

Next Steps

- Latest soiling test station at UC Riverside
  - Automated cleaning with Atonometrics system
  - Multiple coatings

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THANK YOU

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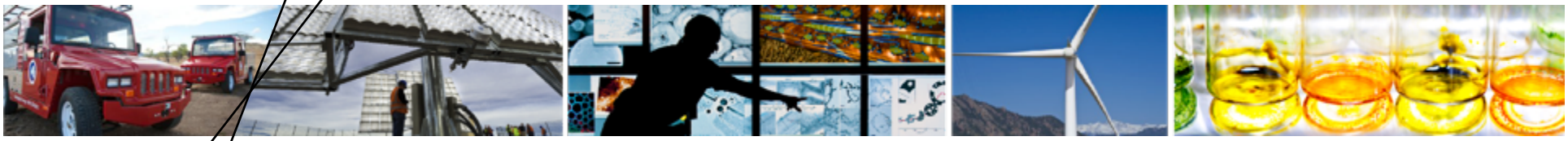
The Modeling of the Effects of Soiling, Its Mechanisms, and the Corresponding Abrasion



PV Module Reliability Workshop

Lin Simpson

February 24, 2016

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

- **Background**
- **Project Description and Objectives**
- **Focus Areas**
  - Soiling Rate Model
  - Mechanisms
  - Standards
- **Summary**
- **Acknowledgements**

Background

- **Problem:**
  - Natural soiling has reduced the energy output of PV systems since the inception of the technology.
  - Soiling is a complex problem that increases uncertainty and drives up LCOE through lost energy production, increased O&M costs, and higher finance rates.
    - Overall, soiling may be adding ¢1/kWh to LCOE in the United States (may be worse in some other parts of the world) depending on the site.
  - In NREL's comprehensive review of solar energy soiling,[1] the issues have been discussed in the literature for more than 70 years, and yet **"the fundamental properties of dust and its effect on energy transfer are still not fully understood, nor is there a clear solution to the problem."**
- **Goal:**
  - NREL's team will work with the PV community to go beyond the past work to try and understand the processes involved so that the effects of soiling can be predicted for different environmental conditions.
  - Provide the PV industry with the tools and knowledge necessary to devise cost effective mitigation.

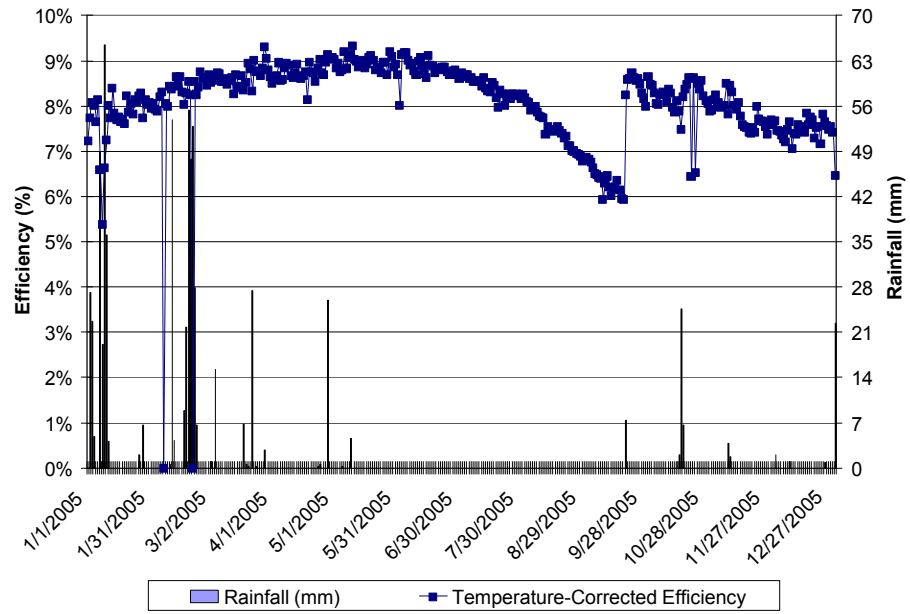
[1]Sarver et. al., Renewable and Sustainable Energy Reviews, 2013, vol. 22, issue C, pages 698-733

Project Description and Overview

- **3 year long competitively selected SuNLaMP project:**
  - Addressing Soiling: From Interface Chemistry to Practicality
- **Soiling reduces PV energy output & increases LCOE two ways:**
  - Indirectly through increased performance uncertainty → higher finance rates
  - Directly through reduced power output
- **Working with stakeholders and PV community from the outset**
  - ***Welcome collaborations and input***
  - Focus on addressing 3 main problems to decrease LCOE
    - **Predictive soiling loss models:** predict annualized (perhaps seasonal) losses at new PV plant sites. (reduce performance uncertainty)
    - **Quantify the different soiling mechanisms:** develop guidelines of the appropriate properties PV module surfaces and coatings might need to reduce soiling. (increased power output)
    - **Standards:** develop durability standards for PV module coatings.
      - Perhaps artificial soiling standard

Historical modeling efforts

- **Time series**
  - Requires measured quantities from the site such as daily soiling rate
- **Site/factor specific**
  - Study impact of factors like panel tilt at a given location
- **Optical**
  - Link the transmission to factors such as particle size, type, or deposition density



Example data used for time series model
(From Kimber et al. 2006, DOI: 10.1109/WCPEC.2006.279690)

- **Our Goal:**

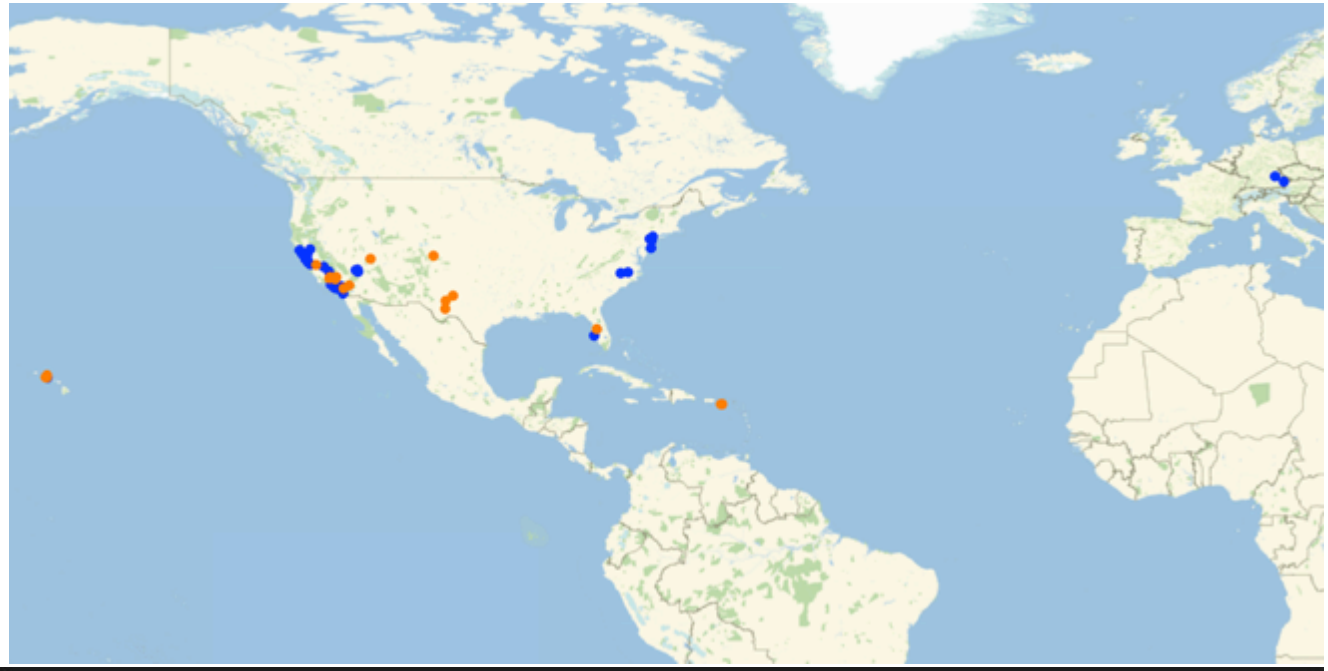
Site data (air quality, land use, climate, etc.) → Annualized energy loss.
Without the need for prospecting or historical production data

Reviews of prior work:
Sarver et al. 2013, DOI: 10.1016/j.rser.2012.12.065
Mani et al. 2010, DOI: 10.1016/j.rser.2010.07.065

Site Specific Soiling Loss Rates

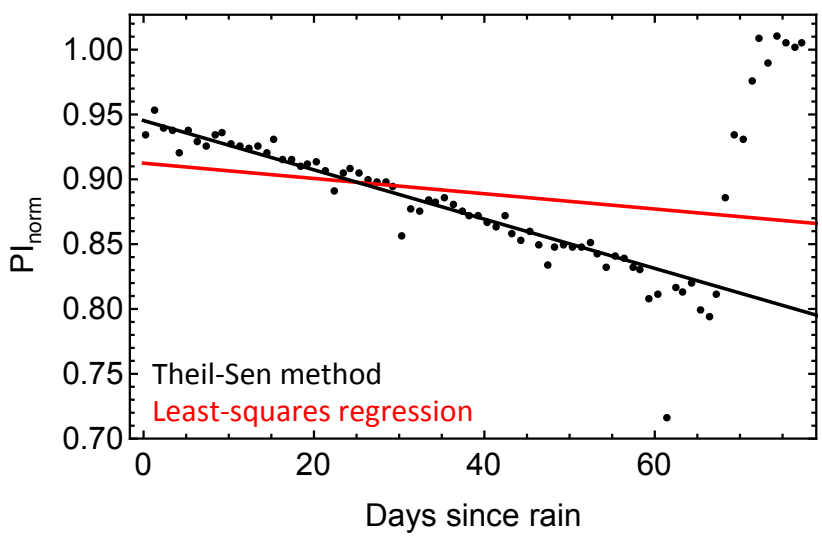
- Industry driven: PV manufactures and power plant owners are sharing high quality data from over 200 sites to enable this effort to be successful.
  - Start with small (~20) but high quality data sets.
    - Creating automatic methods to extract information from production data
  - Supplement the data with potential predictive variables quantified from EPA particulate maps, rainfall maps, NOAA, and USGS (guided by PVQAT 12).

Picture of initial data sites being used for identifying the key model parameters. The sites are representative of the different climatic zones within the US and should provide the requisite information needed for robust models. Different colors are for the different sources of the data.

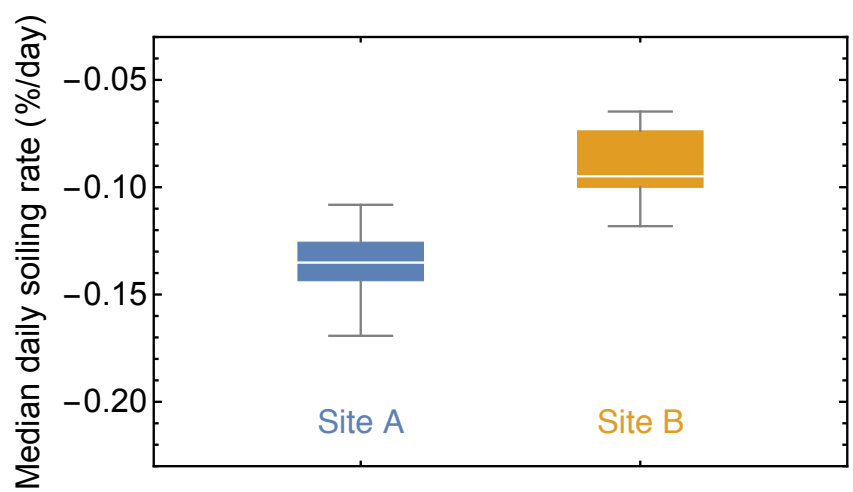


Extracting soiling rates

- To build our model we need a dataset of soiling losses from many diverse sites
- We are building upon prior time series models to develop **scalable** methods for extracting soiling rates from production data
- Our approach considers a statistical sample of soiling intervals from a given site, and requires minimal parameterization, filtering, or knowledge about the system
  - Focuses on empirical modeling that attempts to include all possible predictive variables and predicts annualized and seasonal losses.
  - Annual empirical metric more achievable and provides significant value in **30 year performance predictions**, seasonal metric provides guidance in O&M planning.



A time-series of performance index vs. days since rain showing the benefit of the robust Theil-Sen estimator for extracting soiling rates.



The approach enables statistical comparisons between soiling rates observed at different sites.

Deceglie et al. IEEE PVSC 2016 (submitted)

Initial Studies of Soiling Mechanisms

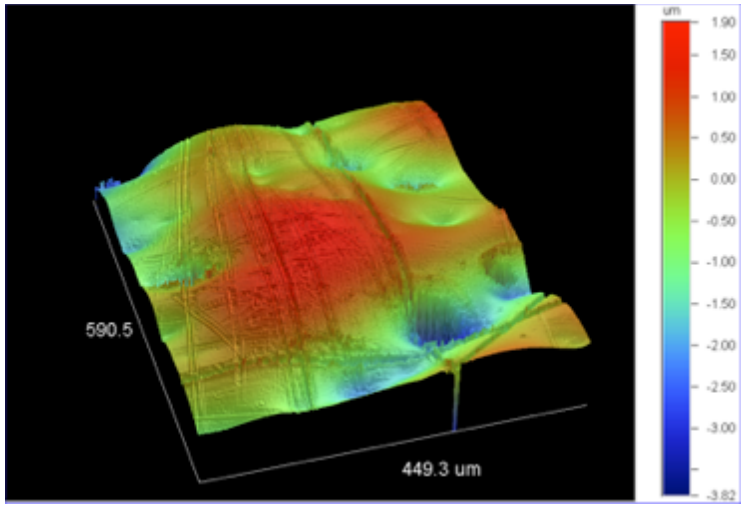
- **Obtained an initial set of PV modules that had been in the field for 17-28 years and compared with controls that had not been deployed.**
  - Using to evaluate what soiling/degradation mechanisms are present and what characterization needs to be done.
  - Ultimately, will get 10 to 20 field modules.
    - Let us know if you have any with interesting observed soiling

Sample ID	Sample Description	Location	Model	Module Type	Years Exposed	Mounting
#1	Tempered glass	Tempe, AZ	Siemens, M55	Aged	18	Open rack
#2		Tempe, AZ	Siemens, M55	Control	0	N/A
#3		Sacramento, CA	ARCO, M55	Aged	28	Open rack
#4		Sacramento, CA	ARCO, M55	Control	0	N/A
#5		Chandler, AZ	ASE Americas, ASE-300-DGF/50	Aged	17	Rooftop

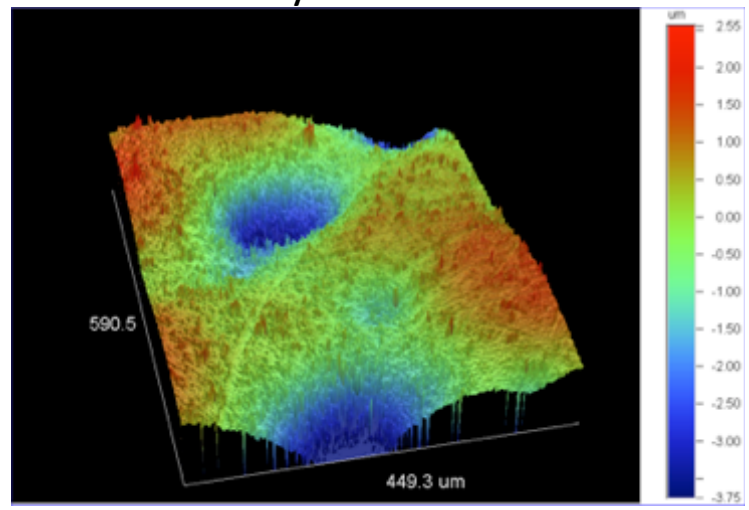
Weathered PV Module Glass Analysis

Siemens M55 module

control



18 years in field



- **White light optical profilometry of module glass**
  - Provides information over large lateral length scales on module glass and AR coatings
  - Scratches and large scale (~mm) hillocks were observed on control sample.
  - The small-scale roughness of control and aged modules appears qualitatively different.
  - SEM and EDS show thin salt layer may be present on glass surface.

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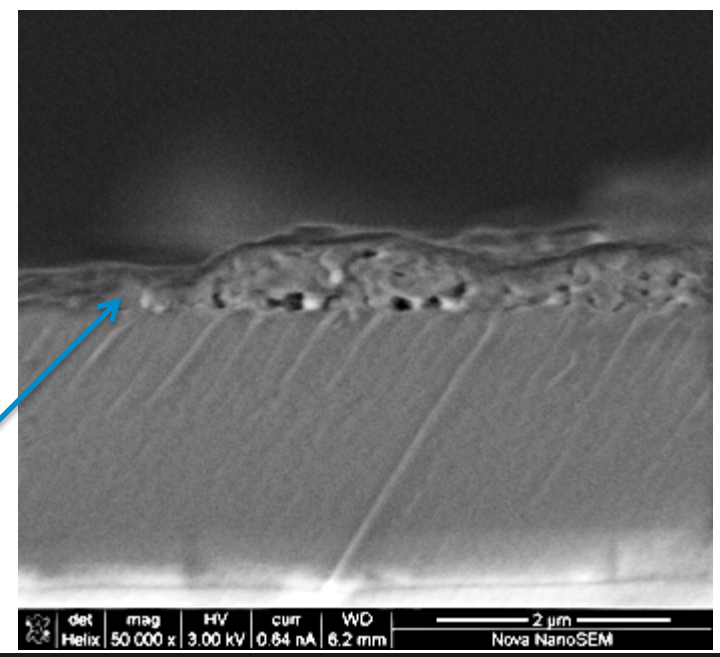
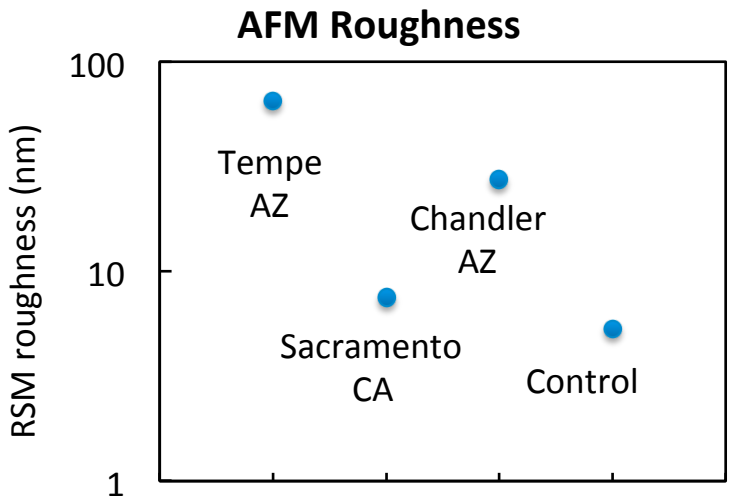
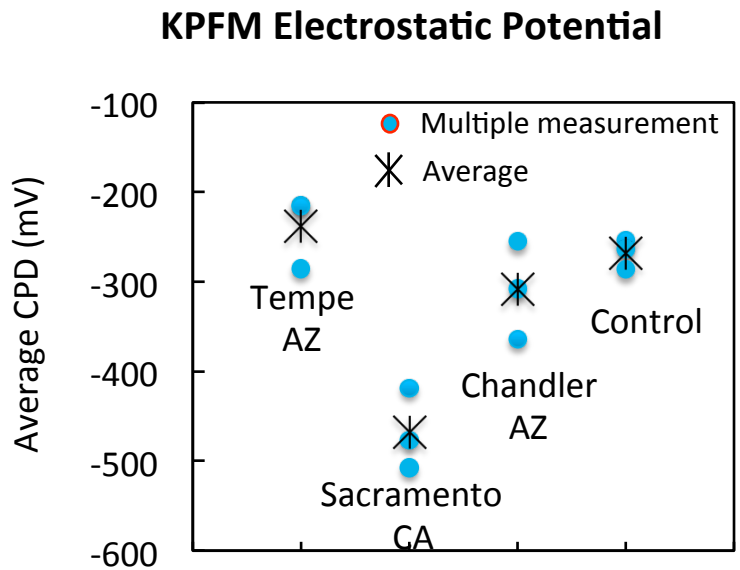
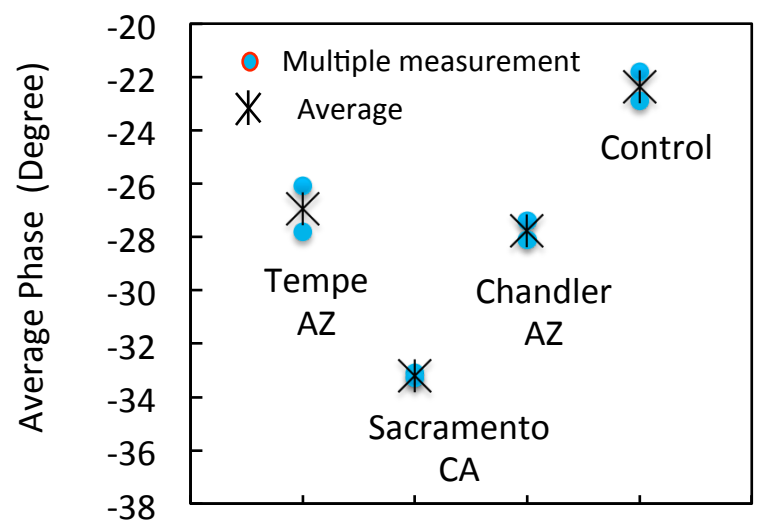


AFM-Based Characterization





- Roughness: Tempe>Chandler>Sacramento
- Phase lag and viscosity/softness: Sacramento>Chandler ≈ Tempe
- Contact Potential Difference: Sacramento>Chandler>Tempe



AFM-based techniques:

- 2D and real 3D data and roughness.
- Phase imaging/lag: elasticity, adhesion &friction.
- Lateral force: inhomogeneity not from topography.
- Force-distance curves: adhesion (e.g. capillary).
- EFM/KPFM: electrostatic interaction.
  - Electrostatic/Kelvin Probe Force Microscopy

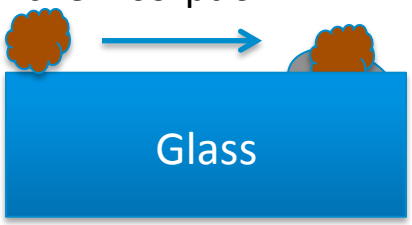
Example Mechanism Investigation

- **Conclusions from initial literature survey**
  - Early work attempted to address mechanism issues more[1]
  - A lot of work identifies soiling issues, but do not evaluate/identify exact adhesion mechanism[2]
- **To go beyond just "observing" soiling we must systematically evaluate each adhesion mechanism involved at each step.**

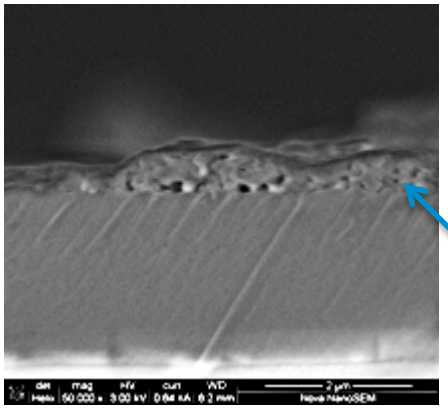
Sample Observations:

- Dust that has been on the surface for a while tends to be harder to remove.
- Humidity and dew cycle seem to increase soiling.
- Soiling is often not uniform.
- One of the main forms of enduring soiling is cementation.
- Soiling rates may be higher in cities than in more agricultural or desert regions.
- Synthetic fibers influenced by electrostatics resulting in an increase/ decrease in their accumulation

Physisorption goes to chemisorption



After outside weathering



Sample questions to answer:

- If gravity or wind brings dust to the surface, what makes it stick?
  - Kaz's recent paper[3] places adhesive forces with dust at 10-300 nN: Humidity had big effect.
- What role does humidity play?
  - Reduces electrostatics?
  - Enables capillary?
  - What is relative strength?
- What is the effect of surface properties and dust composition?
  - Surface roughness?
  - Surface Energy?
  - Conductivity?
- Is the roughness due to weathering from chemical etching of the glass or surface deposits?

1. e.g.,Cuddihy and Wilis, JPL Pub 84-72 (1984)
2. e.g., Mani and Pillai, Ren. And Sust. Energy Rev. 14, 3124 (2010)
3. Kazmerski et.al., 978-1-4799-7944-8/15/©2015 IEEE

Mechanism Investigations

- **To address these mechanism questions, quantify impact of individual mechanisms, e.g.,:**
  - Studing effects of substrate roughness, relative humidity (RH), probe/substrate conductivity, surface energy, and surface contamination on:
    - Van der Waals forces
    - Electrostatic adhesion
    - Capillary forces
    - Hydrogen bonding

    e.g., use Atomic Force Microscopy Based Measurements and Analysis

    force-distance (f-z) curves, lateral force microscopy (LFM), phase imaging (PI), electrostatic force microscopy (EFM).
  - Identifing potential sources of salt; leaching from the module glass, airborne salt, and leaching from deposited soiling materials like alumina-silicate or clay particles.
    - Accelerated testing of glass and dust
- **With individual mechanisms quantified, then evaluate complex or multiple step soiling mechanisms**
  - e.g., cementation

Soiling Mechanisms

- **Working through literature to develop an investigation plan for each combination of mechanisms and surface properties**
- **Identify the specific mechanisms associated with soiling to find appropriate mitigation processes for a given region. Uses include:**
  - Optimize cleaning schedules
  - Techno-economic based preventative approaches
- **Provide the community with an understanding of how to select between different surface properties**

Map of Work to be performed

Adhesion Mechanisms/ Surface Properties	Gravity	Surface Energy	Van der Waals	Capillary	Charge Double Layer	Electrostatic/ coulombic	Complex/ cementation	Chemical Bond
Polymeric	VW	W	TBD	TBD	VS	VS	VS	VS
Textured glass	VW	W	TBD	TBD	TBD	TBD	VS	VS
Nanostrutured	VW	W	TBD	TBD	TBD	TBD	TBD	VS
Smooth glass	VW	W	W	TBD	TBD	TBD	TBD	VS
Photocatalytic	VW	TBD	TBD	VS	TBD	TBD	VS	VS
Hydrophilic	VW	TBD	TBD	VS	TBD	TBD	VS	VS
Electrically conducting	VW	TBD	TBD	TBD	VW	VW	TBD	VS
Hydrophobic / low surface energy	VW	VW	VW	TBD	TBD	TBD	TBD	TBD

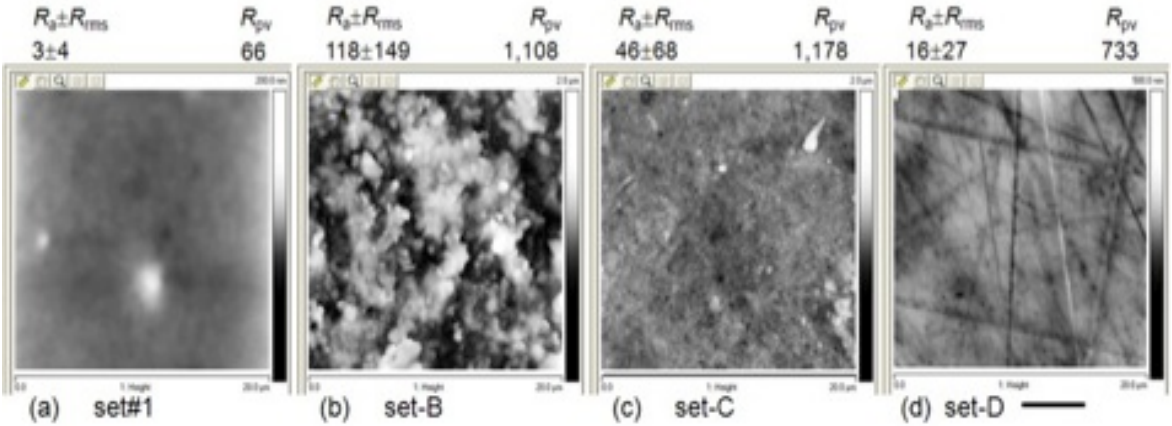
VW - Very Weak, <10 kJ/mol
W - Weak, < 25 kJ/mol
M - Moderate, ~50 kJ/mol
S - Strong, >75 kJ/mol
VS - Very Strong, >100 kJ/mol

Focus more on stronger mechanisms on right.
But must quantify weaker mechanisms to be able to remove contributions.

Coatings Standards: Overview

- **Determine repeatable indoor abrasion test procedures suitable for PV surfaces**
- **Deploy coating samples at various test sites, acquire aged PV modules with standard solar glass.**
- **Correlate degradation of veteran PV modules with indoor abrasion test procedures,**
  - Test variations in accelerated protocols to improve correlation.
  - Incorporate best accelerated test protocols into draft IEC standards. (Validation efforts will need to be ongoing as samples are maintained in the field more than 3 years)
- **Submitted draft standard to IEC.**

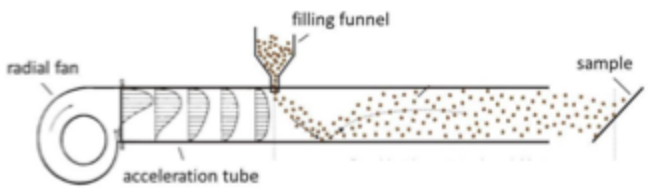
Images of (a) pristine PV module surface, relative to degradation (b)-(d) due to weathering and cleaning. Proc. SPIE, 2010, 7773-02



Indoor Abrasion Test:

Summary and Approach Based on the Literature

- **Relevant existing methods (popular use & literature):**
  - Falling sand test, e.g., ASTM D968 & DIN 52348
  - Forced sand impingement , e.g., MIL-STD-810G or ASTM G76.
  - Machine abrasion (linear or rotary), e.g., BS EN1096-2, ASTM D4060, or ASTM D2486
  - Abrasive media in tumbler or shaker, e.g., DUR-5.2.9 and DUR-5.2.5



Schematic of forced sand impingement test. From Klimm et. al., *Proc. Euro. Weathering Symp*. 2015.

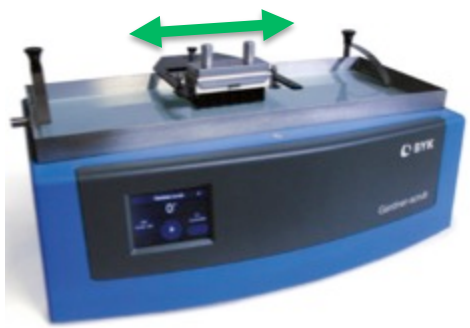
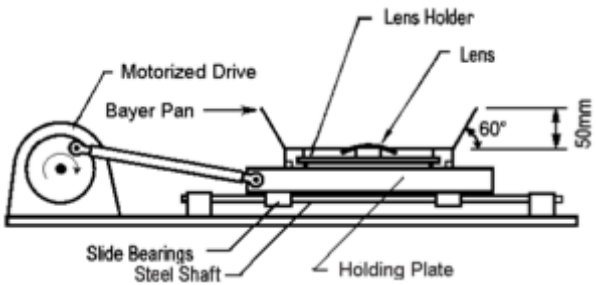


Photo of BYK Abrasion Tester PB-8100. www.byk.com



Schematic of abrasive media "Bayer" shaker from DUR-5.2.5

- **Limitations:**
  - Existing methods (samples & procedure) are not tailored to PV industry
  - Existing methods typically too severe for coated glass, e.g., result in frosted glass.
- **Recommend develop: falling sand, forced sand impingent, linear machine abrasion methods.**

Specimens for Field and Indoor Study

- **Presently acquiring a set of commercial specimens, to be used for the abrasion test standard development and soiling mechanisms study.**
- **3" square coupons in most cases…12" if necessary for manufacturer processing**
- **Field results will be compared to indoor results to validate modes and magnitude of abrasion damage**
- **Field samples will also be examined to quantify accumulated soil facilitating modeling of soiling mechanisms and validating indoor soiling tests.**
- **Also ASU is developing "artificial soiling" techniques that may be the start of a standard**

Table of specimens to be examined in the study.

VENDOR	SUBSTRATE	AR FUNCTIONLIZATION	AS FUNCTIONLIZATION	STATUS
1	PMMA	N/A	N/A	labelled, at NREL
2	glass	graded index	N/A	in fabrication
2	glass	graded index	new	in fabrication
2	glass (reference)	N/A	N/A	at vendor
3	glass (tempered)	N/A	N/A	at NREL
4	glass	1/4l,polymer	hydrophilic in hydrophobic	due Feb 23
5	glass	graded index	hydrophobic	at NREL
5	glass	graded index	olephobic	at NREL
4, 5, 7	glass (reference)	N/A	N/A	at NREL
5	glass	graded index	hydrophillic in hydrophobic	in fabrication
6	glass	1/4l,dielectric	N/A	fabricated
7	glass	graded index	N/A	in fabrication
7	glass	graded index	N/A	in fabrication

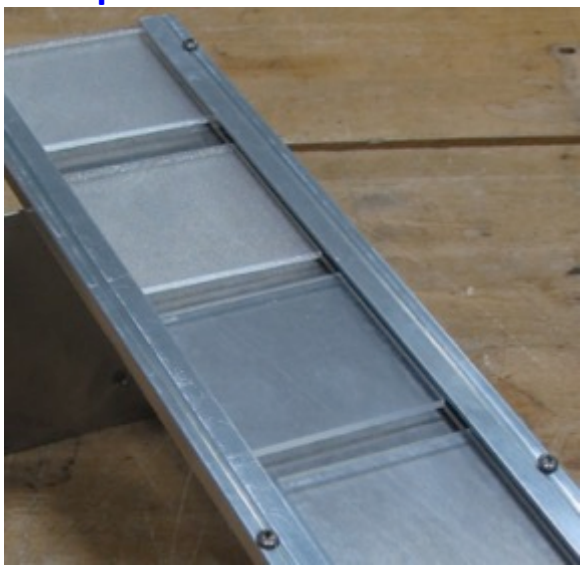
Coupon Deployment

- Sacramento, high soiling agricultural location
- ASU, Tempe Arizona, U.S. dry desert
- Mumbai India, IIT, urban with high soiling rate and monsoon season
- K.A.CARE Northeast Saudi Arabia dry and high frequency sandstorm location
- DEWA in Dubai, both represent desert climate with dew cycles and sandstorms

Easily deployable rack if partner cant provide rack

Coupon identification

Coupon holder



For this task, the deployment sites are being selected based on having very harsh weathering conditions, including high amounts of dust/sandstorms, humidity level, and high temperatures. This should help identify coating abrasion/durability issues quickly to help guide the development of the standards.

Summary

- **Overall, soiling may be impacting PV installations by 4% to 10% or more (LCOE ¢0.3/kWh to ¢1/kWh, respectively) depending on the site from lost energy production, which could be eliminated with an "ideal" solution.**
- **The need to address soiling to remove roadblocks in U.S. PV markets has created intense interest that is best addressed by pooling knowledge from around the world.**
- **Want active collaborations with the PV module community for the different efforts.**

Predict Soiling Rates
- PV performance data, >200 sites
- Data mine important soiling parameters
- Develop robust predictive models
- Validate models

Evaluate Durability with Soiling
- Deploy samples in field
- Analyze field specimens
- Develop accelerated tests
- Correlate results
- Develop IEC standards with international community

Characterize Soiling Mechanisms
- Deploy specimens at sites
- Collect representative samples
- Characterize soiling materials
- Isolate individual mechanisms
- Characterize surfaces
- Identify complex mechanisms

Outcomes

Reduce Performance Uncertainty
- Predict seasonal, annual and 30 year soiling loss rates for new sites
- Help establish cleaning schedules and O&M costs

Module Coating Standards
- Accelerated tests for validating durability and performance of PV coatings in different soiling conditions

Coating Deployment Guidelines
- Critical requirements for coating performance in different environments
- Help establish cleaning schedules
- Enables techno-economic analysis

Lower LCOE

- Financial institutions reduce rates for borrowing
- Integrators reduce cleaning costs
- Coatings companies have standards to meet
- Companies can focus on developing coatings with the right properties for the environments that make economic sense

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  - Milica Mrcarica: DSM
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  - Alan Sellinger: CSM
- **DOE**
  - Inna Kozinsky
  - Geoffrey Kinsey
  - Rebecca Jones-Albertus

Soiling Session Summary

1. **Comparison of indoor and outdoor soiling data - Dr. Karl-Anders Weiss**
    a. **Correlations based on spectral transmittance**
    b. **Huge differences between dust on the ground and dust found on modules need to be understood to ensure relevant soil**
    c. **Possible to develop standard method for indoor soiling - challenge will be to be relevant to different soils at different locations across the world**
2. **3 year soiling study Brenor Brophy - interim look**
    a. **14 Southwest US locations being used to study soiling with and without hydrophobic coatings**
    b. **Coating improved soiling performance**
    c. **Hydrocarbon pollution at one location decreased effectiveness of coating**
    d. **Attention to details matter - manual cleaning not recommended for studies - select sites with known soiling issues (if testing materials)**
3. **NREL project - Dr. Lin Simpson**
    a. **Predictions of soiling losses at a specific site**
    b. **Develop mechanistic understanding of soiling and prioritize - coupons being sent to various locations around the world**
    c. **Standards development for soiling**

Audience discussions

Need for standardization of soil testing
Need for standardization of module soiling performance capability
Need for root cause understanding
Need to transition from short term to long term thinking and measurements of soiling
Separation / understanding of various soiling effects: loose soil blocking light, cemented soil due from moisture assist, abrasion, durability of module surface itself
Challenges of different soils
How to quickly and cost effectively predict soiling effects for a particular site
Proposal for a soiling map

Surface Soiling and Related Reliability Studies in Brasil: Program and Progress

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PVReliability.org
Confiabilidade de Sistemas Fotovoltaicos

Activities and Objectives

This collaborative research program has been commissioned through the government of Brasil (through the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—CAPES, under *Pesquisador Visitante Especial* and *Ciência sem Fronteiras* programs). The **mission** is to enhance ongoing research in solar-technology reliability, linking worldwide efforts with those important for the now-growing solar investments in the Brasil markets. The **objectives** encompass three interrelated areas important to module *surface* reliability and performance—at the very *first* point of interaction for the incoming solar photons:

- **Soiling Science and Technology**—*Creating and validating protocols and procedures, establishing joint test fields in representative climate zones, developing and deploying dust-monitoring stations in key locations where PV installations exist or are planned, collecting samples and monitoring dust-performance relationships, comprehensive dust/soiling chemical and physical analysis, fundamental adhesive-property characterization (from the microscale), and developing a framework for dust testing standards based on Brasil's specific climate (humidity, temperature, precipitation) conditions.*
- **Coatings and Films for Performance Enhancement**—*Developing, testing, and validating nano- and micro-technology-based antireflection and dust mitigation coatings, including novel dual-purpose designs.*
- **Next-Generation Materials Science**—*Materials by Design. Design and realization of next-generation mitigation and dual-use coatings by revolutionary materials science and discovery.*

Climate Zones, Monitoring Sites, and Partners

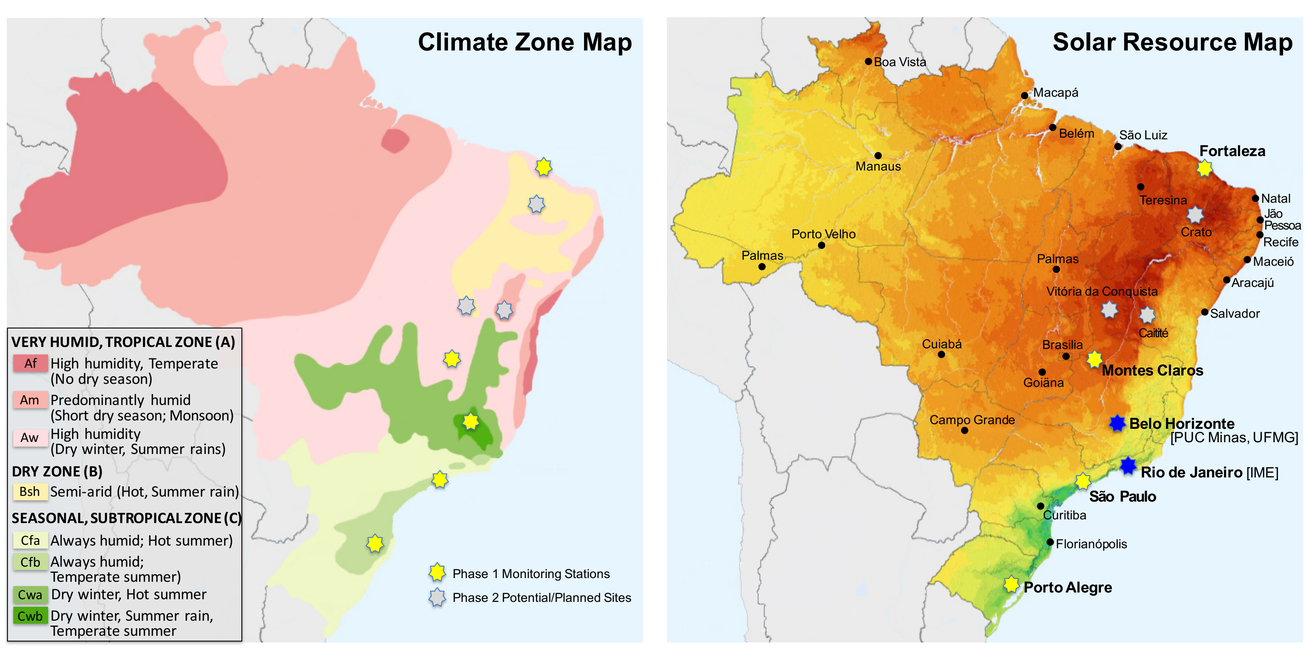
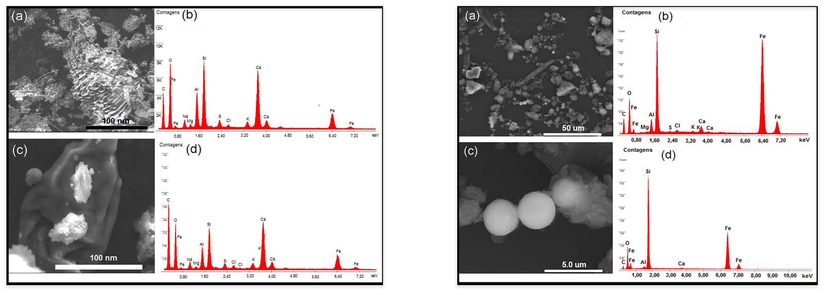


Figure 1. *Left:* Climate zones, based on Köppen-Geiger [Meteorologische Zeitschrift, **15**, 259–263 (2006)], showing chosen first-phase dust-monitoring locations and additional potential monitoring sites (based on climate-zone coverage and priority PV-installation locations.
Right: Collaborating partners (blue suns) and confirmed monitoring sites (blue and yellow suns) shown on solar resource map of Brasil. Other Brasil cities are included for reference.

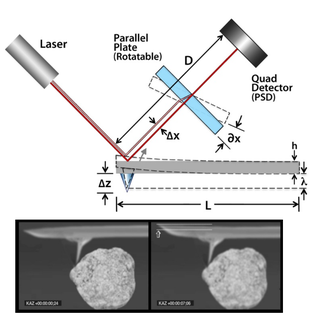
Soiling Investigations: Adhesion, Chemical, and Physical Analyses

The **chemistry and physical characteristics**[a] of dust differ from geographical region to geographical region throughout the world—even at sites within kilometers distance of each other. Typically, the dust found on modules from the Gulf desert regions have 80%–90% quartz and primary silicate minerals, with the remainder being minerals, organics, and area-specific compounds. The samples from rural areas of Brasil have 15% or less quartz and primary silicates, with the majority of the components from secondary silicates, agricultural products, and area-specific minerals. Soluble minerals/organics and components from the fuels (e.g., diesel in samples collected near highways) and soluble minerals/ organics can sometimes be detected, factors that can have significant implications for both adhesion and cleaning.

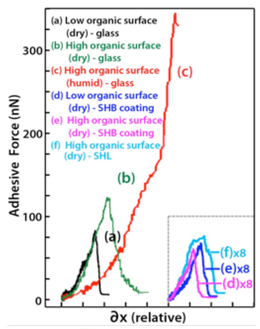


- Module surface dust particles typically reflect the composition of the local environment, such as the **Fe** in the red soils in the EDS spectra of the samples above. The spheres in the data on the right are primarily Fe_xO_y.
- Fertilizers, fibers, and animal hairs are often observed in samples collected from **agricultural** areas (left).
- In the tropical and subtropical regions, various **bioorganisms**, bacteria, molds, & biofilms are routinely present.

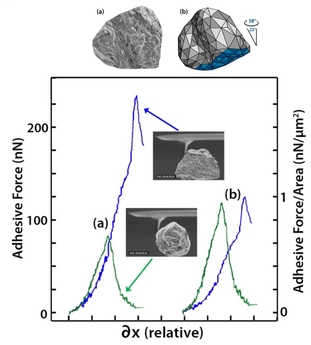
The **adhesion**[a] of dust particles to a module surface depends on many factors, including the condition of the glass surface, the chemistry and morphology of the particle surface, charge, and environmental conditions. We have developed an AFM technique to study the adhesion of individual particles to the module glass surface that allows the correlation to the various particle characteristics.



Technique: The deflection of the laser beam from the top of the AFM cantilever measures the bending of the cantilever, which can be translated directly into the lateral force holding the particle to the surface.



Adhesive Force: Measurement characteristics of various particles with differing surface chemistries to glass (a–c) and superhydrophobic and superhydrophilic surfaces (d–f).



Adhesive Force/Unit Contact Area: Determination of the adhesive force (a) with the more representative adhesion, (b) force/unit area. The con-tact area is estimated from a 3D image-processing technique for the particle shown above the characteristics.

[a] IEEE J. PV – accepted (2016) DOI:10.1109/JPHOTOV.2016.2528409

Materials and Coatings Research

Two research areas are just underway in this project—dealing with the testing, validation, and development of anti-soiling coatings and layers for PV modules deployed in the various Brasil climate zones. This includes incorporating these coatings into the ongoing monitoring program, developing dust mitigation with antireflection requirements, and application of new science approaches leading to improved and perhaps yet-to-be-discovered materials.

Dust Mitigating Coatings: Commercially available (super)hydrophobic hybrid inorganic/organic films, as well as functionalized nanoparticles of SiO_2, ZnO, SnO_x, and ITO, are under investigation for dust-mitigation properties and durability. This work is just underway. The functionalized nanoparticles, using both electrodeposition and solution growth in organic matrices, also have dual-use potential for antireflection coating for the glass as well as the dust-mitigation application.

Design of Materials: The optimization of current dust-mitigating coatings and the discovery of new and better materials for these applications can be explored using recently introduced materials-by-design methodologies. Starting with the current range of hybrid oxides and identifying the target functionalities (e.g., fundamental hydrophobic parameters, durability, optical constraints), modern inverse-design approaches are starting to be explored and evaluated for their potential applications for leading to superior coatings.

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This poster contains no proprietary information.

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CAPES

KleanBoost: Anti-Reflective & Anti-Soiling Glass Coatings

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Introduction

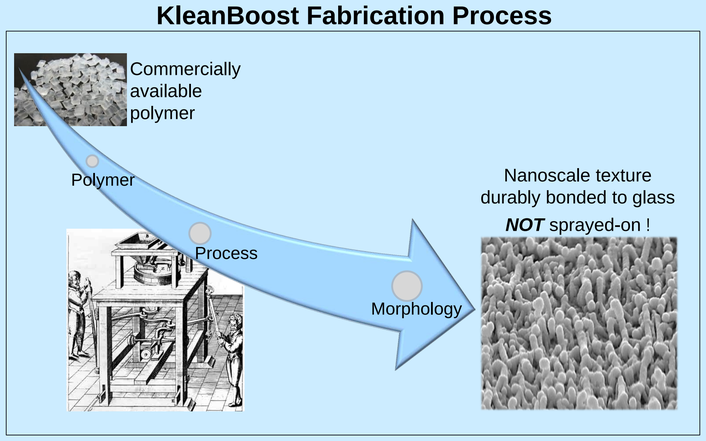
The electrical output of photovoltaic (PV) panels is limited because reflections at the air-glass interface and scattering and/or absorption by dirt on the exterior surface prevent a portion of the incident light from reaching the active semiconductor. As semiconductor material efficiency increases, the impact of losses due to reflections and soiling on the overall solar harvest becomes more significant. To reduce losses, anti-reflection (AR) coatings are used on the exterior glass of the highest efficiency PV panels. However, soiling remains a challenge, especially as large PV arrays are deployed in arid, dusty climates.

To address these challenges, we developed KleanBoost, a high-performance polymeric coating on glass that imparts both anti-reflective and anti-soiling properties. Nano-scale surface features with hierarchical roughness are formed in the inherently photo-stable polymer during the coating process. This texture creates a graded index of refraction on the surface that reduces reflections at wavelengths >350 nm. This same nano-scale texture also imparts superhydrophobicity, which provides the surface with anti- soiling properties. The process is scalable and suited to in- line processing.

In this poster we describe the properties of KleanBoost coatings on glass coupons. Optical properties (% transmission and reflection) are reported from 300 to 900 nm and surface wettability is characterized by contact angle and sliding angle measurements. Durability of the coated glass under simulated rain erosion testing and chemical cleaning agent exposure will be discussed. A system for dispensing and recycling water droplets to remove deposited dust for on-demand cleaning will also be described. The results indicate that the AR- SH coated glass increases transmission by ~3 % across the visible while exhibiting excellent anti-soiling properties under harsh conditions.

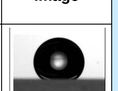
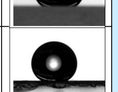
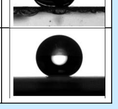
Technology

KleanBoost Fabrication Process



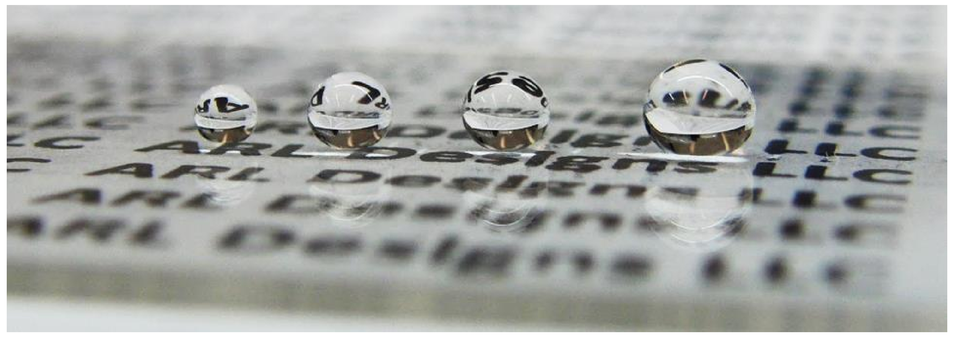
Anti-reflective and anti-soiling properties are achieved in one continuous process by applying a thin layer of an inherently photo-stable, commercially available polymer to bare glass and adjusting the morphology to create a coating with nano-scale features. Controlling the size and density of the features produces a graded refractive index AR coating with a maximum dimension of ~100 nm. Hence the films remain optically transparent throughout the visible.

Effect of Fabrication Process on Wetting

Roughness	Contact Angle	Sliding Angle	Image
Smooth	150º	20º	
Medium	160º	5º	
High	165º	1º	

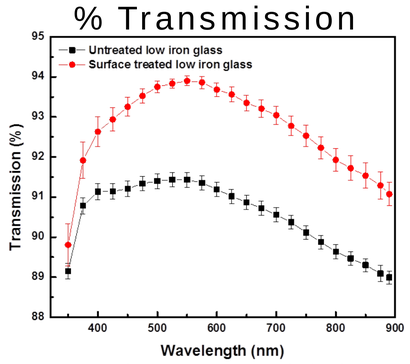
The nano-scale features also create a superhydrophobic surface. As a result water does not adhere to the exterior of the glass. Process parameters control the degree of roughness, and thus the contact angle of water placed on the surface.

Optical Properties



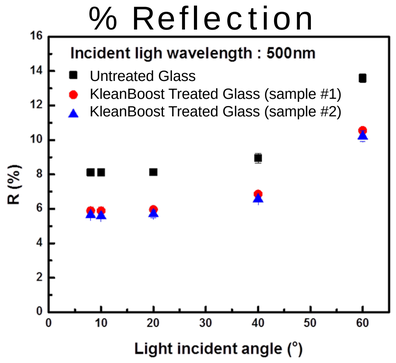
Water droplets on KleanBoost treated low-iron glass

% Transmission



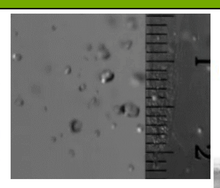
KleanBoost increases %Transmission by ~3%

% Reflection



KleanBoost reduces reflections at all incident angles

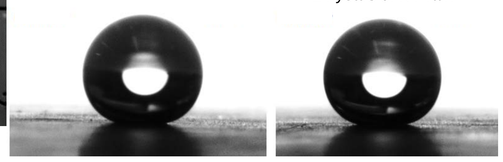
Rain Erosion



Rain Erosion Test:

- o UL-50 nozzle generates water droplets that impinge on sample surface
- o Droplets:
  - 1.5 mm diameter, 3.0 m/sec, 120 mm/minute
- o Accumulation: 120 mm/min;
- o 10 minutes ≈ 1 year of NYC rainfall (1,300 mm/yr)

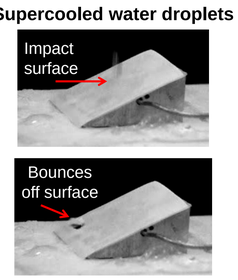
Before | **After Rain Test** ~24 years of NY rain



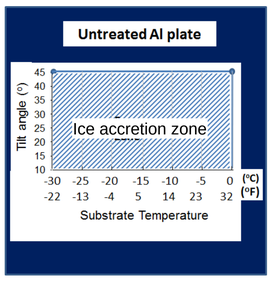
Results: KleanBoost retained anti-wetting properties after ~ 24 years of NY rainfall

Anti-Icing

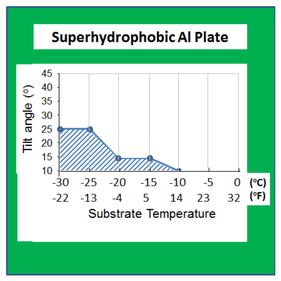
Supercooled water droplets



Supercooled water droplets bounce off KleanBoost treated aluminum surfaces cooled to < 10ºC



Ice accretes at all temperatures <0ºC regardless of tilt angle



Supercooled water droplets do not adhere to KleanBoost treated aluminum at conditions encountered in nature.

Chemical Stability

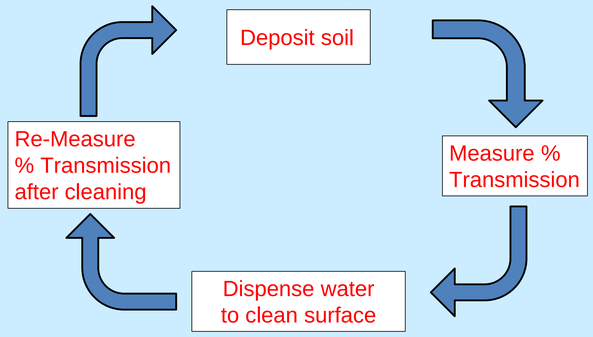
Purpose: Determine susceptibility of KleanBoost to oxidation and insure coating fully covers the surface.

Method: Expose coated glass surface to 5% alkali (NaOH) solution for 9 hours.

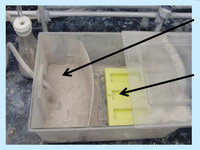
Results: KleanBoost remained superhydrophobic and transparent after the test. No signs of surface oxidation, delamination or glass etching.

Anti-Soiling Properties

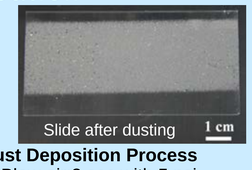
Anti-Soiling Test



Dust Application



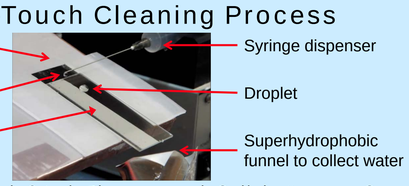
Dust : Standard Arizona Road dust ISO 12103-1, A2 Fine



Dust Deposition Process

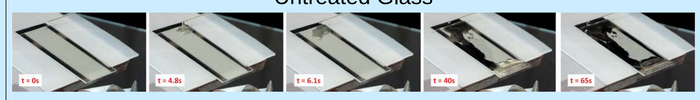
- Blow air:3 sec with 5 psi
- Wait 2 min for dust to settle on glass
- Dust weight: 5-18mg (per slide)

No-Touch Cleaning Process



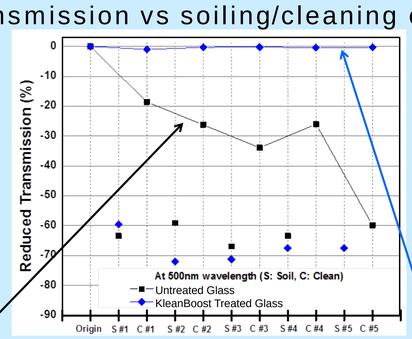
Water used : 6.4 ml , Dispense speed : 3ml/min, # passes: 2

Untreated Glass



KleanBoost Treated Glass

%Transmission vs soiling/cleaning cycles



Untreated Glass

- Becomes progressively coated with dust after each cycle.
- Requires abrasive scrubbing to remove dust

KleanBoost

- Retains >99% transparency after five cycles of soiling/cleaning.
- No-Touch cleaning is highly effective at removing dirt from treated surface

Conclusion

- Anti-reflective, optically transparent coating for glass
- Anti-Soiling
  - dust can easily be removed ***and*** water can be fully recovered
- Anti-Icing
- Durable - No degradation from rain or corrosives
- Low cost

DSM AR coating Performance on PV Glass, Modules and System with Long Term Outdoor Exposure in Different Climates

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Corresponding author: Milica Mrcarica[1] Phone: +31 619287035: Email: Milica.mrcarica@dsm.com

Introduction

Anti-reflective coated (ARC) solar glass has become a state of the art product in photovoltaic industry. DSM has developed and commercialised a high performing core shell sol-gel based anti-reflective coating (ARC) for PV glass. Unlike traditional ARC glass, DSM's coating has low surface roughness and closed surface structure, and demonstrates >2.9% transmittance and Isc gain, and >2.5 Impp and Pmpp gain in coated vs. uncoated patterned glass modules under indoor standard test conditions (STC). However photovoltaic modules and systems manufacturers and installers are interested in the materials' performance and reliability under outdoor conditions and material suitability for different climates [1] [2].

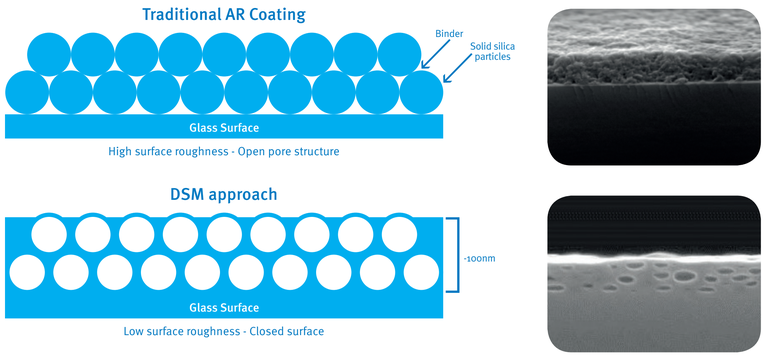

Fig 1. DSM Single layer sol-gel AR-coatings vs. Traditional versus Core-shell approach

In this study, we investigate the impact of long term (7-18 months) outdoor exposure of PV glass, modules and the grid connected system on the performance of DSM AR coating, and the influence of soiling and cleaning in different climate conditions.

Instruments with the highest accuracy available on the market were used to ensure a reliable and relevant measurement of: transmittance for PV glass, IV tracer generated Isc as an optical measure for modules, and Impp at grid connected string level as a power generation measure at PV system level.

The impact of soiling and module cleaning on daily power generation was explained and quantified.

Approach and results

DSM ARC glass performance

DSM AR coating glass samples were aged outdoors for one year in: Negev, Israel: hot desert climate, arid; Gran Canaria, Spain: hot desert climate, maritime and Freiburg, Germany: continental climate, in collaboration with Fraunhofer ISE.

A comparison was done between cleaned and un-cleaned samples, and with unexposed reference from the lab for both DSM coated and uncoated glass. In all cases no degradation of coating or glass was visible or measured. Uncoated glass and DSM ARC glass have a similar performance.

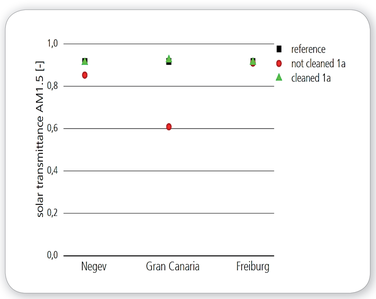

Fig 2. Uncoated glass

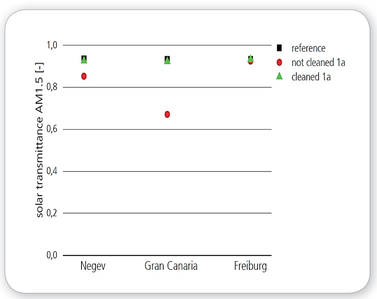

Fig 3. DSM ARC glass

Fig 4. Typical test glass positioning

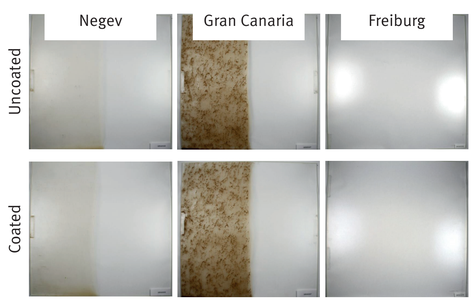

Fig 5. Coated and uncoated glass appearance before and after cleaning

DSM ARC glass PV module performance

In collaboration with Fraunhofer ISE, single modules are being tested in Geleen (NL), on a new DSM off-grid rooftop PV test site. c-Si modules with DSM ARC, and c-Si modules without ARC from the same manufacturing batch have been monitored and compared for over 7 months.

Fig. 6 DSM test site in Geleen, Netherlands

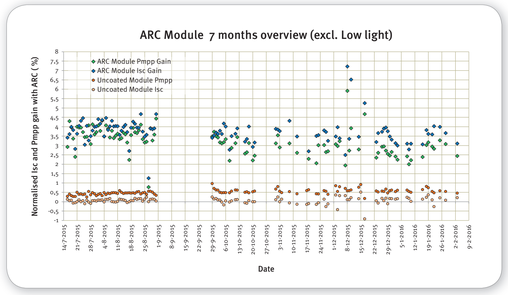

Fig 7. Single panel comparison in Geleen (NL) - Isc gain

Overall, Pmax and Isc over a period of 3 months show a benefit from the DSM ARC from 3.5% to 5% on sunny days and below 3% on cloudy days. The effect of the ARC on days with similar irradiance shows consistency over a period longer than 7 months .

The test location is a low soiling environment; except regular bird droppings. No cleaning process was used in this test; rain appears to be sufficient for cleaning the modules (including bird droppings).

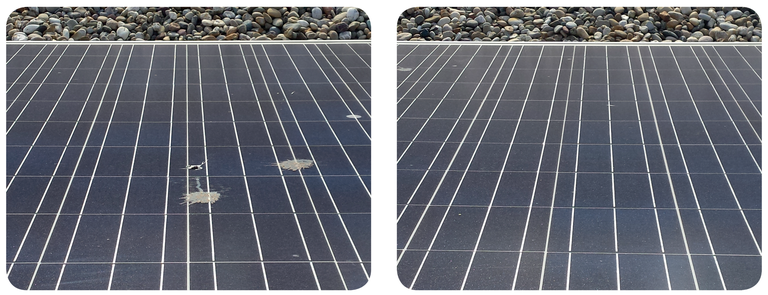

Fig. 8 After rain, most of bird drops are cleaned

DSM ARC glass large PV system performance

DSM installed a grid connected 1 MW plant in Pune – India in July 2014. Besides power generation the site has been designed as a testing and demonstrational location for DSM PV materials . The plant consists of mc-Si modules from the same manufacturing batch with and without DSM ARC glass.

Fig. 9 DSM 1 MW grid connected technology demonstration site in Pune

A highly accurate string monitoring system from Meteocontrol (i-Catcher) has been installed for Impp and Vmpp measurement, capable to differentiate reliably the DSM ARC technology performance vs uncoated glass, quantify soiling and cleaning effect.

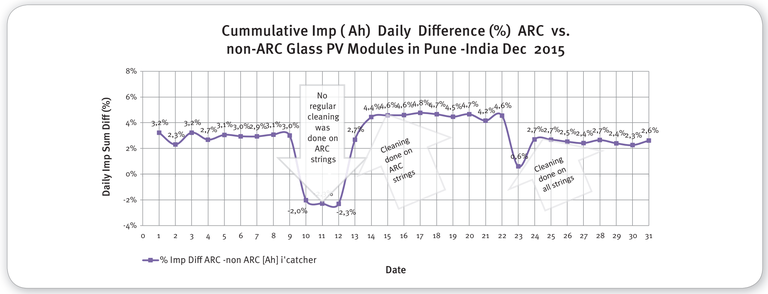

Fig. 10 Monthly Impp gain, soiling and cleaning

DSM ARC shows steady performance of 2.5-4.5% Impp gain after 18 months of outdoor exposure in this high soiling, seasonally humid /dry and hot climate . This soiling level causes higher than 5% Impp loss in two weeks (between cleaning). There is no degradation of the coating due to the regular cleaning. DSM ARC and uncoated module glass show similar dependence on soiling and cleaning.

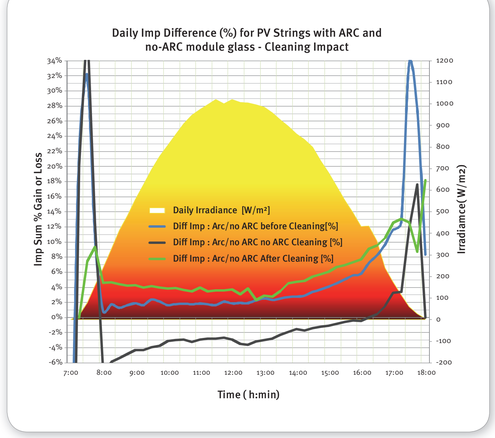

Fig. 11 Daily Impp gain, impacted by soling and cleaning

AR coated strings vs uncoated strings daily Impp gain distribution depends on cleaning and soiling levels. The gain is systematically highest in the mornings and in the evenings (>20%). Different soiling levels on coated and uncoated strings do not change the general response pattern, but shifts the highest irradiation response up or down.

Conclusions and Outlook

- DSM ARC demonstrated a long term outdoor performance and reliability under extreme climate conditions. Module and system optical and power outdoor average daily performance gain is 2.5-5%.
- In the climate and locations with a low soiling level, self -cleaning of modules is sufficient to keep consistent gain from ARC glass modules compared to uncoated glass modules.
- In the climate and locations with a high soiling level, gain depends strongly on cleaning sequence and frequency. DSM ARC has systematically better responses in the afternoon hours and highest under very high light incident angles.
- There is ongoing analysis in DSM on the influence of soiling on DSM coated and uncoated glass modules, as well as the impact, mechanism and cleaning of permanent fouling observed in a hot and humid climate on both coated and uncoated glass.
- DSM has been working on an anti-soiling coating.

References

[1] Gabriela Bunea, Grace Havier, Doug Rose, Lauren Nelson, Jack Peurach: "Performance and Reliability of Modules with Anti-Reflective Coated Glass", Sun Power White Paper. 2010
[2] X. Pan, S. Zhang, J. Xu, Z. Feng, P.J. Verlinden, "Performance of Different Anti-Reflective Coated Glass for PV Modules", EUPVSEC, 2015.

A Simple System to monitor PV performance degradation due to soiling

Ajay Singh and Matthew Perry
Campbell Scientific Inc. Logan, UT USA asingh@campbellsci.com

ABSTRACT

Loss of power produced by a solar panel due to reduced effective irradiance caused by dust accumulation on its surface is a growing concern in the industry. A need to measure and quantify this loss has been increasingly felt. Such a system would improve modelling of performance of PV installations. These systems would also help optimize washing schedules. In this paper a compact system is proposed to monitor the soiling performance loss based on the measurement of short circuit current of two solar panels. One is maintained clean and used as a reference the other is allowed to accumulate dust naturally from the surrounding environment. The details of data collection, filtering and data reduction to estimate a soiling loss index will be presented in the paper.

Introduction

- Exposed to the elements solar panels accumulates dust on them (soiled).
- Amount of radiation reaching the cells decrease
- Power generated by panel decreases.
- Natural events like rain, wind, snow melt etc. clean the panel and panel performance goes back to the normal levels.
- Soiling is affected by Irradiance, rainfall, temperature, wind speed and other climate conditions of a location.
- Also affected by size and composition of dust, frame and cover orientation and properties.
- Fairly complex phenomenon
- Issue is how to define a metric and measure it so that well informed decisions can be made regarding cleaning the panels.
- Simple, easy to setup system and reliability of measurement.

Experimental Procedure and Methodology

- Monitor two solar panels/one solar panel and another reference cell, side by side
  - on the same site
  - Under similar weather and climatic conditions
- Maintaining one clean for reference
- Monitor Isc, Voc, and back of module temperatures
- Calculate effective irradiance received by each solar panel
  - Apply Temperature correction

Calculate effective irradiance received by each panel

$$G_{effTest} = \frac{I_{SC,meas}}{I_{SC,STC}[1+\alpha(T_{mod}-25°\mathrm{C})]} \times 1000\ W/m^2$$

$$G_{effRef} = \frac{I_{SC,meas}}{I_{SC,STC}[1+\alpha(T_{mod}-25°\mathrm{C})]} \times 1000\ W/m^2$$

Define Soiling Loss Index as

$$SLI = \left[1 - \frac{G_{effTest}}{G_{effRef}}\right] \times 100\%$$

System Specifications

- Maximum Voltage 60V
- Maximum Current 20 A
- V_{oc} and I_{sc} Measurements
- Counter for cleaning events
- Manual cleaning of reference panels
- 24 bit ADC measurement accuracy ~ 2µV
- Data communication via RS232 or USB
- Very low power consumption
- Field deployable
- Operating temperature -40° to +70° C
- Soiling loss index ~1% can be detected

Data Reduction

- Measurement during ±60 min of Local Solar Noon
- Measurement Interval of 30 sec
- Incident irradiance ≥ 600 Watts
- Stability criteria for solar irradiance
- 10 min averages
- Daily averages

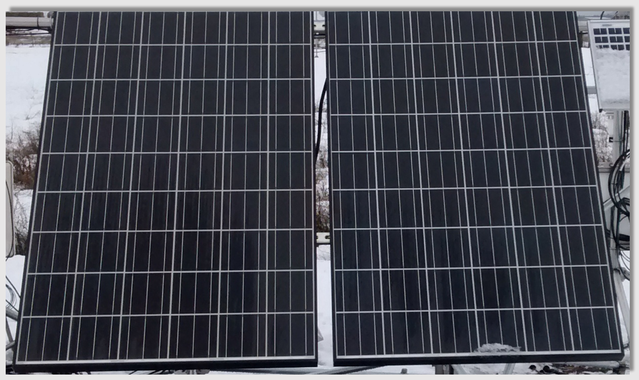

Figure 1: Clean Reference and Test panels

Figure 2: Clean Reference and soiled Test panel

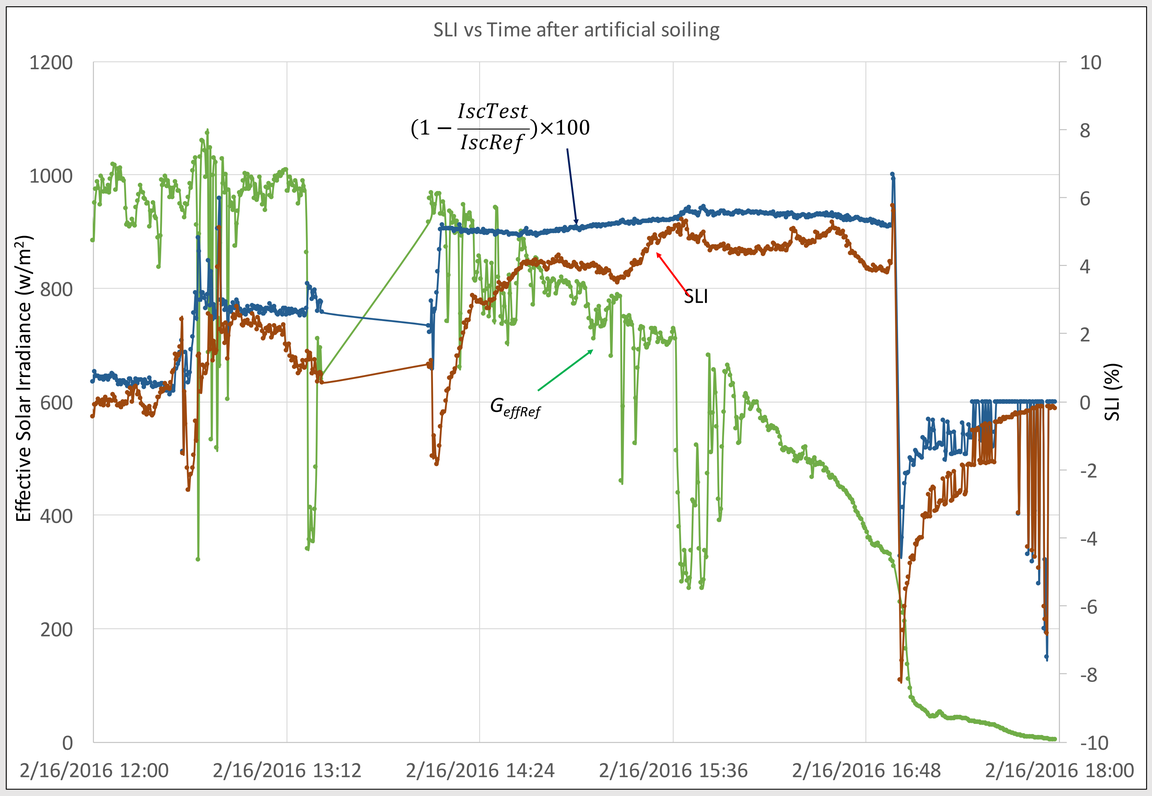

Figure 3: Effective irradiance from the reference panel, SLI and SLI calculated without temperature correction on the currents.

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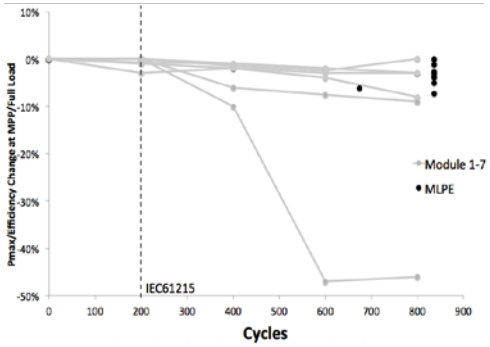

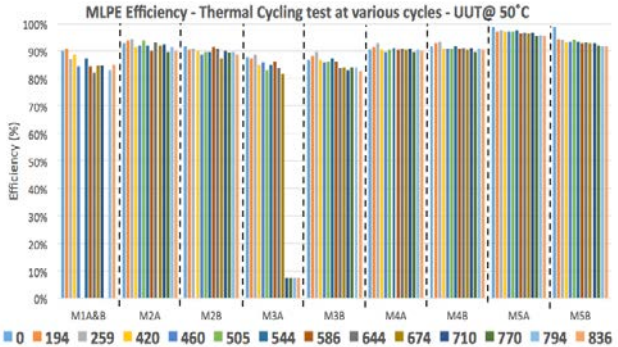

Accelerated Reliability Evaluation of Module Power Electronics

Jack Flicker[1], Govindasamy Tamizhmani[23]

[1]Sandia National Laboratories

[2]Arizona State University

[3]TUV, PTL

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Accelerated Reliability Evaluation of Module Level Power Electronics (MLPE)

Part 1: Test Results

Presented by Jack on Wednesday

Accelerated Reliability Evaluation of Module Level Power Electronics (MLPE)

Part 2: Standardized Protocols

Presented by Mani on Thursday

Jack Flicker[1], Govindasamy Tamizhmani[2]

[1]Sandia National Laboratories

[2]Arizona State University

PREDICTs Project- EERE SunShot

- Very little published work on MLPE Reliability
- Most work predictive design or calculation based
  - MIL-HDBK-217 or Telecordia style calculation based on individual component FIT
  - Determine MTBF for fielded units
- Little published experimental data on MLPE lifetime

Goals:

1. Recommend standard accelerated life test (ALT) protocols for lifetime determination
2. Perform ALTs to determine MLPE failure rates/lifetimes, mechanisms, and environmental stressors

October 2013-December 2014

1. Identify MLPE failure modes and unit lifetimes
2. Determine environmental stressors which cause failure modes
3. Develop a suite of ALTs which reproduce/exacerbate failure modes

April 2015- March 2016

1. Conduct ALTs
2. Verify that ALTs can be correlated to failure mechanisms
3. Draft and submit reliability standard protocol to standards development organization (SDO)

PREDICTs Project Goals

Reliability test, not qualification

- Need both (currently neither exists for the inverter industry)
- Qualification
  - Minimum bar to enter marketplace
  - Meant to weed out inferior products
  - **Not necessarily** correlated to failure mechanisms
  - Pass/Fail criteria
- Reliability
  - Meant to determine **end-of-life**
  - Related to specific failure mechanisms or environmental stressors
  - Test to failure (degradation or catastrophic)

Intrinsic Failure Mechanisms

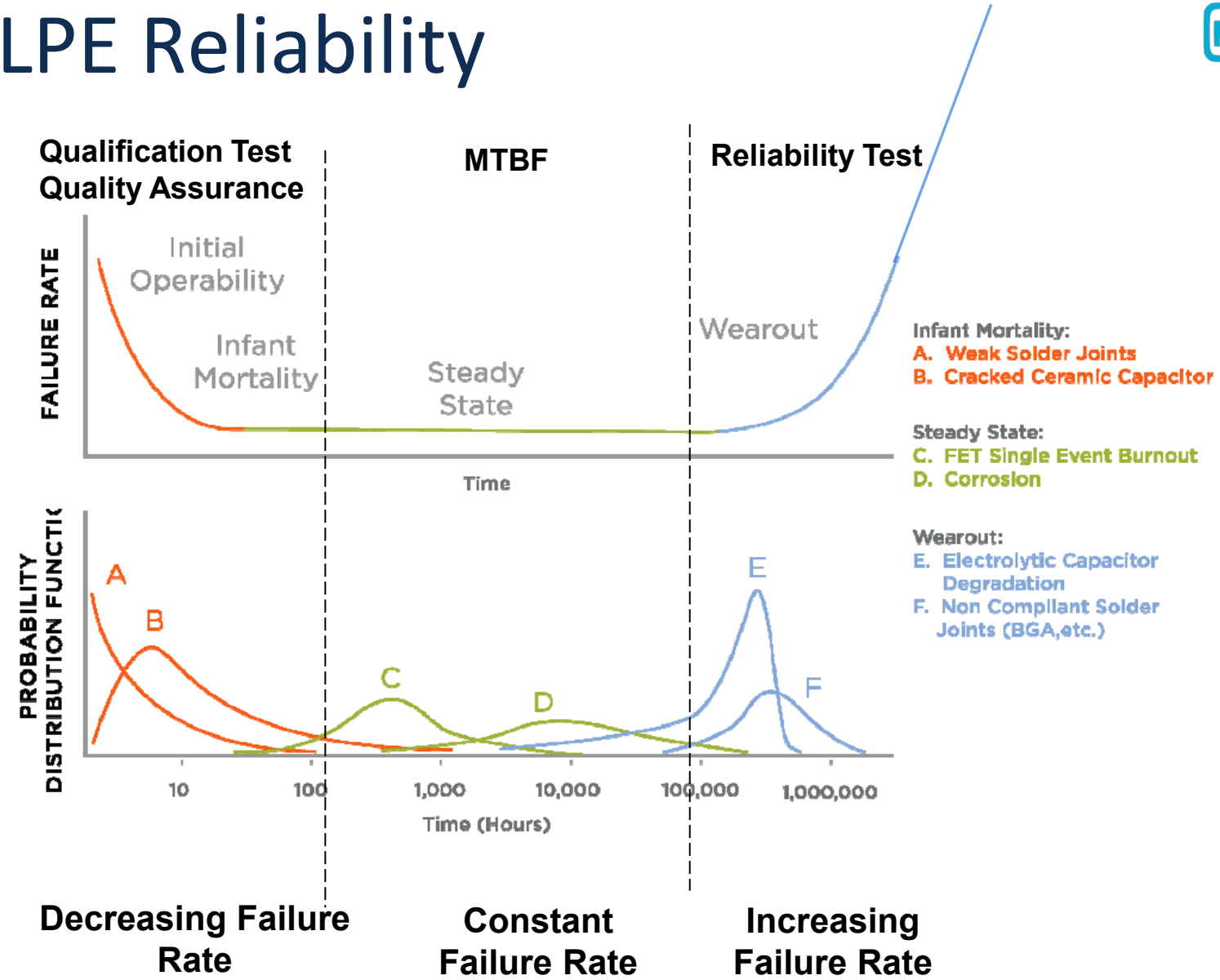
- Wear-out failure
- Not intended to identify
  - Design (*e.g.* IEC61215) or manufacturing (*e.g.* IPC9592) issues
  - **Very** important and need to be handled

Vendor- and technology-**neutral** system-level testing

- Same testing protocols applied to all manufacturers and technologies
- Limits bottom-up (from failure mechanism) approach to testing

*More details on standards open questions/trade-offs in Mani's presentation

MLPE Reliability



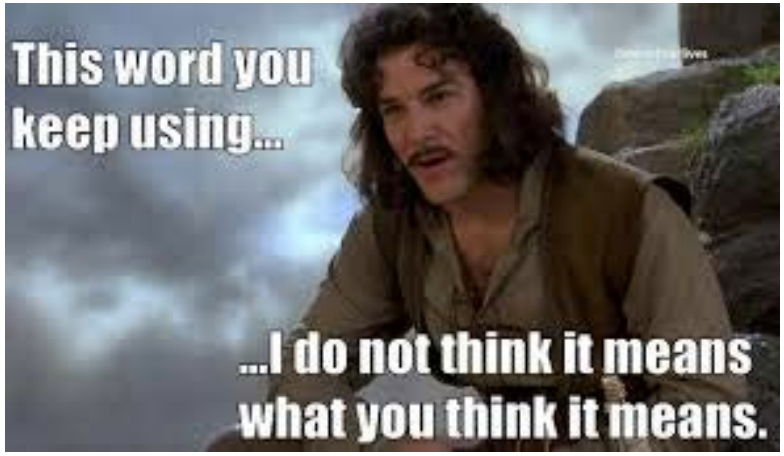
MTBF vs. lifetime

- Mean Time Between Failure (MTBF)
  - Typically only reliability information included in MLPE usage information
  - **Calculated** via MIL-HDBK-217F, Telcordia SR332, etc. based on activation energies or failure rate (FIT)
  - Statistical (only applies to large aggregate populations)
  - Only applicable to "random failure" portion of useful life (*i.e.* "floor" of the bathtub curve
    - Assumes constant failure rate
      - → **Does not** consider extrinsic failure (*i.e.* manufacturer variation)
      - → **Does not** consider wear-out failure

Experimental MTBF is useful for large scale O&M
Calculated MTBF is useful for identifying design weaknesses

But neither has information regarding ***lifetime***

Use with care!



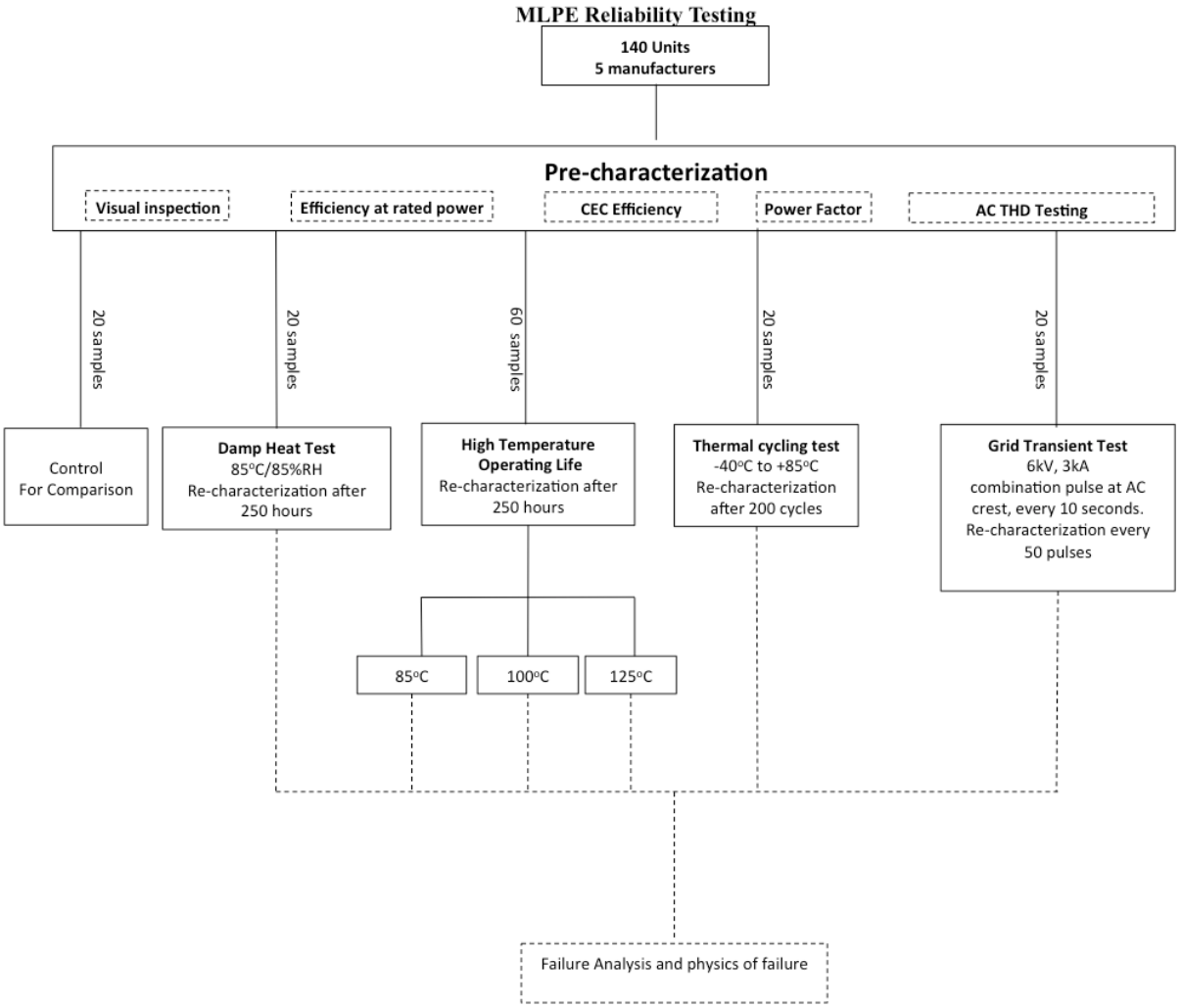
MLPE Reliability Test Protocol

FMEA and anonymous survey of manufacturers (PVSC2015)

- Used to identify most at risk components
- Relevant failure mechanisms
- Environmental stressors

Test	Failure Mode/Mechanism	Stressor	Control Parameters	Critical Measurements	Outcome
Thermal Cycling	solder joint cracking, AC/DC cabling, potting delamination, and power semiconductor packaging delamination	ΔT	High T (85°±2°C), Low T (-40±2°C) , Ramp Rate (100°C/hr), Dwell Time (10 min)	AC and DC Current/Voltage, Communications, Power Quality	Time to Failure, deviation among multiple technologies
Damp Heat	Circuit board corrosion, dendrite formation	Temperature/ RH	Temperature (85°±2°C), RH (85±5%)	AC and DC Current/Voltage, Communications, Power Quality	Time to Failure, deviation among multiple technologies
High Temperature Operating Life	MOSFETs, capacitors, and other power handling and control componentry wearout	Time at Temperature	Temperature (85, 100, 125±2°C)	AC and DC Current/Voltage, Communications, Power Quality	Acceleration Factor and estimated lifetime for multiple technologies
Grid Transient Testing	Overvoltage/current robustness of MOSFETs, capacitors, and safety protection devices	Overvoltage/ Overcurrent	Max Voltage (6 kV), Max Current (3 kA), pulse time (50 and 20 μs)	AC and DC Current/Voltage, Communications, Component current/voltage, Power Quality	Time to Failure, deviation among multiple technologies

MLPE Reliability Test Protocol



Four testing tracks:

- Thermal Cycling (-40 to 85°C)
- Damp Heat (85°C/85% RH)
- High T Operating Life (85, 100, 125°C)
- Grid Transient Testing

5 manufacturers tested

- 2 powered, 2 unpowered units/test
- 140 total units

- Periodic re-characterization of efficiency

- Instantaneous current/voltage

MLPE Reliability Test Results

- All outputs from powered units connected to data logger to record data continuously (1 min data)

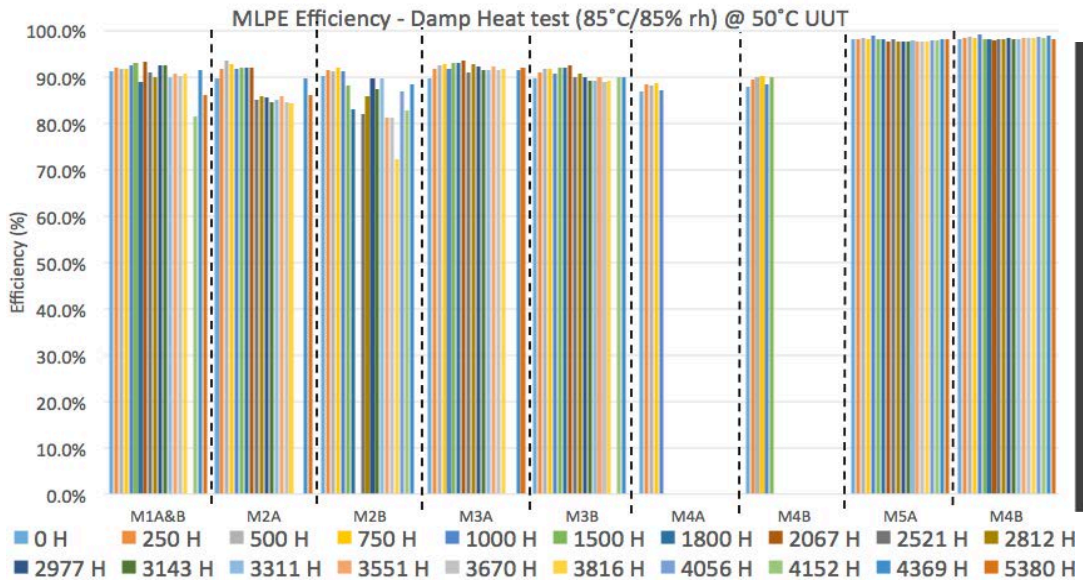
- In situ functionalities and complete efficiencies of all samples measured
    - Characterized periodically depending on test (~250 hrs)
    - Balance between test speed, cost, and data

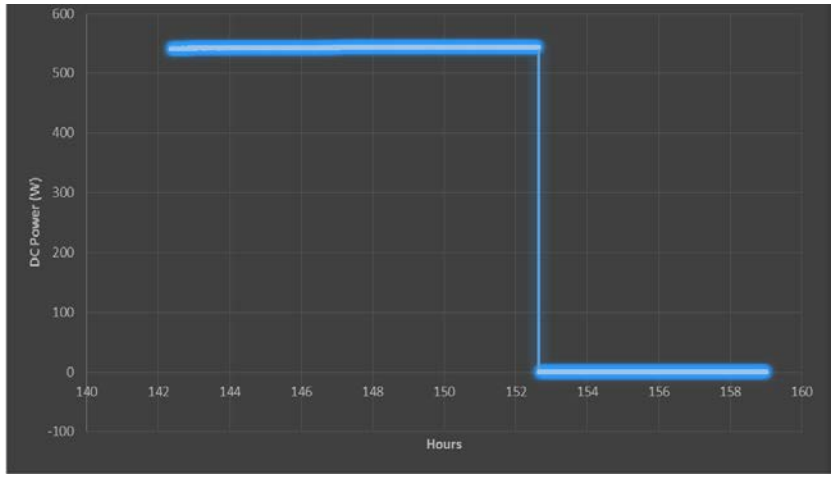
- Visual characterization **was not** used as failure
    - Some units showed signs of corrosion in screws and connectors

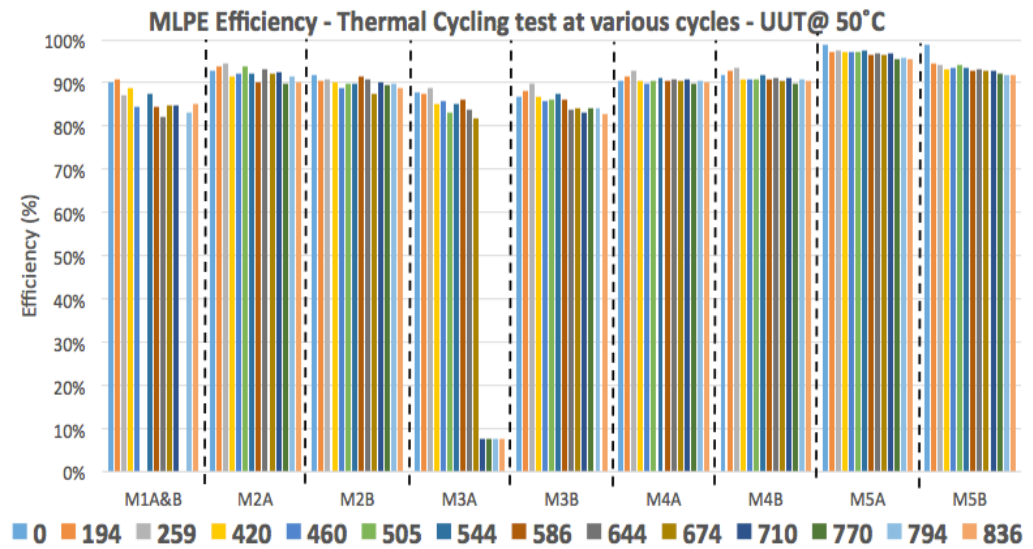
    - Some AC/DC connectors found to become brittle after DH exposure
        → Multiple connectors broken while unpowered units were tested for failure
        → Especially apparent in unpowered units as connected/disconnected repeatedly from the characterization equipment
        → AC side connector damage is especially troubling due to the safety risk from electric shocks as the wires become exposed over time

- Damage to the AC connectors in one unit caused short as AC connector melted
    →Did not permanently damage the unit
    →Unit was functional when the connector replaced

MLPE Reliability Test Results







- No degradation prior to failure
- Long-term after usage
  - Fluctuations in power and efficiency
  - Measurement error of few %
  - Does show some efficiency degradation
  - No consistent

MLPE Reliability Test Results

Device	Thermal Cycling	Damp Heat	Static T (85oC)	Static T (100oC)	Static T (125oC)	Grid Transient
M1A	> 835 cycles	>5380	>1193	>3491	1870	
M1B	> 835 cycles	>5380	>1193	>3491	2135	
M2A	> 835 cycles	>5380	>1193	>3491	3166	400 pulses
M2B	> 835 cycles	4369	>1193	>3491	2638	600 pulses
M3A	710 cycles	1240	>1193	>528	>528	
M3B	> 835 cycles	1550	>1193	>528	>528	
M4A	> 835 cycles	>5380	>1193	1435	1870	300 pulses
M4B	> 835 cycles	4369	>1193	>3491	791	400 pulses
M5A	> 835 cycles	>5380	>1193	152	>3469	
M5B	> 835 cycles	>5380	>1193	>3491	2471	

Thermal Cycling: 1 of 10 units failed at 710 cycles

Damp Heat: 4 of 10 units failed, 6 units 5000+ hours

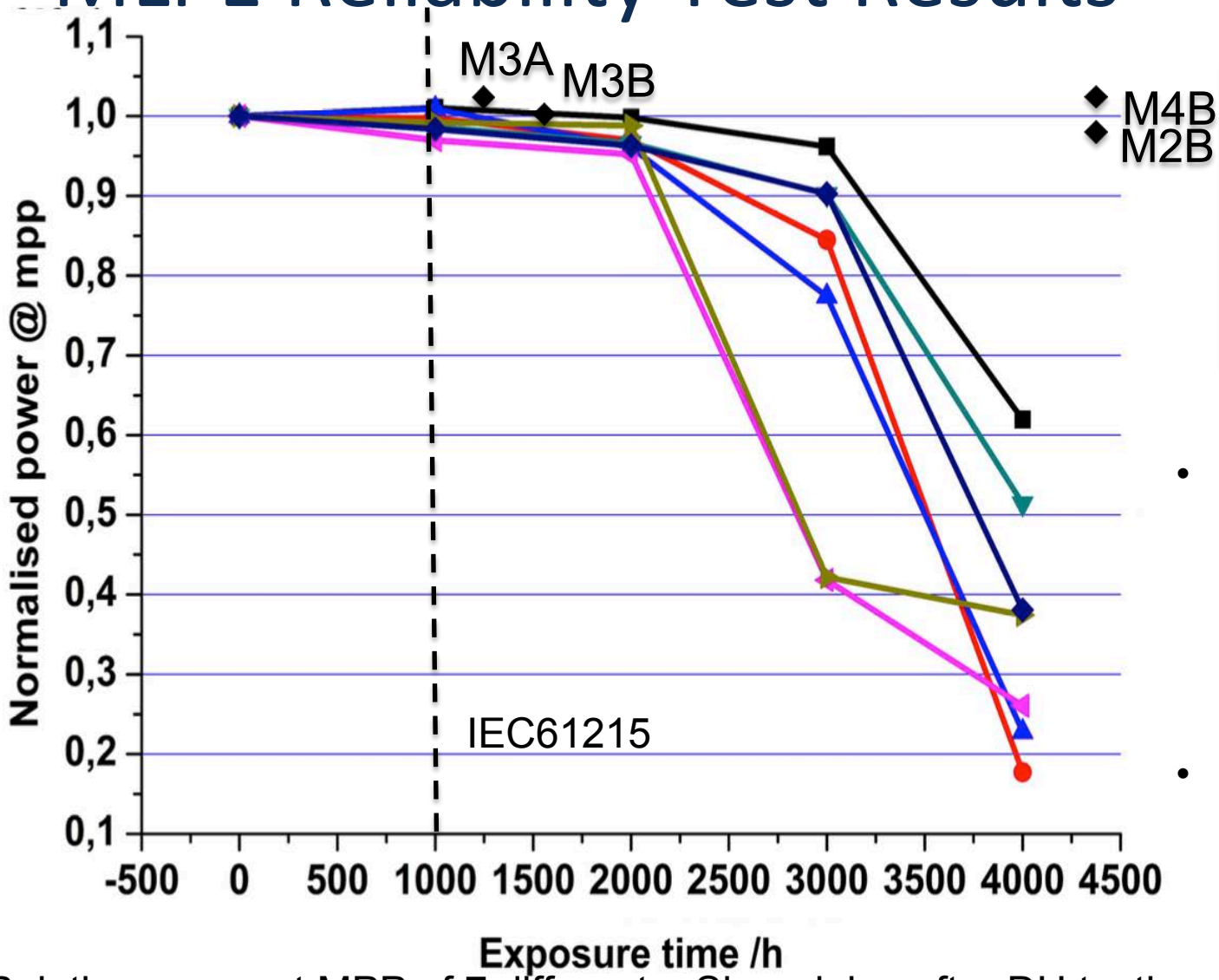
Static 85°C: 0 units failed

Static 100°C: 2 of 10 units failed (1 unit most likely extrinsic)
*Some units derate → full stress not applied to those devices

Static 125°C: 7 of 10 units failed
*ALL units derate
*Significant damage to connectors/cabling, but not cause of failure

How do these numbers compare to module testing?

MLPE Reliability Test Results



M4A, M5A, M5B
M2A
M1A, M1B

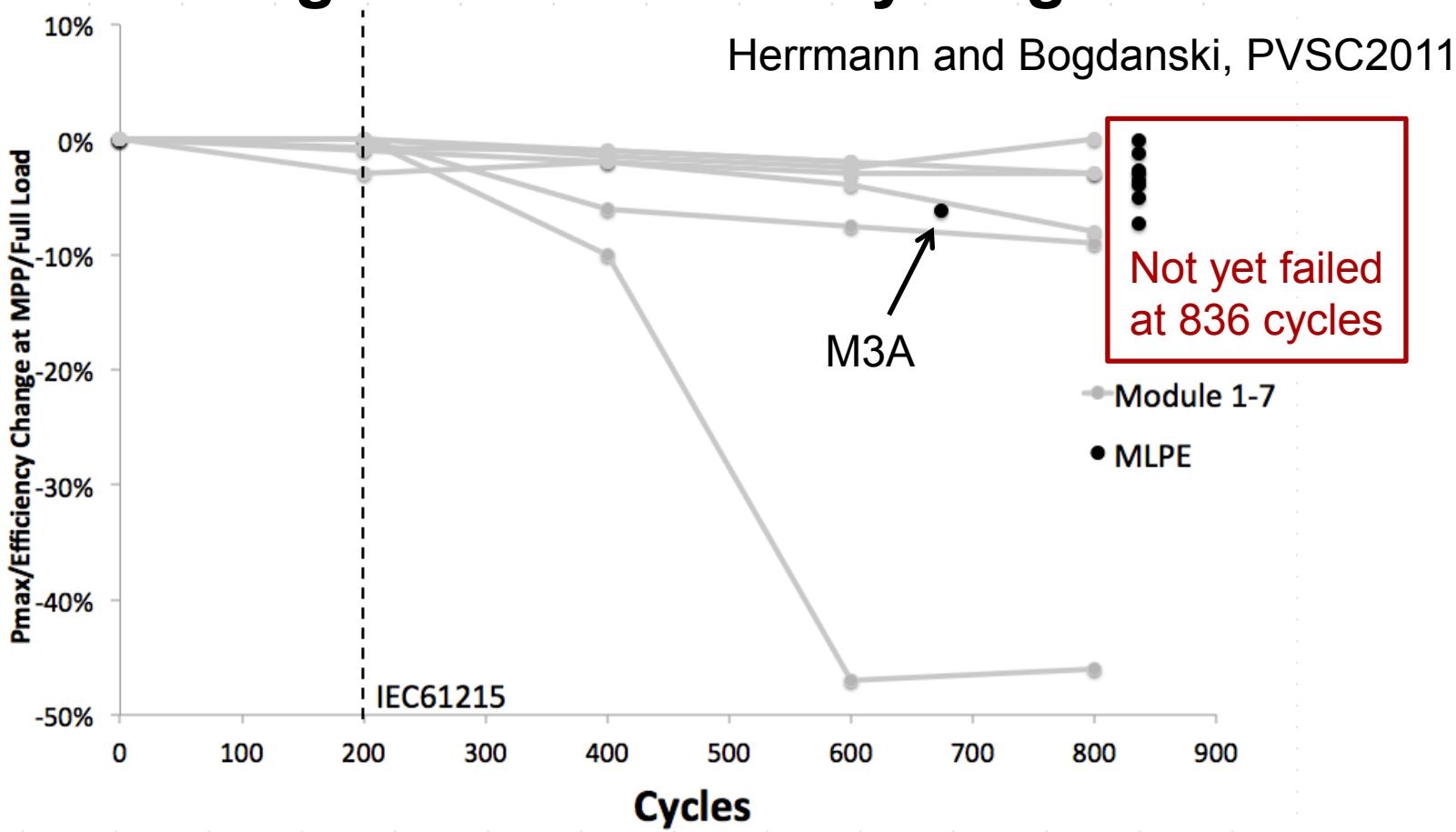
Not yet failed, 5380 hours

- Refrain from direct comparison of **lifetime** due to difference in failure mechanisms
- Does indicate that MLPE units **may** have long lifetimes

Relative power at MPP of 7 different c-Si modules after DH testing (Koehl, PVSC2013)
Compared to full load testing of MLPE units (normalized efficiency)

MLPE Reliability Test Results

Long-Term Thermal Cycling



- Refrain from direct comparison of **lifetime** due to difference in failure mechanisms
  - Fielded MLPE failure mechanisms may be over/under excited by ALT
    - Indicates MLPEs can **pass** certification
    - **Robust** to thermal cycling

More complete analyses in future (PVSC, journal article, final report)

Summary

- Suite of reliability ALTs to a variety of MLPE devices from 5 different manufacturers
  - Periodically re-characterized functionality during testing
  - Instantaneous voltage/current readings during test
- Majority of devices have lasted extent of testing
  - 5,000+ hours DH
  - 800+ thermal cycles
  - 3,000+ hours at 85, 100, and 125°C
- Relatively few MLPE units have failed at after extent of testing
  - → robust devices
  - → ***possibly might*** last as long as PV modules in field under normal usage conditions
  - → Units are now 1 to 2 generations old with reliability improvements every generation
    - → Lifetime of units **constantly** improving
- **Much more testing** (long-term, multi-stress ALTs) needed in the future to truly determine a device's lifetime
  - **Preliminary** step towards determining lifetime
  - Many more **devices** with more **stress** conditions are needed
- Module industry has **decades** of high-volume manufacturing and test
  - Inverter industry won't get there overnight and is in its infancy
  - Need suite of design, supply chain, qualification, and reliability standards for PV BOS

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy under Award Number DE-FC36-07GO17034. This work was funded by the DOE Office of Energy Efficiency and Renewable Energy. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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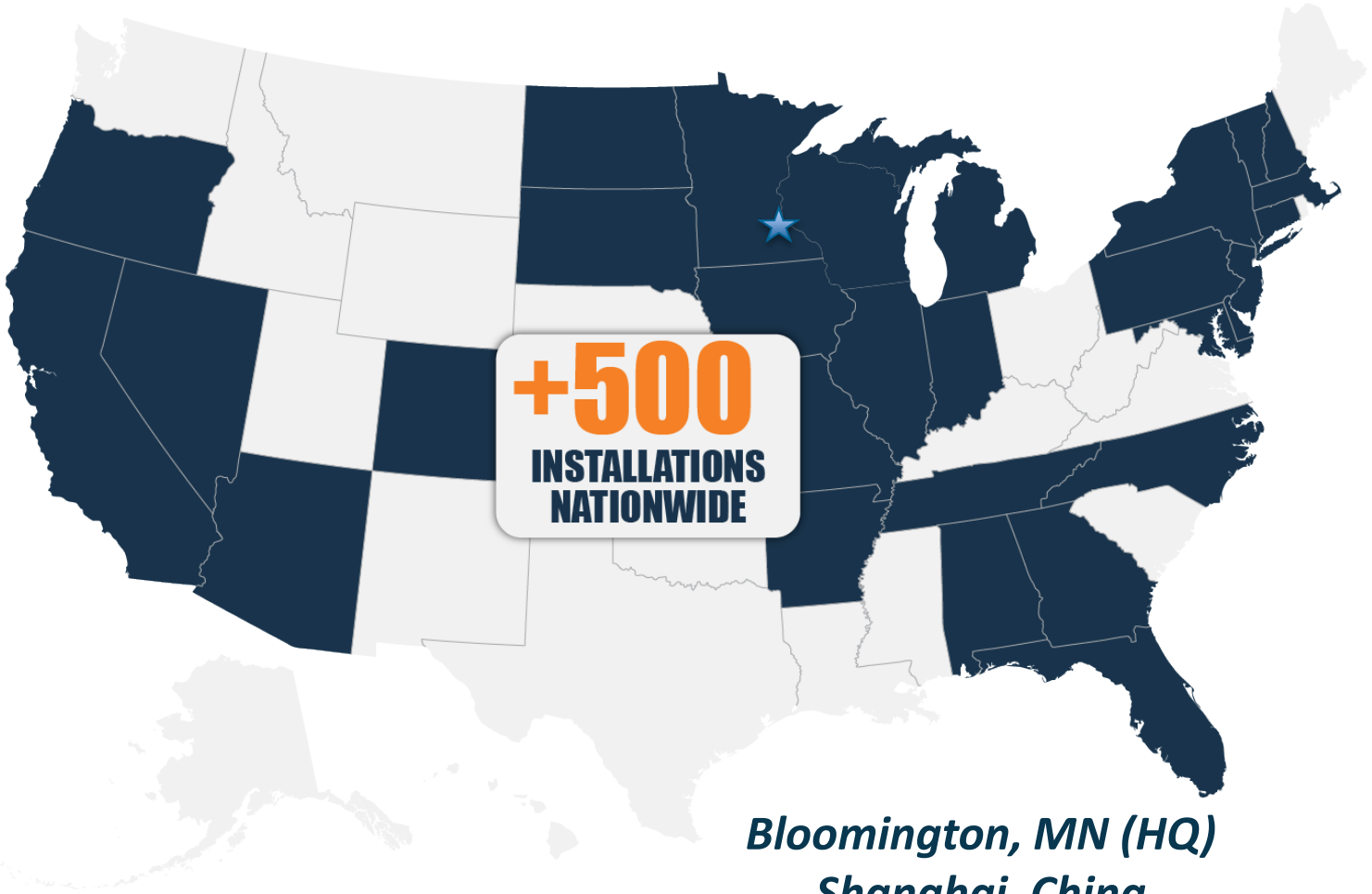
Simply More Energy

Challenges and Opportunities in Implementing a Distributed Parallel MLPE Power Regulation Topology

Tim Johnson

tenKsolar Worldwide Installations

Sites in the USA



Bloomington, MN (HQ)
Shanghai, China

Outside the USA

- Canada
- Ireland
- Italy
- Romania
- United Kingdom
- Germany
- Netherlands
- Switzerland
- El Salvador
- South Africa
- Nigeria
- Kenya
- Ghana
- China
- Japan
- South Korea

Ten K SOLAR

Value of Module Electronics

- **What is MLPE really meant to do?**
  - Remove serial limitations in infrastructure applications
  - Enable Faster Growth in PV by making it foolproof to install
- **Solve Serial DC**
  - Module Mismatch, Stringing, MPPT, etc….
- **Make DC "Plug and Play"**
  - It's easy to install Serial DC incorrectly
  - Hard to diagnose
  - Difficult to maintain

Ten K SOLAR

Market Value of MLPE

- Navigant Research reports that annual installations of global module-level power electronic (MLPE) capacity will grow from 1,185 MW in 2013 to 12,844 MW by 2020.

- IHS Research The worldwide market for module-level power electronics (MLPEs), including PV microinverters and power optimisers, is expected to reach US$1 billion by 2019, according to IHS.

Ten K SOLAR

Challenges of MLPE

- **MLPE is not a coherent market, creating some misidentification**
  - Add on Optimizers
  - Micro Inverters
  - System Integrated
  - Others….

- **Barriers to Entry to "Bankability"**
  - Not as high as they used to be

- **How to address?**
  - Design – Manage component failure so system performs above required service levels.
  - Quality Assurance Systems – IECRE will be a critical standard to enable overall faster growth in the industry.
  - Do specific MLPE types need specific IEC standards?

Ten K SOLAR

The tenK Topology

- Utilize modular, low cost components to create an easy to install, highly reliable, zero maintenance PV system

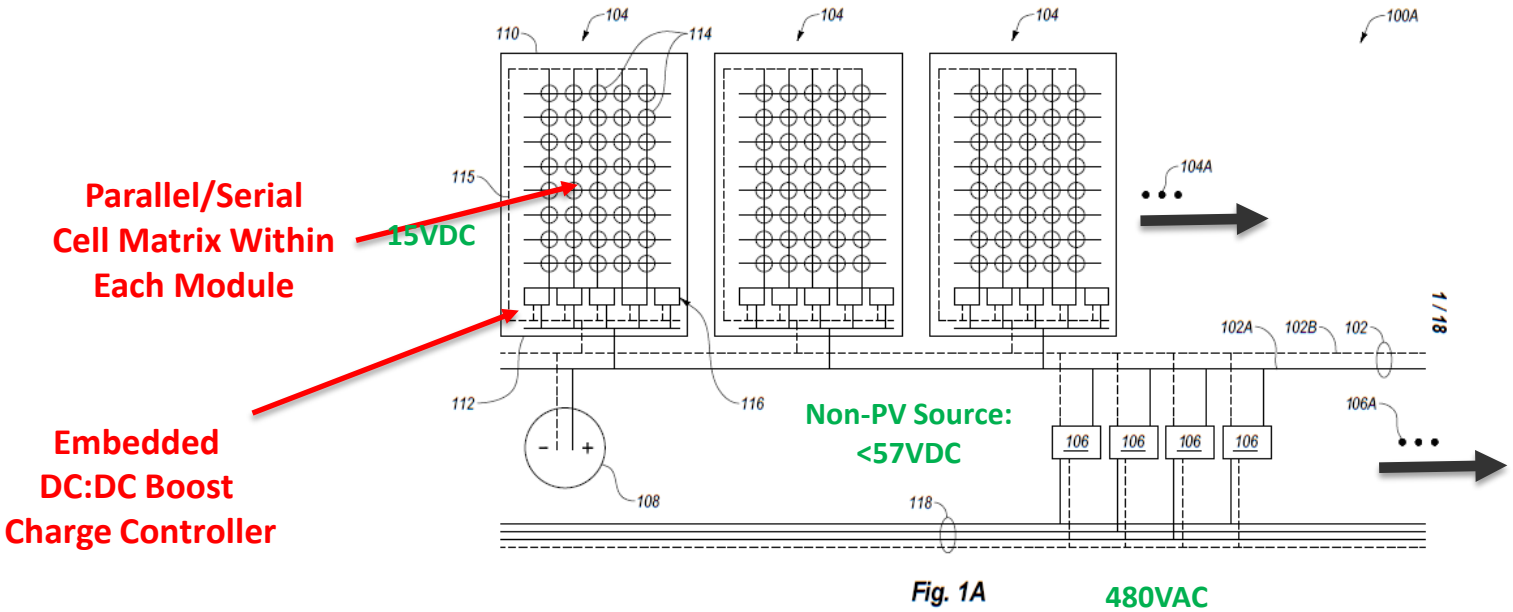


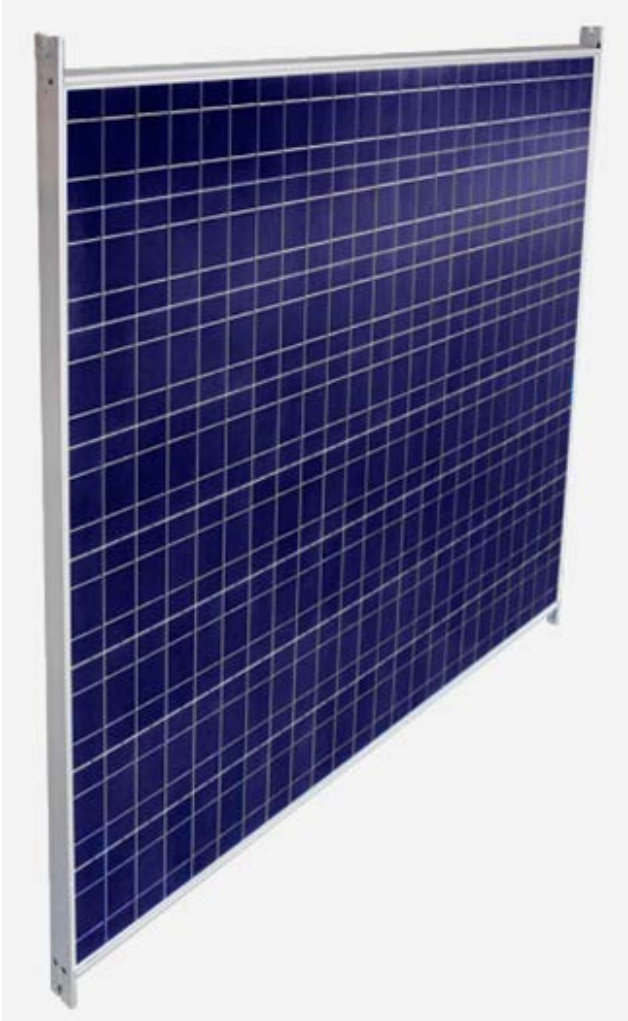
Fig. 1A

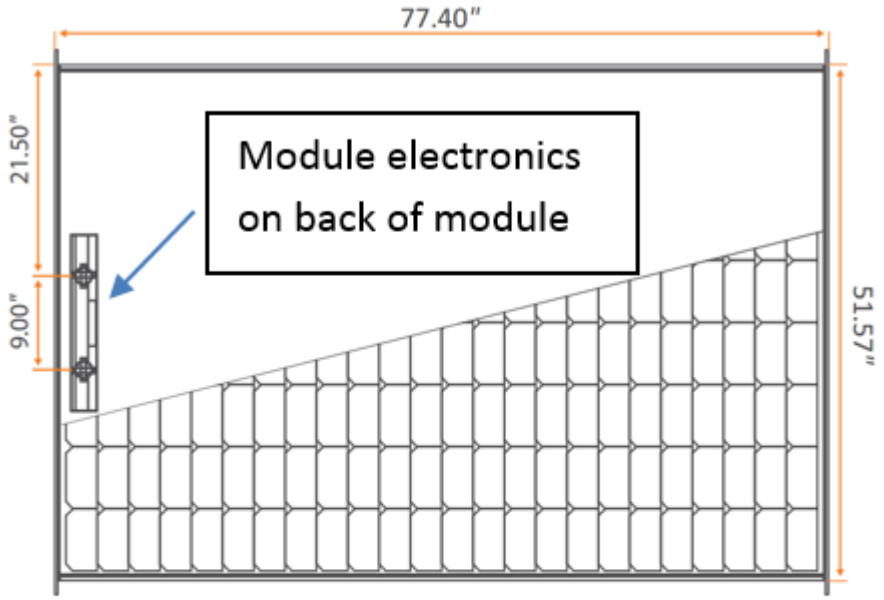
All Modules in Parallel

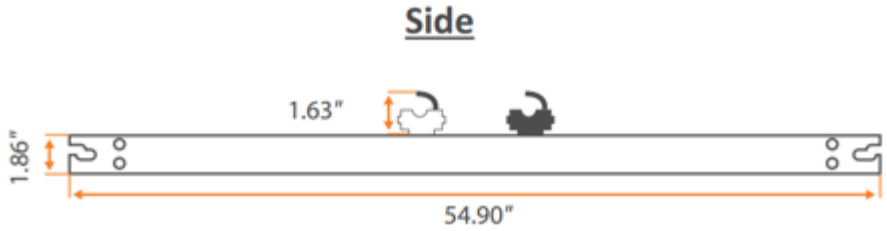
DC Bus Delivers Energy to <u>Group</u> of Inversion Units

<u>Energy From Any Cell Can Go Through Any Inversion Unit</u>

RAIS PV Module



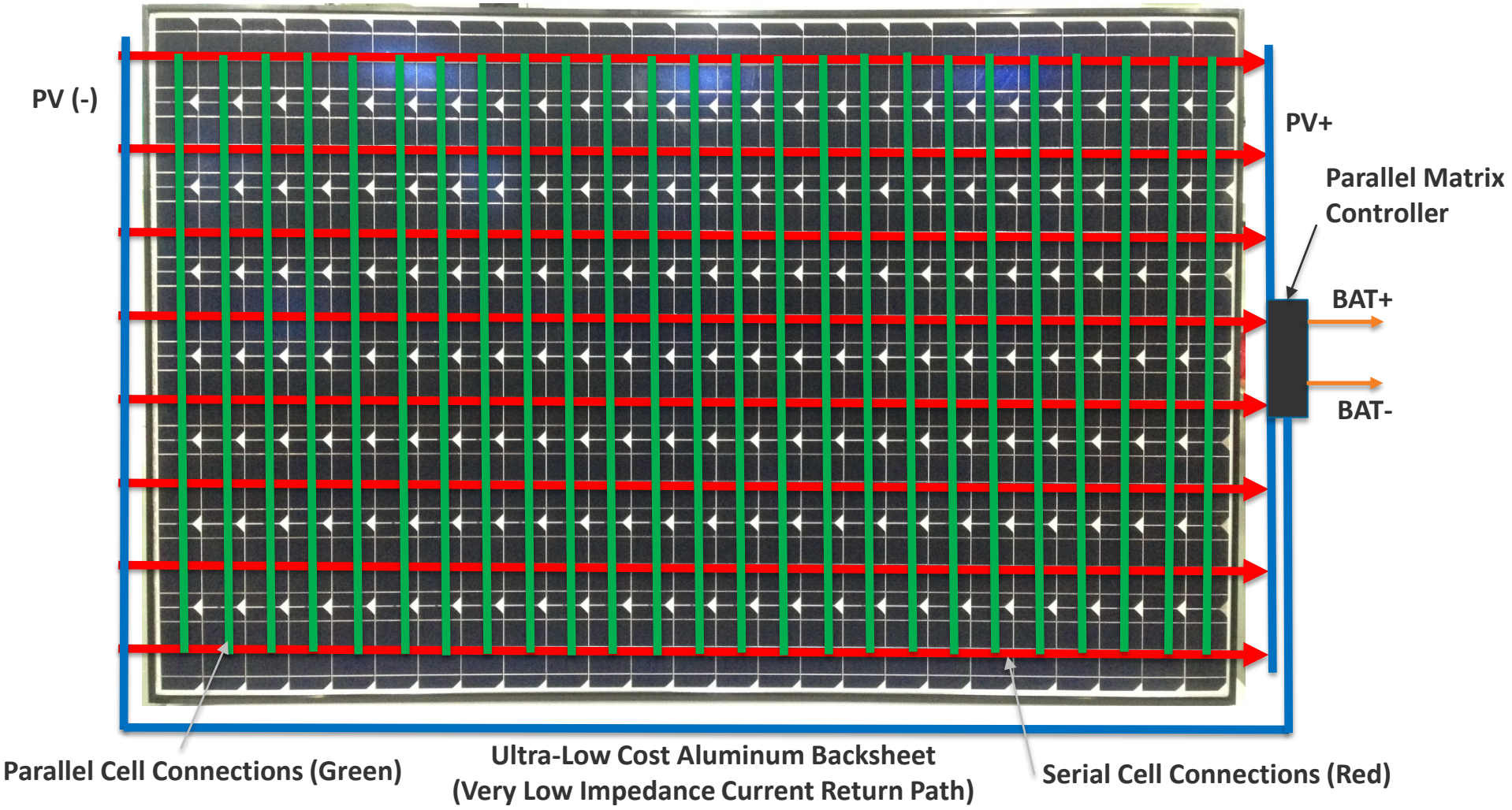




Onboard LED aids installation

Ten K SOLAR

Logical Construction of a tenK PV module



tenK – Dual Listed to UL1703 + UL1741

CSA Group

Certificate: 2275045 **Master Contract:** 248152

Project: 2721970 **Date Issued:** June 27, 2014

Note: Model "Titania" controller certified with "Titan" PV panel.

Model XT-M-450, the following electrical ratings typical at 450 W (STC):

Maximum Output Current at Operating Voltage (Ipmax): 9.1 A

Maximum Output Power: 450 W

Note: Model "Titania" controller certified with "Titan" PV panel.

Notes:

'XXXXXXX' represents: First three (3) digits represent the model number in the numerical format. Last four (4) digits, in the numerical format, represent how the module is kitted and used (what other parts are shipped with it) and for field tracking. As an example, if a module is shipped for use as a residential module, the fifth digit is a 1. If it is shipped as a commercial rooftop module, it is a 2, etc.

Rated electrical characteristics are within +/-10% of measured values at Standard Test Conditions of 100 mW/cm² irradiance, AM 1.5 spectrum, and +25°C.

Samples of PV frame extensions mounted on the Aluminum Fin, part # 1601035, mounted on the Aluminum Railing, part # 2601073 or # 2601076, using all required hardware have been evaluated for bonding continuity from module frame to mounting rails

APPLICABLE REQUIREMENTS

ULC/ORD- C1703-01 - Flat-Plate Photovoltaic Modules and Panels

UL 1703-3rd Edition - Flat-Plate Photovoltaic Modules and Panels

CSA C22.2 No 107.1-01 - General Use Power Supplies

UL 1741 2nd Edition - Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources

UL 1703 UL 1741

ISBN 0-7629-0421-6

Flat-Plate Photovoltaic Modules and Panels

Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources

CSA Listing to UL1703 + UL1741
No Other Module Listed This Way

UL1703 Covers Panel Portion
UL1741 Covers Charge Controller

Grounding Tested to UL2703

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RAIS® Parallel Matrix Controller (RAIS® = Redundant Array of Integrating Solar)

- Contains six DC:DC converters operating off of selectable, parallel buses internal to the module.
- The energy available the module at STC conditions can be produced by four of the six converters operating, thus two are fully redundant. Each converter is internally fused and fully isolated from each other.
- Each DC:DC converter operates only as needed, is virtualized to wear-level across each.
- All electronic boards repeat functionally tested during a continuous module light test where the electronics runs a full diagnostic on the module.

Ten K SOLAR

RAIS® Parallel Matrix Controller (RAIS® = Redundant Array of Integrating Solar)

- Self-starting and used to self-charge the circuit to begin operation when illumination is present on the PV cells.
- Only produce energy when connected to a pre-qualified circuit (circuit cannot be shorted, open or purely resistive), and has an embedded ground fault detection circuit.
- It can also detect arc-fault failures by continuously monitoring the line for voltage fluctuations over a very narrow range of limits.

Ten K SOLAR

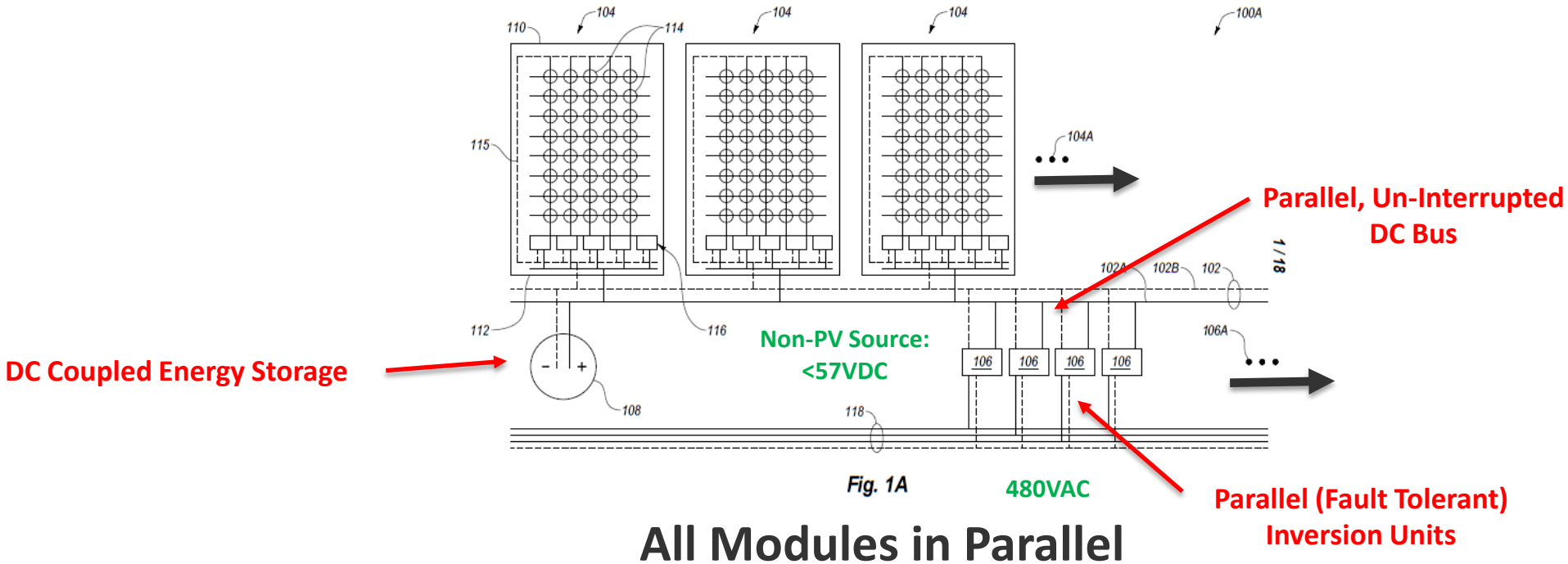
RAIS® Parallel Matrix Controller (RAIS® = Redundant Array of Integrating Solar)

- The Parallel Matrix Controller tracks and stores all performance information over the lifetime of module.
- An LED is used on the circuit board to present both visual and binary information to the user.
- A power-line carrier based digital communication routine allows all modules to be transmit information to a receiving device

Ten K SOLAR

The tenK Topology

- Utilize modular, low cost components to create an easy to install, highly reliable, zero maintenance PV system

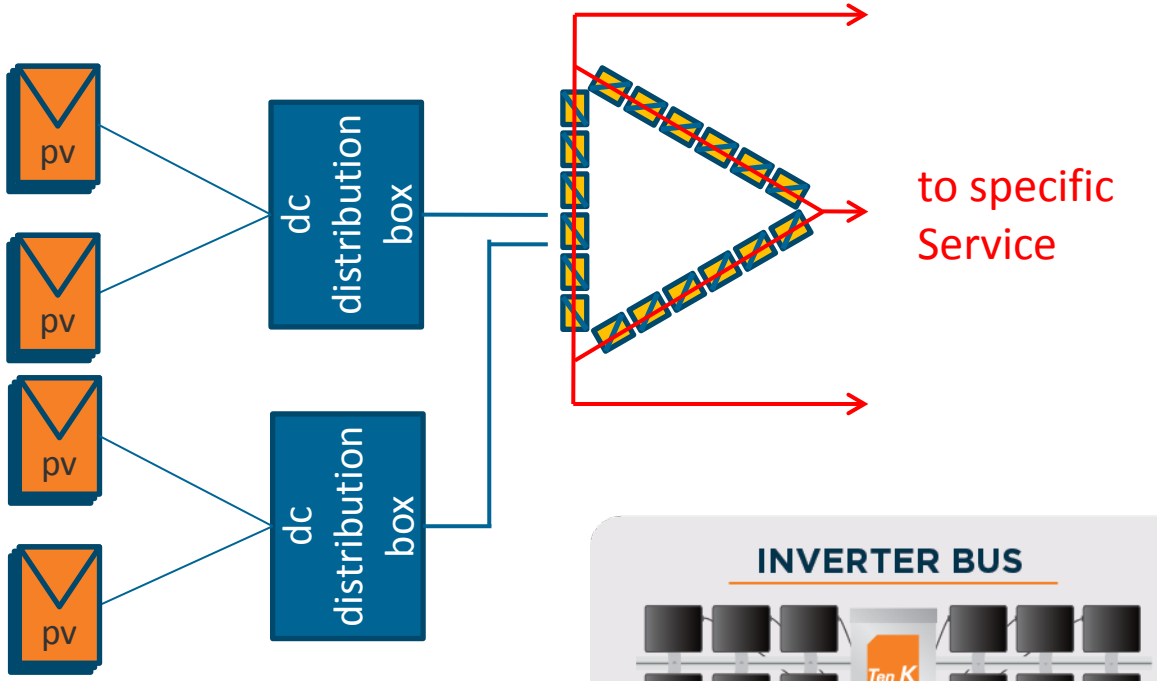


All Modules in Parallel

DC Bus Delivers Energy to <u>Group</u> of Inversion Units

<u>Energy From Any Cell Can Go Through Any Inversion Unit</u>

tenKsolar RAIS Inverter Bus

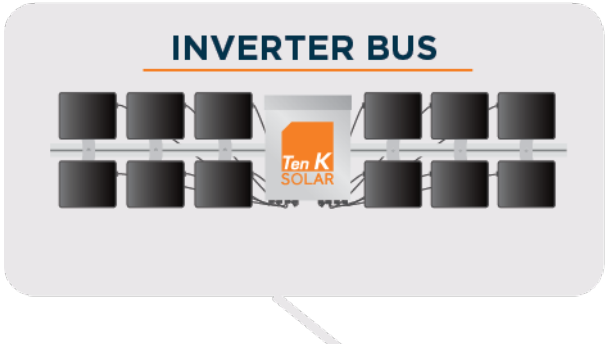


Multiple Inverters Operating Off DC Bus (Fault Tolerant)
No Digital Communication Between Units
All Operate Based Off DC Setpoint Targets
Only Operate as Needed

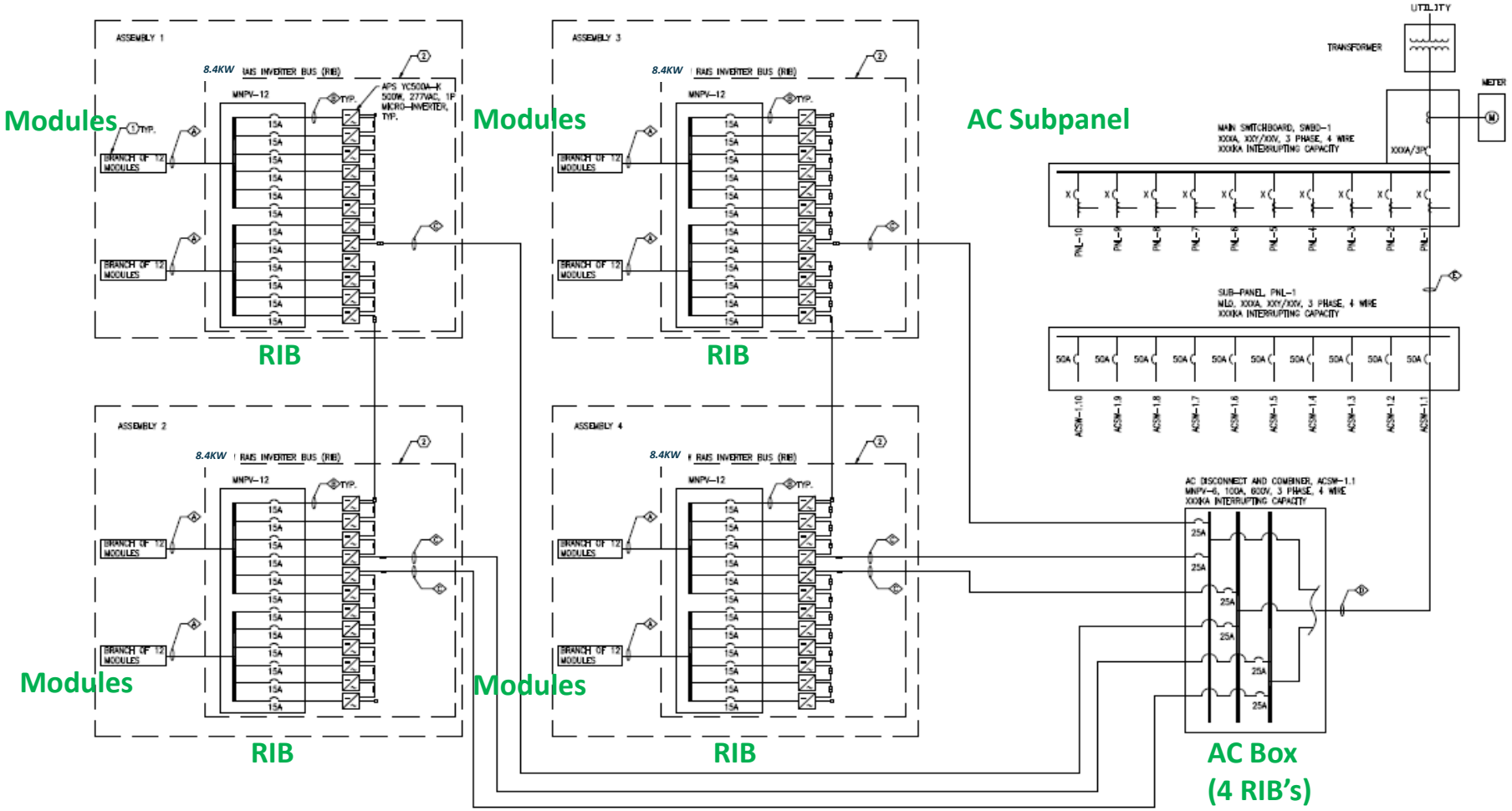
Randomized DC Setpoint Process
Daily Wear Leveling Across All Units

If One Fails or is Damaged
No Impact on Others (Fused)

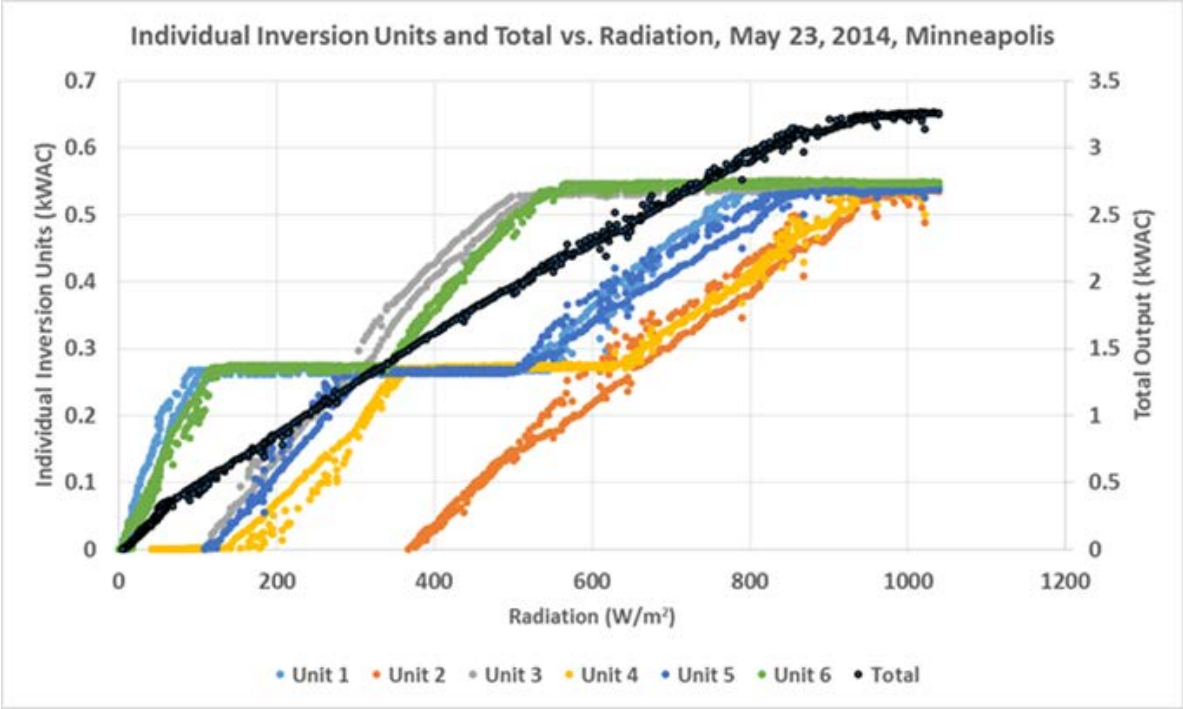
Extremely Simple Repair
Changing Failed Units is a Very Simple Swap-Out
All Units are Inter-operable

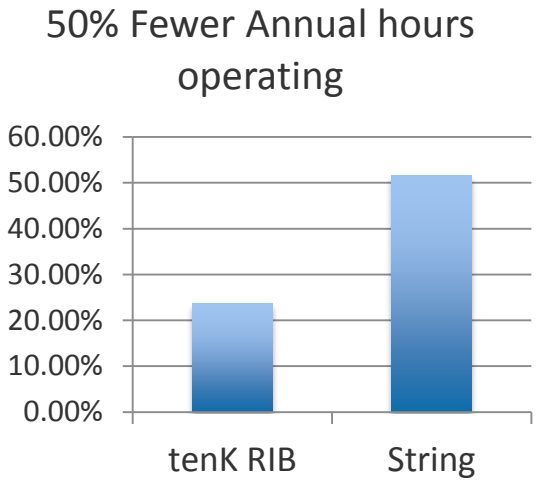


Simplified System Block Design (33.6 kWAC)



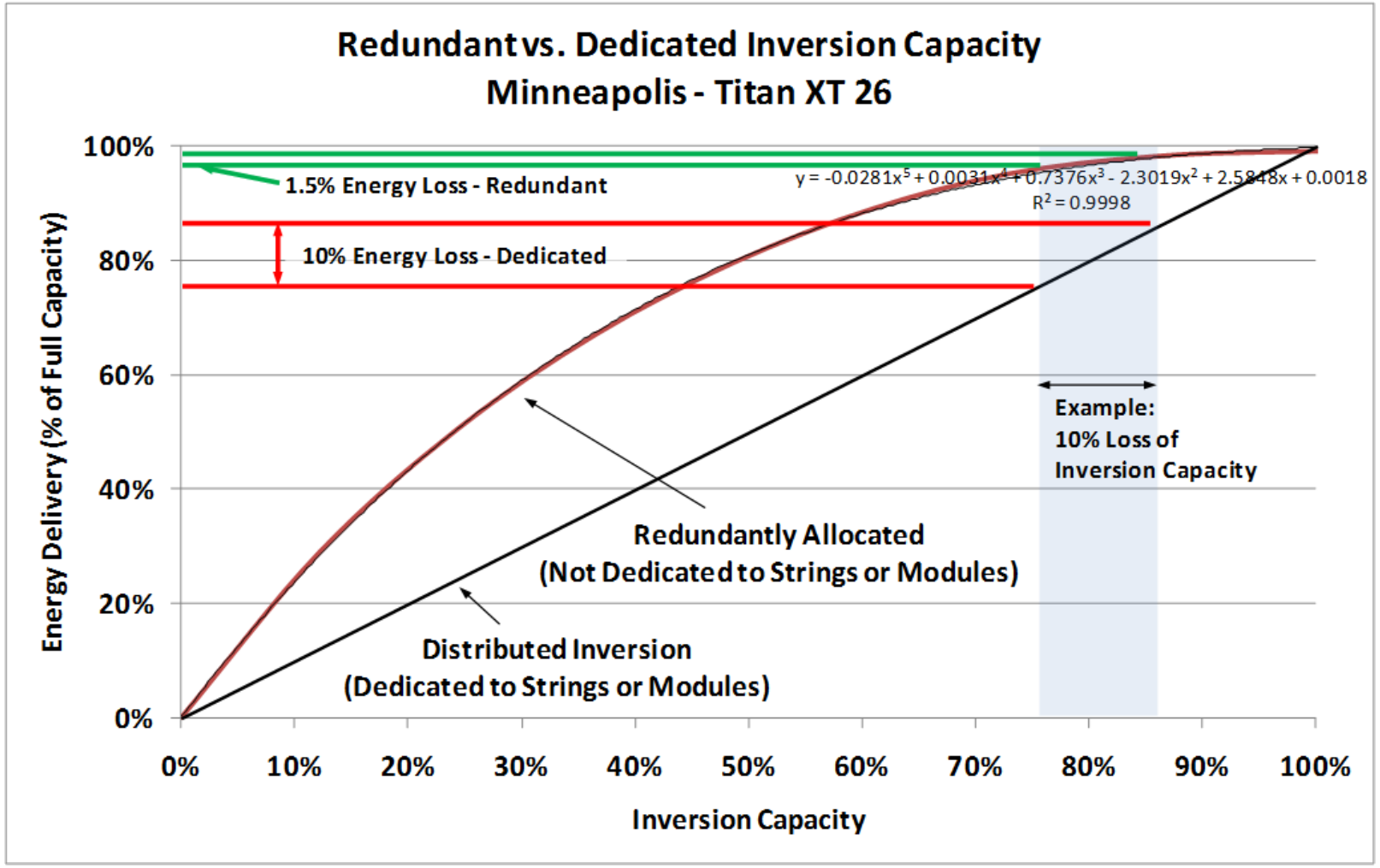
Improved System Longevity – Redundant Inversion



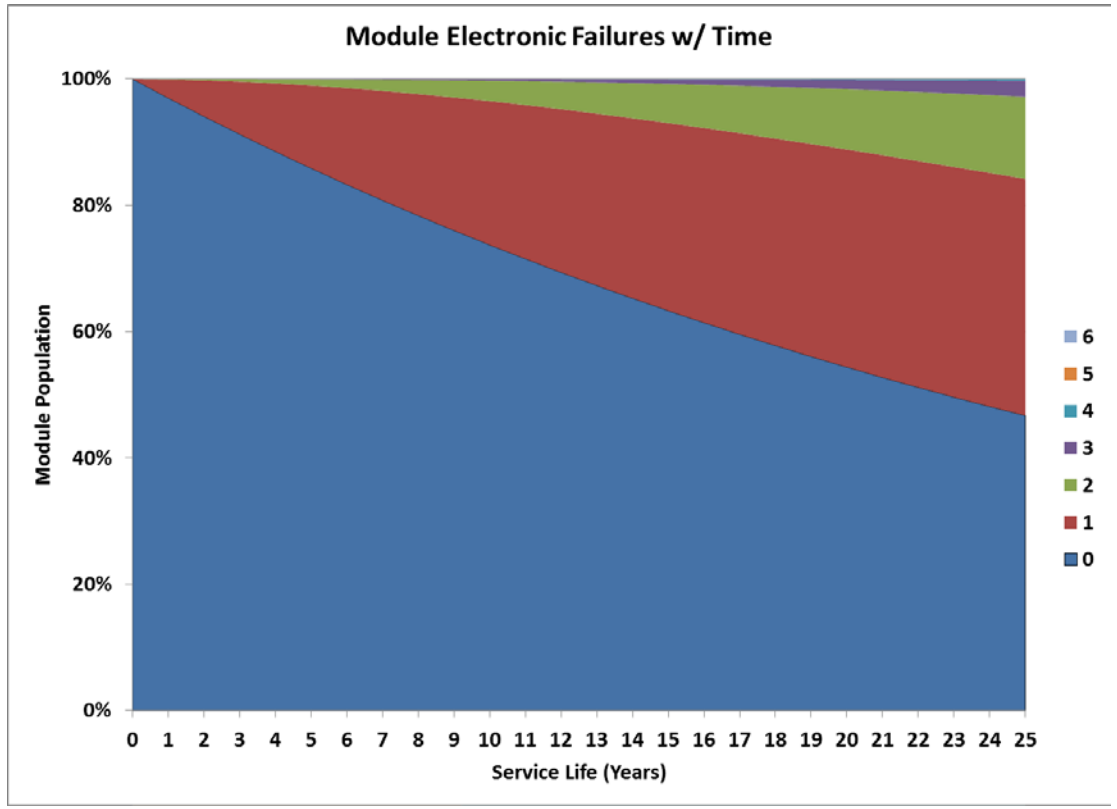


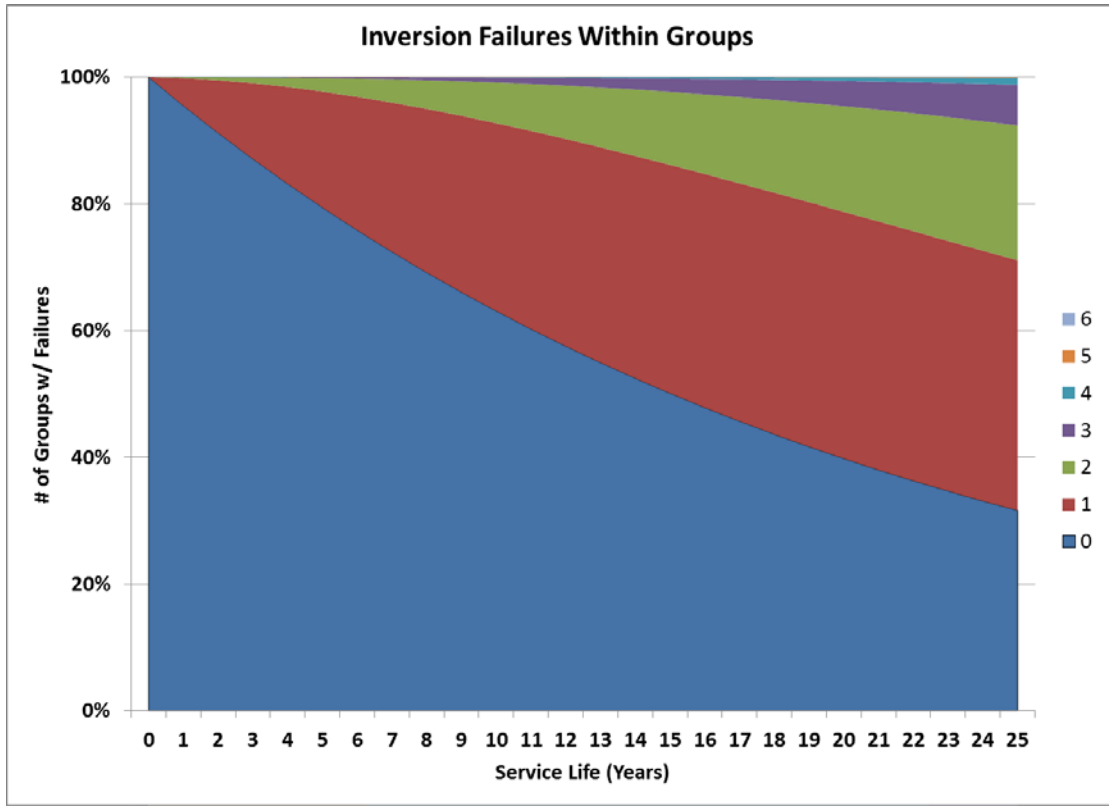
<u>Inversion Units All Come On at Different Times</u>
Note: Total Power Curve is Smooth
Also – Repeats AM and PM
Randomized Each Day
Net Required On-Time: 25% vs. 50% For Module Dedicated Inversion

Benefit of Redundant Inversion



Electronic Failures Grouping in Time





c-Si Degredation X MLPE Availability X Inverter Bus Availability = Output

tenK RAIS PV Module

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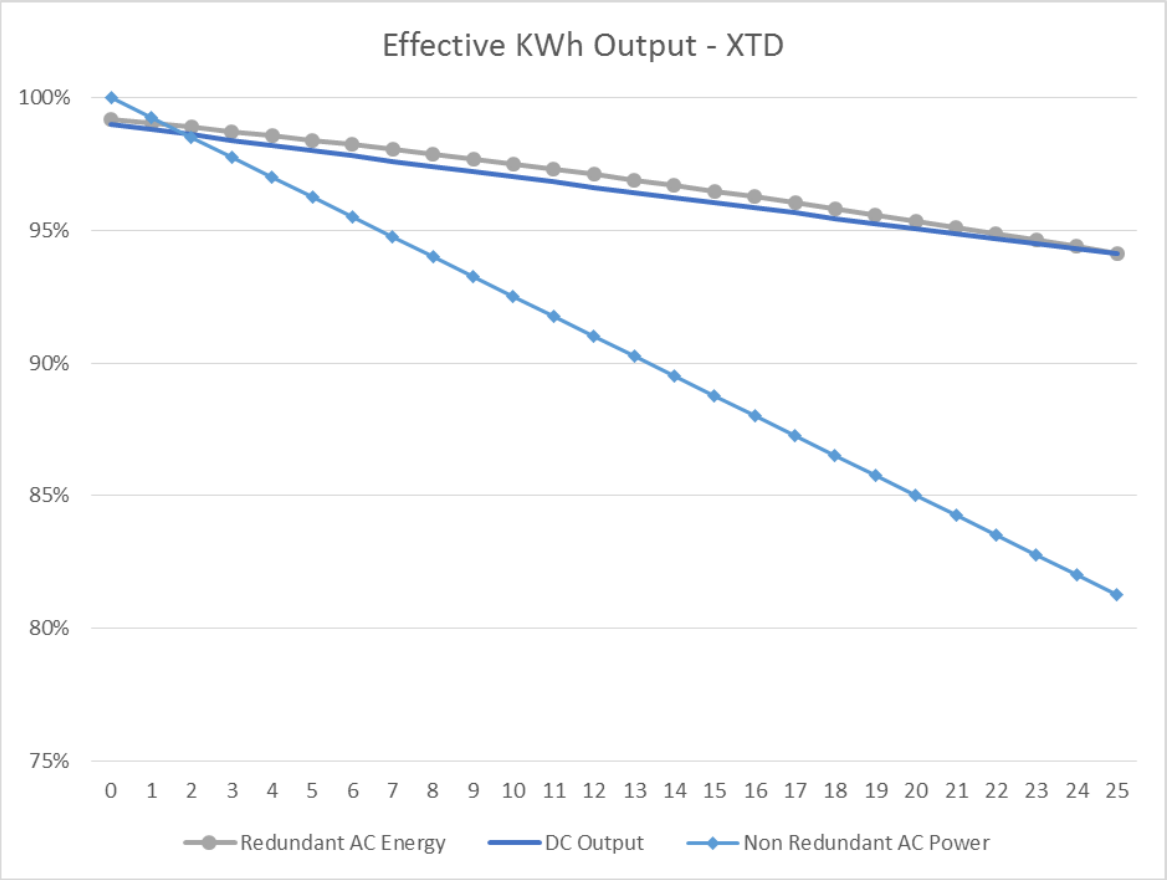
Zero Energy Loss With No Maintenance

As failures are distributed among redundant buses, remaining functioning boost converters on the module and inverters on RIB ensure no effective

In Year 25, 13% Additional Loss in Total AC Power is Compenstated for with redundant bus. Results in Zero lifetime Energy Loss versus Expected with No Maintenance or Corrective Actions for Inversion.



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Thank You

www.tenksolar.com

empower

micro systems

Defining Accelerated Test Requirements for Microinverters using a Physics-of-Failure (PoF)-based Approach

Arvind Vasan, Regan Arndt, and Milan Ilic

NREL Photovoltaic Module Reliability Workshop, Golden, CO

February 24, 2016

Solar Energy | Energy Storage | Electric Vehicles

INTRODUCTION

- Microinverters are module-level power electronic systems that are expected to have a service life of more than 25 years.
- The assurance for long-term performance of microinverters can be provided only through an understanding of the dominant failure mechanisms and by performing appropriate tests at accelerated stress levels.
- No standards exist for the reliability evaluation of module-level power electronics (however, TC82 WG6 have plans to include reliability of BOS).
- Typical approach twice or thrice the requirements specified in IEC 61215 (extended reliability or qualification testing).

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CHALLENGE IN RELIABILITY ASSESSMENT

- Is simply doubling or tripling the number of test cycles or test time specified in IEC 61215 sufficient to meet 25 years?
- A product that has failed the extended-qualification tests may actually perform reliably in field - This could lead to the initial rejection of a true reliable product.
- Similarly, a product that passed the extended-qualification tests may fail prematurely in the field, leading to the acceptance of a non-reliable or defective product.
- **A mere pass result from extended-qualification tests does not guarantee that the reliability requirements will be met under intended use conditions, unless relationship has been established between conditions in the test and field.**

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WHAT IS PHYSICS OF FAILURE (POF)?

PoF is a methodology for building-in reliability, based on assessing:

- the impact of hardware configuration and life-cycle stresses;
- the materials at potential failure sites;
- root-cause failure mechanisms.

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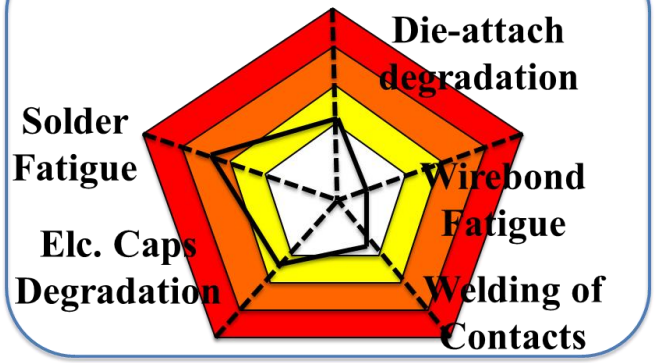
RECOMMENDED - PoF RELIABILITY ASSESSMENT METHODOLOGY

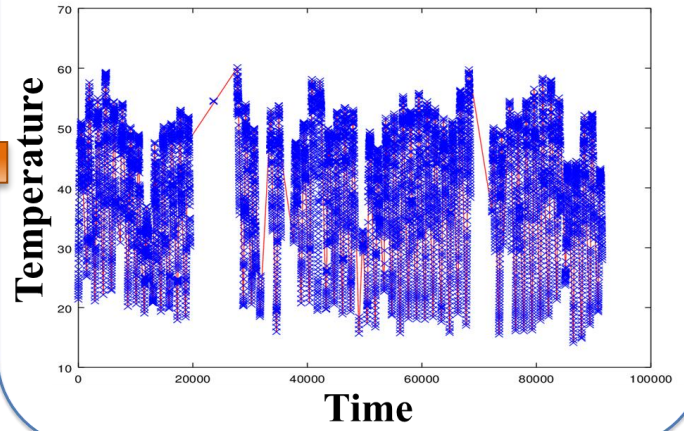
Design Capture

Failure Modes, Mechanisms, and Effects Analysis (FMMEA)

Risk Assessment



Life Cycle Loads



Mechanism 1

$$N_f = 0.5\left[\frac{\Delta\gamma}{2\varepsilon}\right]^c$$

Mechanism 2

$$L_x = L_0 2^{\left[\frac{T_0 - T_x}{10}\right]} \times 2^{\left[\frac{-\Delta T}{10}\right]}$$

Mechanism 3

$$N_f = A\left(\Delta T_J^{\alpha}\right) exp\left(\frac{E_a}{K_B T_J}\right)$$

K. Upadyayula and A. Dasgupta, “Physics-of-Failure guidelines for accelerated qualification of electronic systems,” *Quality and Reliability Engineering Intl.*, vol. 14, pp. 433, 1998 .

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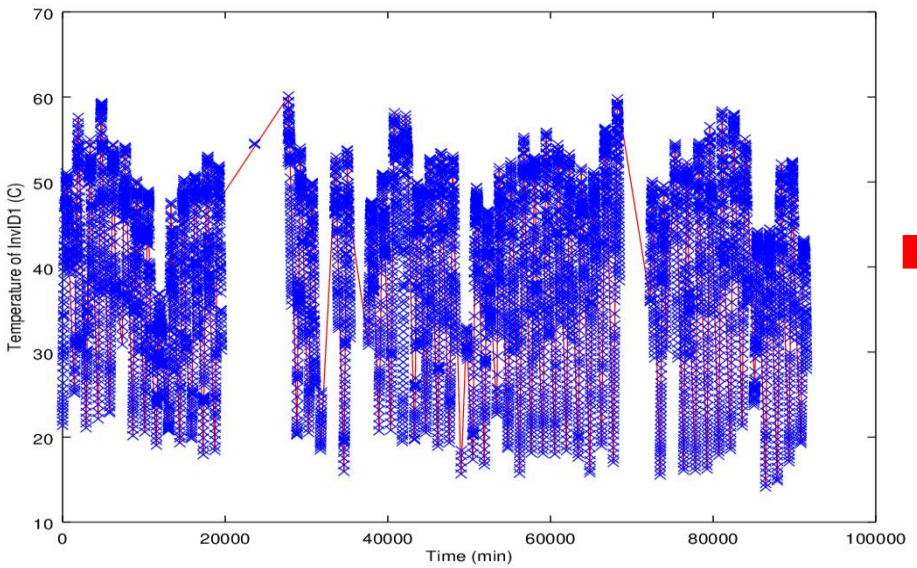
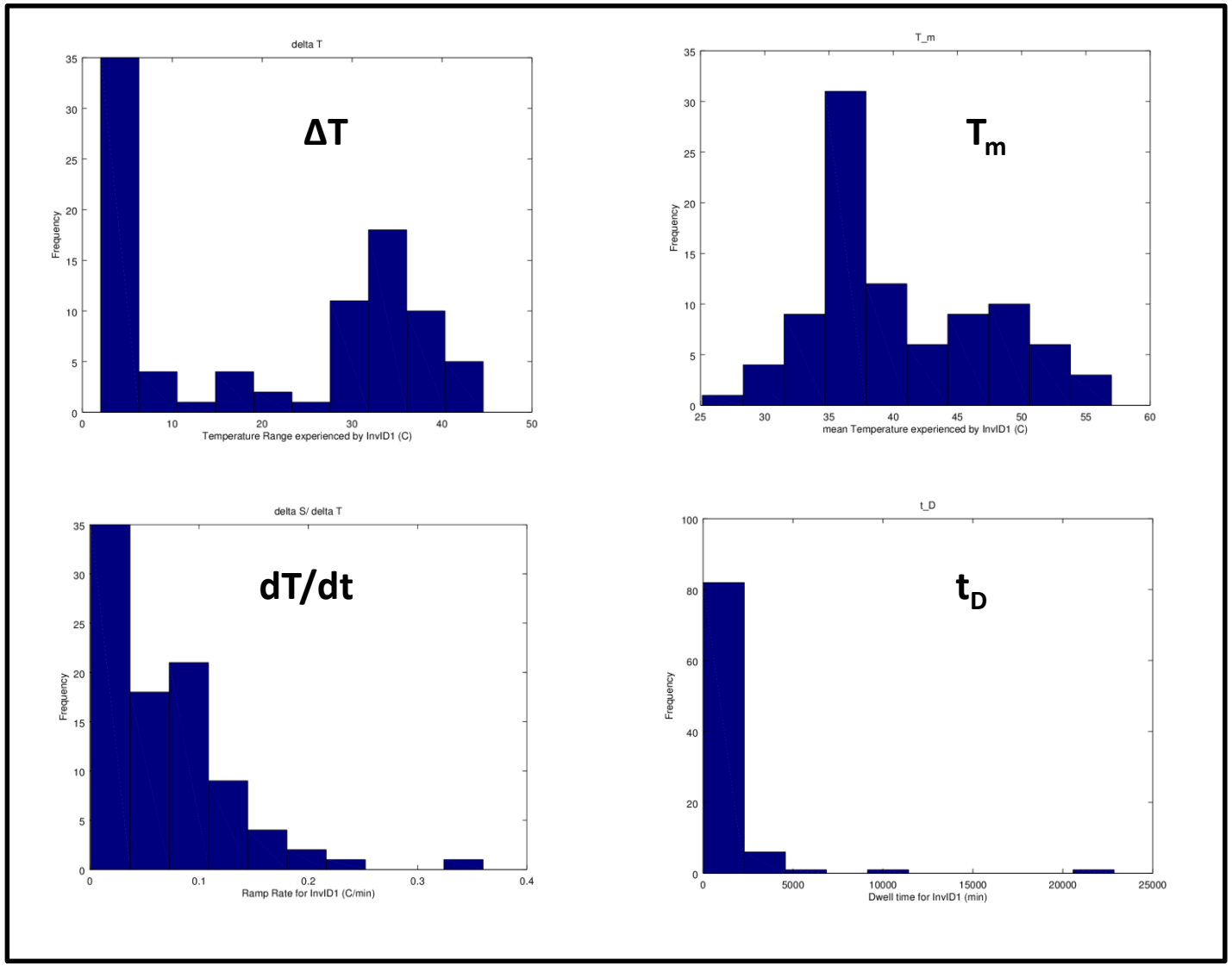
STEP 1: DEFINING THE APPLICATION ENVIRONMENT





From field measurements, 4 parameters are extracted using ordered overall range (OOR) and Rain flow counting (RFC) algorithms. These include:

- **Temperature range (ΔT)**
- **Mean temperature (T_m)**
- **Ramp rate (dT/dt)**
- **Dwell time (t_D)**

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ESTIMATE ACCUMULATED DAMAGE IN APPLICATION ENVIRONMENT

- **Damage estimated using Engelmaier model and Miner's rule.**

Engelmaier Model

Cycles to failure: $$N_f = \frac{1}{2}\left(\frac{\Delta\gamma}{2\varepsilon_f}\right)^{1/c}$$

Fatigue ductility exponent

$$c = c_0 + c_1 T_{SJ} + c_2 ln\left(1 + \frac{1440}{2 \times t_{ramp} + 2 \times t_{dwell}}\right)$$

Cyclic strain range

$$\Delta\gamma = \frac{L_d(\alpha_S - \alpha_C)\Delta T}{h}$$

Miner's Rule

$$D_T = \sum_i \frac{n_i}{N_{f,i}}$$

c_0, c_1, c_2 — Model constants corresponding to the solder material used

ε_f ← Fatigue ductility coefficient

L_d ← Design parameter

α_S ← CTE of PCB

α_C ← CTE of component

W. Engelmaier, "Fatigue life of leadless chip carrier solder joints during power cycling," *IEEE Trans. Compon. Hybrid Manuf. Technol., vol. 6, pp. 232, 1983.*

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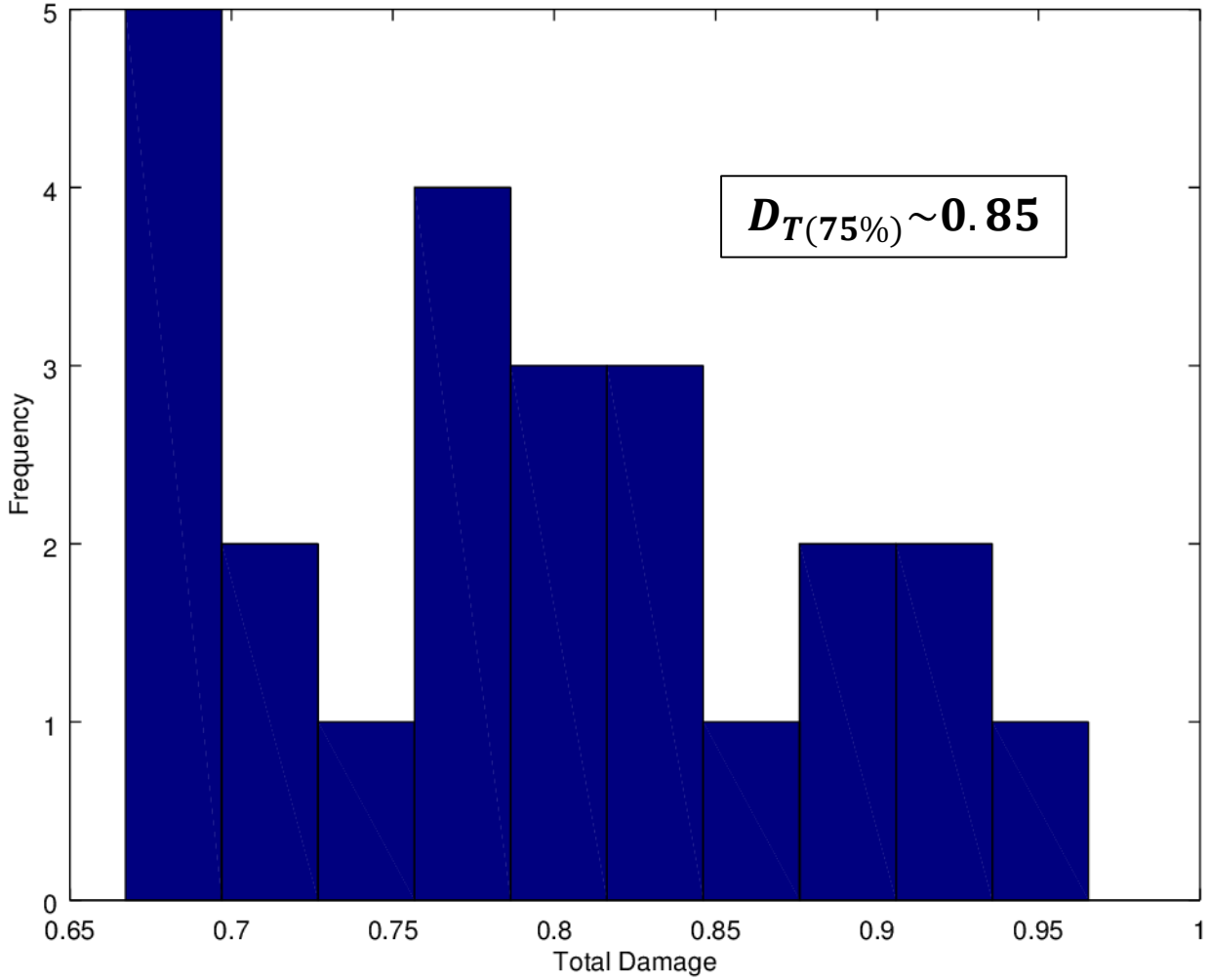
STEP 2: ESTIMATED TOTAL DAMAGE (25 YR SERVICE LIFE)

2 strings x 12 microinverters = 24 units in Davis, CA



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STEP 3: CALCULATING EQUIVALENT DAMAGE IN ACCELERATED TEST

- **Assuming -40 to +85C for temperature cycling @3C/min and 30 min dwell**

Equivalent Cycles to Failure $\boldsymbol{ECTF = D_{T(75\%)} \times N_f}$

$N_f = 1180$ cycles $\boldsymbol{ECTF = 1001}$ **cycles (100 days)**

- **Assuming -40 to +85C for temperature cycling (suggested in IEC61215) @1.65C/min and 15 min dwell**

$N_f = 1057$ cycles $\boldsymbol{ECTF = 897}$ **cycles (132 days)**

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STEP 4: APPLYING A SAFETY FACTOR

- The accelerated test needs to be designed with a statistically-based sample size (n).
- For zero failures, with Weibull failure distribution assumed:

$$m = \left[\frac{ln(1-C)}{n \times ln(R)}\right]^{1/\beta}$$

Safety Factor

	C = 0.6	C = 0.9
n = 8	1.0211	1.2856
n = 16	0.8586	1.0811

Reliability Factor $R = 0.9$

Weibull Shape Factor $\beta = 4.0$

$$t_{Test} = m \times ECTF$$

Total number of cycles

	C = 0.6	C = 0.9
n = 8	1022	1287
n = 16	860	1082

Recommendation: Test 8 units for 1300* cycles with zero failures from -40 to +85C @3C/min with 30 min dwell

IEC61215 recommends 200 cycles of -40-to-+85C @1.65C/min with 15min dwell, which is 20% damage or 5 yrs service life.

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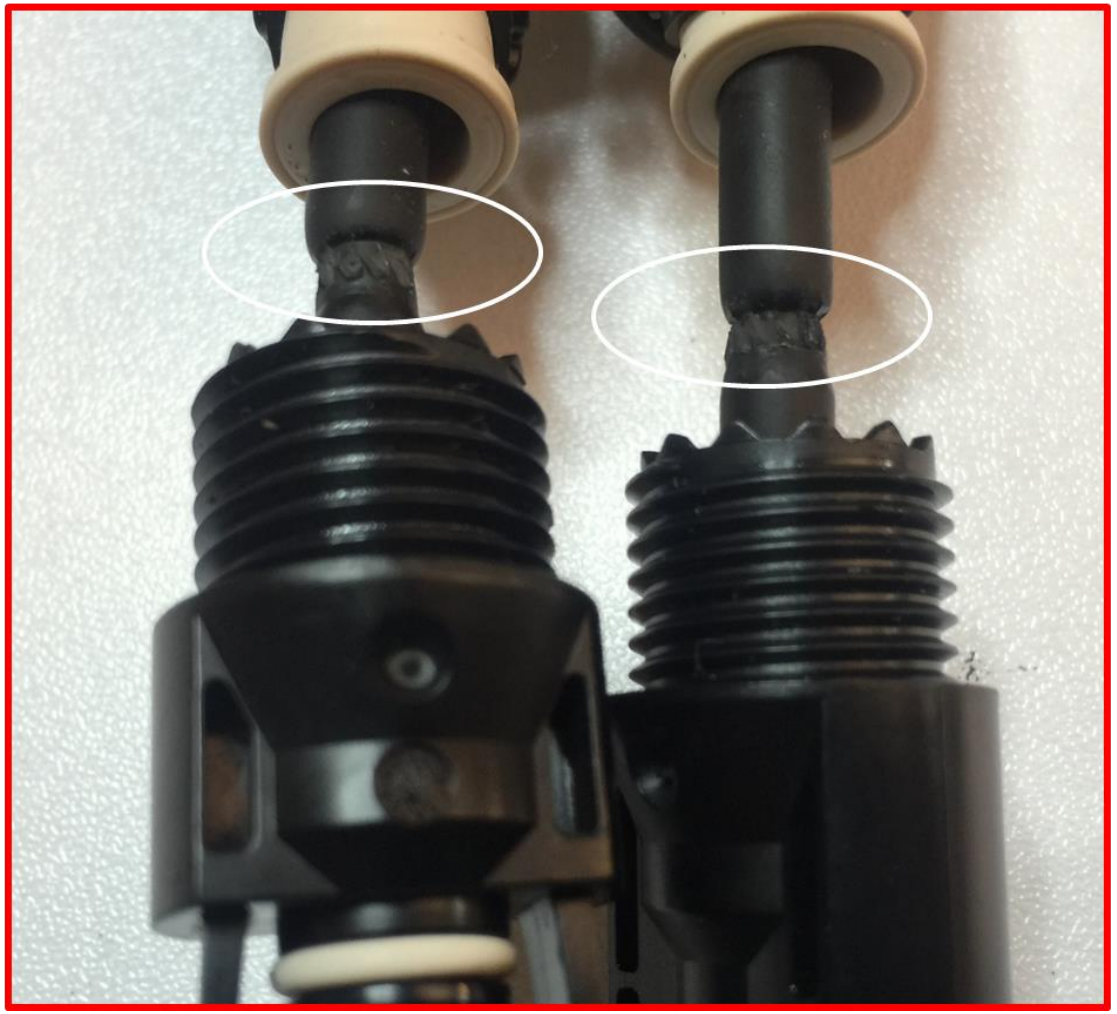
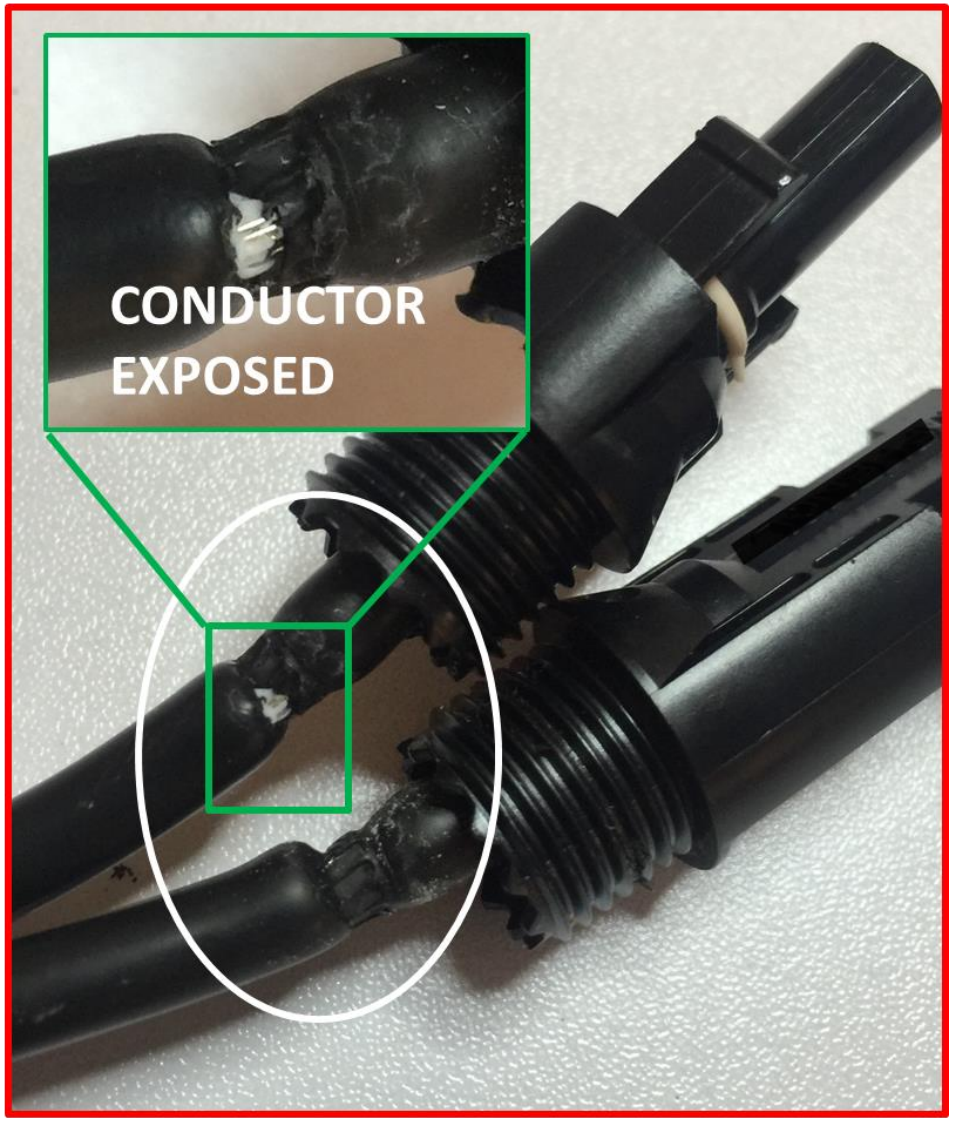
LATENT FAILURE MODES REVEALED (1)

CABLE SPLICING BY STRAIN RELIEF





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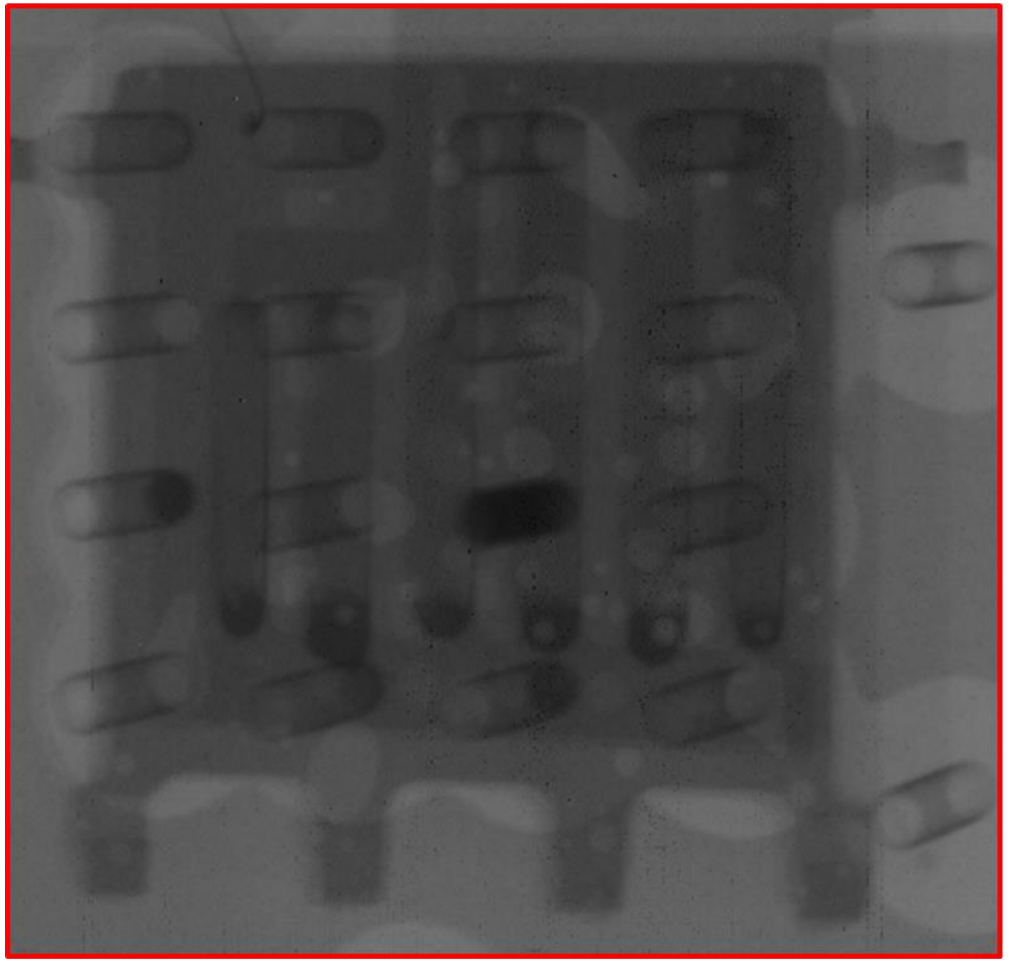
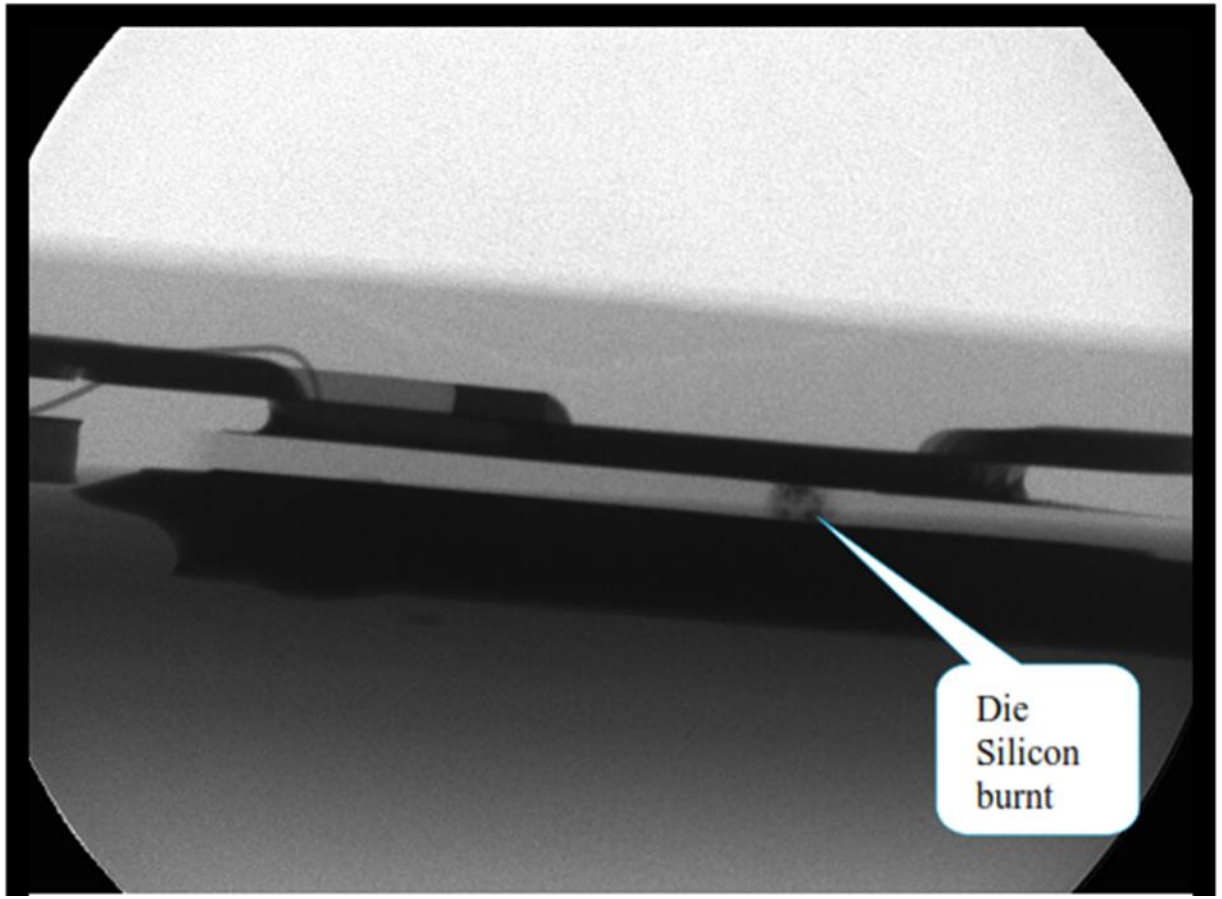
LATENT FAILURE MODES REVEALED (2)



MOSFET DIE-ATTACH DEGRADATION



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SUMMARY

- Current approach for defining reliability test could result in the rejection of a true reliable product or acceptance of a defective product.
- The accelerated stress tests are effective in assessing the reliability of module-level power electronics, provided a relationship is established between the test and field.

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Smart Embedded Power

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Power Electronics Session

Q1: Chris Deline, question to Jack Flicker: What would happen if electronics were tested together with modules?
Jack Flicker: This changes microenvironments, which depend on inverter mounting, and therefore differ between manufacturers; therefore results would differ for specific manufacturers.

Q2: Chris Deline, question to Arvind Vasan: What were your testing conditions?
Units are behind but not attached to the module. There is internal temperature sensor.

Q3: from moderators to all presenters: What are the barriers for integrated inverters?
Arvind Vasan: standard is not available
Jack Flicker: historically string inverters are more widely used
Tim Johnson: standards are very important for a small company

Q4: John Wohlgemuth question to Arvind Vasan: Perhaps two failure modes identified in your study are due to the more rapid thermal change in your modified testing procedure?
Arvind Vasan: We have not looked at that

Q5: Chris Flueckiger, question to all presenters: what kind of standards are lacking most?
Jack Flicker: Need qualification standards first
Tim Johnson: cost aspect is a concern in regard to new standards
Arvind Vasan: qualification standards first, reliability standards later

Comment, John Wohlgemuth: each manufacturer will have to have their own reliability tests, so standards for reliability will be needed later

Q6: from moderators to all presenters: What is the end game for inverters? AC or DC?
Jack Flicker and Tim Johnson: It depends. Trend is DC.

Heat Management in Microinverters with Conductive Potting

Authors: John Greenzweig, Dan Su, Albert Giogini, Matt Perry, David McDougall – HB Fuller Corportation

Potting compounds can greatly decrease the working temperature, release the stress caused by temperature variation and external force, maintain long-term sealing, so as to greatly increase the safety and reliability of the inverter.

Thermally conductive fillers are easily incorporated into the polymer matrix to dissipate heat from hot components and extend the life of the microinverter.

<u>Silicone Potting</u>

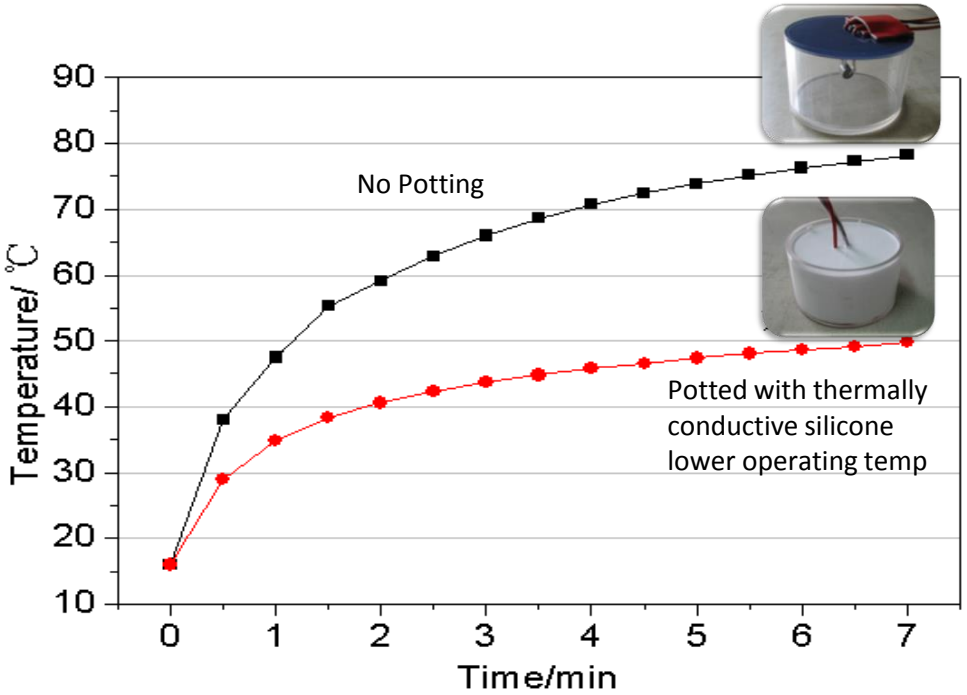
Silicones are low modulus, stress relieving polymers that operate over a wide temperature range. Silicones meet most of the UL and IEC requirements for safety and performance.

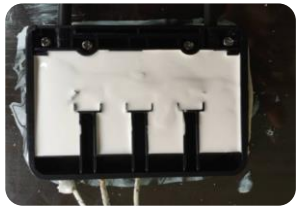
<u>Urethane Potting</u>

Urethanes are very stable polymers with excellent adhesive properties and variable hardness's. Can be delivered as liquid or hot melt solids.

<u>Epoxy Potting</u>

Epoxies have strong adhesion to most substrates and are trough and durable materials. The formula can be easily tuned to meet many mechanical requirements.





Junction Box After Potting

Junction Box Before Potting

TONSAN
together . we create

H.B. Fuller

Accurate Modeling of Mismatch Losses in PV Installations; Effects of Thermal Gradients and Module Degradation

M. Propst. N.A. Olsson

Pearllaboratories
2649 E. Mulberry St, Unit 15
Fort Collins, CO 80512

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Background

Mismatch losses arise when individual modules operate away from the maximum power point due to the constraints imposed by serial and parallel interconnections

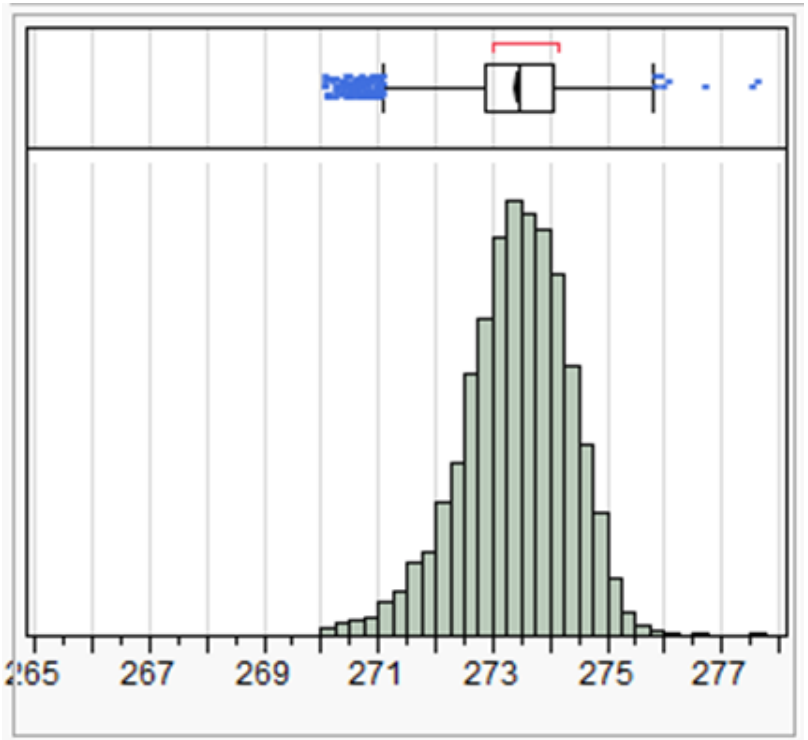
1. Current mismatch within a string
2. Voltage mismatch between strings caused by current mismatch within a string
3. Voltage mismatch between parallel strings

Sources of mismatch

- Current mismatch within a string
  - Manufacturing variations
  - Uneven soiling
  - Cloud and object shading
  - Uneven degradation
- Voltage mismatch
  - Manufacturing variation
  - Thermal gradients across and array
  - Uneven degradation
  - Voltage drop across conductors

Manufacturing Variations

Test results from factory



N=8340
Isc rms=+/- 2%
Voc rms= +/- 2%

PVSYST calculated mismatch loss: 0.4%

(Assuming a random distribution)

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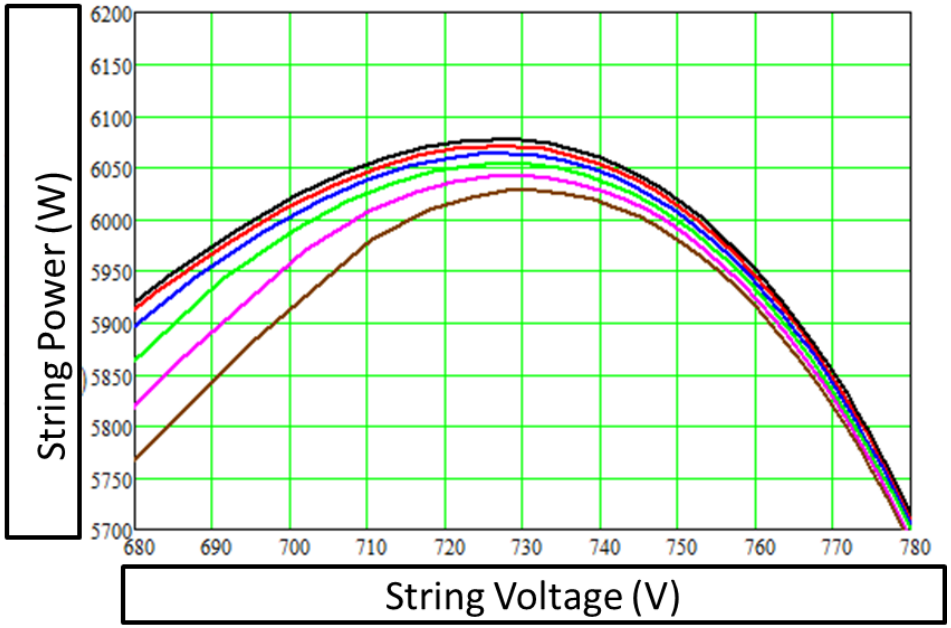
Small Isc mismatch within a string

Isc reduced 0%, 1%, 2%,3%, 4% and 5% for 2 of 20 modules



Isc mismatch	String Power (W)	Powerloss (W)	Mismatch loss (%)
0%	6077.3	0	0.00%
1%	6070.7	6.6	0.01%
2%	6063.1	14.2	0.03%
3%	6053.9	23.4	0.09%
4%	6042.2	35.1	0.18%
5%	6027.5	49.8	0.32%

The power losses for modest Isc mismatch is small

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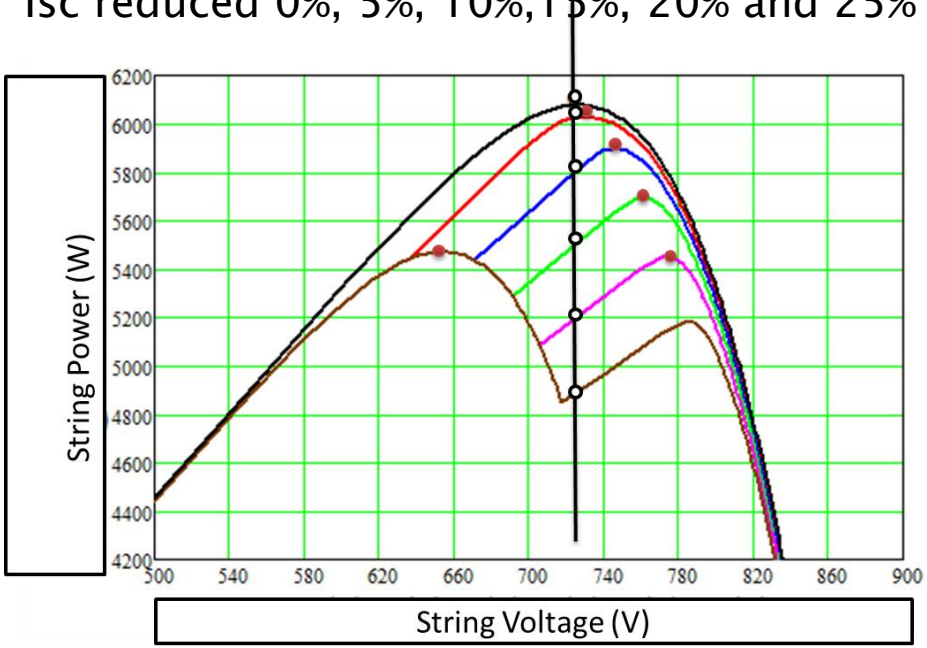
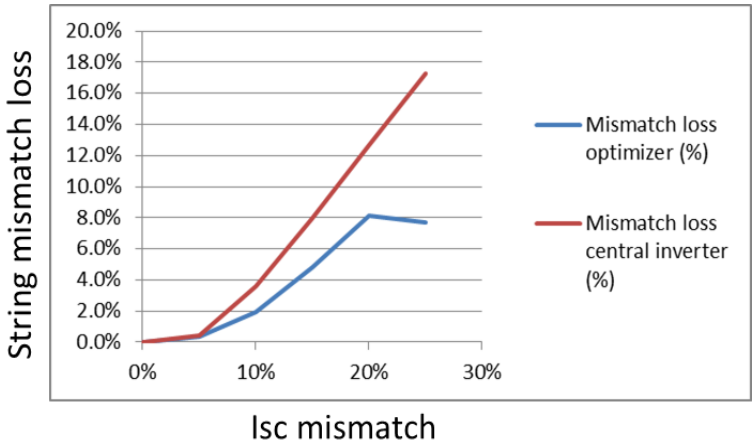
Large Isc mismatch within a string

Isc reduced 0%, 5%, 10%,15%, 20% and 25% for 2 of 20 modules





Black circles: Operating point for central inverter
Red dots: Operating point for string optimizer

Large mismatch losses when bypass diodes are activated

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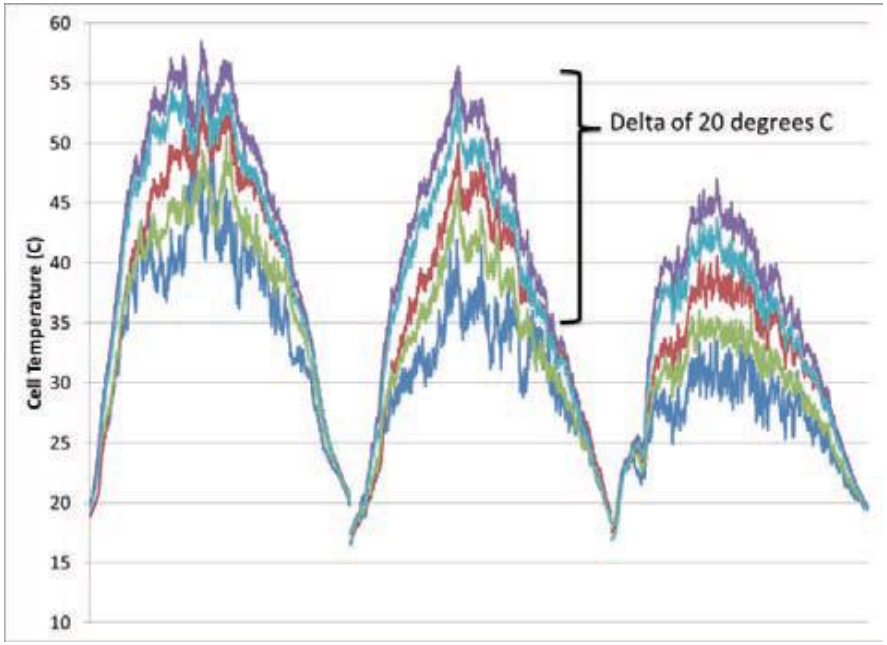
Thermal gradients; Voltage mismatch

Field data *



20C temp delta=7% Voc delta

* Trina Solar 2012

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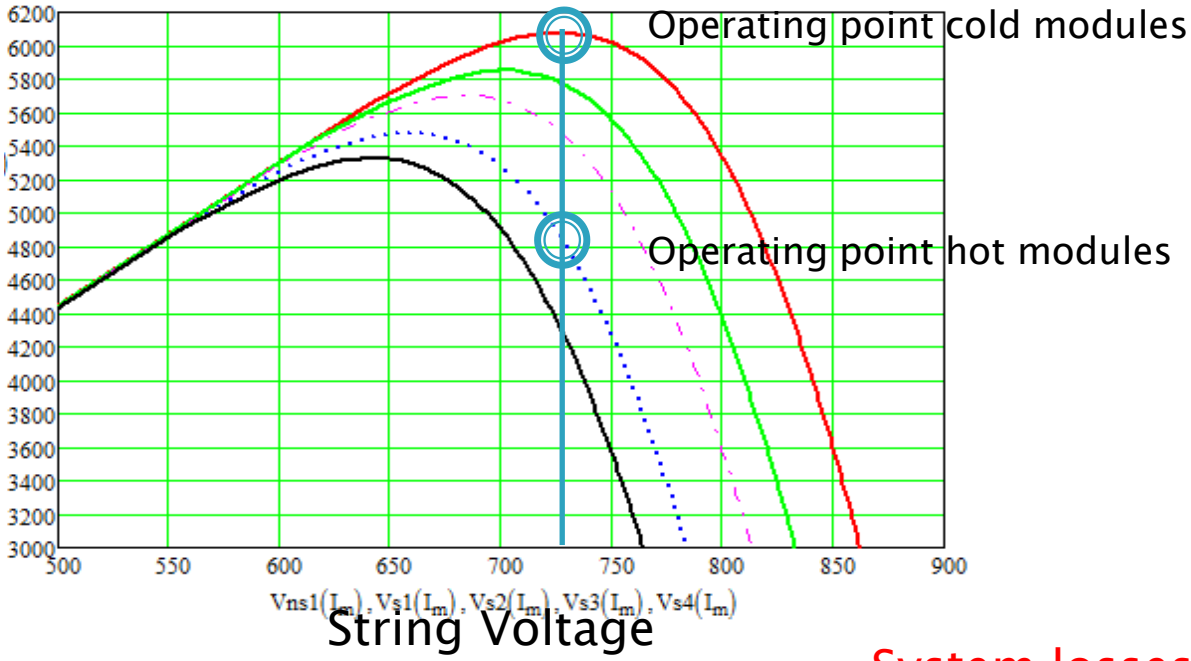
Voltage mismatch between strings

Voltage mismatch of 0%, 3%, 5%, 7% and 10%



System losses depends on number of strings affected

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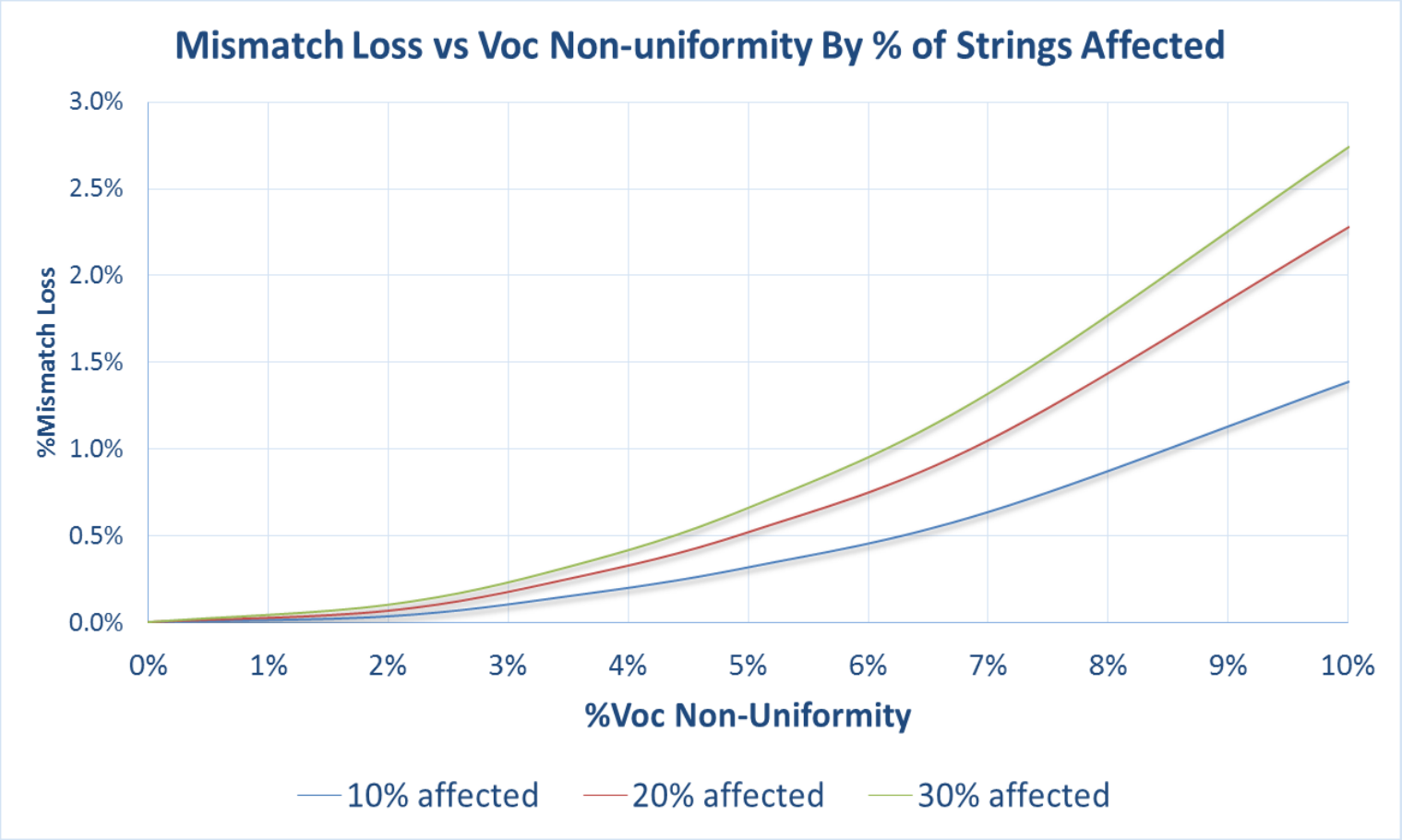
Voltage mismatch between strings



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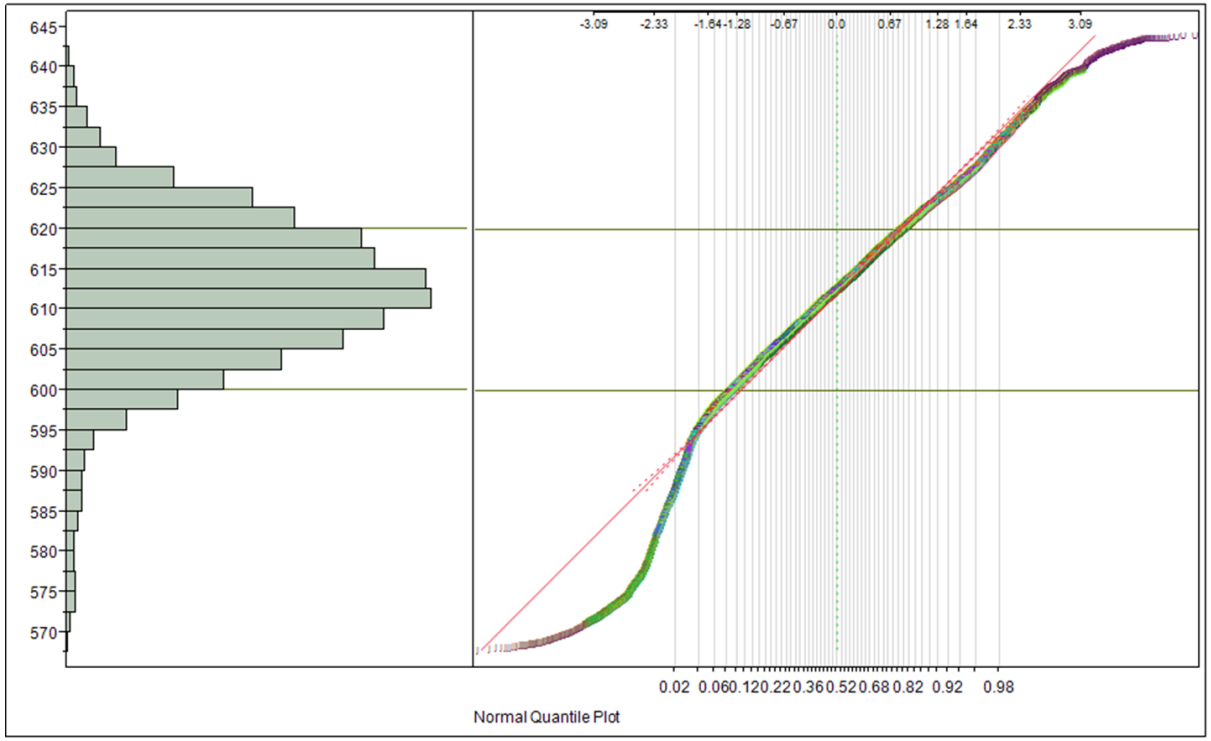
Vmp mismatch: field data

150 strings of 20 modules in cold climate



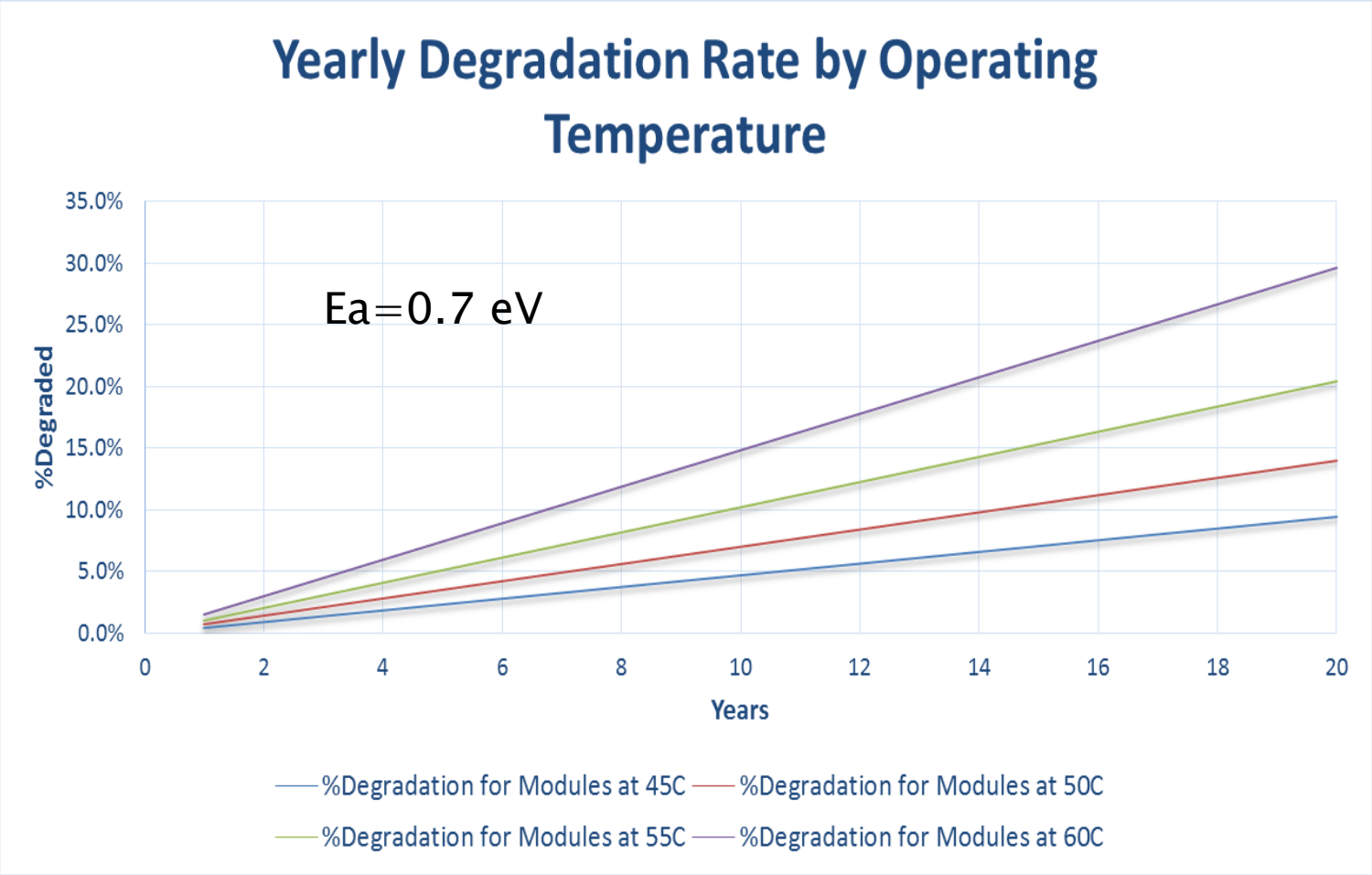
Quantiles

100.0%	maximum	643.96
99.5%		636.22
97.5%		629.68
90.0%		623.66
75.0%	quartile	618.6
50.0%	median	612.42
25.0%	quartile	606.3
10.0%		600.44
2.5%		590.12
0.5%		575.78
0.0%	minimum	567.92

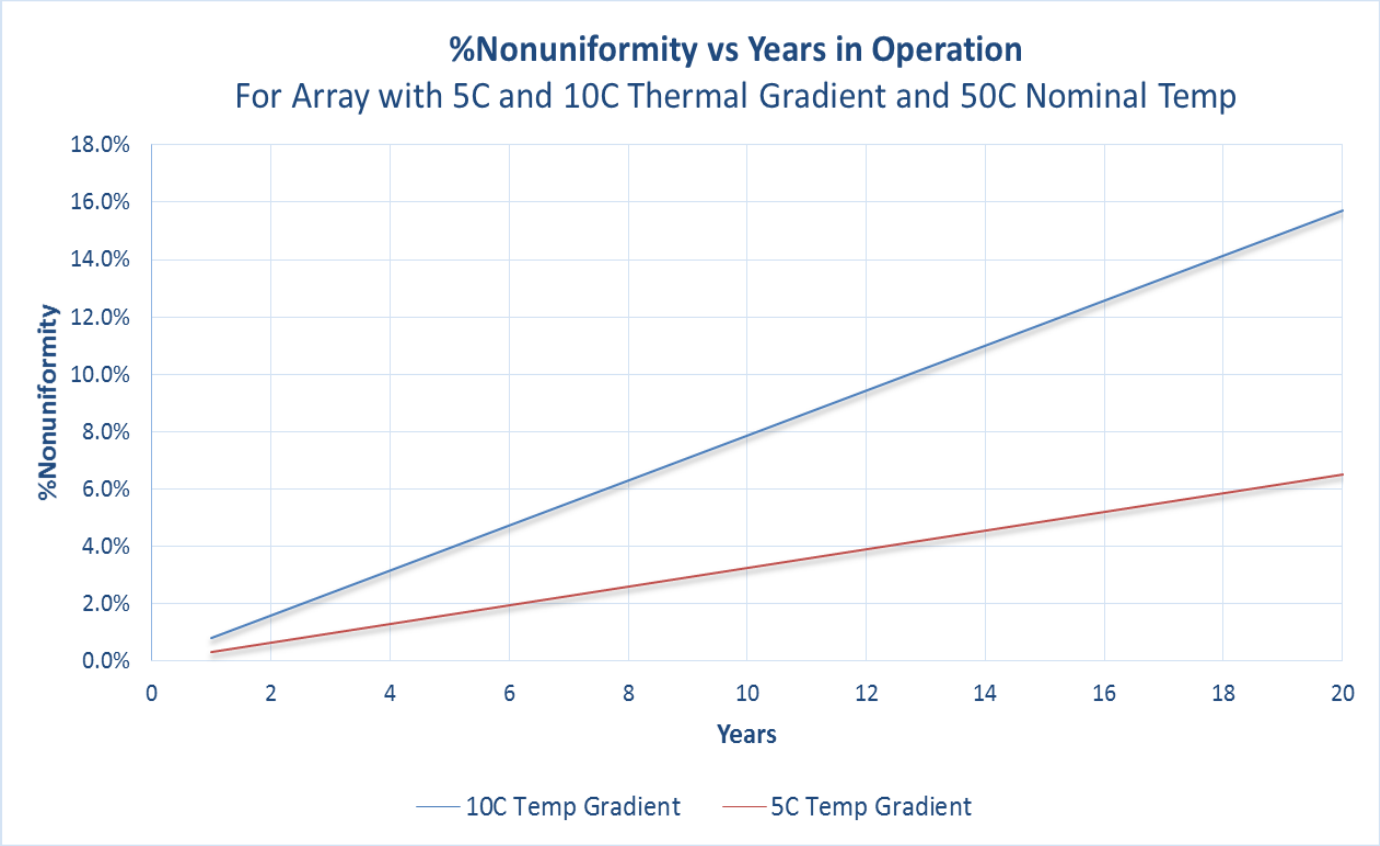
Summary Statistics

Mean	612.03354
Std Dev	9.7770395
Std Err Mean	0.0158042
Upper 95% Mean	612.06452
Lower 95% Mean	612.00257
N	382712

Effect of variable degradation rates



Non-uniformity from uneven degradation rates



Uneven degradation rates caused by thermal gradients leads over time to substantial non-uniformity

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Summary

TYPE	DEFINITION	Mismatch Loss	Considerations
Mfg Module Mismatch	Variation in electrical parameters due to process variation	0.2% to 1%	Defined by the manufacturer, the distribution in parametric values from the manufacturing process.
Thermal Gradients	Difference in temperature across modules within an array	0% to 1.5%	Size and layout of the array, tilt, racking, ground cover, climate. This will likely not degrade or improve over time.
Uneven Soiling	Non-uniform soiling of module surfaces	0% to 2%	Size and layout of the array, tilt, climate, ground cover. Modules and strings near edge of array or service "roads" will soil more quickly.
Cloud Shading	Power spikes (increases and decreases) due to clouds passing over an array	0% to 0.1%	Very hard to predict, overall impact integrated across a year is small, these are short duration spikes.
Voltage Drop in Conductors	Voltage drop along the home run cabling to the inverters	0% to 0.5%	Size and layout of the array, adequately sized cabling and/or matched cable lengths wherever possible
Variable Degradation	Cells and modules may degrade at different rates	0% to 2.5%	Compounded by thermal gradients, rates roughly double for every 10C increase in operating temperature. This value will increase over time.
	TOTAL:	0.2% to 8.1%	Huge range in possible values, likely increases over time

Modeling systems with no mismatch losses is not appropriate

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Moving towards informed decisions when module performance deviates from the expected

Joseph Walters[1,2], Eric J. Schneller[1,2], Siyu Guo[1,2], Kristopher O. Davis[1,2], and John Elmes[3]
[1]Florida Solar Energy Center, University of Central Florida, Cocoa, FL, USA
[2]c-Si Division, U.S. Photovoltaic Manufacturing Consortium, Orlando, FL, USA
[3]ApECOR, Orlando, FL 32826

Introduction

The c-Si US PVMC is working with the power electronics company ApECOR in conjunction with FSEC on in-situ PV module monitoring to advance detection algorithms that drive to actionable information to maximize field yield. The work has three areas of focus: 1) develop and test power electronics that will reside between the module and a micro-inverter to capture Current-Voltage data under a range of operating conditions (including in the dark) , 2) develop data analysis methods that utilize time-series I-V data to quantify power loss and identify root-cause mechanisms, and 3) develop software intelligence that will provide operations and maintenance personnel actionable information when modules deviate from expected performance.

In-situ PV module performance monitoring

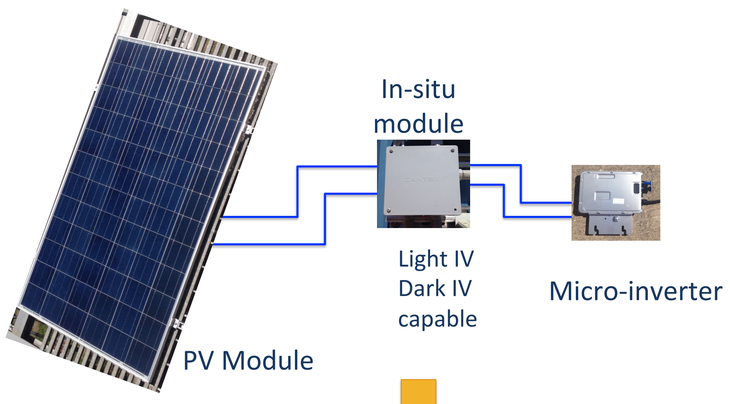
The industry currently provides module level monitoring capability through companies like Tigo Energy, SolarEdge, ABB, and Enphase. Additionally the industry is moving towards smart modules with integrated module power electronics to optimize performance and maximize energy field yield.
The c-Si US PVMC is partnering with ApECOR and the Florida Solar Energy Center to develop the means to capture and communicate the IV characteristics of modules while grid connected. Parameters will be monitored under-

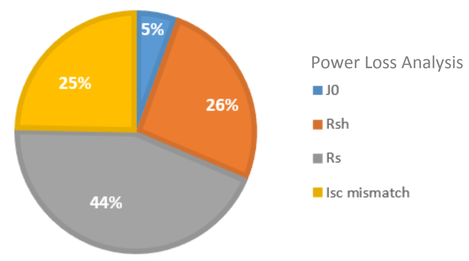
- Wide range of illumination conditions (included dark)
- Temperature variations
- Seasonal changes
- Different module technologies (silicon)

This work intends to expand on the work by Quiroz, et al. [1] and Spataru, et al. [2]

This effort will provide a means of validating new analysis methods for reporting on module performance.

[1] J. E. Quiroz, J. S. Stein, C. K. Carmignani, and K. Gillispie. *in Proceedings 42nd IEEE PVSC*, 2015, pp. 1-6.
[2] S. Spataru, D. Sera, T. Kerekes, and R. Teodorescu. *Solar Energy*, vol. 119, pp. 29-44, 2015.



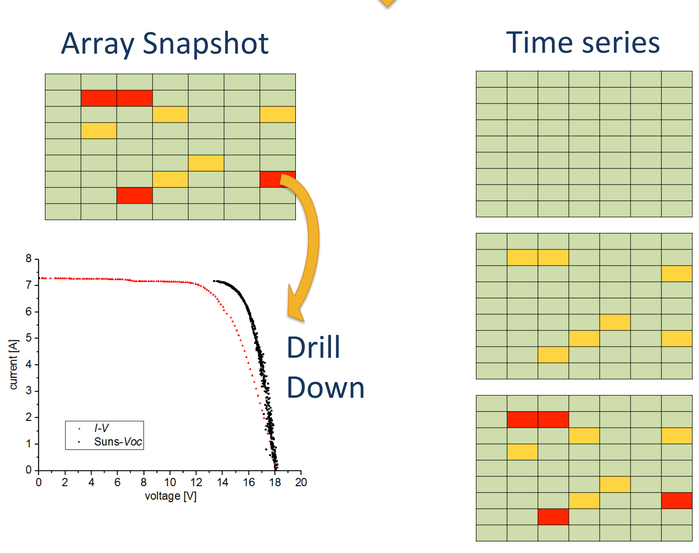


PV module parameter modeling – partitioning the power loss

PV module level IV measurements provide fundamental information about the modules behavior. Not only are the standard Voc, Isc, Pmax available but other parameters like series resistance (Rs), shunt resistance (Rsh), and fill factor (FF) may also be deduced. The poster entitled "Detecting loss mechanisms of c-Si PV modules by Suns-*V*oc and multi-irradiance *I-V* measurement " presented by Siyu Guo at this conference details those modeling efforts.

The intent of the modeling activity is to

- Develop new algorithms
- Determine the portion of the IV curves that needs to be captured and under what conditions
  - Number and location of data points per curve, monitoring frequency (capture rate)
  - Operating conditions (Temperature, illumination levels (light or dark), wind, season
  - Sensitivity to module technology
- Validate the methods –comparing models/algorithms against field data
- Partition the power losses by module parameter



Application (Software) intelligence

Turning data into an actionable information system is critically important. The informatics application will provide

- Dashboards
  - Visual representation of the performance levels
- Field view mapping
  - Selectable icons to drill down to specific performance attributes
  - Time series information (graphical or movie)
- Recommended maintenance and repair activity
  - Based on failure modes
  - Based on power loss ($) and cost to repair
- Commonality studies
  - Provide insight into manufacturing, installation, O&M processes

Conclusion

While module level monitoring is available today it has not yet gained mass market penetration. Research continues on methodologies and algorithms the can be cost effectively implemented to detect when modules are underperforming. This work intends to develop and advance some of the those algorithms and work towards providing informatics based solutions to presenting actionable information to maximize field production.

Acknowledgments

This material is based upon work supported by the Department of Energy's Office of Energy Efficiency and Renewable Energy, in the Solar Energy Technologies Program,under Award Number DE-EE0004947.

U.S. PHOTOVOLTAIC MANUFACTURING CONSORTIUM PVMC

UNIVERSITY OF CENTRAL FLORIDA

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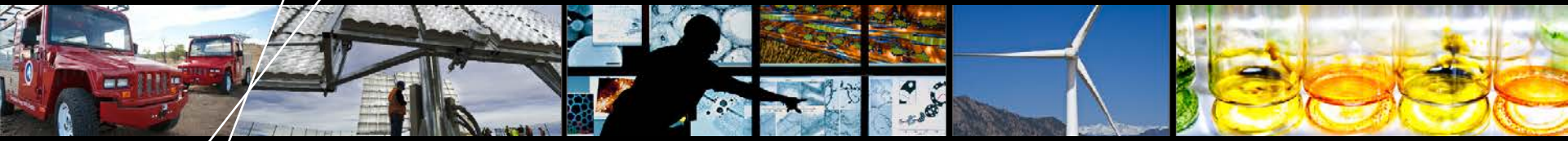
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

A Physics-Based Model to Analyze Satellite Data and the Availability of Solar Resources



Dr. Manajit Sengupta

Aron Habte , Anthony Lopez, Dr. Yu Xie and Andrew Weekley, NREL
Christine Molling CIMMS, University of Wisconsin
Dr. Christian Gueymard, Solar Consulting Services

PV Module Reliability Workshop
February 23-25,2016

Work is funded by the US Department of Energy

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

National Solar Radiation Data Base

http://nsrdb.nrel.gov

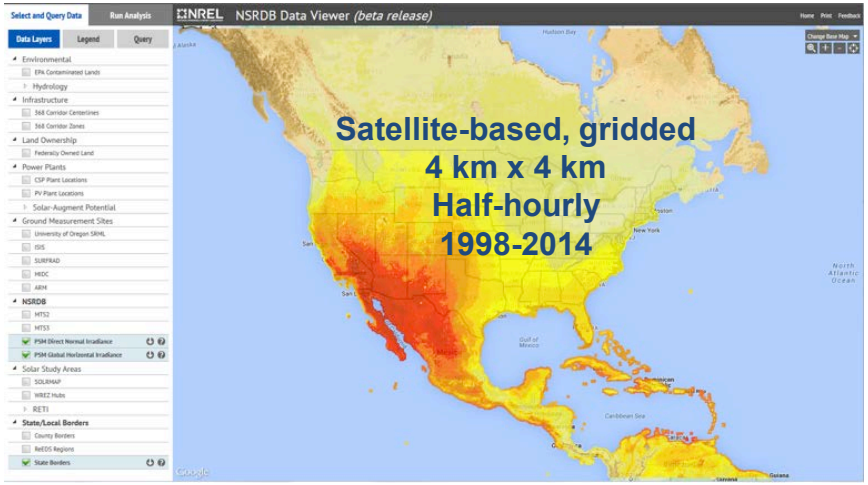
Evolution of Solar Resource Data

1952-1975 SOLMET[1] [ERDA, NOAA, 1979]

1961-1990 NSRDB[2] [DOE, NOAA, 1994]

1991-2005 NSRDB-II[3] [DOE, NOAA, 2007]

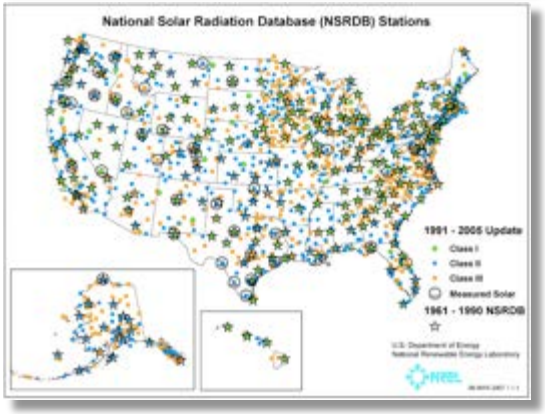
1991-2009 NSRDB-III[3] [DOE, CPR, 2012]
1998-2014 NSRDB [DOE, NOAA, UW 2015]



(1)
248 stations with
26 ***Measurement***
Stations
1977-80

(2)
239
Modeled
Stations with
56 partial
measureme
nt stations
1990

(3)
1,454 ***Modeled***
Locations
1991-2005



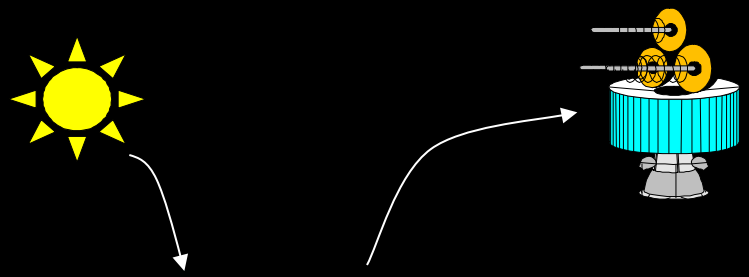
How do satellites model surface radiation?

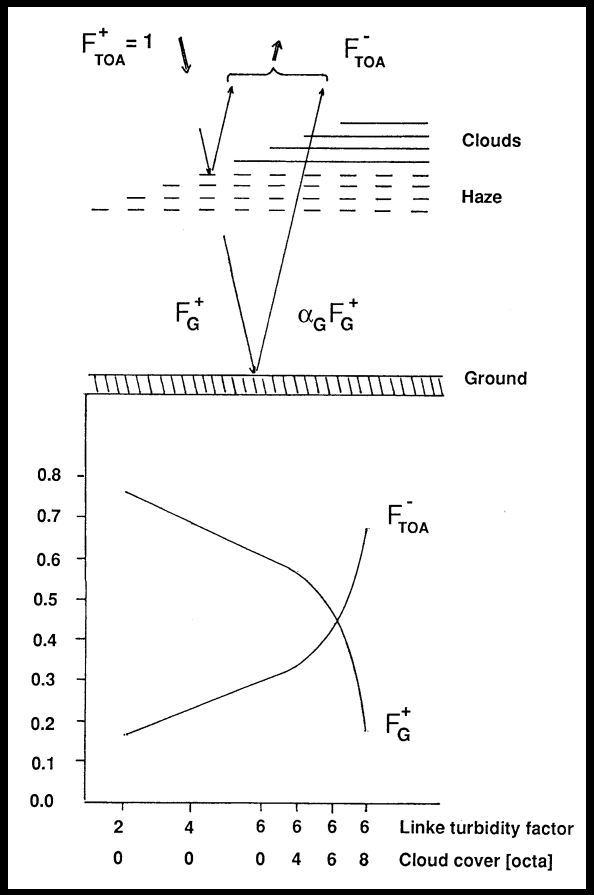
- **Empirical Approach (Industry standard traditional approach):**
  - Build model relating satellite measurements and ground observations.(cloud index and clearness index)
  - Use those models to obtain solar radiation at the surface from satellite measurements.

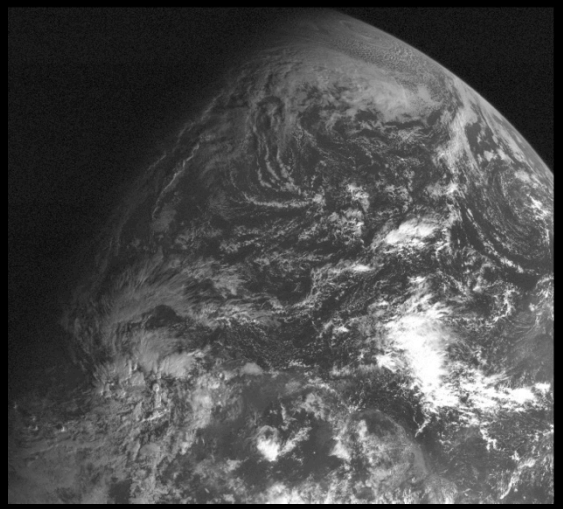
- **Physical Approach: (the new approach)**
  - Retrieve cloud and aerosol information from satellites
  - Use the information in a radiative transfer model

Empirical Approach to Satellite Modeling

Basic principle







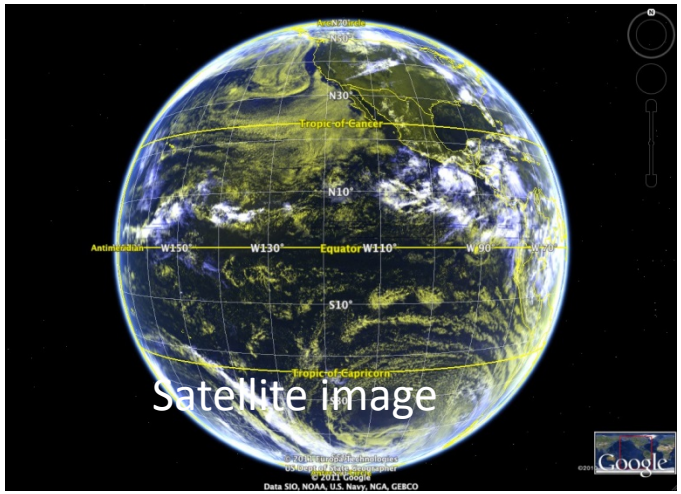
$$\frac{F^+_G}{F^+_{TOA}} = a - \frac{b\ F^-_{TOA}}{F^+_{TOA}}$$

Clearness Index

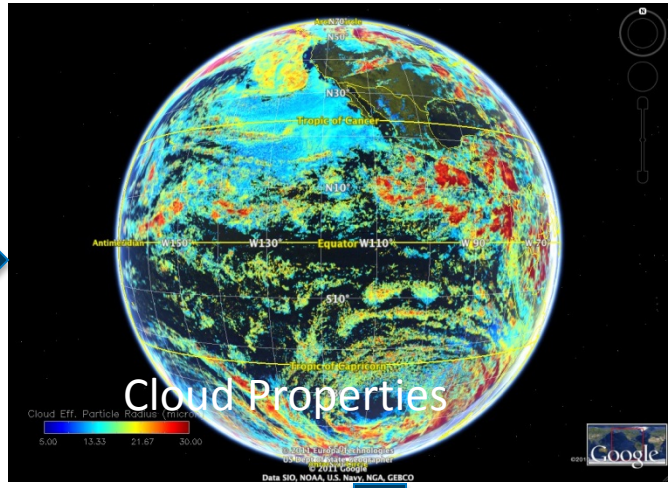
Satellite Reflectance (cloud Index)

Richard Perez, et al.

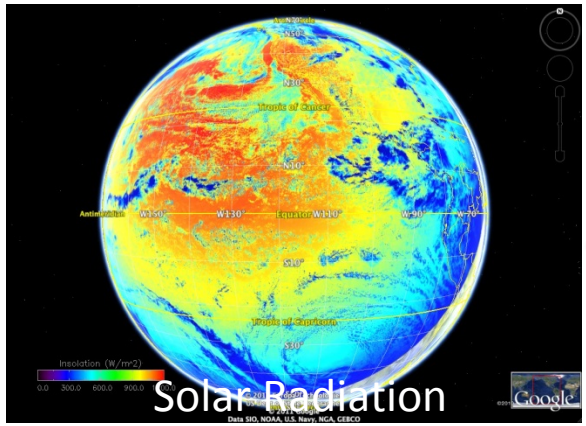
Physical Approach to Satellite Modeling



Satellite based Cloud Retrieval Model



Radiative Transfer Models



Physical Approach to Satellite Modeling

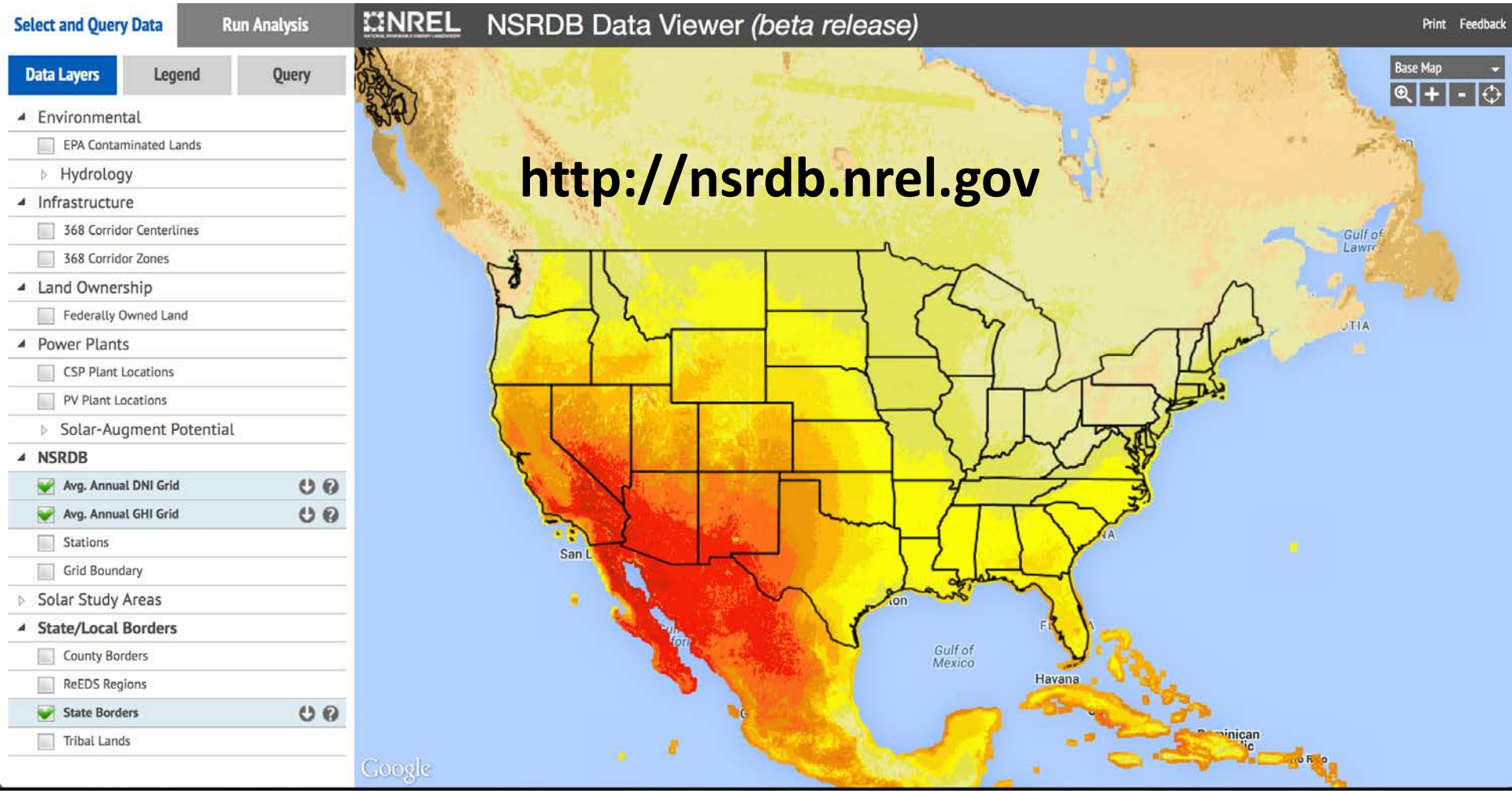
Satellite Retrieval:
Inputs: Satellite radiance from 5 channels of GOES
Outputs: cloud mask
Cloud properties including cloud type and cloud optical thickness

Ancillary data:
Aerosols from MODIS and MISR satellites
Ozone TOMS/OMI satellites
Water Vapor from NWP model (GFS)
Snow from NSIDC
Atmospheric Profiles Temperature, Pressure from (GFS)

Radiative Transfer Model:
(e.g. Bird, SOLIS, REST2)
Inputs: Aerosol, Water Vapor, Ozone, Elevation, cloud mask, cloud properties

Output: GHI and DNI under all sky conditions

Accessing the NSRDB Data



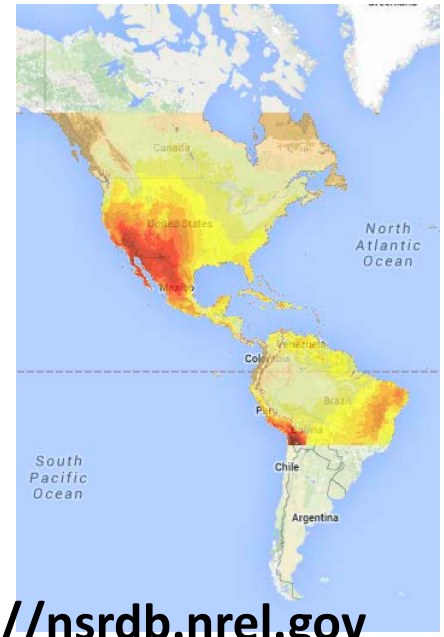
GIS based data access with web-service for multi-pixel download

Includes ancillary meteorological data for PV/CST modeling using SAM and PVWatts

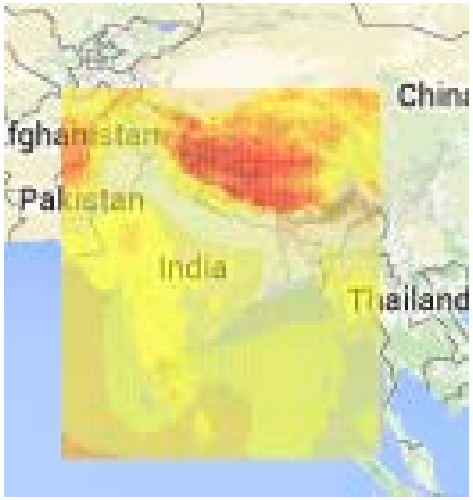
Product Availability and Timelines

USA and North and South America

- **Current product (4 km half hourly) available from 1998-2014 (Model V2).**
- **Typical Meteorological Year (TMY) product is also available.**
- **Semi-annual updates with major modeling changes to be deployed for December update.**
- **From 2016 annual datasets from previous year will be available by following June.**
- **Investigation into feasibility of monthly update.**
- **Multiple summary products to be developed to add value to current datasets.**



http://nsrdb.nrel.gov

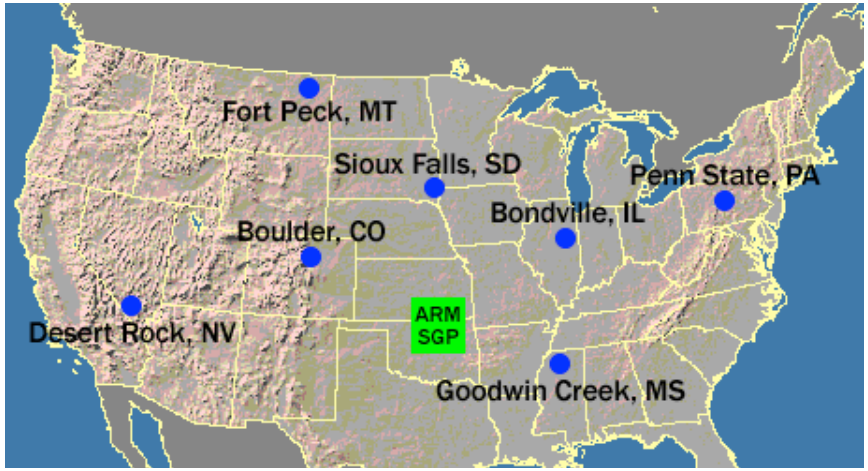


India and South East Asia

Data available from 2000-2014.

TMY will be available by end of March 2016.

Validation of Satellite product using Ground Data



http://www.esrl.noaa.gov/gmd/grad/surfrad/

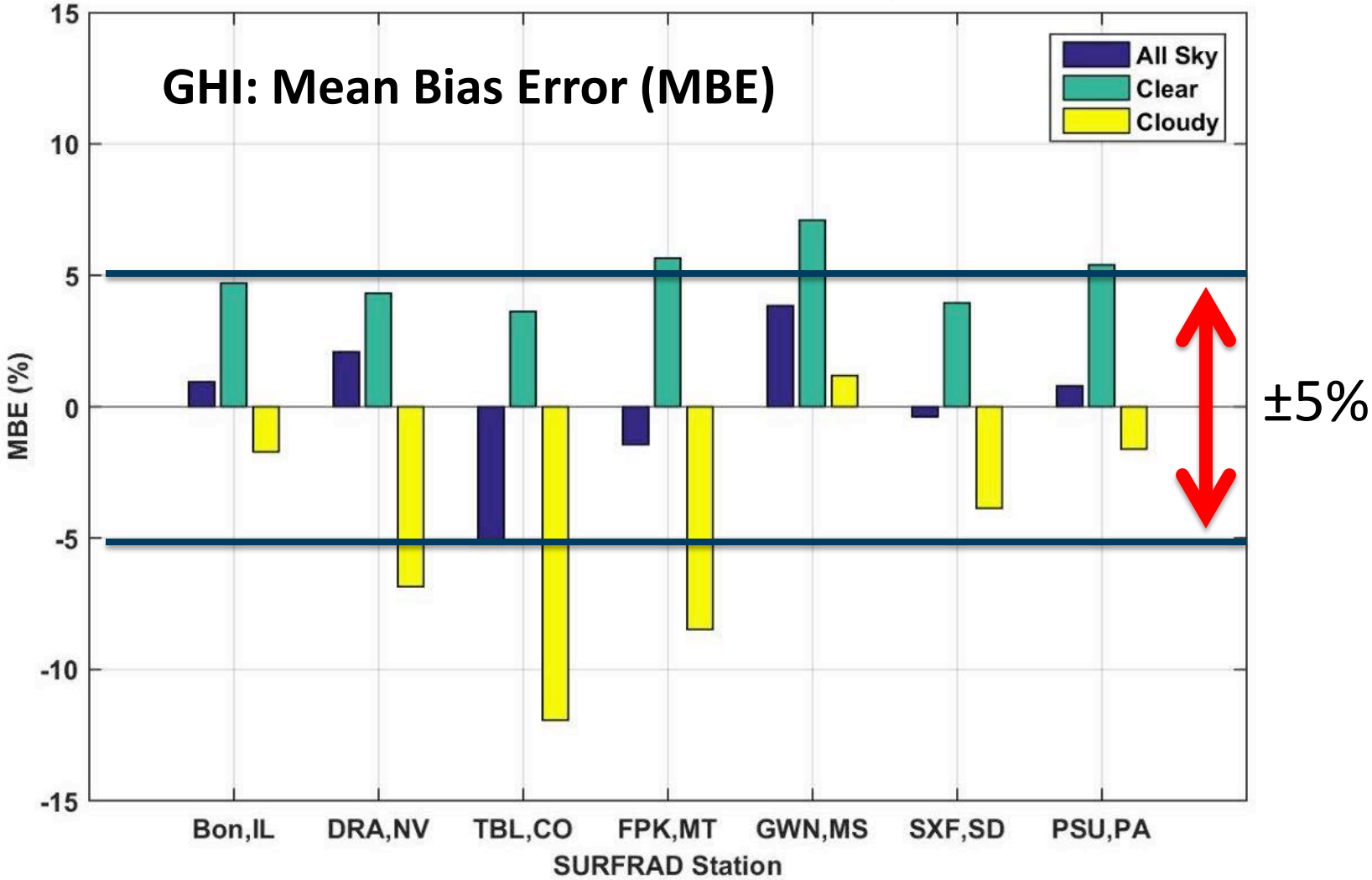
NOAA SURFRAD

DATASTREAMS:
GHI, DNI and Diffuse

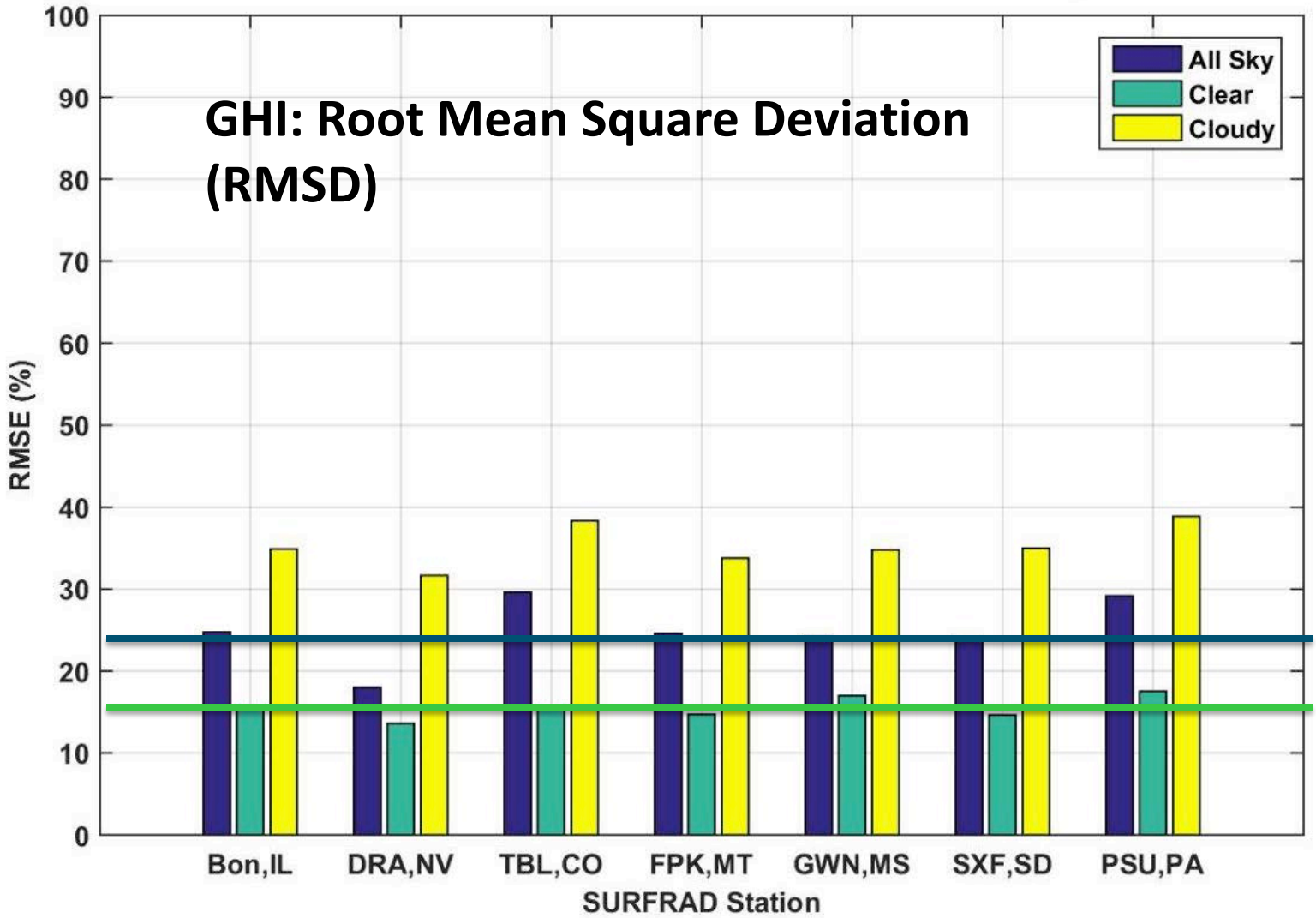
Comparison with 2005-2012 satellite product

Code	Name	Latitude	Longitude	Elevation	Time Zone	Installed
BND	Bondville, Illinois	40.05° N	88.37° W	230 m	6 hours from UTC	Apr-94
TBL	Table Mountain, Boulder, Colorado	40.13° N	105.24° W	1689 m	7 hours from UTC	Jul-95
DRA	Desert Rock, Nevada	36.63° N	116.02° W	1007 m	8 hours from UTC	Mar-98
FPK	Fort Peck, Montana	48.31° N	105.10° W	634 m	7 hours from UTC	Nov-94
GCM	Goodwin Creek, Mississippi	34.25° N	89.87° W	98 m	6 hours from UTC	Dec-94
PSU	Penn. State Univ., Pennsylvania	40.72° N	77.93° W	376 m	5 hours from UTC	Jun-98
SXF	Sioux Falls, South Dakota	43.73° N	96.62° W	473 m	6 hours from UTC	Jun-03

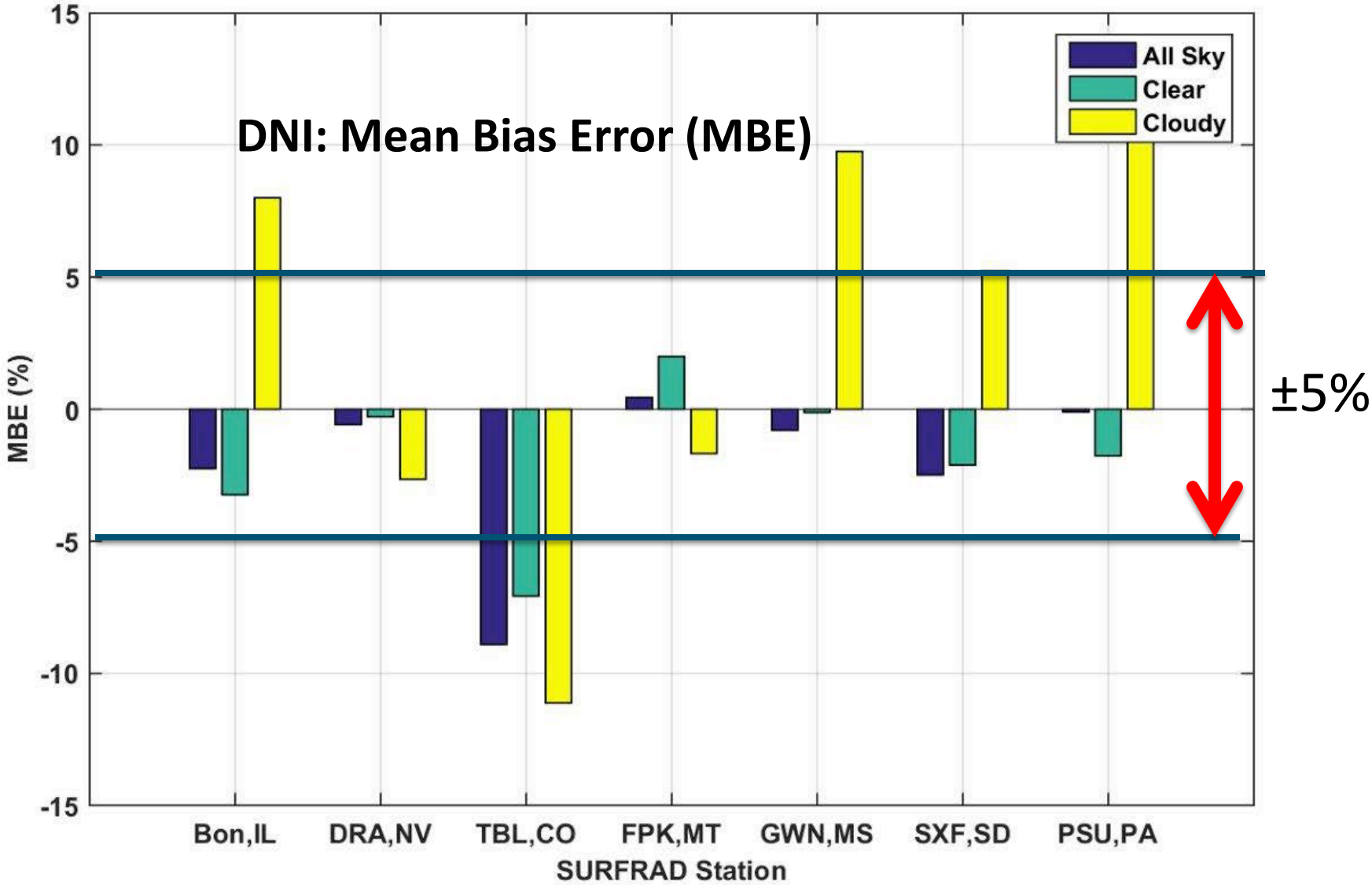
Validation with Surface Measurements



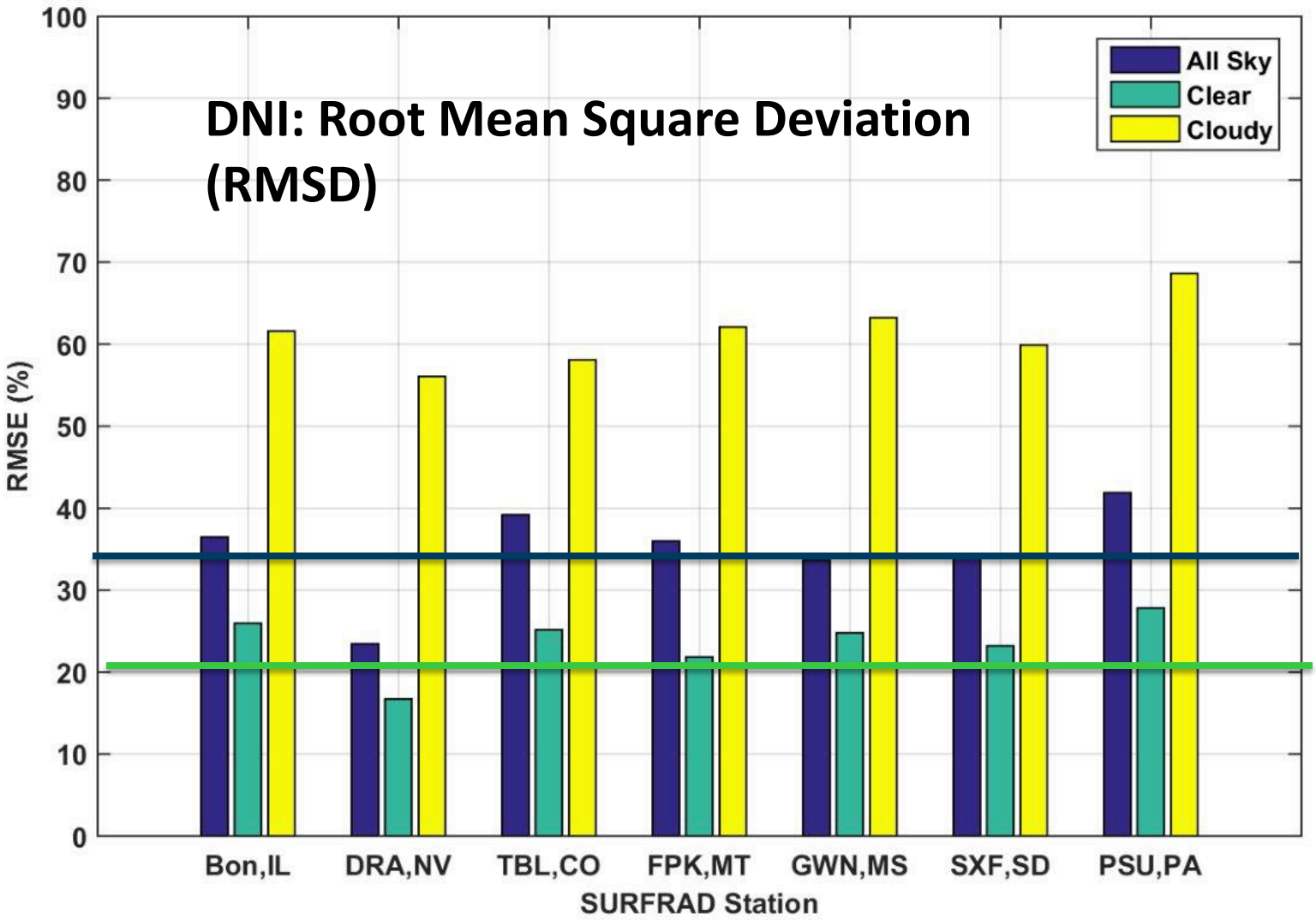
Validation with Surface Measurements



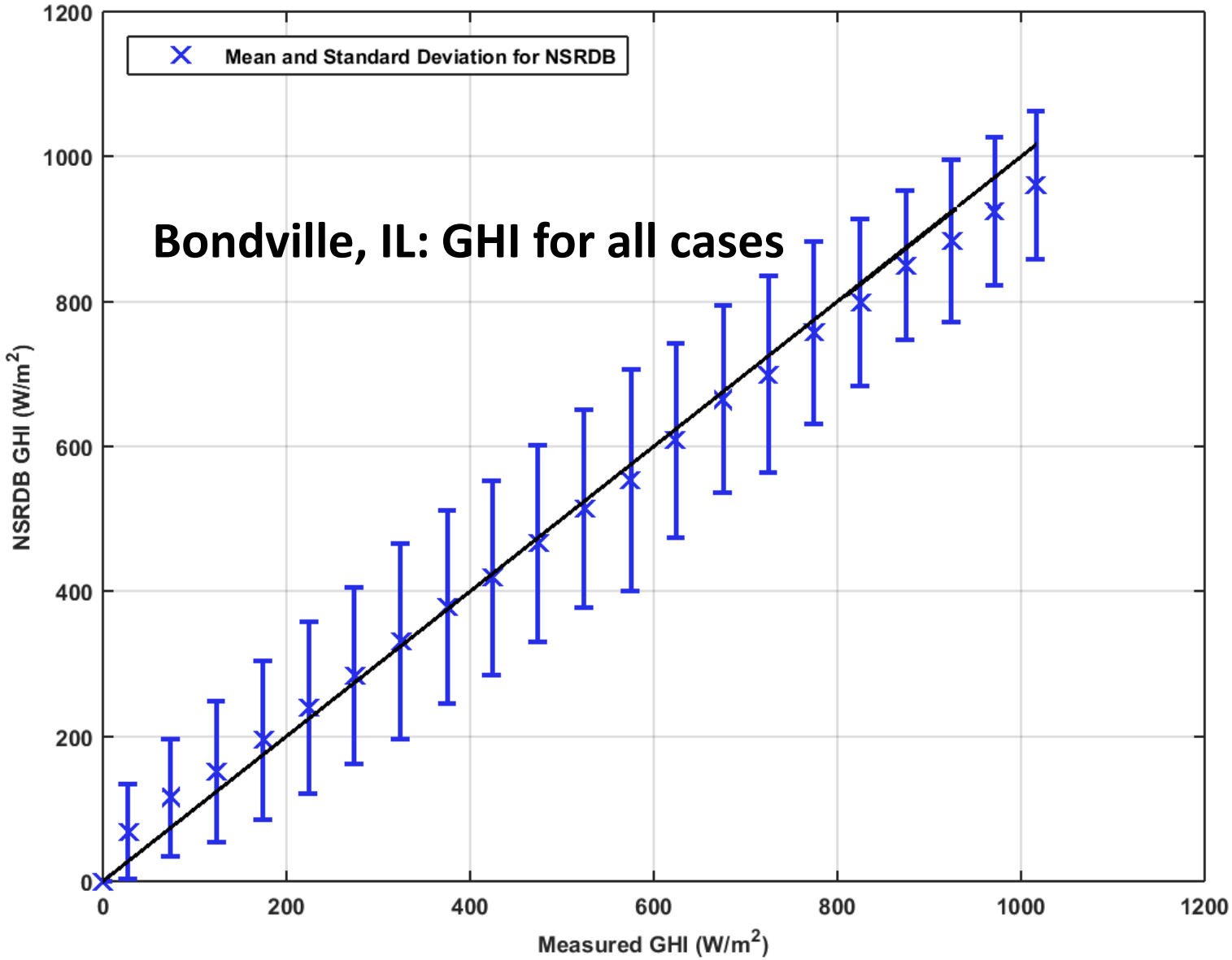
Validation with Surface Measurements



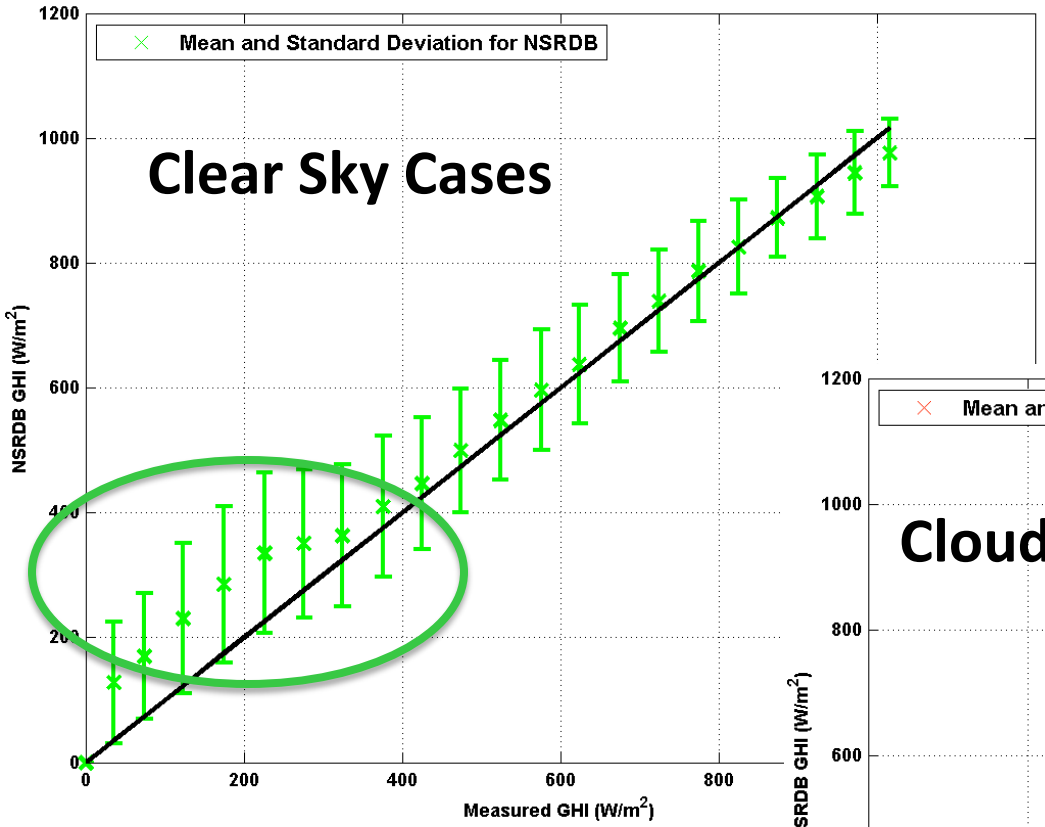
Validation with Surface Measurements



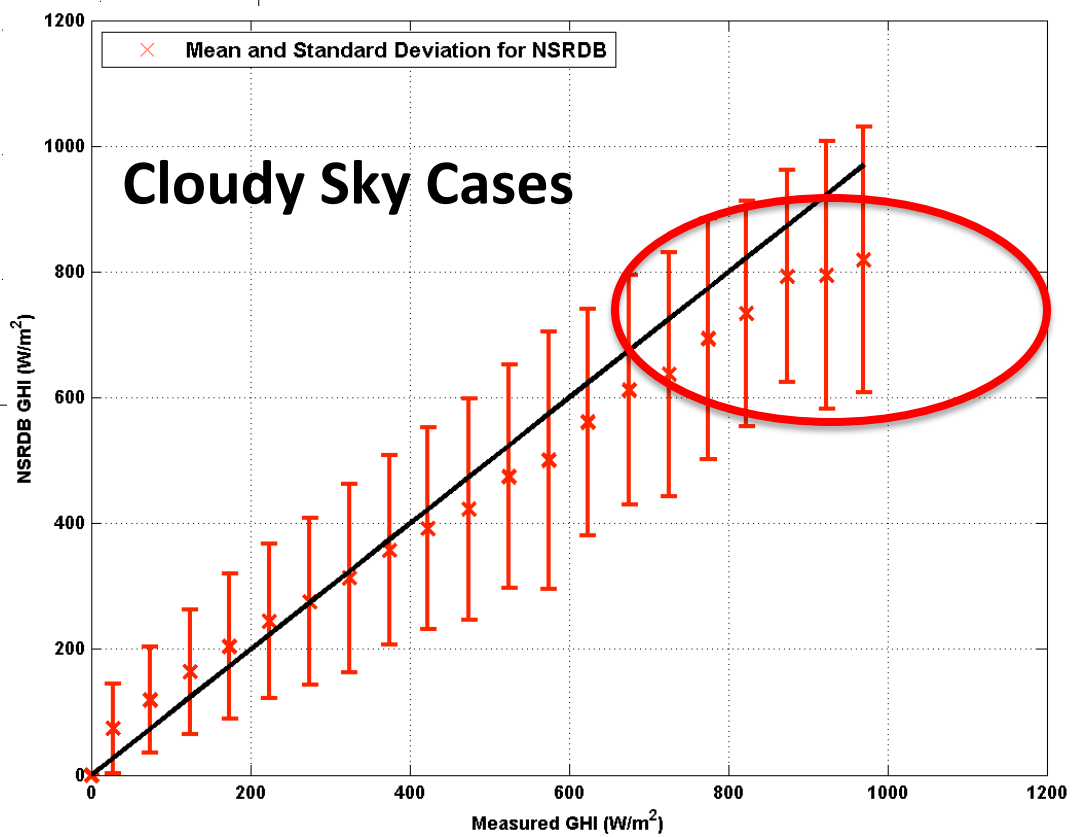
Validation with Surface Measurements



Validation with Surface Measurements



Bondville, IL: GHI



Conclusions

- New gridded satellite product available publicly from NREL.
- Dataset freely available from (http://nsrdb.nrel.gov).
- Resolution of NSRDB is 4 km, 30 minute.
- 1998-2014 currently available with 2015 update available in June.
- Accurate aerosol and water vapor information is critical in properly modeling clear sky GHI and DNI.
- Significant uncertainty in cloudy cases mostly from uncertainty from broken and thin clouds.

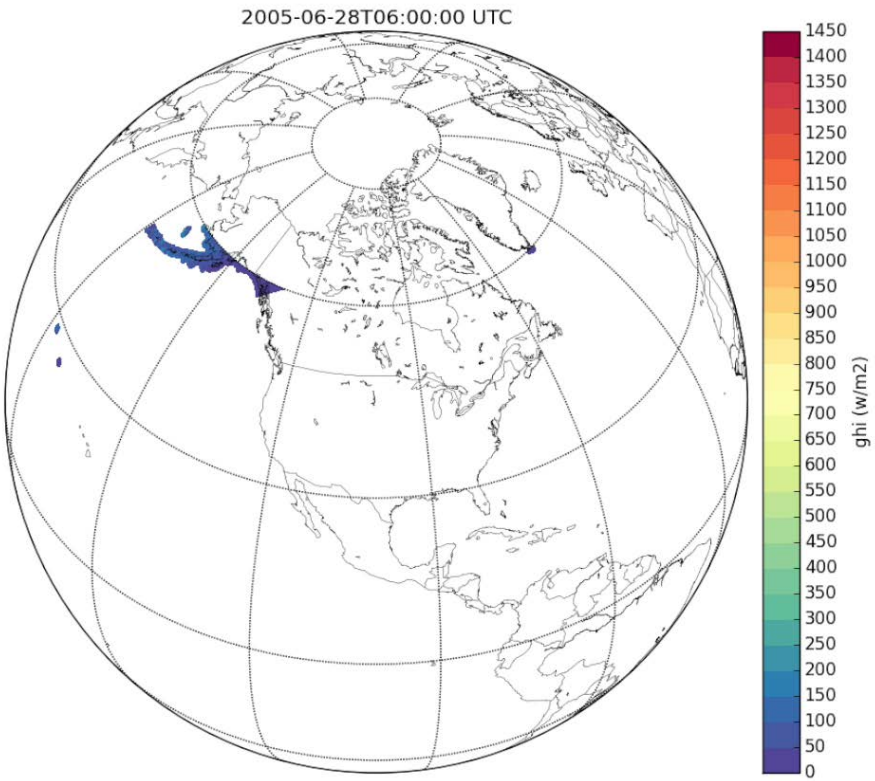
Future Work

- **Inclusion of daily variability from MACC aerosols.**
- **Improved surface albedo time series to reflect land use changes.**
- **Improved identification of high albedo surfaces (sand and snow).**
- **5 minute data from GOES-R.**
- **Time Series of Spectral and UV datasets in the plane of array.**

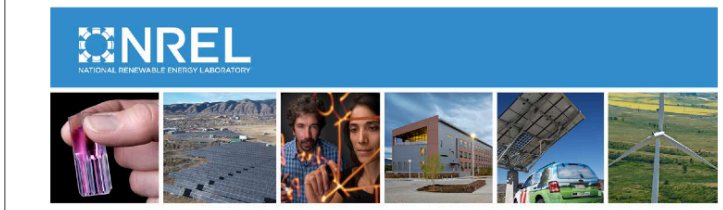
Thank You!

Contact: manajit@nrel.gov

http://www.nrel.gov/solar_radiation



http://nsrdb.nrel.gov



Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications

M. Sengupta,[1] A. Habte,[1] S. Kurtz,[1] A. Dobos,[1] S. Wilbert,[2] E. Lorenz,[3] T. Stoffel,[4] D. Renné,[5] C. Gueymard,[6] D. Myers,[7] S. Wilcox,[4] P. Blanc,[8] and R. Perez[9]

[1] *National Renewable Energy Laboratory*
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[7] *National Renewable Energy Laboratory—Retired*
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This update was prepared in collaboration with International Energy Agency Solar Heating and Cooling Programme Task 36 and Task 46

NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency & Renewable Energy Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-5D00-63112
February 2015

Contract No. DE-AC36-08GO28308

http://www.nrel.gov/docs/fy15osti/63112.pdf

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Field experience: Degradation Rates, Lifetimes & Failures

PV Module Reliability Workshop

Lakewood, CO

Dirk Jordan, Sarah Kurtz

2/24/2016

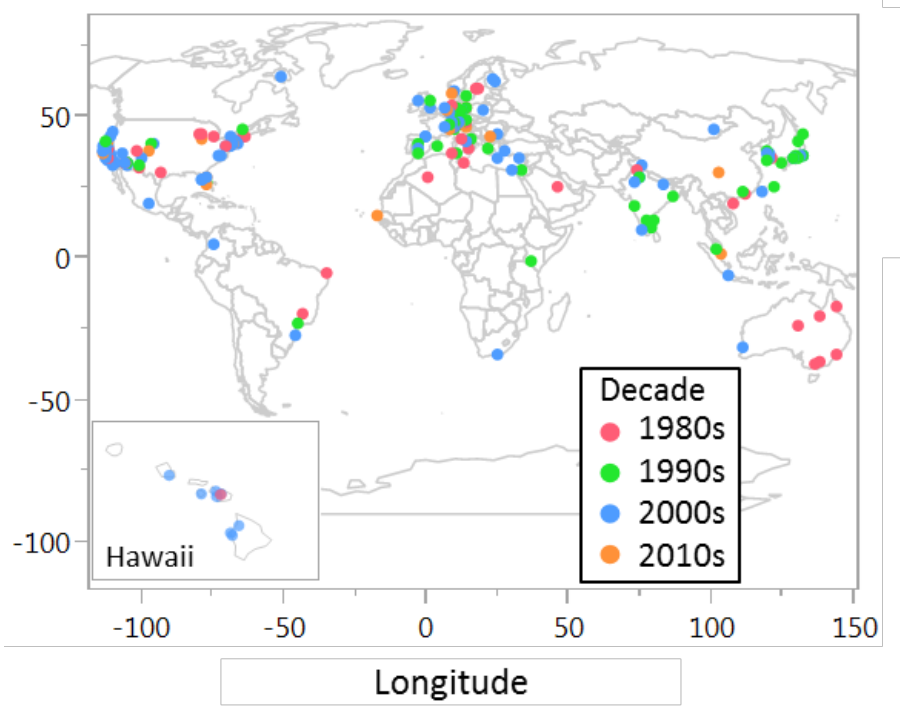
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Outline

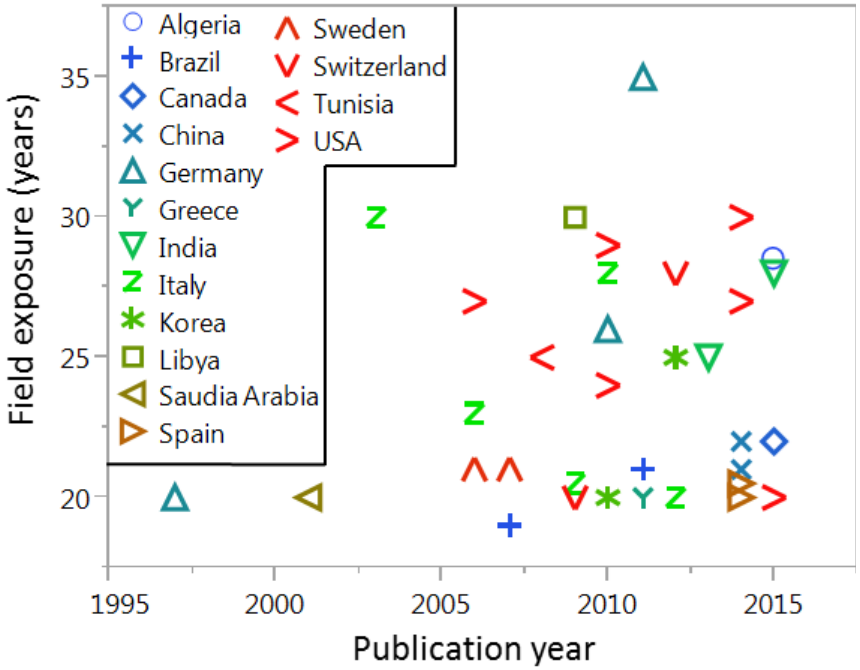
- Degradation rates
  - Study type (using nameplate rating vs. multiple measurements)
  - Climate
  - Module vs. system
- Degradation curves - non-linearity
- Failure modes

> 30 system studies of 20+ years field exposure

Geographic distribution of degradation rates (R_d)



Studies of systems > 20+ years in field

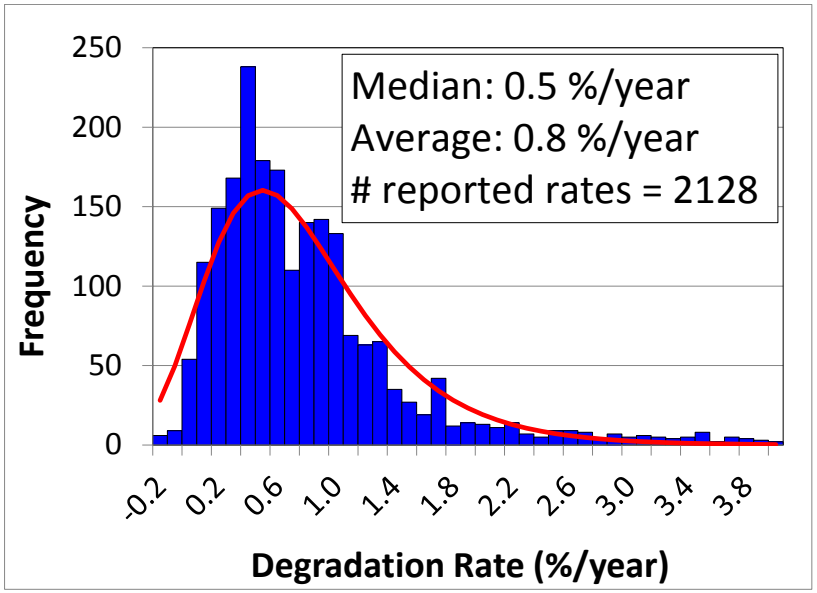


Increased interest in recent years in long-term performance & degradation

Sampling bias is present – representative of the population?

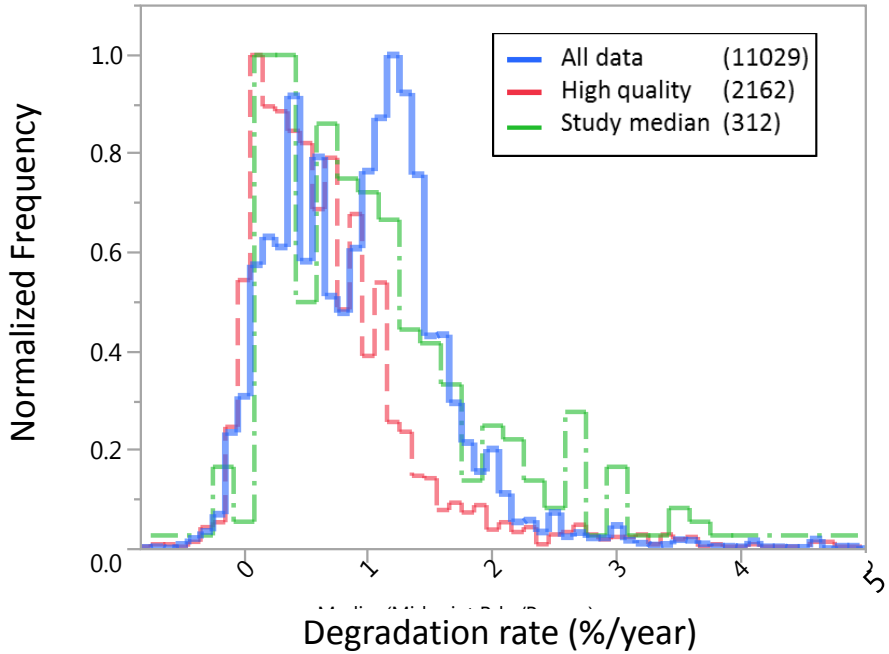
Literature survey

2011



Jordan et al., "Degradation Rates – An Analytical Review", Progress in PV, 2011

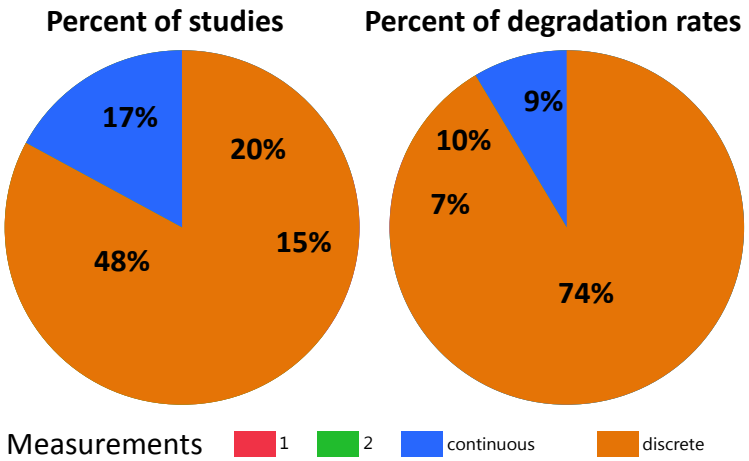
2016



Jordan et al., "Compendium of photovoltaic degradation rates", Progress in PV, 2016

- Few studies with > 1000 modules
- Aggregated distribution is dominated by particular module, system, mounting, method etc.
- Counteract overrepresentation → analyze in different ways
- Median per study & system → second peak disappears
- High quality data (multiple measurements, calibrations etc.) → second peak disappears

Majority of R_d are determined by single measurement.



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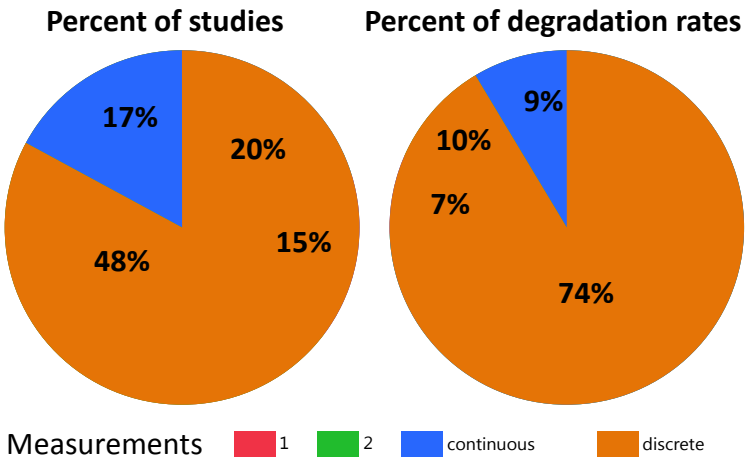
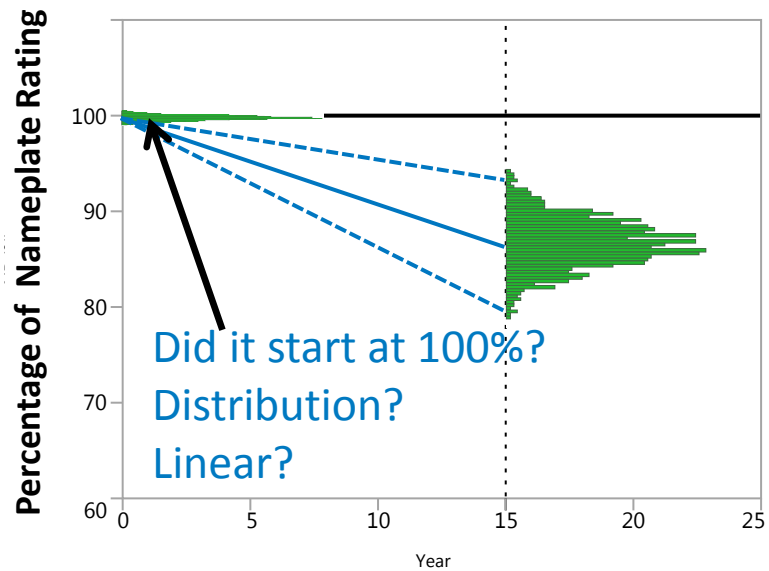
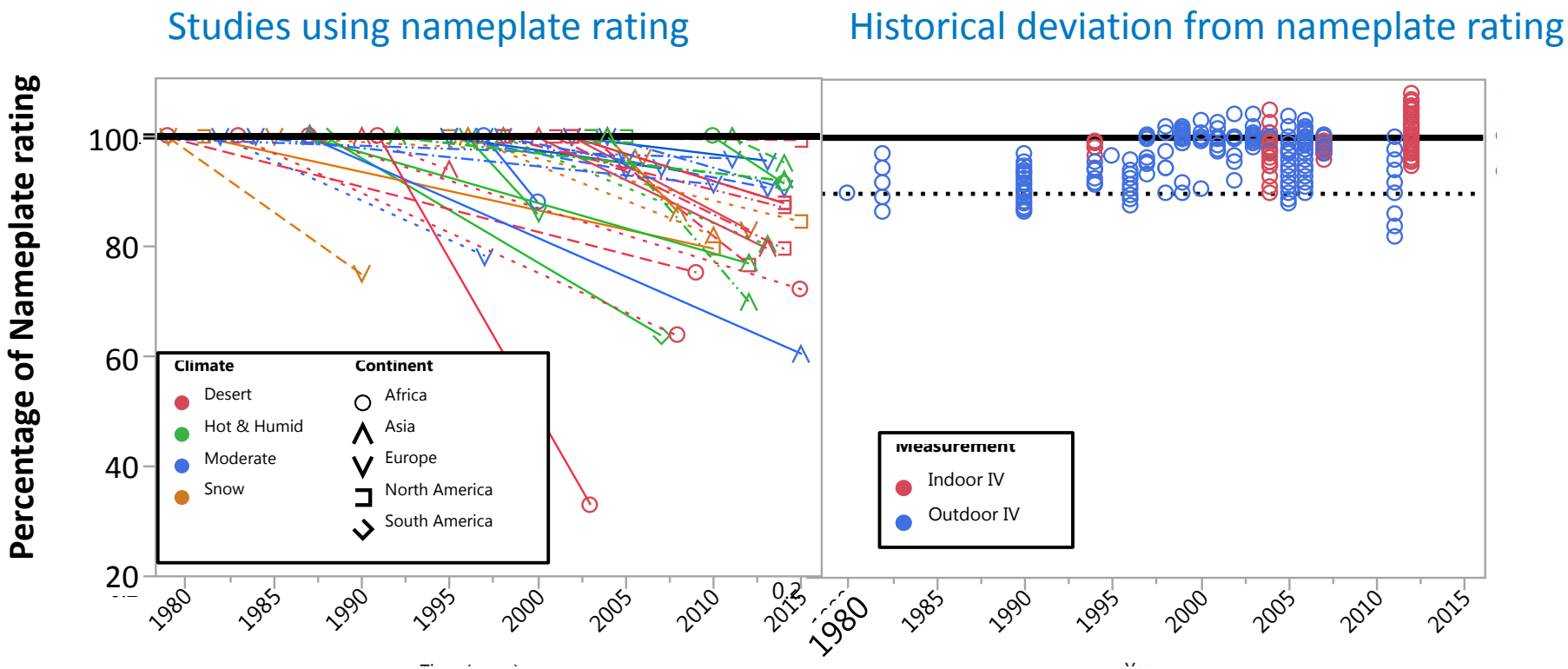


How are R_d determined with 1 measurement?



R_D using nameplate rating may have significant error.

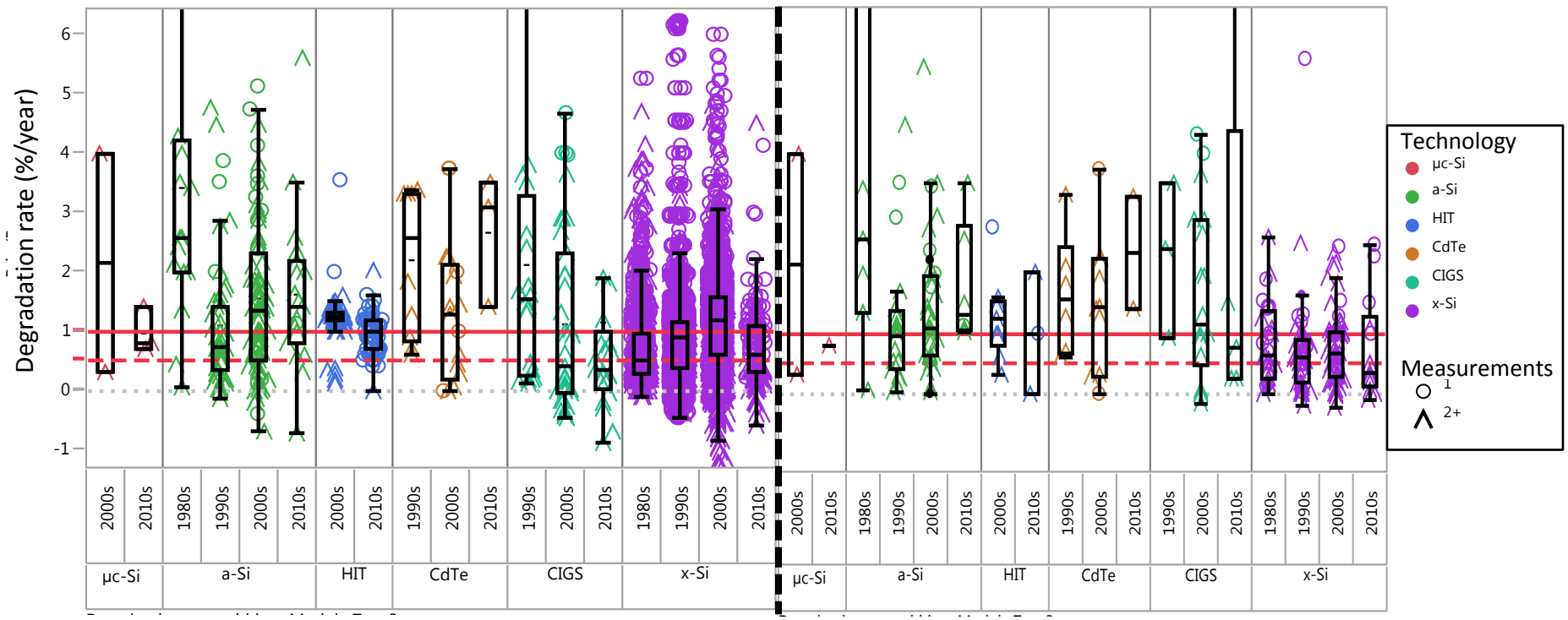


- Indoor IV seem closer to nameplate rating (though limited data)
- Outdoor seem farther away trending towards nameplate rating. Outdoor data may include light-induced degradation (LID)

Reducing sampling bias x-Si → median 0.5 - 0.6, mean 0.8 %/year

All degradation rates

Median per study & system



Significant difference between all R_d & median per study & system

a-Si R_d > 1 %/year

Hetero interface (HIT) R_d similar to a-Si than x-Si

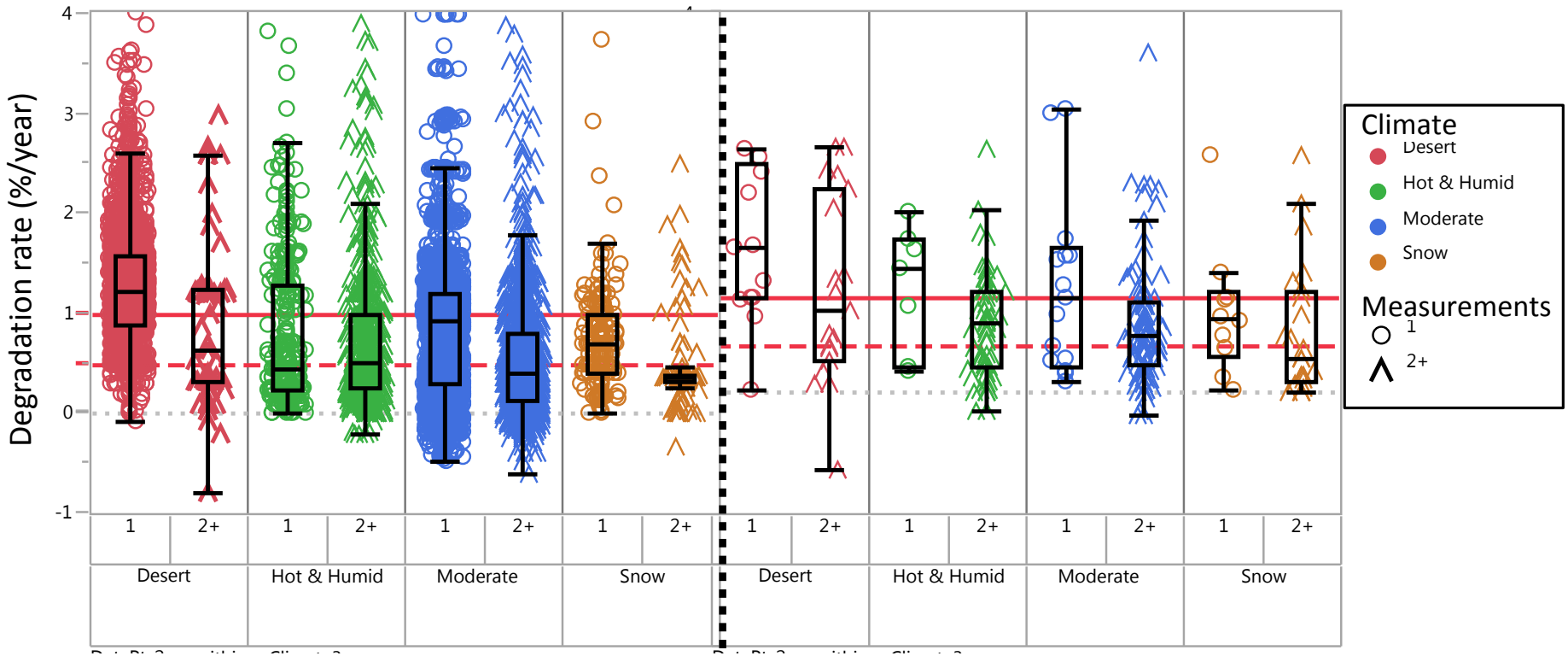
CIGS around 0.5 %/year

Hotter climates appear to show higher R_d

Climate category: simplified Köppen-Geiger

All degradation rates

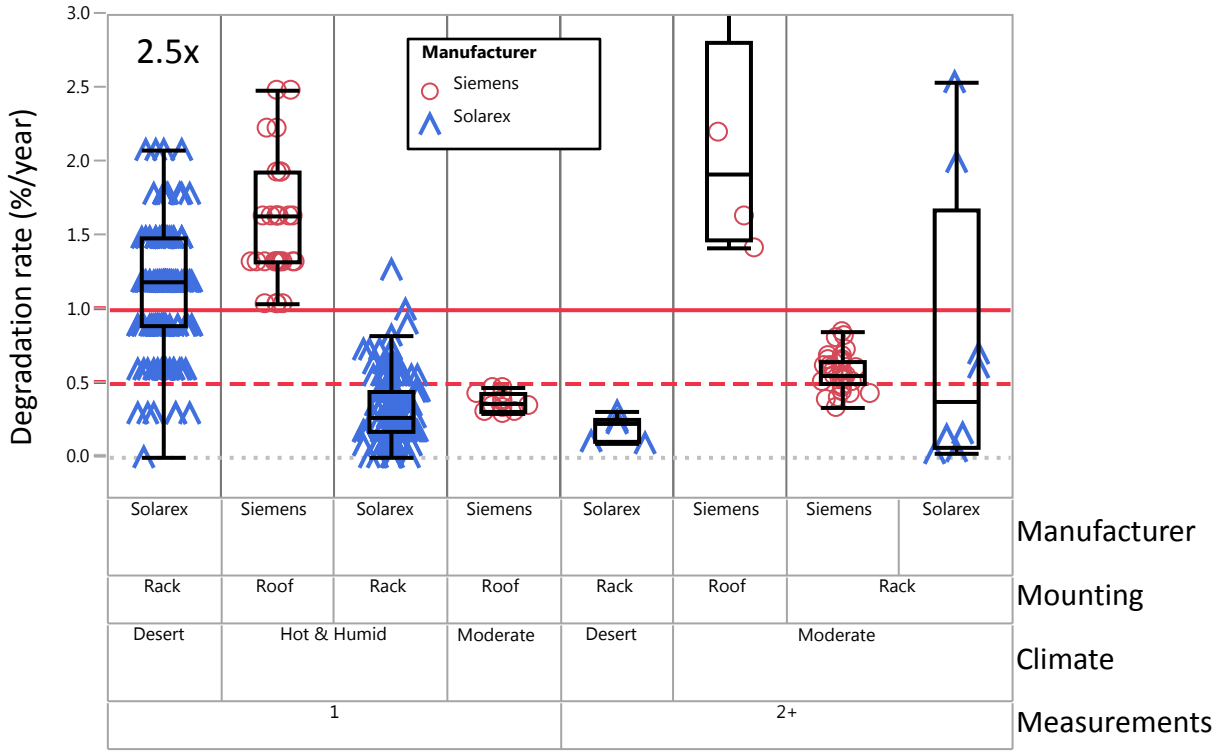
Median per study



1-measurement studies show statistically significant higher rates

Hotter climates appear to show higher R_d

Some modules more susceptible to hotter climates & mounting.



Solarex:

Show low median R_d across climates

Desert (1-measurement) shows higher R_d → 1-axis tracker & 2.5x concentration

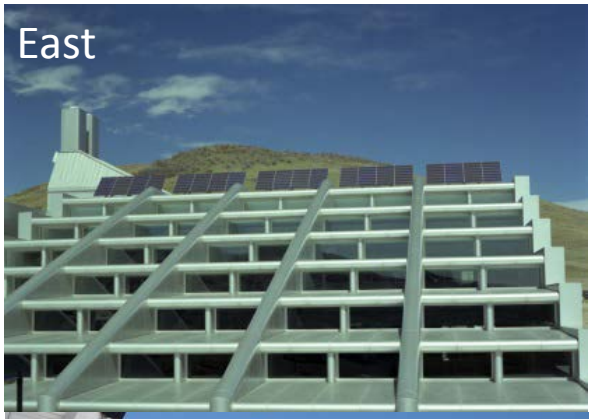
Siemens:

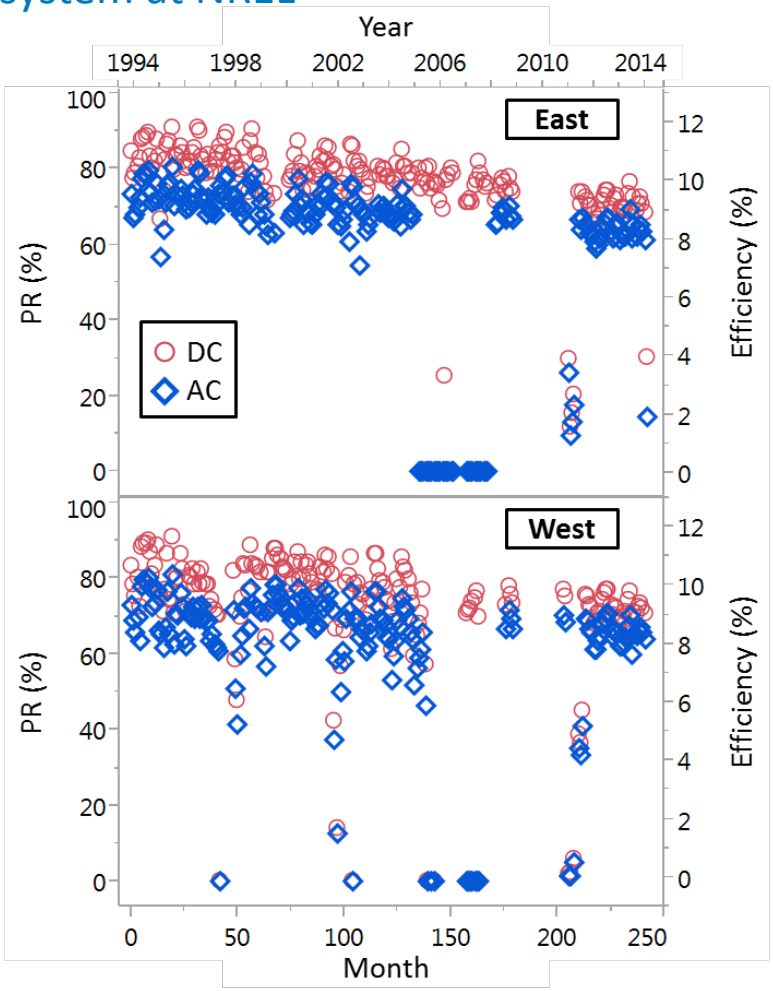
Roof mounting shows higher R_d even for moderate climate

Hot & Humid shows higher R_d than Solarex

System vs. module degradation?

20 year old mono-Si system at NREL

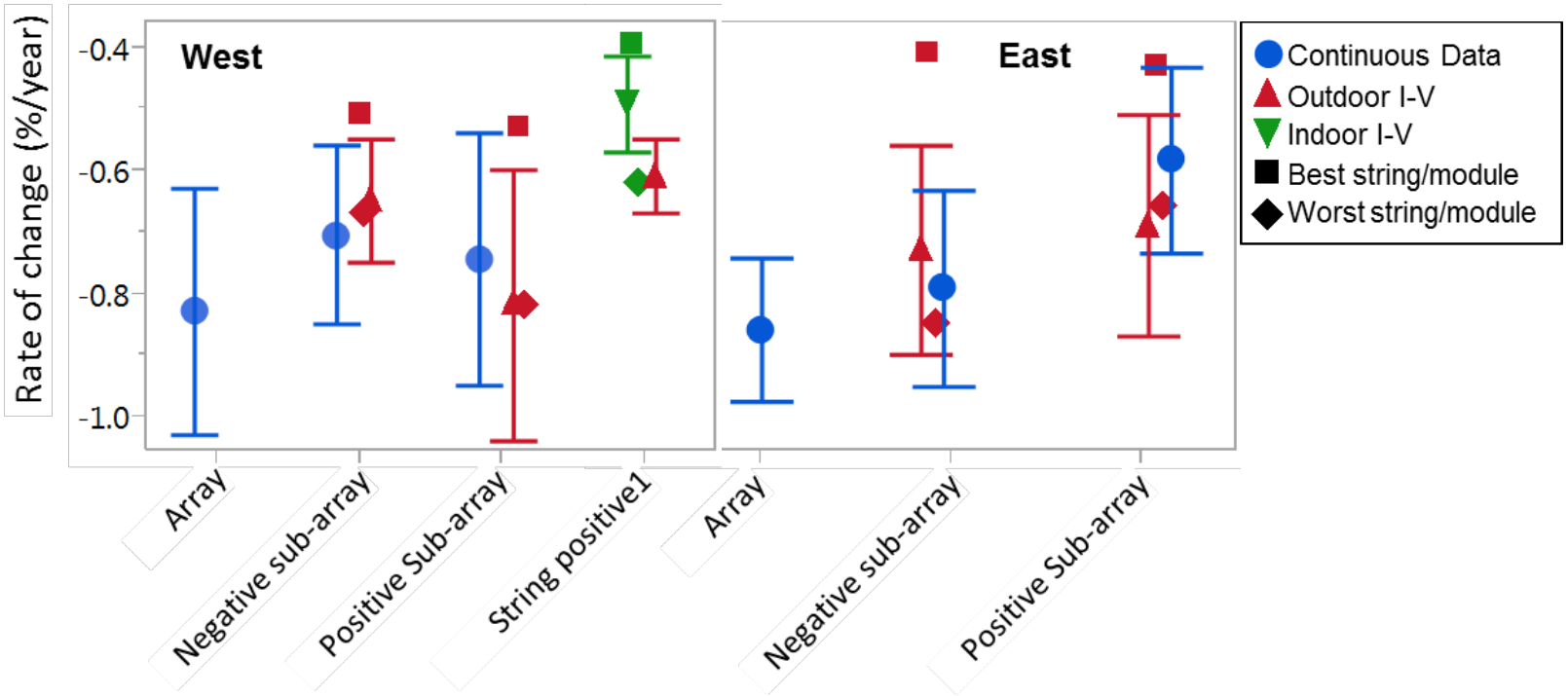




Siemens M55 modules
Size: 7.4kW

Performance and Aging of a 20-Year-Old Silicon PV System, Jordan et al., J. PV, 2015.

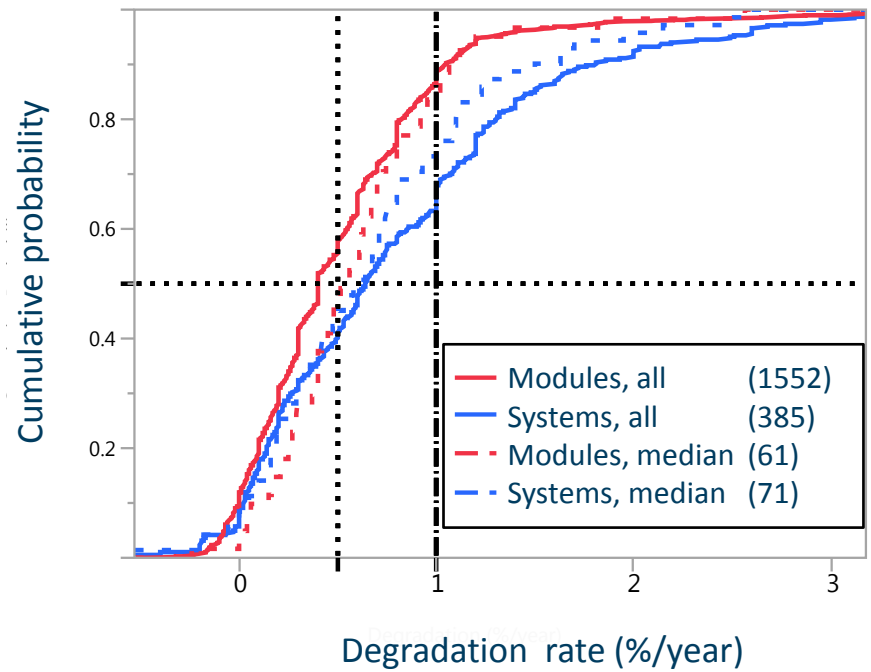
System & module degrade similarly



- The worst string appears to determine the subarray and array performance
- System degradation matches module degradation if modules degrade similarly, System degradation > average module degradation when large spread

At median systems & modules degrade similarly

High –quality, x-Si data



At median modules degrade a little less than systems but in general very similar

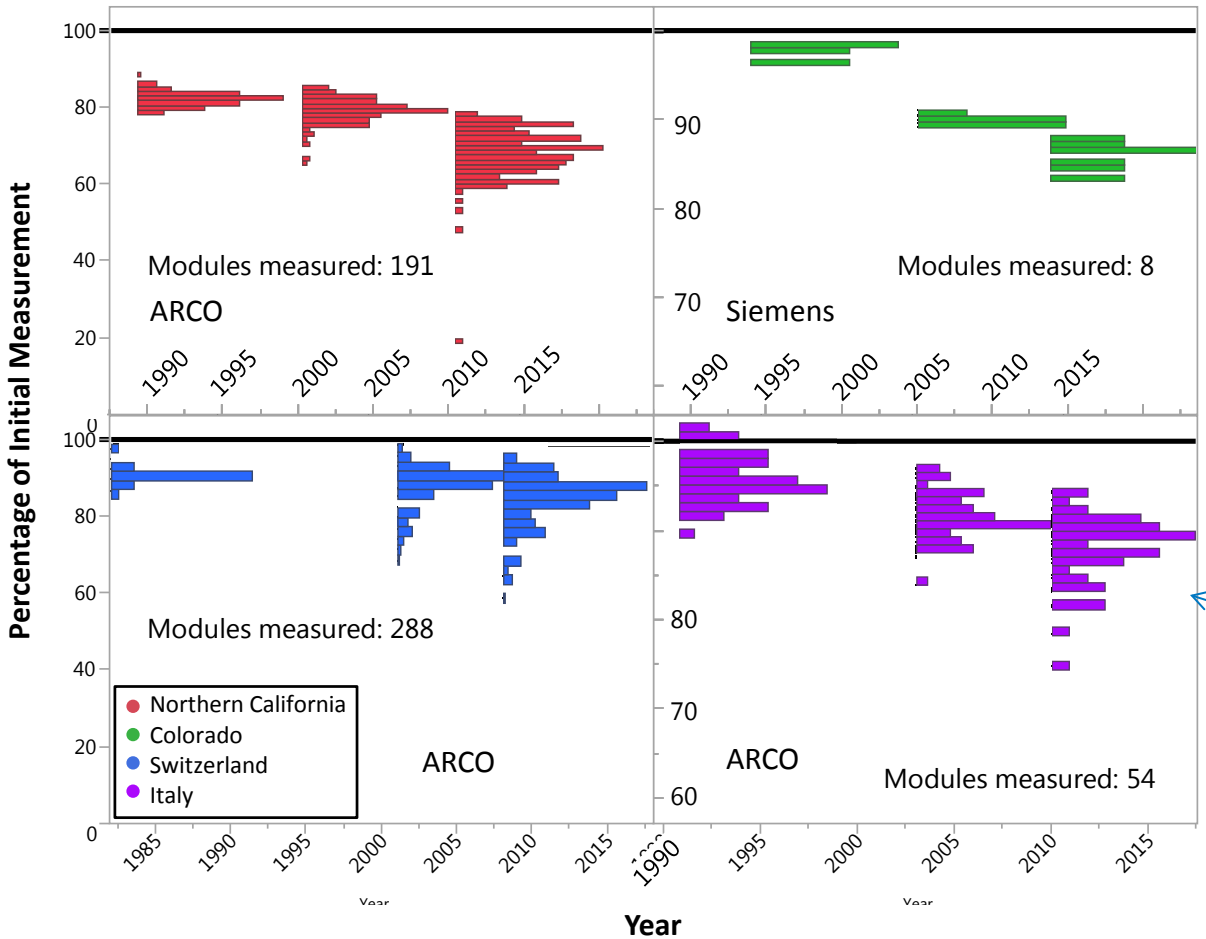
For less well-performing products more significant gap between modules & systems

Appears linear for most modules, worst modules non-linear

Studies that measured sample modules several times in 20+ years

20 years

30 years



1st measurement taken after 11 years

Distribution skews towards low end → worse performing modules show some non-linearity

Central tendency & better modules → fairly linear

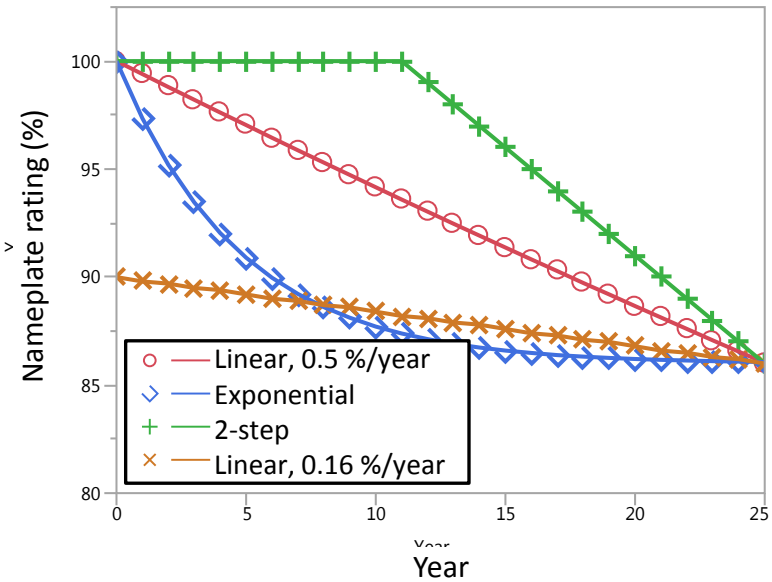
Simulation assumption for LCOE impact

Hypothetical commercial PV system near NREL:

Size: 100 kW, tilt: 40º, azimuth: 180º → PVWatts
Tax rate: 30%

Parameter	Distribution	Mean	Range	Unit
Initial production	Normal	159,437	± 2%	kWhr/year
Initial cost	Triangular	1.6	1.4 – 1.8	$/W
Discount rate	Uniform	7.5	6 – 9	%
Residual value	Uniform	5000	0 – 10,000	$
O&M cost	Triangular	20	17 – 25	$/kW/year
O&M escalation	Triangular	2	0 – 4	%

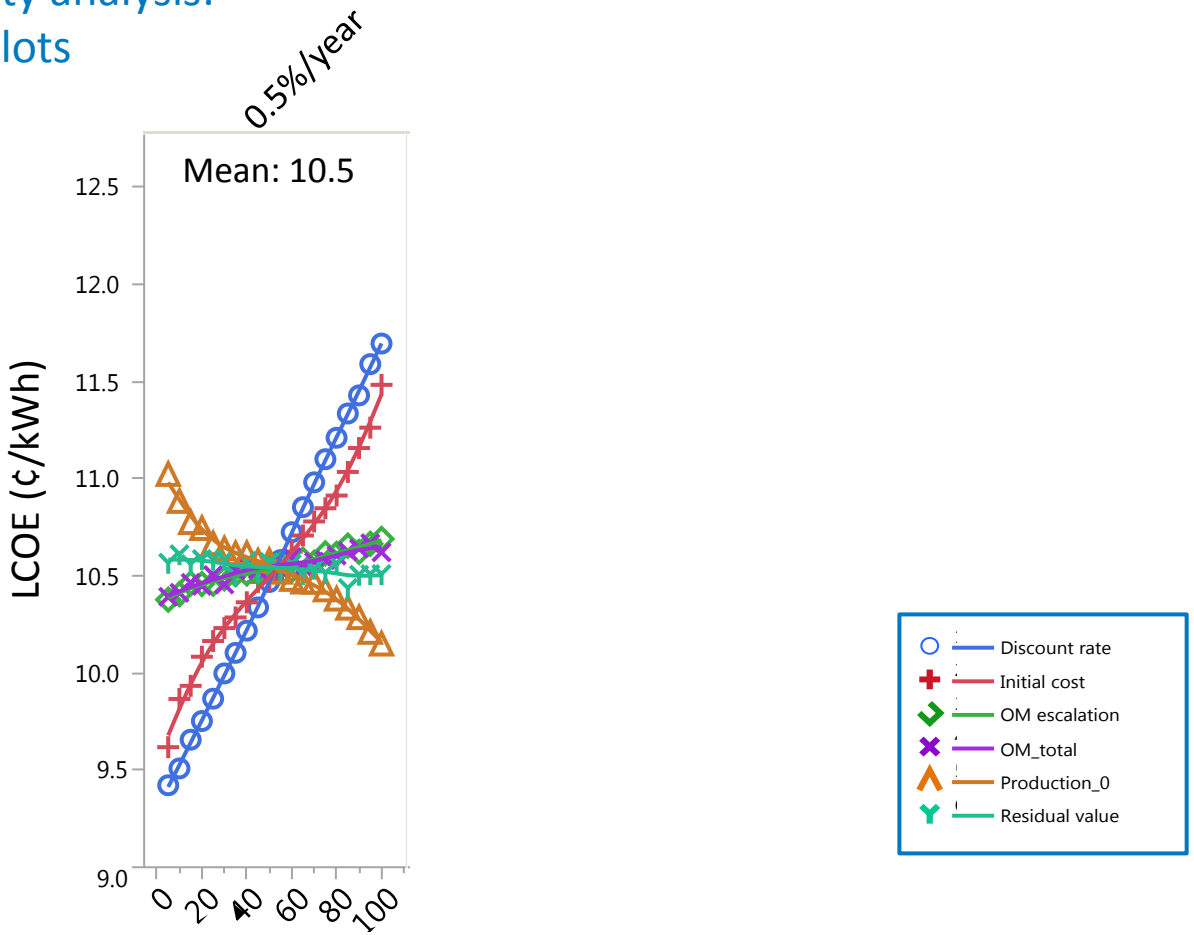
Input degradation curves



$$(1) \quad LCOE(\$/kWh) = \frac{Total\ Life\ Cycle\ Cost}{Total\ Lifetime\ Energy\ Production} = \frac{Initial\ Cost + \sum_{n=1}^{N} \frac{O\&M\ cost \cdot (1 - Tax\ Rate)}{(1+r)^n} - \frac{Residual\ Value}{(1+r)^n}}{\sum_{n=1}^{N} \frac{Initial\ Production \cdot (1 - R_D)^n}{(1+r)^n}}$$

Degradation *curve* has significant impact on LCOE

Sensitivity analysis:
Spider plots



See most important factors, can read the impact directly of axis.

Different trends:
⇓ $\text{Production}_{\text{initial}}$ ⇑ LCOE ;
⇓$\text{Cost}_{\text{initial}}$ ⇓LCOE

Most important factor:

Discount rate ≈ 2.3 ¢/kWh; $\text{Cost}_{\text{initial}}$ ≈ 1.8 ¢/kWh; $\text{Production}_{\text{initial}}$ ≈ 0.8 ¢/kWh; O&M < 0.5 ¢/kWh

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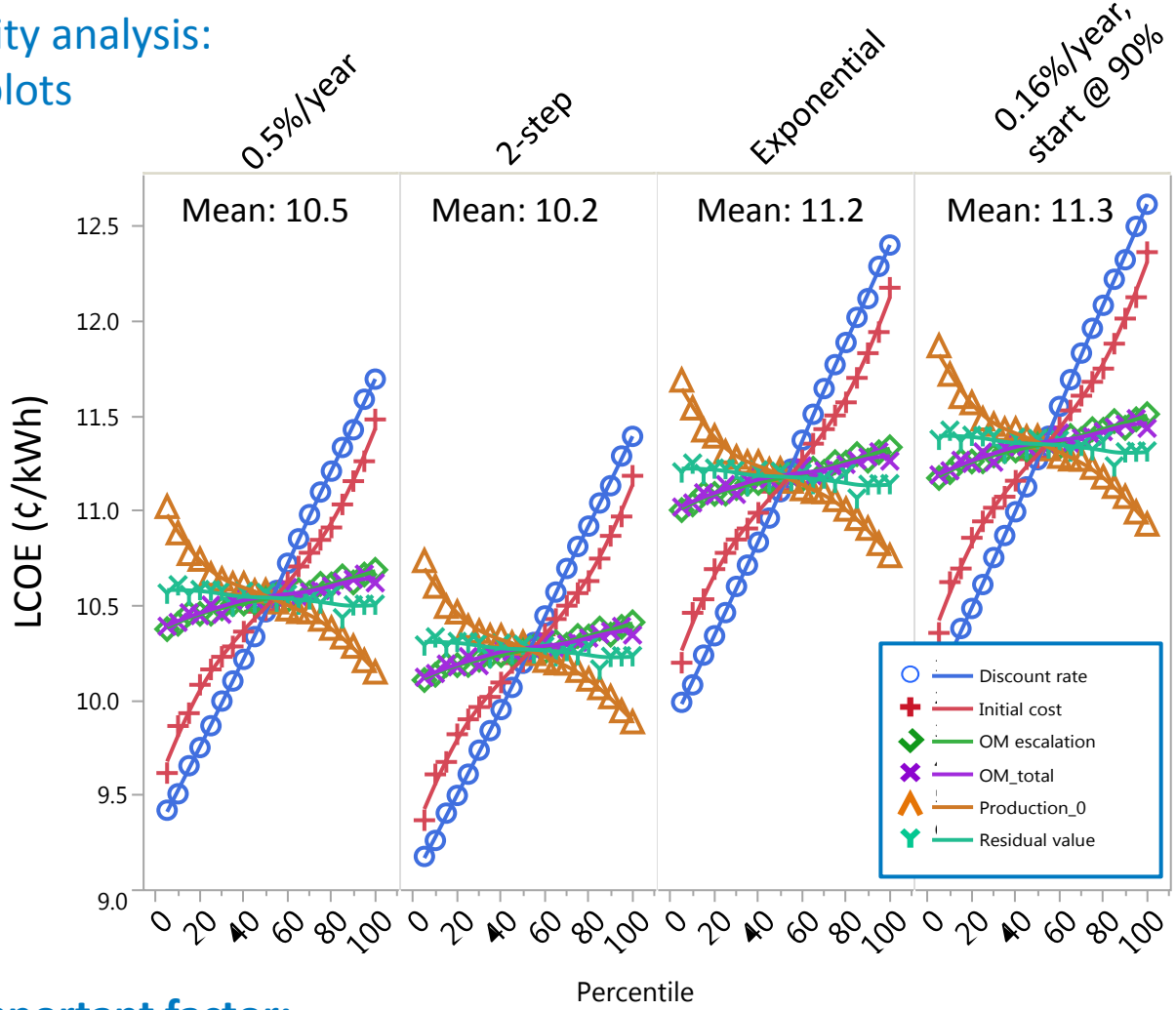

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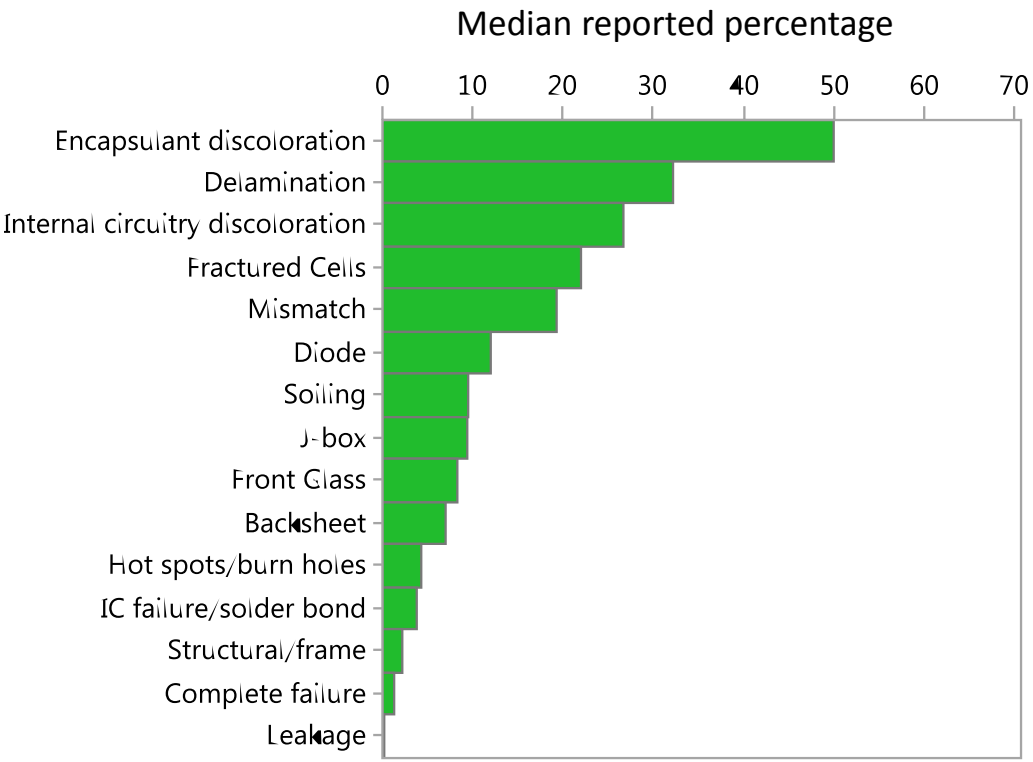
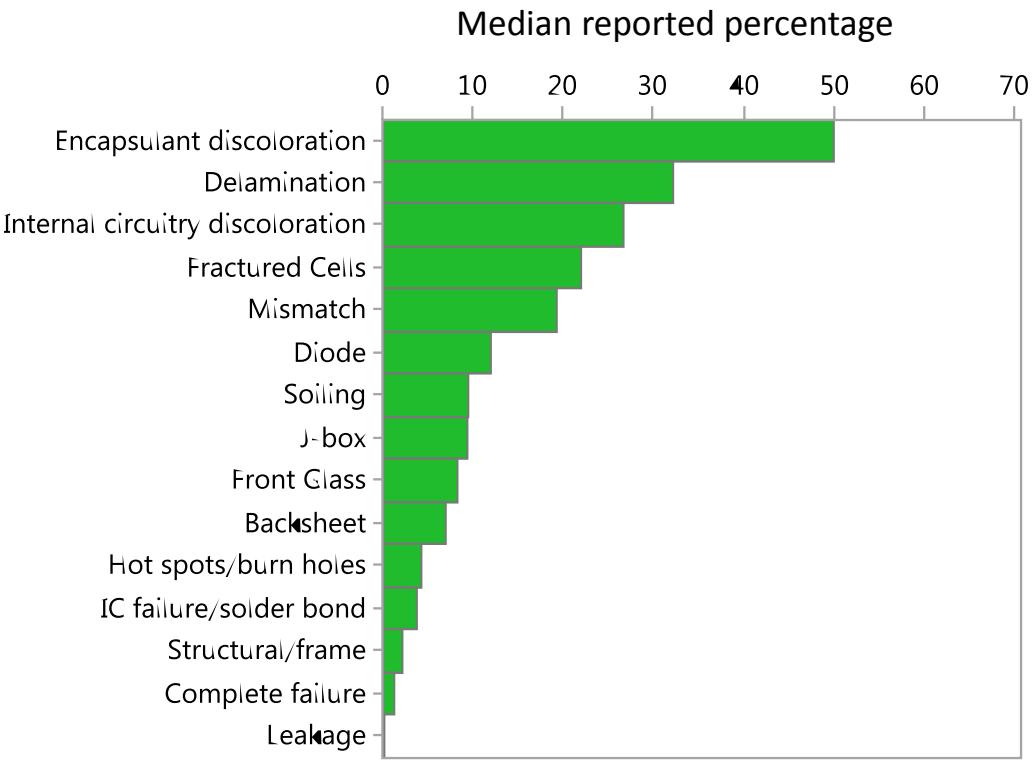
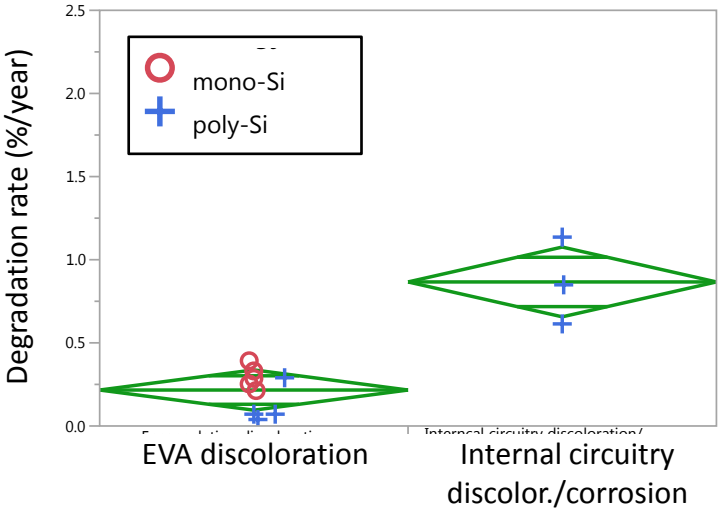
Degradation curve type ≈ 1.1 ¢/kWh

Discoloration most commonly reported failure mode



Discoloration most commonly reported failure mode





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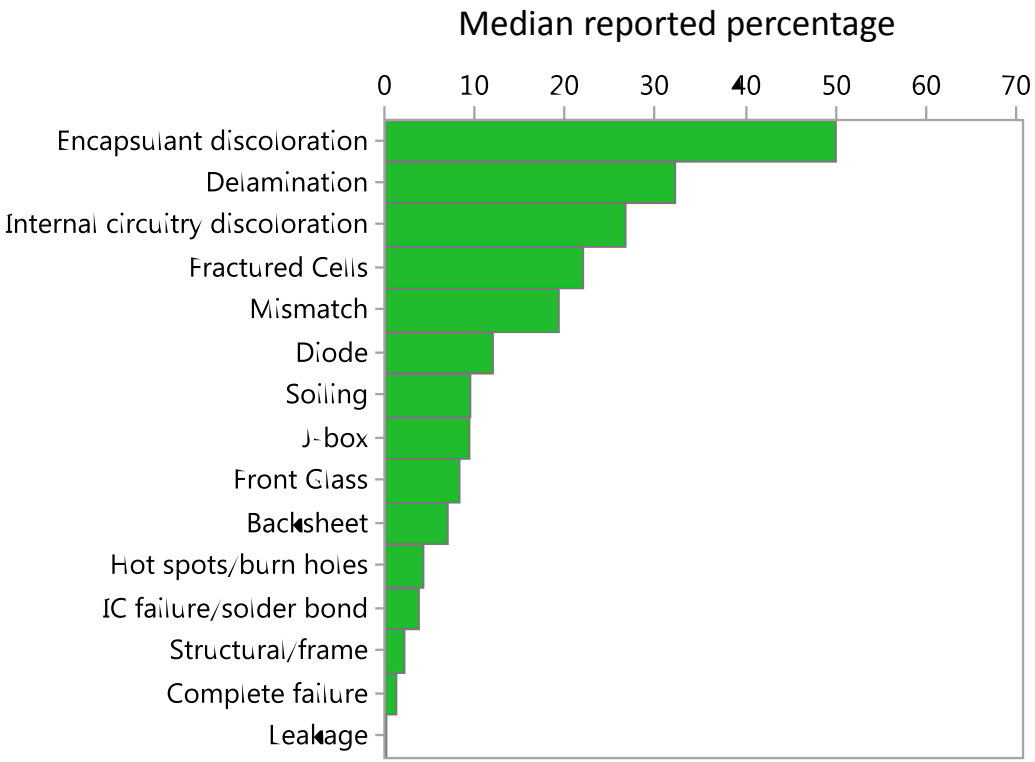

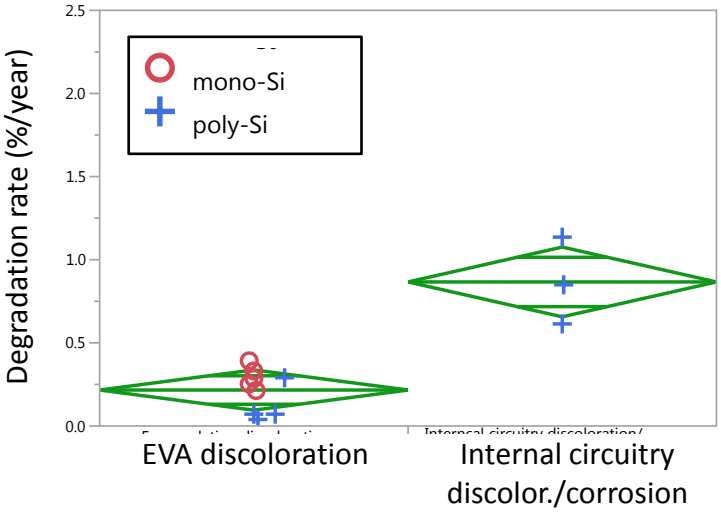

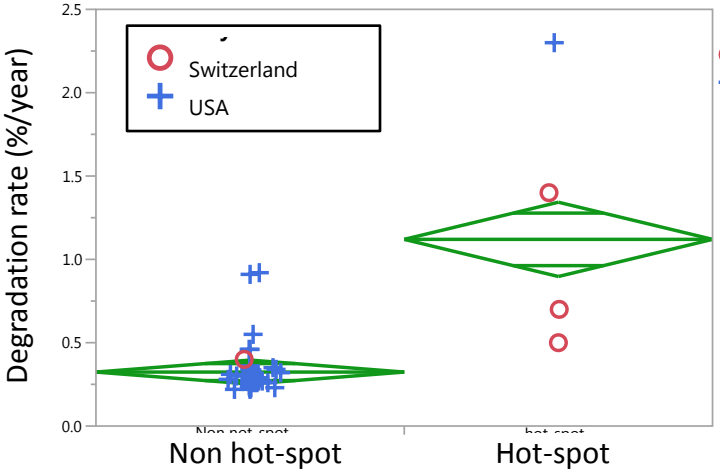

Majority of studies report encapsulant discoloration.

Next most frequent failure modes are internal circuitry discoloration, delamination & hot-spots.

Encapsulant discoloration associated with lower power loss.

Hot-spots in 1-1 comparison studies showed higher power loss.

Summary

- 1-measurement studies show significantly higher R_d because of nameplate rating deviation
- Increased R_d in hotter climates & mounting for some products
- x-Si has median in 0.5 – 0.6 %/year range, mean in 0.8 %/year range
- Non-linearities have significant financial impact, need to more accurately measure curves instead of relying solely on rates.
- Discoloration is the most commonly observed failure mode but is associated with less power loss. In contrast, hot-spots are not as frequently observed but show greater power losses.

PV degradation *rates*

PV degradation *rates*

Why can't you just give me a number?

PV degradation ***rates***

Why can't you just give me a number?

Is one number sufficient?

Acknowledgments

Thank you for your attention

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This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory

PV System Certification Workshop

Beyond LCOE: System reliability observations from the field

Suncycle USA

Eric Daniels

Suncycle history

- Founded in 2007 to conduct field audits, diagnostics, failure and repair of solar assets
- Often called for warranty service and assessments for manufacturers, insurers, owners and operators
- Over 3 million solar modules assessed and serviced
- Economic in-field module quality audits, acceptance testing, IR, EL and Pmp using mobile and mini labs
- Approach: economical for most any location and scalable from residential to commercial or utility systems

Beyond LCOE: System reliability field observations

- **LCOE:** Levelized Cost of Energy
  - Used to determine the cost of energy for a solar power system over time
  - Typically includes allowance for inverter replacement and annual O&M
  - Emphasis on lowest cost drives system design and installation practices
  - EPC/designer may only carry a 1 to 2 year performance obligation
  - *Components of LCOE and design may not support system longevity*

- **LCOO**: Lowest Cost of Operation? Perhaps another metric for longevity
  - FMEA at system level, MTTR
  - System design for cost vs maintenance, system
  - System design for site maintenance
  - Document retention: as built; key site service points; operating instructions; methods to speed service and survive staff and asset turnover

- *There appears to be a gap between factors that optimize LCOE vs. longevity*

Defects vs. failures

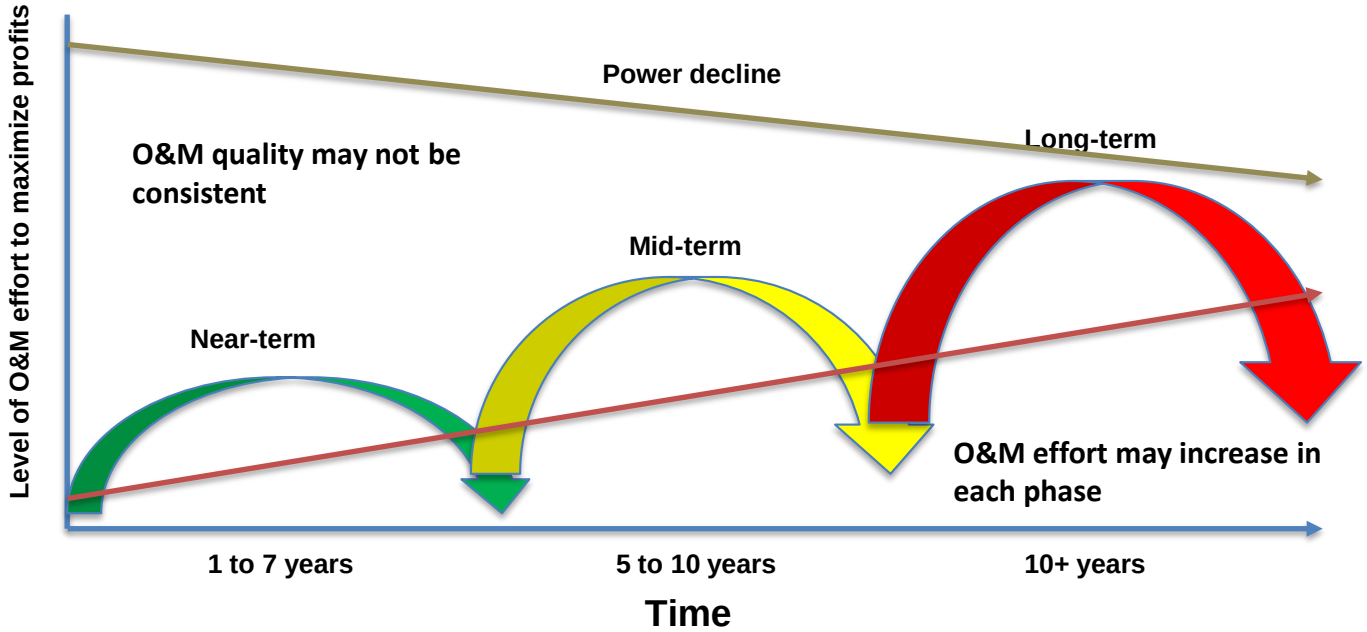
- *"A defect is everything in a PV module that is not as it is expected to be. A defect may imply a PV module failure or not. A defect is a much broader term than a failure. A defect does not necessarily result in a safety or power loss for a PV module but specifies a part of a PV module that is different from a perfect PV module."*

  Report IEA-PVPS T13-01:2014

- Defects are usually noticed when they become failures. Identifying defects isn't easy
  - Factory monitoring assumes availability of tools, processes and data integrity
  - Field audits push responsibility to supplier, but has complex problem resolution
  - A cursory review of new installations and systems reaching 10+ years suggests distinct stages for defect creation
  - Suggests field based quality audits and assessments are complementary to factory quality audits and provides on-site assurance during all phases of construction and operation

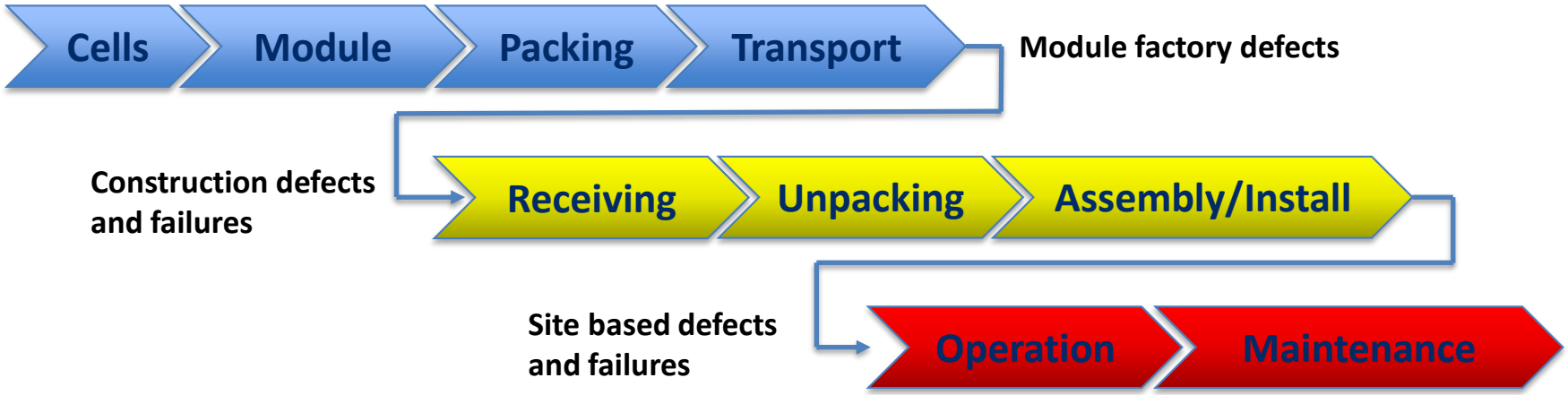
 © Suncycle USA 2016

Timeline for defects and failures, O&M



- As system ages, maintenance challenges become more significant
- Short-term: eg infant mortality; installation error; visible damage; snail trails
- Mid-term: eg hotspots; contact/soldering failure; cable & wiring failures; delamination; initial module handling; O&M related faults; isolated power loss
- Long-term: eg galvanic corrosion; encapsulant integrity; broader power loss

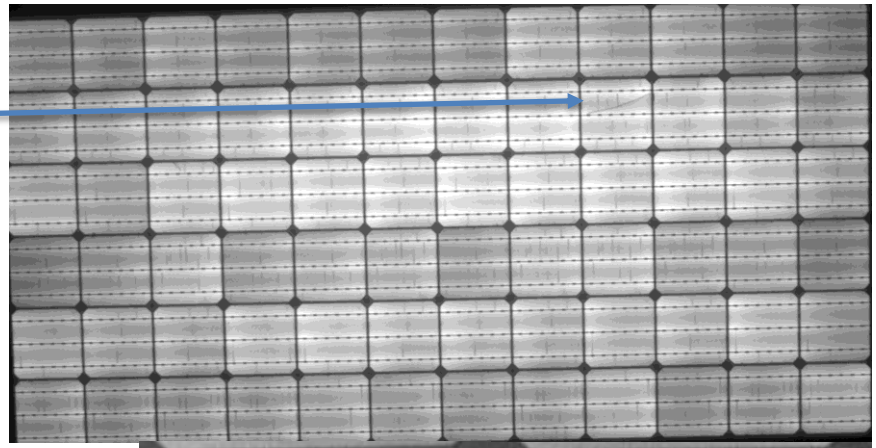
Stages for defect origination



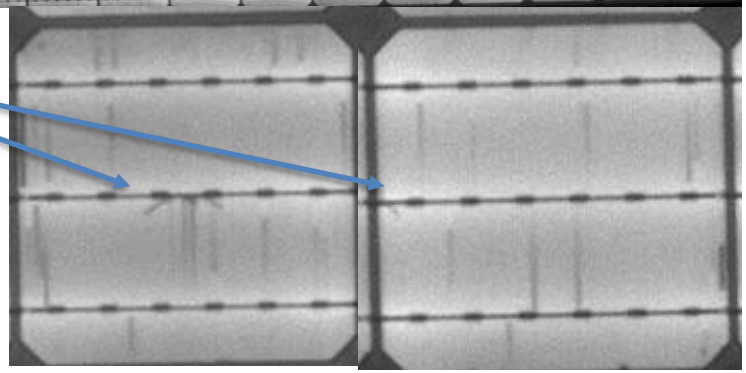
- Modules with failures typically do not leave the factory. Defects depend on the manufacturer's QA capability and criteria
- System defects and failures can be introduced during construction and by O&M. May not be visible
- Factory audits therefore insufficient to assure component quality

Near-term defects as received

- Modules with cell cracks are usually screened via Electroluminescent EL examination during final testing at the factory. Some cracks may pass depending upon QA practices



- Though EL images may appear ok, less apparent defects may pass due to equipment inspection capability, severity, materials and QA criteria



- *Images are by Suncycle USA at job site*

Near-term

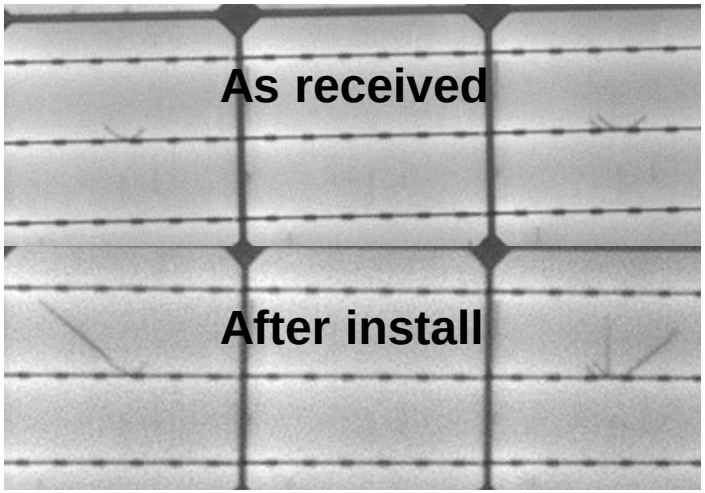
- Conditions & handling after leaving factory:
  - Unpacking
  - On-site storage
- Assembly
- On-site transportation

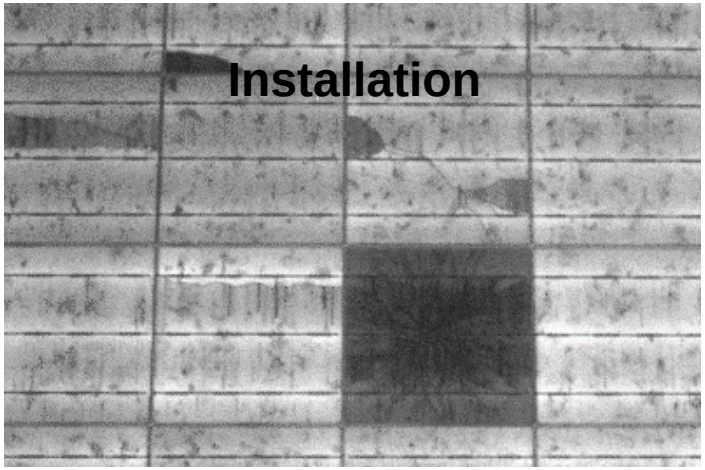
Severe twisting on panels

Glass compression, cell failures

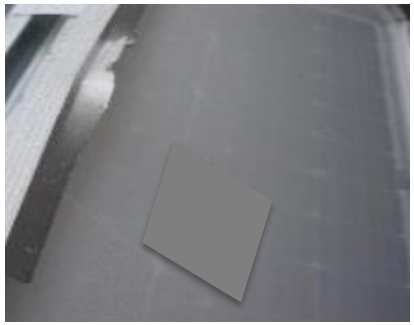
Near-term

- Regular handling and transportation at job site may exacerbate defects that were present upon arrival
- Some construction related damage may be visible
- Some construction related damage may not be visible. May be attributed to severe handling, walking on arrays or other on-site practices

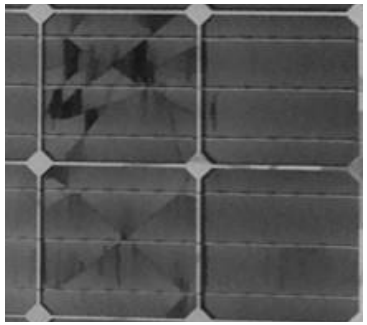




Visible

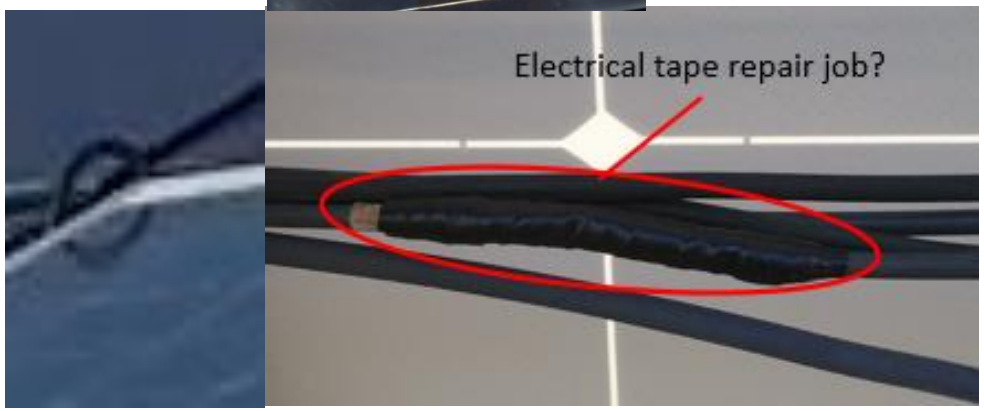


Not visible



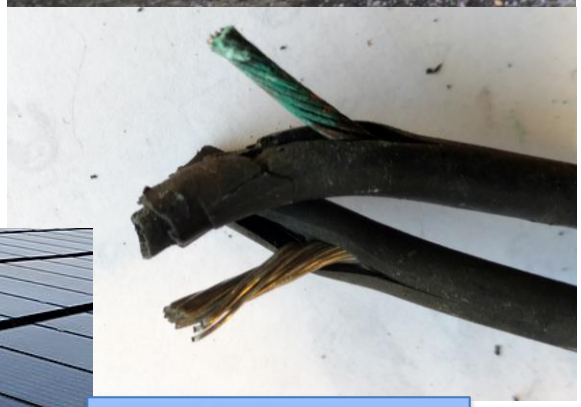
Mid-term

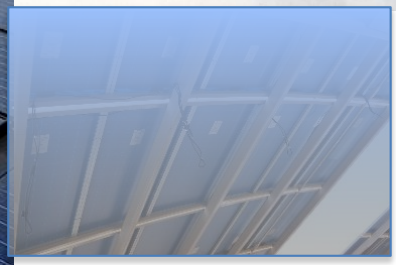
- System design & maintenance
  - Temporary repair vs. replacement
  - May be tied to O&M contract period
  - Repair induced concerns, cables, walking on modules
  - Documentation
- Site maintenance
  - Ability to service system
  - Access to site maintenance
  - Documentation
  - Instructions for on-site staff



Mid-term

- System vs site maintenance
- Component vs O&M induced problems
  - Roof drains
  - Cable ties
  - General access for cleaning
- New business opportunity for repair kits?



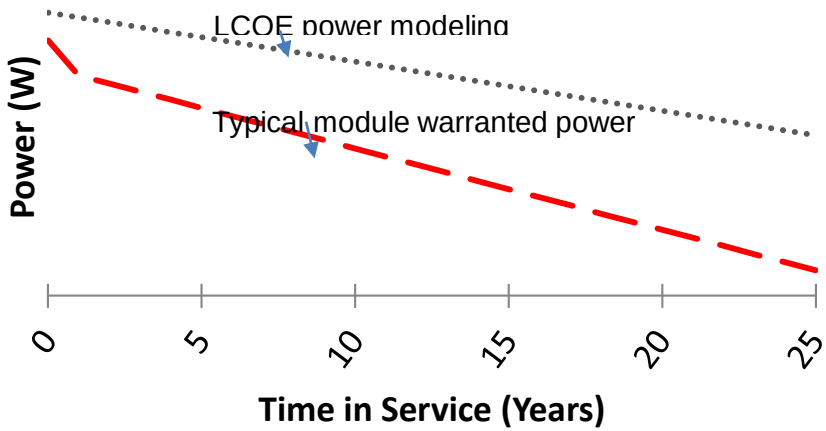


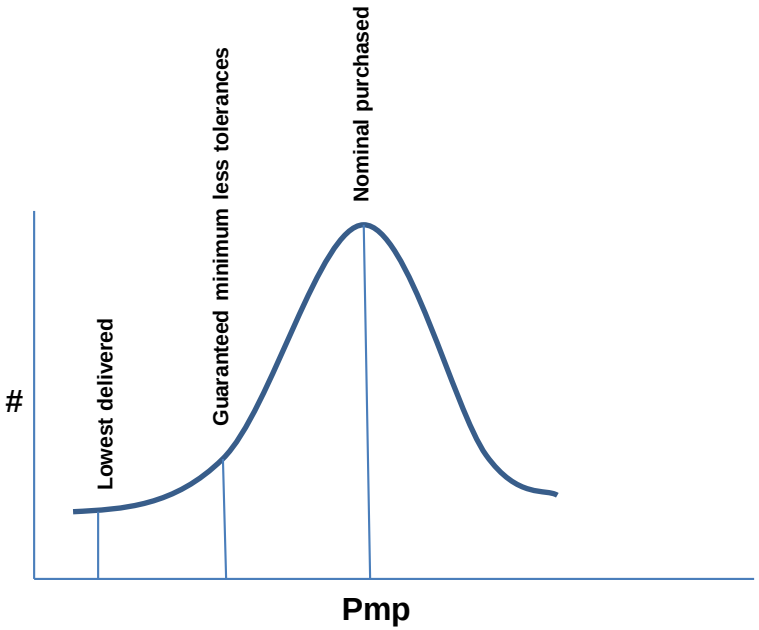
Long-term

- Loss of ARC properties due to cleaning
- Galvanic effects on metallization
- Delamination
- Technology generation
  - EVA vs PVB
  - Cell technologies
- Replacement options
  - Old module designs vs. new
  - ~256 vs. Quad core trade out?

Power measurements

- On-site power measurements affected by temperature, LID and soiling
- Acceptable power ranges subject to agreement with supplier
  - Nominal vs actual
  - Warranty range allowance
  - Equipment accuracy, measurement tolerance, calibration and accuracy of reference
  - Age of module





For one client found average power to be in range of nominal

However, some modules were found to be below lower guaranteed minimum

Summary

- LCOE vs LCOO? Links between near-term optimization vs longevity
- Improper handling after delivery of modules to a job site may have significant impact on long-term performance and warranty coverage
- Systems should allow for maintenance, consider 3rd party construction and O&M audits
  - Field audits and agreed quality standards may encourage delivered module quality improvement
  - Field audits may encourage training and improved construction processes
  - Field audits over time may improve quality of O&M
- Consider generation planning
  - Once a solar power plant, always a power plant?
  - What options can be built in for future code updates, new technologies and components?

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Contact information

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UNCERTAINTY FOR GROUND TO SATELLITE SOLAR INSOLATION TUNING PROCESSES

By: James Alfi, James Christopherson, Ganesh Mani, and Yiping He

Background

- The use of satellite data has become more prevalent in the solar industry for energy estimates.
- Integration of satellite data into public tools such as PVwatts and Solar Prospector has helped shift the industry away from typical meteorological year (TMY) datasets to satellite based solar resource files.
- SolarAnywhere is a leading vendor of high quality satellite data processed using the latest algorithms from Dr. Richard Perez. SolarAnywhere datasets do not have any ground corrections applied, which allows the end user to perform at their discretion. The reported U95 uncertainty of the raw satellite data is 5%, and by performing ground corrections there is an opportunity to remove bias and lower the uncertainty.
- There are many methods used to perform a ground-satellite data correction.
  - Simple linear regression can be used with either hourly or daily data to correct for bias present between the ground and satellite data.
  - More complex non-linear methodologies such as those used by Clean Power Research, attempt to correct the satellite data through multiple channels such as clear sky, cloudy conditions, and seasonally.

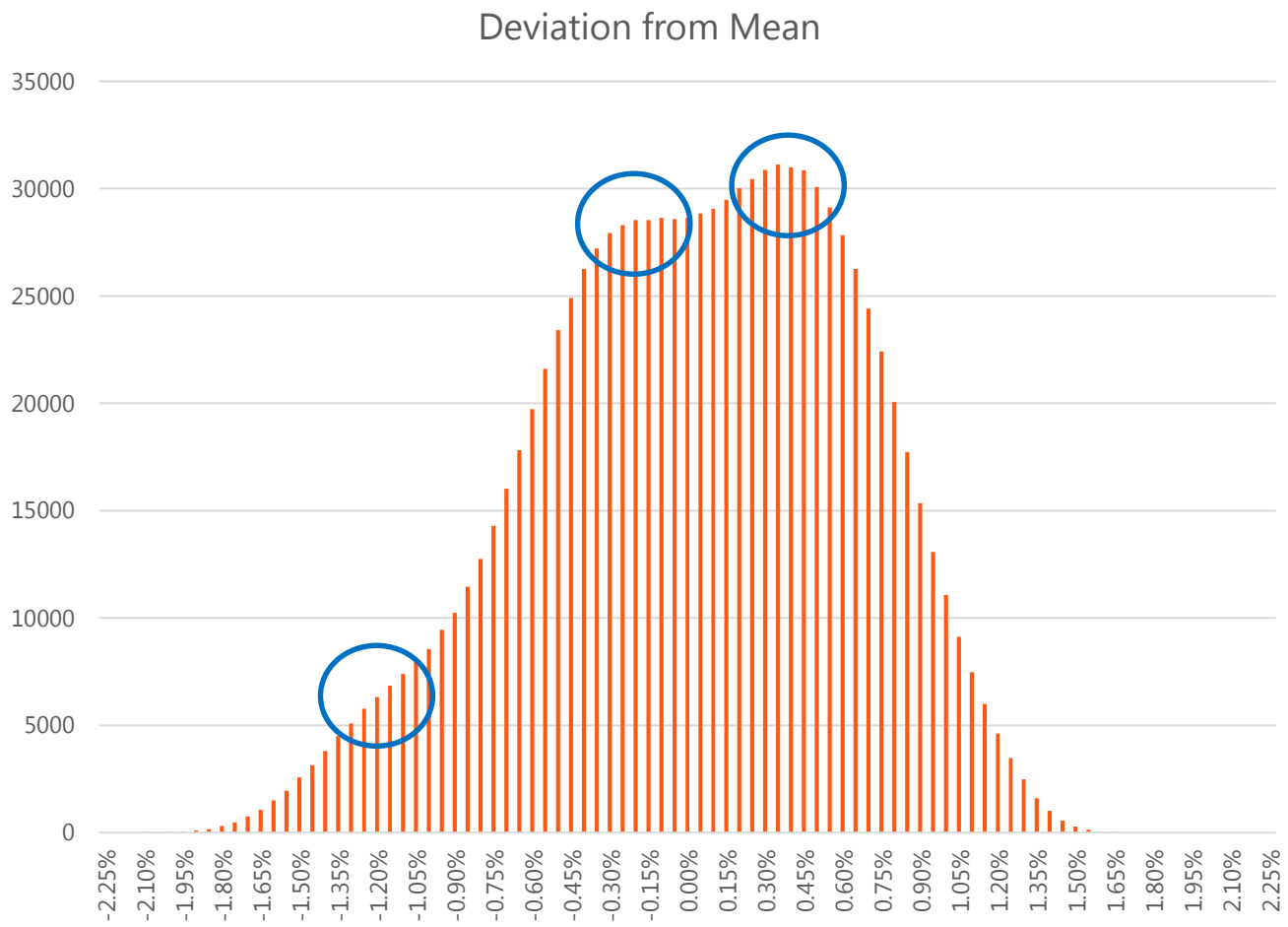
- **Independent of the method used to correct the satellite data, the resulting long term dataset must have a representative uncertainty reported. Ideally the method(s) used to calculate the uncertainty would be a statistically sound methodology that could be used in conjunction with any ground-satellite correction process.**

Limitations of Uncertainty Calculation

- **Traditional calculation methods to determine uncertainty have proved to be insufficient in capturing the uncertainty of the final long term dataset.**
- For a ground-satellite correction based on least-squares regression, uncertainty is driven by residuals and the variability of the input dataset. These methods are not sufficient for solar insolation ground-satellite corrections:
  - The resulting long term average of a ground-satellite correction is dependent on the time period that is being used for regression, thus simply looking at the residuals from the regression would not account for the uncertainty and error that is present from correlating higher than average, lower than average, or outlier years.
  - All traditional uncertainty methodologies assume that the relationship between X and Y are linear. The fact that the long term average is dependent on the time period used would imply that while the relationship is linear, there are nonlinear artifacts that affect the correlation.
  - Solar data is variable by nature. Traditional methods look at relative standard deviation or standard error to estimate uncertainty. Applying this same method to estimate uncertainty of solar data is not representative as solar insolation varies constantly every day and hour. It is not the same as estimating the uncertainty of height measurement predictions for a population. While ground-satellite correlation on sites with higher variability are more uncertain due to the nature of correlation, estimating the uncertainty in solar data requires a different approach than traditional methods.
- For ground-satellite corrections that are not based on least-squares regression, standard error or fit metrics are often used to estimate the uncertainty of the dataset.
  - Root mean square error (RMSE), mean absolute error (MAE), and mean bias error (MBE) are often used but again, they do not sufficiently calculate the uncertainty of the long term dataset.
  - The listed metrics will quantify the error between the ground data and the corrected long term satellite data, however, they fail to capture the impact of the time period of data being used and the amount of data being used.

Impact of Time Period Used for Correlation

- To illustrate the impact of the time period used, the following test was performed:
  - A site was chosen with ~3 years of ground data.
  - A total of 1,048,501 correlation iterations were run.
  - Each iteration represented a possible combination of one full year sampled from the 3 years of data.
  - Only full months were sampled.
- Although difficult to see, the distribution is trimodal, showing that each year of ground data created a rough distribution around it.



How to Improve Uncertainty Calculations

- An iterative Monte Carlo uncertainty calculation would generate the most representative result.
  - By performing an adequate number of iterations, the results should converge and a distribution should be formed by the results.
  - Assuming the resulting distribution (of annual kWh/m2 in this case) is normal, relative standard error could be used to generate a more representative uncertainty value.
- The methodology developed to calculate uncertainty for ground-satellite correlations combines bootstrapping and a Monte Carlo based approach. Bootstrapping provides the ability to run countless iterations with a limited dataset (although 1 year + is suggested).

Proposed Methodology

1. Input ground and satellite data can be daily sums or hourly data, the same process can be used. However, hourly data is recommended since more points are available. There is no requirement on size of the dataset, but at least one full year of ground data is highly recommended.
2. The amount of data to be sampled from each month is randomly varied for each iteration between 50% and 100% of all available data pairs. Linear weighting is used to more heavily weight smaller sample sizes. Linear weighting is used because there is no need to run 100% of the samples more than once, and less possibilities exist as your sample percentage increases.
3. All of the data pairs for each of the 12 months (including all available years of data) are aggregated. The number of data pairs sampled for each iteration is based on the random sampling percentage generated for the iteration.
4. The ground-satellite correction is performed based on the sampled data. In regards to this study, a monthly least-squares correlation is performed. A least-squares slope is generated for each of the twelve months, and also an annual slope based on all sampled data pairs. Monthly slopes are used to correct the long term satellite data unless the coefficient of determination for the month is poor, then the annual slope will be used.
5. A P50 long term mean is generated for each iteration.
6. The process is repeated at least 50,000 times or until convergence is seen.
7. Output of each iteration is the annual P50 long term mean, and the random sampling percentage which was used for the iteration.
8. A histogram is created with the results from all of the iterations and simple statistics are calculated.
9. The relative standard error per Equation 1 is calculated and represents the standard uncertainty (U68).
    1. $RSE = \sigma\mu$

Implementing the Methodology

- Implementation of the described methodology could be done using:
  - A scripting language (Python)
  - FORTRAN
  - Matlab
  - Other similar methods
- EDF Renewable Energy has a proprietary FORTRAN program which performs the Monte Carlo simulation and also provides the user with additional inputs.

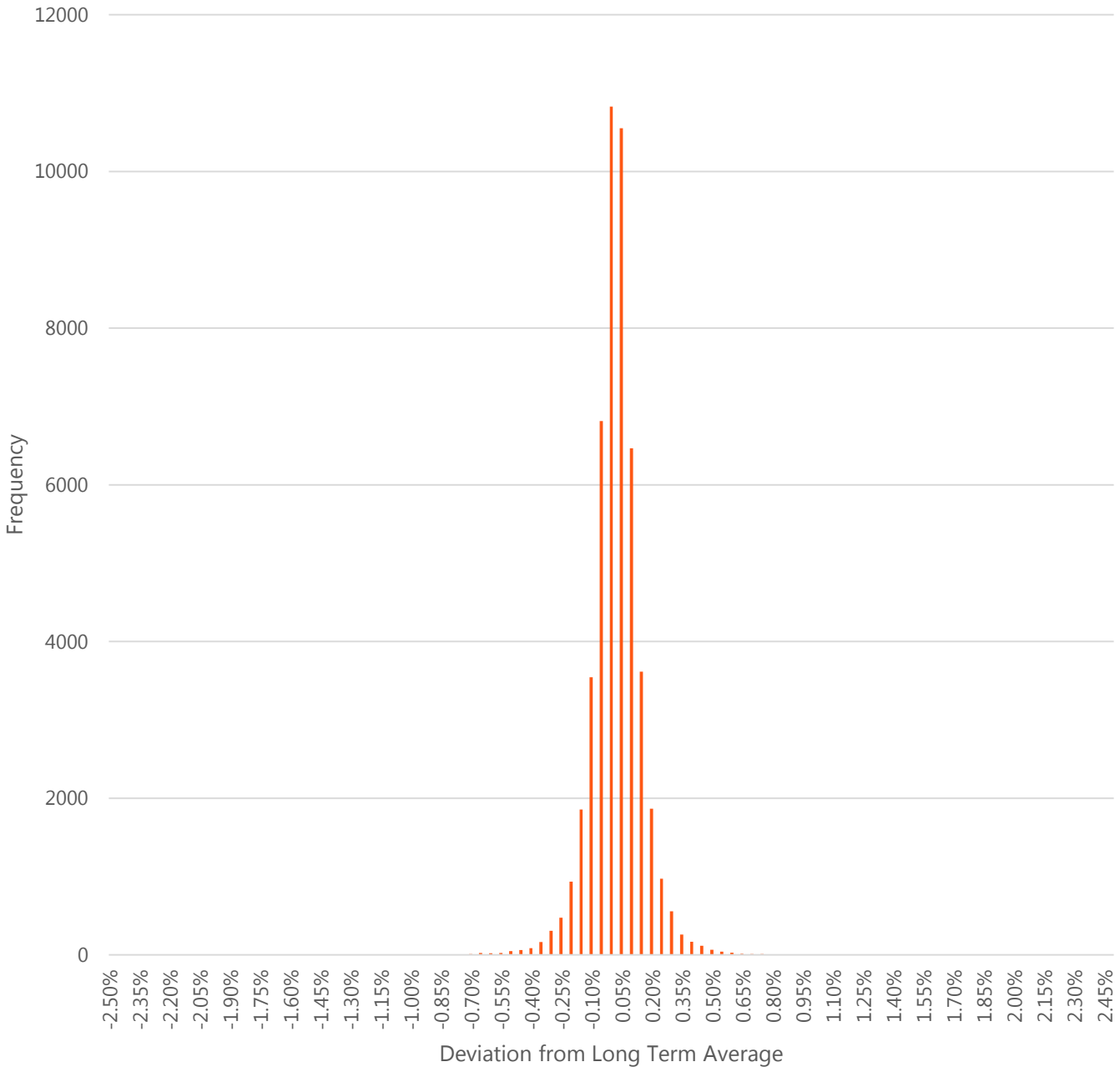
Results

- The proposed methodology was run for two solar meteorological stations.
- SolarAnywhere satellite data was used for correlations.
- The results show that randomly choosing data pairs in random quantities will still converge to a long term mean, without much variance.
- It is not surprising to see the site in Central Texas resulting in a higher RSE since the climate is much more variable.
- Both uncertainty values are quite low, and provide a realistic estimate of the uncertainty associated with the tuning/correlation process.

Station Location	CA Desert	Central Texas
No. of Months of Ground Data	36	25
No. of Monte Carlo Simulations	50,000	50,000
Average R2 For Monthly Regressions	0.96	0.94
Minimum R2 for Monthly Regressions	0.95	0.90
Long Term Resource Mean	2149.93	1747.61
Calculated RSE	0.13%	0.28%

Results (Cont.)

- The distribution to the right is from the site in California.
- The distribution is very tight, as expected since the RSE is very low.
- It is expected that cloudier areas will result in a higher uncertainty.
- With more data, a lower uncertainty should and can be achieved since there will be greater levels of convergence.
- More sites will be run, including sites with more and less data to validate the methodology presented.



EDF renewable energy

Novel architecture and detector technology used in a next generation pyranometer.

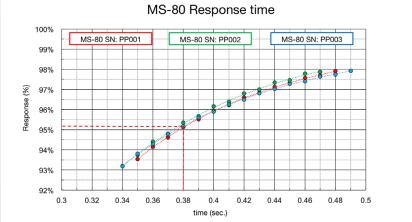
William Beuttell[1], Kees Hoogendijk[2], Toshikazu Hasegawa[3], Eiji Takeuchi[3], and Akihito Akiyama[3]
[1]EKO Instruments USA Inc., [2]EKO Instruments EU B.V., [3]EKO Instruments Co.,Ltd

For roughly 100 years, the development of pyranometers has been slow with minor deviations from the original architecture and detector technology. EKO Instruments recently developed the MS-80 Secondary Standard Pyranometer which represents the largest change in development history. The MS-80 uses a unique detector technology and has a new sensor geometry to maximize benefits from this new technology. Test results of the typical sensor characteristics are shown.

	MS-80	ISO 9060 Secondary Standard
Detector	Thermopile	Thermopile
Response time 95%	< 0.5 s	< 15 s
Zero offset A - Thermal radiation (200W/m²)	< 1 W/m² (unventilated or ventilated)	< 7 W/m² (ventilated)
Zero offset B - Temperature change (5K/hr)	+/- 1 W/m²	+/- 2 W/m²
Long-term stability (change/yr)	< 0.5 % / 5 yr	< 0.8 % / 1 yr
Non-linearity (100 to 1000W/m²)	+/- 0.2 %	+/- 0.5 %
Directional response (at 1000W/m² | 0 to 80°)	+/- 10 W/m²	+/- 10 W/m²
Spectral selectivity (0.35 to 1.5µm)	+/- 3 %	+/- 3 %
Temperature dependency (-20 to 50°C)	<1% (70K band)	<2% (50K band)
Tilt response (0-90° | 1000W/m²)	< 0.2 %	< 0.2 %
Wavelength range (nm)	285 to 3000	300 to 3000

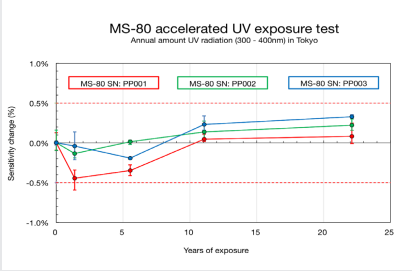
Faster and More Precise

Using a unique thermopile technology the MS-80 has reached unprecedented levels of performance while improving intercessor repeatability. Conventional sensors have a response time of several seconds, 3-5 at best. The MS-80 has an analog response of 0.5 s @95%.



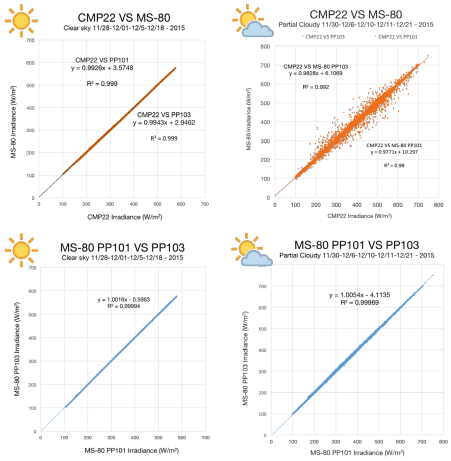
MS-80 does not require expensive components it is cost effective and the perfect solution for network applications involving many deployed sensors.

Embedding the detector inside the sensor body now allows for an isolated detector as well as an environment which is immune to the effects of humidity, changes in barometric pressure and UV radiation. This design has very promising long term stability as displayed in accelerated UV exposure testing data.



A Cooperative Research and Development Agreement (CRADA) is being pursued between EKO and the National Renewable Energy Laboratory (NREL). Additional comparative outdoor measurements will be made and presented later this year.

Outdoor Comparison

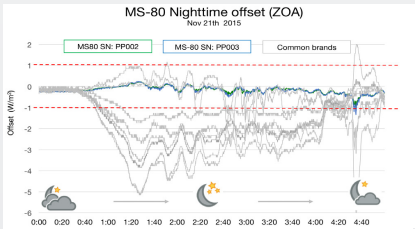


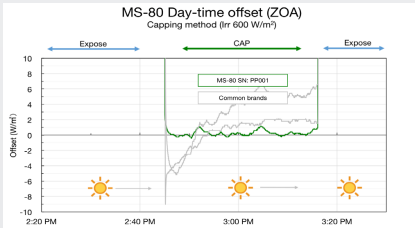
Conclusion: Comparing outdoor data from a high quality Kipp & Zonen CMP22 pyranometer, we found very good agreement between the MS-80 and the CMP22 under clear conditions. Due to the fast response time we also noticed great agreement amongst MS-80 sensors while measuring outdoors under variable atmospheric condition.

While this is only a sample of the performance gains made by EKO, the MS-80 represents a new direction of sensor development that will now allow the highest level of performance to be available to more users.

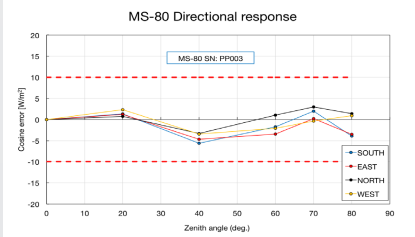
Lowest Thermal Offsets

An area of major improvements in sensor performance involved the reduction of thermal offsets. Previous attempts used expensive outer and inner domes made of quartz.





The detector is contained inside the sensor body. Without a diffuser, the sensor would have a truncated angular response. Using a diffuser, the MS-80 has achieved a true cosine response.



www.eko-usa.com

ASSESSMENT OF 11 KW PV ARRAY AFTER 18+ YEARS ON LAKE MICHIGAN ISLAND

Cedric G. Currin, Currin Corporation, Midland, Michigan, USA currcorp@tm.net 989-835-7387

Q. This PV array was installed nearly 19 years ago. When should we plan to replace it?

A. Replacement is not needed for at least 5 more years, but power will continue to decrease very gradually.

ISLAND, LOCATION, AND ENVIRONMENT

- In northern Lake Michigan, PV array at 45.1232 N, 85.9770 W
- 110 meters from Lake Michigan shore; elevation ~180 meters
- Humid continental climate [Koppen Dfb climate classification]
- In-season daily weather data available:
  http://mesowest.utah.edu/ Click on Michigan; station NMI4M
- Seasonal temperature: 0 - 25°C [>30°C rare]
- Minimum winter temperature: -20°C
- Relative humidity: Typically 50 - 90%
- Average wind velocity: ~4.8 m/s
- Precipitation: Typically 850 mm/year; pH ~4.7
- Snow depth, maximum: Typically 0.6 - 0.8 m [estimated]
- Air quality: Class II (CAA)
- POA irradiance: May - July 6.0 kWh/m^2-day; September 4.5 kWh/m^2-day; October 3.1 kWh/m^2-day

INSTALLED PV MICROGRID POWER SYSTEM

- Installed on North Manitou Island of Sleeping Bear Dunes National Lakeshore (~25 km west of mainland Michigan)
- Provides continuous 240V 60 Hz power to small historic village; load typically 25 - 50 kWh/day during May- early November season
- System designed 1995; installed by park staff late summer 1996
- Modules: 216 Siemens SM-55; monocrystalline silicon cells
- Strings: 24 strings, each 9 modules (charging 120 V battery bank)
- Subarrays: 3, 30° tilt; fuses, blocking diodes in combiner boxes
- String wiring in type LFNC conduit
- Limited commissioning data indicated all modules matched manufacturer's max-power-point data
- 2800 Ah 120 V VRLA battery bank; 15 kVA inverter; 2 - 40 kW gen-sets
- Largest PV array in northern Great Lakes region when installed

SYSTEM OPERATION AND MAINTENANCE

- No solar power records kept; typically 75 A maximum array output
- No array systemic failure
- No array maintenance other than weed control
- 6 modules vandalized; replaced
- 1 module fractured, probably by stone impact from weed control
- No fuse blown nor blocking diode failure
- No charge controller failure
- 2800 Ah 120 V battery bank replaced 2014
- 15 kVA inverter replaced May 2015; new MPPT charge controller
- Array rewired for 18 strings, 12 modules/string for MPPT controller

ARRAY ASSESSMENT TASK DETAILS

- To determine performance degradation, estimate remaining life
- June 12 -15, 2015:
  Cool - 13-25°C ambient
  Usually high clouds; insolation 30 - 100% full sun
  Generally high humidity; some light fog, condensation
- Instruments:
  Portable digital multimeters [no I-V instrument available]
  Reference module: 2 W/0.820 A Isc @ 1.0 kW/m^2
  IR temperature probe
- String measurements: Isc, Imp, Ileakage, Voc, Vmp
- Modules in single string: Isc, Voc
- Visual: Every module for integrity, darkening, deposits
  Every cell for corrosion, delamination, fracture
  Array structure, combiner boxes, wiring integrity

STRING POWER DEGRADATION

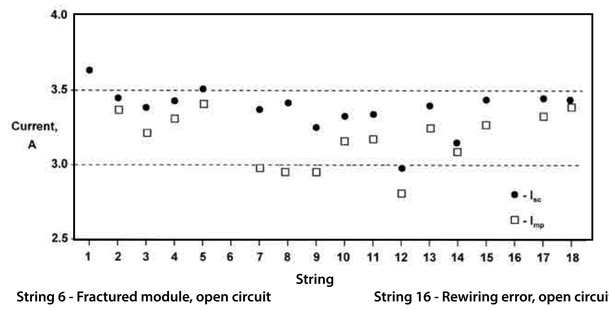
Based on voltage and current measurements made on 11 strings during 1.9 hour period with POA insolation in 0.38 - 1.04 kW/m^2 range; ambient temperature ~20 - 25°C; cell temperature ~30 - 35°C

Parameter	Isc	Imp	Voc	Vmp	FF	P/str	ΔP/yr
Data sheet	3.40 A	3.05 A	260. V	209. V	0.72	637.W	Ref
Measured	3.32 A	3.11 A	237. V	158. V	0.63	491.W	1.22%
Modified*	3.32A	2.98 A	237. V	172. V	0.65	511.W	1.05%

** Since measured Imp/Isc = 0.937 is substantially greater than data sheet Imp/Isc = 0.90, the MPP tracker appears to be controlling at lower string voltage than the actual Vmp for these strings. Modified data are based on calculated Imp = 0.90 (3.32) = 2.98 A and estimated FF = 0.65. Observed P/str calculations do not include any optical surface loss, string circuit loss, nor cell temperature correction from STC. If these factors total ~4%, then P/str increases to ~530 W and ΔP/yr decreases to 0.9% loss/year.*

STRING CURRENT

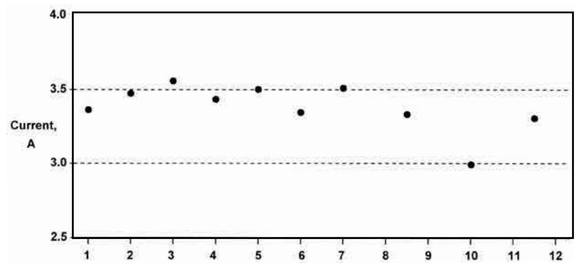
Measurements made with POA irradiance in 0.38 - 1.04 kW/m^2 range; ambient temperature ~20 - 25°C; cell temperature ~30 - 40°C



String 6 - Fractured module, open circuit **String 16 - Rewiring error, open circuit**

MODULE SHORT-CIRCUIT CURRENT

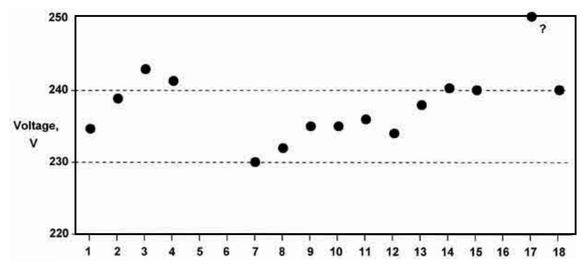
Measurements made on modules in String 16 (after wiring was corrected) with POA irradiance in 0.25 - 0.70 kW/m^2 range; ambient temperature ~18°C; cell temperature ~30°C



Circuits between modules 8 and 9 and also between modules 11 and 12 could not be accessed. Currents shown are short-circuit currents of each series-connected pair of modules.

STRING OPEN-CIRCUIT VOLTAGE

Measurements made with POA irradiance in 0.38 - 1.04 kW/m^2 range; ambient temperature ~20 - 25°C; cell temperature ~30 - 40°C



String 5 - Voc measurement not recordedString 6 - Fractured module, open circuit
String 16 - Rewiring error, open circuit

STRING GROUND LEAKAGE CURRENT

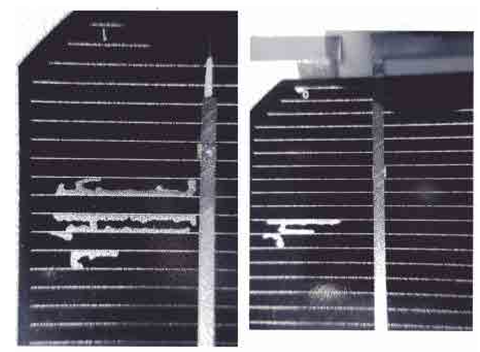
Time	Temp, °C	Dew	Strings	Min I leakage	Max I leakage
08:00	12	Heavy	6	8 µA	53 µA
08:40	16	Light	5	1 µA	8 µA
09:20	22	None	5	1 µA	1 µA

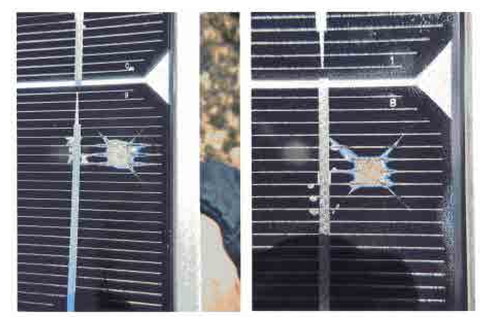
No wind; Voc = 242 - 248 V

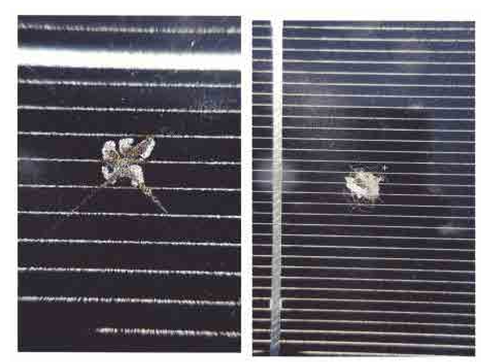
ARRAY VISUAL OBSERVATIONS

- Array structure rigid; modules securely attached
- Slight surface deterioration of array wiring, combiner boxes
- One fractured module (stone impact)
- Module surfaces clean; few small bird deposits
- No visible back-sheet degradation
- Frequent deposit/growth near module edge seal
- Uniform slight darkening of cell central area
- Corrosion/delamination:

Not readily visible	<2 mm^2:	~20 % of cells
Visible	>2 mm^2:	~80 %
Significant	>50 mm^2:	~12 %







ACKNOWLEDGMENTS

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Lee B. Jameson, Facility Manager
Dennis Steele, Island Maintenance Supervisor
of Sleeping Bear Dunes National Lakeshore

Lessons Learnt from Lab Testing

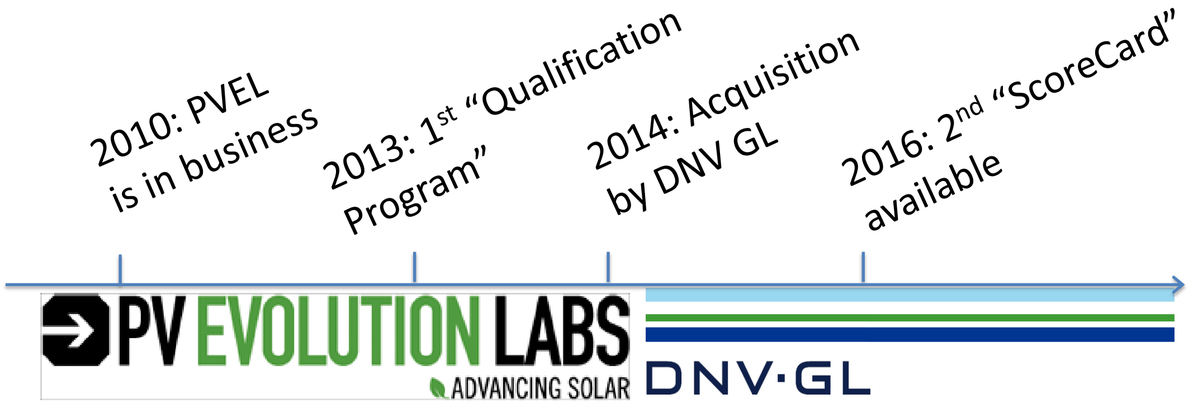
Frederic DROSS, Jenya MEYDBRAY
DNV GL, Berkeley, California, USA, www.dnvgl.com
frederic.dross@dnvgl.com

Presented at the NREL Reliability Workshop 2016, Boulder, Colorado

PVEL Qualification Program

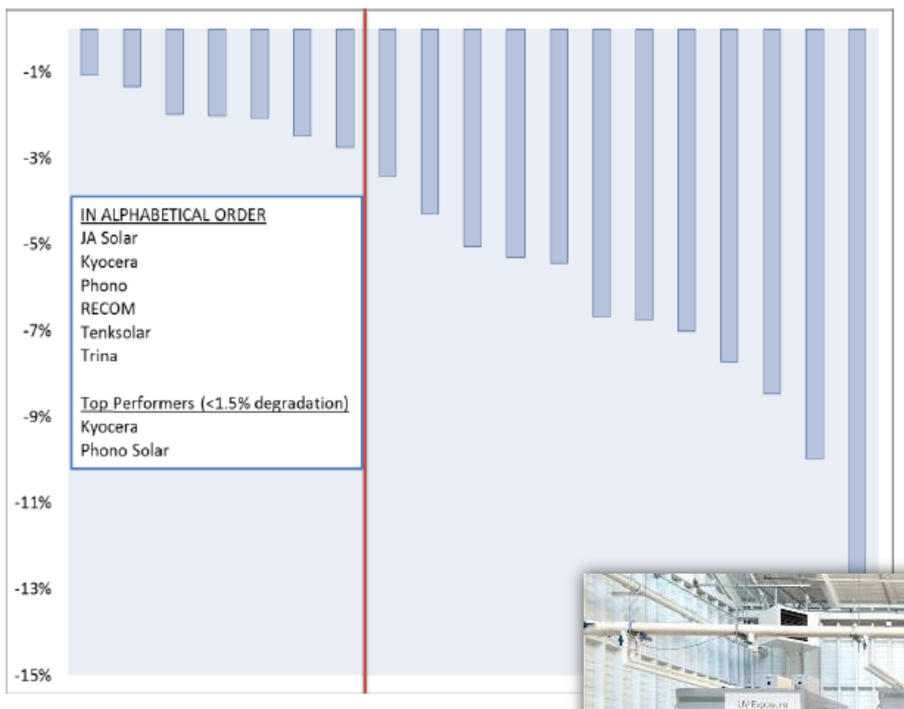
Test	Thermal Cycling	Damp Heat	Humidity Freeze	Mechanical Load	PID
Product Qualification Program	800 TC cycles	3,000 DH hours	30 HF cycles	Dynamic Load	600 hours
IEC 61215 Standard	200 TC cycles	1,000 DH hours	10 HF Cycles	Static mechanical load	None

- More than 130 Downstream Partners rely on DNV GL test data to buy modules
- More than 40 Qualification Programs executed today

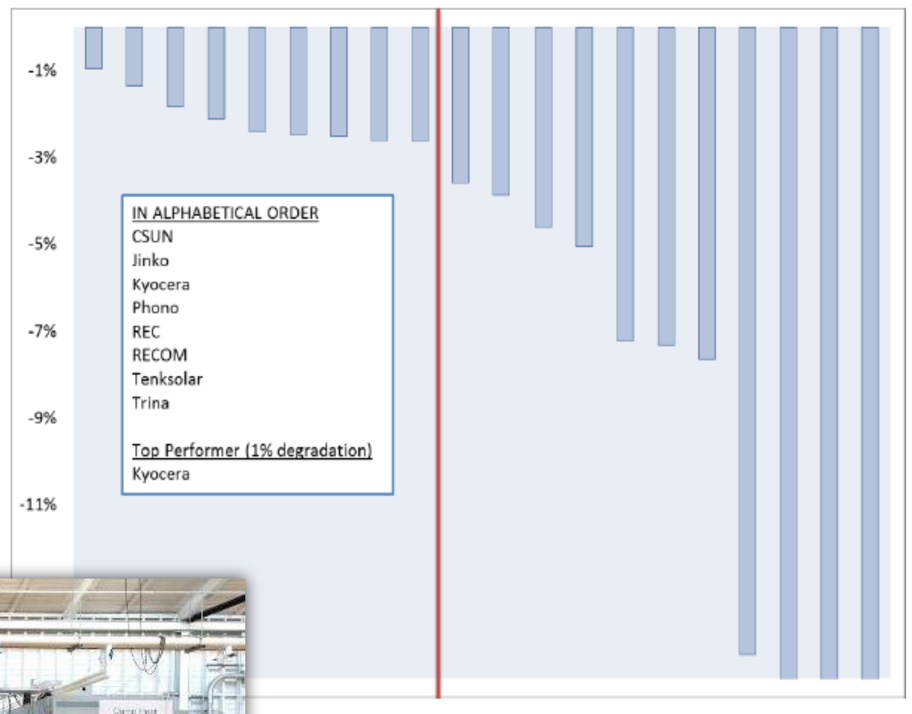


Results

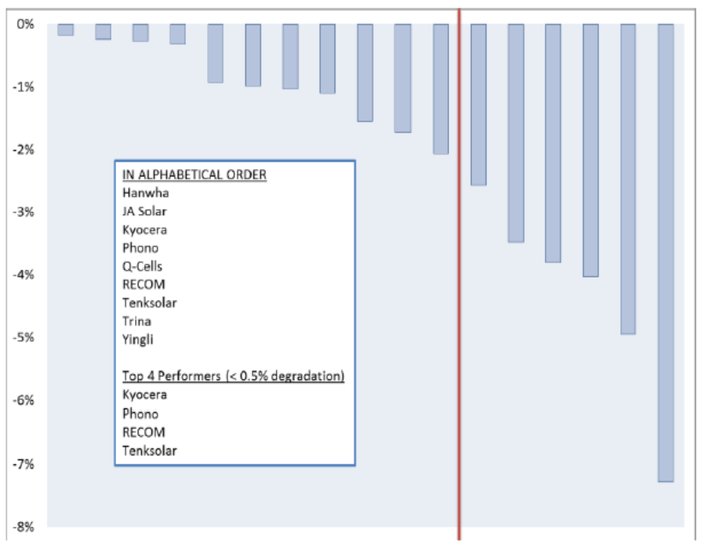
- Degradation observed after 800 Thermal Cycles



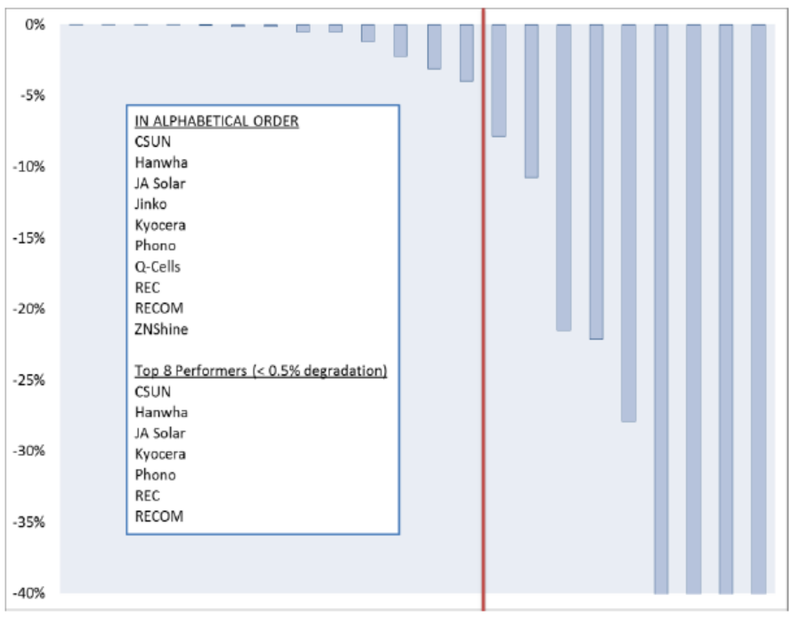
- Degradation observed after 3000h Damp Heat



- Degradation observed after 1000 cycles of Dynamic Mechanical Load, 50 Thermal cycles , and 10 cycles of Humidity Freeze



- Degradation observed after 100h of PID test



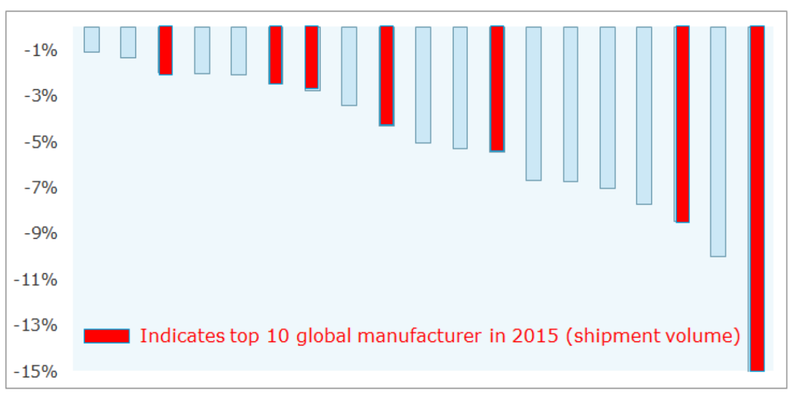
Some statistics

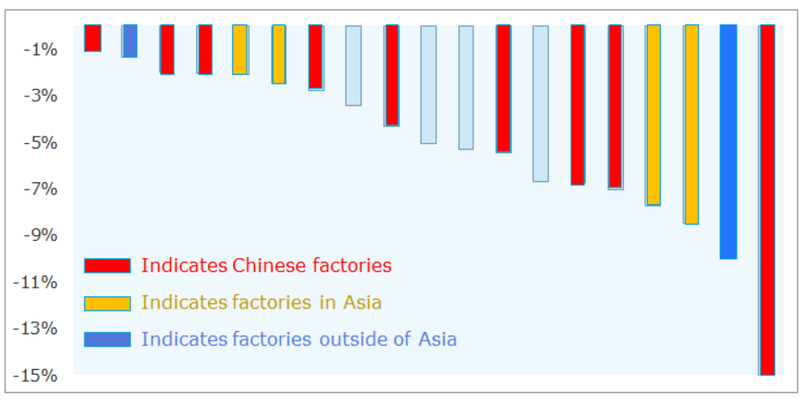
Test	33rd percentile	66th percentile
TC800	-3.0%	-5.9%
DH3000	-2.2%	-6.7%
DML seq.	-0.9%	-3.4%
PID 600h	-1.1%	-5.6%
UV90	-0.4%	-1.1%
HF30	-1.3%	-2.5%

- Disclaimer: DNV GL Labs probably test on average modules of higher quality/reliability than the global fleet of installed modules

Looking for correlations

- Degradation observed after 800 Thermal Cycles





- Little to no correlation found with size of the company and/or location of the factory

Take-aways

- Comprehensive testing shows a lot of variability among different module manufacturers
- Little correlation to shipment volume or factory location
- The test results are function of the BOM and of the know-how of the manufacturer

Detecting loss mechanisms of c-Si PV modules by Suns-*Voc* and multi-irradiance *I-V* measurement

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[2]c-Si Division, U.S. Photovoltaic Manufacturing Consortium, Orlando, FL, USA
Contact: siyu.seu@gmail.com

Introduction

- The outdoor monitoring has been widely applied for fault detection of PV modules.
- In most of the cases, PV module degradation is non-uniform.
- Using fitting method to extract parameters might not be well applied on a PV module.
- A method is proposed to accurately quantify the power loss of PV modules due to different degradation mechanisms.
- This work can be further applied to the degradation analysis of PV modules and system.

Method

- Equivalent circuit model is used to model the *I-V* and *suns-Voc* curve of a PV module.
- Both uniform and non-uniform degradation can be considered.

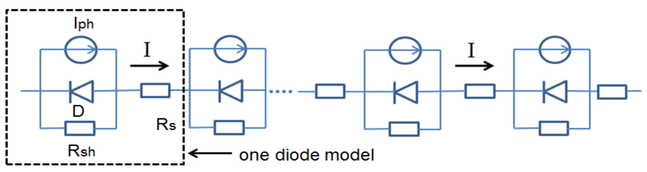
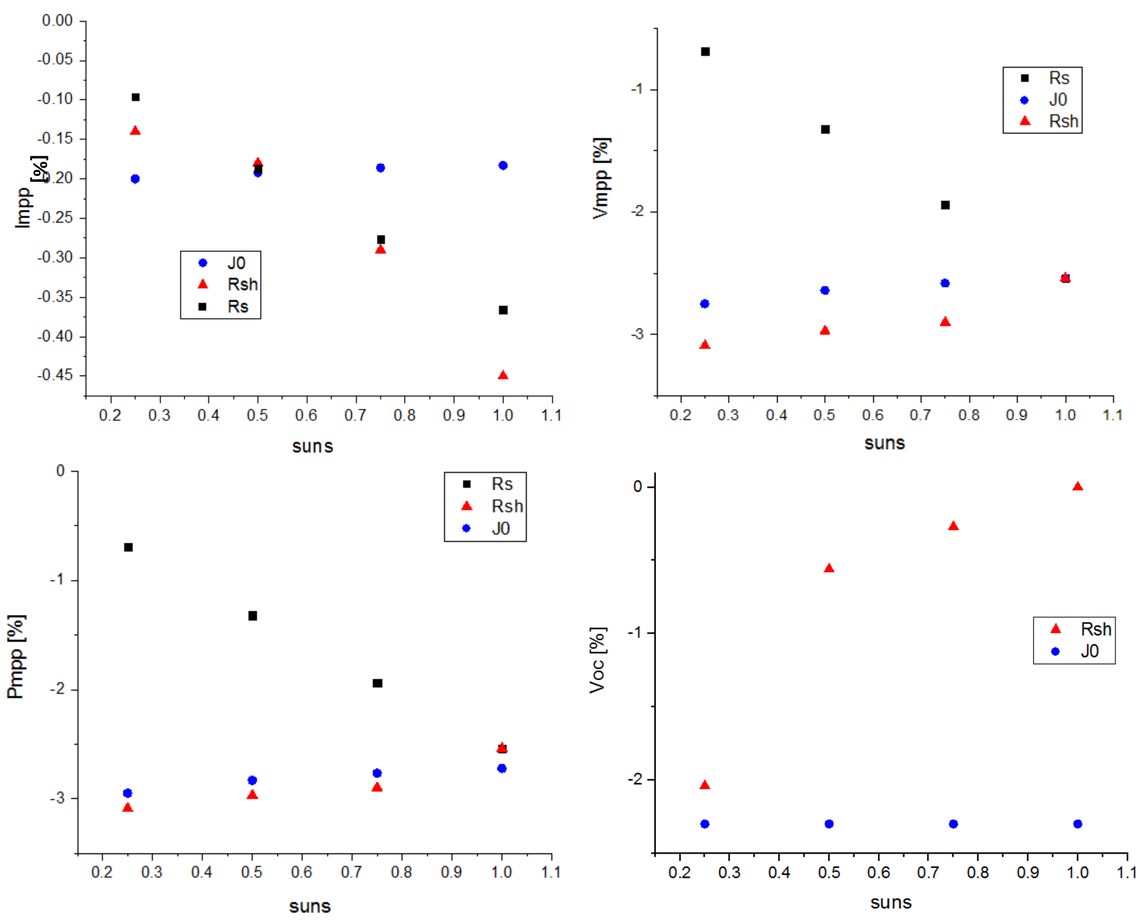


Fig. 2: The equivalent circuit of a PV module built in LTspice.

Extracting information using multi-irradiance *I-V*

- A PV module can be evaluated by its *I-V* characteristics (I_{sc}, V_{oc}, I_{mpp}. V_{mpp}).
- Three modules with different problems (degradated R_s, R_{sh}, J_0) are simulated. All modules have around 2.5% power degradation under STC.
- The *I-V* characteristics of the three modules are compared with the *I-V* characteristics of an ideal PV module under multi-irradiance. The relative change is plotted.



Reference

[1] M. K. Forsyth et. al, "Use of Suns-*Voc* for Diagnosing Outdoor Arrays & Modules", *40th IEEE PVSC*, pp. 1928-1931 (2014)

[2] S. V. Spataru et. Al, "Fault identification in c-Si PV modules by complementary analysis of the light and dark current-voltage characteristics", *Prog. Photovolt. (2015)*

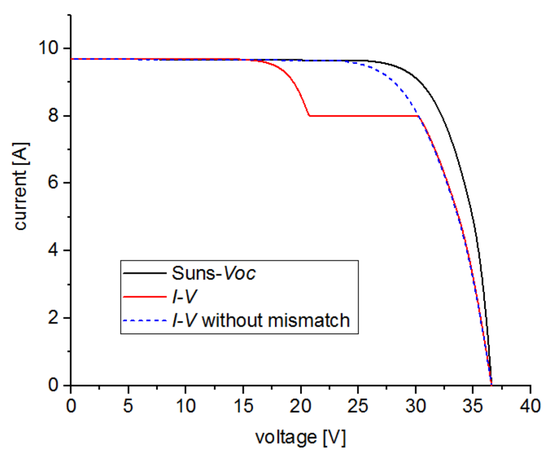
- The relative decrease of the I-V parameters changes with the increasing of irradiance :
  ↑↑: largely increase ↓↓: largely decrease ↓: slightly decrease
  —: keep constant N: not affected

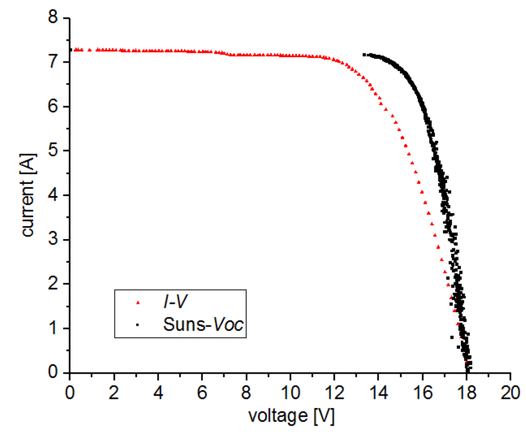
Loss on	I_{mpp}	V_{mpp}	P_{mpp}	V_{oc}
R_s	↑↑	↑↑	↑↑	N
R_{sh}	↑↑	↓	↓	↓↓
J_0	—	↓	↓	—

- The potential loss mechanism can be deduced.
- Under high illumination condition, the influence from R_{sh} on V_{oc} can be ignored, thus the influence from J_0 can be quantified.

Extracting information using *Suns-Voc*

- *By comparing I-V and Suns-Voc* curve, power loss due to R_s can be quantified [1].
- Under non-uniform degradation, this method is more accurate than fitting method.
- Power loss due to current mismatch can also be extracted using *Suns-Voc* result.

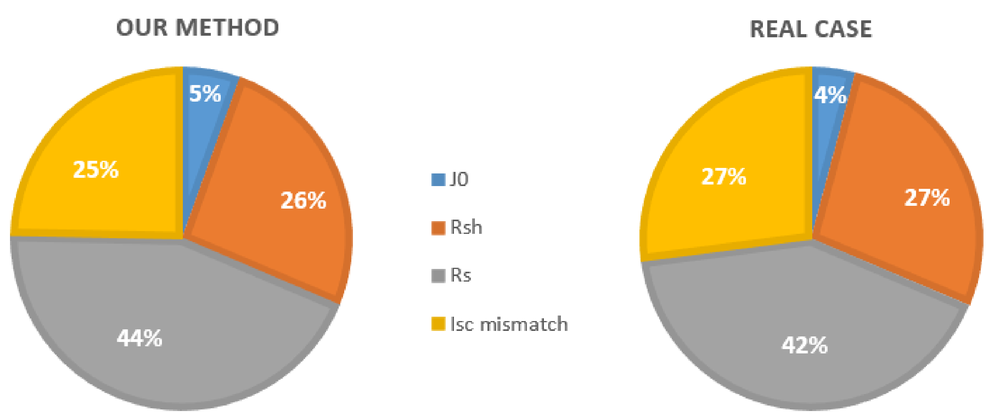




14.3 Wp loss on R_s

Case study

- Combined methods are used to investigate a PV module with serious non-uniform degradation. (2 cells are seriously shunted, 4 cells have very high recombination rate)



Conclusion

- Method proposed in this work can accurately identify the degradation parameters of a PV module.
- Each parameter (R_s R_s, R_{sh}, J_0) is linked to certain faults (shunting, contact, PID, LID, soiling, partial shading...). The degradation mechanisms of the PV module can be further deduced. A complete fault-detection system can be built.

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Measuring degradation rates when irradiance are missing or erroneous

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National Renewable Energy Laboratory, Golden, CO 80401, USA

1 Introduction

Quantifying long-term performance is important to:

1. *Reduce uncertainty, risk and reassure investors.*
2. *Predict lifetime.*
3. *Correlate accelerate testing with degradation.*

Common problem:

Questions regarding the stability of the irradiance sensor.

Erroneous irradiance measurements.

Missing irradiance measurements.

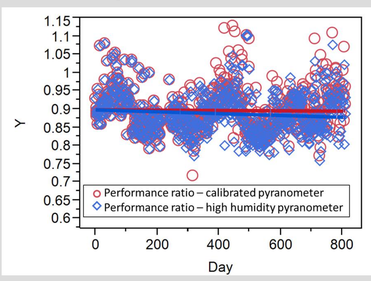
Can long-term performance be determined without reliance of irradiance?

2 Pyranometer Drift

Drifting pyranometer

Cartridge filled with saturated NaCl resulting in high humidity leading to drift.

System evaluation

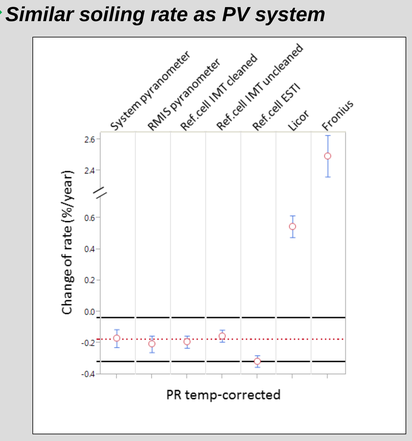


Pyranom.	R_d (%/year)	Uncertainty (%/year)
Regular	-0.18	0.38
High humidity	-1.15	0.36

Using the drifting pyranometer makes PV system appear to be degrading at ca. 1 %/year.

3 Reference Cells

- *Same angle-of-incidence response as system*
- *Similar spectral response (if spectrally matched) as PV system*
- *Similar soiling rate as PV system*

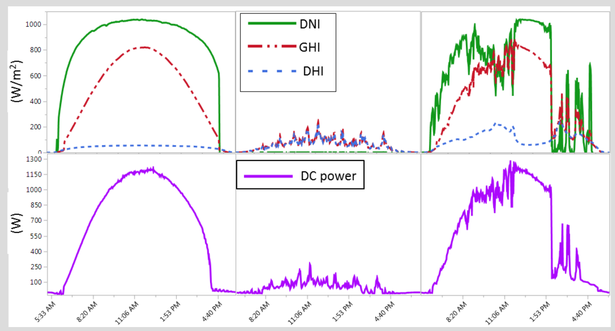


Determine degradation of one system using various pyranometers & reference cells.

…. but they can drift too!

4 Identification of clear days

Strategy: 1st step is to identify the type of day



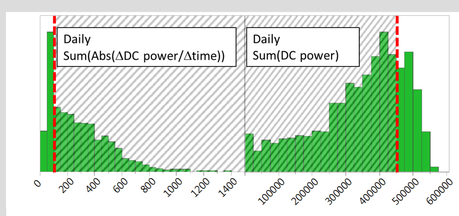
Clear day: only gradual changes but sum of Dc power is high

Cloudy day: small changes but sum of DC power very low

Partial cloudy: lot of changes

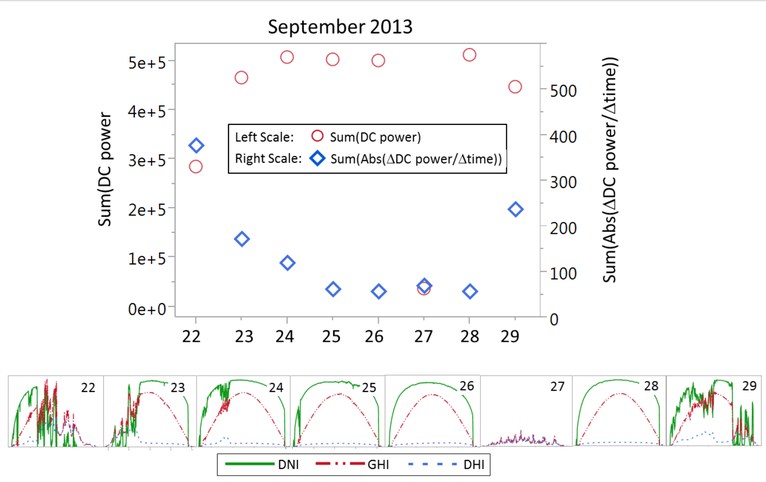
5 Identification of clear days

Filter strategy using 1 min data:



1. *Remove (shaded area) all days with high fluctuations (sum[Abs[ΔDC power/Δtime]])*
2. *Remove all days with low integrated power*

6 Example comparison

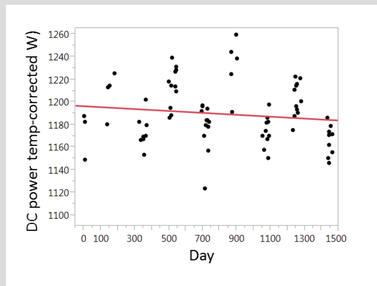


Determine clear days using PV system response only

7 Long-term performance

Filtering:

1. *Clear days*
2. *Sun position the same: angle-of-incidence < 10º*
3. *Outlier (DC power), stability (ΔDC power/Δtime)*
4. *Determine Tcoeff & correct DC power*



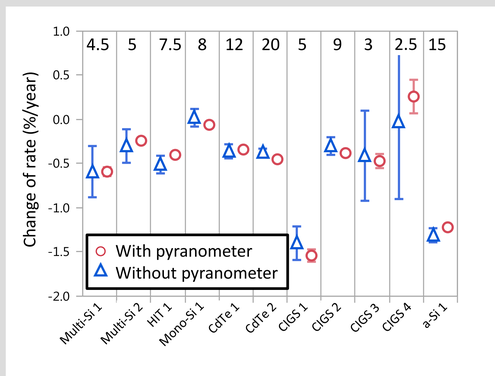
Fluctuation may be spectral effects

Daily DC power temp-corrected: R_d=(-0.30±0.19) %/year

Daily array responsivity (DC power/Gpoa) temp-corrected: R_d=(-0.24±0.03) %/year

General good agreement although higher uncertainty

8 Comparison w/ & w/o Gpoa



Fielded years

Uncertainty is statistical uncertainty only

Larger uncertainty without Gpoa but overall good agreement for 11 systems

9 Conclusion

Accurate PV performance often depend on accurate irradiance measurements.

Pyranometers can drift and mask true degradation of PV system.

Reference cell have several advantages over broadband irradiance measurements but can drift too.

Used PV system response to determine clear days, not relying on irradiance measurements.

Use that technique to determine long-term performance without irradiance. (low soiling region)

Generally, good agreement between degradation trends with and without irradiance, however higher uncertainty when not using irradiance.

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory

Comparison of Single-Axis PV Systems in China

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System Solution Design Department, Huawei Technologies Co., Ltd, Shanghai, CHINA

Introduction

- PV tracking mounting structure is commonly used to optimize the incidence of the sun over PV modules throughout the entire day.
- PV systems based on tracking are able to deliver a larger amount of energy compared to fixed tilt systems with the same rated PV power.
- The single-axis trackers move on one axis, and can be horizontal, vertical or tilted single-axis trackers.
- Horizontal trackers have the module surface always parallel to ground whereas the inclined single-axis trackers are tilted at a fixed angle.

FIGURE 1: Horizontal single-axis tracking system of 1.39 MW

FIGURE 2: Inclined single-axis tracking system of 1.28 MW

Methodology

- The two PV sub-systems (or blocks) under analysis is part of a 800 MW PV power plant located in North-West China (Qinghai province) and has been in operation since October 2015 .
- Two blocks have a single axis tracking system where one is a horizontal (East-West) tracking (1.39 MW) and the other is inclined at 35° (1.28 MW), see figures 1 & 2..
- The PV plant consists of 270 W_p PV panels, 40 kW Huawei string inverters (Model: SUN 2000-40TL) and Huawei Fusion solar cloud management system.
- The energy generated by the power plant is monitored at intervals of every 15 mins. This data is used to generate energy generation of the month (kWh/MW/month) and the daily generation profile shown in figure 3 & 4.
- The soiling loss was calculated using the string-level P_{max} values. The measured P_{max} was converted to STC value and compared to rated STC P_{max} parameter, to find the string damping (or degradation).

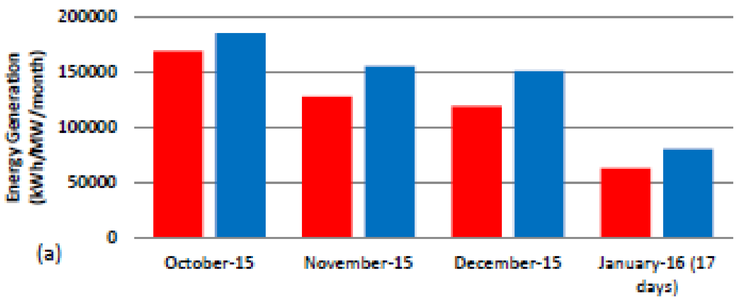

FIGURE 3: Monthly energy generation data of inclined (shown in BLUE) and horizontal (shown in RED) single-axis tracking PV system.

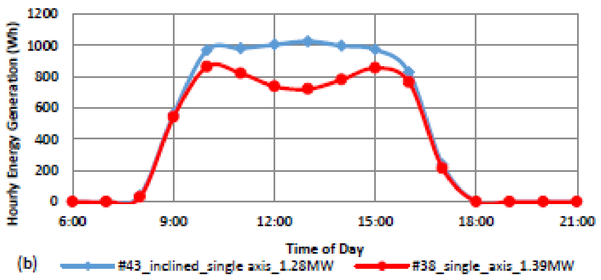

FIGURE 4: Hourly energy generation data of inclined (shown in BLUE) and horizontal (shown in RED) single-axis tracking PV system.

FIGURE 5: PV modules before and after cleaning

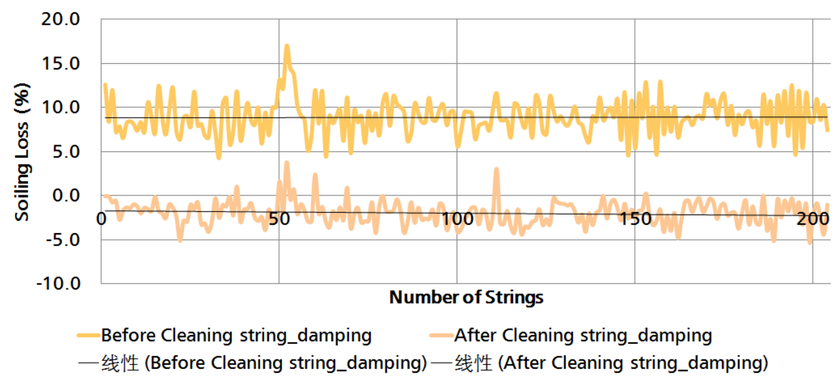

FIGURE 6: The PV string damping (or degradation) before and after cleaning of the horizontal single-axis tracking PV system, showing an approximately 10% reduction.

Results

- Monthly energy generation of the inclined single-axis tracking block is approximately 20% higher than the horizontal single-axis tracking block, as shown in figure 3.
- The reason for this increase is that the inclined tracking block generates about 20% more energy in the peak sun shine hours, as shown in figure 4.
- Analysis of the daily generation (kWh/KWp/day) showed that the inclined tracking system generated close to one kWh extra as compared to the horizontal tracking system.
- The horizontal single-axis tracking block showed approximately 10% loss due to the deposition of dust on the PV module surface [see figure 5 & 6].
- The negative value of string damping after cleaning is due to the error in estimation of equivalent string temperature and in STC translation.

ACKNOWELDGEMENT
We would like to thank Huawei management team for their support during this work. We especially acknowledge the help of the supporting staff Mr. Tangdi and Mr. Weizhiqiang.

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Study of PV module degradation which has been exposed over 20 years in representative climates of Japan

Feb.23.2016

Japan Electrical Safety & Environment Technology Laboratories
Tadashi Obayashi

1. Preface

The outdoor exposure test has been carried out in Kitami(Hokkaido), Tosu (Saga) and Miyako (Okinawa) since 1991 by NEDO project. There are representative climate places in Japan . It had been conducted from 1991 to 1999 by the Japan Quality Assurance Organization (JQA). It has been taken over by JET in 2001 and has continued since then.

We have investigated the degradation of silicon photovoltaic modules which were commercially produced in the early 1990s.We have tried to understand the visual and performance degradation there.

The purpose of this test is to understand

(1) the Japan's climate which corresponds to the Köppen climate classification.

(2)the differences of visual and performance degradation between three exposure sites.

(3)the relationship between climate conditions and visual and performance characteristics .

2. Köppen and Japan's Climate Classification

(1) The Köppen climate classification

The Köppen climate classification was devised in 1923 by Wladimir Köppen who was a climatologist of Germany. It focuses on vegetation distribution, temperature and precipitation. There are five climate divisions which are the Equatorial zone(A), the Arid zone(B), the Warm Temperate zone(C), the Snow zone(D)and the Polar zone(E)

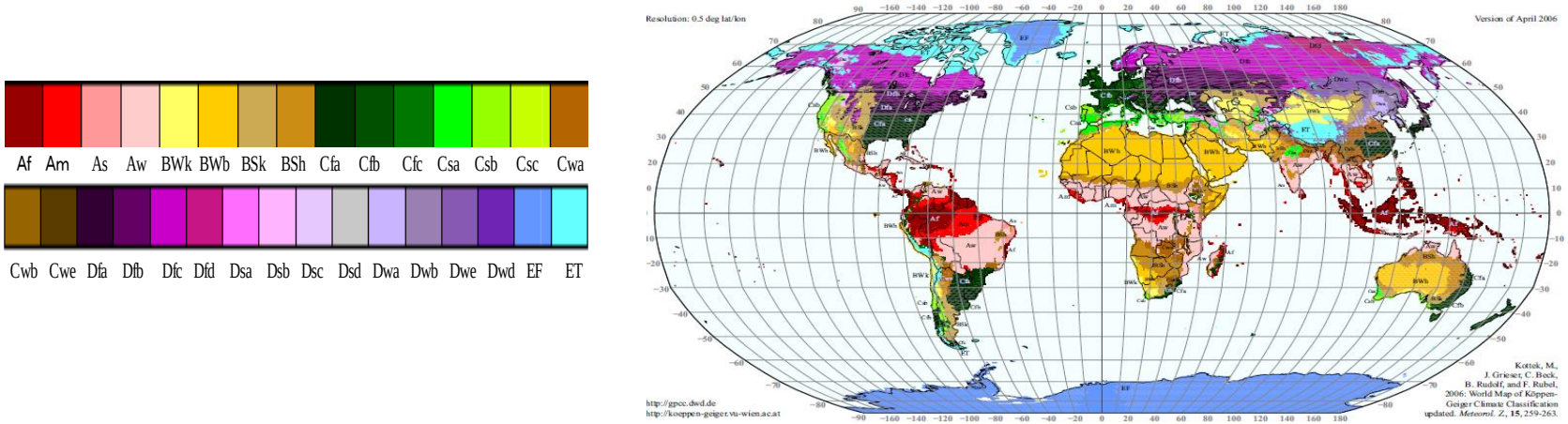


Fig.2-1 Köppen Climate Classification

Main climates		Precipitation		Temperature			
A:	Equatorial	W:	Desert	h:	Hot Arid	F:	Polar Frost
B:	Arid	S:	Steppe	k:	Cold Arid	T:	Polar Tundora
C:	Warm Temperate	f:	Fully Humid	a:	Hot Summar		
D:	Snow	s:	Summer Dry	b:	Warm Summer		
E:	Polar	w:	Winter Dry	c:	Cool Summer		
		m:	Monsoonal	d:	Extremely Continental		

(2)Average Temperature of Cities in Japan

Japan's climate division corresponding to the Köppen climate classification is shown in table 2-1. Average temperature is a mean value temperature in the coldest month.

It is more than 18 ℃ in the Equatorial zone(A), -3 ℃ to 18 ℃ in the Warm Temperate zone(C), and less than -3 ℃ in the Snow zone. It is 17.0 ℃ in Naha, and -3.6 ℃ in Sapporo .

Table 2-1 Average Temperature of Cities in Japan

	Sapporo	Sendai	Tokyo	Niigata	Nagoya	Osaka	Hiroshima	Tottori	Kochi	Fukuoka	Naha
January	-3.6	1.6	5.2	2.8	4.5	6.0	5.2	4.0	6.3	6.6	17.0
February	-3.1	2.0	5.7	2.9	5.2	6.3	6.0	4.4	7.5	7.4	17.1
March	0.6	4.9	8.7	5.8	8.7	9.4	9.1	7.5	10.8	10.4	18.9
April	7.1	10.3	13.9	11.5	14.4	15.1	14.7	13.0	15.6	15.1	21.4
May	12.4	15.0	18.2	16.5	18.9	19.7	19.3	17.7	19.7	19.4	24.0
June	16.7	18.5	21.4	20.7	22.7	23.5	23.0	21.7	22.9	23.0	26.8
July	20.5	22.2	25.0	24.5	26.4	27.4	27.1	25.7	26.7	27.2	28.9
August	22.3	24.2	26.4	26.6	27.8	28.8	28.2	27.0	27.5	28.1	28.7
September	18.1	20.7	22.8	22.5	24.1	25.0	24.4	22.6	24.7	24.4	27.6
October	11.8	15.2	17.5	16.4	18.1	19.0	18.3	16.7	19.3	19.2	25.2
November	4.9	9.4	12.1	10.5	12.2	13.6	12.5	11.6	13.8	13.8	22.1
December	-0.9	4.5	7.6	5.6	7.0	8.6	7.5	6.8	8.5	8.9	18.7

From the temperatures listed above , the climate of Japan belongs to the Warm Temperate zone(C), and the Snow zone(D).

(3)Japan's climate which corresponds to the Köppen climate classification

Kitami belongs to the Snow zone , Miyako and Tosu belong to the Warm Temperate zone of Köppen's climate classification

3. Climate Conditions of JET Exposure Sites

(1)Environment of Exposure Sites

1） Climate Conditions

The climate conditions of the exposure sites are listed in table 3-1. We considered a salt erosion in Miyako and snow damage in Kitami. and Fig 3-1 shows a photograph of the exposure sites. Fig 3-2 and Table 3-2 show climate divisions in Japan.

Table3- 1 Installation Characteristics of Exposure Sites

Exposure Site	Climate Cord & Division	Installation	* 1 Salt Damage	Accumulated Snow	Beginning Period
Kitami	1.a	ground	Absence (northeast 35km)	Presence (57cm)	1991
Tosu	2	ground	Absence (southwest 35km)	Presence (4cm)	1992
Miyako	6	ground	Presence (south 2km)	None(0cm)	1993

Note1: Weather parameters taken from the Japan Meteorological Agency past weather data (http://www.data.jma.go.jp/obd/).The numerical values of the Kitami is cited the value of the Abashiri. （) shows ”Abashiri”value

Note2: Numerical value of * 1 in the presence or absence column of salt damage in ( ), indicate the direction and distance of the approximate to the nearest coast.

Figure 3-1 Photograph of Exposure Sites.

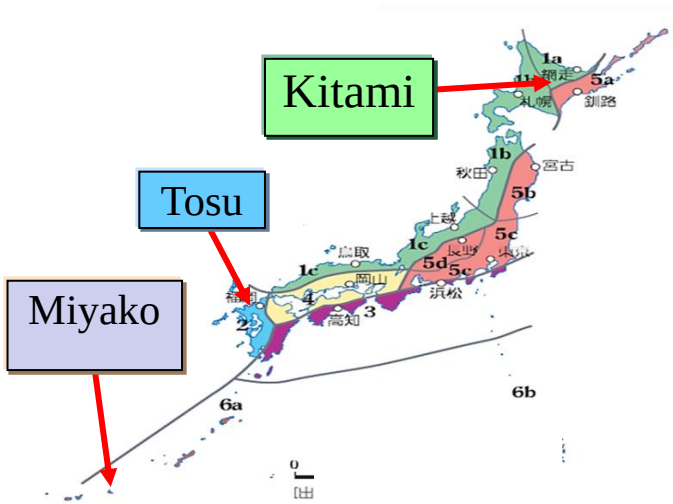


Fig.3-1 Climate Division of Japan by Takeshi Sekiguchi.

Table3-2 .Climate Code and Division

1	Japan Sea	a	Okhotsk
		b	Tohoku and Hokkaido
		c	Hokuriku snd Sanin
2	Kyushu		
3	Nankai		
4	Setouchi		
5	East	a	Tobu Hokkaido
		b	Tohoku and Joban
		c	Tokai and Kanto
		d	Central Highlands
6	Okinawa		

(2)Weather Conditions (Radiation, Temperature, Humidity, Etc)

1)Weather Observations From Japan Meteoroidal Agency(JMA)

The dates of weather conditions of the three sites are shown in Table 3-3.These were taken from JMA's past weather data retrieval.

Table 3-3 Weather Conditions of the Exposure Site

Exposure site	Climate Division	Average Daily Temperature T(℃)	Temperature Difference ΔT(max-mini℃) (daily mean)	Humidity (%)	Amount of Solar Radiation (MJ) (average)	Sunshine Hours per Year (hours)
Kitami	1.a	6.1	40.4	(74)	(12.6)	1775.5
Tosu	2.	16.5	31.2	70	13.2	1969.0
Miyako	6.	23.6	15.6	77	14.7	1766.2

Notes1: The numerical values of the Kitami site column ( ) is cited the value of the "Abashiri"

2) Weather Observation Data in Exposure Site

Table 3-4 Weather Observation Data in Exposure Site

Item		Kitami	Tosu	Miyako
Amount of Solar Radiation	Monthly average integrated value (kWh / m2)	108	114	132
	(Culmination when the solar radiation intensity kW / m2)	(0.50)	(0.60)	(0.60)
UVA Dose	Monthly average integrated value (kWh / m2)	4.9	5.4	8.0
UVB Amount	Monthly average integrated value (kWh / m2)	0.04	0.08	0.14
Temperature	Monthly average (℃)	7	16	23
	Monthly highest (℃)	27	33	32
	Monthly minimum (℃)	-13	1	15
Relative Humidity	Monthly average (%)	66	81	78
Sea Salt Stageicles Amount (mgNaCl/㎡・day)		--	--	51.8

4. Results and Discussion

(1)Visual Inspection

1）Visual Degradation Levels and Criteria

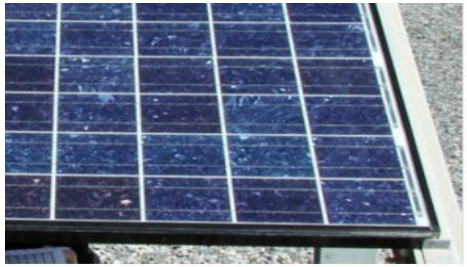
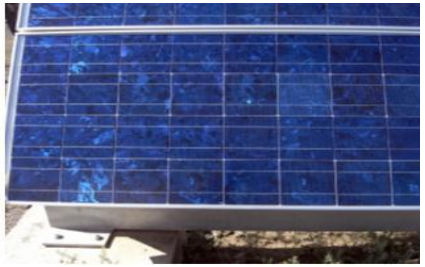
We classified the visual degradation of the module into five levels which are shown in Table 4-1. and photographs of the degradation Levels are shown in Fig 4-1.

Table 4-1 Degradation Levels Classification, and the Criteria

Levels	Criteria
Level 0(L0)	Non defects without the performance degradation
Level 1(L1)	Small defects without the performance degradation
Level 2(L2)	Evident defects which might affect the performance degradation
Level 3(L3)	Evident defects having the performance degradation which could affect the safety.
Level 4(L4)	Evident defects having the degradation of performance and safety .
Level 5(L5)	Evident defects could cause fire, electric shock, and fear of injuries.

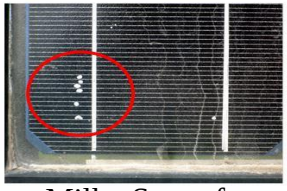
Photographs of the degradation Levels (L0, L1, L2, L3, L4, L5)

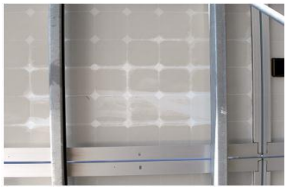
①Level 0 (L0) modules
--Non defects without the performance degradation

②Level 1 (L1) modules
--Small defects without the performance degradation

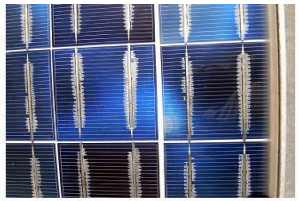
Yellowing of Encapsulant

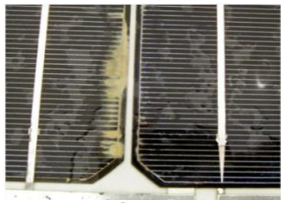

Milky Spot of Encapsulant


Back Sheet Discoloration

③Level 2 (L2) modules
--Evident defects which might affect the performance degradation

Yellowing of Encapsulant


Delamination of Encapsulant


Finger Corrosion

④Level 3 (L3) modules--Evident defects having the performance degradation which could affect the safety.

Delamination

Tab Corrosion

Whitening

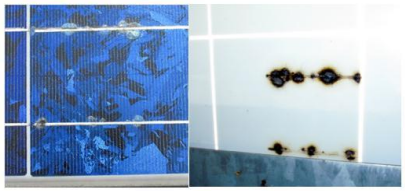
⑤Level 4(L4) ---Evident defects having the degradation of performance and safety .

Shortage within cell

Overheat of Solder Connection

⑥Level 5(L5) --Evident defects could causing the fire, electric shock, and fear of injuries..

J-Box Detached


Burned Back Sheet

Cracks in Back Sheet

Photo 4-1 Degradation Levels and the Photographs

2) Result of Visual Inspection

The results are shown in Table4-2. We have observed the parts which are interlayers, encapsulants, conductive-parts and cells and so on. We have found out the degradation level 1(L1) and level 2(L2). We couldn't found the difference of visual degradation level between these three sites.

Table 4-2 Results of Visual Inspection of the Long-Term Exposure Test

Exposure Site	Module Type	Visual Inspection Region and Degradation Level				
		Interlayer	Encapsulat	Conductive Part	Cell	Other
Kitami	c-Si	L0	L0	L0	L0	L0
	p-Si(A)	L0	L2	L0	L0	L2
	p-Si(B)	L2	L0	L0	L0	L0
Tosu	c-Si	L0	L0	L0	L0	L2
	p-Si(A)	L0	L0	L0	L0	L2
	p-Si(B)	L2	L0	L0	L0	L0
Miyako	c-Si	L0	L0	L0	L0	L2
	p-Si(A)	L2	L0	L0	L0	L2
	p-Si(B)	L2	L0	L0	L0	L2

(2) Electrical Performance

1) Estimate Method and Samples

The most basic module measurement is to measure the I-V Characteristics. We focused on the decrease in Pmax per year. I-V measurement has been continued from 1991 to obtain the knowledge about the module quality which is required for the long-term reliability. We have chosen two kind of silicon modules which are manufactured by three different manufactures. These were exposed over 20 years at three sites .

Table 4-3 shows module types, sample numbers and the beginning period.

Table 4-3 Type and Module Numbers Subjected to Long-Term Exposure Test

Type	Load Condition	Module Numbers		
		Kitami (from 1991)	Tosu (from1992)	Miyako (from1992)
c-Si	Load Resistance is Corresponding to Pmax	2	2	2
p-Si(A)		2	2	2
p-Si(B)		2	2	2
Total		6	6	6

Symbol (A) (B) in Note : Symbol s show the different manufacturer.

2) Results of Electrical Performance

The degradation of I-V characteristics are shown in table 4-4 and Fig 4-2. The normalized Pmax values are decreased less than 0.5% per year in each exposure site. We could not find the distinctive Pmax differences between them.

①c-Si: Performance of Tosu site's c-Si showed the significant output reduction. As a result of research, the cause was the poor connection.

②P-Si: In Tosu and Miyako sites, the output rate of change of p-Si(a) and p-Si(b) was different. This difference was also the influence of the contact of the connector.

In Japan representative 3 climate sites, the significant differences of performance degradation are not recognized.

Table 4-4 Output Measurement Result of Long-Term Exposure Test

Site	Type	Normalized Pmax (%/Year) of I-V Characteristics (STC)
Kitami	c-Si	-0.0
	p-Si(A)	-0.1
	p-Si(B)	-0.1
Tosu	c-Si	-0.4(-0.1) ------the influence of the poor connection
	p-Si(A)	-0.0
	p-Si(B)	-0.3 ------the influence of the poor connection
Miyako	c-Si	-0.0
	p-Si(A)	-0.0
	p-Si(B)	-0.3 ------the influence of the poor connection

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The degradation of I-V characteristics(STC)--Normalized Pmax (%/Year)

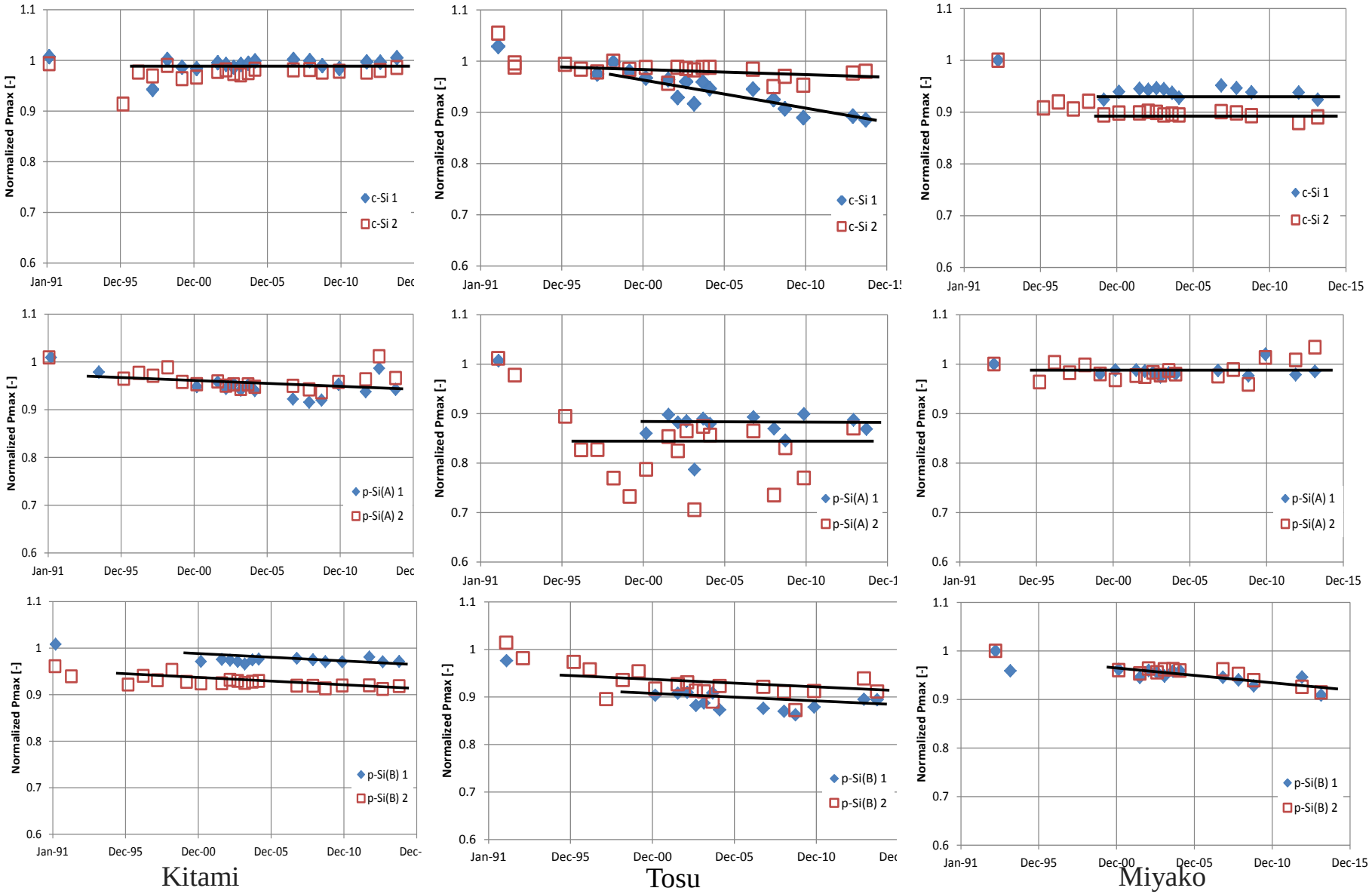


Fig 4-2 Relation between the Output Performance and the Exposure Years

5. Summary

The outdoor exposure tests have been carried out in Kitami (Hokkaido), Tosu (Saga), Miyakojima (Okinawa) from 1991 by NEDO project. There are presentative climate places in Japan. We have investigated the degradation of silicon photovoltaic modules which were commercially produced in the early 1990s. We have tried to understand the visual and performance degradation there.

(1)The climate of Japan belongs to the Warm Temperate zone and the Snow zone of Köppen's climate classification. Kitami belongs to the Snow zone , Miyako and Tosu belong to the Warm Temperate zone of Köppen's climate classification

(2) In Japan's representative three climate sites, the significant differences of visual and performance degradation are not recognized.

We believe that it is important to define climate zones based on scientific findings out of field data to help manufactures design PV modules to fit the conditions of the target location where modues are installed. We are planning to make further analysis to find definitions of the PV specific climate zones applicable to Japan and other mid-latitude areas.

Natural Resources Canada | Ressources naturelles Canada

Analysis of a 22-year old PV system in Quebec, Canada – Part II (Module I-V Analysis and Visual Observations)

Poster Presentation By: Tanya Dhir, Relsol Inc. & Yves Poissant, CanmetENERGY

System Overview

Location:	Montreal, Canada
System size:	24 kW
Number of modules:	540
Initial year of operation:	1992
Mounting configuration:	Roof Open Rack
Fixed tilt or tracking:	45 degrees, fixed tilt
Date of Disconnection:	October 2014
Date of Removal:	October 2015
Date of Inspection:	January 2016

Cell type:	Monocrystalline Si (some poly)
Module Manufacturer:	Astropower Canada
Encapsulant:	EVA
Backsheet:	PVF/PET/Tie Layer
Average Initial P_{max}:	44.4 W (A, B, C subset)
Module Efficiency:	10%
Module Configuration:	36 cells in series, 1 diode

Installed in 1992, the 540-module PV array near Montreal, Quebec is possibly the oldest continually monitored PV system in Canada. The climate is temperate, with low temperatures, significant snow falls and freeze-thaw events in winter, and high temperatures in summer.

The modules remained on the roof until October 2015, at which time they were brought indoors for inspection and I-V characterization in January 2016. This poster presents some of the results from this characterization.

Module Power Degradation

- Initial measured I-V data was available for the majority of modules in Arrays A, B, and C, yielding an average maximum power of 44.4 W (Fig. 1). Modules from Array DC are not included for the purposes of degradation calculations in this Poster. Modules which had been moved were also excluded from degradation analysis, since they have different exposure histories.
- The average Power Degradation for Arrays A, B, and C was 14%, which is approximately 0.63% per annum over the 22 years under load (Fig. 2). Note that system performance loss is expected to be greater due to module mismatch and system losses not considered in the current study.

Fig. 1

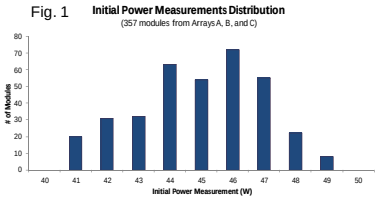
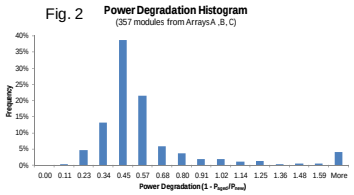


Fig. 2



Visual Defects

- After 23 years outdoors, the majority of modules showed front delamination, likely between the cell and front encapsulant, and rear delamination of the backsheet in a wavy pattern. However, this appears to have less effect on the power output of the modules, compared to the presence of front-side cell defects (excluding delaminations). Fig. 3 shows that the evaluation of the module has a general correlation to its performance. Multiple defects are often present on a given module, with 89% of modules having 2 or more defects. However, 77% of modules do not have defects of the front cells or junction box.

Fig. 3a

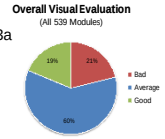


Fig. 3c

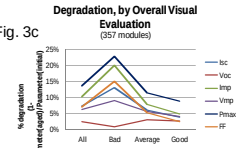
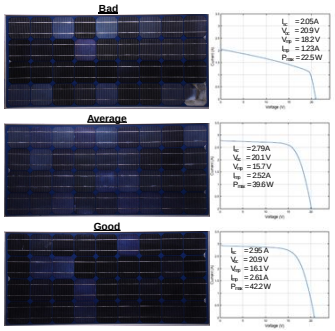


Fig. 3b



Spatial Distribution

- The modules were mapped out according to their physical position in the array. Array A is located in Div 1-4, Array B in Div 4-6, and Array C in Div 11-14. A DC array was located in Div 7-11. Div 8 modules were used extensively for experiments. The Power Degradation of each module, as well as the various visual defects, where plotted in terms of spatial position, in order to evaluate positional-dependencies (Fig.4a).
- Fig.4b shows that moisture damage was observed more frequently on modules located in the bottom row of the top arrays where snow tended to accumulate.
- Large I-Beams formed the structure for the array, and it is possible that these large beams impacted temperature, air flow, and snow accumulation.

Fig. 4a

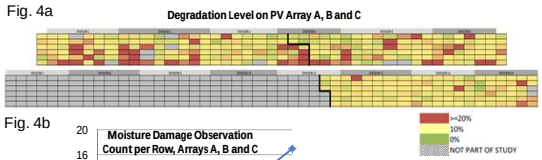
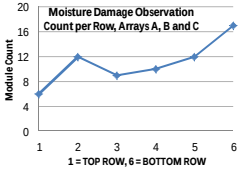


Fig. 4b



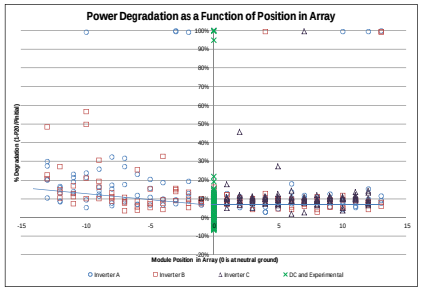
Next Steps

- Further analysis of the modules is anticipated, including defect characterization and analysis of monitored system/array performance data.
- Some of the modules will be returned to an outdoor rack for further exposure.

System Grounding

- This system was unique in that it included several different string configurations. Arrays A & B were centrally-grounded through the Omnion inverters, therefore half the strings were positively-grounded, and the other half negatively-grounded. Array C was negatively grounded, first externally from the Abacus inverter, and then internally through the replacement Fronius inverter. All arrays were disconnected from the inverter and left open circuit for the last year, and possibly during interim maintenance. Array DC consisted of individual modules, not connected in series.
- There was no intentional grounding of module frames.
- As shown on Fig. 5, there appears to be little correlation between module position relative to ground Pmax for negatively grounded strings. However, there is more degradation with positively-grounded strings. This is possibly related to potential induced degradation (PID).

Fig. 5



Acknowledgements: Alexandre Côté, Mohammed-Amin Bessioud, Vincent-Martin Blanchard and Dave Turcotte

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Performance analysis of a 558 kW_p ground-mounted, single-axis tracker PV system at the CSIR (South Africa)

2016 NREL PV MODULE RELIABILITY WORKSHOP (PVMRW), GOLDEN COLORADO, USA

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INTRODUCTION

The Council for Scientific and Industrial Research (CSIR) Energy Centre developed a novel methodology that can be applied by public entities in South Africa and elsewhere in the world to allow for the procurement of PV assets at the lowest possible lifetime cost, measured in Levelised Cost of Electricity (LCOE). This methodology was successfully implemented in the procurement of the CSIR's first own 558 kWp, ground-mounted, single-axis tracker PV system on the main campus in Pretoria, South Africa. A very competitive LCOE of 83 ZAR-ct per kWh (in May 2015 Rand value, 6.8 $-ct per kWh) and a very high quality PV system were achieved.

For the initial performance analysis, operational data was measured and collected from 1 October 2015 until 31 January 2016. Pyranometers measured Global Horizontal Irradiation (GHI) and global irradiation in module plane in Wh/m²/day. The tracking system follows the astronomical movement of the sun in a pre-programmed manner, hence no intraday optimisation of the tracking profile occurs. The axis of tracking is horizontal in N-S direction and the modules move from a +55° inclination in the morning towards the East, to a -55° inclination in the evening towards the West. On average, over the entire observation period of four months (October 2015 to January 2016), the tracking gain was 20%. Tracking gain is defined as the ratio of global irradiation in module plane to global horizontal irradiation. It was furthermore observed that on certain days, the tracking gain was higher than the average 20%, whereas on some days it was even below 0%.

HYPOTHESIS

The following hypothesis was formulated and subsequently tested: "Tracking the modules always leads to a gain compared to a fixed module angle over a day."

APPROACH/METHODOLOGY

The CSIR Energy Centre developed a methodology which is the first of its kind in the South African public procurement context for PV that allows evaluation of proposals for the purchase of a PV asset in an EPC contract based on LCOE. The methodology includes a "control loop" to ensure actual delivery of the promised LCOE.

For the performance analysis, days were categorised into three types: high, medium, and low GHI. Days with high GHI (I) are generally characterised as those with a blue sky from morning to evening, no cloud cover and little aerosols in the air. Days with low GHI (III) are typically overcast with cloud cover throughout the day. Days with medium GHI (II) are in between, with scattered cloud cover or with sunny/cloudy periods changing throughout the day.

RESULTS AND DISCUSSIONS

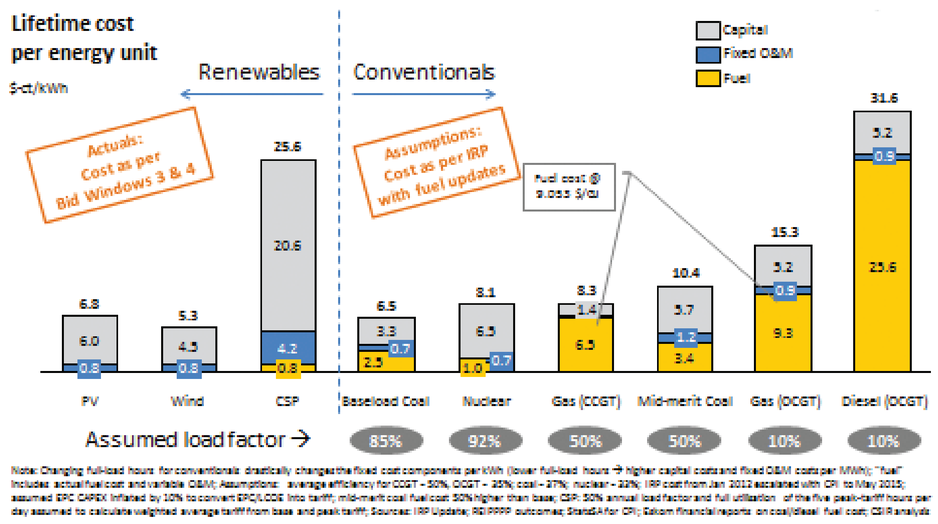
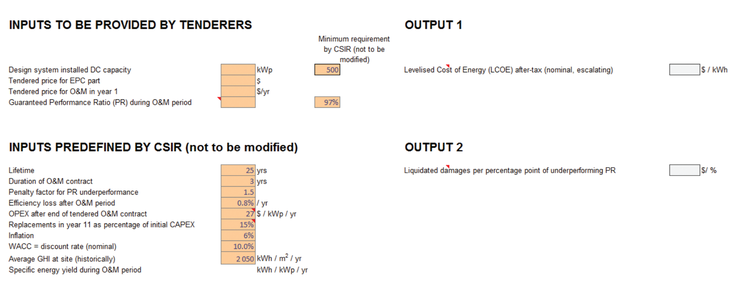


Figure 1: Cost comparison of alternative new-build options for the South African power system

- Wind and solar PV reached "new-build parity"
  ⟶LCOE from wind/PV ≤ LCOE of all new-build options (system view)
- LCOE of roof-top PV in South Africa (6.3-7.1 $-ct per kWh) below residential electricity tariffs (8.77-11.1 $-ct/kWh without Value Added Tax) resulting in "retail grid parity" already achieved!
  ⟶this is a huge incentives for public entities who are electricity customers (e.g. schools, hospitals, government buildings, etc.) to install PV systems to supplement their grid supply ("first movers")
- Care should be taken to buy assets at lowest LCOE as opposed to an EPC Price



INPUTS TO BE PROVIDED BY TENDERERS

			Minimum requirement by CSIR (not to be modified)
Design system installed DC capacity		kWp	500
Tendered price for EPC part		$	
Tendered price for O&M in year 1		$/yr	
Guaranteed Performance Ratio (PR) during O&M period			97%

OUTPUT 1

Levelised Cost of Energy (LCOE) after-tax (nominal, escalating)		$ / kWh

INPUTS PREDEFINED BY CSIR (not to be modified)

Lifetime	25	yrs
Duration of O&M contract	3	yrs
Penalty factor for PR underperformance	1.5	
Efficiency loss after O&M period	0.8%	/ yr
OPEX after end of tendered O&M contract	27	$ / kWp / yr
Replacements in year 11 as percentage of initial CAPEX	15%	
Inflation	6%	
WACC = discount rate (nominal)	10.0%	
Average GHI at site (historically)	2 050	kWh / m² / yr
Specific energy yield during O&M period		kWh / kWp / yr

OUTPUT 2

Liquidated damages per percentage point of underperforming PR		$/ %

Figure 2: Screenshot of CSIR-developed, Excel-based model showing inputs requested from bidders, predefined parameters by the CSIR LCOE calculation and outputs

- A model based on LCOE is proposed to determine the price ranking
- Bidders need to provide four inputs into the model
- A number of quality criteria are defined as gatekeepers to filter the proposals
- The model calculates two outputs: LCOE and Liquidated Damages (that need to be paid in case of underperformance during the control period of three years)

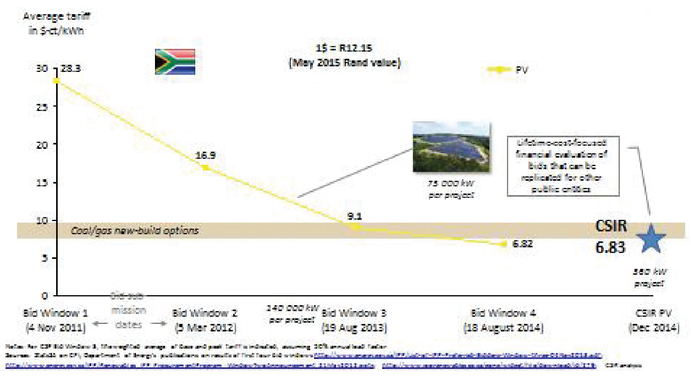


Figure 3: Comparison of the results of CSIR's PV plant with the first four bid windows of the South African Department of Energy's Renewable Energy Independent Power Producers Procurement Programme (REIPPPP)

- Across the four windows of REIPPPP, the price of PV dropped by 75%
- PV in South Africa is cost competitive today!
- The price of 6.82 $-ct per kWh compares favourably with the 6.83 $-ct cents per kWh pricing from Round 4 REIPPPP
  ⟶ a PV plant of relatively small scale in Pretoria, not the sunniest region in South Africa, can compete very well with large, utility-scale projects in the sunniest parts of South Africa

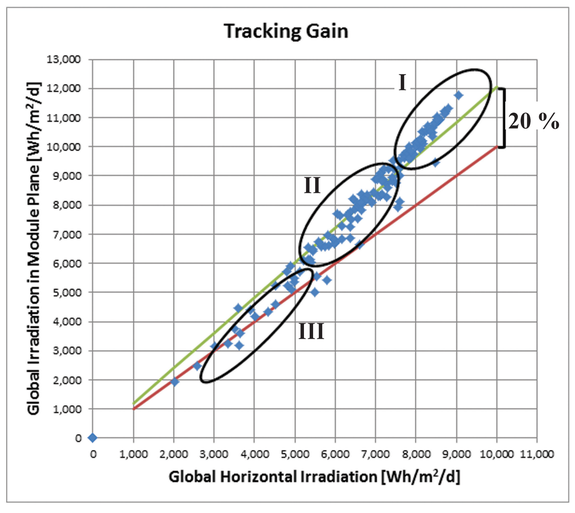


Figure 4: Scatter plot of global horizontal irradiation plotted versus global irradiation in the module plane

- In category I days, the tracking gain is indeed higher than average. The explanation can be that on such a blue sky day with low amount of aerosols in the air, the source of light is in fact very close to a point source (the sun). In such a situation of direct sunlight, tracking makes most sense and the tracking gain is thus high.
- On category III days, the source of light takes on the form similar to that of a plane, especially on completely overcast days with white clouds (the entire sky is then the source of light). On such days, the tracking system essentially moves the modules away from the source of light (the entire sky, which is a horizontal plane).
- There are indeed days where tracking led to a lower-than-horizontal solar energy amount hitting the module plane, hence the hypothesis that tracking is always better than a fixed-tilt positioning of the modules could be falsified. The control strategy of following the astronomical movements of the sun therefore cannot be the optimum. What needs to be tested now is what a better control strategy is.

CONCLUSIONS

The business approach of procuring PV assets, which looks at LCOE of a PV investment was incorporated into the evaluation process of a public EPC tender. The defined methodology was applied in the procurement of a first 558 kWp PV system with single-axis tracker configuration and achieved very competitive LCOE of 6.83 $-ct per kWh. It will now be made available to other public entities as a guideline to procure PV assets (rooftop or ground-mounted) cost optimally.

The initial performance monitoring results of the PV system indicate that the single axis tracking array increased the solar irradiation in module plane by 20% on average over the global irradiance on the horizontal plane. It could also be shown that tracking the astronomical movement of the sun is not the optimal tracking strategy. Further data analysis is needed, especially with respect to: (1) different temperatures and intraday weather conditions for all seasons, (2) determination of the optimum achievable solar irradiation in module plane per day, (3) deriving a tracking methodology that tries to achieve this optimum per day.

EVOLUTION OF MEASURED MODULE POWER VS LABELLED MODULE POWER OF CRYSTALLINE SILICON BASED PV MODULES

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European Commission, Joint Research Centre, Institute for Energy and Transport, Renewables and Energy Efficiency Unit, Via E. Fermi 2749, TP-450, I-21027 Ispra (VA), Italy.

Introduction

This poster outlines the evolution of measured module power vs labelled module power of crystalline silicon PV modules over a number of decades at the ESTI laboratory. Manufacturers tolerance in nameplate power have changed over the years with many claiming ±10% in the 80's and 90's. The declared tolerance over recent years has been reduced to ±5% then ±3% and today values of -0/+3 % are quite common. To know the declared tolerance of modules in a fielded system is useful additional information when looking at the aging of PV system, when the original module power may either be unknown or missing with the passage of decades. Therefore, researchers have to rely on the labelled power for the starting point of the system. Measurements at the ESTI laboratory have been performed since the early 1980's. A comparison of those modules which incorporated either a label (or an associated data sheet or online information) to their measured output power have been analysed. This work presents some selected results from crystalline silicon based modules, extracted from various time periods from the 80's to 2014.

Module characteristics

In this work, a set of 891 crystalline silicon based modules was analysed. The label values were either obtained directly from the label attached to the module, the manufacturers datasheet, or from online information.

The measurement date was taken as the reference year for each module, this simplification may result, for some modules, being listed as a year after their production date.

The majority of module data originates from various type approval test performed by the laboratory, together with some module calibrations. As type approval testing is based on relative measurements most of the data come from crystalline module measurements which do not incorporate a measurement of the spectral response and subsequent Mismatch Factor (MMF) correction).

There are no data available from the years 1993 and 2000.

An average of 29 modules by year were analysed with a maximum of 101 modules in 2002 belonging to 50 different manufacturers.

Electrical performance

I-V characteristics were obtained using different solar simulators, Spectrolab LAPSS, PASAN IIIB or under natural sunlight. The pulse length of the Spectrolab was around 2ms, while the PASAN IIIB is 10ms and the measurement under natural sunlight varying but up to 1sec. All the I-V curves were corrected to 1000W/m^2 and were measured very close to 25ºC and therefore not temperature corrected to 25ºC.

Although rigorous uncertainty calculations were not performed in the 80's, the tendency has been to reduce the uncertainty in P_{max} with time. Currently the best module uncertainty for calibration is ±1.0%, though this incorporates MMF correction which was not applied to this dataset.

Overall Results

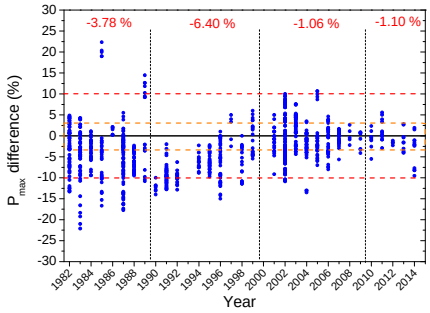

Fig. 1 Difference between P_{max} measured and P_{max} from label.

A clear tendency is apparent in the difference between measured and labelled power, with the average difference decreasing over the decades.

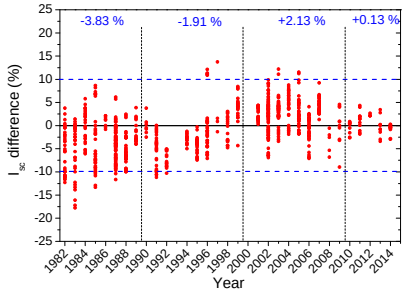

Fig. 2 Difference between I_{sc} measured and I_{sc} from label.

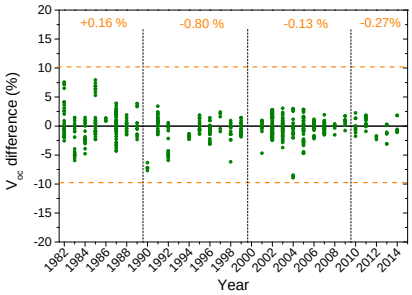

Fig. 3 Difference between V_{oc} measured and V_{oc} from label.

Statistical analysis

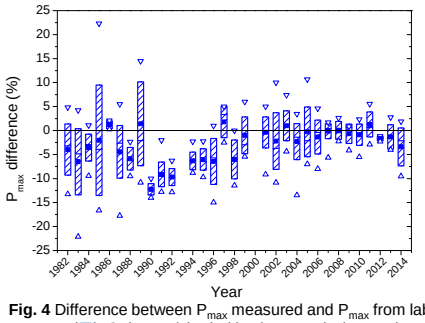

Fig. 4 Difference between P_{max} measured and P_{max} from label. Average (■), Std. Dev (shaded box), Max Min (open triangles)

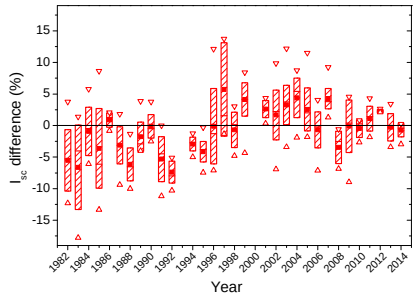

Fig. 5 Difference between I_{sc} measured and I_{sc} from label. Average (■), Std. Dev (shaded box), Max Min (open triangles)

The box plots of P_{max} and I_{sc} indicate the tendency of variations across the decades and the standard deviation of the measurements. Both have improved in relation to the labelled values of P_{max}.

Average Results

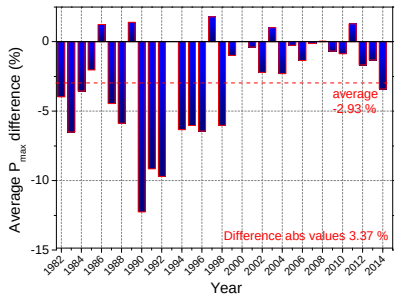

Fig. 6 Average difference between P_{max} measured and P_{max} from label.

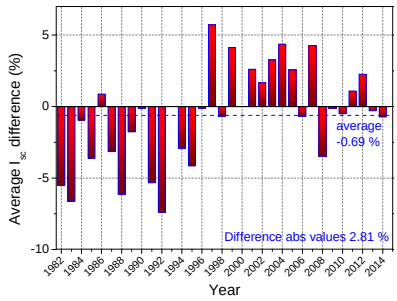

Fig. 7 Average difference between I_{sc} measured and I_{sc} from label.

The average P_{max} results show the general improvement over time, while the average I_{sc} results switched between lower (measured to labelled) values in the 80's to mid 90's to higher (measured to labelled) values from the mid 90's to mid 2000's. This change was probably due the method of operation of the factory solar simulators, with the "Golden module" used to set the value of P_{max} as opposed to I_{sc}.

Conclusions

- ✓ The difference between measured and labelled power has decreased over the decades.
- ✓ P_{max} and I_{sc} have shown the greatest variations over this period.
- ✓ V_{oc} has not shown a significant tendency with average values close to labelled.
- ✓ Care should be exercised in using labelled power of modules/systems in ageing studies due to the offset in earlier decades.

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The information contained here does not include confidential information and is suitable for public release

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SILICON PHOTODIODE PYRANOMETER CALIBRATION METHOD AND ACCURACY

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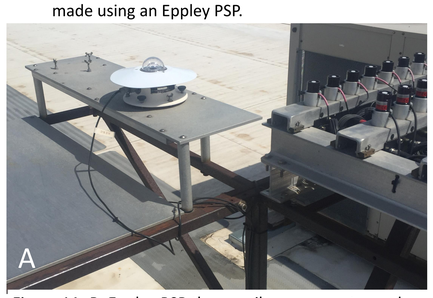
INTRODUCTION

- Silicon photodiode (SPD) pyranometers provide a low-cost solution for high installation-density solar irradiance measurements (1).
- SPD pyranometers have different spectral and cosine responses than ISO 9060 Secondary Standard Pyranometers. SPD sensors can be calibrated to give accurate measurements of integrated daily total radiation and reasonable estimates of hourly values, but instantaneous irradiance measurements are subject to considerable errors under some sky conditions (e.g. at low sun angles).
- Here we describe a calibration procedure in which a set of *reference* LI-200R pyranometers are calibrated outdoors against a Secondary Standard Pyranometer (Eppley Precision Spectral Pyranometer, The Eppley Laboratory, Inc, Newport, RI) under a defined set of conditions: clear skies with the sun at 45 ± 2° from zenith. This produces a calibration that is reproducible and has known bias.
- *Production* LI-200Rs are then calibrated over several days outdoors against the *reference* LI-200R sensors at all sun angles and most sky conditions, including cloudy skies. This provides precise and repeatable calibrations because *production* and *reference* pyranometers have the same spectral, cosine, and temperature responses. Magnitude of the calibration coefficient is ultimately tied back to clear skies with the sun at 45°.
- The Secondary Standard instruments themselves are calibrated to the same conditions by national calibration laboratories.
- Accuracy of sensors calibrated in this way is assessed by comparison to independent measurements made using an Eppley PSP.



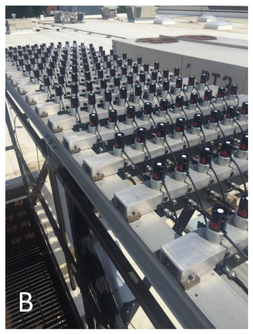


Figure 1A, B. Eppley PSP thermopile pyranometer and production LI-200R sensors at LI-COR calibration facility in Lincoln, NE USA between March and September annually.

THERMOPILE AND SILICON PHOTODIODE PYRANOMETERS

Figure 2. The Eppley Precision Spectral Pyranometer.

- The Eppley PSP is an ISO 9060 Secondary Standard Pyranometer with a spectral range from 0.285 to 2.8 microns which does not match the spectral response of the silicon photodiode.
- The Eppley PSP exhibits a different response to than the LI-200R at very low solar elevation angles. This is due to cosine response differences, and spectral differences during periods with larger air mass (Fig 4.)
- These differences are mitigated by using reference LI-200R silicon photodiode sensors to serve as calibration references for production LI-200R sensors. This calibration includes all sun angles and a variety of sky conditions.

Figure 3. LI-COR LI-200R Pyranometer

- Spectral response closely matching spectral response of photovoltaics.
- Cosine corrected to 82° angle of incidence.
- No error induced from orientation.
- Response Time: Less than 1µs (2 m cable terminated into a 147 Ohm load)

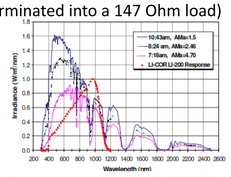


Figure 4. Spectral response of LI-200R Pyranometer compared to global solar irradiance at different times of day (2).

CALIBRATION METHODS

Reference LI-200R Calibration to Thermopile

i. Eppley and Reference LI-200R sensors collect data pairs averaged over 1 minute.
ii. Select cloudless days and solar elevation angle ± 2° of 45°.
iii. Select equal number of AM and PM points over a period of at least 3 days.
iv. Compute LI-COR to Eppley ratio for each data pair.

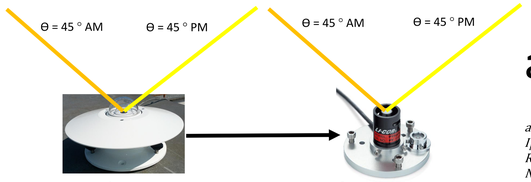


Figure 5. Representation of Eppley PSP and Reference LI-200R.

$$a_L = \frac{\Sigma\left(\frac{I_E}{R_L}\right)}{N}$$

a_L = LI-COR Reference LI-200R Calibration Constant(µA/Wm^{-2})
I_E = Eppley PSP Irradiance (Wm^{-2})
R_L = Responsivity of LI-COR Reference LI-200R (µA)
N = Number of coincident one-minute readings recorded

Equation 1. Reference LI-200R Calibration to Thermopile.

Production LI-200R Calibration to Reference LI-200R

i. 4 to 6 reference LI-200Rs are used to calibrate up to hundreds of production LI-200R sensors.
ii. Day is divided into series of thirty minute time segments.
iii. One minute averages of irradiance are output each minute by each production sensor.
iv. A reading is recorded if it is above 50% of modeled clear sky irradiance
v. Each time-segment must contain at least sixty readings collected during periods when measured irradiance is within 10% of modeled irradiance.

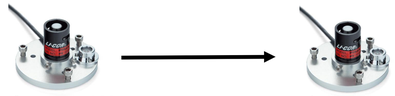


Figure 6. Production LI-200R Calibration to Reference LI-200R.

$$R = \left(\frac{a}{E_0}\right) \times E$$

R = Responsivity (µA)
E = Irradiance (Wm^{-2})
a = Calibration Constant (µA x 1000)
E_0 = 1000Wm^{-2}

Equation 2. Reference to Production LI-200R.

RESULTS: ACCURACY OF PRODUCTION LI-200R PYRANOMETER COMPARED TO ISO 9060 SECONDARY STANDARD

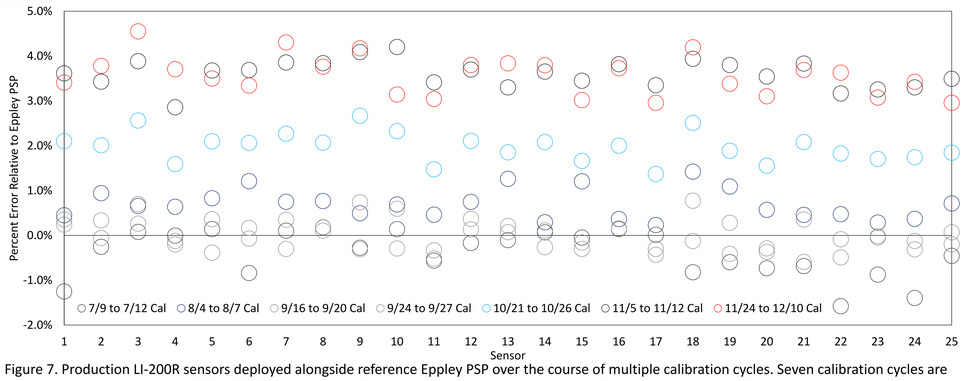


Figure 7. Production LI-200R sensors deployed alongside reference Eppley PSP over the course of multiple calibration cycles. Seven calibration cycles are performed, each with a set of (25) LI-200R sensors recording one-minute averages of irradiance. Data sets from July to September represent periods when production calibration would take place. Mean errors of integrated daily totals of irradiance range from -0.4% to 0.2%. Mean errors of integrated daily totals of irradiance range from 1.9% to 3.4%.

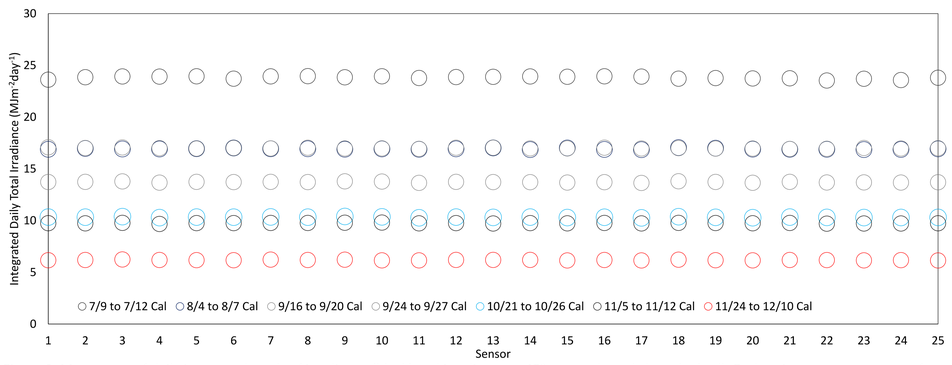


Figure 8. Mean error of daily integrated totals of irradiance (black) and irradiance at 45° sun angle and clear sky (red). Each point represents mean of (25) production sensors for each calibration cycle.

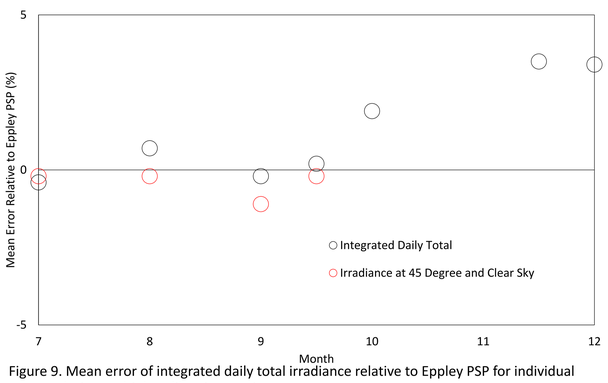


Figure 9. Mean error of integrated daily total irradiance relative to Eppley PSP for individual sensors during multiple calibration sessions.

7/9/2015 to 7/12/2015			8/3/2015 to 8/12/2015			9/15/2015 to 9/21/2015			9/15/2015 to 9/21/2015		
Pyranometer Eppley PSP	Mean Irradiance (Wm^{-2})	Error Relative to Reference	Pyranometer Eppley PSP	Mean Irradiance (Wm^{-2})	Error Relative to Reference	Pyranometer Eppley PSP	Mean Irradiance (Wm^{-2})	Error Relative to Reference	Pyranometer Eppley PSP	Mean Irradiance (Wm^{-2})	Error Relative to Reference
	713.10	0.0%		713.10	0.0%		710.60	0.0%		713.10	0.0%
1	712.28	-0.1%	26	712.28	-0.1%	51	704.34	-0.9%	76	712.28	-0.1%
2	712.49	-0.1%	27	712.49	-0.1%	52	703.05	-1.1%	77	712.49	-0.1%
3	713.86	0.1%	28	713.86	0.1%	53	703.89	-0.9%	78	713.86	0.1%
4	710.09	-0.4%	29	710.09	-0.4%	54	701.76	-1.2%	79	710.09	-0.4%
5	712.76	0.0%	30	712.76	0.0%	55	702.42	-1.2%	80	712.76	0.0%
6	712.05	-0.1%	31	712.05	-0.1%	56	703.19	-1.0%	81	712.05	-0.1%
7	712.46	-0.1%	32	712.46	-0.1%	57	702.30	-1.2%	82	712.46	-0.1%
8	711.94	-0.2%	33	711.94	-0.2%	58	703.86	-0.9%	83	711.94	-0.2%
9	713.97	0.1%	34	713.97	0.1%	59	702.01	-1.2%	84	713.97	0.1%
10	714.06	0.1%	35	714.06	0.1%	60	702.37	-1.2%	85	714.06	0.1%
11	710.12	-0.4%	36	710.12	-0.4%	61	702.47	-1.1%	86	710.12	-0.4%
12	712.60	-0.1%	37	712.60	-0.1%	62	704.30	-0.9%	87	712.60	-0.1%
13	711.86	-0.2%	38	711.86	-0.2%	63	703.88	-0.9%	88	711.86	-0.2%
14	711.72	-0.2%	39	711.72	-0.2%	64	703.41	-1.0%	89	711.72	-0.2%
15	710.64	-0.3%	40	710.64	-0.3%	65	702.58	-1.1%	90	710.64	-0.3%
16	712.06	-0.1%	41	712.06	-0.1%	66	704.59	-0.8%	91	712.06	-0.1%
17	709.87	-0.5%	42	709.87	-0.5%	67	702.79	-1.1%	92	709.87	-0.5%
18	713.84	0.1%	43	713.84	0.1%	68	702.90	-1.1%	93	713.84	0.1%
19	712.79	0.0%	44	712.79	0.0%	69	702.00	-1.2%	94	712.79	0.0%
20	710.57	-0.4%	45	710.57	-0.4%	70	702.79	-1.1%	95	710.57	-0.4%
21	712.54	-0.1%	46	712.54	-0.1%	71	701.58	-1.3%	96	712.54	-0.1%
22	710.58	-0.4%	47	710.58	-0.4%	72	701.54	-1.3%	97	710.58	-0.4%
23	711.58	-0.2%	48	711.58	-0.2%	73	703.20	-1.0%	98	711.58	-0.2%
24	710.38	-0.4%	49	710.38	-0.4%	74	702.63	-1.1%	99	710.38	-0.4%
25	711.89	-0.2%	50	711.89	-0.2%	75	703.19	-1.0%	100	711.89	-0.2%
	Mean Error	**-0.2%**		Mean Error	**-0.2%**		Mean Error	**-1.1%**		Mean Error	**-0.2%**

Table 1. Production LI-200R sensors deployed alongside Eppley PSP over the course of multiple calibration cycles.
Four calibration cycles are performed, each with a set of (25) production LI-200R sensors recording one-minute averages. Data is filtered to only include clear skies and solar elevation angle of 45°±2°. Mean errors of irradiance under constrained conditions are between -0.2% and -1.1%.

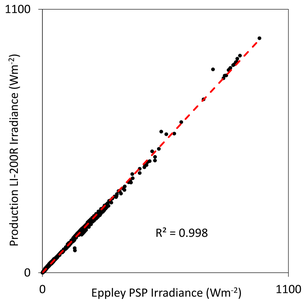


Figure 10. Regression analysis of Production LI-200R Irradiance and Eppley PSP Irradiance at all zenith angles and variety of sky conditions on September 24th, 2015.

CONCLUSIONS

- Using the calibration method described, the LI-200R provides irradiance measurements that closely match a thermopile instrument. The irradiance measured by the production LI-200R sensors at 45° and under clear skies, matches the measurements made by the ISO 9060 Secondary Standard Eppley PSP to within 2% of reading, on average.
- The integrated daily totals of irradiance match to within 2% during the calibration cycle period (March to September), and within 4% outside this time period, during times with prolonged periods of low solar elevation angle. This increase in error during the late winter could be attributed to the increased effect caused by the spectral mismatch between thermopile and silicon photodiode sensors. The cosine dependency of the Eppley PSP is also a factor in the increased relative error.
- In both instances (45° sun angle with clear skies and integrated daily totals), the mean accuracy of production LI-200R sensors relative to the Eppley PSP is within sensor specifications.

REFERENCES

(1) Kerr, J. P., G. W. Thurtell, and C. B. Tanner. "An integrating pyranometer for climatological observer stations and mesoscale networks." Journal of Applied Meteorology 6.4 (1967): 688-694.
(2) King, David L., and Daryl R. Myers. "Silicon-Photodiode pyranometers: operational characteristics, historical experiences, and new calibration procedures." Photovoltaic Specialists Conference, 1997., Conference Record of the Twenty-Sixth IEEE. IEEE, 1997.

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Massive Data Analytics from Real-World Power Plants Cross-Correlated with Laboratory Applied Aging Conditions

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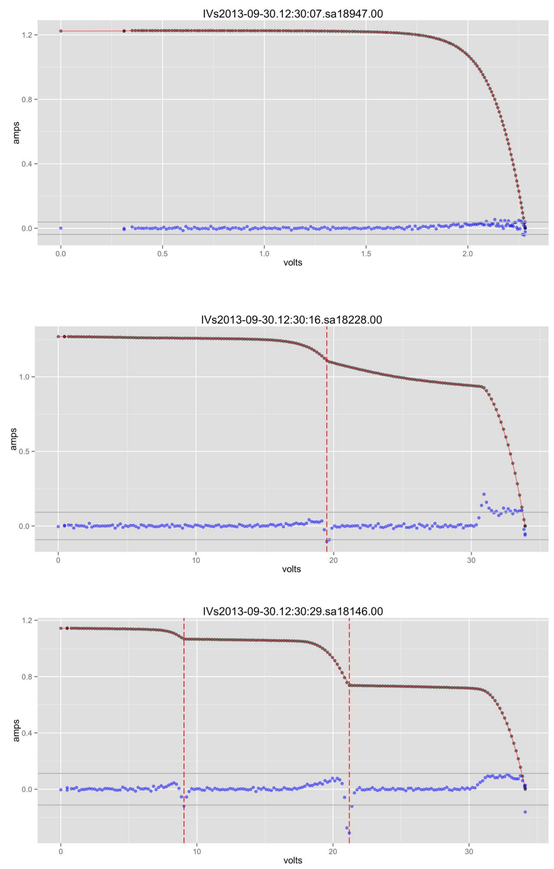
Case Western Reserve University, Cleveland, Ohio United States

REAL WORLD IVs

We observe anomalous I-V curves in the real world!!

Due to *heterogeneity* – either in irradiance, or current collection Causing bypassing!

REAL I-V CURVES WITH AUTOMATED BYPASS DETECTION



REAL I-V CURVES WITH AUTOMATED BYPASS DETECTION

- Machine learning techniques allow for ID of anomalous curves
- 1.5M curves processed in 2 hours

- Provides time series of power, and classification for data mining
- Pairwise plots of variables exemplify visualizing big data
- Data can be used as linkage to lab

Goal

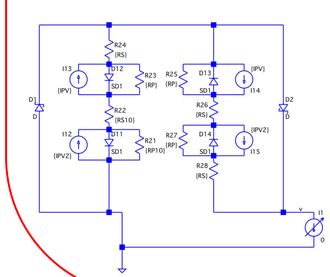
A validated and verifiable methodology for accurately predicting the long-term, real-world performance of PV power plants is highly sought after.

- Laboratory based experimentation
  - characterizing mesoscopic performance of PV modules considering the interfaces of disparate materials
  - yielding dense information but suffers from
  - small sample populations. Specific real-world sites collect health and diagnostic information from complete
- current vs voltage characteristics provide a linkage between the real-world and the laboratory-generated dense data.
- statistical and machine learning techniques
  - detect anomalous behavior in the real-world performance,
  - subset by climate, and
  - cross-correlate the anomalies with a library of Lab data, i.e. "Engineered damage"

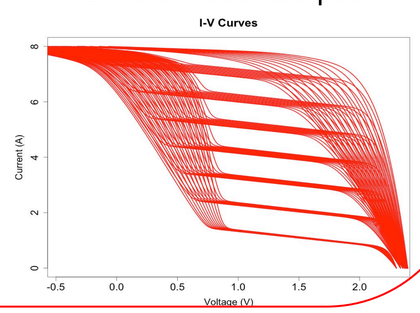
Simulations show bypassing turn on at different V if Rs heterogeneity and irradiance is varied!

We want to track V for bypassing

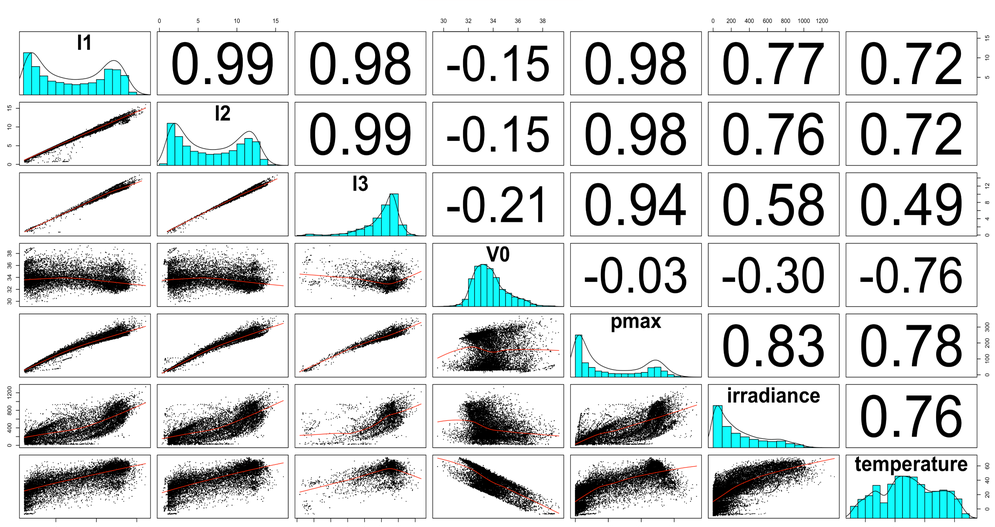
SPICE Model



SPICE Model Output



We plot every variable vs every other variable: A Pairwise scatter matrix and linear correlation coefficients



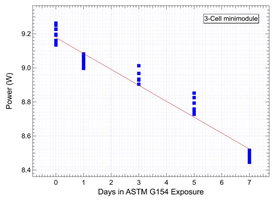
ENGINEERED DAMAGE:

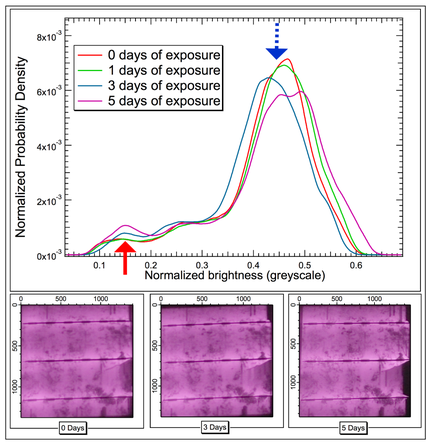
Instead of Accelerated Testing, engineer damage:

- Control the damage in PV and mimic real world I-V curves

What did we do?:

- Expose a "naked" cell to ASTM G154, cycle 4
- multifactor conditions with high UV, temperature, humidity

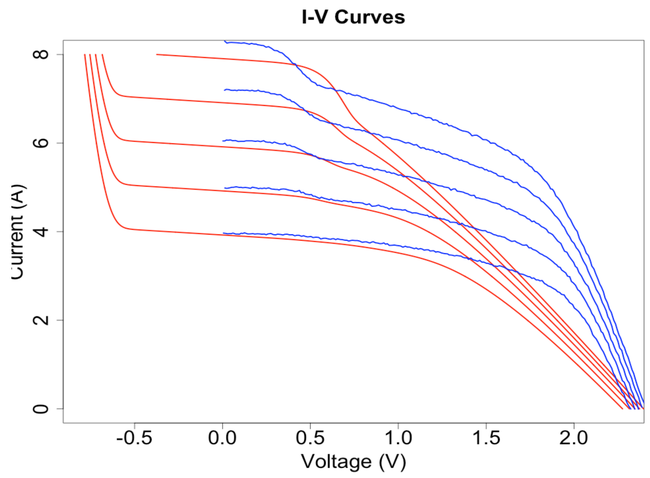




We can control degradation of performance!

- Fabricate heterogeneous 4 cell minimodule:
  - 3 new cells
  - 1 degraded cell
  - Added bypass diodes

IV Curves acquired: under uniform irradiance bypassing turns on (blue)
Similar behavior to simulation



Validates this method!

THANKS TO:
EERE Award DOE-EE-0007140, MLEET

References:.
[1] French et al. COSSMS
[2] Y. Hu, Y. Xu, T. Peshek, J. Sun, and R. H. French, "Data Science Approach to Time Series Analysis of Real-World PV modules," presented at the 2014 PV Module Reliability Workshop, NREL, Golden CO, 25-Feb-2014.

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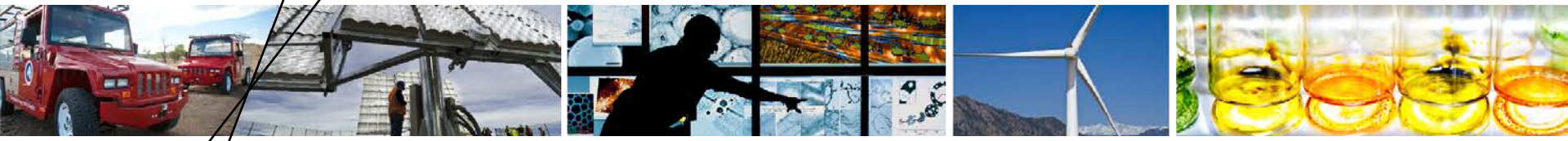
Development of IEC Module Standards By WG2



John Wohlgemuth

February 24, 2016

NREL PV Module Reliability Workshop

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Areas for WG2 Standards

- Measurement Principles
- Qualification and Safety Tests
- Power and Energy Ratings
- Specialized Stress Tests
- Module Components
- Module Materials
- PV Module Lifetime Predictions

Published Standards

IEC 60891: Temperature and Irradiance Corrections to I-V Curves

IEC 60904- 1 to 10: Measurements Principles for PV Devices

IEC 61215: Edition 2 – Crystalline Si Qualification Testing

Soon to be replaced by series of standards IEC 61215-1 (Test Requirements), IEC 61215-1-1 to -1-5 (Technology Specific Requirements and IEC 61215-2 (Test Requirements)

IEC 61646: Edition 2 – Thin Film Qualification Testing

Soon to be withdrawn

IEC 61730-1: Edition 1 – PV Module Safety – Requirements for Construction **Soon to be replaced by edition 2**

IEC 61730-2: Edition 1 – PV Module Safety – Requirements for Testing

Soon to be replaced by edition 2

IEC 61853-1: "Irradiance and temperature performance measurements and power rating"

Published Standards (Continued)

IEC 61701: 2012 Edition 2 – Salt mist corrosion testing of PV modules

IEC 62716: 2013 - Ammonia corrosion testing of PV modules

IEC 62790: 2014 Junction boxes for PV modules – Safety requirements and tests

IEC 62852: 2014 Connectors for DC applications in PV systems – Safety requirements and tests

IEC 62759: 2015 - Transportation testing of PV Modules

IEC TS 62804-1: 2015 - System voltage durability (PID) testing of c-Si PV modules

IEC TS 62941: 2016 Guideline for increased confidence in PV module design qualification and type approval

New standards in Measurement Principles

IEC 60904-1-1: I-V Curves for multi-junctions

Status: Draft CDV to circulate soon.

IEC 60904-1-2: I-V Curves for Bifacial Devices

Status: Just approved as a New Work Item

IEC 60904-8-1: Spectral Response for multi-junctions

Status: Draft CDV to circulate soon.

IEC 60904-12: IR Thermography

Status: Approved as a New Work Item

IEC 60904-13: Electroluminescence

Status: CD circulating now with a response date of 4/8/16.

New standards in Qualification & Safety Testing

Markus Beck talked about Edition 3 of IEC 61215 yesterday.

Chris Flueckiger talked about Edition 2 of IEC 61730 yesterday.

IEC TS 62915 : Retest Guidelines for both 61215 and 61730

- **Status: Should circulate as DTS for final vote soon.**

Qualification Testing of Flexible Modules

- **Status: New Work Item Approved**

New Standards for Power and Energy Ratings

IEC 61853-2: "Spectral response, angle of incidence and determination of module temperature"

- **Status: FDIS should be circulated soon.**

IEC 61853-3: "Calculations of module energy rating"

- **Status: CD circulating with response date of 4/8/16.**

IEC 61853-4: "Time periods for calculation of energy rating"

- **Status: CD circulating with response date of 4/8/16.**
- **If you want weather data from your region included now is the time to submit it.**

New Standards for Specialized Stress Tests

IEC TS 62782: Cyclic (Dynamic) mechanical load testing of PV modules

- Status: Publication expected soon.

IEC 62938: Non-uniform snow load

- Status: CDV under review by WG2.

IEC TS 62804-2: PID Testing of Thin Film Modules

- Status: Approved as a New Work Item.
- Beginning process of developing acceptable test procedure for PID of thin film modules.
- If you care about this now is the time to participate.

New Standards for Module Components

IEC 62916 TS Bypass diode electrostatic discharge

- **Status: DTS circulating with responses due 4/1/16.**

IEC 62979 Ed. 1.0: Photovoltaic module bypass diode thermal runaway test

- **Status: CDV in preparation.**

New Standards for Module Materials

IEC 62788-1-2: Measurement of encapsulant and backsheet resistivity

Status: FDIS submitted but not circulated yet.

IEC 62788-1-4: Measurement of encapsulant optical transmission

Status: FDIS in preparation.

IEC 62788-1-5: Measurement of encapsulant shrinkage during processing

Status: FDIS in preparation.

IEC 62788-1-6 Measurement of EVA crosslink density

Status: FDIS in preparation.

IEC 62788-2: Polymeric materials used for frontsheets and backsheets

Status: CDV in preparation.

IEC 62788-5-1: Suggested test methods for use with edge seal materials

Status: Still trying to find countries to participate in Project.

New Standards for Module Materials

IEC 62788-5-2: Edge-Seal durability evaluation guideline

Status: Still trying to find countries to participate in Project.

IEC 62788-6-2: Moisture permeation testing with polymeric films materials

Status: Still trying to find countries to participate in Project.

IEC 62788-7-2: Environmental exposures - Accelerated weathering tests of polymeric materials

Status: CDV in preparation.

IEC 62805-1: Measurement of haze of TCO glass

Status: CDV under review by WG2.

IEC 62805-2: Measurement of transmittance and reflectance of TCO glass

Status: CDV under review by WG2.

Additional Work for Qualification Testing

- **Considering amendment to 61215 Ed 3 for adding the following:**
  - Cyclic (Dynamic) Mechanical Load before 50 TC/10HF
  - PID with pass/fail
  - Improved thin film Hot Spot Test
  - Bypass diode thermal runaway test
  - How do we deal with operations at higher temperatures.

If you have any other suggestions for additions to IEC 61215 now is the time to speak up.

High Temperature Operation

- **Today most of the qualification, safety, component and material standards deal with general open air climates (-40 °C to + 40 °C ambient) in an open rack configuration.**
- **WG2 is just beginning the process of deciding how to modify the requirements and tests for cases where either the ambient goes above (or below) the range in the present standard or where the module is insulated (like on a roof) and will run hotter.**
- **This will impact as a minimum**
  - Qualification Testing IEC 61215 (The whole series)
  - Safety Certification IEC 61730-1 and 61730-2.
  - All of the component tests (J-boxes, connectors and diodes to start)
  - Maybe some of the material tests
  - The climate specific test sequence (IEC 62892) will also have to address higher operating temperatures for long term operation, but that was the original plan.

High Temperature Operation (Cont)

- **How do we proceed?**
  - Modify each of the standards to add requirements for higher temperatures.
  - Put all the additional temperature requirements into the Climate Specific Standard and leave everything else as is.
  - Write a new standard that addresses the necessary changes to all of the other standards already in print.
- **How do we rate modules for temperature?**
  - Rack mount versus roof mount or BIPV.
  - Have each module (and component) carry a maximum ambient temperature label for which it has been qualified for performance and safety.
- **We need to determine which tests will have to be modified and which are fine as is.**

PVQAT

- **Three major areas of effort**
  - Module Durability (Climate Specific Testing)
  - Manufacturing Consistency (IEC TS 62941)
  - System Verification (IECRE)
- **Participation open to all who want to contribute to the effort.**
- **Program relies on research done by volunteers around the world.**
- **Effort is to guide world wide research and to establish a conformity assessment system to improve the durability and reliability of installed PV systems.**

PVQAT Task Groups – Volunteers Wanted

1. PV QA Guidelines for Module Manufacturing
2. Testing for thermal and mechanical fatigue
3. Testing for humidity, temperature and voltage
4. Testing for diodes, shading and reverse bias
5. Testing for UV, temperature and humidity
6. Communications of rating information
7. Testing for snow and wind load
8. Testing for thin film modules
9. Testing for CPV
10. Testing for Connectors
11. QA for PV Systems
12. Soiling and Dust

Climate Specific Testing of PV Modules

- **Climates under consideration**
  - **Different climate zones – General, Hot & Dry, Hot & Humid**
  - **Different Mountings – Open rack, Roof mount with no back cooling**
- **The major failure/degradation modes observed in field for module types that have passed the Qualification tests are:**
  - **Discoloration of the encapsulant with loss of transmission**
  - **Failure of interconnect ribbons and solder bonds**
  - **Corrosion of cell metallization accompanied by delamination of the encapsulant**
  - **Broken or cracked cells**
  - **PID**
- **The last 2 we hope to cover in modifications to IEC 61215.**
- **The first 3 we plan to address in Climate Specific Test Sequence because they are wear out mechanisms that occur beyond qualification.**

Climate Specific Testing (Cont)

- **Test Procedure for Thermal Cycling**

  Status: New Work item circulating in TC82 with responses due 3/4/16.

  Nick Bosco talked about this in C-Si session this morning.

- **Test Procedure for Encapsulant Transmittance (UV exposure test)**

  Status: New Work item circulating in TC82 with responses due 4/1/16.

  Task Group 5 work on UV testing of EVA led to proposal for ~ 6 month UV test of coupons to determine whether encapsulant will discolor during operation in the field.

- **Testing Procedure for Delamination**

  Status: Still working to identify useful test sequences.

  Have identified several different types of delamination in fielded modules.

  Experimenting with different test sequences to duplicate field results.

Contacts

TC 82

- http://www.iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID:1276
- George Kelly, TC82 Secretary
  solarexpert13@gmail.com
- Alex Mikonowicz, US TAG
  acmmkr@verizon.net

PVQAT

- http://www.pvqat.org/ (Contacts listed for each of the Task Groups)
- Sarah Kurtz, PVQAT Steering Committee
  Sarah.Kurtz@nrel.gov
- John Wohlgemuth, PVQAT Steering Committee & Convenor of WG2
  John.Wohlgemuth@nrel.gov

- **10 poster sessions, total 84 posters.**
- **Judging Panel (14 members):**

  Chris Deline (NREL)
  Bill Gambogi (DuPont)
  Xiaohong Gu (NIST)
  Liang Ji (UL)
  Amy Lefebvre (Arkema)
  Sanjay Roberts (NREL)
  Leo Micheli (NREL)
  David Miller (NREL)
  Peter Neretnieks (Solibro Research)
  Kei Sakurai (AIST)
  Tony Sample (EC Jointed Research Center)
  Ian Tappan (NREL)
  Karl-Anders Weiss (Fraunhofer ISE)
  Masaaki Yamamichi (AIST)

- **The judges have selected 16 Awards based on sessions, and 1 Grand Award among overall posters**

Winners:

- **Poster Session I: The Connection between Cost and PV Reliability**

101. Methods to Streamline Data Communications in the Solar Power Industry and Benefits — Jon Previtali and Dixon Wright (Wells Fargo)

- **Poster Session II: General PV Module Reliability**

113. Analytical Methods to Detect Metal Migration in PV Modules from the Service Environment — Alex Bradley, Kate Stika, Gail Raty, and Bill Gambogi (DuPont)

- **Poster Session III: Modules in Extreme Climates**

127. Effect of Hot Cells on the Power Degradation Rate of PV Modules — Rajiv Dubey, **Shashwata Chattopadhyay**, Rajiv Dubey, Vivek Kuthanazhi, Jim Joseph John, Chetan Singh Solanki, Anil Kottantharayil, Brij M. Arora, K.L. Narasimhan, Juzer Vasi, Birinchi Bora, Yogesh Kumar Singh, O.S. Sastry (NCPRE, IIT Bombay)

- **Poster Session IV: General Standards**

1st Prize: 145. Module Deflection Profiles for MLT — Larry Pratt, Nick Riedel, Greg Peacock, and Michael Yamasaki (CFV Solar Test Lab)
2nd Prize: 133. A Better Way to Bend: Vacuum and Air Pressure for Mechanical Load Testing of Solar Panels — Andrew M. Gabor, Rob Janoch, and Andrew Anselmo (Brightspot Automation)

- **Poster Session V: Crystalline Silicon Modules**

1st Prize: 178. Understanding PV Backsheet Degradation under Different UV Light Intensities and Temperatures — Li-Chieh Yu, Yadong Lyu, Chiao-Chi Lin, Jae Hyun Kim, Tinh Nguyen, and Xiaohong Gu (NIST)
2nd Prize: 157. Electroluminescence and Photoluminescence Imaging for Module Degradation Characterization — Steve Johnston, Peter Hacke, and Mowafak Al-Jassim (NREL)
3rd Prize: 161. Effect of Solar Cell Reverse Biased Voltage on Photovoltaic Modules Partial Shade Performance — Elsa Kam-Lum, Adria Brooks, Daniel Cormode, and Alexander Cronin (Total New Energies, USA)

- **Poster Session VI: Thin Film Modules**

1st Prize: 102. Overcoming Perovskite Degradation by Eliminating Free Volume and Gas Diffusion — Colin D. Bailie, Kevin A. Bush, Ye Chen, Andrea R. Bowring, Wei Wang, Wen Ma, Tomas Leijtens, Farhad Moghadam, Michael D. McGehee (Standford University)
2nd Prize: 126. Monitoring of Moisture Ingress in PV Modules — Marko Jankovec and **Marko Topic** (University of Ljubljana)
3rd Prize: 114. Parameterization of Thin Film Modules — Marzella Görig, Carolin Ulbrich, Bart Pieters, Andreas Gerber, and Uwe Rau (Juelich)

- **Poster Session VII: Soiling**

130. Surface Soiling and Related Reliability Studies in Brasil: Program and Progress — Lawrence L. Kazmerski, Antonia Sonia A.C. Diniz, Cristiana Brasil Maia, Marcelo Machado Viana, Suellen C. Silva Costa, Pedro Paiva Brito, Cláudio Dias Campos, Sergio de Morais Hanriot, Leila R. de Oliveira Cruz, and Govindaswami TalizhMani (University of Colorado, Boulder)

- **Poster Session VIII: Integrated Module (Power) Electronics, Including Microinverters**

140. Accurate Modeling of Mismatch Losses in PV Installations; Effects of Thermal Gradients and Module Degradation — M. Propst and **Anders Olsson** (Pearl Laboratories)

- **Poster Session IX: System and Resource Assessment**

1st Prize: 166. Evolution of Measured Module Power vs Labelled Module Power of Crystalline Silicon-Based PV Modules — Tony Sample and Juan Lopez Garcia (EU JRC)
2nd Prize: 156. Clear Day Filtering and Long-Term Performance without Irradiance — Dirk C. Jordan and Sarah R. Kurtz (NREL)

- **Poster Session X: Systems**

112. REC Component Reliability Studies: Extended Reliability & Compatibility of PV Connectors — Chun Wan Ho (REC Solar)

Grand Prize:

173. Electrical Detection of Gap Formation Underneath Finger Electrodes on c-Si PV Cells Exposed to Acetic Acid Vapor Under Hygrothermal Conditions — Tadanori Tanahashi, Norihiko Sakamoto, Hajime Shibata, and Atsushi Masuda (AIST)

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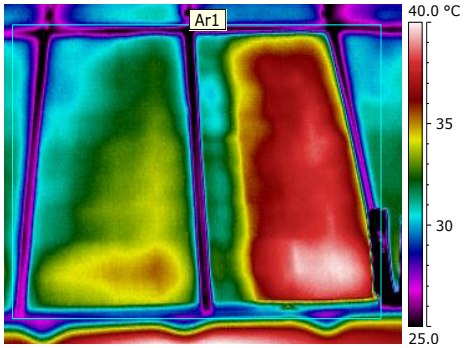
Sandia National Laboratories



PV System Reliability: An O&M Perspective

NREL PV Module Reliability Workshop

Geoffrey T. Klise
Sandia National Laboratories
February 25, 2016

SAND2016-1812C

U.S. DEPARTMENT OF ENERGY

SunShot U.S. Department of Energy

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Overview

- How does O&M impact reliability? Or, reliability impact O&M?
- O&M costs and reliability – goals, trends, and recent insights from PV stakeholders
- System and component "Availability" best practices
  - Availability data standards – improved cataloging of events that impact equipment operational time and performance
- Current efforts to improve O&M with a reliability focus
  - PVROM
  - SAM tool improvements

How does ***O&M*** impact ***Reliability*****?**
Or, ***Reliability*** impact ***O&M*****?**

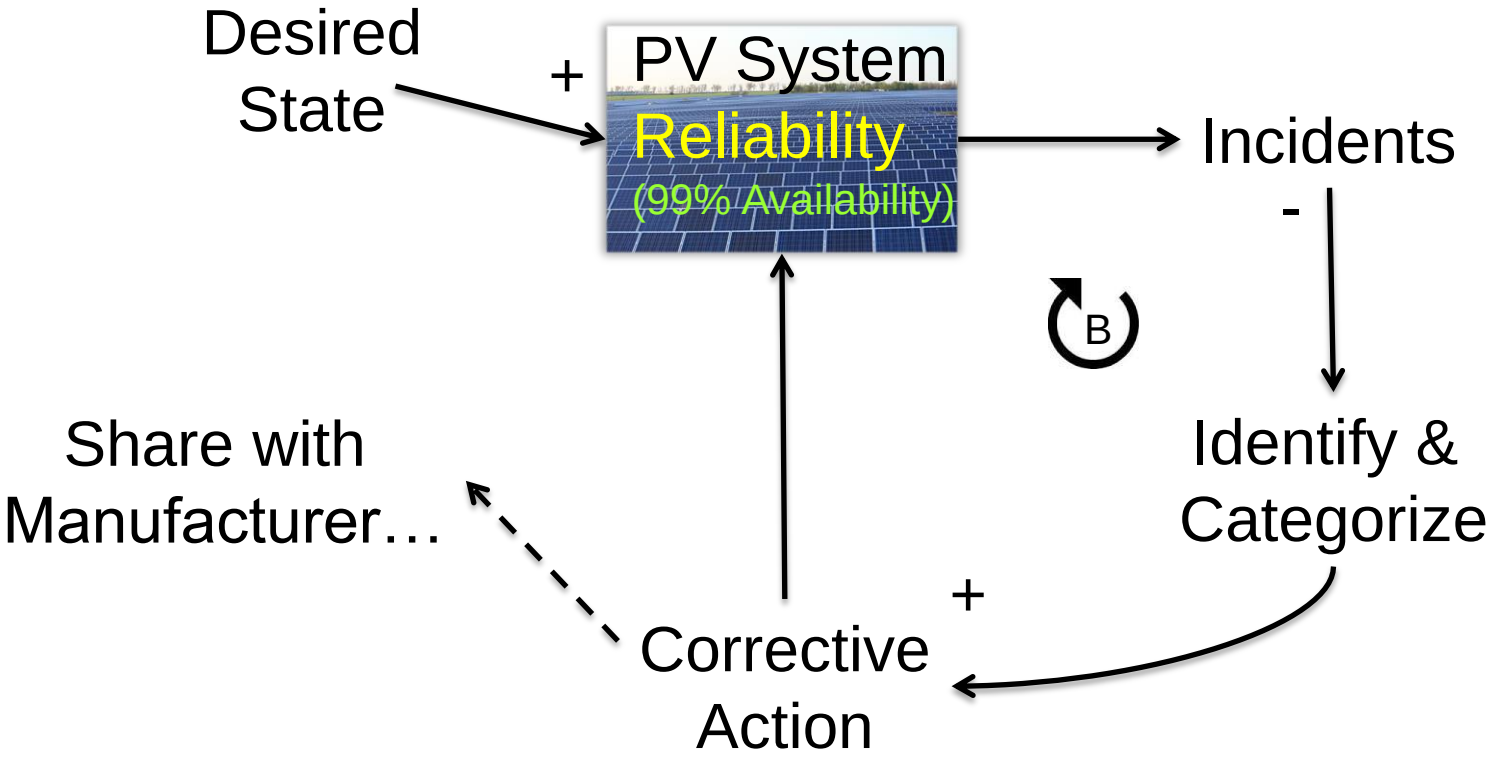
O&M and System Reliability Nexus

- **Operations** provides information to make decisions and triage response activities
- **Maintenance** is the response activity, whether planned or reactive, to ensure that equipment up-time leads to expected system performance and energy generation

Beyond filling tickets… How then does O&M become reliability-focused?

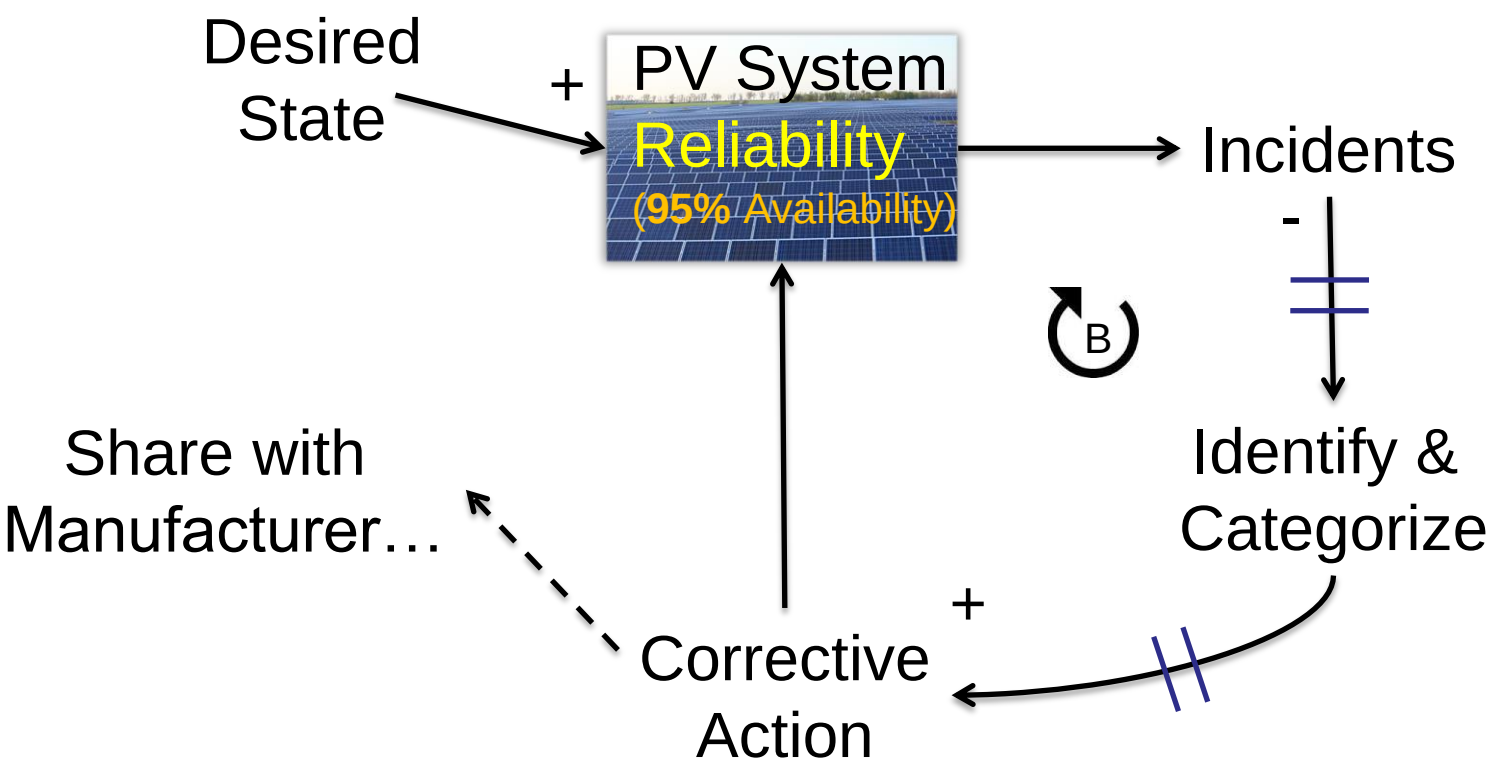
- By increasing preventative maintenance?
- Through faster response times?
- Through more intelligent machine-learning algorithms?

Simple Incident Response



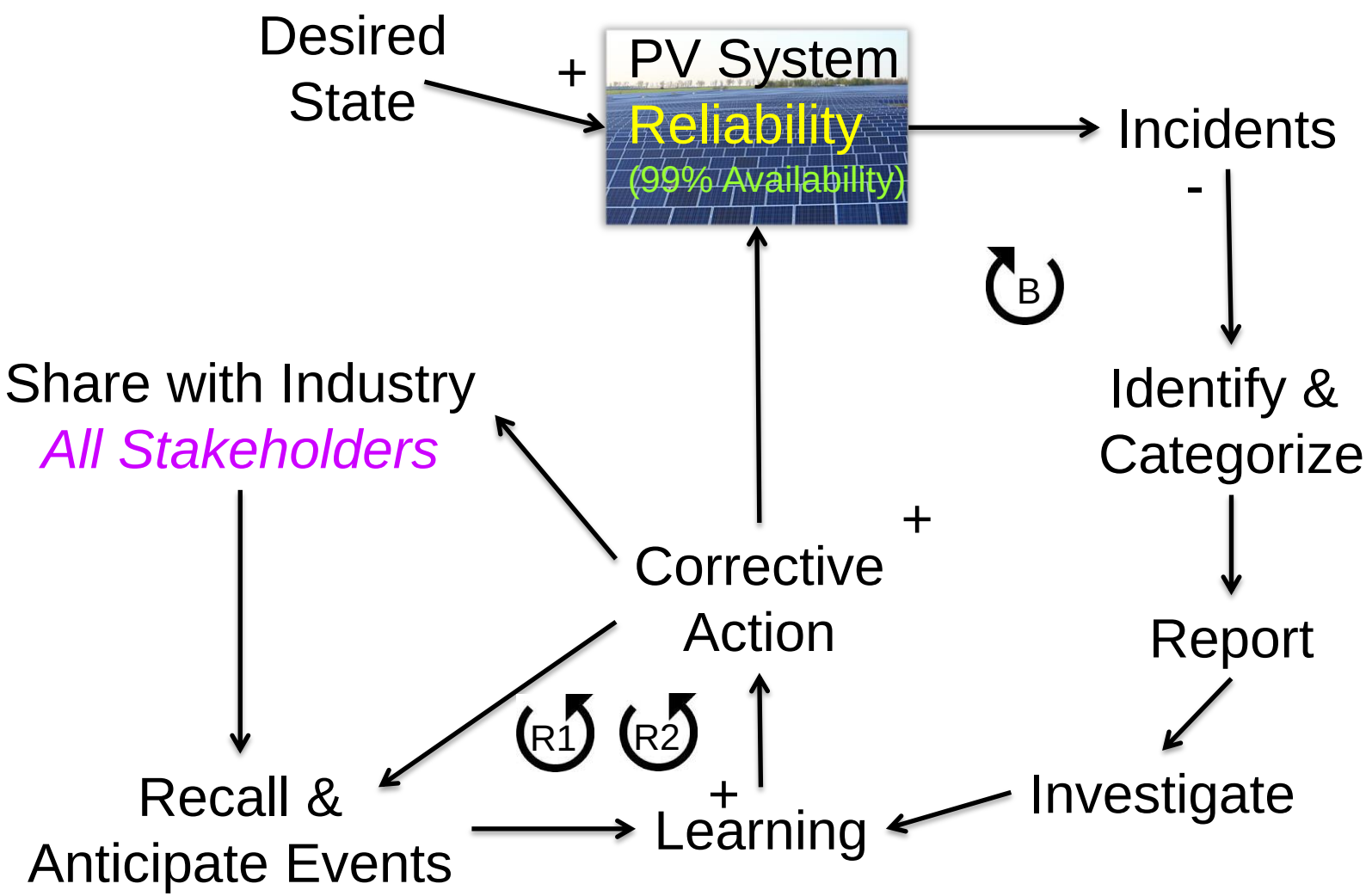
Adapted from Cooke, D.L., 2003, "Learning from Incidents"

Simple Incident Response



Adapted from Cooke, D.L., 2003, "Learning from Incidents"

Incident Response - Reliability Focus



Adapted from Cooke, D.L., 2003, "Learning from Incidents"

O&M Costs and Reliability:
Trends, Goals, and Recent Insights from PV Stakeholders

Recent PV O&M white paper – 2015

Research rationale: Little information exists regarding the budgeting process, actual metrics ($/kW-yr), consensus best practices, and industry gaps

- Joint effort by EPRI and Sandia National Labs
- Focus: Utility-scale solar PV
- Data/insights derived from:
  - In-depth interviews & on-line survey

Respondent Type	Respondents
Interview Sample	
Utility / IPP	6
Turnkey Solar Company	2
O&M Provider	5
Insurance / Bank	4
Independent Engineer	1
Total	**18**
Survey Sample	
O&M Provider	8
Owner	5
EPC	3
Asset manager	4
Total	**20**

The publicly-available white paper is available for download at:
http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002006218

PV O&M *Budget* – Utility Scale

Caveats

- $/MW or kW-yr metric can skew perspectives
  - Other metrics can be more instructive
- Normalizing O&M budget figures for comparison can be difficult
- The constituent parts of O&M budget don't always add up to overall average budget
- $/kW-yr O&M costs tend to decrease as system size increases
  - Returns diminish as plant size grows
  - O&M of smaller systems can be 2-4x more expensive than for larger sites

Budget Item	Budget Range ($/kW-yr)
Overall Budget	$10.00 - $45.00/kW-yr*
General Site Maintenance	$0.20 - $3.00/kW-yr
Wiring Electrical Inspection	$1.40 - $5.00/kW-yr†
Panel Washing	$0.80 - $1.30/kW-yr†
Vegetation Management	$0.50 - $1.80/kW-yr†
Inverter Maintenance	$3.00 - $7.50/kW-yr†
Inverter Replacement	$6.00 - $10.00/kW**
Racking / Tracker Maintenance	Insufficient data
Spares	$2.00 - $20.00/kW-yr***

Source: EPRI

Notes: Budget numbers for utility-scale plants; encompass an entire range of baseline, cost-plus, and warranty terms.

** Constituent O&M budget components are non-linear; will not necessarily add up to overall budget on a $/kW-yr basis.*

*** Inverter replacement metrics based on a $/kW, cover one-time equipment replacement and installation activity over the course of a plant's lifetime.*

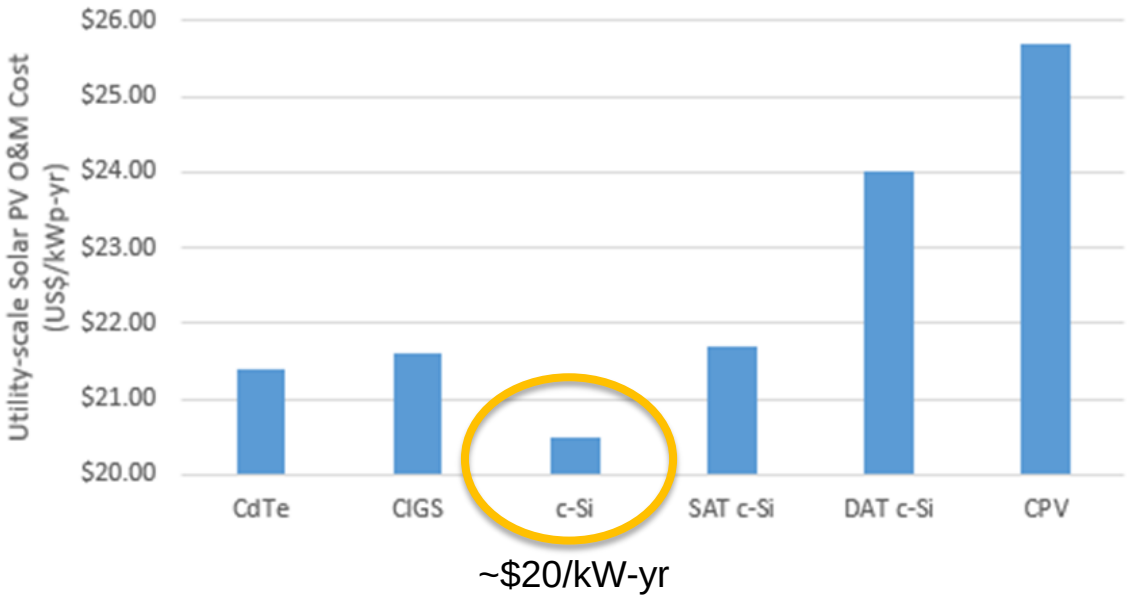
**** Budget range for spares primarily encompasses equipment procurement and storage costs.*

† Price points based on a 1x annual frequency (i.e., per event)

PV O&M *Costs* – Utility Scale

- Budgets historically low (and remain so)
- No one-size-fits-all approach
  - Budgets typically 1-5% of MW-scale plant's $/kW-yr price tag
  - Variation based on
    - System / fleet characteristics
    - Business interests
    - O&M approaches (scope)
    - Contractual arrangements
    - Miscellaneous: labor rates, local energy prices, project volume, profit taking
  - Broad structure guides budgeting process that is informed by multiple factors/attitudes

Avg. Utility-Scale PV O&M *Costs*, by Technology



Source: EPRI, PID 3002005779

Note: O&M estimates developed using bottoms-up approach; incorporates detailed info from EPCs, and input from industry data (i.e. equipment cost and labor indices), market analyst info, and developer feedback. Estimates for conceptual 10-MW_{dc} plants

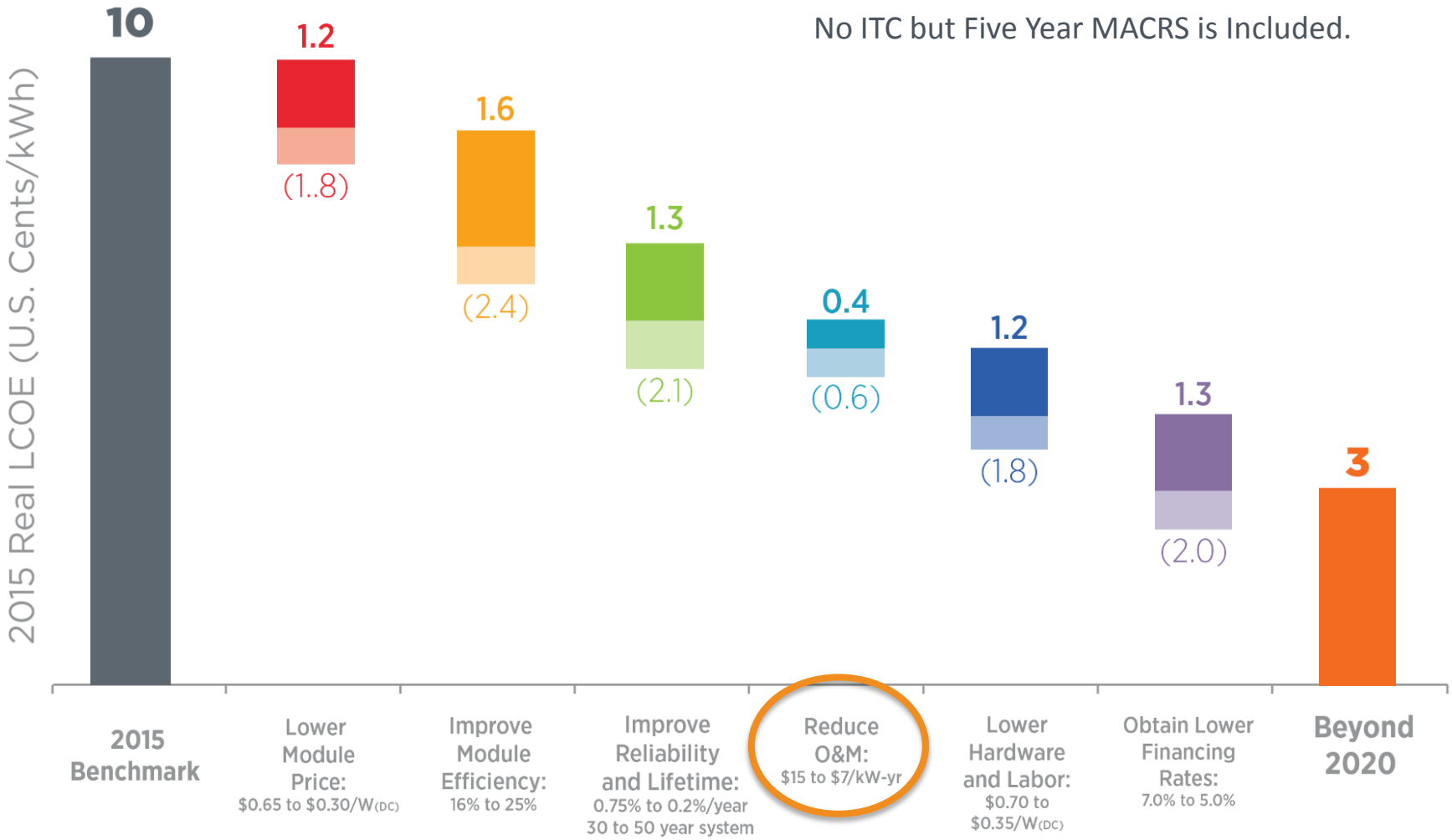
Towards 2030: A Pathway To 3¢/kWh

SunShot U.S. Department of Energy

energy.gov/sunshot

Benchmark 100 MW Utility Systems With 1,480 kWh/kW First Year Performance.

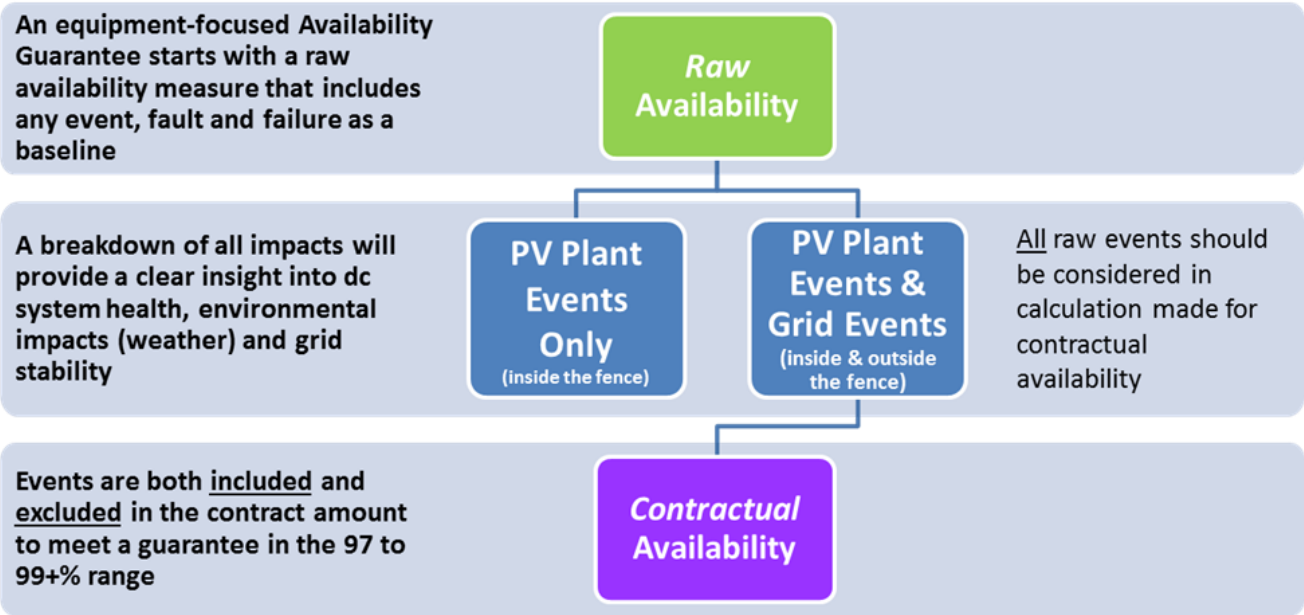
No ITC but Five Year MACRS is Included.

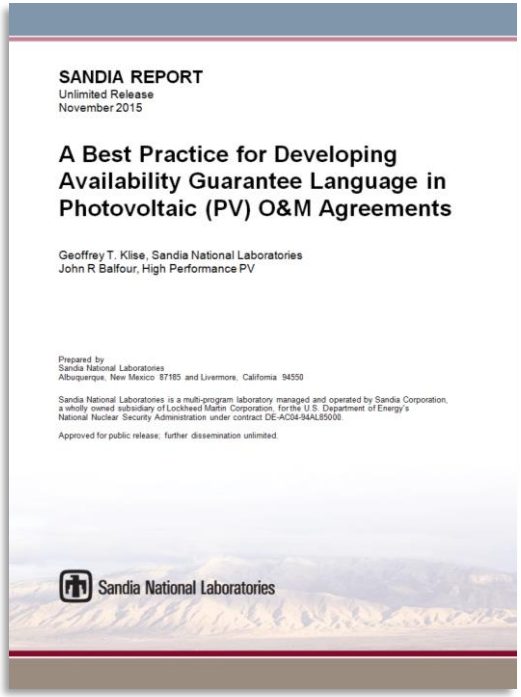


System and Component "Availability" Best Practices

Availability Guarantee Best Practices

Methods, equations and classifications for collecting data to support availability calculations




SANDIA REPORT
Unlimited Release
November 2015

A Best Practice for Developing Availability Guarantee Language in Photovoltaic (PV) O&M Agreements

Geoffrey T. Klise, Sandia National Laboratories
John R Balfour, High Performance PV

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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http://energy.sandia.gov/download/35866/

- Reviewed 11 O&M contracts for their “Availability Guarantees”
- Categorized contractual elements

Availability Guarantee Best Practices

New availability data collection & analysis classification

Raw Component Availability

$$A_{raw\_i} = 1 - \frac{DownTime_i}{TotalTime_i}$$

Raw System Availability

$$A_{raw\_sys} = \frac{\sum_{i=1}^{n} A_{raw\_i} \times NP_i}{\sum_{i=1}^{n} NP_i}$$

Irradiance-Weighted Raw Availability

$$A_{raw\_irr} = 1 - \sum \left(\frac{DownTime_{i\_irradiance}}{\sum irradiance} \right)$$

Contractual Availability

$$A_{exclude\_i} = 1 - \frac{DownTime_i - ExcludedTime_i}{TotalTime_i - ExcludedTime_i}$$

Data Area/System Class	A	B	C
Data Granularity	High	Medium	Low
Components measured and potentially subject to availability calculation	Inverter, combiners (ac, dc), disconnects, modules, transformer, DAS, SCADA	Inverter, Combiners (dc), disconnects, DAS	Inverter
Necessary Instrumentation	DAS, SCADA, POA irradiance, Utility grade meter, inverter	DAS, SCADA, inverter, irradiance	DAS, inverter
Timestep	1 to 15 minutes	15 minutes	15 minutes
External Grid Events	Grid outage, curtailment, grid support	Grid outage, curtailment	Grid outage

- Suggested best practices for improved language for **raw** and **contractual** availability
- Developed equations and examples for determining component and system availability

Collecting time-based event data and maintenance response supports reliability analysis

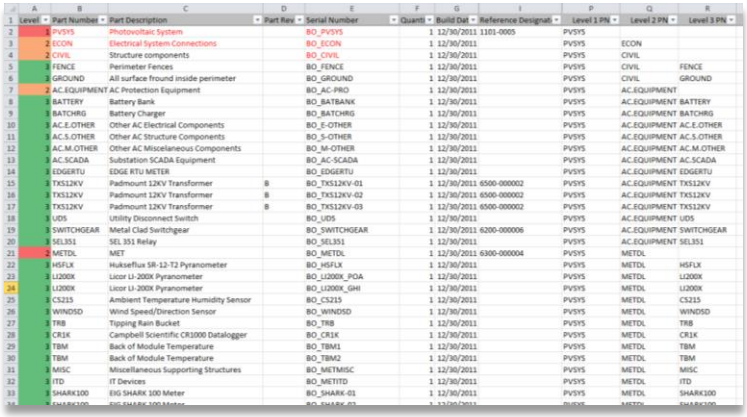
Current Efforts to Improve O&M with a Reliability Focus:

- PV Reliability Operations Maintenance *Process*

Time-Based Data Collection

- PV System Serialized
- Database of stored incidents

Incidents Recorded



Level	Part Number	Part Description	Part Rev	Serial Number	Quantity	Build Date	Reference Designator	Level 1 PN	Level 2 PN	Level 3 PN
1	PVSYS	Photovoltaic System		BO_PVSYS	1	12/30/2011	1101-0005	PVSYS		
2	ECON	Electrical System Connections		BO_ECON	1	12/30/2011		PVSYS	ECON	
2	CIVIL	Structure components		BO_CIVIL	1	12/30/2011		PVSYS	CIVIL	
3	FENCE	Perimeter Fences		BO_FENCE	1	12/30/2011		PVSYS	CIVIL	FENCE
3	GROUND	All surface fround inside perimeter		BO_GROUND	1	12/30/2011		PVSYS	CIVIL	GROUND
2	AC.EQUIPMENT	AC Protection Equipment		BO_AC-PRO	1	12/30/2011		PVSYS	AC.EQUIPMENT	
3	BATTERY	Battery Bank		BO_BATBANK	1	12/30/2011		PVSYS	AC.EQUIPMENT	BATTERY
3	BATCHRG	Battery Charger		BO_BATCHRG	1	12/30/2011		PVSYS	AC.EQUIPMENT	BATCHRG
3	AC.E.OTHER	Other AC Electrical Components		BO_E-OTHER	1	12/30/2011		PVSYS	AC.EQUIPMENT	AC.E.OTHER
3	AC.S.OTHER	Other AC Structure Components		BO_S-OTHER	1	12/30/2011		PVSYS	AC.EQUIPMENT	AC.S.OTHER
3	AC.M.OTHER	Other AC Miscelaneous Components		BO_M-OTHER	1	12/30/2011		PVSYS	AC.EQUIPMENT	AC.M.OTHER
3	AC.SCADA	Substation SCADA Equipment		BO_AC-SCADA	1	12/30/2011		PVSYS	AC.EQUIPMENT	AC.SCADA
3	EDGERTU	EDGE RTU METER		BO_EDGERTU	1	12/30/2011		PVSYS	AC.EQUIPMENT	EDGERTU
3	TXS12KV	Padmount 12KV Transformer	B	BO_TXS12KV-01	1	12/30/2011	6500-000002	PVSYS	AC.EQUIPMENT	TXS12KV
3	TXS12KV	Padmount 12KV Transformer	B	BO_TXS12KV-02	1	12/30/2011	6500-000002	PVSYS	AC.EQUIPMENT	TXS12KV
3	TXS12KV	Padmount 12KV Transformer	B	BO_TXS12KV-03	1	12/30/2011	6500-000002	PVSYS	AC.EQUIPMENT	TXS12KV
3	UDS	Utility Disconnect Switch		BO_UDS	1	12/30/2011		PVSYS	AC.EQUIPMENT	UDS
3	SWITCHGEAR	Metal Clad Switchgear		BO_SWITCHGEAR	1	12/30/2011	6200-000006	PVSYS	AC.EQUIPMENT	SWITCHGEAR
3	SEL351	SEL 351 Relay		BO_SEL351	1	12/30/2011		PVSYS	AC.EQUIPMENT	SEL351
3	METDL	MET		BO_METDL	1	12/30/2011	6300-000004	PVSYS	METDL	
3	HSFLX	Hukseflux SR-12-T2 Pyranometer		BO_HSFLX	1	12/30/2011		PVSYS	METDL	HSFLX
3	LI200X	Licor LI-200X Pyranometer		BO_LI200X_POA	1	12/30/2011		PVSYS	METDL	LI200X
3	LI200X	Licor LI-200X Pyranometer		BO_LI200X_GHI	1	12/30/2011		PVSYS	METDL	LI200X
3	CS215	Ambient Temperature Humidity Sensor		BO_CS215	1	12/30/2011		PVSYS	METDL	CS215
3	WINDSD	Wind Speed/Direction Sensor		BO_WINDSD	1	12/30/2011		PVSYS	METDL	WINDSD
3	TRB	Tipping Rain Bucket		BO_TRB	1	12/30/2011		PVSYS	METDL	TRB
3	CR1K	Campbell Scientific CR1000 Datalogger		BO_CR1K	1	12/30/2011		PVSYS	METDL	CR1K
3	TBM	Back of Module Temperature		BO_TBM1	1	12/30/2011		PVSYS	METDL	TBM
3	TBM	Back of Module Temperature		BO_TBM2	1	12/30/2011		PVSYS	METDL	TBM
3	MISC	Miscellaneous Supporting Structures		BO_METMISC	1	12/30/2011		PVSYS	METDL	MISC
3	ITD	IT Devices		BO_METITD	1	12/30/2011		PVSYS	METDL	ITD
3	SHARK100	EIG SHARK 100 Meter		BO_SHARK-01	1	12/30/2011		PVSYS	METDL	SHARK100
3	SHARK100	EIG SHARK 100 Meter		BO_SHARK-02	1	12/30/2011		PVSYS	METDL	SHARK100

pdf

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

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

Drag a column header here to group by that column

Incident Number	Serial Number	Occurrence Date	State	Responsible Part	Category	Creator	Incident Owner
SAN-18	SGS-3	02/10/2003 05:00 PM	Closed	MOD: PV Module	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN
SAN-24	SGS-12	06/28/2003 08:44 AM	Closed	INV: Inverter	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN
SAN-25	SGS-8	06/30/2003 05:00 PM	Closed	MOD: PV Module	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN
SAN-52	SGS-32	09/29/2003 05:46 AM	Closed	INV: Inverter	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN
SAN-54	SGS-31	10/18/2003 06:10 AM	Closed	INV: Inverter	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN
SAN-55	SGS-9	12/19/2003 05:25 AM	Closed	TXL: 480V/34.5kV Transformer	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN
SAN-58	SGS-2	01/25/2004 05:00 PM	Closed	INV: Inverter	Hardware Failure	SYSTEM ADMIN	SYSTEM ADMIN
SAN-61	SGS-32	04/19/2004 12:48	Closed	INV: Inverter	Hardware	SYSTEM	SYSTEM ADMIN

Category: Environment-induced Failure/Suspension
BOM Level 2 Part Number: Array Electrical Connections: ECON
Unit Location: N/A
Downtime for Service: N/A
Response Time: N/A

System/Component Information

BOM Level 1 Part Serial Number: SGS-29
Part Name: SGS Solar System Power Block
BOM Level 1 Part Number: SGSSS
Version:
System Status:
Under Warranty: Yes No
System Hours: 41088
Unit Location:
System Down Event:

Incident Disposition

Occurrence Date: Jul 6 2008 Time: 05:19 AM PM Local Time
State: Closed
Report Type: Unplanned Field Event
Category: Environment-induced Failure/Suspension
BOM Level 2 Part Number: [ECON: Array Electrical Connections]
Owner: [ADMIN, SYSTEM]
Creator: [ADMIN, SYSTEM]
Actions: None
Description: Row box ground fault due to plastic conduit expansion pinching row wire against metal conduit
Fault Codes (0):

Incident Repair Information

Service Response Date: Feb 2016 Time: AM PM Local Time
ASP Field Service Tech:
Status of Troubleshooting: None
Resolution: repaired
Repair Duration: 91 (1.5 = hour and a half)

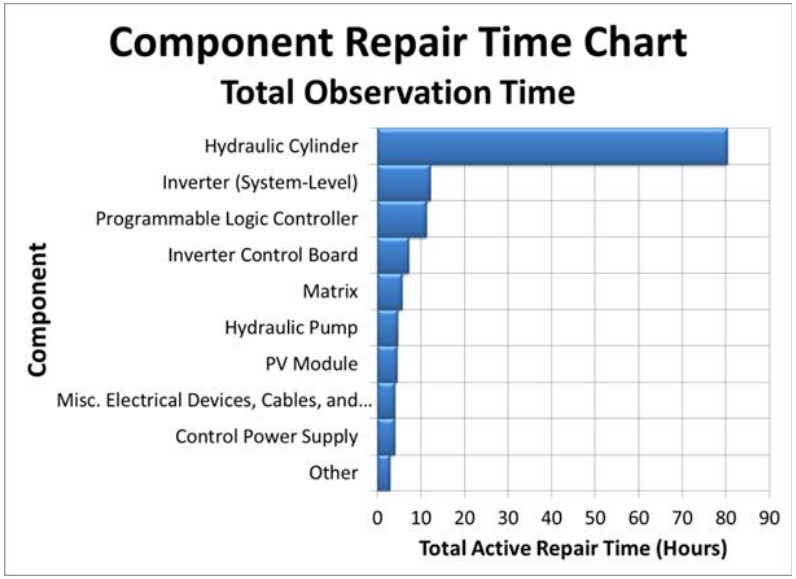
Repair or Replace Parts, Add / Modify Parts

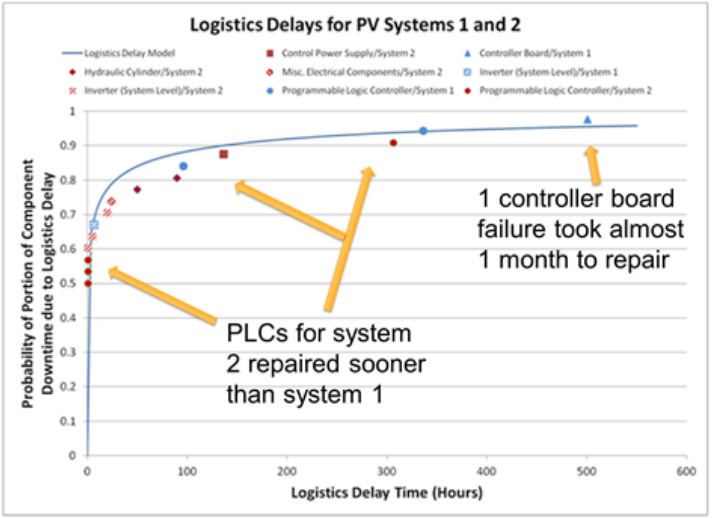
Original Part SN	Original Part Name / Failure Type / Return Type	Orig Part # / Part Disposition / RMA Number - Rcvd	Rev / Hours to Failure / SO Number	Failure Analysis Report	Replacement Part SN / Starting Age	Rpl Part #	Rev
ECON-29	Array Electrical Connections	ECON	N/A	New	ECON-29	ECON	N/A
	Non-inverter Inoperable - Other-induced	Repaired	41088.00				
	N/A	N/A - N/A	N/A		N/A		

Initiating Event:

Time-Based Data Analysis

System Component	Abbreviation	Quantity	Maintenance Actions	Active Repairs	Avg. Active Repair Time (hrs)
AC Disconnect Switch	ADS	69	0	0	0.00
Combiner Box	CB	142	0	0	0.00
Data Acquisition System	DAS	43	4	3	0.13
DC connectors, e.g. MC4	DCCON	41	0	0	0.00
DC Disconnect Switch	DDS	97	0	0	0.00
Misc. Electrical Devices, Cables, and Connectors	ECON	43	1	1	2.00
Fuses, ac and dc	FUSE	41	1	1	0.00
DC Home Runs	HOMERUN	41	0	0	0.00
Utility Power Meter	MET	61	0	0	0.00
PV Module	MOD	15957	4	4	2.08
Module Mounting System	MOUNT	41	0	0	0.00
Programmable Logic Controller	PLC	35	10	8	1.13
HV Transformer	TXL	31	0	0	0.00
Utility Disconnect Switch	UDS	44	0	0	0.00
Inverter Equipment					
Inverter	INV	54	9	0	0.68
Control Power Supply	CPS	39	1	1	2.00
Inverter Control Board	CRTLBRD	41	4	2	1.79
Inverter Control Software	CTRLSW	54	1	1	0.63
Cooling Fan	FAN	54	1	1	0.66
Inverter fuses, wires, etc	IECON	47	1	1	0.00
Power Matrix	MAT	61	4	4	0.71
LV Transformer	TXS	27	0	0	0.00





- Development of non-repairable failure distribution parameters

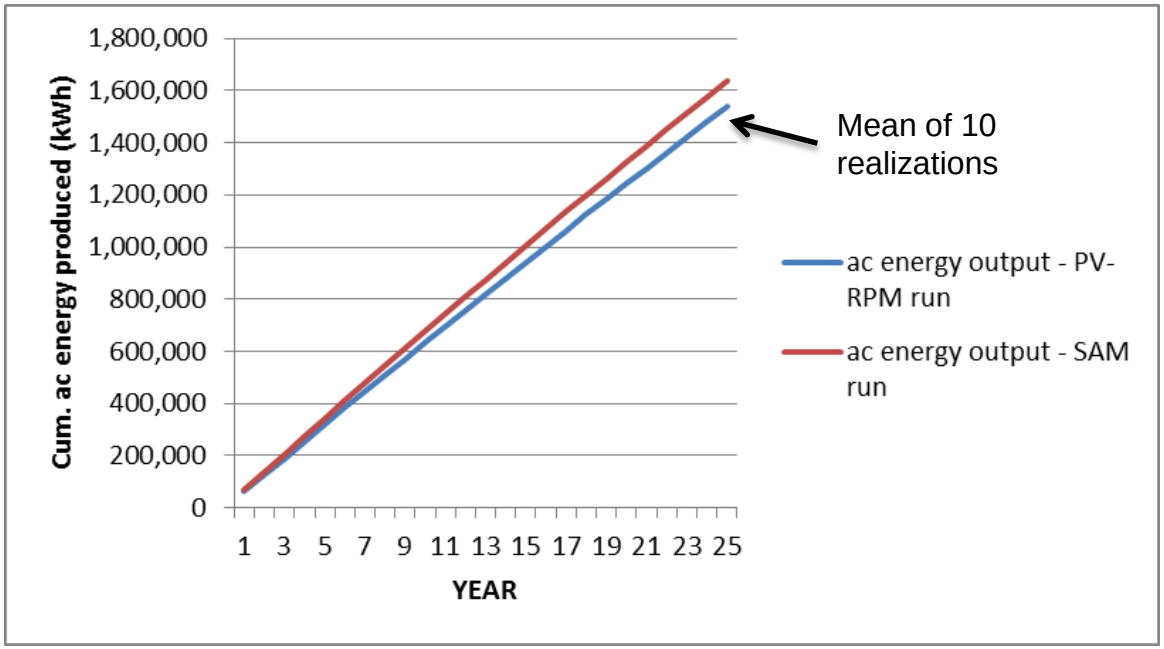
Component	Distribution	1st Model Parameter	2nd Model Parameter
AC Disconnect Switch	Lognormal	$\mu = 7.048$	$\sigma = 3.863$
Photovoltaic Modules	Weibull	$\beta = 0.825$	$h = 4.498\times10^{6}$
480/34.5 kV Transformer	Weibull	$\beta = 0.668$	$h = 2{,}554$

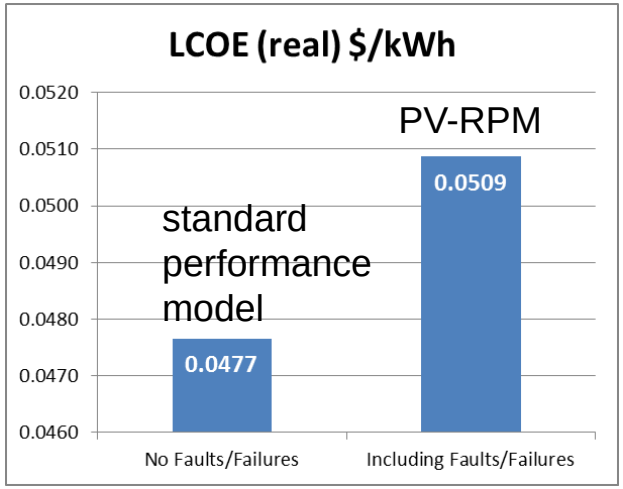
Current Efforts to Improve O&M with a Reliability Focus:

- Adding probability distributions to the System Advisor Model

Reliability for PV Performance Modeling

- Adding fault and failure impact into the System Advisor Model from Sandia PV-Reliability Performance Model (RPM)
- Example analysis below, with LCOE differences when faults and failures are represented probabilistically



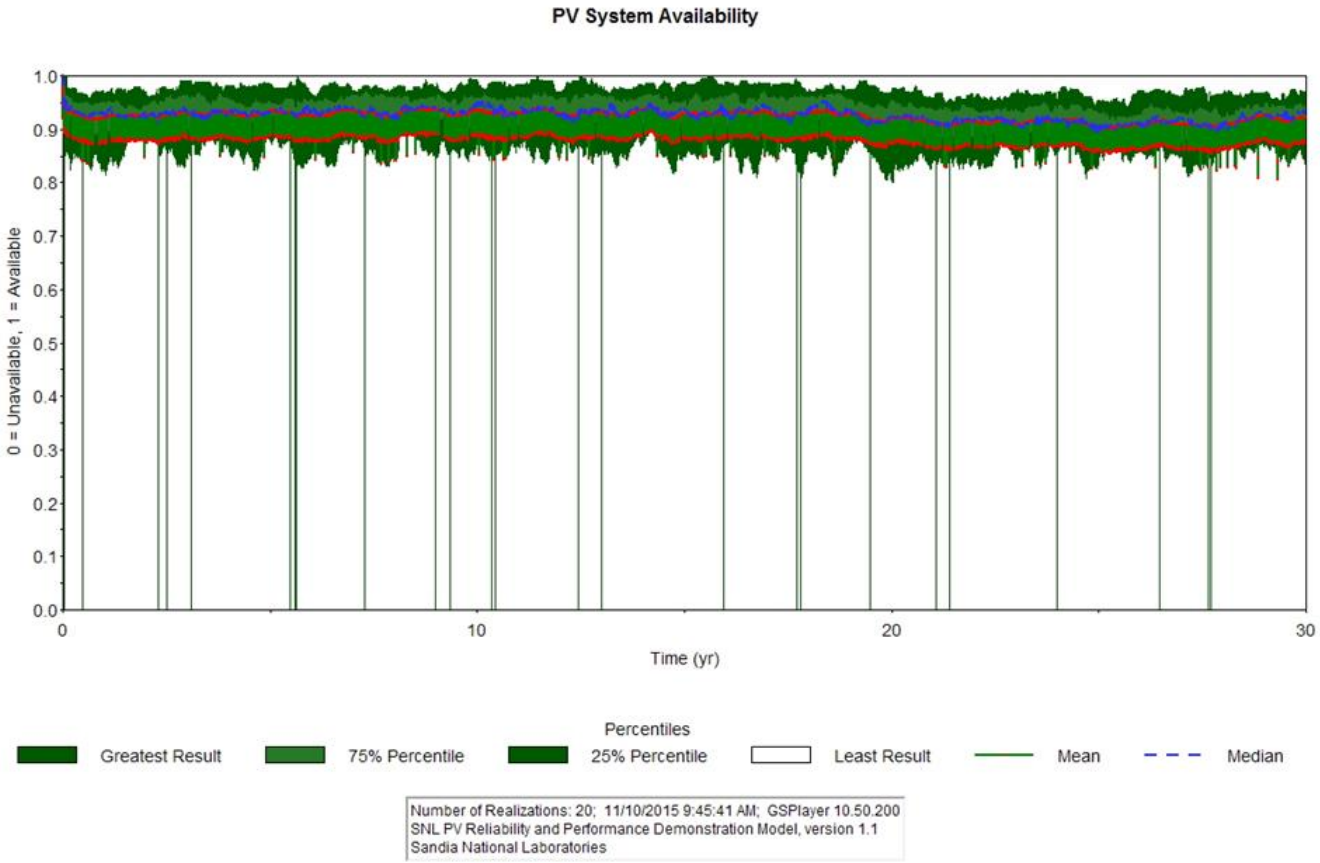


Hypothetical analysis shows 0.3 cent difference in LCOE

6% difference in cumulative ac energy production over 25 years

Reliability for PV Performance Modeling

- Instead of forcing Availability into a performance model with scheduled maintenance and 'guesses' on when components fail…
- Estimates of equipment availability can be represented probabilistically and used to improve contractual expectations and compliance



- Grid events (Availability of 0 due to external event, in this example) can also be expressed as probabilities

EPRI-Sandia PV Systems Symposium

May 9-11th at the Biltmore Hotel in Santa Clara, CA

Sandia National Laboratories

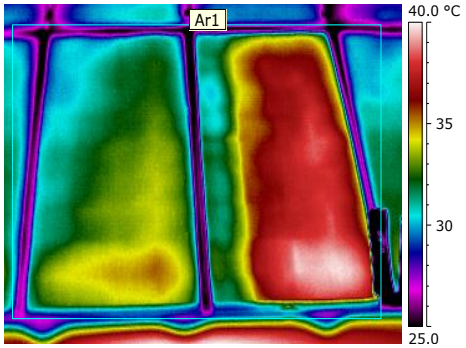
EPRI ELECTRIC POWER RESEARCH INSTITUTE

A symposium, comprised of three one-day workshops, on the technical challenges and opportunities related to solar PV systems and technologies

Registration opens 2/28
Submit abstract until 3/4

- **5th PV Performance Modeling Workshop** — May 9
  - Solar Resource Data Sources and Uncertainty
  - Spectral Corrections for PV Performance Modeling
  - Modeling Challenges for New PV Techs
  - PV Modeling Tools Update
- **Side Meeting: PVLIB for Matlab and Python** — May 10
  - Current status of the PVLIB and future plans
  - Gaps to focus on for new development
- **PV Grid Integration into Distribution Workshop** — May 10
  - Distribution Modeling for Planning and Screening
  - Advanced Inverter Functionality
  - Challenges of High-Pen PV on Distribution
  - Distributed Control and Operation Mgmt
- **PV Life Cycle Workshop** — May 11
  - Improving Current and Future PV System Design
  - Budgeting for PV O&M
  - Reliability Analysis of PV Plus Storage
  - Reliability and Lifetime of PV Systems

http://energy.sandia.gov/wp-content/uploads/2012/04/2016-PV-Systems-Symposium-Save-the-Date-final.pdf



Thank You

Geoff Klise

gklise@sandia.gov

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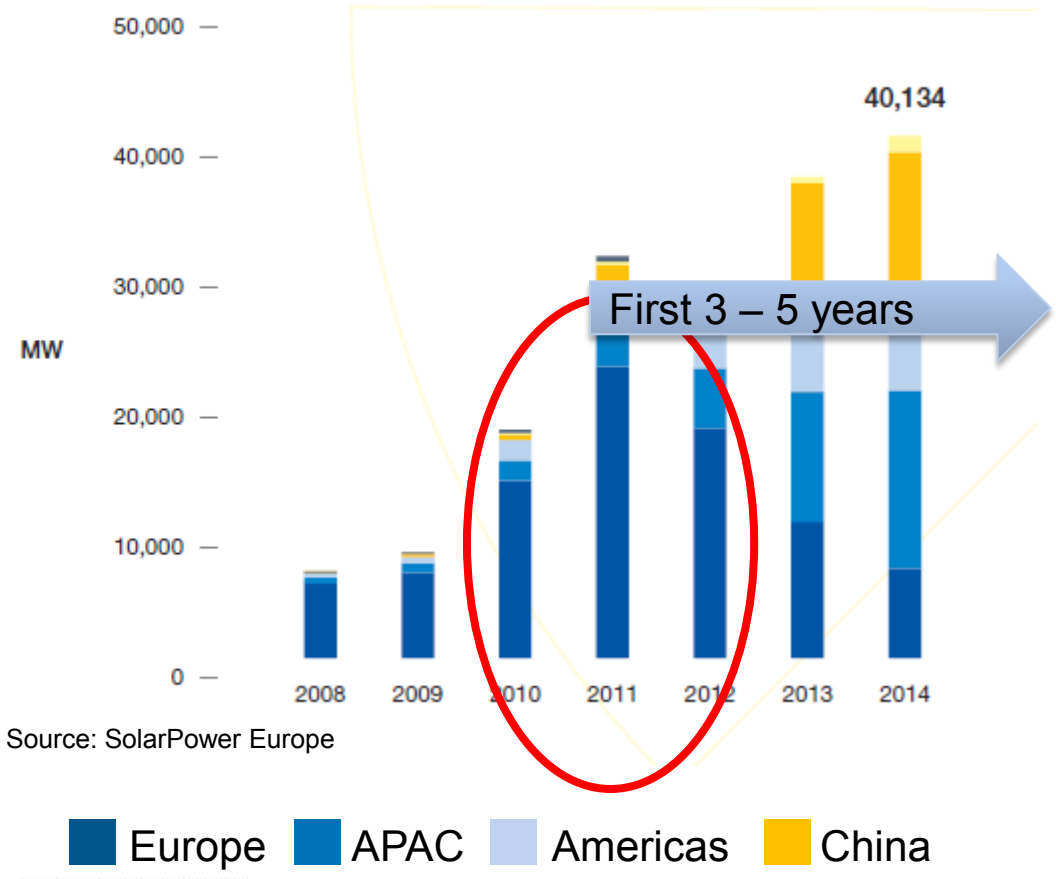
Test Procedures for determining long term degradation from early degradation indicators

Matthias Heinze, Nicolas Bogdanski
TÜV Rheinland Group

How early is ‘early degradation’?



Source: SolarPower Europe

<u>Findings today (and last 3 years):</u>

Significant amount of arrays show early degradation.

- Yellowing
- Snail trails
- Broken cells (time of formation?)
- Delamination
- Hot-spots
- PID
- LeTID
- etc.

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Reasons for ‘early degradation’?

Installation period 2008 - 2012

<u>Reasons for major quality problems were:</u>

- A lot of new companies entered the market
- Not all important lessons learned at that time
- Material mixture due to supply shortages
- Missing quality assurance system
- New (non established) materials were used
- etc.

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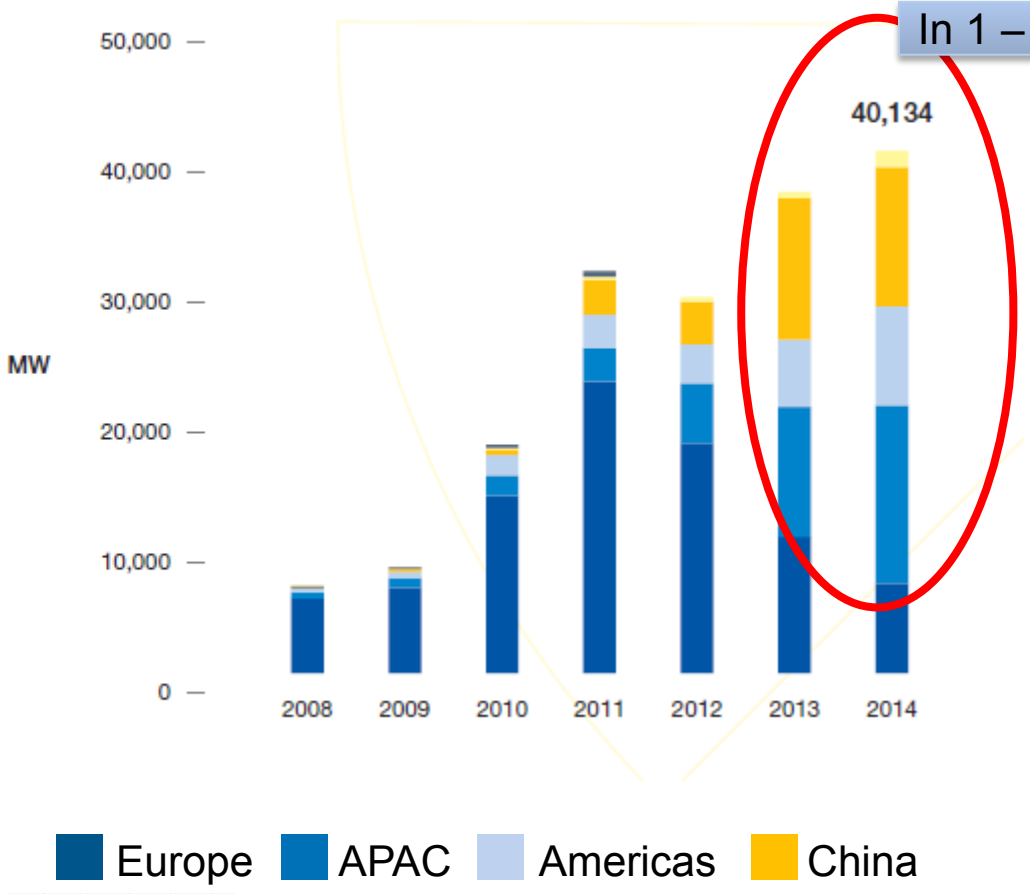
Future ‘early degradation’?



Degradations will be the same, n
may arise.

- Yellowing
- Snail trails
- Broken cells (time of formation
- Delamination
- Hot-spots
- PID
- LeTID
- PLeTID ???
- etc.

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Reasons for ‘early degradation’?

Installation period 2016 – 20xx

Probable reasons:

- Cost pressure
- ~~A lot of new companies enter the market~~
- Still not all important lessons learned
- ~~Material mixture due to supply shortages~~
- Missing quality assurance system
- New (non established) materials are used
- Increased system voltage

The relative amount of early degradation very likely is going to decrease.

! Increasing demand for evaluation of degraded arrays to assess further progress of degradation

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Costumer's Expectations

Plant owners

Manufacturers

- Extend of degradation
- Impact performance
- Root cause degradation
- Evaluation warranty status
- Valuation reports
- Future progress degradation

Investors

Insurance companies

Gains more and more importance with a relevant amount of arrays being sold

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Evaluation of degradation

Common stepwise procedure:

Classification degradation	Definition adapted test procedure	Evaluation, interpretation test results
▪ Type of degradation ▪ Amount of modules affected ▪ Distribution of degradation within array	▪ Definition relevant amount sample ▪ Selection of adapted stress tests ▪ Definition of additional analysis methods	▪ Outlook on further progress of degradation ▪ Potential future power loss ▪ Probable cause of degradation ▪ Evaluation resale value

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Key issue: How to evaluate future degradation progress

Two very different approaches :

A)

Test procedures and evaluation according to IEC requirements

Standard test conditions, established procedures and test methods, commonly accepted

Advantage

- Not ‘yet another test procedure’
- Commonly accepted test parameters and requirements
- Cost saving

Disadvantage

- Discussion about relevance of result due to previous exposure
- Probably over-stressing of samples
- May not fit to all degradation findings

B)

Adapted test procedures and adapted requirements

Adapted test conditions, fitted to actual location and degradation type

Advantage

- Can be fitted to actual location
- Degradation specific procedures
- All degradation types can be covered

Disadvantage

- ‘Yet another test procedure’
- Test results may be rejected by manufacturers (warranty case) due to unexplained relevance of tests
- Probably higher costs

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Example A: Evaluation of yellowing

Facts:

- Plant, several MW, all modules affected by yellowing
- TUV to evaluate severity, future progress, warranty issues

Background:

Yellowing can be more than an optical effect. Potential threads are performance loss, delamination, loss of insulation properties

Procedure:

- Comparison of affected modules with reference samples
- IEC stress tests (UV, HF, DH)
- Analysis methods beyond IEC methods (YI, peel test, cross cuts)
- Material composition, comparison to certified composition

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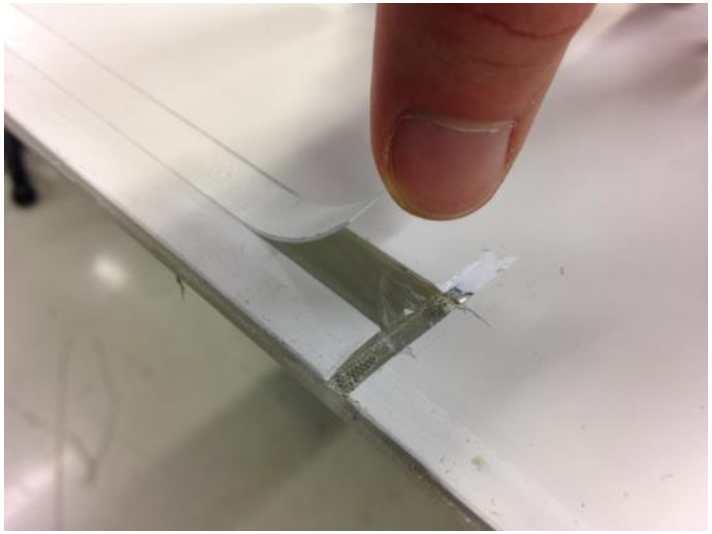
Example A: Evaluation of yellowing

Results safety:

- Severe loss of adhesion
- Large bubbles after DH test
- Delamination at the edges

Fail regarding IEC requirements!



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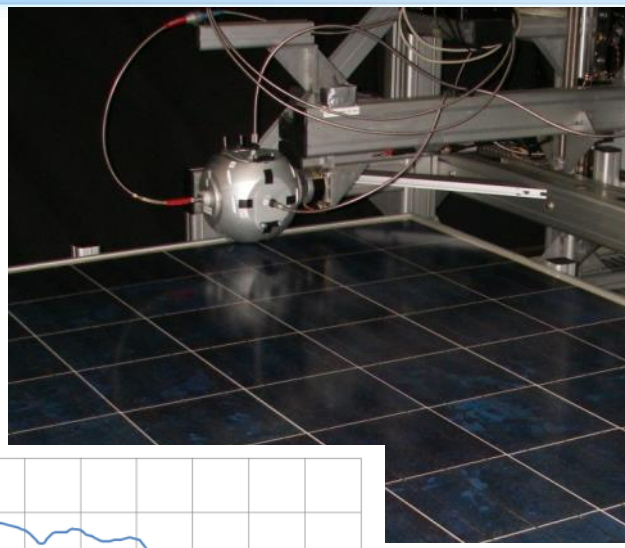
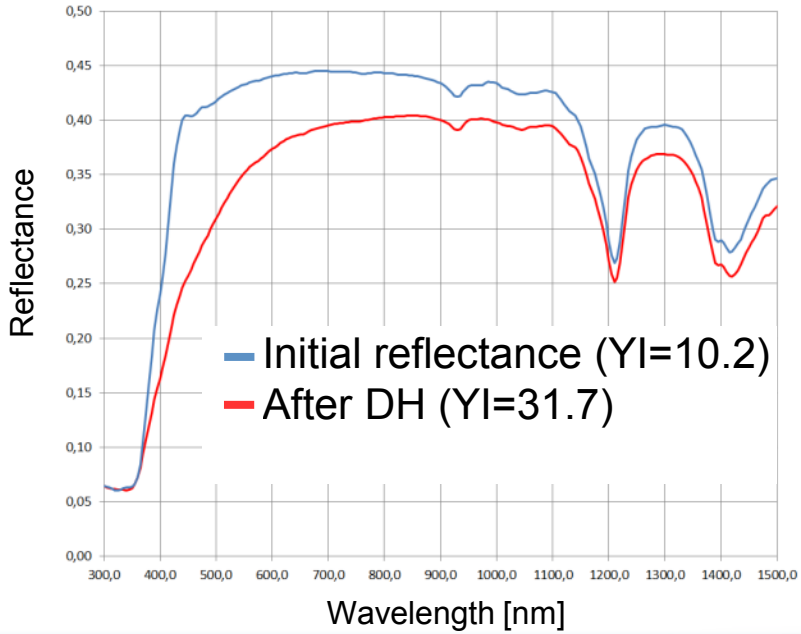
Example A: Evaluation of yellowing

Results yellowness:

- Samples showed a significant increase of the yellowness index (YI)
- No significant change in front of the cell
- No significant change of MPP

Pass regarding IEC requirements!





Compare IEC 62788-1-4

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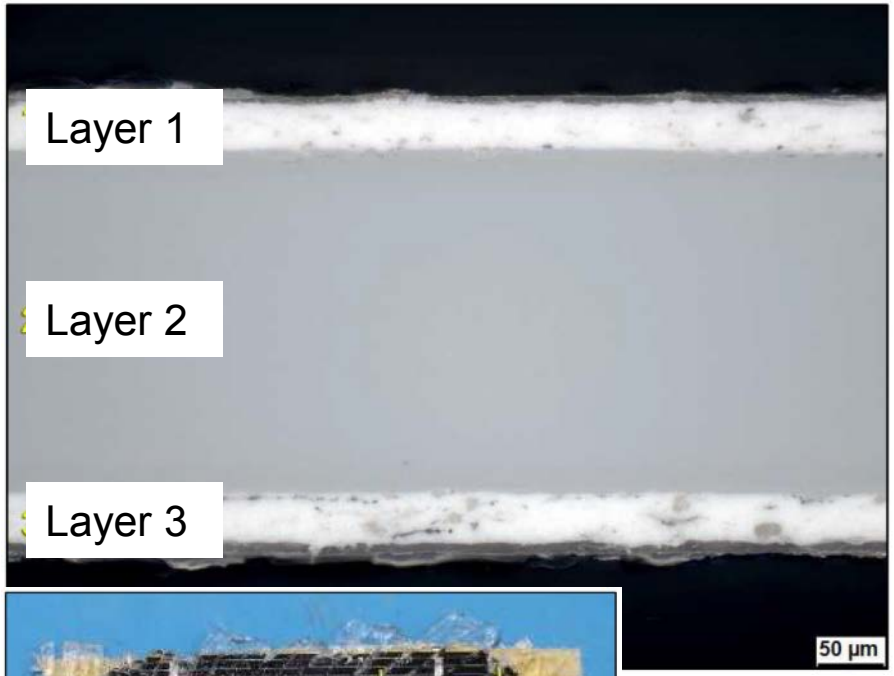
Example A: Evaluation of yellowing

Results certification status:

- Yellowing was mainly caused by backsheet (e-layer)
- Certified material composition should not show early degradation
- Comparison of certified and actual composition to reveal deviation of composition



Cross section analysis

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Example B: Evaluation of hail impact

Facts:

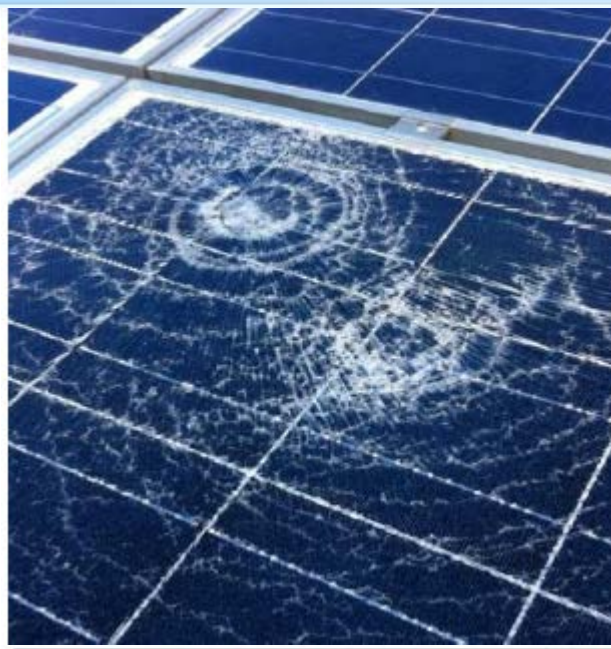
- Plant, several 100 kW, many modules affected by hail impact
- TUV to evaluate current and potential future performance loss, advice for replacement

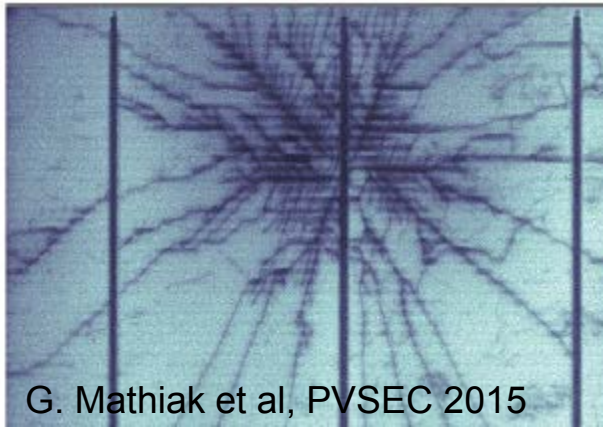
Background:

Cell cracks are(when not combined by glass cracking) often hidden and can strongly affect performance and may further progress with time.

Procedure:

- STC measurement of representative amount of samples
- Adapted stress tests (TC, ML, (DH))
- Hail impact test





G. Mathiak et al, PVSEC 2015

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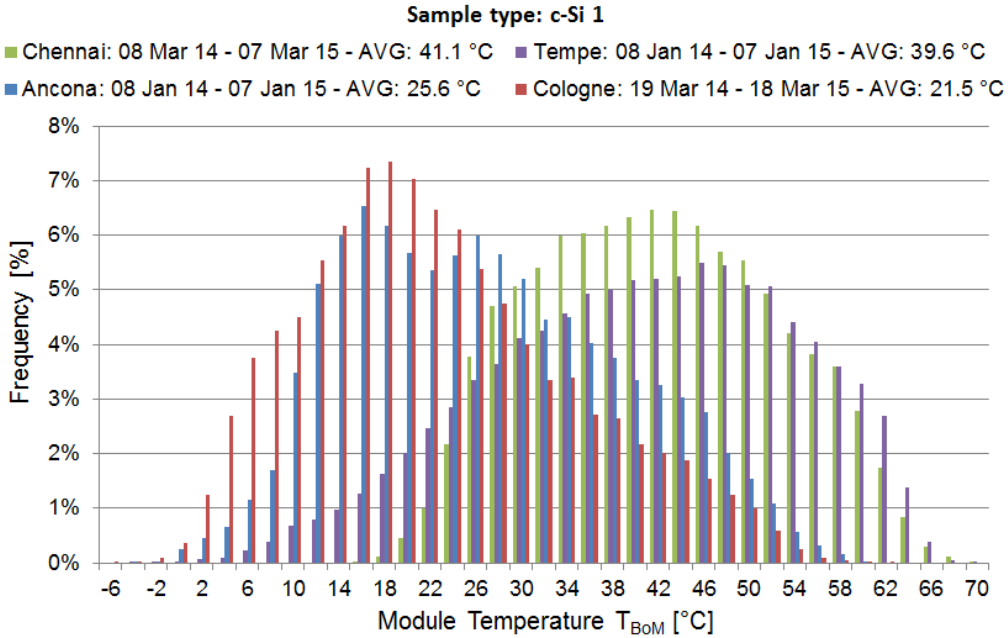
Hail impact: compilation test procedure
- impact through temperature gradients -



3-5 different stress levels

- Maximum temperature gradient
- Mean temperature gradient
- Gradients in-between

365 cycles altogether
weighting according to histogram
using differently affected modules

Weather data at location → Module temperature histogram → Temperature gradients for testing → Test profile one year

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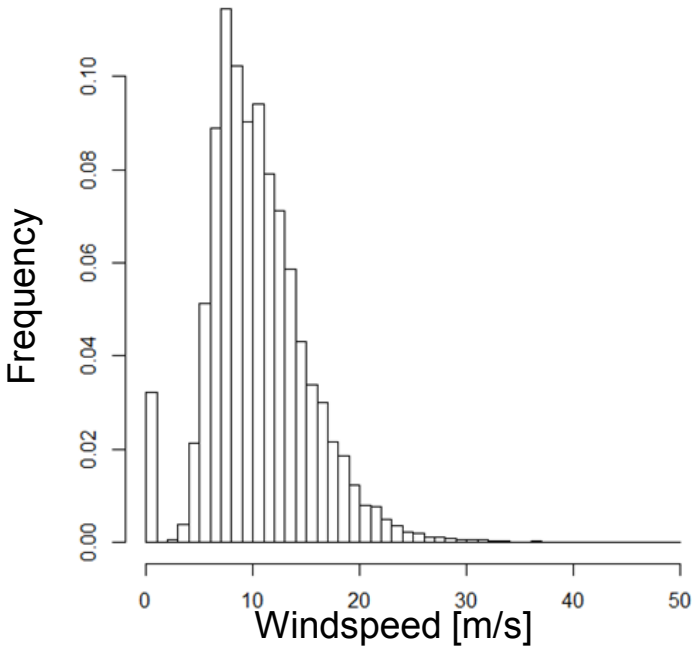
Hail impact: compilation test procedure
- impact through wind -



3-5 different stress levels

150 Pa	243 cycles
200 Pa	80 cycles
250 Pa	59 cycles
300 Pa	23 cycles
400 Pa	7 cycles
500 Pa	5 cycles
600 Pa	1 cycle

Wind data at location → Wind speed histogram → Mechanical load histogram → Test profile one year

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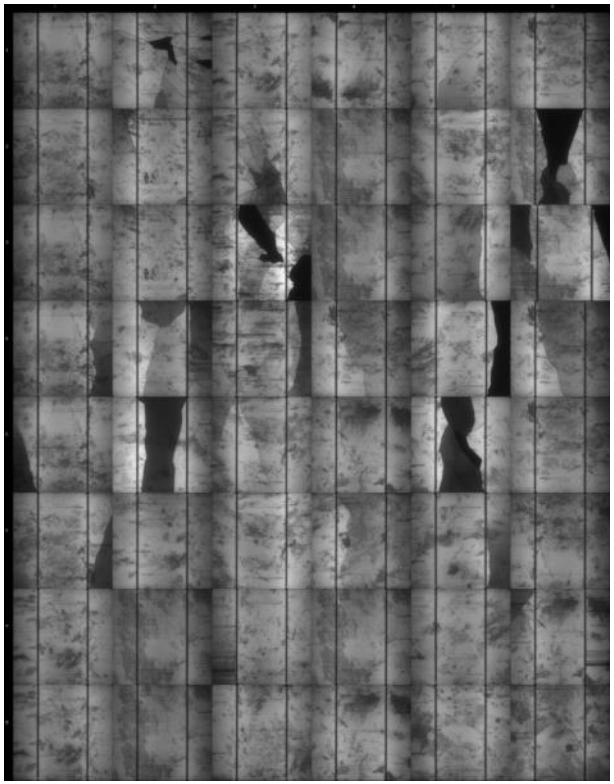
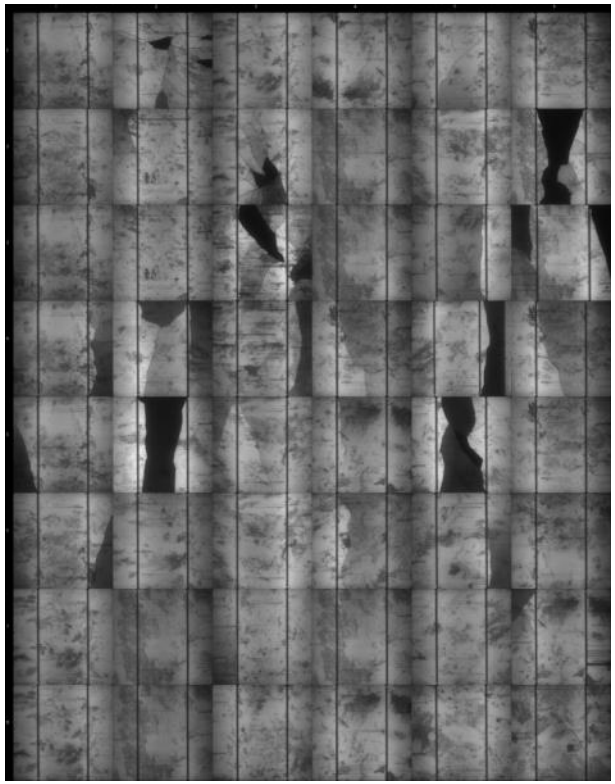
Hail impact: adapted sequential testing

Electroluminescence images of modules under test

Initial

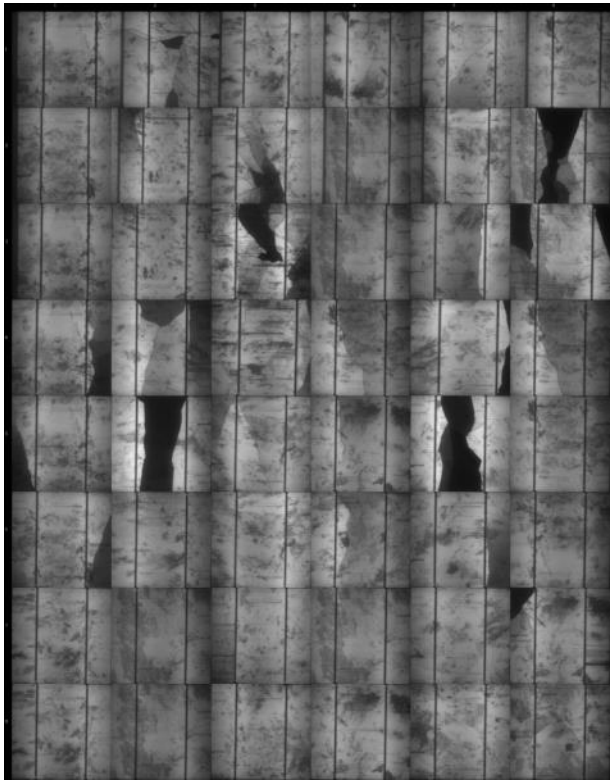


First sequence



Power loss:
-2,1 %

Final (3rd sequence)



Power loss:
-4,0 %

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Hail impact: adapted sequential testing

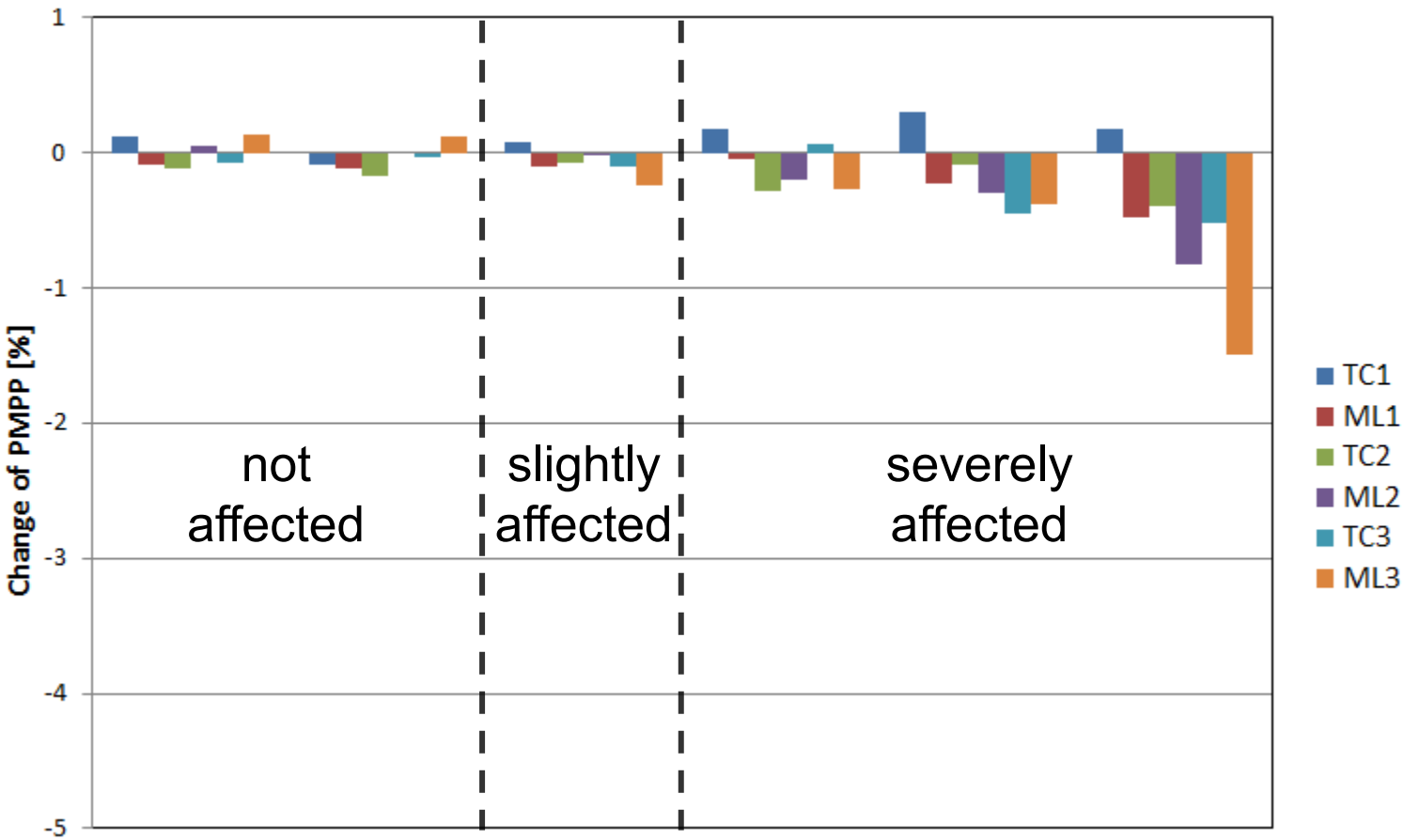
Comparison EL-images => changes are not easy to detect

Initial

After 3 sequences

Hail impact: adapted sequential testing

Type A



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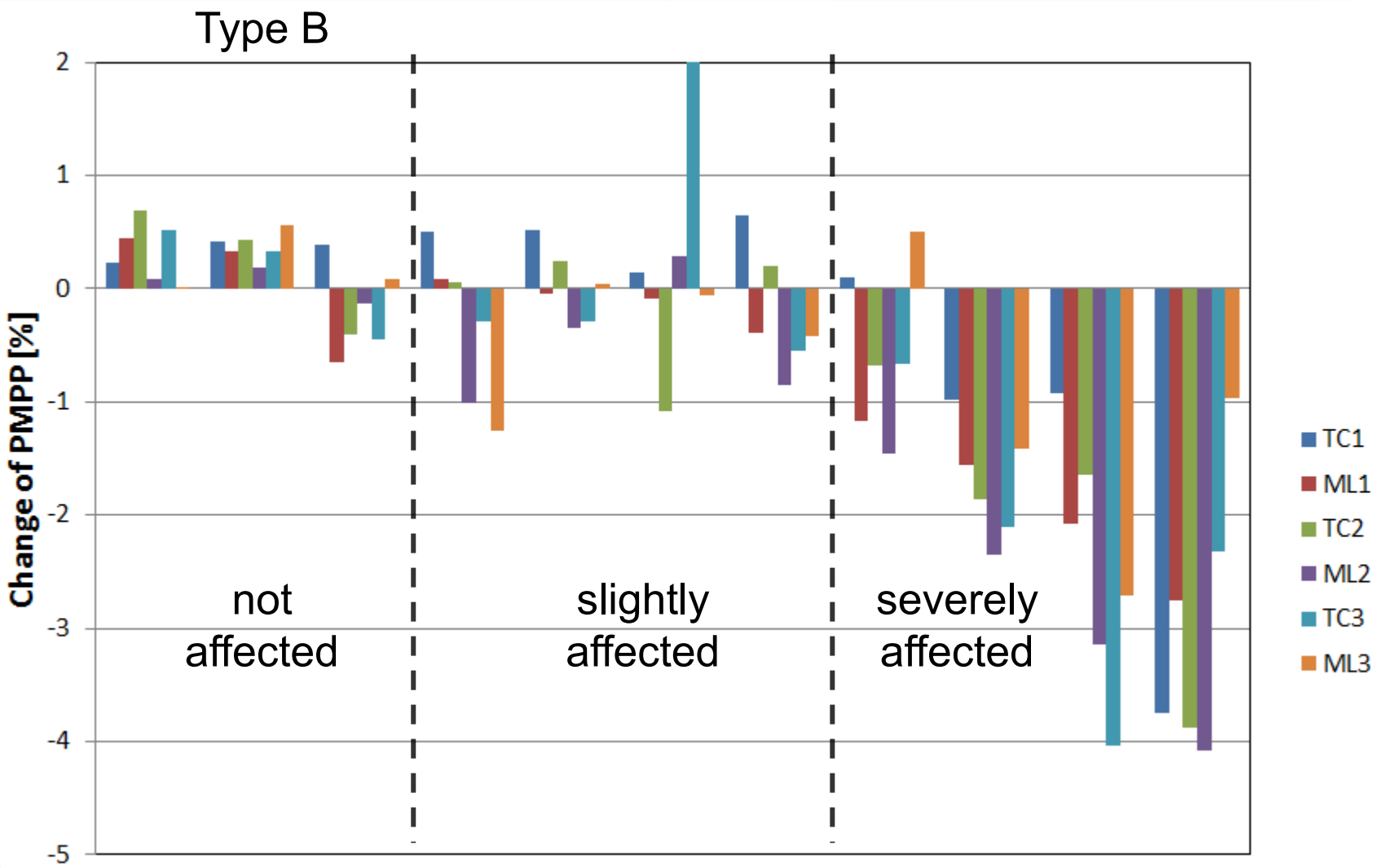
Hail impact: adapted sequential testing



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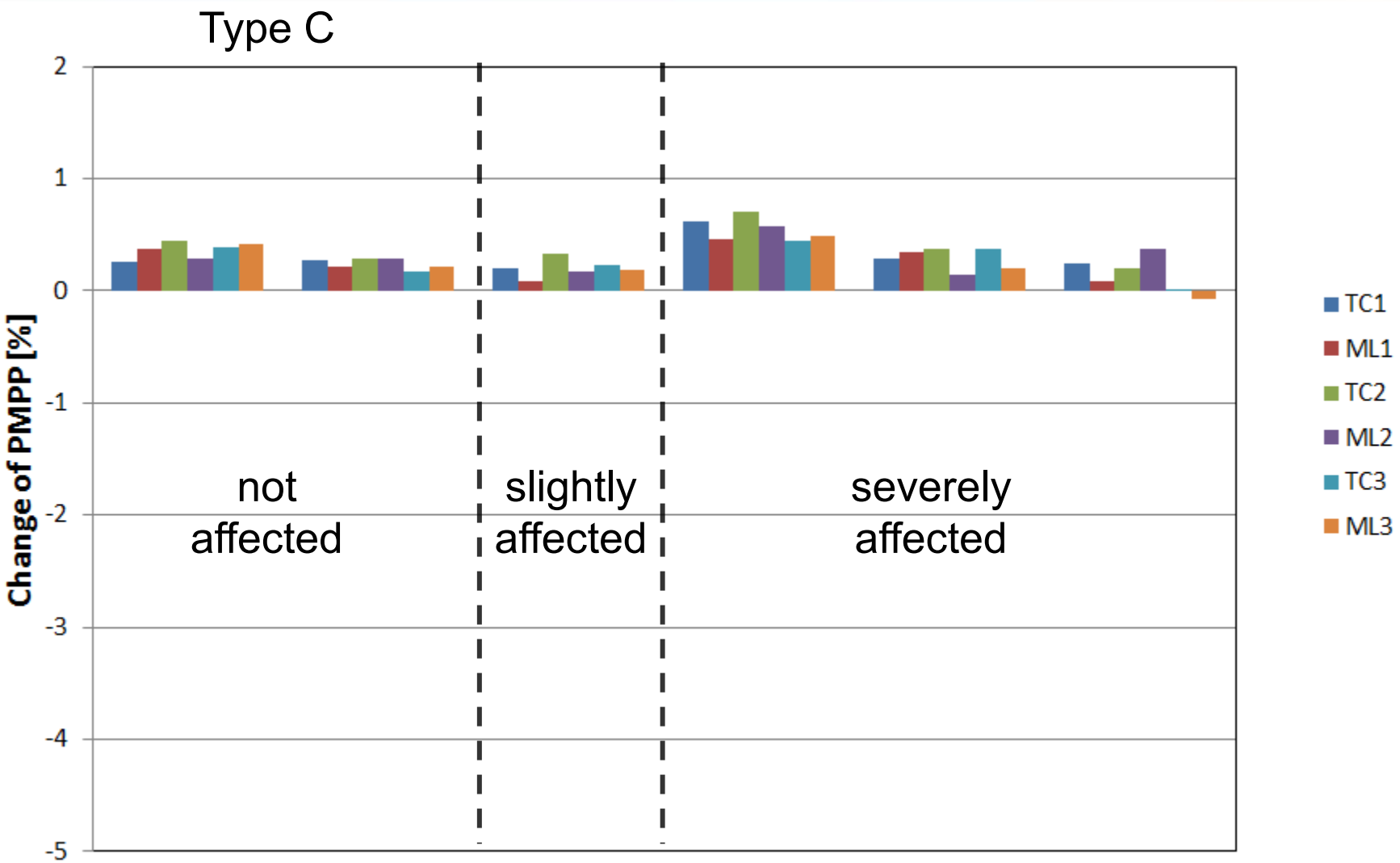
Hail impact: adapted sequential testing



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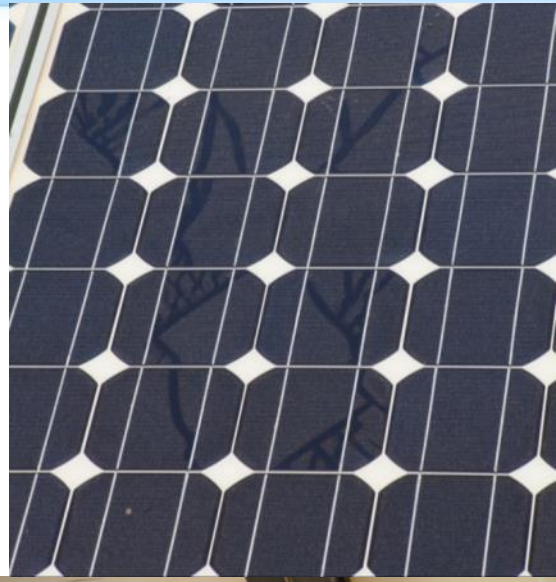
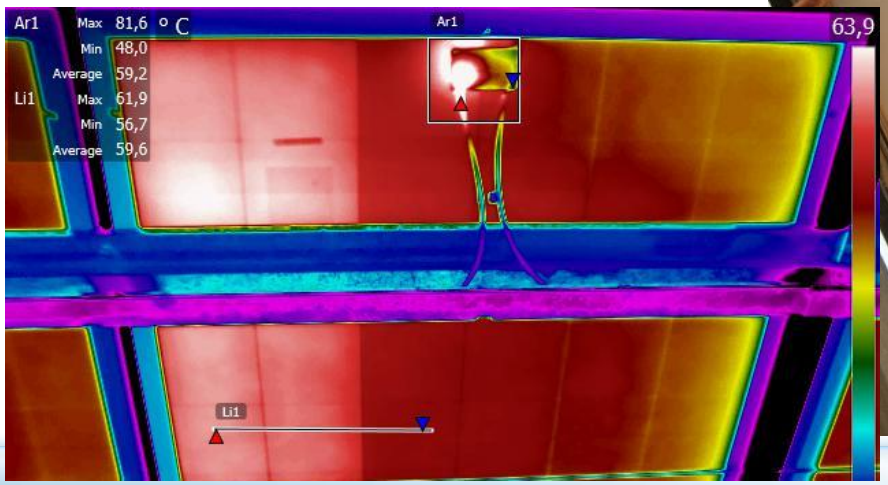
Further degradation patterns

Evaluation of other types of degradation occurring in the field cover

- Snail trails
- Cracking of backsheet
- Glass corrosion / ARC degradation
- Thin film specific degradation
- Hot spots / bypass diode failure
- Interconnection failure
- etc.





Source: Peter Bentz

TÜVRheinland®
Precisely Right.

Summary

- Demand for evaluation of degraded power plants will strongly increase
- Proper monitoring of large plants can support early detection and better estimation of stress test results
- Up to now broadly accepted test procedures are missing
- Develop a common understanding of how to interpret test results
- Let’s get into discussion to find common procedures

TÜVRheinland®
Precisely Right.

Thank you for your Attention !

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Precisely Right.

The Big Picture

How Updated US Codes and Standards Address PV System Safety

Jason Fisher / Principal Compliance Engineer

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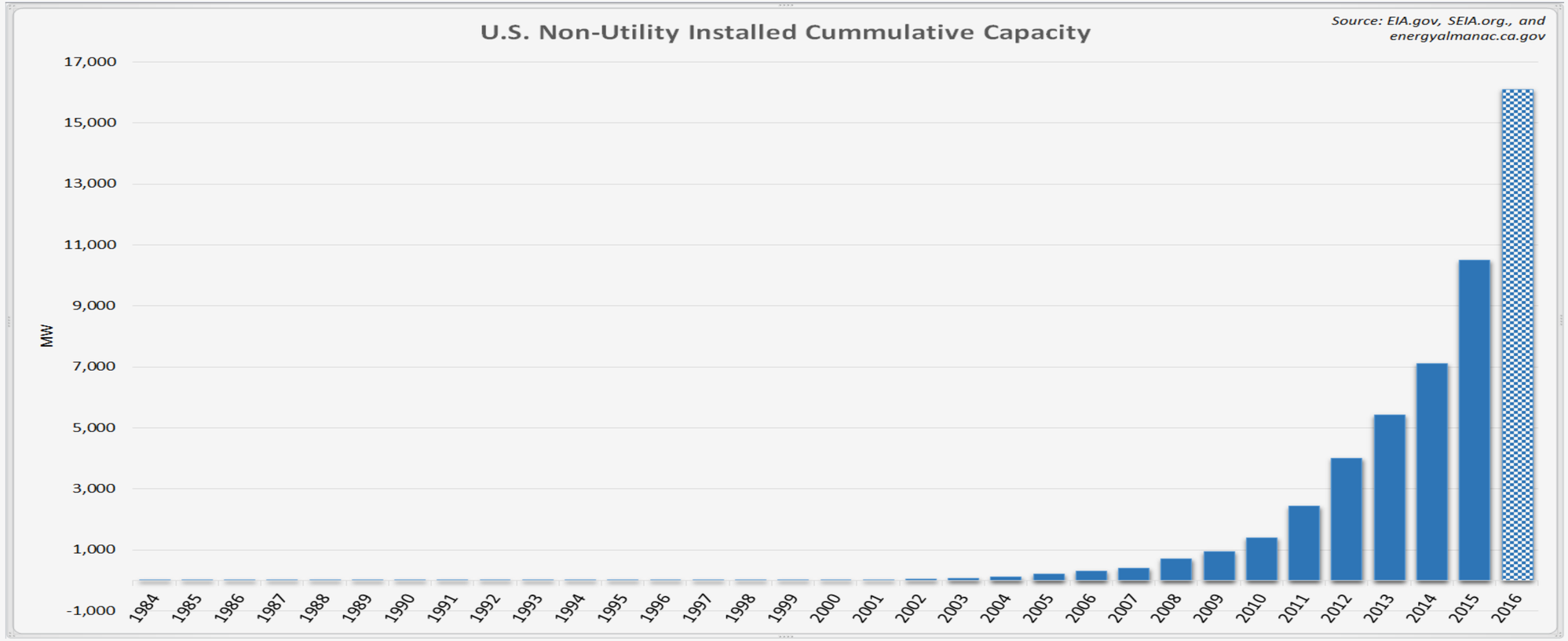
Installed PV Rooftop Capacity 1984-2016(est)



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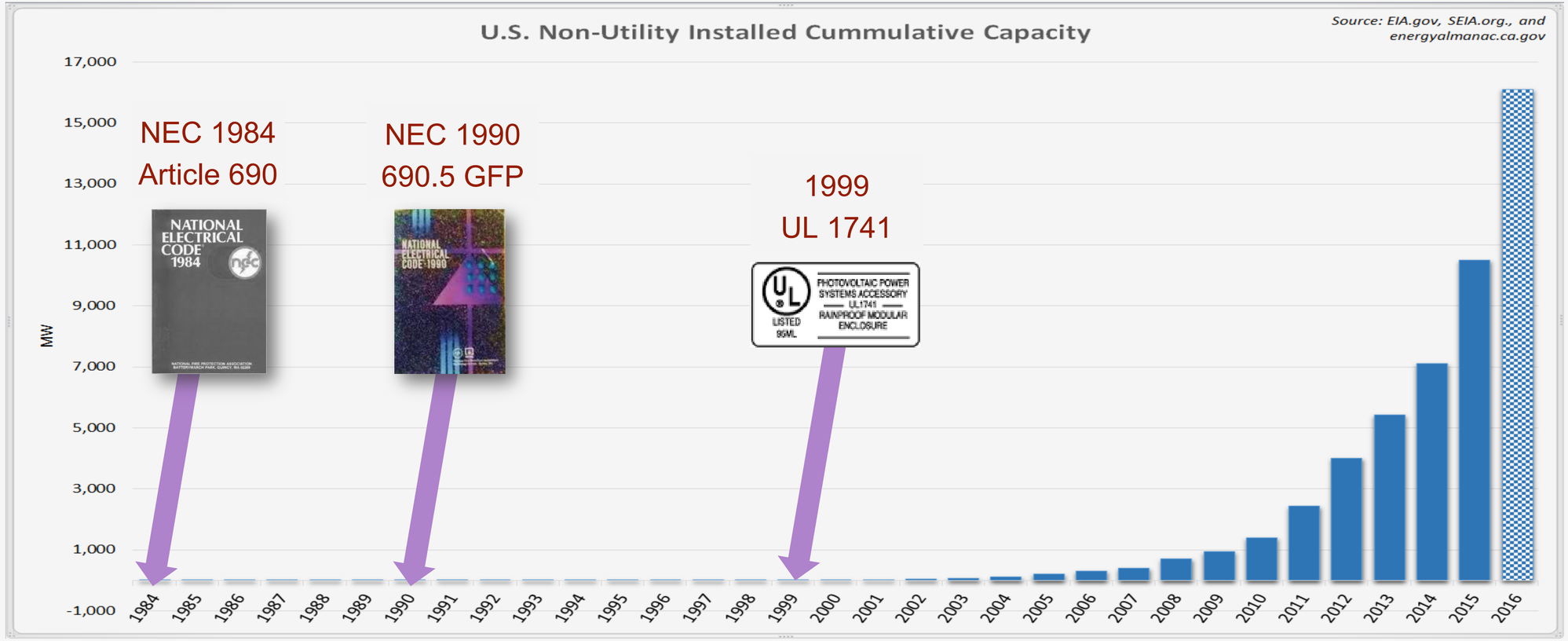
Major Code and Standards Changes



Images: Courtesy of https://commons.wikimedia.org., nfpa.org, www.iccsafe.org

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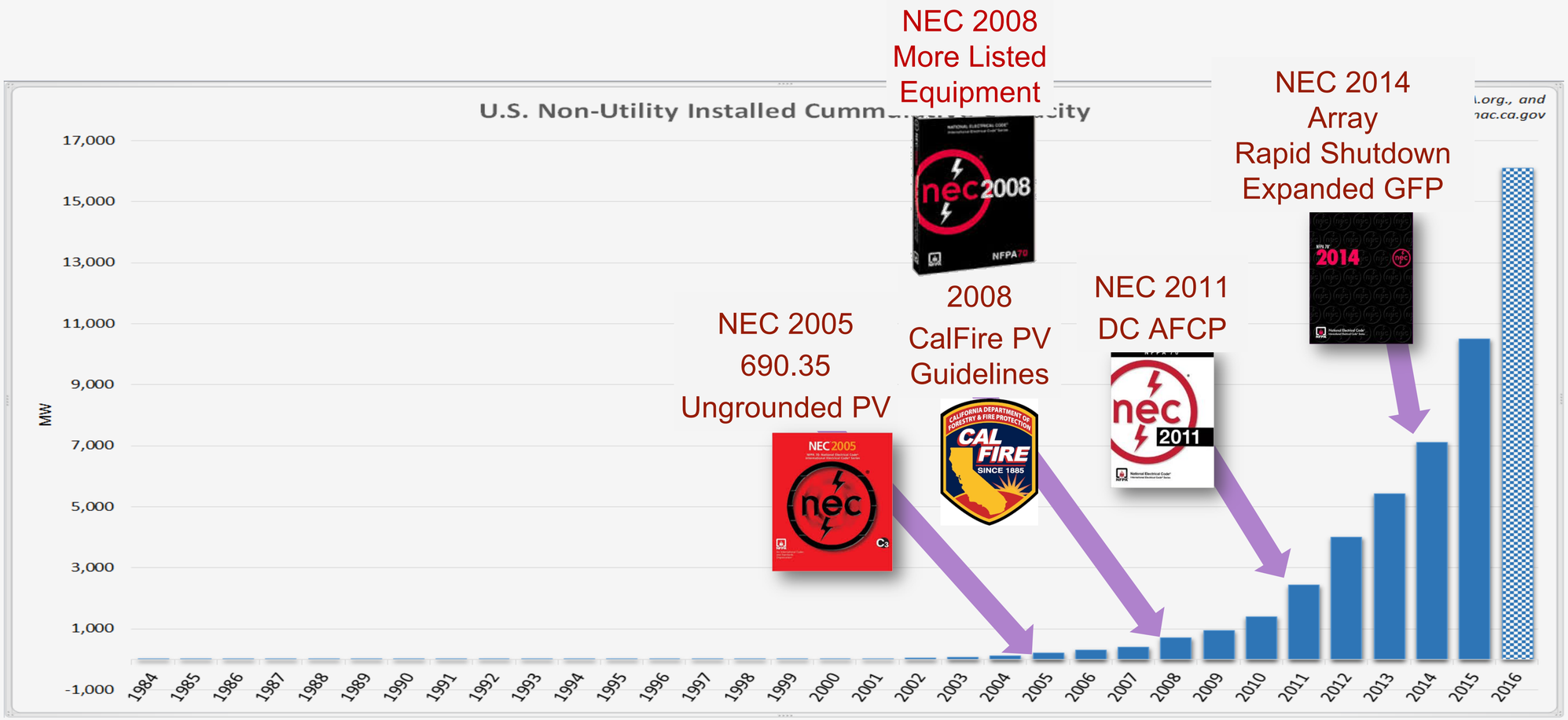
Major Code and Standards Changes



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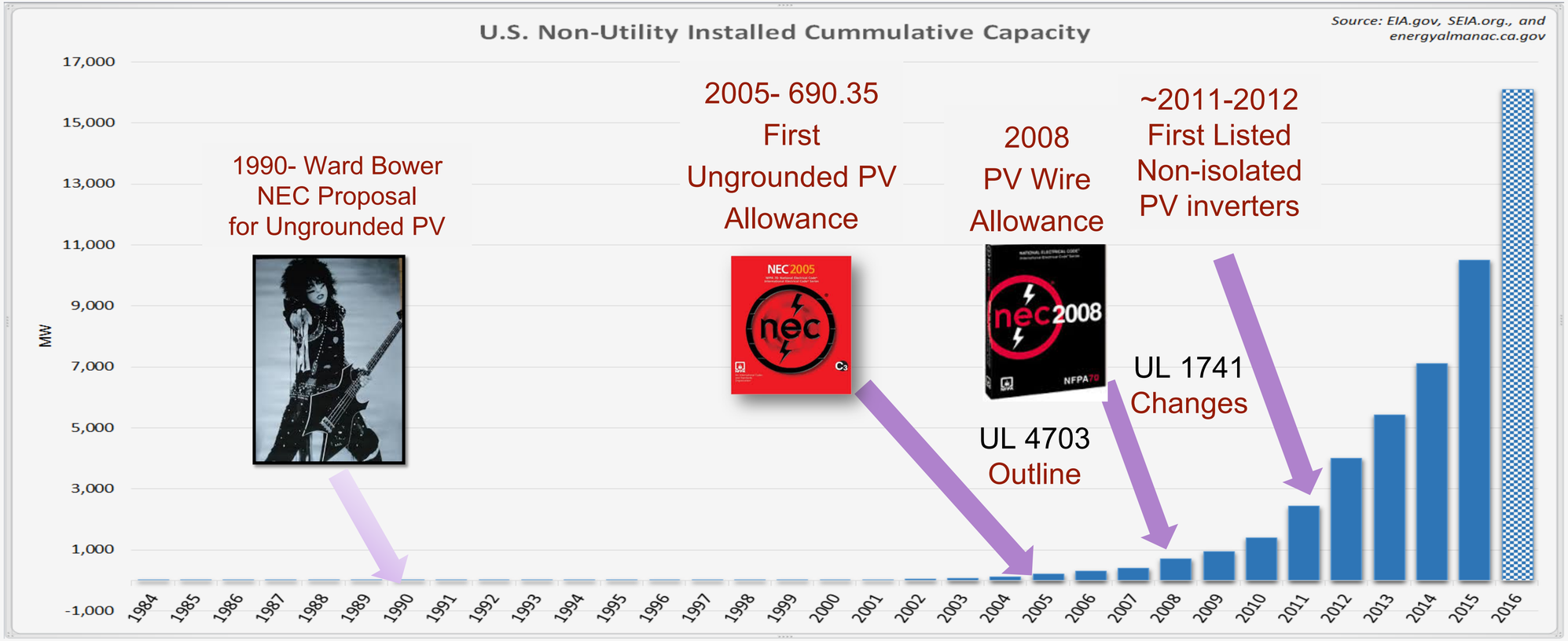
Ungrounded (aka Transformerless, aka Non-Isolated, aka Ground referenced under operation) Systems



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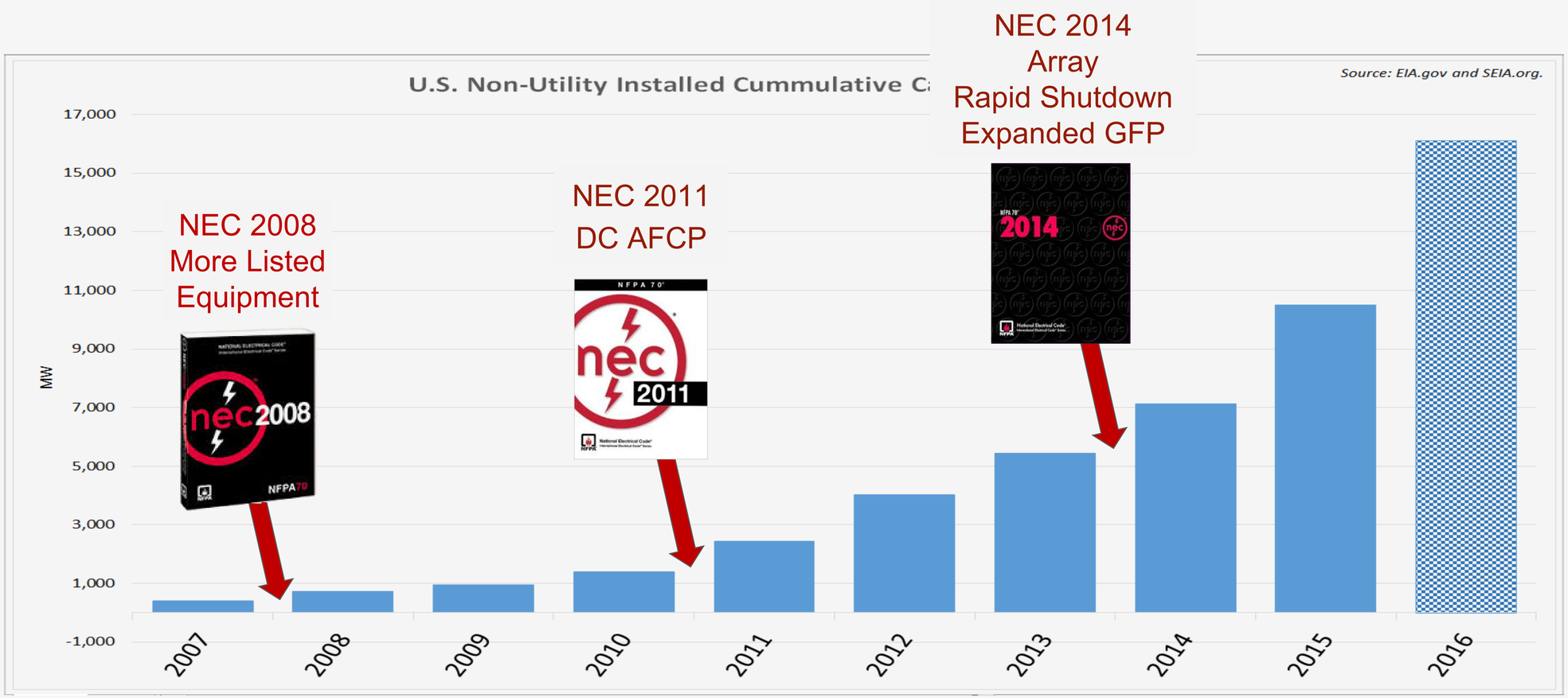
Electrical Code Publication (~10 years)



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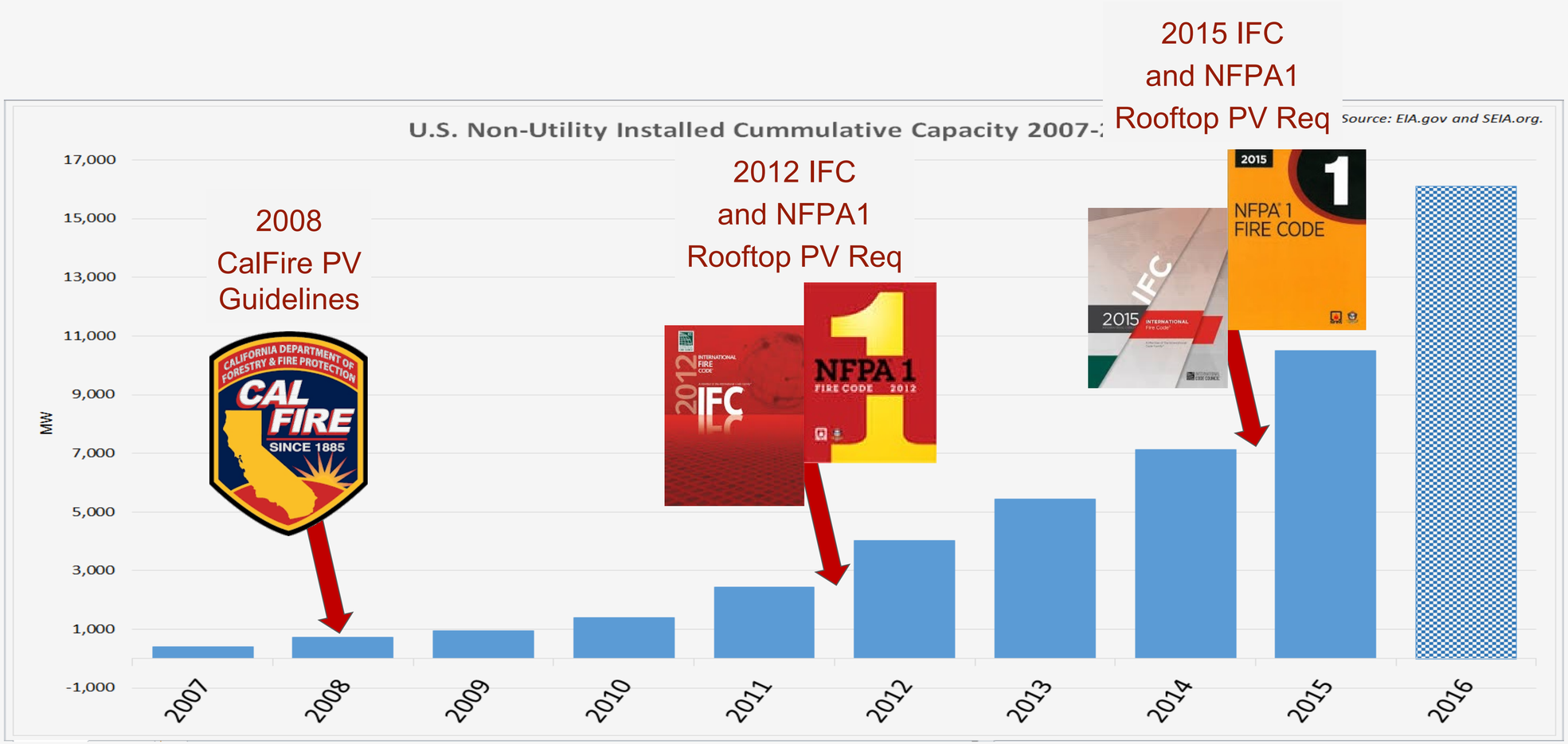
Fire Code Publication



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NEC 2017 (Second Draft) Highlights on PV Safety

System Grounding Options Clarified and Restricted:

- Functional (Reference) Grounded systems are now identified
- Solidly Grounded systems only for small systems not on buildings

Ground Fault Protection:

- On all systems (except Solidly Grounded as above), on all dc conductors

Arc Fault Protection:

- On all dc circuits over 80V

Rapid Shutdown both Outside and Inside the PV Array:

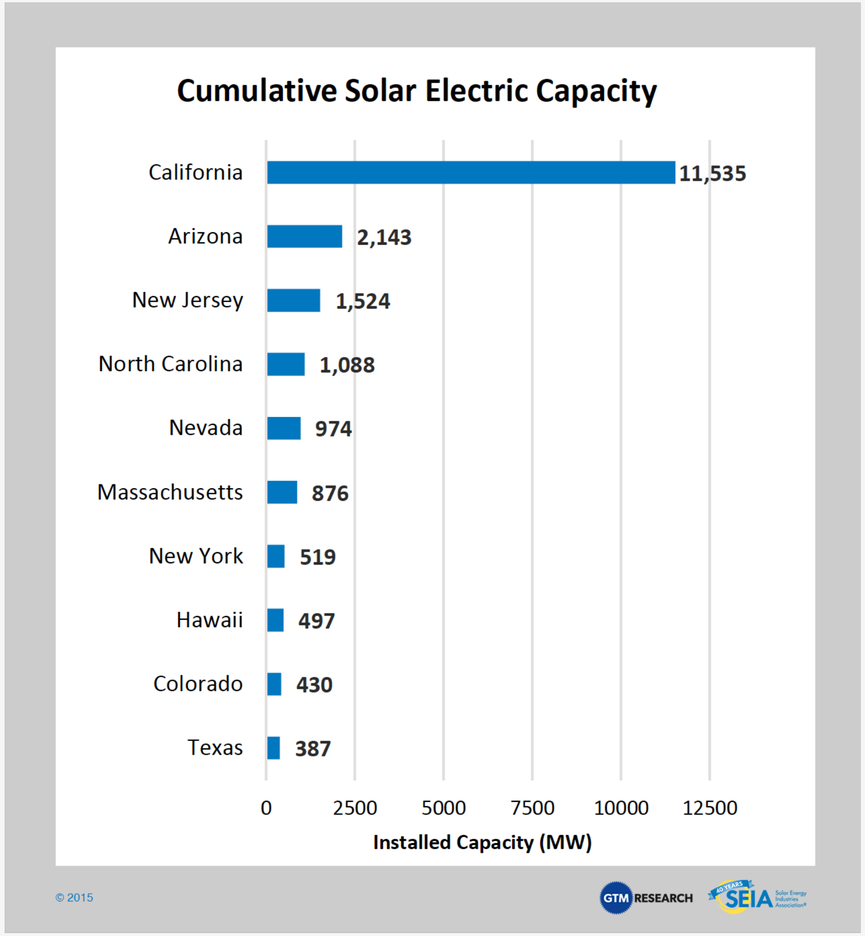
- Outside the Array +/-30V within 30 sec
- Inside the Array either: A Rapid Shutdown Listed Array, an 80V Array, or a Non-Conductive Array

Improved Disconnects, Equipment Grounding, and Marking language.

PV Installed Capacity by State

California represents about 50% of all installed PV capacity in the U.S.

While Code and Standard publication is national, actual adoption and enforcement is local.



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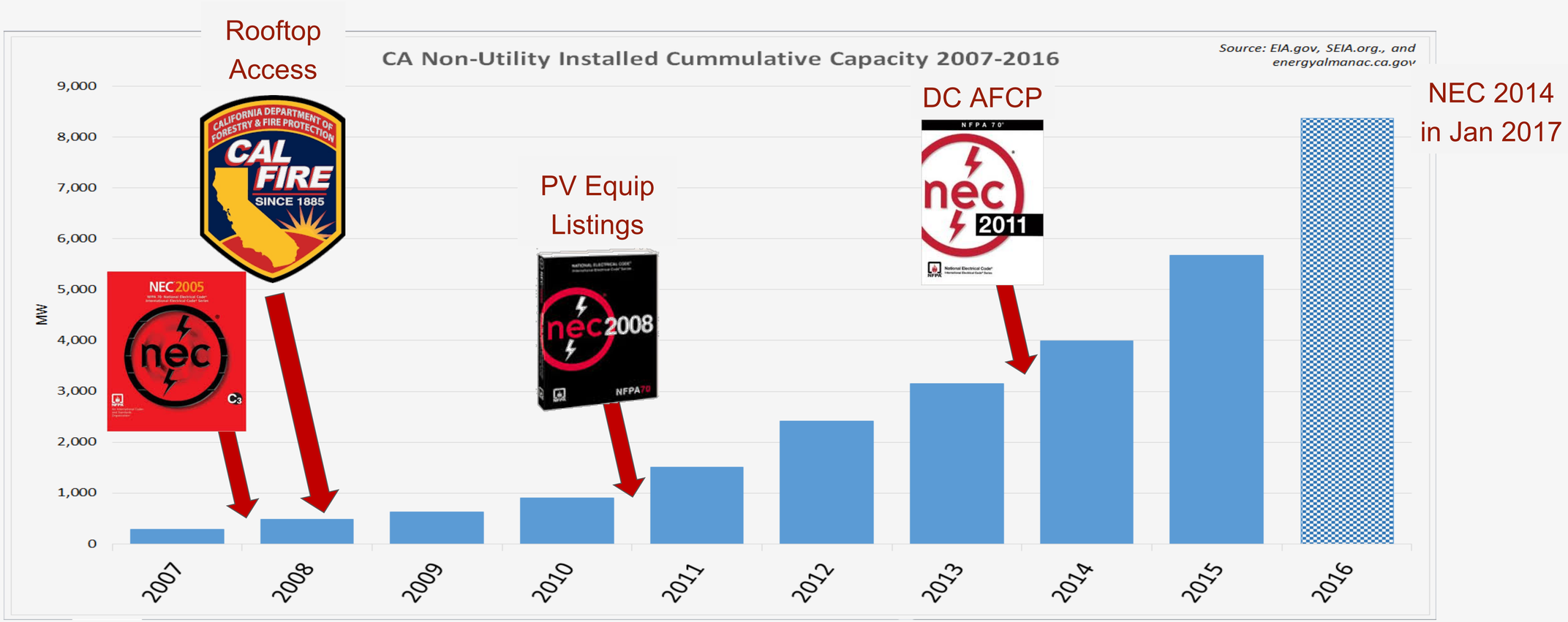
CA Adoption



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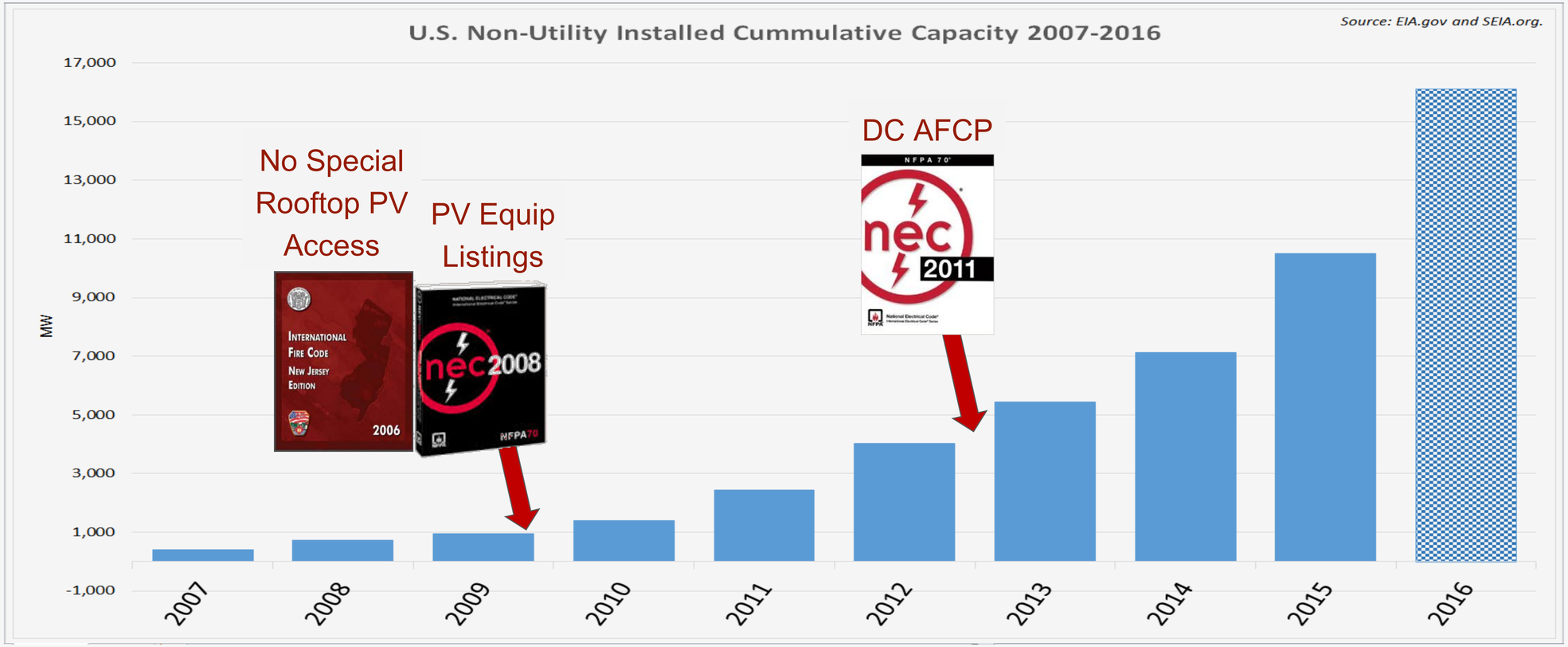
NJ Adoption



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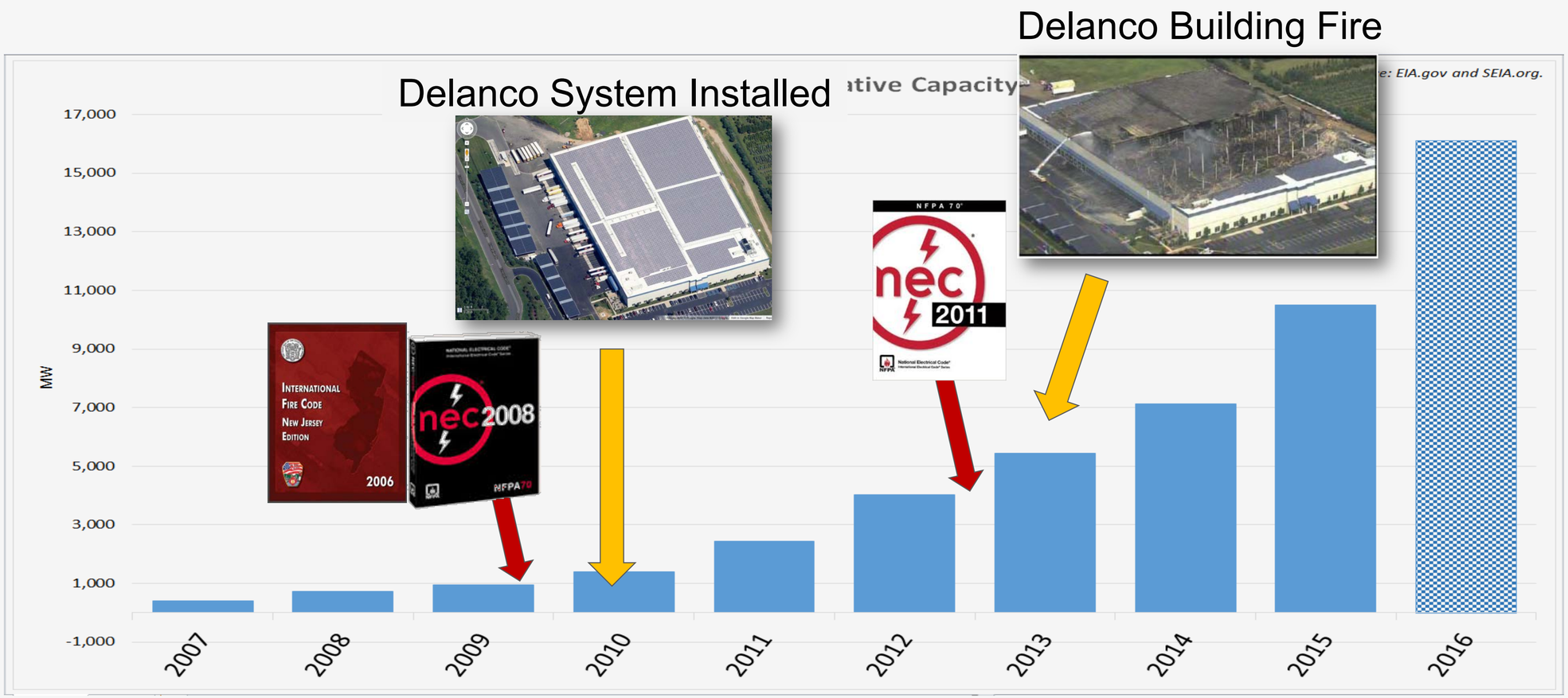
NJ Adoption



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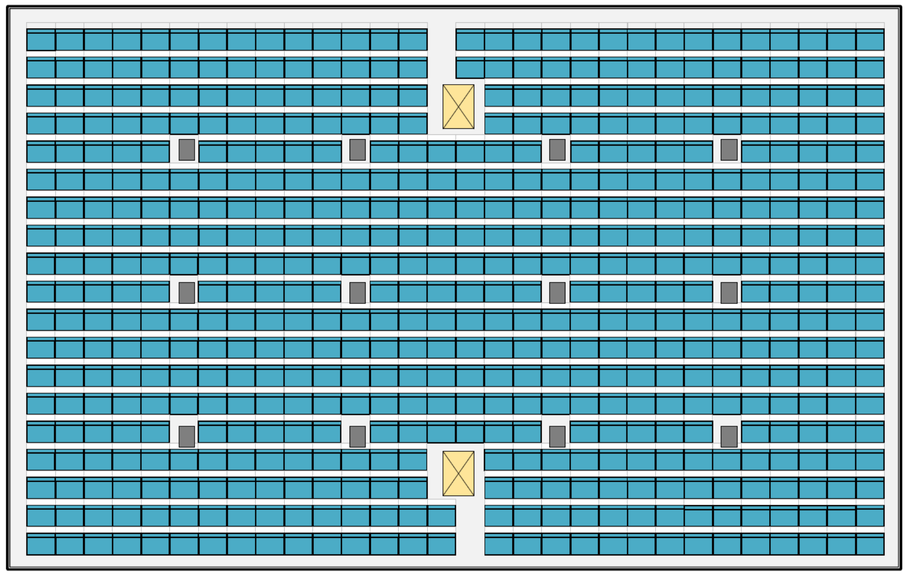
Example 2010 Commercial Rooftop PV System outside of CA

- NEC 2008
- Pre-2012 Fire Code.
- Grounded PV System (low R to grd).
- Limited Ground Fault Protection. Blind Spots.
- No Arc Fault Protection.
- No Access Pathways, Few Ventilation Opportunities.
- No Rapid Shutdown.
- Remote Central Inverters Dominate Market.
- Infrequent Signage and Marking.
- Firefighting Training is Rare.

- Many New Markets:
  Limited Trained Installers.
  Unfamiliar AHJs, Inconsistent Permitting and Inspections.



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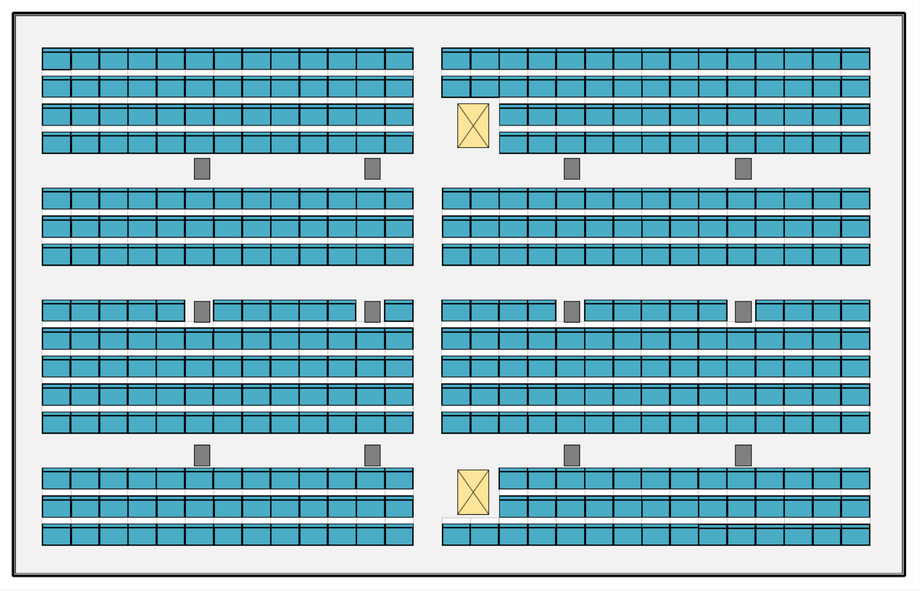
Example 2016 Commercial Rooftop PV System in most of U.S.

- NEC 2014 / 2012+ Fire Code (IFC or NFPA1)
- Non-isolated (Ungrounded) Systems Most Popular
- GFP on All Conductors (no Blind Spots)
- Arc Fault Protection on DC Conductors
- Fire Access Pathways and Ventilation Opportunities
- Rapid Shutdown Outside Array
- Decentralized Rooftop Inverters Dominate Market
- Standardized Signage and Marking
- More Firefighter Training
- More Listed Products
- Fire Classified Rooftop Systems
- Bonding Evaluation of PV Arrays
- More Trained Installers. Financers Drive Installation Quality Standards.
- More Informed AHJs, More Standardized Inspections and Licensing Enforcement.



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Summary of Important PV Safety C&S in U.S.

Reference	Year Published	Importance
NEC Article 690	1984	Minimum PV Safety Requirements for Persons and Property
NEC 690.5	1990	First Specific Requirement for PV DC Ground Fault Protection
NEC 690.35	2005	Allowance for Ungrounded PV Systems
CAL FIRE / IFC / NFPA 1	2008 - 2012	Specific Fire Code requirements for PV Systems
NEC 690.11	2011	Requirement for Arc-Fault Protection of PV DC Circuits
NEC 690.12	2014	Rapid Shutdown for All PV Conductors Outside of Array. Expand DC GFP to All Conductors.
Product Safety Standards Continuous Improvement	1986 -	Evolving 1741, 1703, newly developed 2703, 3703 (trackers), 4703 (PV wire), 6703 (connectors), UL 1699B (arc-fault), etc.

Safety Issues Are Being Addressed, Not Ignored.

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System Reliability Challenges

1. PV safety systems must be coordinated and tested to ensure they reliably perform their safety functions over time. How will different systems work together? How will we handle repair and replacement of different equipment over system lifetime?

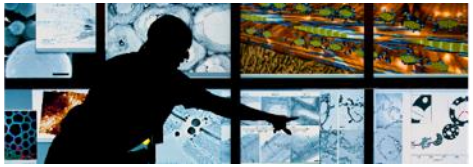
2. There is limited field experience with many significant and complex PV safety systems. Field experience is critical to assess equipment and solutions that have highest safety value at lowest negative impact on reliability. More data is needed.

3. Long-term performance and serviceability of PV safety systems must be considered. Safety systems are at risk of being bypassed or removed in the future if reliability is ignored.

Codes Have Been Updated, Time to Focus on Execution.

Thank you

PV System Performance Assessment with IEC 61724-1,2,3 and Its Use in IECRE Certification



Michael Gostein[1] and Sarah Kurtz[2]

[1]Atonometrics. [2]NREL.

With support from Tim Dierauf, John Dise, Jim Eichner, Robert Flottemesch, Janine Freeman, Tobias Gerstmaier, Tasos Golnas, Kirby Hunt, Dirk Jordan, Adrianne Kimber, Christof Koerner, Mark Liffmann, Mark McKahan-Jones, Matthew Muller, Jeff Newmiller, Lauren Ngan, Pramod Krishnani, Robert Rennie, Evan Riley, John Robinson, Ryan Smith, Ted Spooner, Itai Suez, Wuthipong Suponthana, and many others

Thursday, Feb. 25, 2016

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

What do we want to know about a PV plant?

Guarantees

- How much energy/power was produced?
- How much *should* have been produced?
- Is the system meeting expectations / guarantees?

Problems

- Is there a problem in the system? Where?
- Is the system degrading? How fast?

Technology Assessment

- How are the installed technologies performing, relative to others?

Why?

- Plant performance is worth a lot of money
- Test data needed to evaluate performance guarantees

IEC 61724 Background

- IEC 61724 released 1998
  - Covers PV system monitoring
  - Defines basic metrics e.g. Performance Ratio

- Update to 61724 underway since 2013
  - Better address included measurements and precision
  - Adapt to different system types
  - Update metrics
  - Address how monitoring data can be used, e.g. for performance guarantees
  - Implement as multi-part series

New IEC 61724 Series In Progress

61724-1 - Monitoring

- What to measure and how to measure it

61724-2 – Capacity Evaluation

- Determining power capacity (short-term)

61724-3 – Energy Evaluation

- Comparing actual to expected energy (long-term)

Parts 1, 2, & 3 likely to be published in 2016

61724-1: Monitoring

Standard Addresses:

- Which parameters should be measured?
- How?
- With what precision/accuracy?
- How many sensors?
- Ground-based or remote?
- Sensor maintenance?
- How frequently to measure?

- What metrics?

Monitoring System Classifications

Class A	Class B	Class C
High Precision	**Medium Precision**	**Basic Precision**

Typically-targeted system size:

Utility

Commercial

Residential

Specific requirements for each class

Ground-Based vs. Remote Sensing / Estimation

- For Class A, require ground-based measurements <u>with appropriate sensor maintenance</u>

- For Class B and C, allow estimation from remote measurements (e.g. satellite data, regional weather data)

Measurements – Solar Resource

Parameter	Symbol	Units	Monitoring Purpose	Required?		
				Class A High precision	Class B Med. precision	Class C Basic precision
In-plane irradiance (POA)	G_i	$W \cdot m^{-2}$	Solar resource	√	√ or E	√ or E
Global horizontal irradiance	GHI	$W \cdot m^{-2}$	Solar resource, connection to historical and satellite data	√	√ or E	
Direct normal irradiance	DNI	$W \cdot m^{-2}$	Solar resource, concentrator	√ for CPV	√ or E for CPV	
Diffuse irradiance	G_d	$W \cdot m^{-2}$		√ for CPV with < 20x concentration	√ or E for CPV with < 20x concentration	
Circumsolar ratio	CSR					

Measurements – Environmental Factors

Parameter	Symbol	Units	Monitoring Purpose	Required?		
				Class A High precision	Class B Med. precision	Class C Basic precision
PV module temperature	T_{mod}	°C	Determining temperature-related losses	√	√ or E	
Ambient air temperature	T_{amb}	°C	Connection to historical data, plus estimation of PV temperatures	√	√ or E	√ or E
Wind speed	W_S	$m \cdot s^{-1}$	Estimation of PV temperatures	√	√ or E	
Wind direction	W_q	degrees		√	√ or E	
Soiling ratio	SR		Determining soiling-related losses	√ if soiling losses expected to be >2 %		
Rainfall		cm	Estimation of soiling losses	√	√ or E	
Snow			Estimation of snow-related losses			
Humidity			Estimation of spectral variations			

Measurements – Electrical Output

Parameter	Symbol	Units	Monitoring Purpose	Required?		
				Class A High precision	Class B Med. precision	Class C Basic precision
PV array voltage (DC)	V_A	V	Energy output, diagnostics and fault localization	√		
PV array current (DC)	I_A	A		√		
PV array power (DC)	P_A	kW		√		
Output voltage (AC)	V_{out}	V	Energy output	√	√	
Output current (AC)	I_{out}	A		√	√	
Output power (AC)	P_{out}	kW		√	√	√
Output energy	E_{out}	kWh		√	√	√

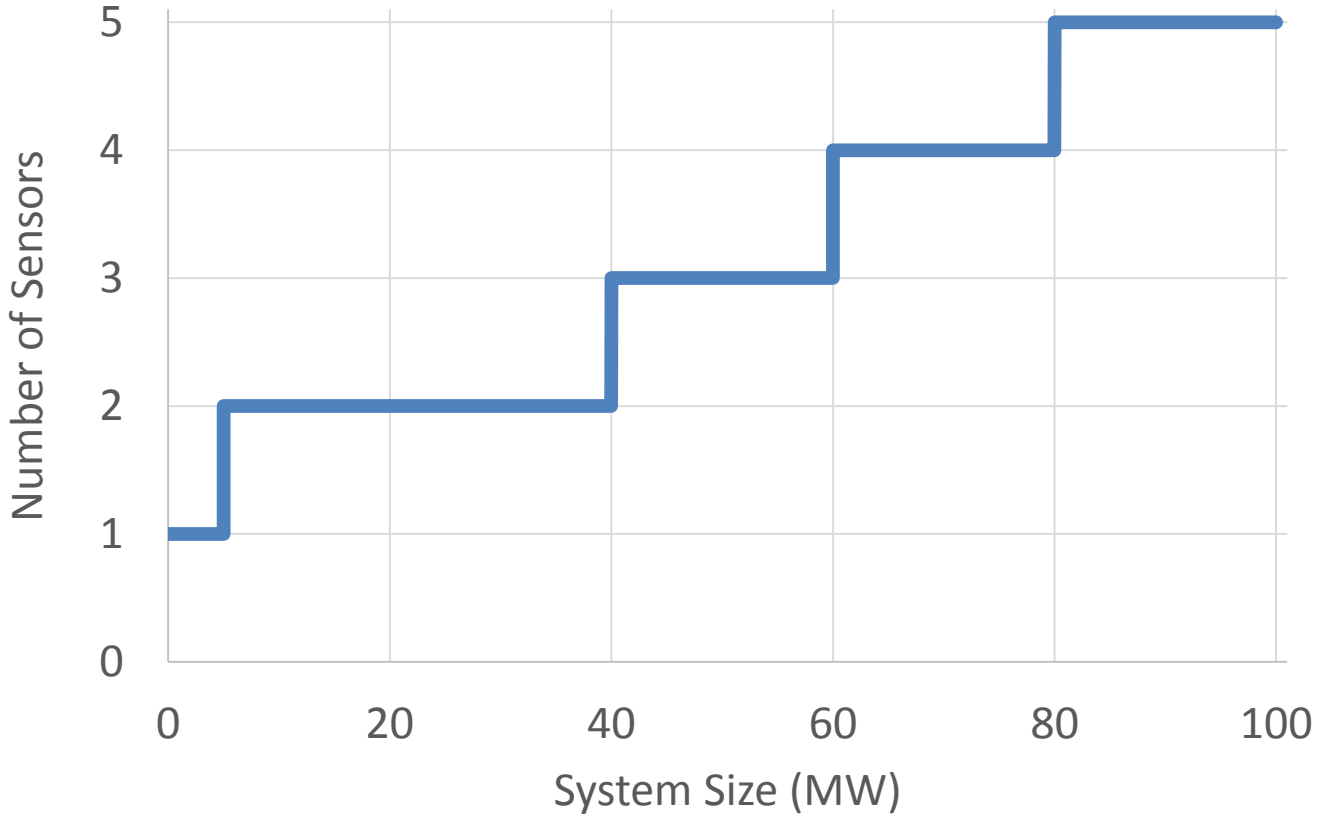
Sensor Requirements for Each Class

- Sensor type
- Required precision
- Sensor mounting
- Sensor maintenance & calibration

Number of Sensors

Typical Requirement:

1 per 20 MW; minimum of 2 if ≥ 5 MW



Performance Ratio – Traditional

- Traditional performance ratio depends on PV temperature
- Shows seasonal variation
- Complicates use for system assessments

$$PR = \left(\sum_k P_{\mathrm{out},k} \times \tau_{\mathrm{k}} \right) \Bigg/ \left(\sum_k \frac{P_0 \times G_{\mathrm{i,\,k}} \times \tau_{\mathrm{k}}}{G_{\mathrm{i,ref}}} \right)$$

Performance Ratio – Temperature-Corrected

- Introduce temperature-corrected performance ratios to reduce seasonal dependence

$$PR'_{\text{annual-eq}} = \left(\sum_k P_{\text{out,k}} \times \tau_{\text{k}} \right) \Bigg/ \left(\sum_k \frac{(C_k \times P_0) \times G_{\text{i, k}} \times \tau_{\text{k}}}{G_{\text{i,ref}}} \right)$$

$$C_{\text{k}} = 1 + \gamma \times (T_{\text{mod,k}} - T_{\text{mod,avg}})$$

61724-2: Capacity Evaluation
61724-3: Energy Evaluation

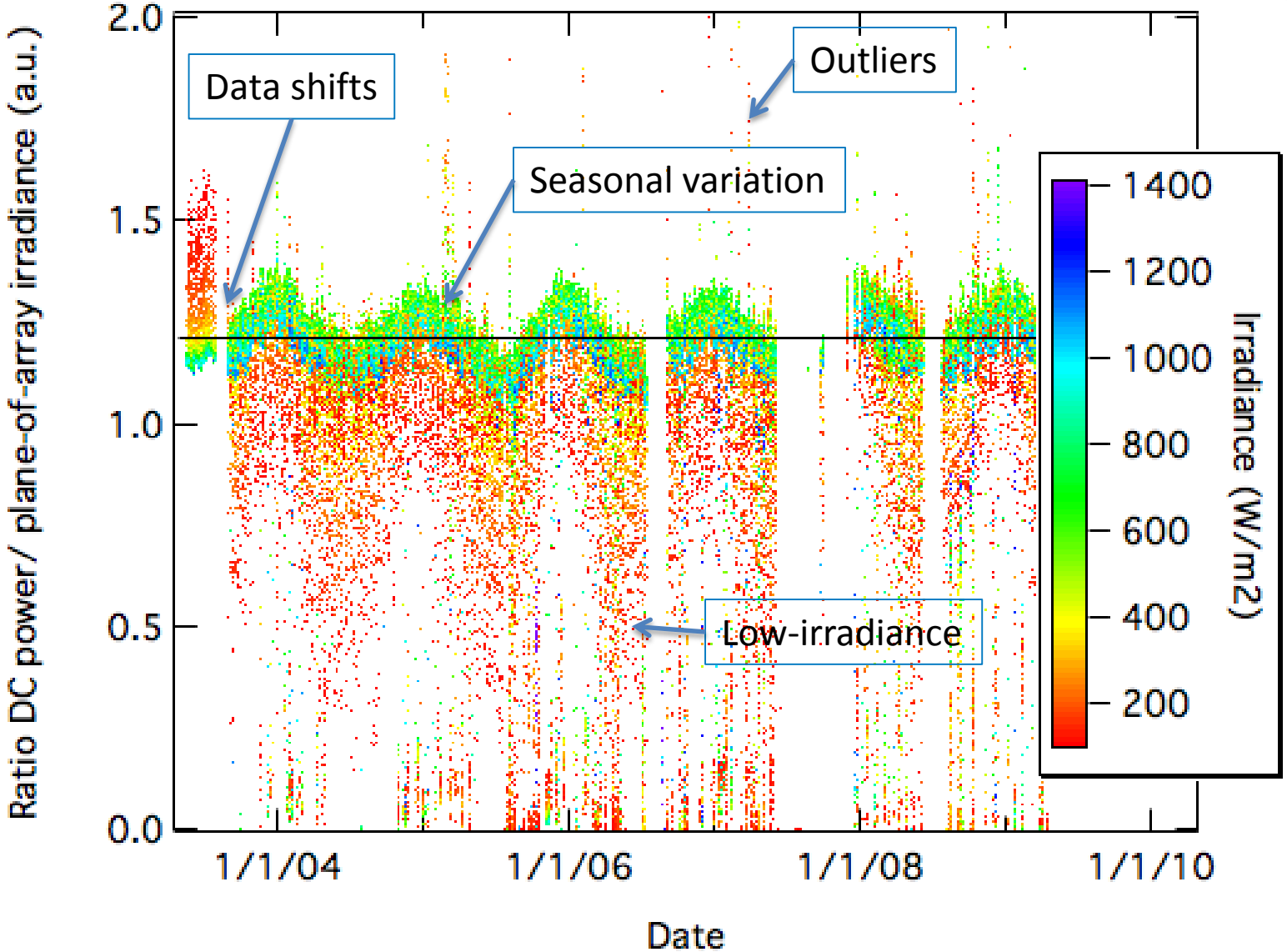
Outline

- Millions of dollars can ride on result of tests
  - Capacity (power) test (short-term test)
  - Energy test (one-year test)
- Challenges:
  - Imperfect data
  - *Historical and measured weather data formats may differ*
    - Defining terms: *Predicted vs Expected*
  - *System Boundary vs Test Boundary*
- Status of IEC 61724-2 (Capacity test) and IEC 61724-3 (Energy test)
- Implementation in IECRE plant certificate

IEC 61724-2 (Capacity test) and -3 (Energy test):

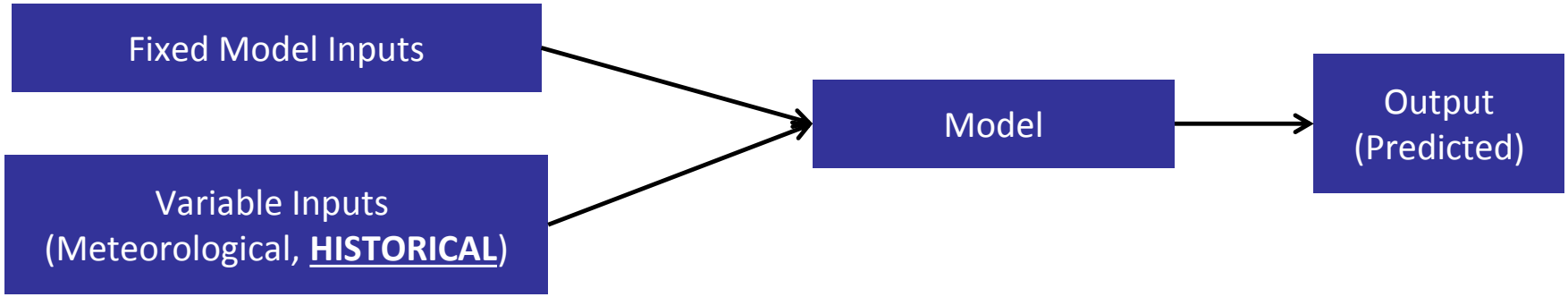
- Capacity Test Purpose: Short-term test to determine the performance of PV system under stable, full-sun conditions
  - Based on non-regression approach published by Tim Dierauf
  - Performance guarantee defines performance under chosen conditions (that will not result in clipping)
  - Measured data are adjusted to reference conditions and then compared to the performance guarantee
- Energy Test Purpose: Long-term (annual?) test to determine the performance of PV system under full range of conditions
  - Based on user-chosen model for energy
  - Aligns test boundary with system boundary
  - Requires model to be applied consistently for the prediction made before the test and for the data collected during the test

Challenges: Imperfect data; Efficiency changes

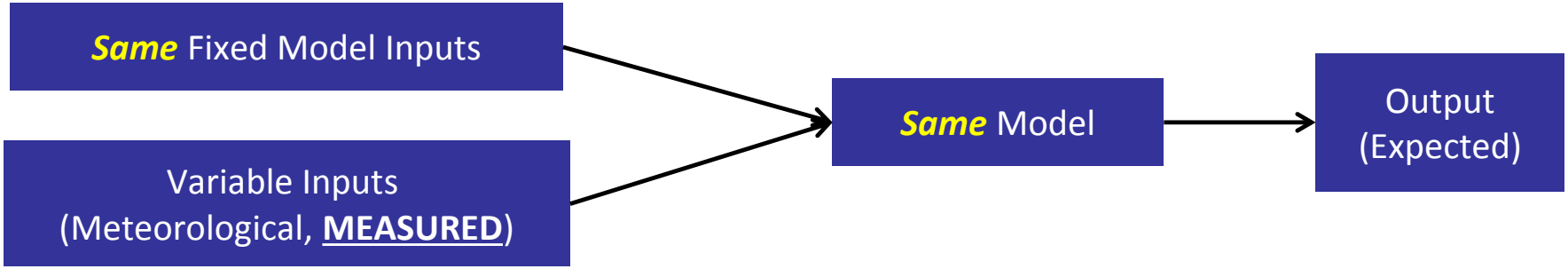


Model with Historical or Measured Data

Setting the ***Predicted*** Value



Generating the ***Expected*** Value



Generating the ***Measured*** Value

Output of Plant (Measured)

Comparison of typical weather data sets

Historical weather

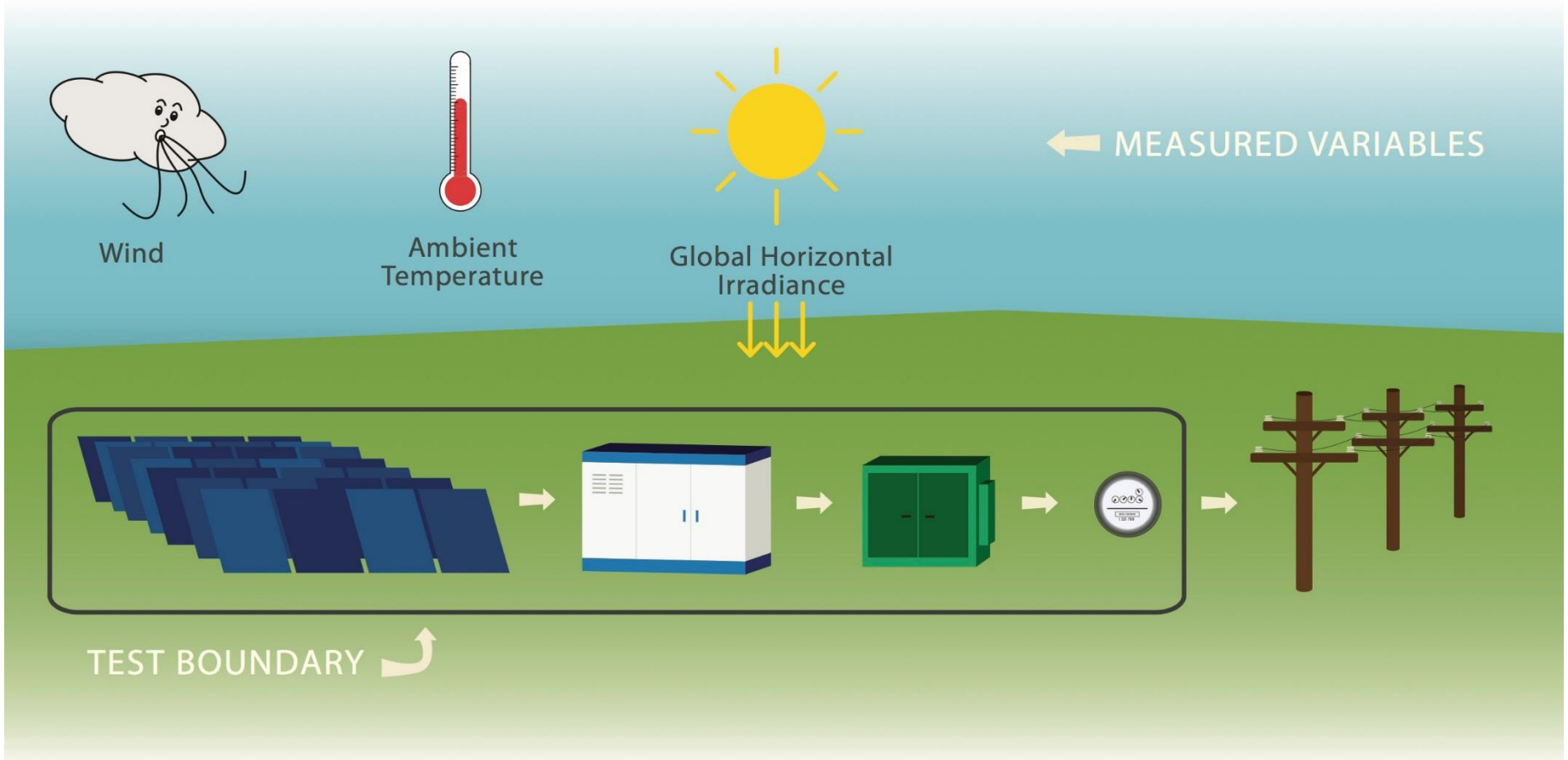
- Derived from satellite data
- Hourly
- Horizontal irradiance

Measured weather

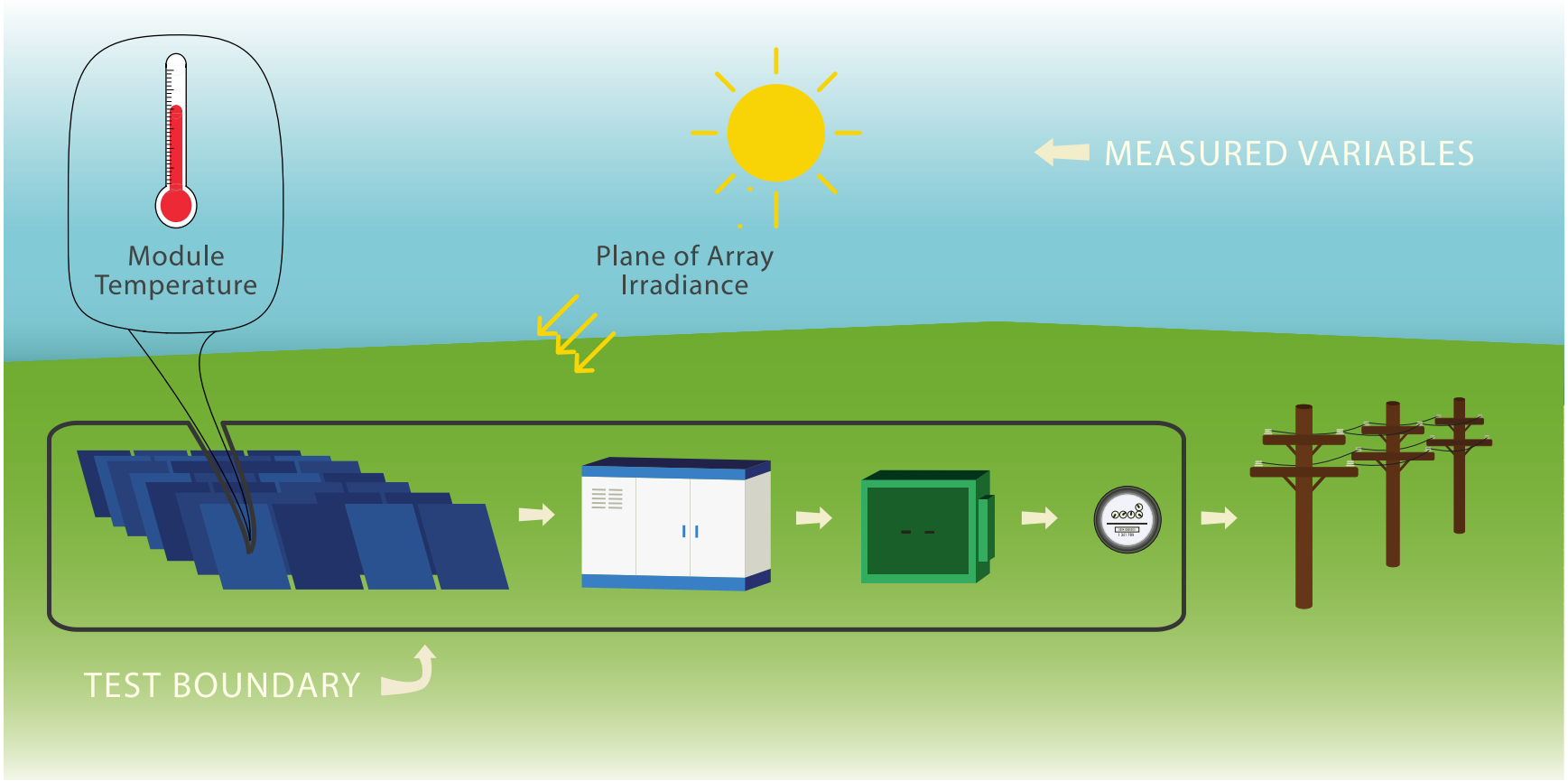
- Ground sensor
- Variable frequency, aggregated to hourly
- Global horizontal or plane of array irradiance?

Differences in data sets complicate application of consistent model

System boundary aligns with test boundary



What if system boundary doesn't align with test boundary?



If measure module temperature, the system boundary ≠ test boundary: improper module installation may appear to be hot weather

IECRE

IECRE Implementation

1. Results from tests to be captured in standardized database
2. IEC 61724-2 helps determine Substantial Completion
3. IEC 61724-3 applied after one year of data collection in the field
4. IEC 61724-3 may be applied every year to track electrical output over the life of the system
5. Publication of IECRE documents and implementation scheduled for 2016

Accelerated Reliability Evaluation of Module Level Power Electronics (MLPE)

Part 2: Standardized Protocols

GovindaSamy TamizhMani (Mani)[1] Jack Flicker[2]

[1]Arizona State University & TUV Rheinland PTL

[2]Sandia National Laboratories

Motivation

- No consensus based qualification or reliability test standard/protocol exists
  - Identify the required accelerated tests based on an industrywide survey using RPN (risk priority number) approach for each failure
    - Survey results were presented at the IEEE PVSC 2015 conference
  - Experimentally determine the time/cycle-to-failure (TTF) for each accelerated reliability test
    - Test results were presented at this workshop (PVMRW 2016) on Wednesday; referred as PART 1
- Based the reliability test results (TTF), develop two protocols
  1. Qualification test protocol
  2. Reliability test protocol

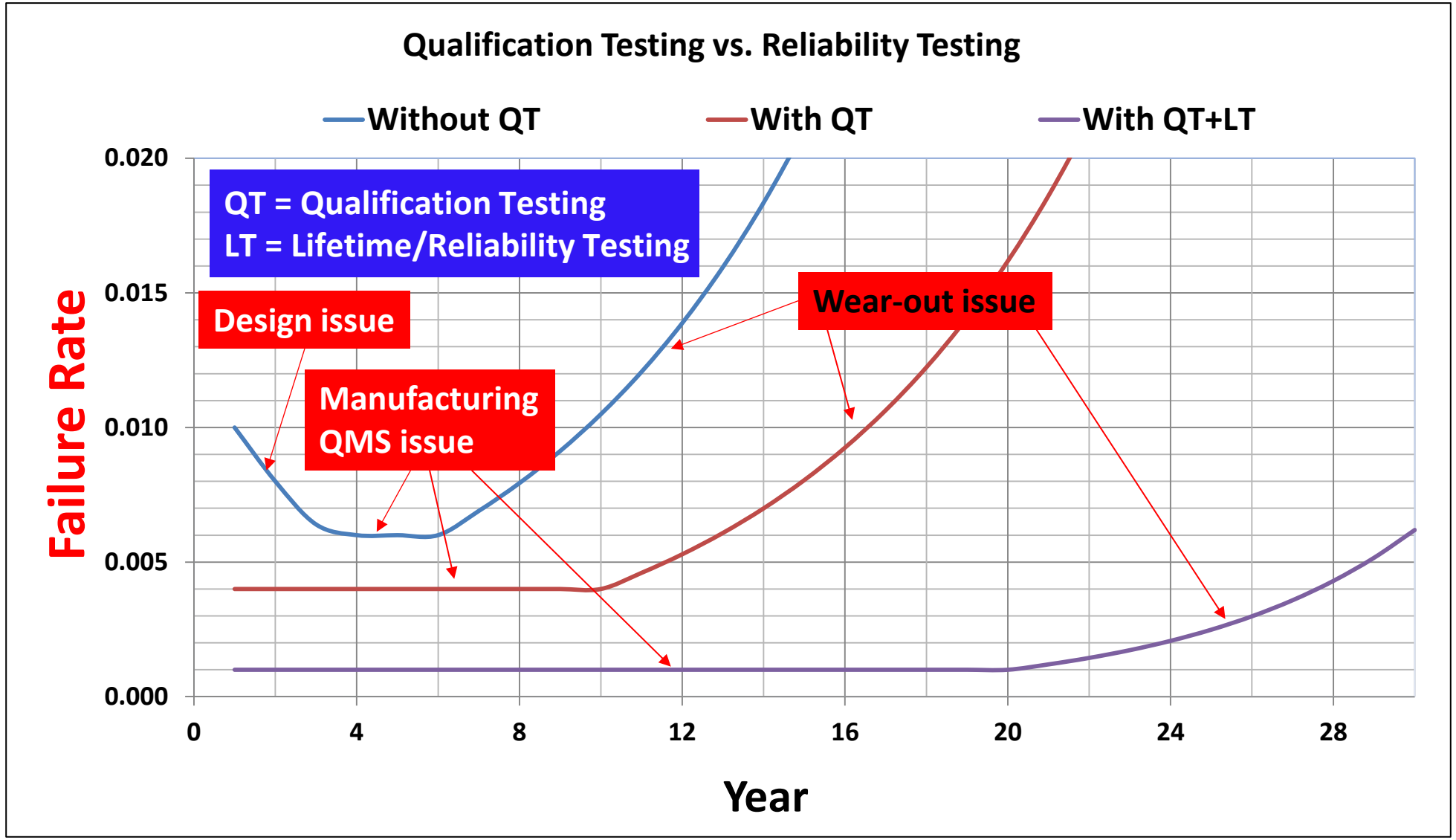
This presentation focuses on the development of the qualification test and reliability test standards/protocols

Qualification test standard vs. Reliability test standard

- Qualification test standard/protocol
  - Meant to determine the near-term catastrophic issues
    - ➢ Design issues
    - ➢ Not intended to identify the manufacturing issues (e.g. see IEC 62941 for PV module manufacturing QMS)
  - Minimum bar to enter marketplace
  - Shorter time
  - Lower cost
  - Pass/fail test (define failure)
  - Not necessarily correlated to failure modes/mechanisms

- Reliability test standard/protocol
  - Meant to determine the lifetime issues
    - ➢ Wear-out issues
    - ➢ Not intended to identify the manufacturing issues (e.g. see IEC 62941 for PV module manufacturing QMS)
  - Minimize warranty returns
  - Longer time
  - Higher cost
  - Test-to-failure (define failure)
  - Correlated to failure modes/mechanisms

Qualification testing vs. Reliability testing



Qualification tests shall be designed to eliminate the near-term catastrophic design issues

Open questions / Trade-offs

- Applicable across industry?
  - Different designs
  - Different algorithms
  - Materials
- How to account for different unit behaviors in different stress conditions?
  - *e.g.* derating at different temperatures, air flow rate, thermocouple location on UUT, ambient temperature vs. UUT temperature

- What constitutes **failure**?
  - Device degradation
  - Visual appearance
  - Wet resistance
  - Restarts/drop-outs (degradation in energy harvest)
  - Communications vs. Power failure

- **Cost** vs. **Scientific rigor**
  - Powered vs. unpowered
  - PV simulator vs. DC power supply
  - Sample size vs. statistics

Qualification and Reliability Tests: Stress Limits and Test Duration

Goal: Determine time limits (or number of cycles) for qualification tests based on the time/cycle to failure (TTF) table generated from the reliability test program

Time/Cycle to Failure (TTF) Table Generated from the Reliability Test Program of Sandia-ASU-TUV

Device	Thermal Cycling (cycles)	Damp Heat (hours)	Static T 85°C (hours)	Static T 100°C (hours)	Static T 125°C (hours)
Stressor (purpose)	Cyclic temperature (e.g. cyclic fatigue)	Static temperature and humidity (e.g. corrosion)	Static temperature (e.g. static fatigue)	Static temperature (e.g. electrolyte loss in capacitor)	Static temperature (e.g. activation energy determination)
M1A	835	5380	>1193	3491	
M1B	835	5380	>1193	3491	
M2A	835	5380	>1193	3491	
M2B	835	4369	>1193		
M3A	710	1240	>1193		
M3B	835	1550	>1193		
M4A	835	5380			
M4B	835	4369			
M5A	835	5380			
M5B	835				
Powered/Unpowered (measure efficiency at 50°C periodically or at the test end)	Powered (connector fail at IEC61				ered (thermal derating and cable/connector failure permitted)
TTF Medi				3491	2303
Relia			5380	3491	2303
		5400/2 = 2700	5400/2 = 2700	3500/2 = 1750	Only for reliability program; not required for qual. program
(days)	60	113	113	73	Not applicable
ation andard Level (months)	2	4	4	2	Not applicable
Sample size [2 (IEC61215); 5 (Qual+); 8-10 (draft IEC62093)]	10?	10?	10?	10?	10?
Failure (efficiency drop > 5% , visual, wet resistance)	2 failures allowed for retest?	2 failures allowed for retest?	2 failures allowed for retest?	2 failures allowed for retest?	Not applicable
Or can we simply follow IEC 61215 for TC and DH tests?	200 cycles	1000 hours	1000 hours?	350 hours? (3x lower as that of 85°C)	Not applicable
Additional qualification tests: TC50+HF10+UV sequence (IEC61215); Salt mist (IEC61701); Shock & vibration (IPC9592)					
Failed	Passed	Ongoing			

Stress and time limits for the qualification tests shall be objectively developed based on a vendor-neutral reliability test program similar to the one shown on the next two slides.

This proposed/potential test program needs to be discussed in SDO committee meetings for consensus!

Qualification and Reliability Tests: Stress Limits and Test Duration

Goal: Determine time limits (or number of cycles) for qualification tests based on the time/cycle to failure (TTF) table generated from the reliability test program

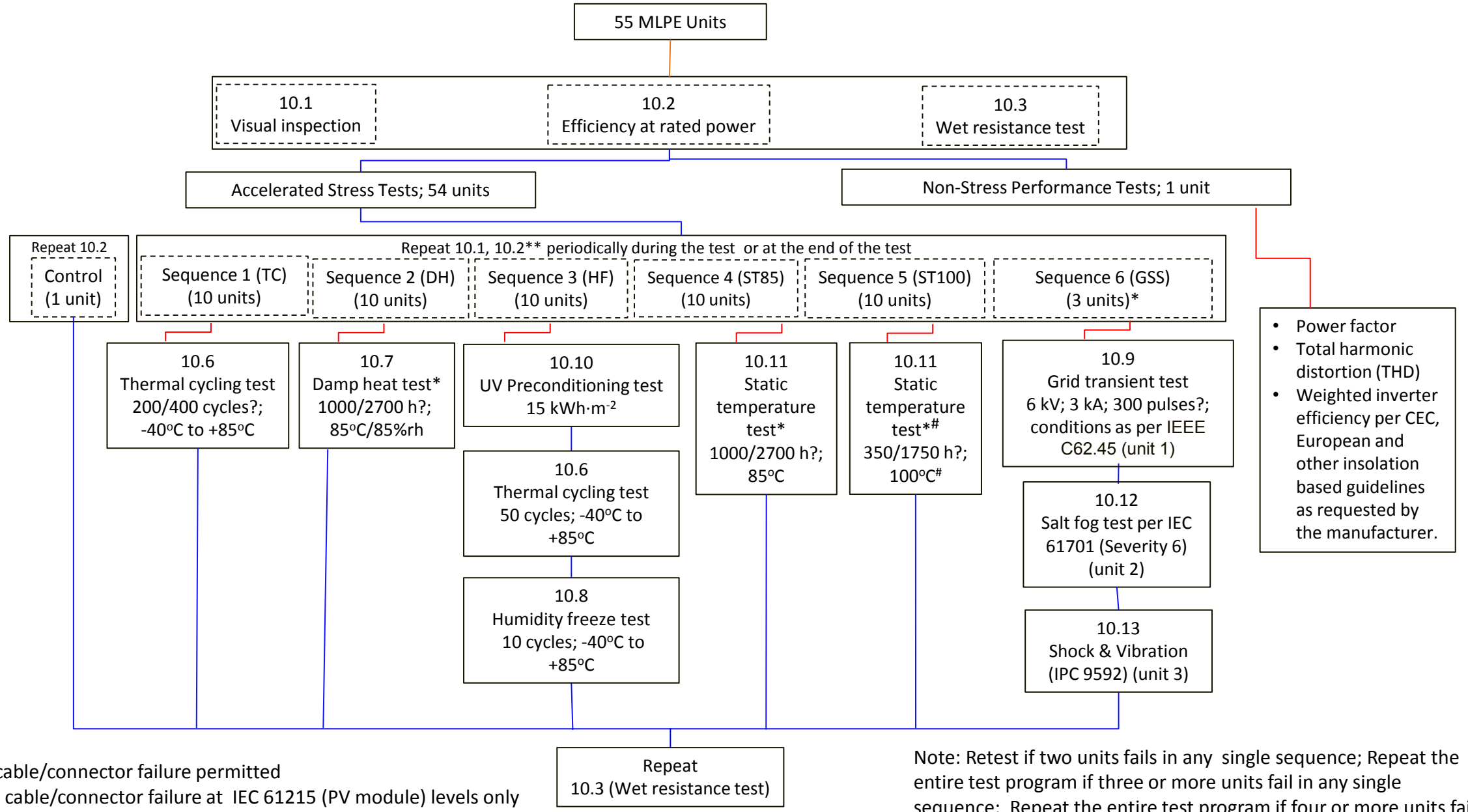
Time/Cycle to Failure (TTF) Table Generated from the Reliability Test Program of Sandia-ASU-TUV

Device	Thermal Cycling (cycles)	Damp Heat (hours)	Static T 85°C (hours)	Static T 100°C (hours)	Static T 125°C (hours)
Stressor (purpose)	Cyclic temperature (e.g. cyclic fatigue)	Static temperature and humidity (e.g. corrosion)	Static temperature (e.g. static fatigue)	Static temperature (e.g. electrolyte loss in capacitor)	Static temperature (e.g. activation energy determination)
M1A	835	5380	>1193	3491	1870
M1B	835	5380	>1193	3491	2135
M2A	835	5380	>1193	3491	3166
M2B	835	4369	>1193	3491	2638
M3A	710	1240	>1193	>528	>528
M3B	835	1550	>1193	>528	>528
M4A	835	5380	>1193	1435	1870
M4B	835	4369	>1193	3491	791
M5A	835	5380	>1193	152	3469
M5B	835	5380	>1193	3491	2471
Powered/Unpowered (measure efficiency at 50°C periodically or at the test end)	Powered (connector failure at IEC61215 level)	Powered (connector failure at IEC61215 level)	Powered (connector failure at IEC61215 level for DH)	Powered (thermal derating and cable/connector failure permitted)	Powered (thermal derating and cable/connector failure permitted)
TTF Median	835	5380	Test Ongoing (>5380?)	3491	2303
Reliability Standard Minimum Level (cylces or hours)	835	5380	5380	3491	2303
Qualification Standard Level (cylces or hours)	800/2 = 400	5400/2 = 2700	5400/2 = 2700	3500/2 = 1750	Only for reliability program; not required for qual. program
Qualification Standard Level (days)	60	113	113	73	Not applicable
Qualification Standard Level (months)	2	4	4	2	Not applicable
Sample size [2 (IEC61215); 5 (Qual+); 8-10 (draft IEC62093)]	10?	10?	10?	10?	10?
Failure (efficiency drop > 5% , visual, wet resistance)	2 failures allowed for retest?	2 failures allowed for retest?	2 failures allowed for retest?	2 failures allowed for retest?	Not applicable
Or can we simply follow IEC 61215 for TC and DH tests?	200 cycles	1000 hours	1000 hours?	350 hours? (3x lower as that of 85°C)	Not applicable

Additional qualification tests: TC50+HF10+UV sequence (IEC61215); Salt mist (IEC61701); Shock & vibration (IPC9592)

Failed	Passed	Ongoing

Potential approach for the MLPE qualification standard development



* cable/connector failure permitted
** cable/connector failure at IEC 61215 (PV module) levels only
\# Thermal derating permitted

Note: Retest if two units fails in any single sequence; Repeat the entire test program if three or more units fail in any single sequence; Repeat the entire test program if four or more units fail in the test program

Summary

- Based on the reliability test results (TTF) obtained in the PREDICTS project, a potential approach for the development of qualification standard and reliability standard has been developed and proposed.
- The proposed approach needs to be discussed in standard development committee meetings to develop a consensus-based standard for the industry.

Funding support from DOE/SunShot/PREDICTS is sincerely acknowledged.

Questions?

Sandia National Laboratories

Arizona State University

TUV Rheinland PTL

Tigo

DESIGN FOR RELIABILITY

Company Mission

Tigo’s mission is to deliver your smart PV technology needs, designed to yield maximum energy harvest at minimal cost, guaranteeing customers their greatest ROI.

Technology Overview

Tigo's Heritage: Leader in Optimization Technology

GEN I

Energy Maximizer System

External Optimizer

(2008 - Late 2012)

GEN II

Energy Maximizer System

Integrated Optimizer

(Late 2012 – Late 2015)

GEN III

"TS4" Platform

Modular Optimizer

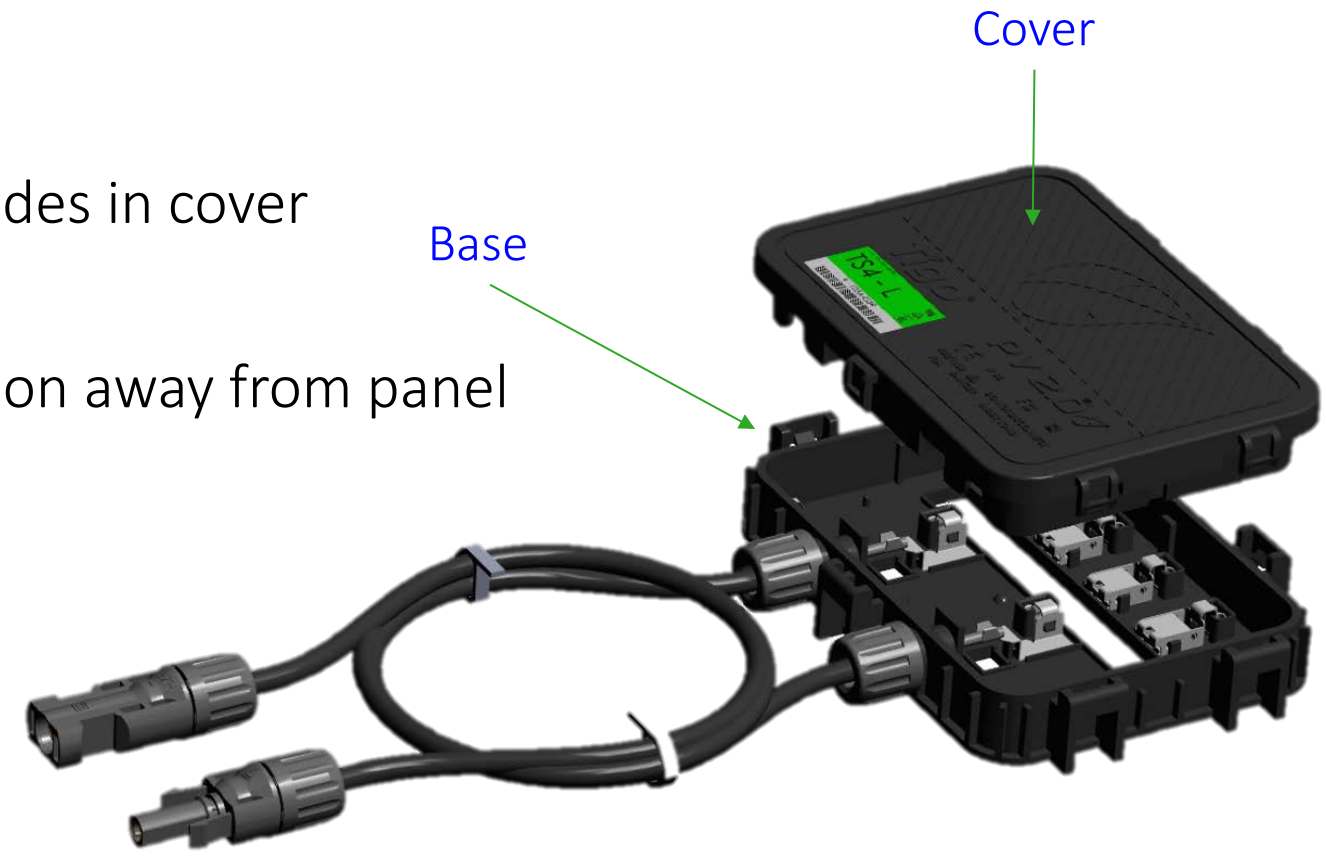
(Late 2015)

- Universal Modular Platform
- Applicable for EVERY PV module and inverter
- Cloud Connect: open communication platform
- Integration into 3rd party inverters (Late 2014)

- Over 1.1 million units sold, with installations at over 17,000 sites worldwide . Ranging from 2kw to 8mw installations.
- Systems operating in Antarctica, Australia, China, Japan, Americas, Europe, Middle East
- Deployments in residential, commercial and utility scale systems
- Over 100 Terabytes of data collected

TS4: Universal Modular Platform for EVERY PV Module

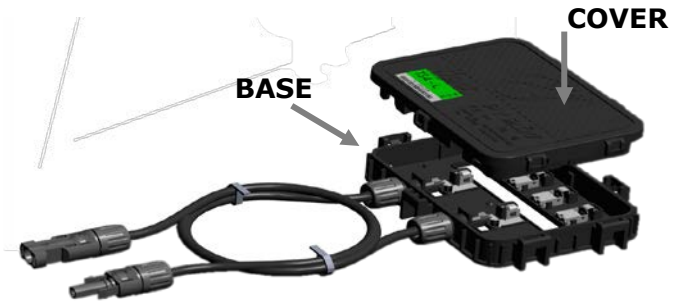
- Designed to easily facilitate any PV Module functionality
- Electronics in cover
  - Simple plug and play
  - All needed functions – even Diodes in cover
  - Easy to Upgrade
  - Highest reliability: heat dissipation away from panel



As simple as a USB or a Power Plug

Tigo TS4 Platform

TS4 OVERVIEW



As simple as a USB or Power Plug

- Designed to work with any PV Module
- Electronics in cover
  - Easy to upgrade
  - Highest reliability: heat dissipation away from panel
  - Selective functionality
- Cost competitive

TS4 MODULES

Diodes TS4-D | **Monitoring TS4-M** | **Safety - RSS TS4-S** | **Optimization TS4-O** | **Long Strings TS4-L**

- Start with a TS4 "dumb" PV Module ("diodes" only), convert any to a Smart Module as needed
- Convert to a **Monitoring, Safety (RSS), Optimized, or Long String** at any point
- Unique plug-n-play modularity supporting flexible solutions
  - Pay only for your needs, with the change of the cover
- Replace diode not module – no rewiring, no need to adjust the physical position in the array, etc.

Select Functionality: Diodes

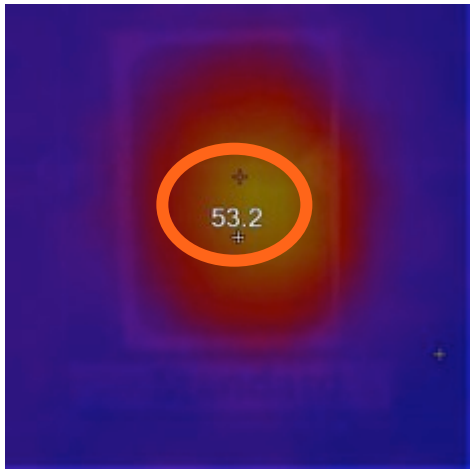
DIODES | MONITORING | SAFETY | OPTIMIZATION | LONG STRING

- **Module: TS4-D**

- **Benefits**
  - √ **Field replaceable**
    - Example: Bad 50¢ diode → Replace cover vs entire module
  - √ **Reliability**
    - Best performance
    - Heat dissipation away from the module
    - 5°C less with TS4-D after 1 hour of bypassing

TS4

Standard Jbox



- **More reliable than a standard JBox**

Select Functionality: Monitoring

DIODES | **MONITORING** | SAFETY | OPTIMIZATION | LONG STRING

- **Module: TS4-M**

- **Benefits**
  - √ **Module level monitoring**
    - Capable of measuring at 2 second increments
  - √ **Enhanced operation & management**
  - √ **PV-2.0 data synchronization**
  - √ **Module barcode tracking**
  - √ **Fleet management**
  - √ **CRM Integration**
  - √ **Warranty tracking**

Select Functionality: Safety

DIODES → MONITORING → SAFETY → OPTIMIZATION → LONG STRING

- **Module: TS4-S**

- **Benefits**
  - √ **NEC 690.12 rapid shutdown compliant**
  - √ **Module-level deactivation**
  - √ **Automatic or manual shutdown**
  - √ **Over-voltage protection**
  - √ **Remote shutdown for revenue protection**
  - √ **Includes all benefits of monitoring / diode**

Select Functionality: Optimization

DIODES → MONITORING → SAFETY → OPTIMIZATION → LONG STRING

- **Module: TS4-0**

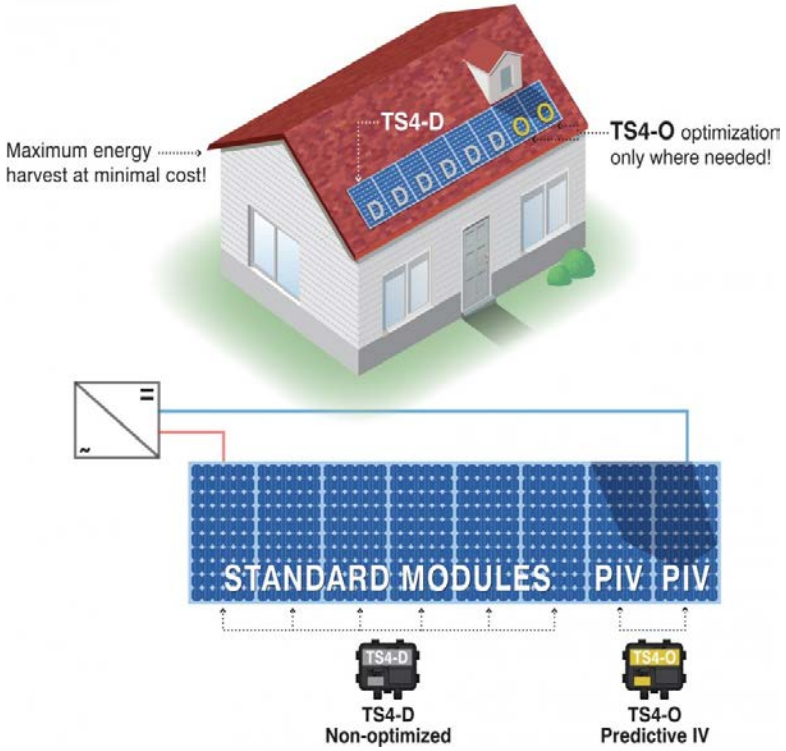
- **Predictive IV Technology (PIV)**
  - State-of-the-art technology with no central communication required
  - Tracking algorithm utilizes module's unique parameters and advance analytics, incorporates MPPT, impedance matching techniques, historical module and system behavior statistics

- **Benefits**

  √ **Advanced energy harvesting**
  - PIV *predicts* the most optimum settings allowing each PV Module to generate the maximum energy

  √ **Shade and age tolerance**
  - Can mix old and new modules
  - Maximize roof usage

  √ **Includes all benefits of safety / monitoring /diode**



Select Functionality: Optimization with Selective Deployment

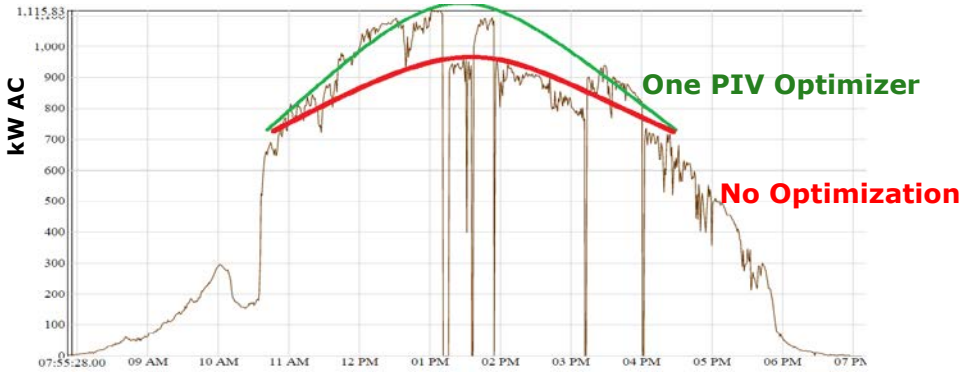
DIODES → MONITORING → SAFETY → OPTIMIZATION → LONG STRING

- **Module: TS4-0**

- **Selective Deployment**
  - Selectively deploy optimizers according to specific needs
  - A single optimizer selectively placed on shaded module, recovered 18.5% energy relative to without optimization
  - The PIV based optimizer used in case study demonstrated communication-less operation
  - Applicable to *ANY* module on a single string

EXAMPLE: ONLY 3 MODULES SHADED

PROJECTED POWER CURVE LOSS



Select Functionality: Long String

DIODES → MONITORING → SAFETY → OPTIMIZATION → LONG STRING

- **Module: TS4-L**
  - Reducing the voltage of each panel, to enable more modules per string
  - Increase string length by up to 30% relative to without optimization
  - Enables more panels per inverter - More KwH per $ invested

- **Benefits**
  - √ **Lower costs due to less components**
  - √ **Faster Installation**
  - √ **Greater design flexibility**
  - √ **Lower wire-losses**
  - √ **Advanced energy harvesting**
  - √ **Includes all benefits of optimization and safety**

Product Reliability

Reliability: by design

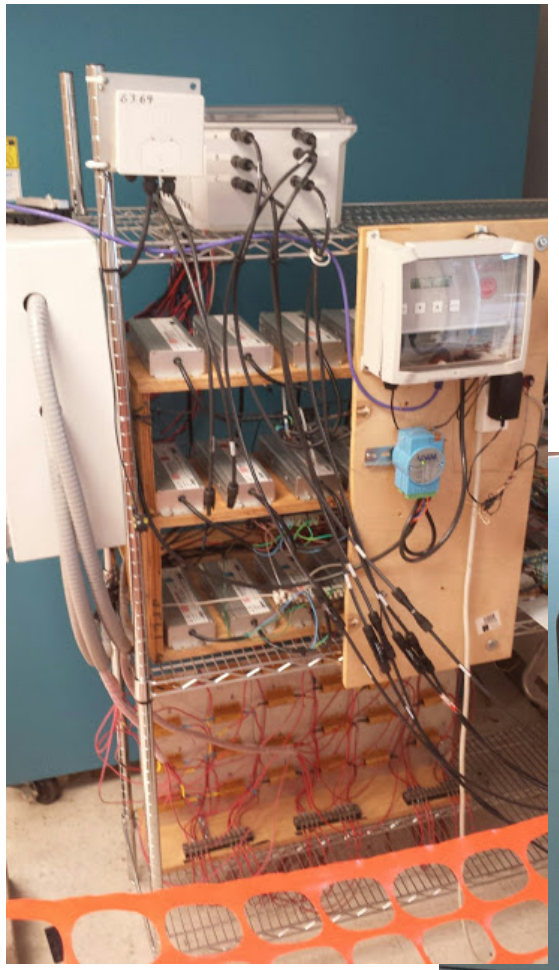
- Operating in low temperature
- Low count component
- Component selection
- Minimize switching
- Minimize component stress
- Mechanical protection

Reliability: by design

- Low voltage design (< 60v)
- High reliability components (ceramic capacitors only, no relays, no aluminum capacitors, no optocouplers, low RdsON MOSFETs)
- Extra copper PCB for better heat transfer
- Potted units – both for conducting heat and environmental protection
- Every component is used up to 50%-60% of the absolute maximum rating
- Operating most of the time on high efficiency mode, 99.6% efficiency, no heat build up
- Prevent from bypass diodes to conduct
- Low component count including ASIC integration
- Pre-loading preventing the module switching in low light condition, like morning and evening

Reliability: by internal cycling

- We run our test in the labs by simulating night and day, during the day the module produce maximum power and during the night they shutdown.
- This is done to eliminate the baking affect during non-operational hours and to simulate morning/evening turn on
- Chamber runs -40c to 85c cycles.



Reliability: by external cycling

- We constantly run reliability tests with outside credited laboratories.
- Certified by UL1741, UL1703 and TUV standards
- Verified by more than 10 biggest PV module manufactures reliability acceptance test programs

© RAMPF Polymer Solutions GmbH & Co. KG

Laboratory-Testreport
Research & Development

RAMPF
discover the future

Summary and conclusion
After 3000 hours at 85°C and 85% of HR , we have not seen any negative evolution on the cured sample We have just observed a small decrease of the shore hardness due to this extremely severe test. But product is still not liquid. And we consider that it will not become liquid in the following weeks/months. If during your test , our 21 2350 is become liquid , as announced since the beginning , it is for sure due to a bad or a wrong mixing ratio. A bad or a wrong mixing ratio has per consequence that you will not get the right final polymer. If you don't get the right polymer defined, don't expect to have a product with high resistance to temperature and humidity. The parts on test are closed , it means that we cannot see anything . But no resin has flowed outside the part. But we can also observe on the cables , that this test is extremely severe!!

Our recommendations on the use of the material are based on many years of experience and current scientific and practical knowledge. They are, however, provided without any obligation on our part and do not relieve the buyer of the need for suitability tests. They do not constitute a legal relationship, nor are any protected third party rights whatsoever affected thereby.

Reliability: by simulation

- By using best in class application Reliasoft The empiric results are being backed-up and reassured

Name: TS4-Circuit

Failure Rate(t) (FIT): 113.204 ~2420 yrs

Category: MIL-HDBK-217F

User Name: Bijay Shrestha

Name	Part Number	Category	Reference Designator	Supplier	Failure Rate(t) (FIT)	MTBF (hrs)	Contribution	Quantity
Logic circuit		Block			70.396	1.42E+05	0.6219	1
Q15,Q14		Transistor, HF Si FET			12.102	8.26E+05	0.1719	2
C35		Capacitor			6.857	1.46E+06	0.0974	1
C42		Capacitor			6.857	1.46E+06	0.0974	1
C22		Capacitor			6.857	1.46E+06	0.0974	1
C30		Capacitor			6.857	1.46E+06	0.0974	1
C26		Capacitor			6.857	1.46E+06	0.0974	1
T2		Transformer			4.367	2.29E+06	0.062	1
Q12		Transistor, HF Si FET			4.047	2.47E+06	0.0575	1
D13		Diode, Low Frequency			1.943	5.15E+06	0.0276	1

Report generated by Lambda Predict 9 - www.ReliaSoft.com

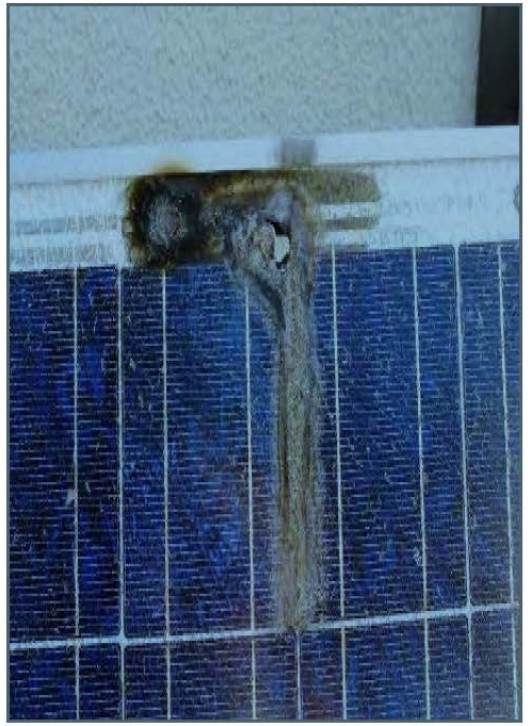
System Reliability

Diode failure modes

- If a bypass diode fails short, between 1/3 -3/3 of the PV module production is lost

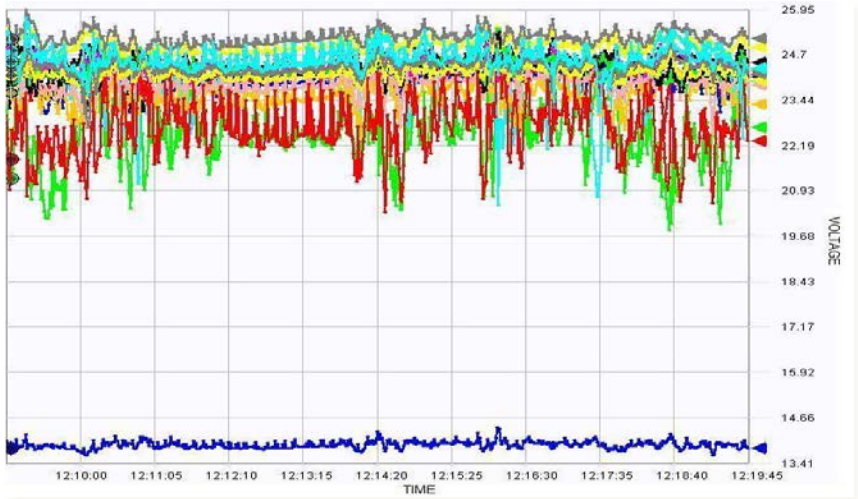
- If a bypass diode fails open, and the module is shaded, damage due to hot spots can accrue.

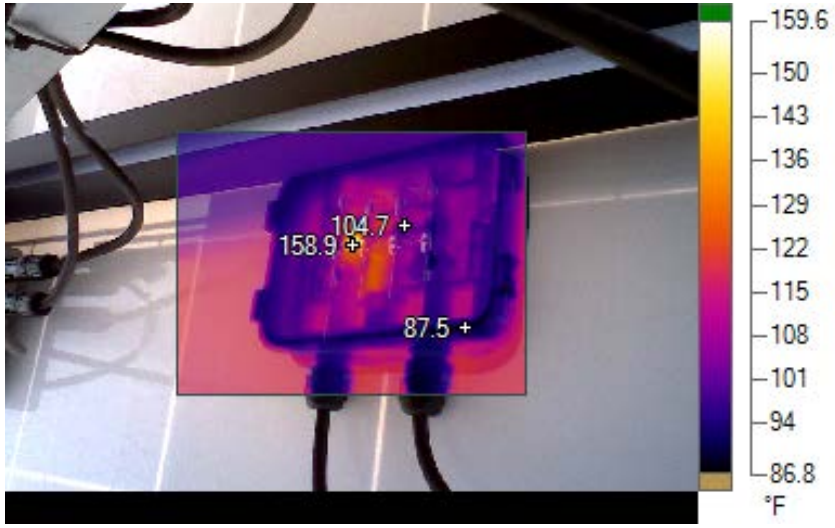
Cell damage due to hot spot



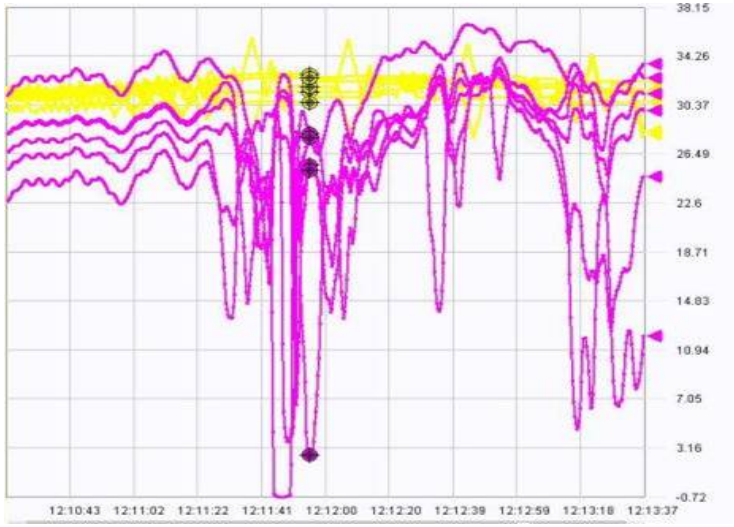
Hot spots destroy the panel

Finding Diode Failures





Conclusion: Improving System Reliability with MLPE



- Eliminate thermal stress of diodes
- Prevent activation of diodes during cloud events or other shading conditions
- Prevent mismatch from creating “hot” modules
- Detect errors at commissioning
- Streamline preventative maintenance
- Diagnose failures immediately

THANK YOU

Ten K SOLAR
Simply More Energy

Assessment of a Redundant Low Voltage Parallel PV System

Tim Johnson

Worldwide Installations

Sites in the USA

Bloomington, MN (HQ)
Shanghai, China

Outside the USA

- Canada
- Ireland
- Italy
- Romania
- United Kingdom
- Germany
- Netherlands
- Switzerland
- El Salvador
- South Africa
- Nigeria
- Kenya
- Ghana
- China
- Japan
- South Korea

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Points to Share

- How topology of solar PV materials employed affects system reliability
- Does it meet a customer need?
- What are the application strengths of that PV topology.

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Why reliability is so important in solar?

- Long expected lifetimes (25-30 years typical)
- Large upfront costs

- "Bankability"
  - You have a lot riding on the decision when choosing solar equipment..
  - Don't want to make a poor decision!

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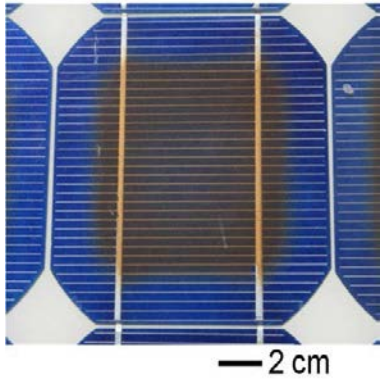
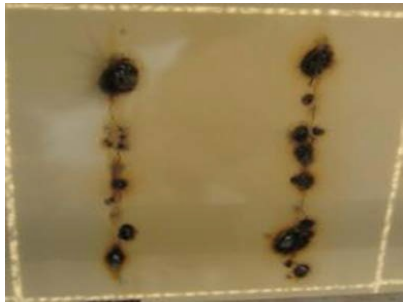
Simply More Energy

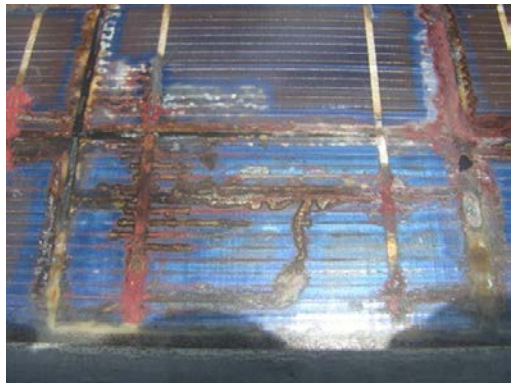
It’s different….and it works!

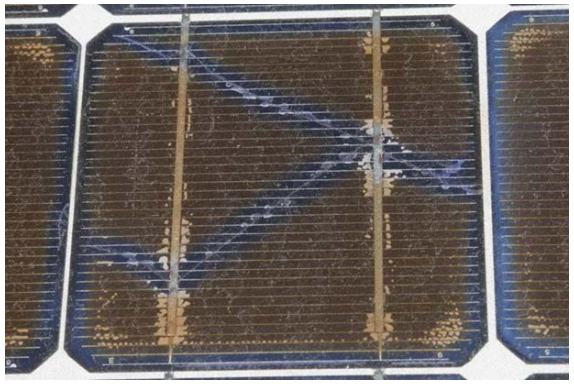
NREL Study: Observations of Typical PV Module Failure Modes

- Discoloration with loss of optical transmission
- Failure of interconnect ribbons and solder bonds
- Broken or cracked cells
- Corrosion of cell metallization often accompanied by delamination of the encapsulant
- Catastrophic failure including broken glass
- Potential Induced Degradation (no photo)





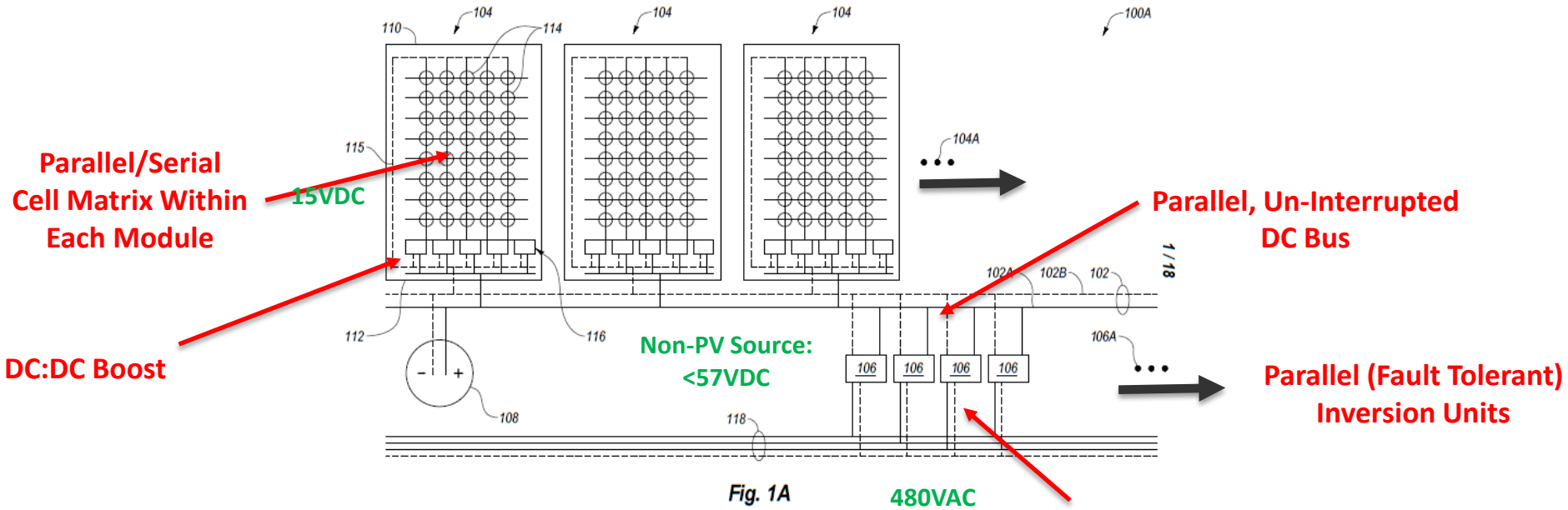




**** Use of Field Observations to Assess PV Module Reliability***
J. Wohlgemuth 2009, 2015

The tenK Topology

- Utilize modular, low cost components to create an easy to install, highly reliable, zero maintenance PV system

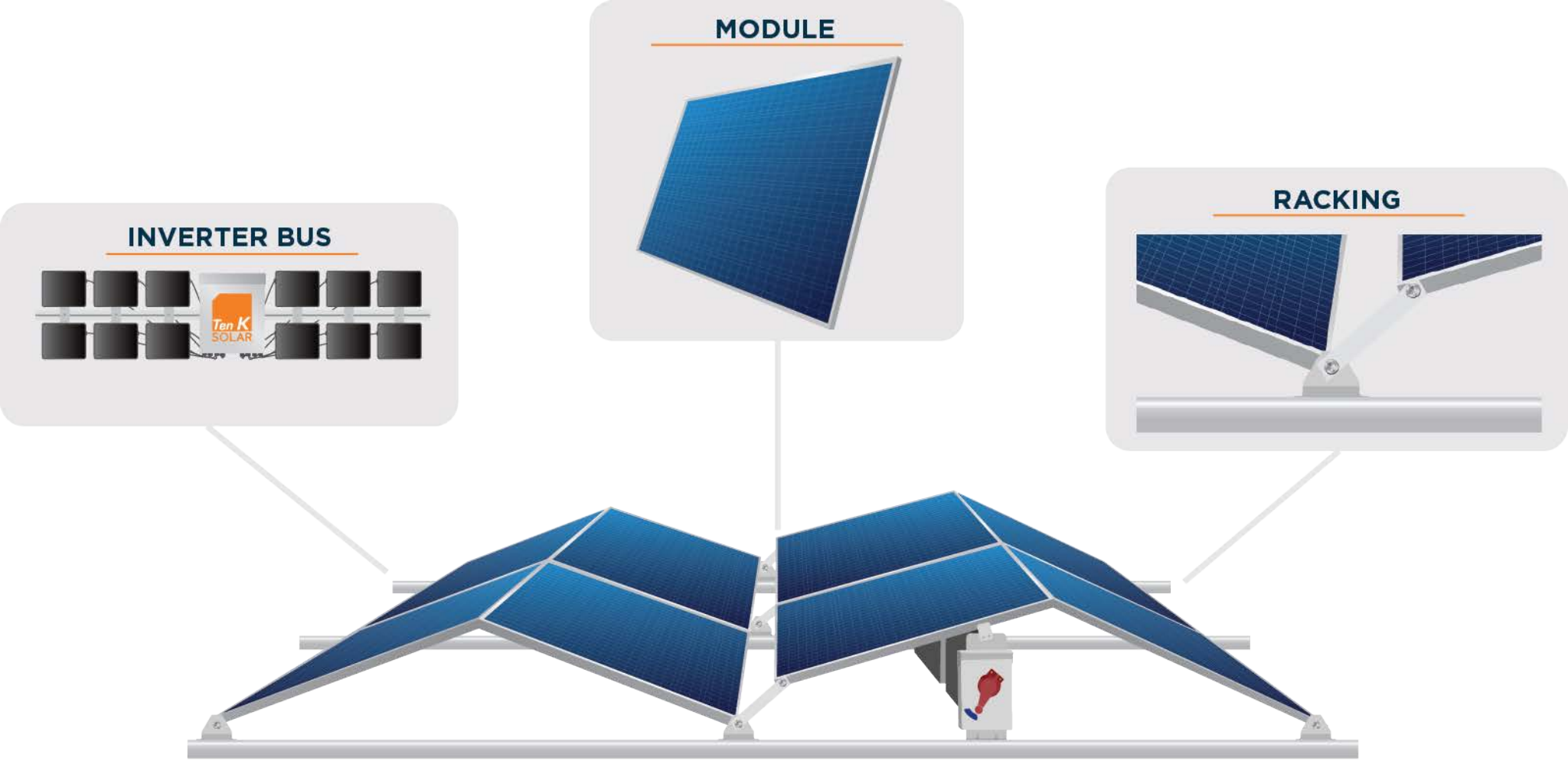


All Modules in Parallel

DC Bus Delivers Energy to <u>Group</u> of Inversion Units

<u>Energy From Any Cell Can Go Through Any Inversion Unit</u>

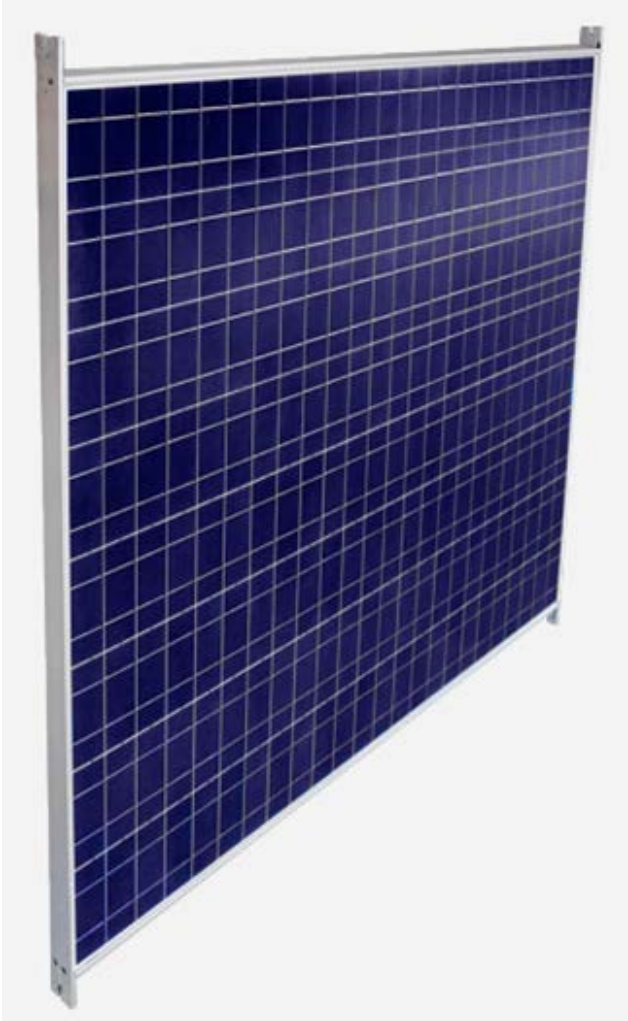
Revolutionary Solar Energy Systems

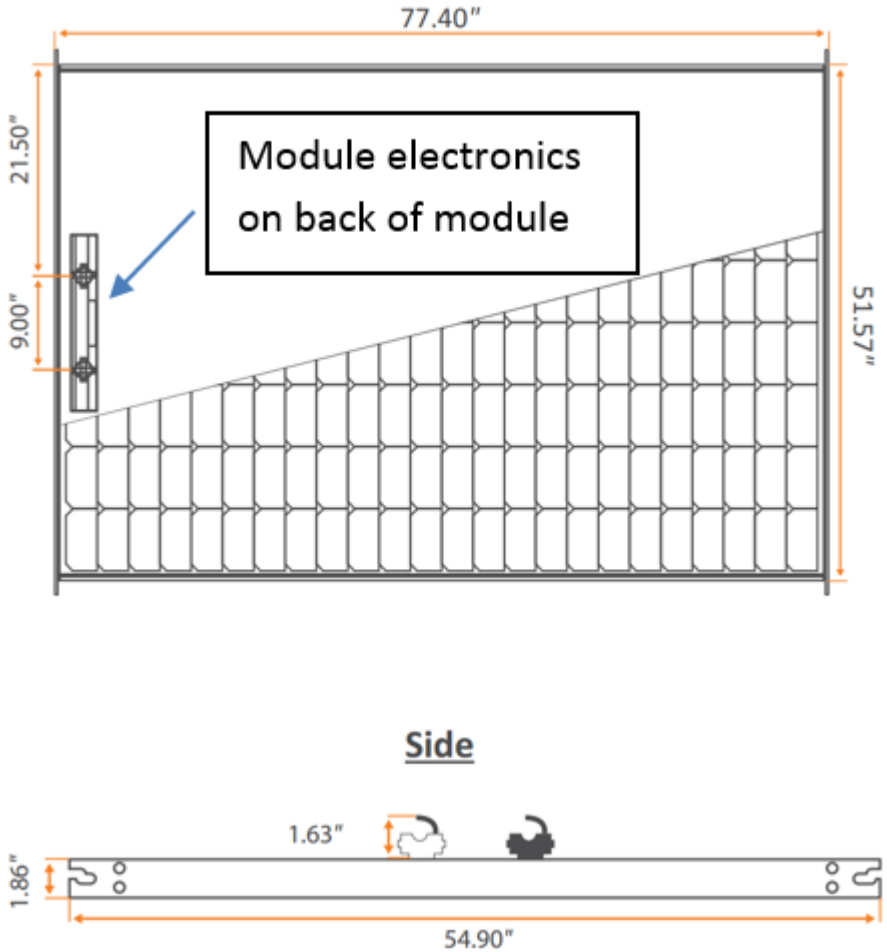


TEN K SOLAR INTEGRATED MODULE PV SYSTEM

Best overall lifetime performance and financial return.

RAIS PV Module





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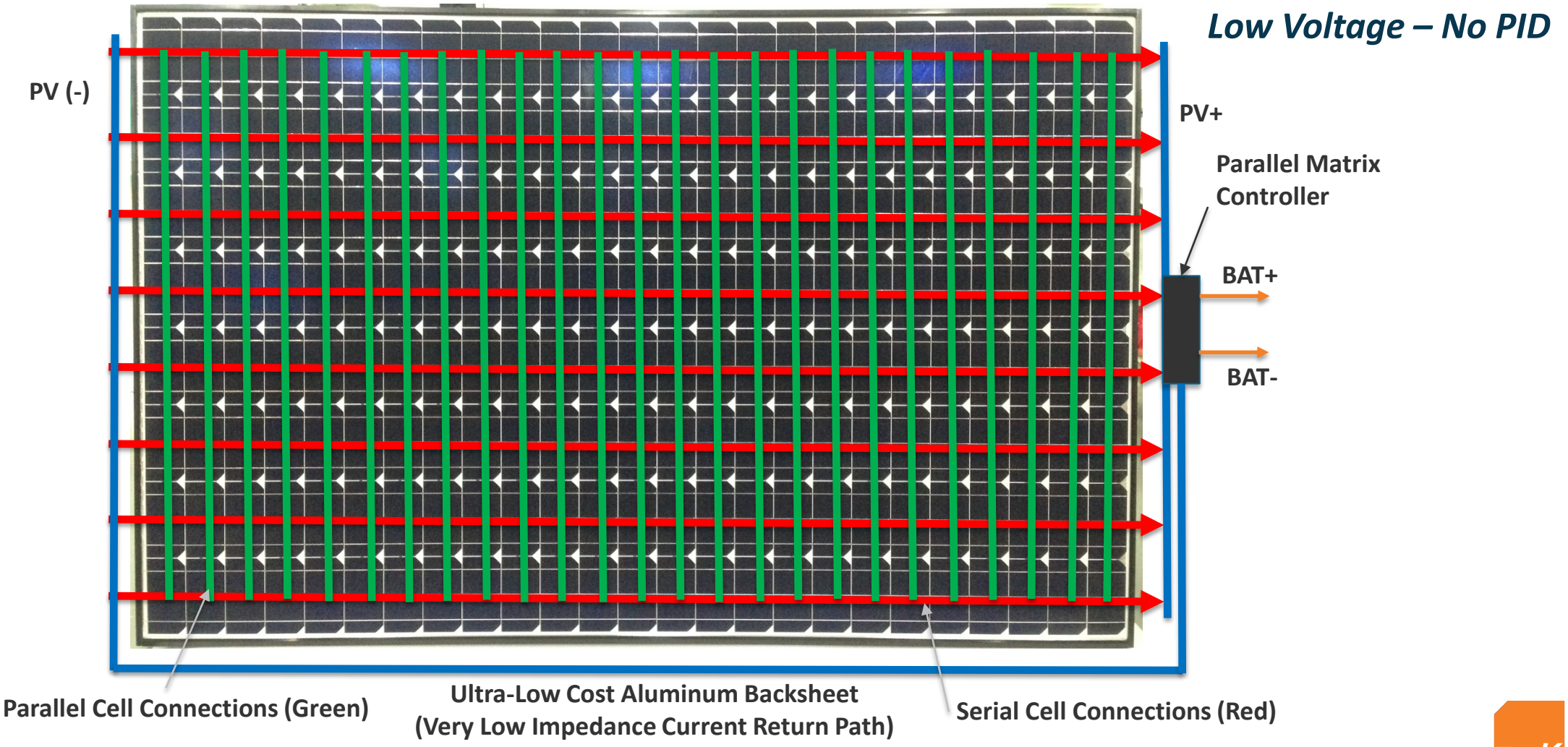
Logical Construction of a tenK PV module

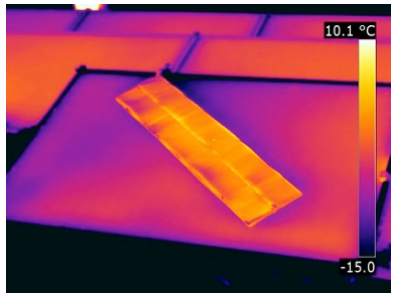


Why Parallel Connections?

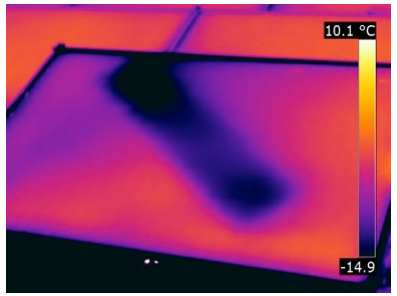
– Parallel Matrix Cell Connections provides multiple pathways for current to flow

- Broken Cell Interconnects
- Shading
- Catastrophic Failure

Actual tenK module on roof in direct sun



Strip of cardboard applied to module
22% Area blockage, 25% Loss of power
Only 3% electrical loss w/ aggressive diagonal shade test

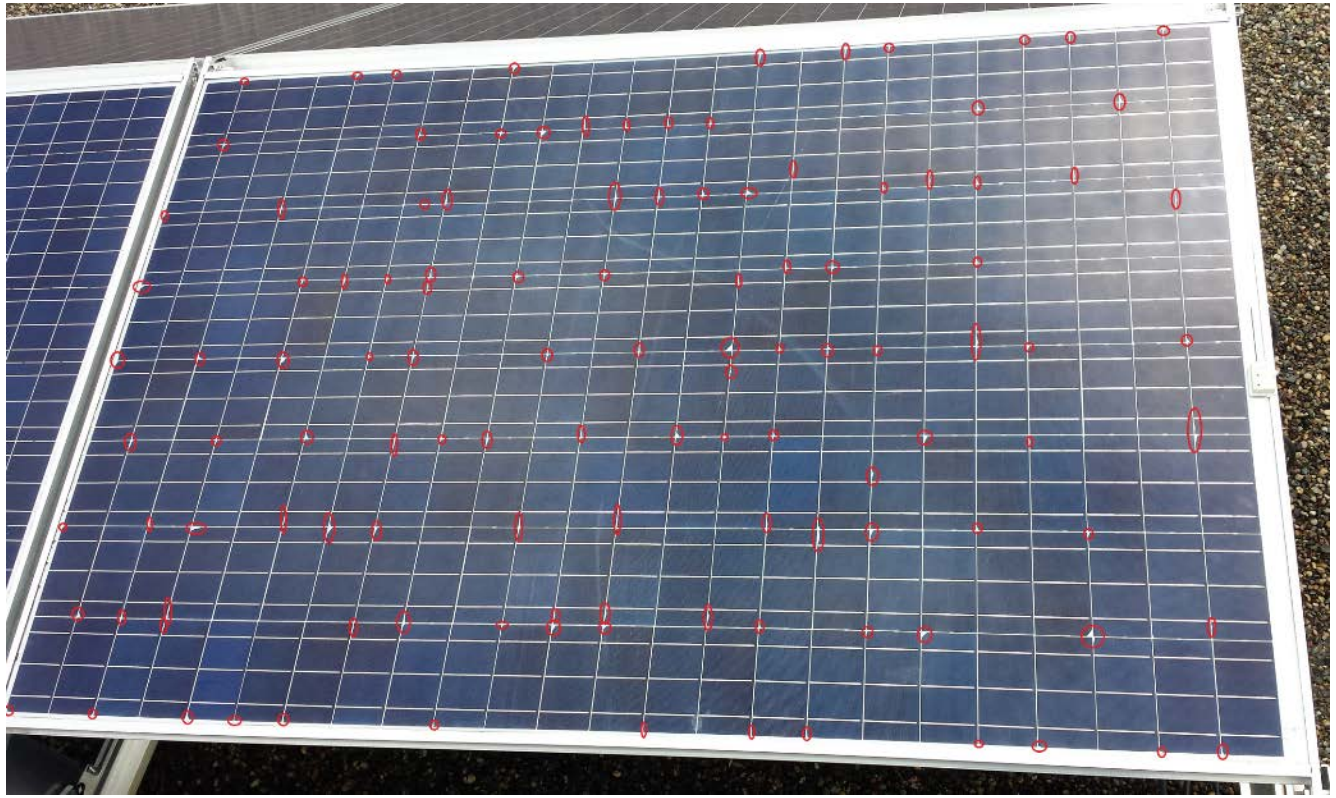


Cardboard removed, IR photo shows covered area is cool.
Energy loss is proportional to shade, no hot spot created

Minimal Effect from Broken or Defective Cells.

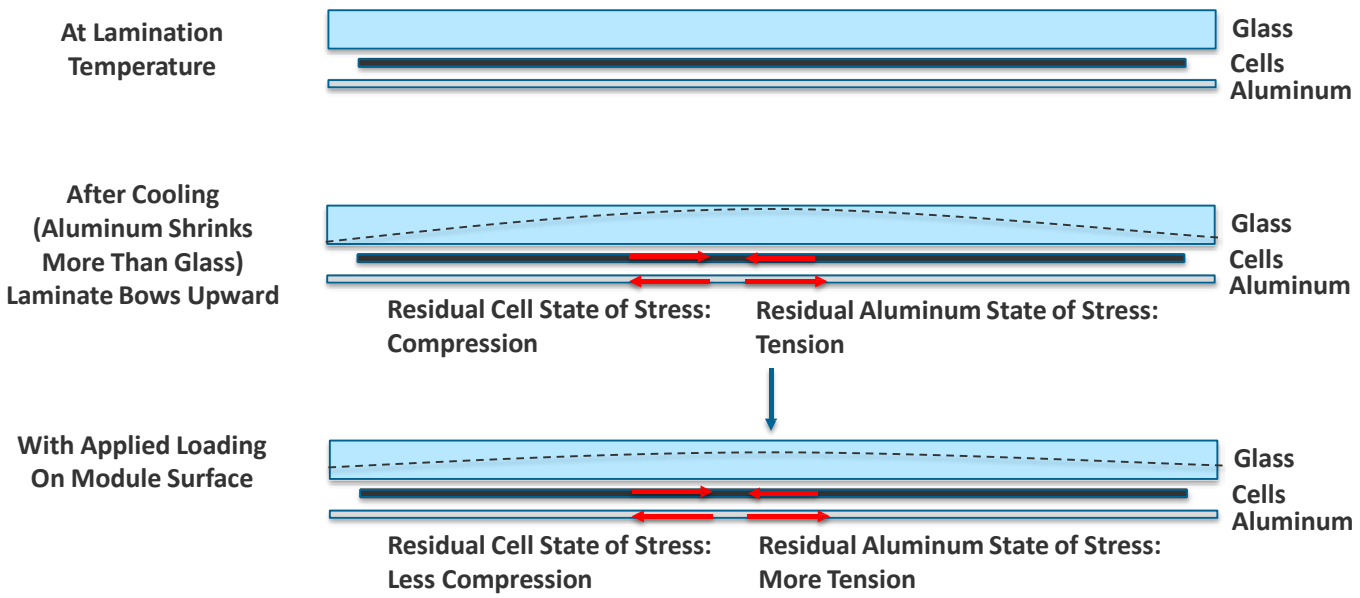
Module Built with 100% Defective Cells (Rejects):
1.7% Loss of DC Power vs. Prime Cells

Four Year Old System on Minneapolis Rooftop – Most Modules Shattered from Tornado:
Array Still Produces Full AC Power



Robustness provided by strength of AL Backsheet

Aluminum back sheet puts cells in compression adding to robustness against cracking and associated energy loss



Aluminum Strength: 200 MPa Yield Strength
Plastic: <10 MPa Yield Strength

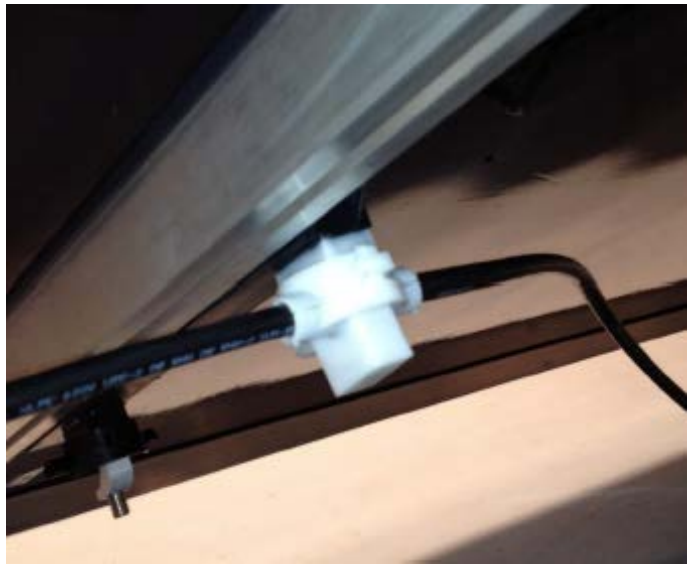
Corrosion Prevention

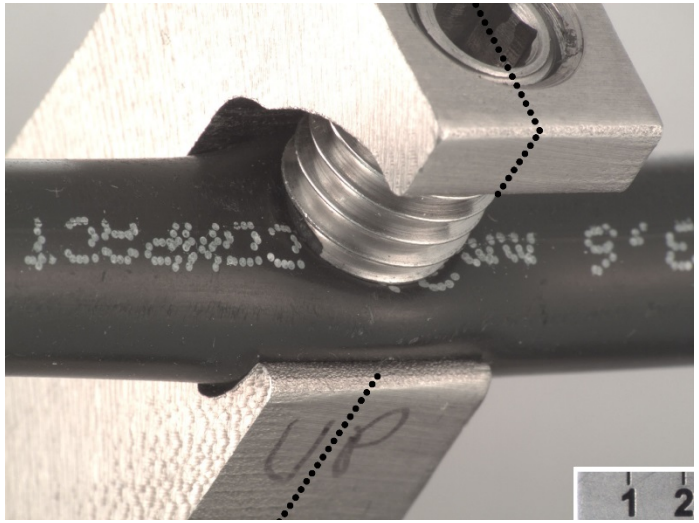
- Aluminum Backsheet Has a Very Low WVTR
  - Aluminum backsheet is highly resistant to water ingress – 10,000 X more resistant than plastic!
  - Edge Seal very robust - tested to 5000 hrs + without significant loss in power

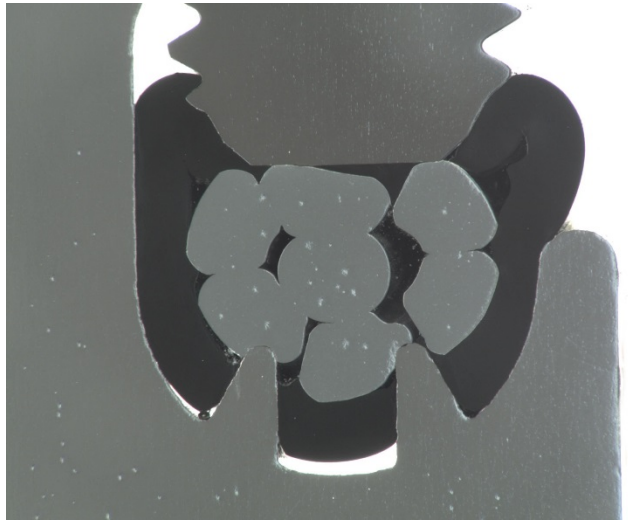
- Aluminum Getter Behavior
  - water reacts harmlessly with the aluminum in the module and not with the cells, copper or EVA

Ten K SOLAR

Robust Utility Grade Connectors







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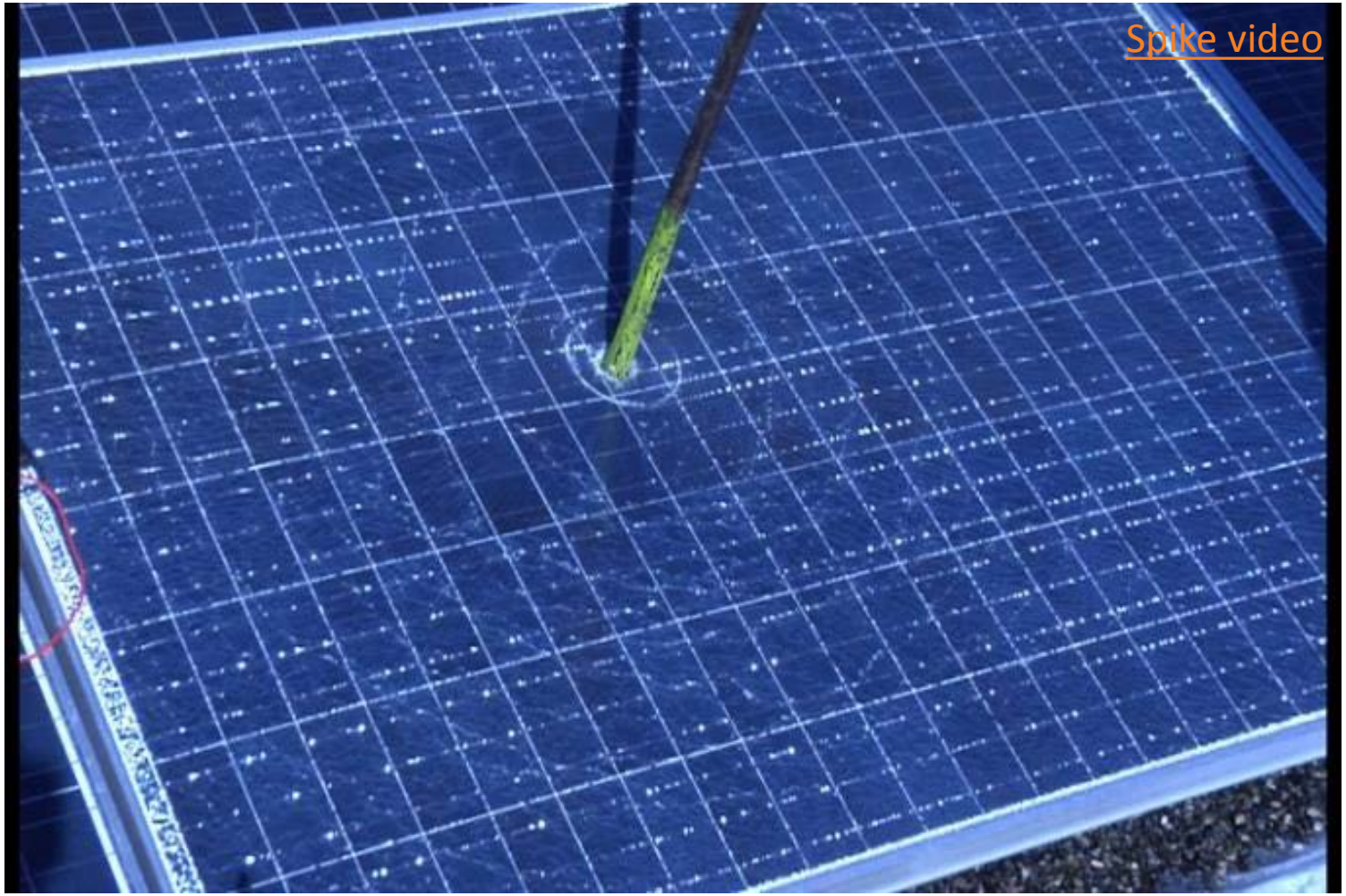
Resilience to Catastrophic Failure

Metal Spike Piercing Through Module:

Only experienced 1.3% Loss of AC System Power!



Ten K SOLAR

tenK – Dual Listed to UL1703 + UL1741

CSA Group

Certificate: 2275045 **Master Contract:** 248152

Project: 2721970 **Date Issued:** June 27, 2014

Note: Model "Titania" controller certified with "Titan" PV panel.

Model XT-M-450, the following electrical ratings typical at 450 W (STC):

Maximum Output Current at Operating Voltage (Ipmax): 9.1 A

Maximum Output Power: 450 W

Note: Model "Titania" controller certified with "Titan" PV panel.

Notes:

'XXXXXXX' represents: First three (3) digits represent the model number in the numerical format. Last four (4) digits, in the numerical format, represent how the module is kitted and used (what other parts are shipped with it) and for field tracking. As an example, if a module is shipped for use as a residential module, the fifth digit is a 1. If it is shipped as a commercial rooftop module, it is a 2, etc.

Rated electrical characteristics are within +/-10% of measured values at Standard Test Conditions of 100 mW/cm² irradiance, AM 1.5 spectrum, and +25°C.

Samples of PV frame extensions mounted on the Aluminum Fin, part # 1601035, mounted on the Aluminum Railing, part # 2601073 or # 2601076, using all required hardware have been evaluated for bonding continuity from module frame to mounting rails

APPLICABLE REQUIREMENTS

ULC/ORD- C1703-01 - Flat-Plate Photovoltaic Modules and Panels

UL 1703-3rd Edition - Flat-Plate Photovoltaic Modules and Panels

CSA C22.2 No 107.1-01 - General Use Power Supplies

UL 1741 2nd Edition - Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources

UL 1703	UL 1741
Flat-Plate Photovoltaic Modules and Panels	Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources

ISBN 0-7629-0421-6

CSA Listing to UL1703 + UL1741
No Other Module Listed This Way

UL1703 Covers Panel Portion
UL1741 Covers Charge Controller

Grounding Tested to UL2703

Ten K SOLAR

tenK Also IEC61730-2 + IEC61215

TÜV INTERCERT SAAR

CERTIFICATE

Certificate No. 13-PPV-0006010/03-TIC

WE HEREBY CERTIFY THAT THE PHOTOVOLTAIC MODULES WITH THE MODEL

XT-A
(Tested Type)

Cell Number	Cell Size	Cell Technology	Power [W]
192	156 x 78 mm	polycrystalline	410

Types extended for similarity* with polycrystalline cell technology without need of re-testing
(according to IECEE "Retesting guideline"):

Type	Cell Number	Cell Size	Power [W]
XT-B*	192	156 x 78 mm	420

MANUFACTURER & LICENSE HOLDER

tenKsolar, Inc.
9549 Penn Avenue South Suite D MN 55431- Bloomington - USA

IS IN COMPLIANCE WITH THE REQUIREMENTS OF

IEC 61215 : 2005
Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval
&
EN 61730-2 : 2007**
Photovoltaic (PV) module safety qualification
To be used in plants at a total voltage up to : 70 Vdc (application Class A)

AS RESULT OF THE TEST IN OUR APPOINTED LABORATORY

EA ACCREDITED LABORATORY N. 0192

REPORT No. TIC-PVQ01-18103-130081 & TIC-PS201-18103-130081

Expiring date 03.10.2018
(Providing that the testing basis continues unchanged)

For Selling in Europe

Note – Class A at <70VDC Max System Voltage

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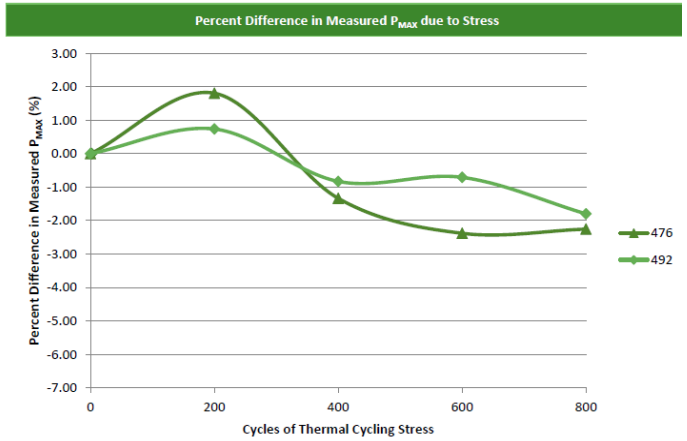
Test Results

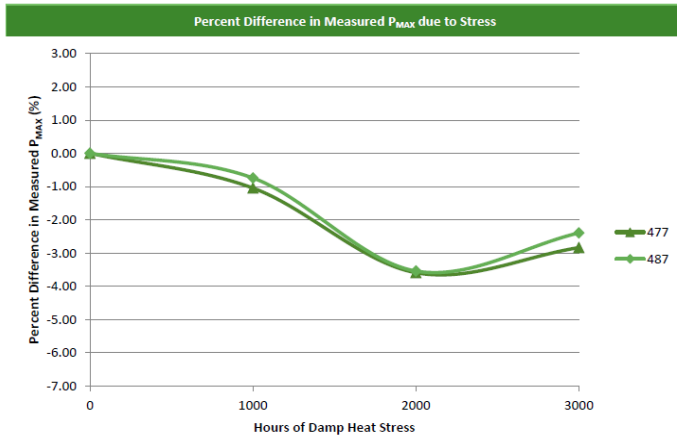
Results from DNVGL (PVEL) testing

- All Tests Performed with Embedded Electronics (Non-Powered)
- Achieved designation in Top Performing Group
- TC800 (-2.03%)
- DH3000 (-2.62%)
- HF30 (-0.13%)
- DL + TC50 + HF10 (-0.18%)

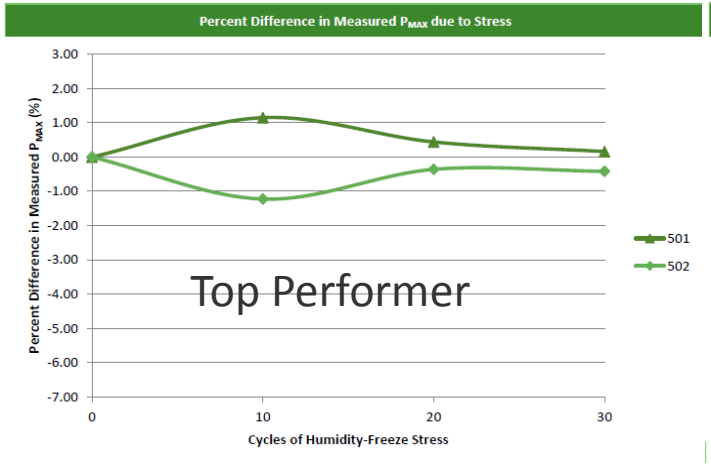
Thermal Cycling Results



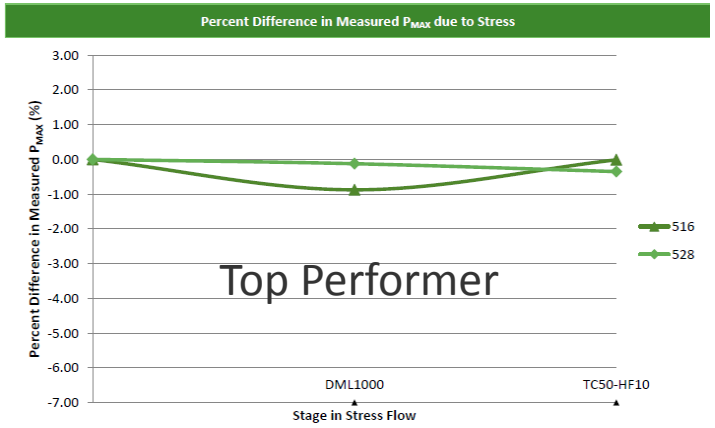
Damp Heat Results



Humidity Freeze Results



Dynamic Mech Load + TC 50 + HF10 Results

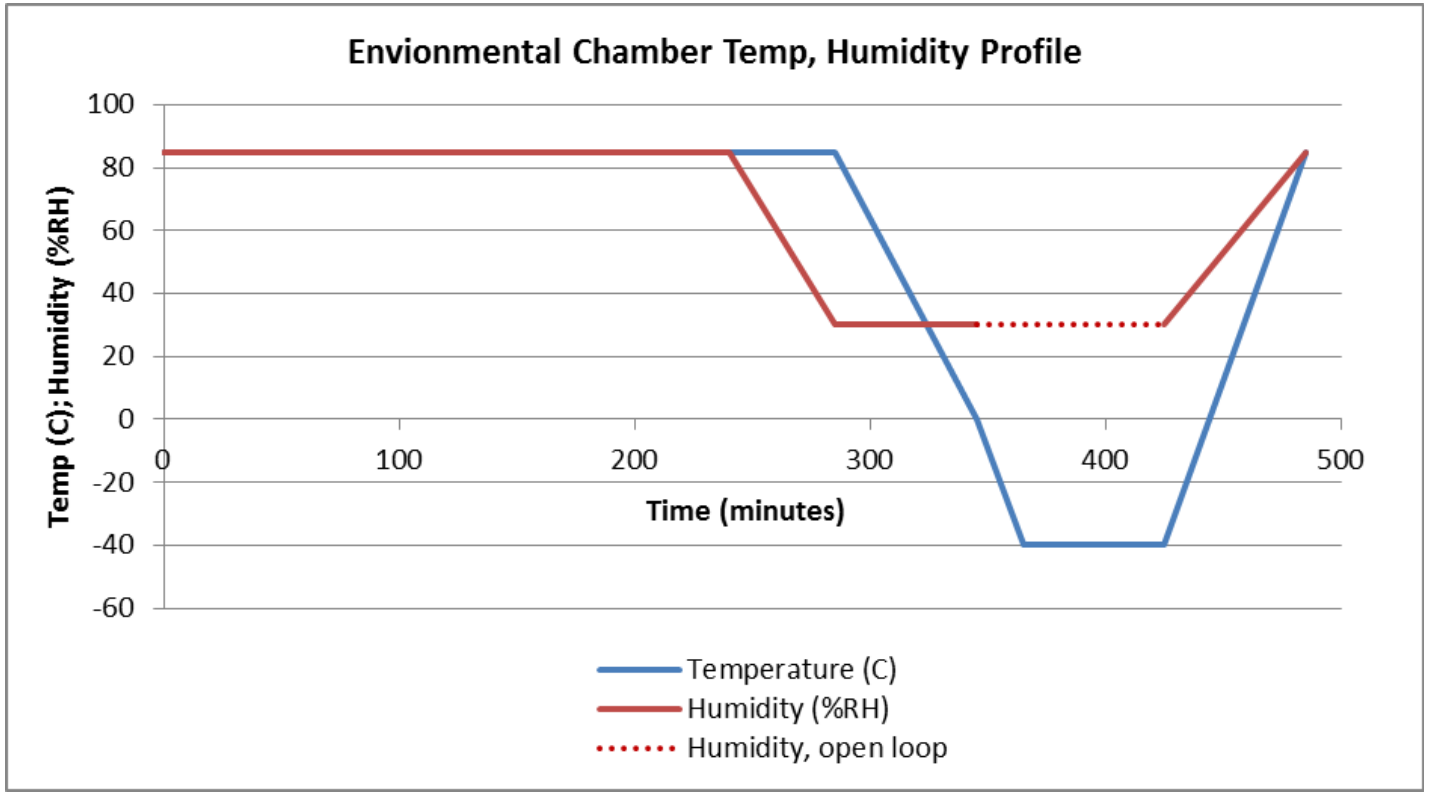


OMT: Accelerated Life Test

The repeating chamber profile cycle is shown here. It consumes 485 minutes (8.08 hours). The initial ramp from ambient conditions is not shown, but takes an hour.

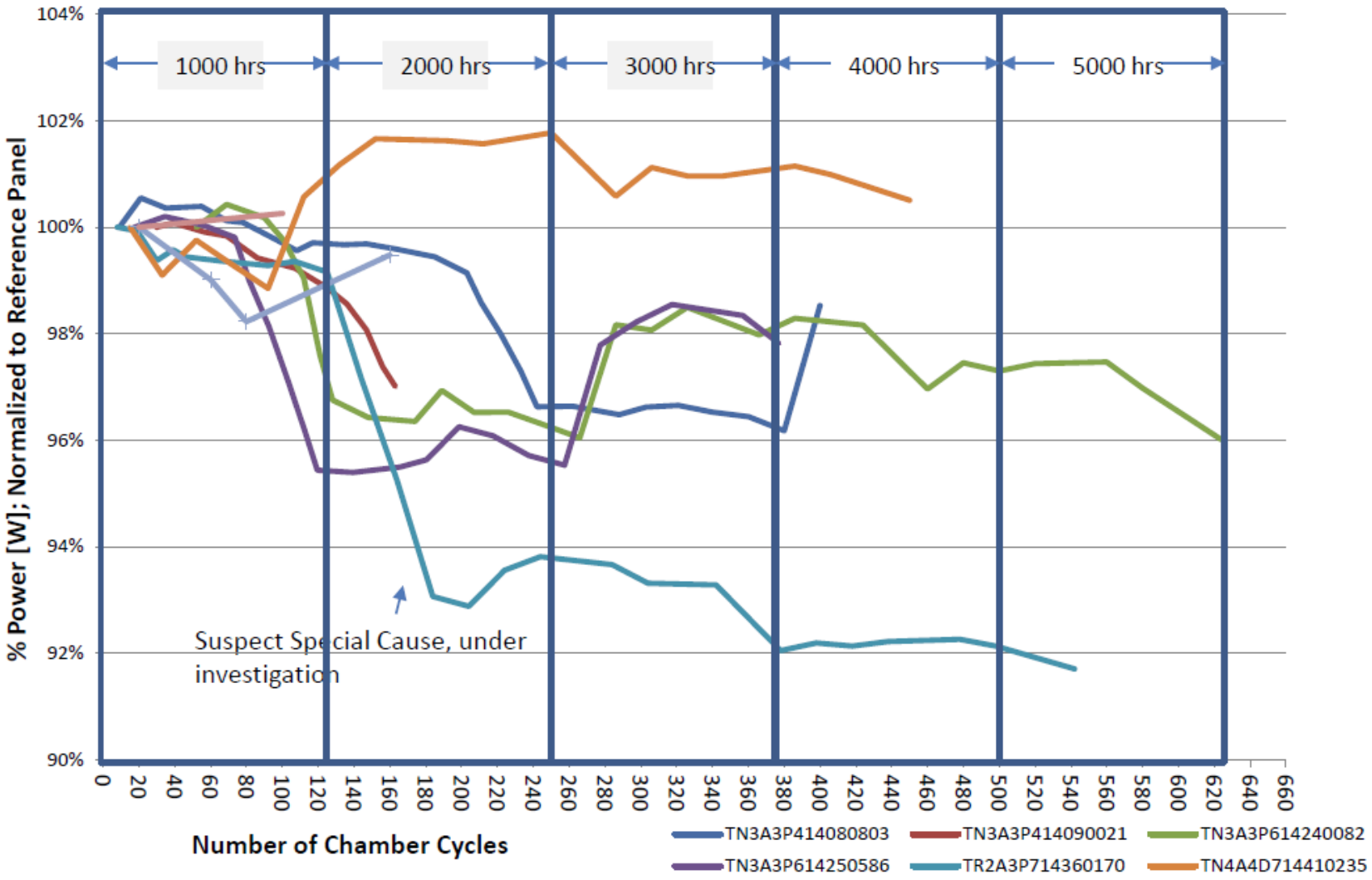
Ongoing Durability Test @ tenK

5 Hrs Extended Damp Heat (85/85) w/ Embedded 3 hr - 40° C Freeze Cycle



Ten K SOLAR

Results from Ongoing Durability Testing



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Extended FMEA

Failure Modes	Ten K Design Change to Eliminate	Validation
Broken Interconnects	Serial **and** Parallel Interconnects on Every Cell,	Broken / Damaged Cell Module Build - No Impact
Broken Cells	Module Indep. Serial and Parallel Interconnects on Every Cell, Module Indep.	Broken / Damaged Cell Module Build - No Impact
Corrosion	Al/Glass Pkg (No Moisture or O_2) + Serial/Parallel, Module Indep. Al/Glass Pkg (No Moisture or O_2),	Long-Term Damp Heat
Delamination of Encapsulant	Use High Quality Encap	Long-Term Damp Heat, Humidity--Freeze
Encapsulant Loss of Elasticity or Adhesion	Edge Seal Design (Al/Glass Edge) Al/Glass Pkg (No Moisture or O_2),	Humidity + UV Testing
Solder Bond Failure	Serial and Parallel Interconnects, Redundant Panel Interconnects	Temp Cycling, Large Scale IR Camera Imaging
Broken Glass	tenK Uses 3.2 mm (Same as Conventional) w/ Al. Stengthened	Hail Damage Threshold (45 mm) + Module Still Works When Shattered
Hot Spots	Serial and Parallel Interconnects, Low Voltage, Al Thermal Cond	Hot Spot Testing, Large Scale IR Camera Imaging
Ground Faults	. Low PV Voltage, Integrated Ground Fault in Module	UL1703 Safety Testing
Junction Box Failures	DC Bus Bond to Aluminum	UL1703 Jbox Adhesion, UL1703 Arc Testing
Connection Failures	Low Voltage+Redundant Connections Un-Interrupted DC Bus, Utility Connector, Robust Wiring, Low Voltage,	UL1703 Testing
Structural Failures	Aluminum Stiffened Backsheet, Nested Frames, WAVE Config	UL1703 Testing
Bypass Diode Failures	No Bypass Diodes	
Open Circuits Leading to Arcing	Utility Connector, Low Voltage, Module J_{sc}=0, V_{oc}=0, Al/Glass Pkg,	UL1703 Certification
Potential Induced Degradation	PV Voltage <16VDC	Product Testing

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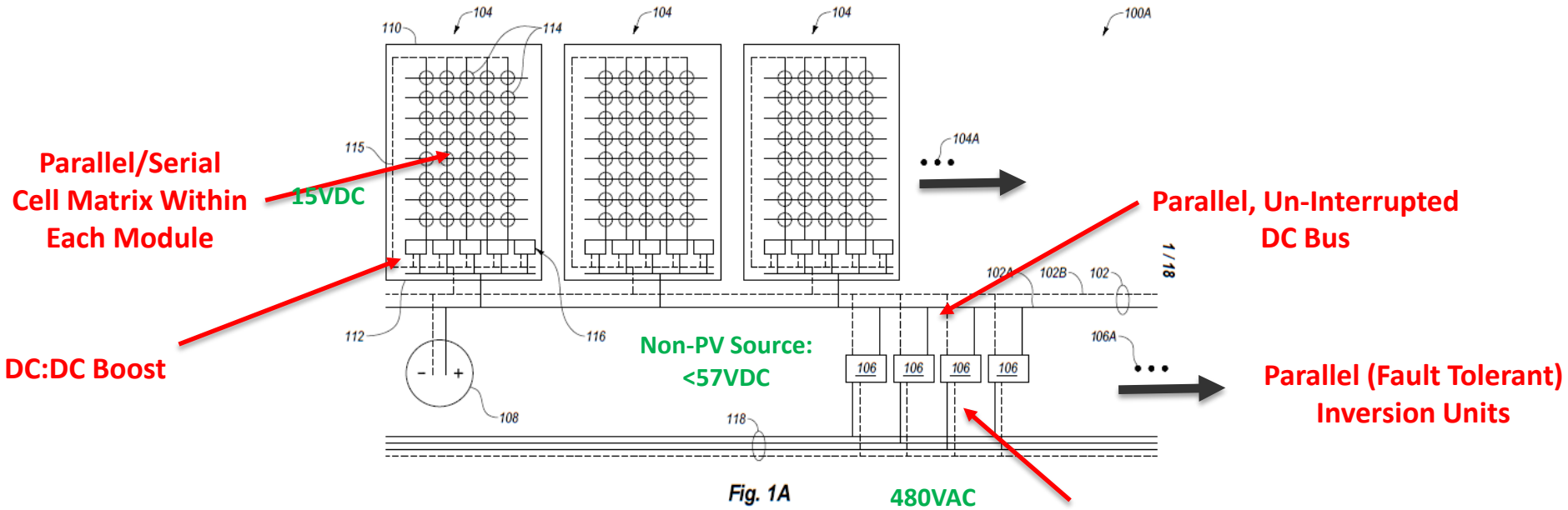
Module -> System

The tenK Topology

- Utilize modular, low cost components to create an easy to install, highly reliable, zero maintenance PV system



All Modules in Parallel

DC Bus Delivers Energy to <u>Group</u> of Inversion Units

<u>Energy From Any Cell Can Go Through Any Inversion Unit</u>

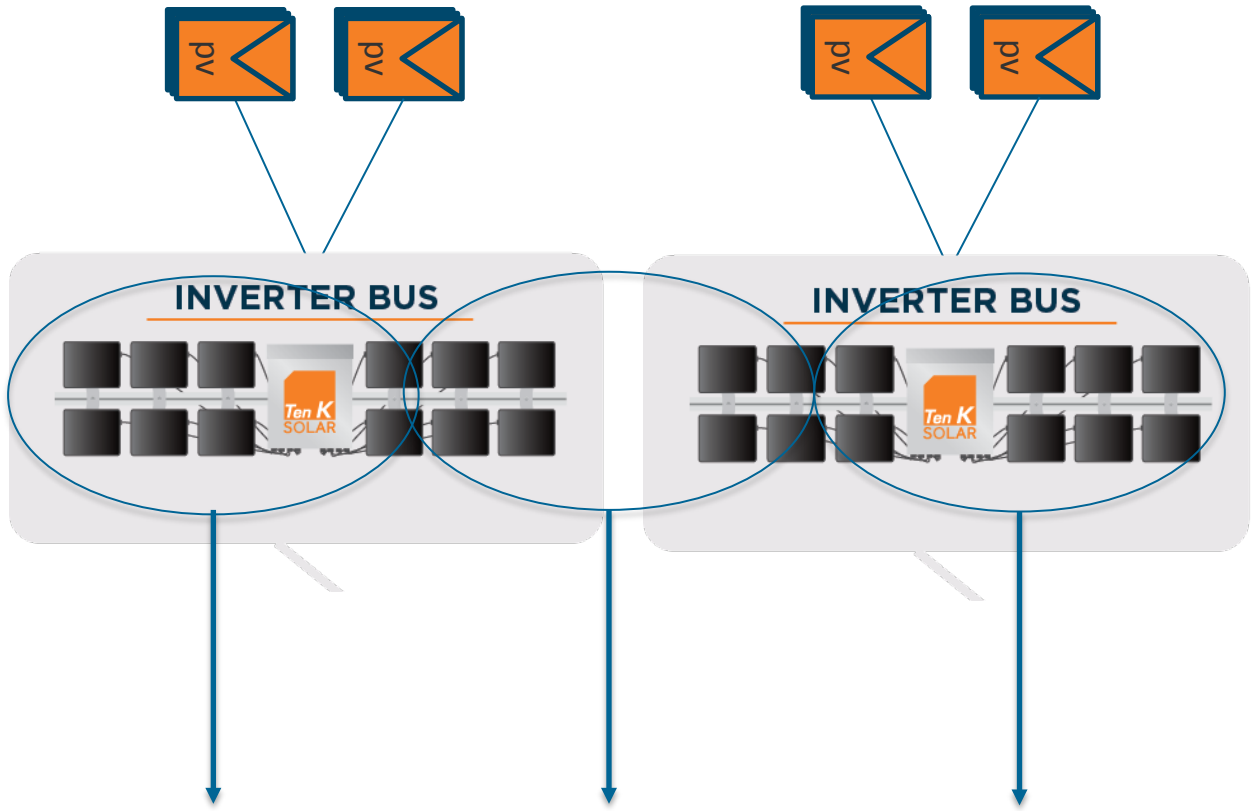
Why use microinverters for inversion units.

- Micro inverters have inherent reliability advantages over String Inverters
  - Size – more granular power output
  - Complexity – fewer parts / smaller in size.
  - Environmental Sealing – Nema 4X - can be immersed in water
  - Low Voltage - less stress on components
- If designed well, expect be able to achieve field failure rates sufficiently low to meet our requirements at the right cost

Ten K SOLAR

tenKsolar RAIS Inverter Bus

Removes 1:1 Module to Micro-Inverter Dependency



To Specific AC Interconection

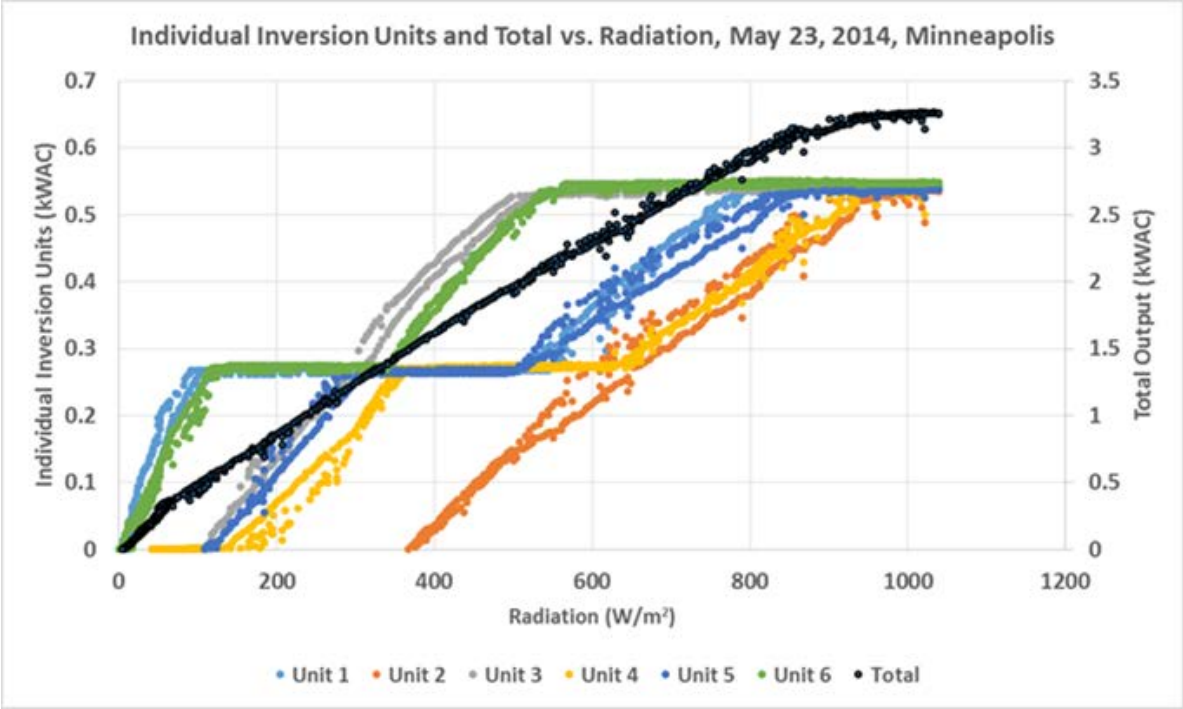
Multiple Inverters Operating Off DC Bus (Fault Tolerant)
No Digital Communication Between Units
All Operate Based Off DC Setpoint Targets
Only Operate as Needed

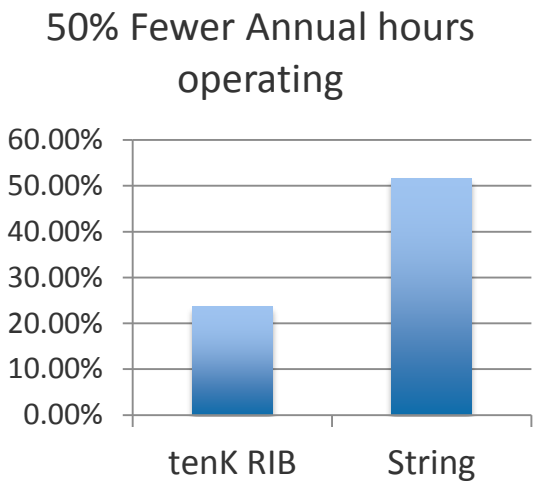
Randomized DC Setpoint Process
Daily Wear Leveling Across All Units

If One Fails or is Damaged
No Impact on Others (Fused)

Extremely Simple Repair
Changing Failed Units is a Very Simple Swap-Out
All Units are Inter-operable

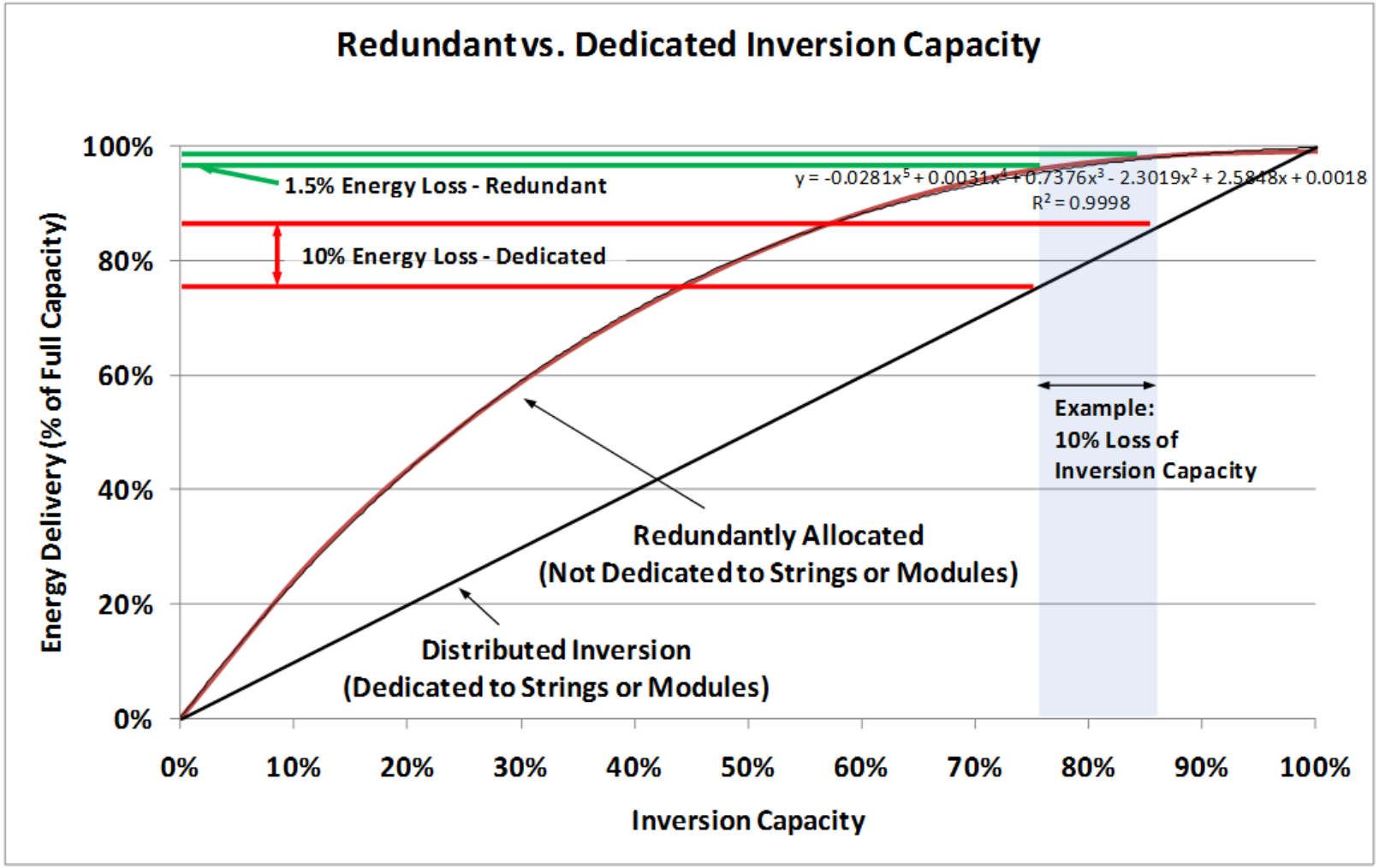
Improved System Longevity – Redundant Inversion





<u>Inversion Units All Come On at Different Times</u>
Note: Total Power Curve is Smooth
Also – Repeats AM and PM
Randomized Each Day
Net Required On-Time: 25% vs. 50% For Module Dedicated Inversion

Benefit of Redundant Inversion

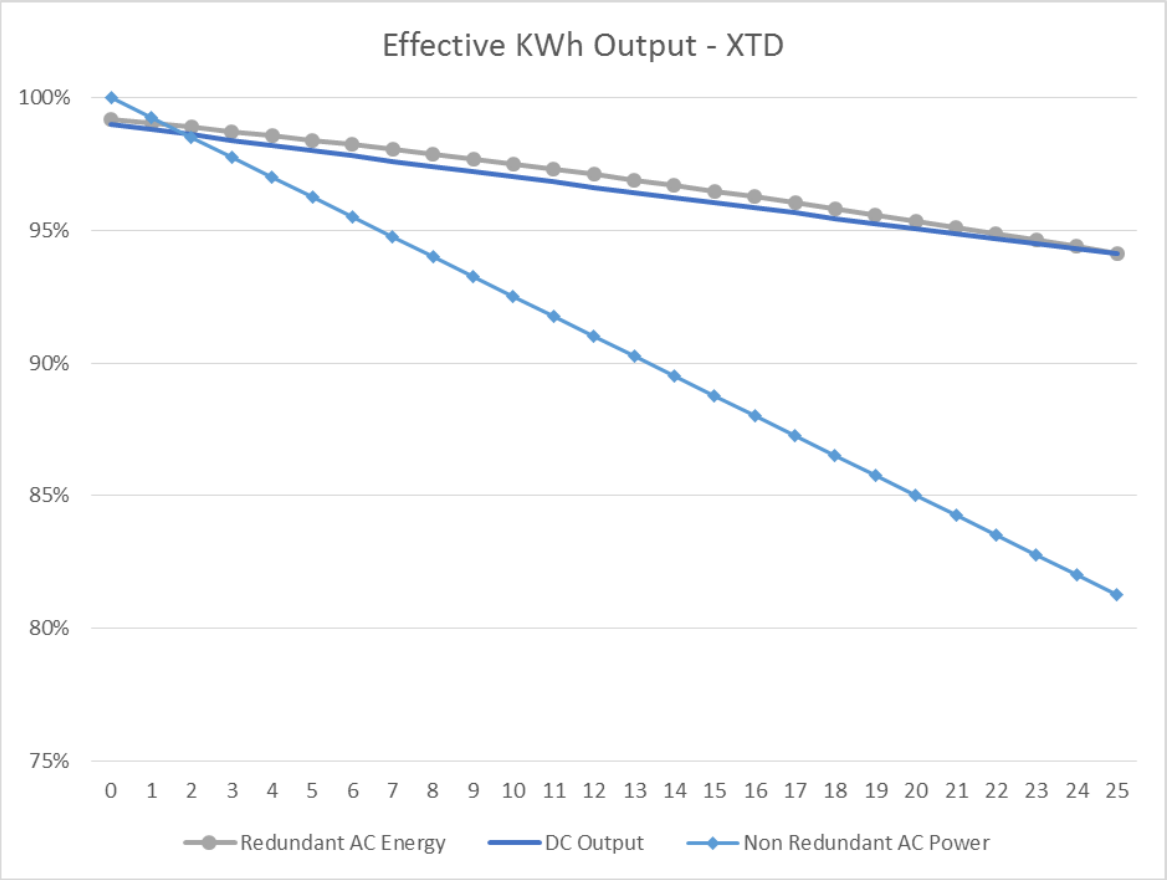


Zero Energy Loss With No Maintenance

As failures are distributed among redundant buses, remaining functioning boost converters on the module and inverters on RIB ensure no effective energy loss

For purposes of demonstration of the value of redundancy, these calculations assume an AFR of 0.75%, much lower reliability than commercially expected design points.

In Year 25, 13% Additional Loss in Total AC Power is Compenstated for with redundant bus. Results in Zero lifetime Energy Loss versus Expected with No Maintenance or Corrective Actions for Inversion.



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Financial Return

More Solar on the Roof: Everyone wins

Actual Rooftop Project - 268 kW w/ Conventional increases to 385 kW with Ten K DUO

	Conventional	Ten K DUO	
IRR on Cash Flows	12.66%	14.81%	*Better Investment*
Project Investment	$503,534	$634,675	*More Business for EPC*
Additional Cash Invested	N/A	$130,133	*Levers Project for Higher Return*
IRR on Additional Cash Invested	N/A	22%	
Total kWh	9,634,675 kWh	14,254,760 kWh	*More Solar for the Off-Taker*

More Energy

Better Overhead Absorption

Lower O&M

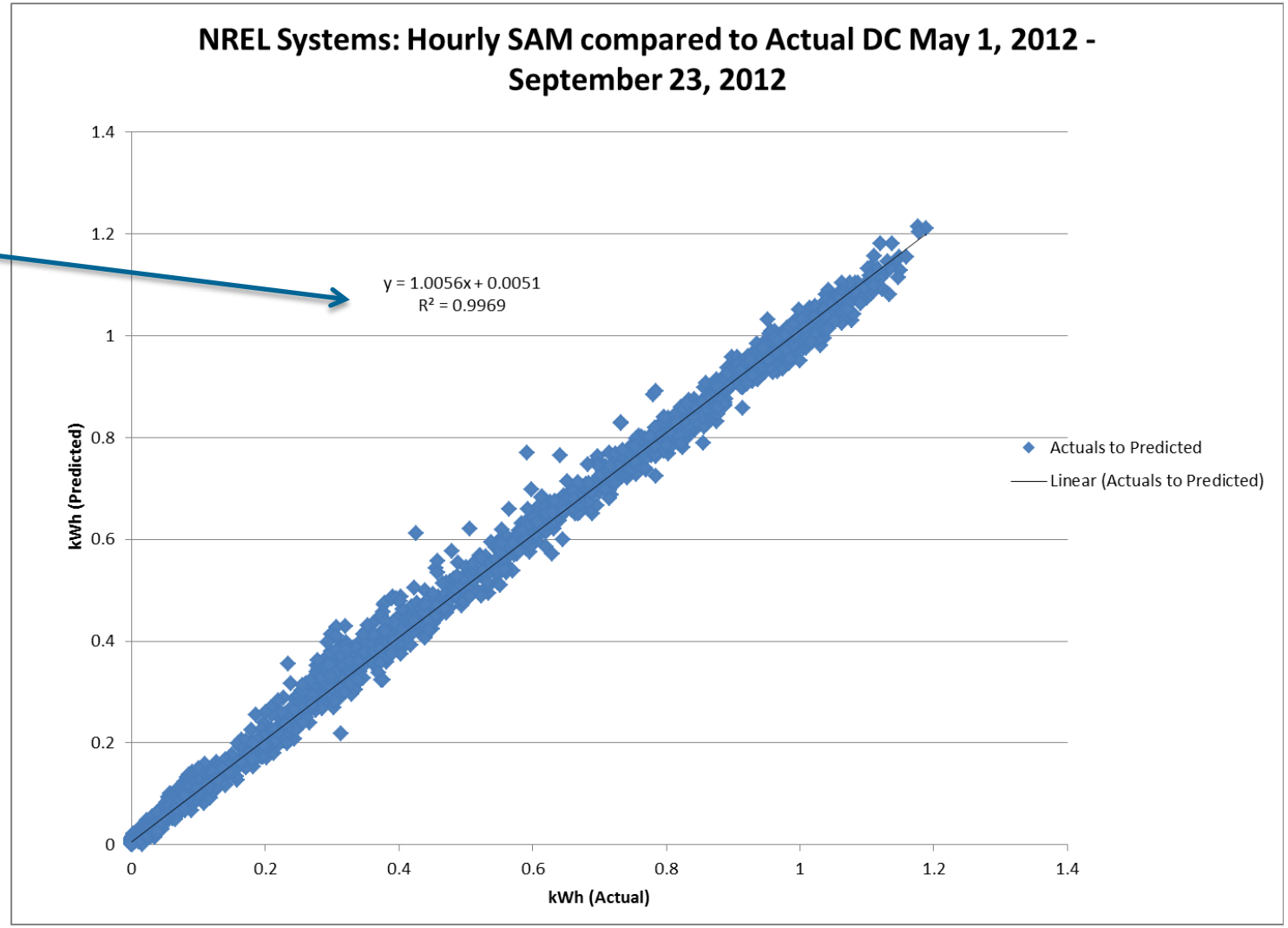
No Inverter Replacement

Lower Degredation

Ten K SOLAR

Demonstrated Energy Performance

In addition, for tenKsolar, ratio of Expected Output to Actual Output is Within 0.5% accuracy, given available solar resource



Ten K SOLAR

Low Voltage Means Reliability and Safety

The only module in the world with Voc = Jsc = 0

Arc faults and fires are a real rooftop solar hazard
Impossible with tenK

System design ensures all components can only **fail safe.**

Liability is by far the most significant risk to commercial system owners

Ten K SOLAR

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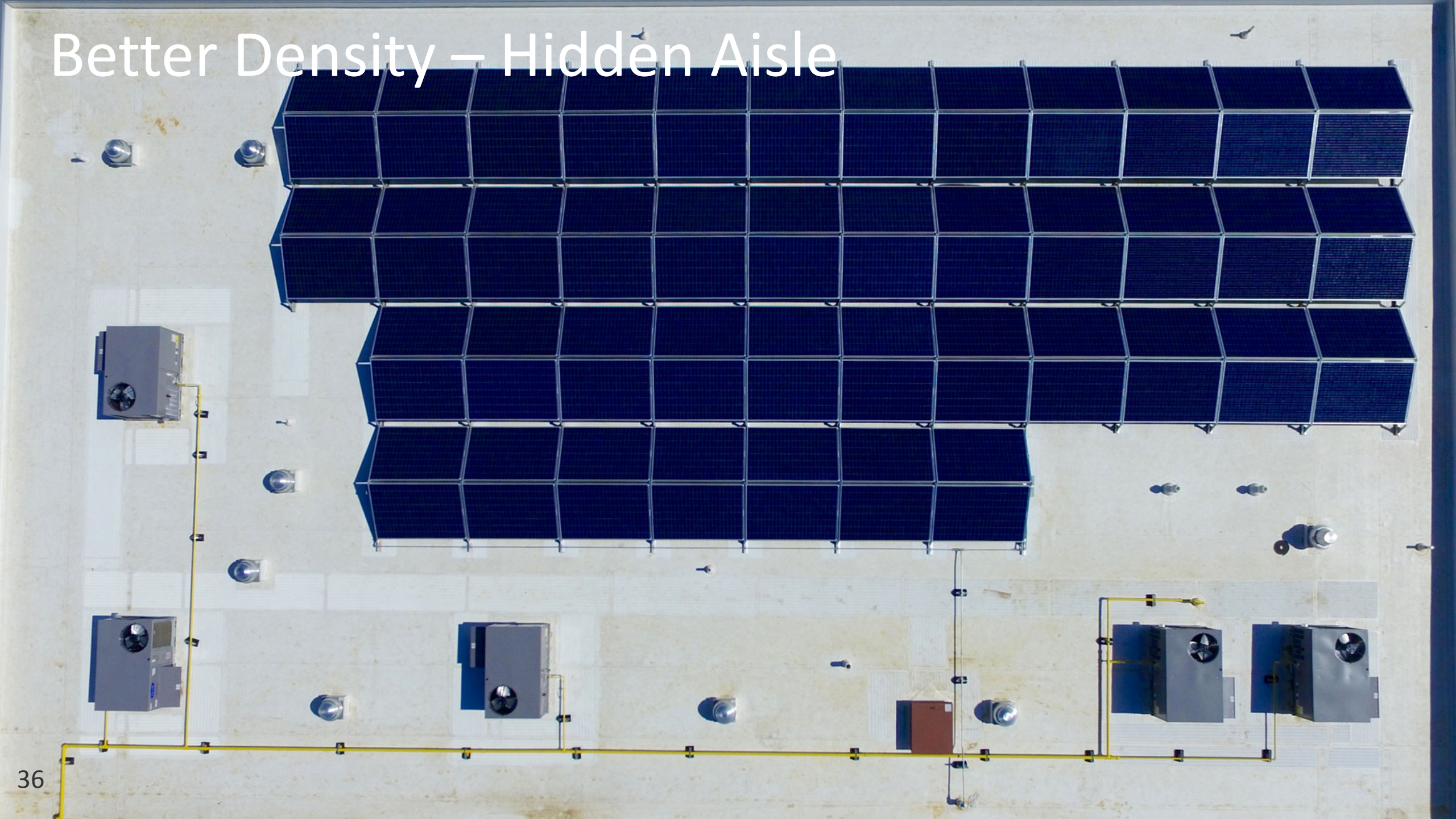
Simply More Energy

Application Strengths

Better Density – Hidden Aisle



More Energy

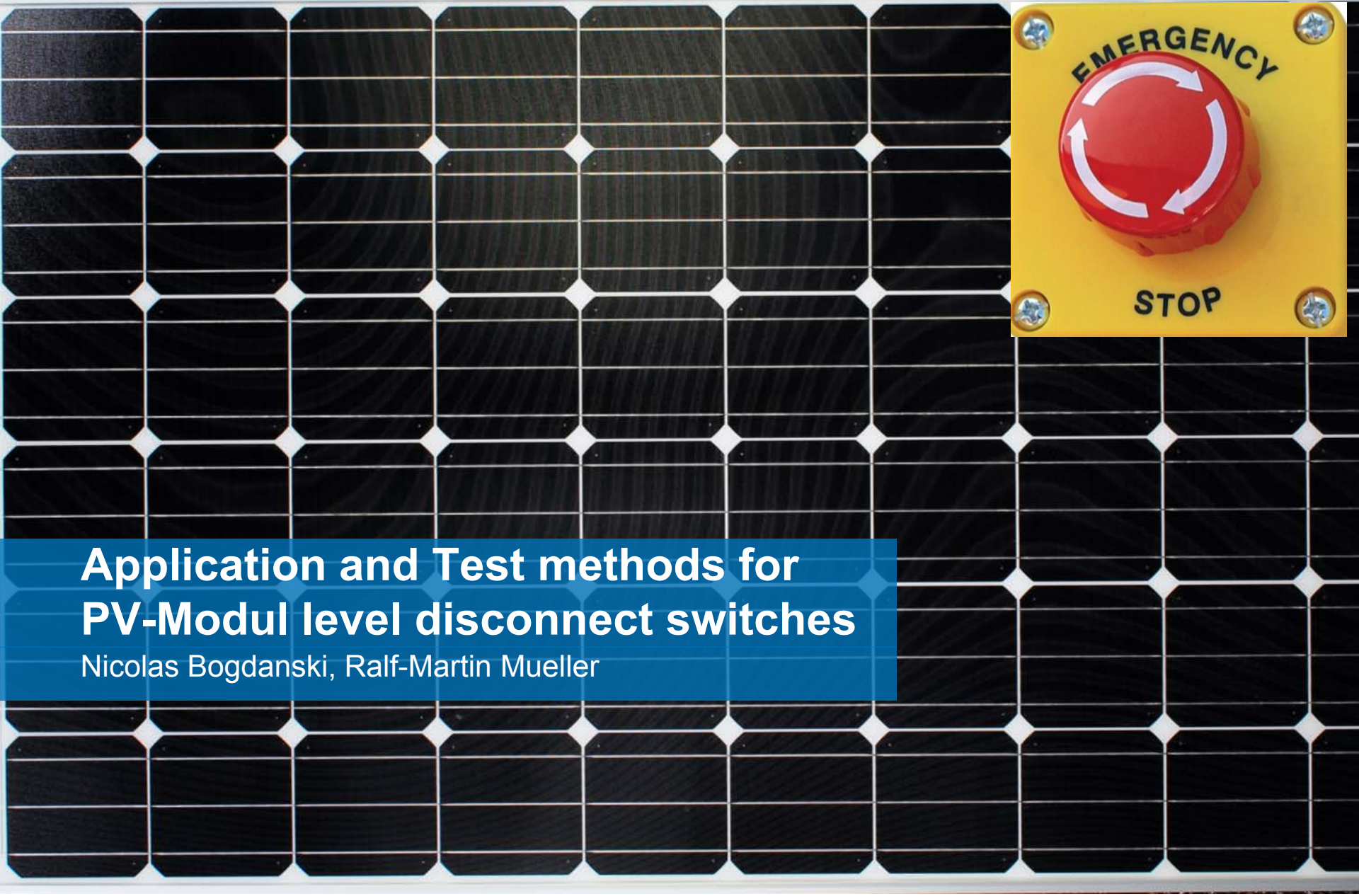
Direct DC Off Grid Applications

Ten K SOLAR

Simply More Energy

Thank You

www.tenksolar.com



Application and Test methods for PV-Modul level disconnect switches

Nicolas Bogdanski, Ralf-Martin Mueller

TÜVRheinland®
Precisely Right.

Übersicht

- Types of modul switches
- Emergency-off modul switches
- Specific test methods for module switches
- Summary

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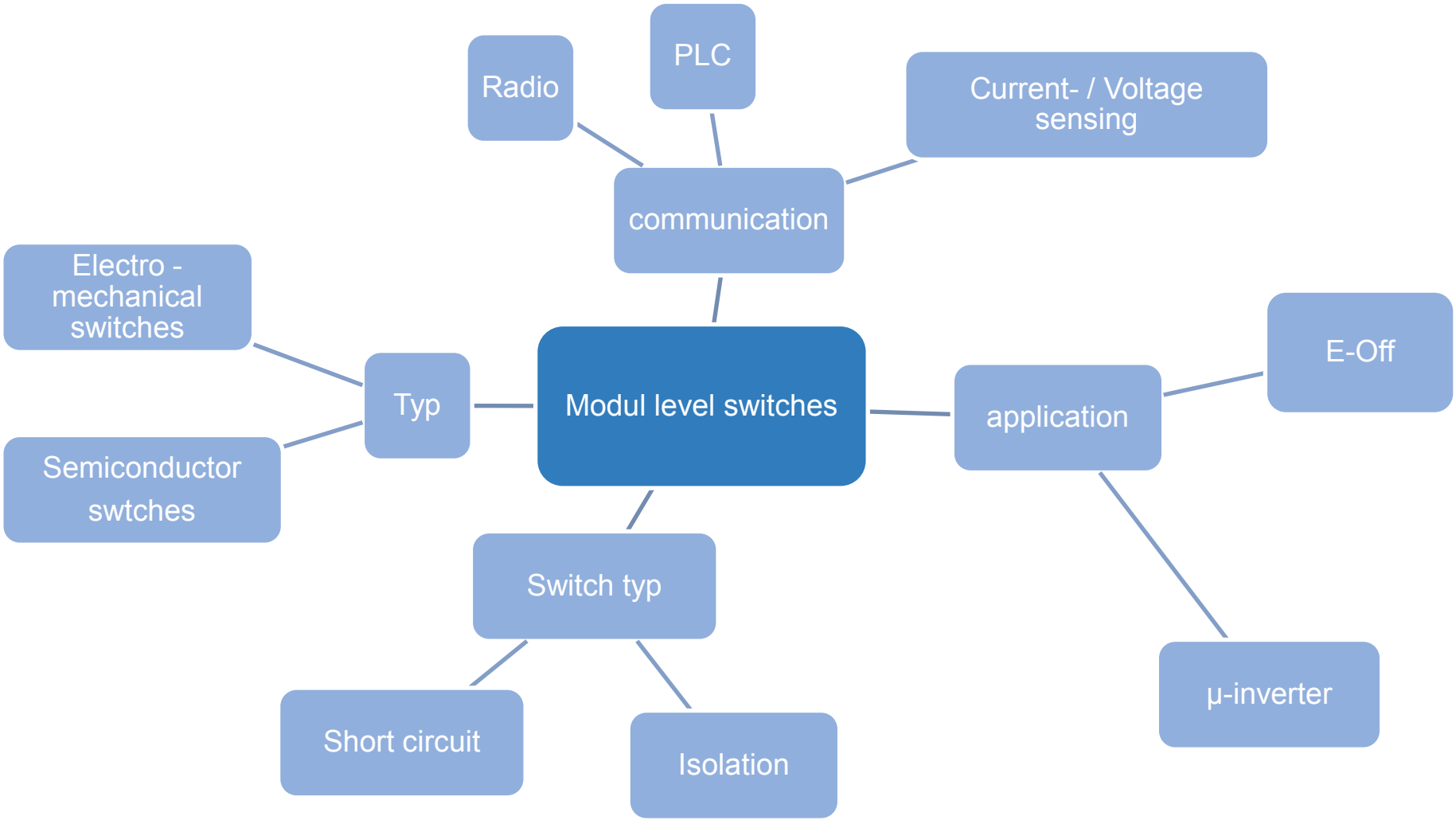
modul switches: topology



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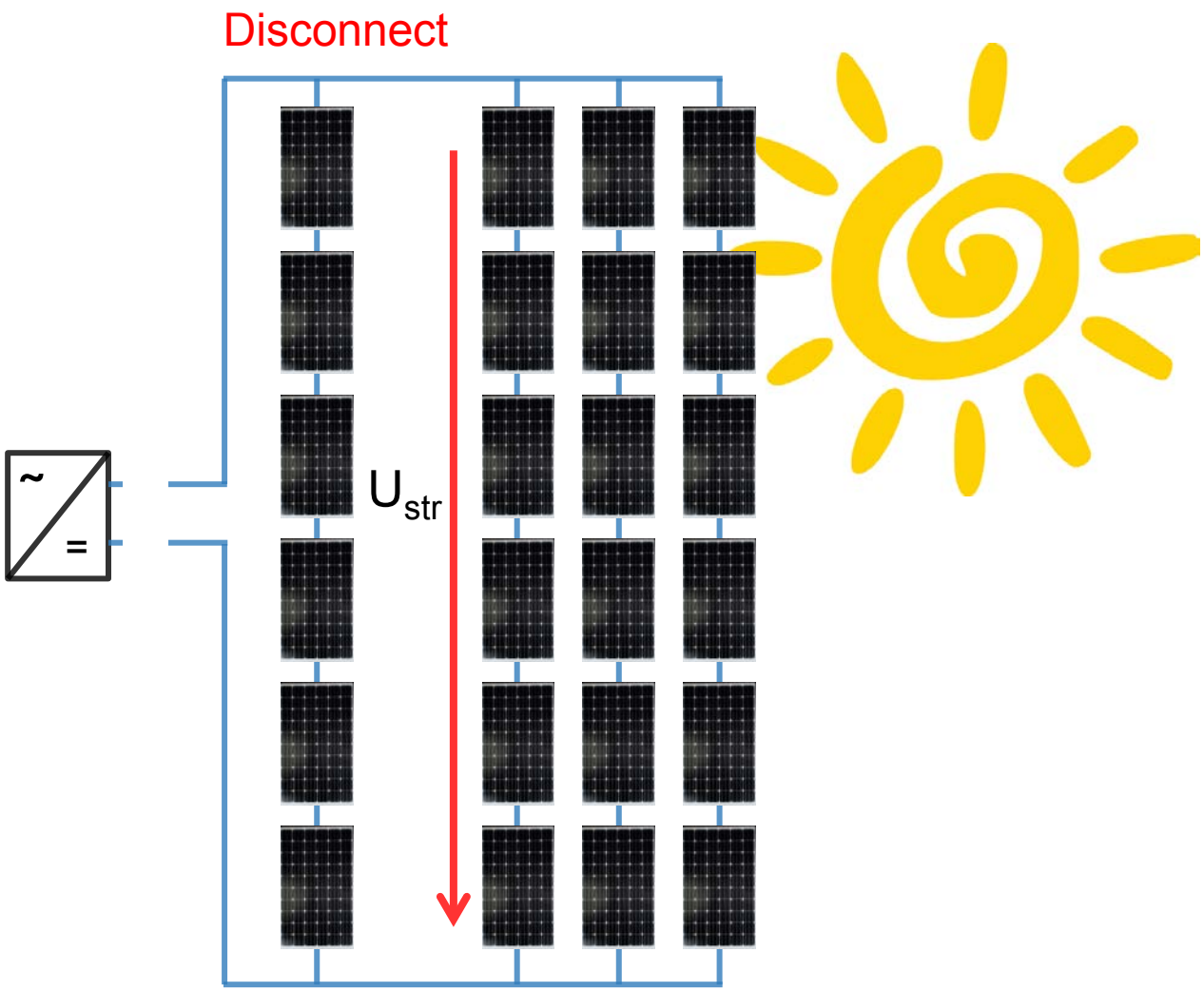
Switches in strings



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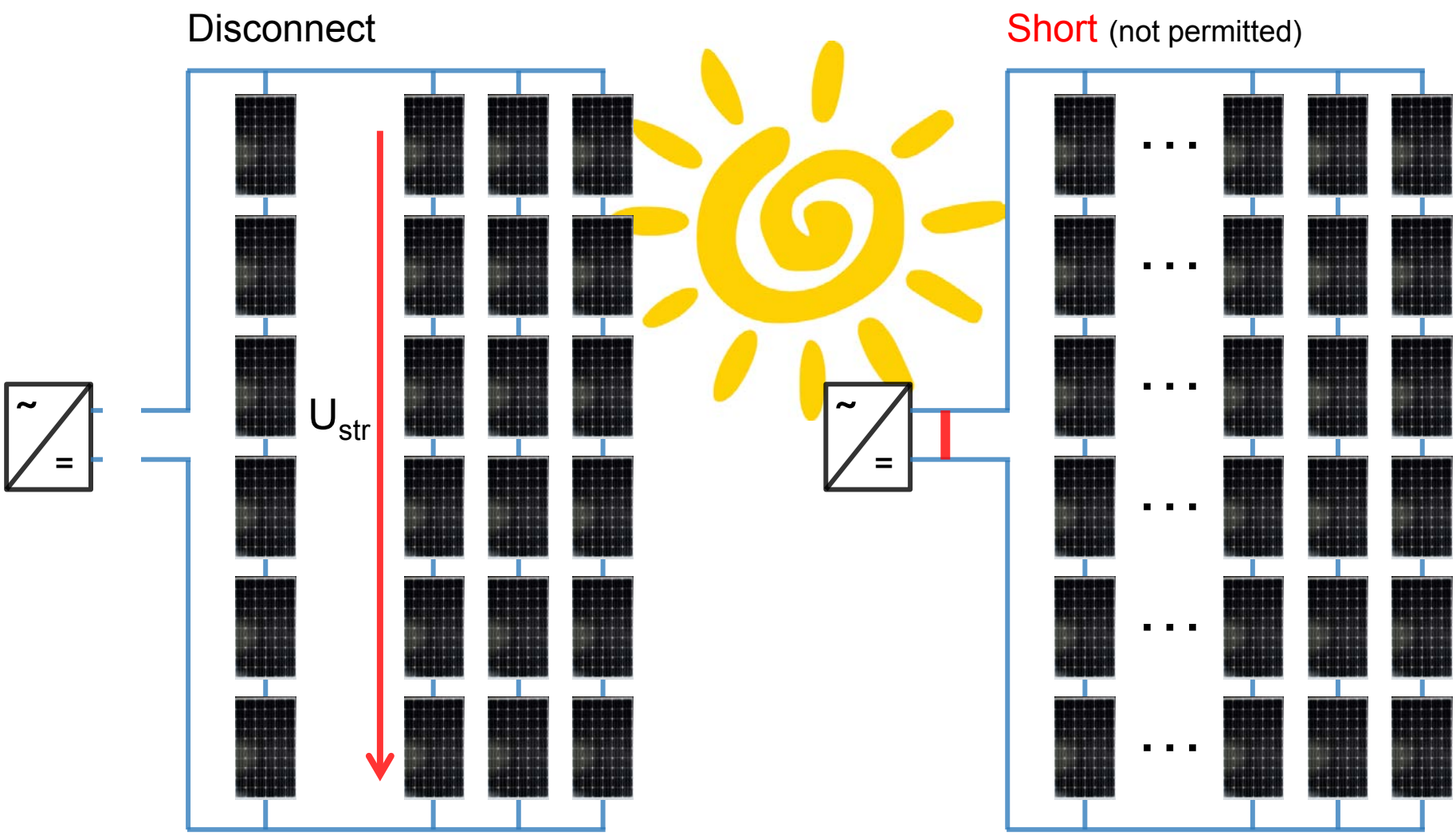
Schalter auf Strangebene



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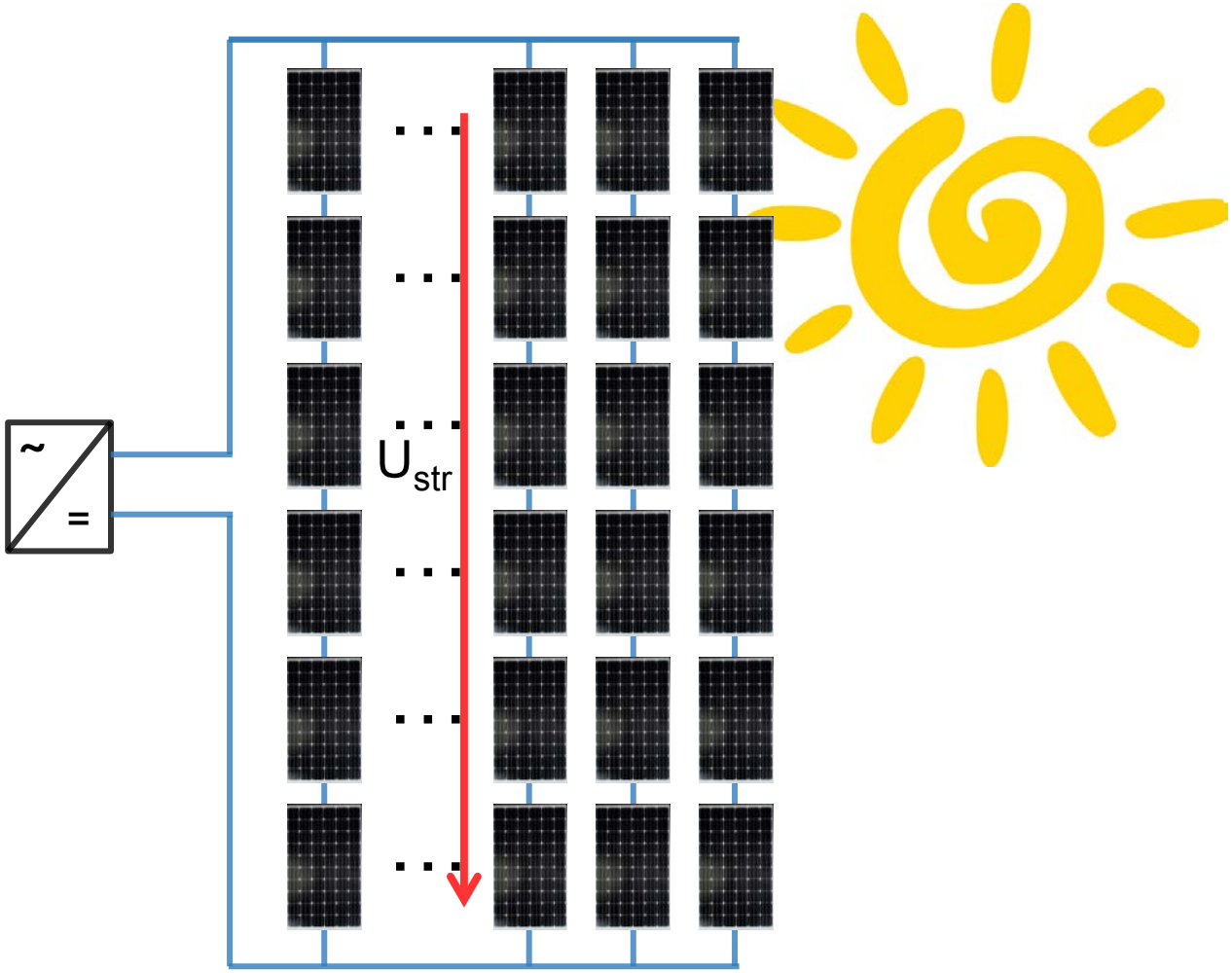
Modul level switch



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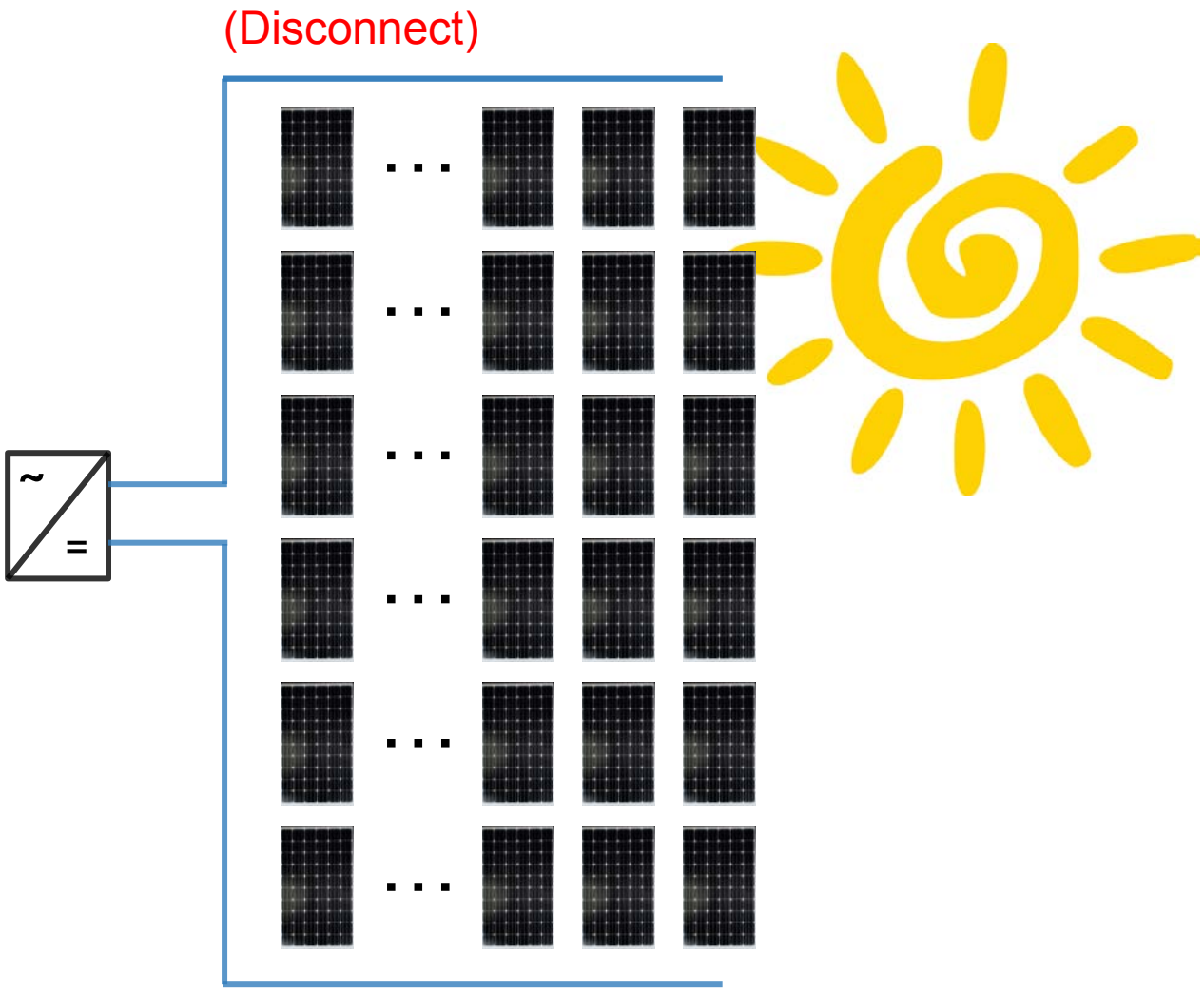
Modul level switch



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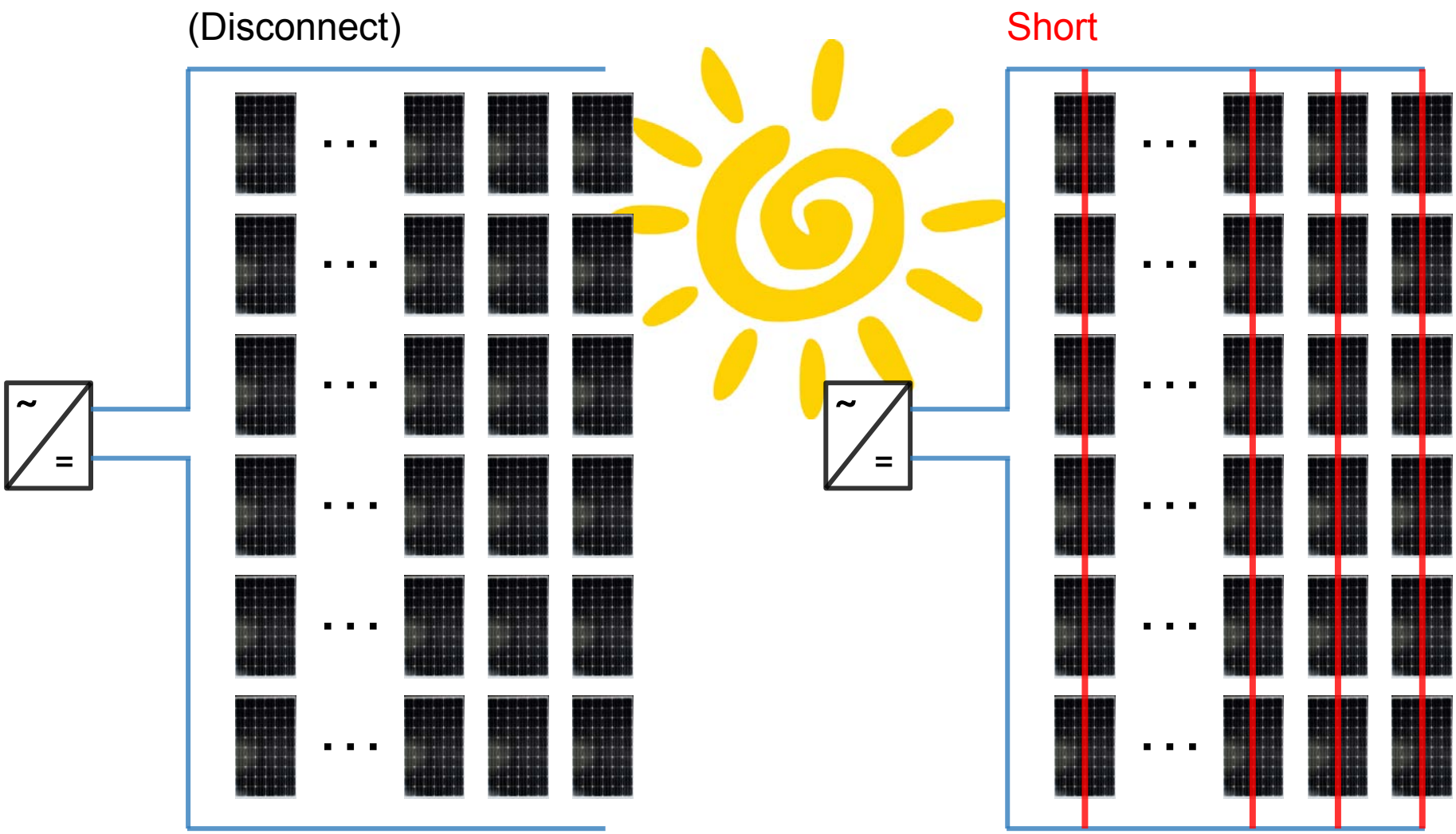
Modul level switch



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Modul level switch

- Modul switch for Emergency Off Emergency Off
  - Rapid-shutdown, Fire fighter disconnect
  - Voltage reduction in emergency to acceptable“ level
- Inverter with integrated Off function
  - DC/DC-Inverter
  - DC/AC- Inverter (micro inverter)
  - Additional function: Voltage reduction

Principal:
No voltage reduction for string => Disconnect or shorting on modul level

!

Increased safety required for Off function:

=> Actuation must always lead to safe disconnect

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Precisely Right.

Modulschalter in den USA Pflicht?

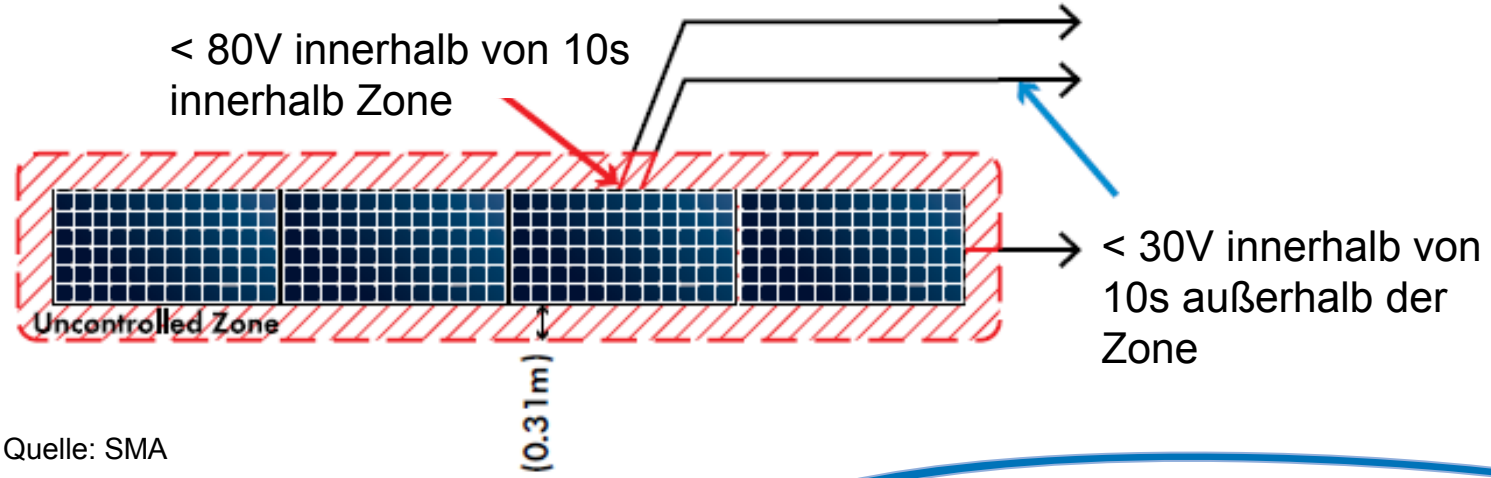
- geplante Änderungen NEC 2017 USA -

690.12 COMPLIANT

COMPLIES WITH NEC 690.12
MODULE LEVEL
RAPID SHUTDOWN

Planned change to National Electrical Code (NEC), ‚rapid shutdown':

- Voltage <u>within</u>, uncontrolled zone' U < 80 V within10s
- Voltage <u>outside</u>, uncontrolled zone' U < 30 V within 10s



Quelle: SMA

Only feaseable with modul level switch!

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Precisely Right.

Negativ Experience with string switches in Australia!

Firefighter switches are required in Australis since 2012!

- Before requirement no PV fires
- Now increased fires induced by low quality switches

REMOVE THE SOLAR DC ISOLATOR FROM THE ROOF!

This campaign has ended.

Campaign created by
Lucas Sadler

TO: ELECTRICAL STANDARDS AUTHORITIES

Please remove the need to install a DC Isolator on the roof alongside a Solar PV Array.

Please mandate that all DC Isolators are removed from current installations before we have more fires or worse a solar fire related fatality.

Why is this important?

The firefighter device putting solar systems - and homes - at risk

CHRISTOPHER T. J. DUSCH | 10 JUN, 11:16 AM |
CLIMATE | POLICY & POLITICS | RENEWABLE ENERGY | SOLAR ENERGY

The Australian solar PV market is on fire. Generous subsidies and support mechanisms have produced almost 2 million solar PV installations across the country, placing Australia among the leaders in solar PV deployment. It is also literally true; in that Australia is suffering a spate of solar-related fires, hundreds of them. The cause of these fires isn't the solar panels themselves but, rather, a device installed next to solar panels called a rooftop DC isolator (or disconnect) switch – a uniquely Australian requirement.

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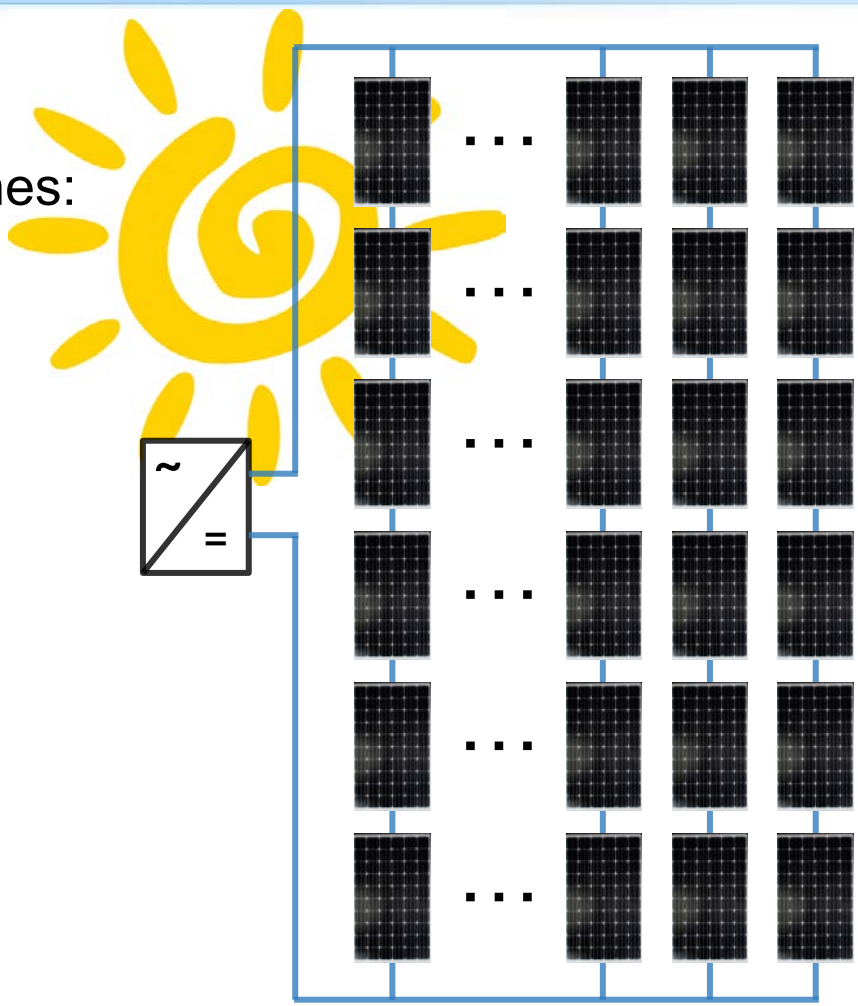
Precisely Right.

Specific tests for modul switches

Expanded requirements for modul switches:

- Stressed by climate
- Stressed by lightning
- Stressed by frequent operation
- Stressed by reverse currents



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Specific tests for modul switches
- Climatic stresses-

Spezification 2PfG 2305/06.13 (Test standard TÜV Rheinland)
‚Requirements for electronics to be integrated or implemented with PV modules‘

Test no.	Test sequence 1	Test sequence 2	Test sequence 3	Test sequence 4	Test sequence 5
Before	--	Preconditioning[1]	Preconditioning[1]	Preconditioning[1]	--
1	Resistance against aging *10 days @100 °C*	Initial measurement of contact resistance	Damp heat test *+85 °C @ 85% humidity*	Temperature cycle test *TC50*	Heating test *@max. operating Temperature*
2	Ingress protection *IP code*	Temperature cycle test *TC200*	Reference measuring of ratings	Humidity freeze test	Wet leakage current
3	Touch current test	Reference measuring of ratings	Touch current test	Reference measuring of ratings	--
4	High voltage test	Wet leakage current	Wet leakage current	Wet leakage current	--
5	Surge test	High voltage test	High voltage test	--	--
6	--	Measurement of contact resistance	--	--	--

No failures observed during climate tests

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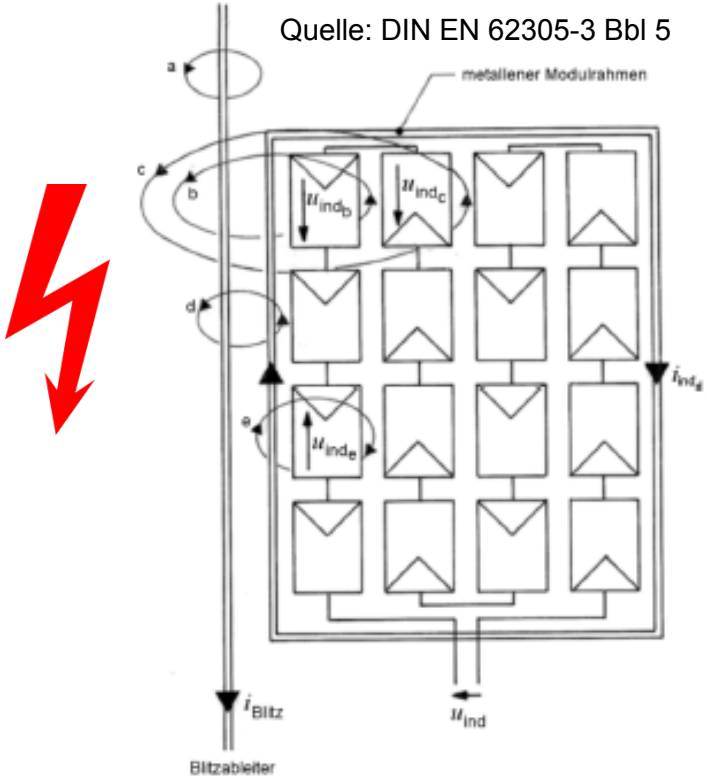
Specific tests for modul switches
- Stressed by lightning induced currents-

Quelle: DIN EN 62305-3 Bbl 5



- Lightning induced voltage in PV module

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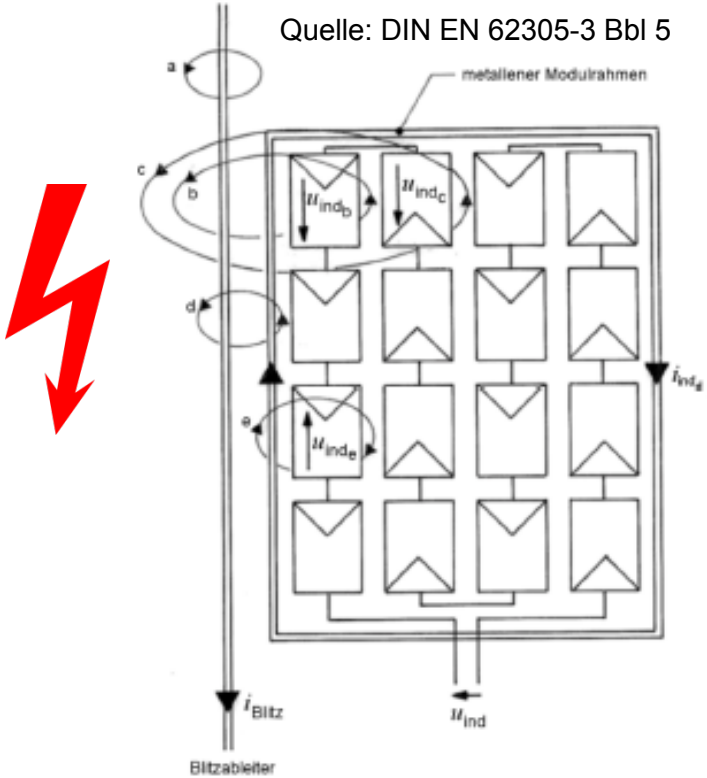
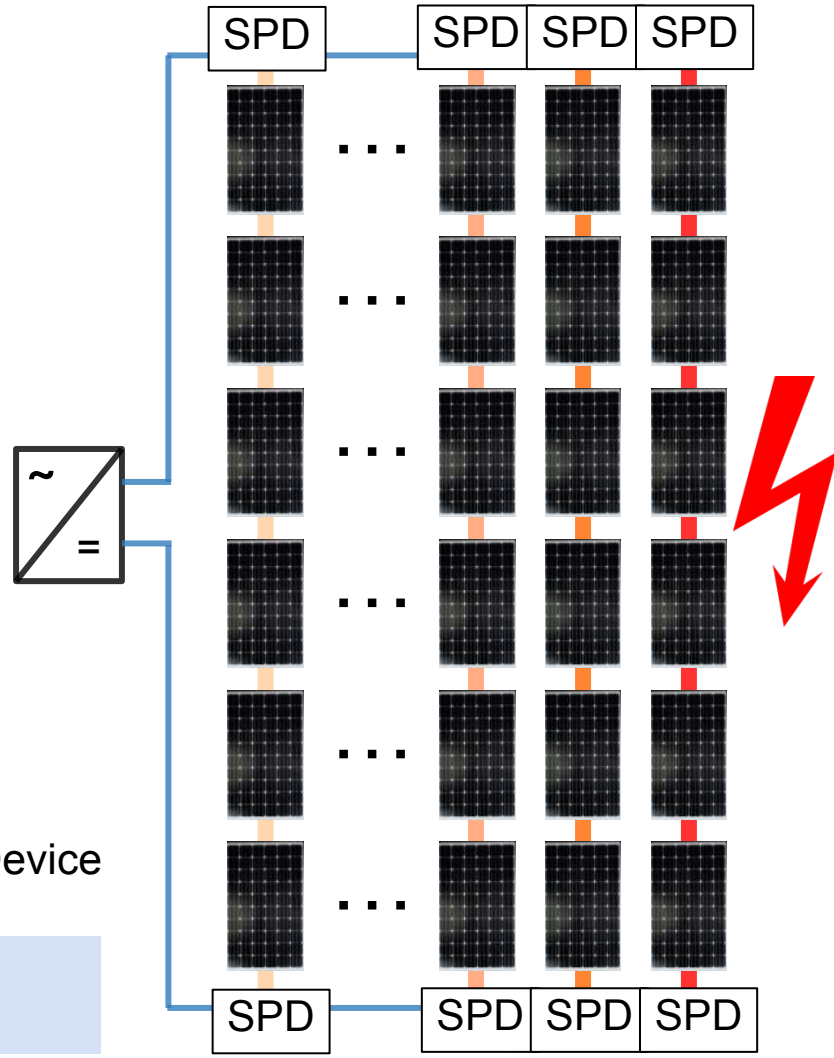
Precisely Right.

Specific tests for modul switches

- Stressed by lightning induced currents-

Quelle: DIN EN 62305-3 Bbl 5





- Lightning induced current in PV module
- Module, Inverter protected by Surge Protection Device (SPD)

! Lightning induced current transits switch

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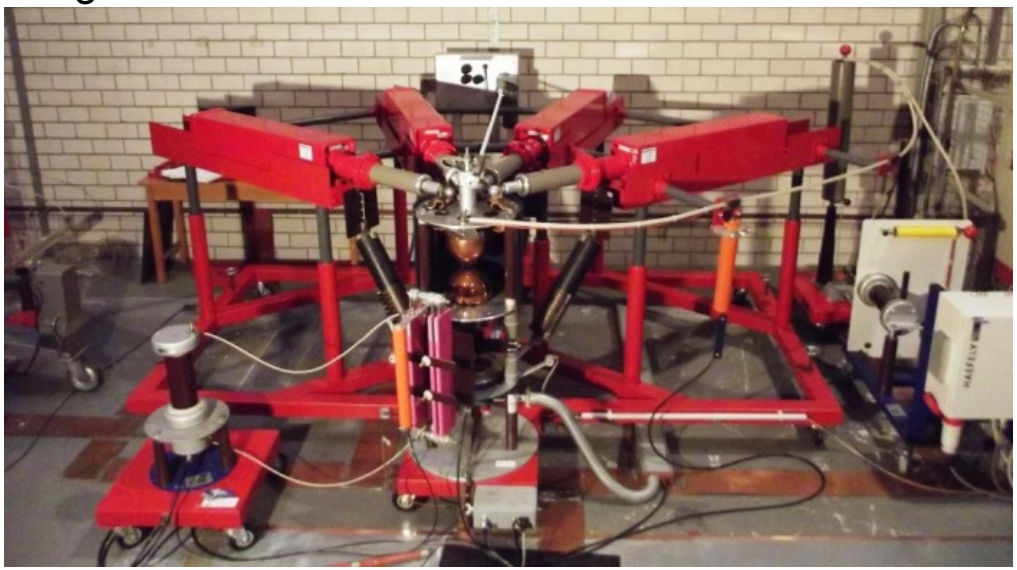
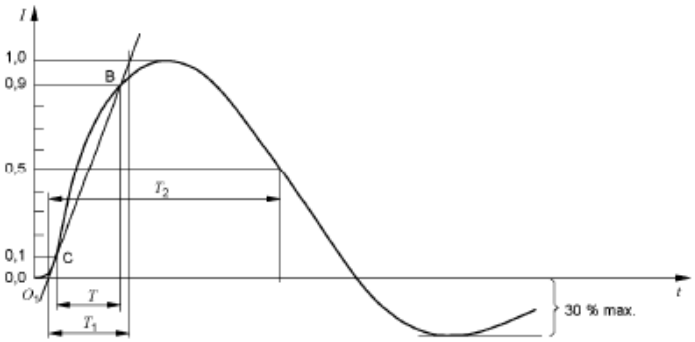
Specific tests for modul switches
- Lightning induced current stress -

Surge test fixture TH Köln





Stirnzeit T_1 = 1,25 × T = 8 µs ± 20 %
Rückenhalbwertzeit T_2 = 20 µs ± 20 %

Messung	Charakteristik	Anforderung an Prüfling	Resultat
Induced current	Puls (8/20), 20 kA	5 Surges in closed state	Functionality retained

! This test is especially severe for Semiconductor devices

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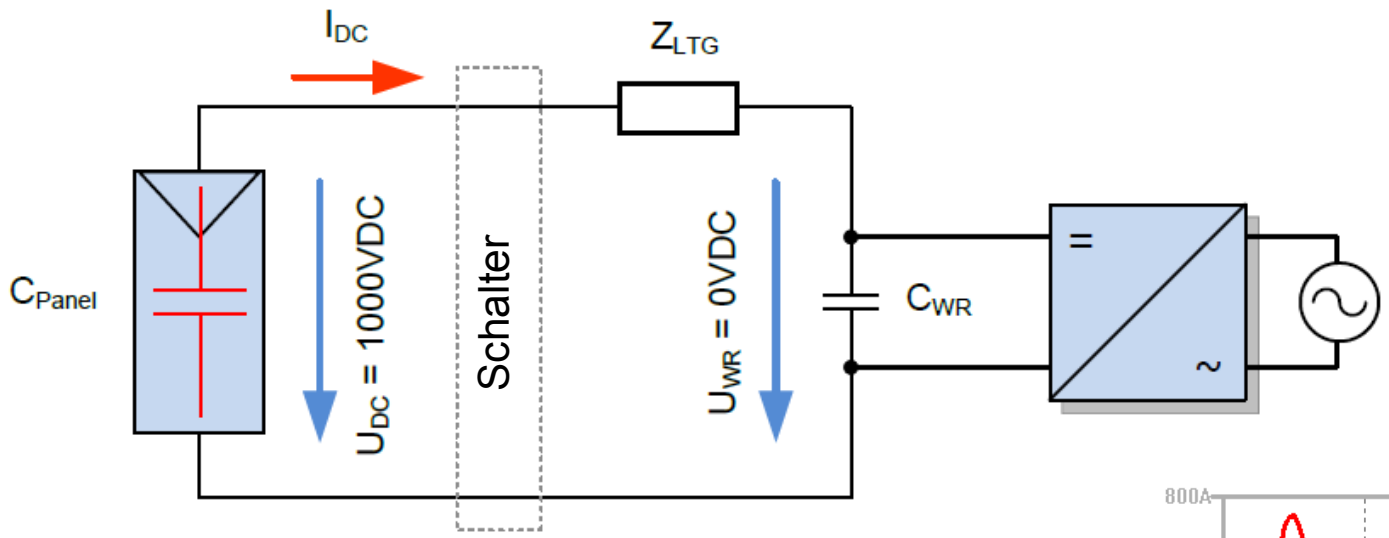
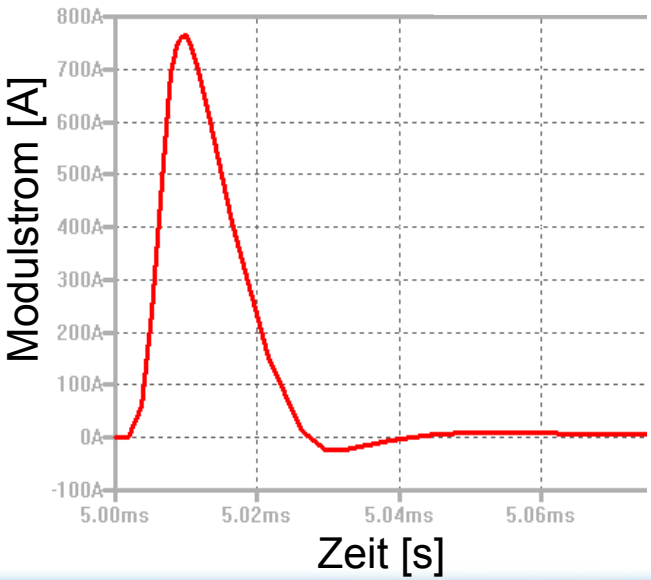
Precisely Right.

Specific tests for modul switches

- Stress by frequent operation -



Quelle: SMA



- Switching of module within inverter capability
- Transiente currents ≈ 1 kA

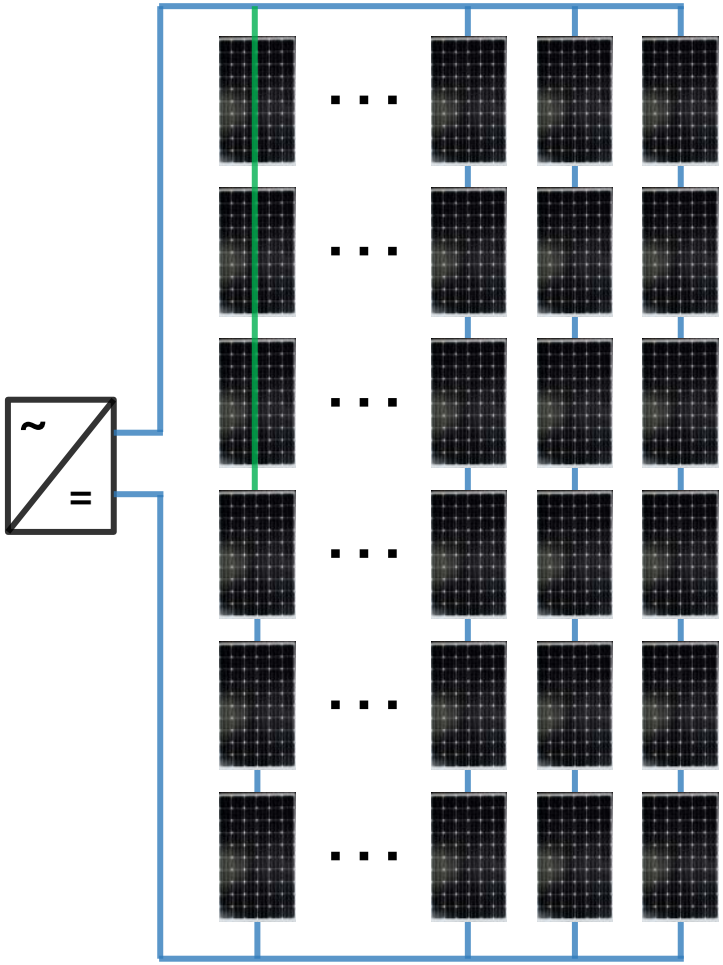
! Some module switches failed after few repetitions.

TÜVRheinland®
Precisely Right.

Specific tests for modul switches
- Stress by reverse currents -

Synchronicity of shorting:

– If NOT synchron…



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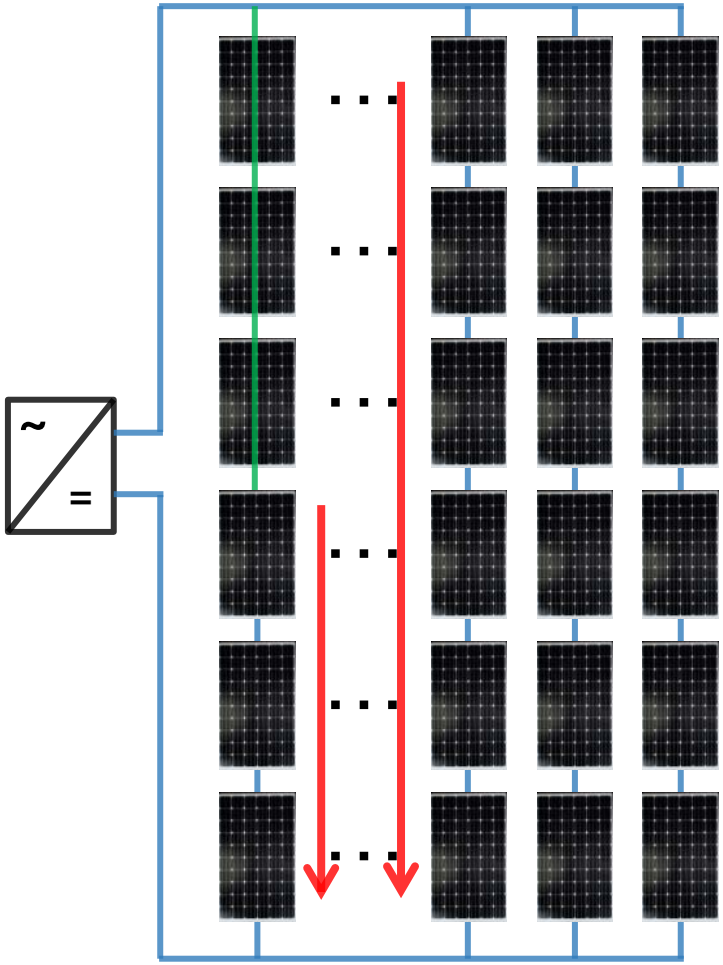
Precisely Right.

Specific tests for modul switches
- Stress by reverse currents -

Synchronicity during short circuit switching:

– If NOT synchron …

– Different voltage levels.



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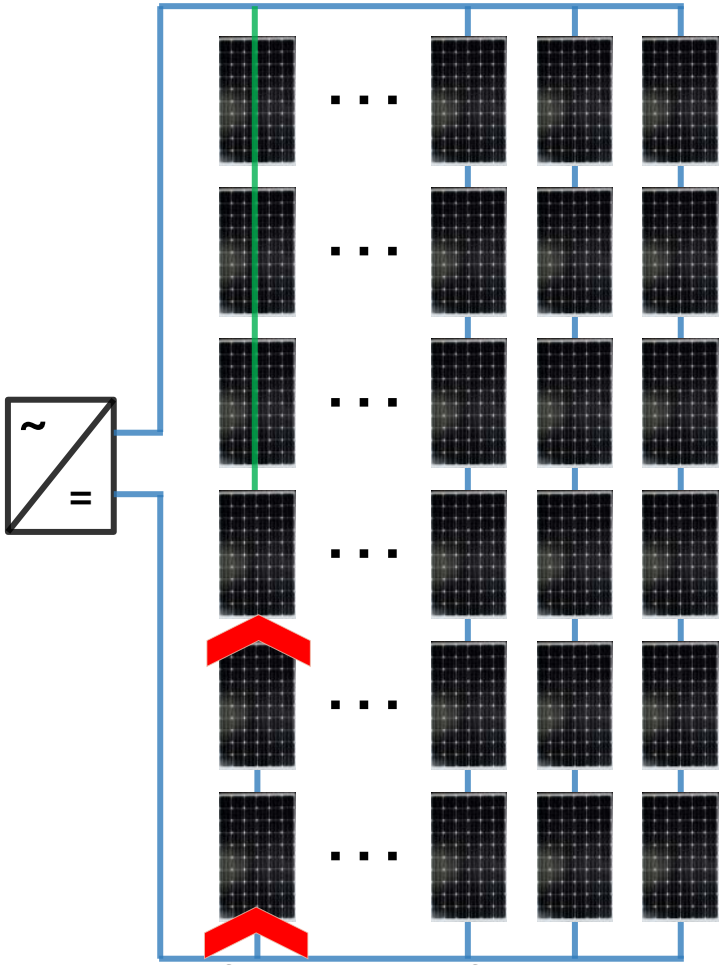
Precisely Right.

Specific tests for modul switches
- Stress by reverse currents -

Synchronicity during short circuit switching:

- If NOT synchron …

- Different voltage levels.
- These cause reverse currents in affected string that could damage the switch.
- Switches must be tested for reverse currents.



Note:
Only critical for systems of > 3 strings, for > 3 strings fuses are required.

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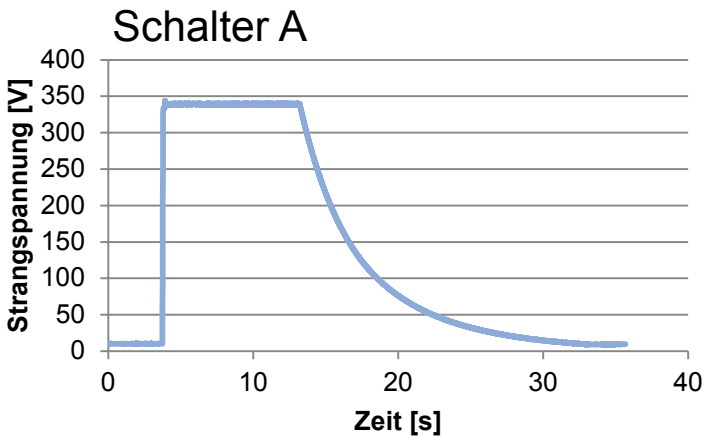
Precisely Right.

Specific tests for modul switches
- Stress by reverse currents -

Meassurement Synchronicity :

– Some switch types exhibit synchron behavior



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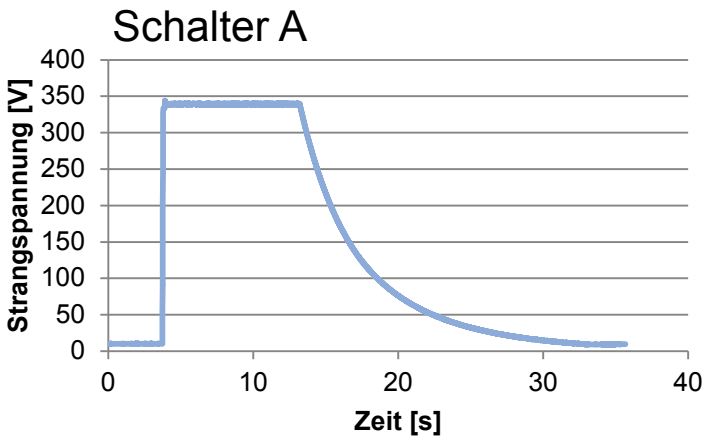
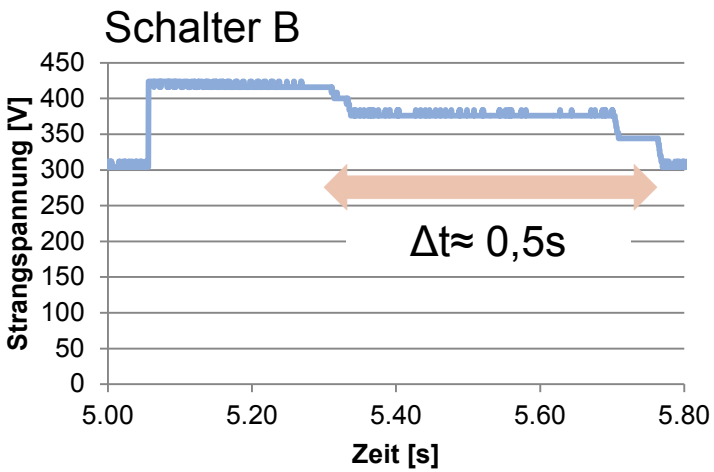
Precisely Right.

Specific tests for modul switches
- Stress by reverse currents -

Meassurement Synchronicity :

- Some switch types exhibit synchron behavior
- Other switch types show clear a-synchron behavior





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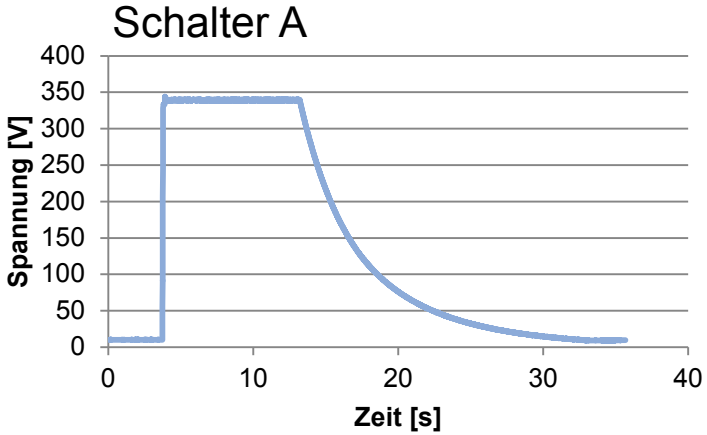
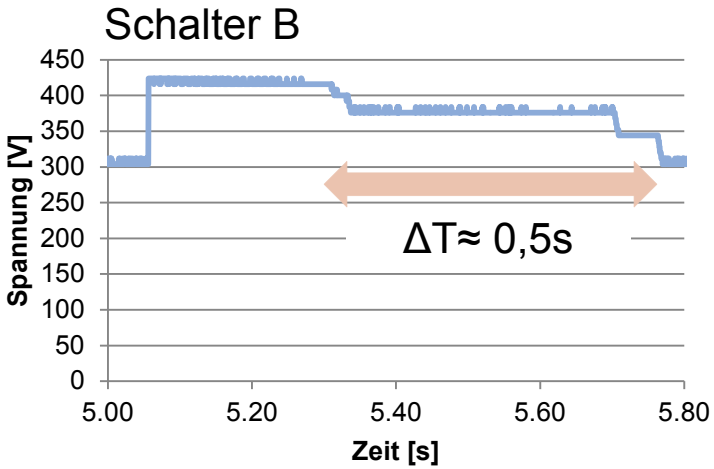
Specific tests for modul switches
- Stress by reverse currents -

Meassurement Synchronicity :

- Some switch types exhibit synchron behavior
- Other switch types show clear a-synchron behavior



Reverse current stresses can be elminated with other measures.



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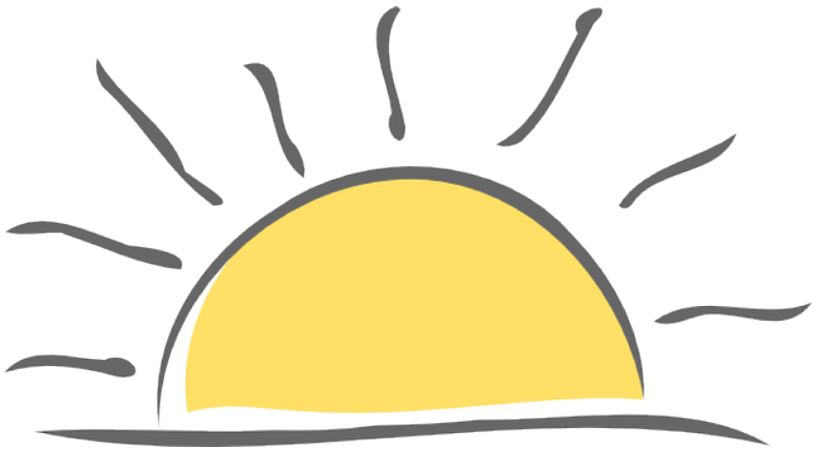
Additional considerations

– Behavior during sunrise



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Additional considerations

- Behavior during sunrise
- RF interference behavior

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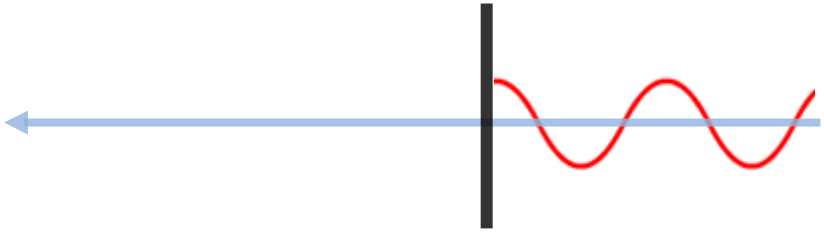
Additional considerations

- Behaviour during sunrise
- RF interference
- Behaviour with impared PLC function



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Additional considerations

- Verhalten bei Sonnenaufgang
- Störverhalten bei Funkkopplung
- Verhalten bei gestörter PLC
- Indikation Funktionsfähigkeit

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Summary

- If module level switches are used as E- Off switches additional requirements must be applied
- The example Australia shows that requiring modul level E – off switches can cause more hazards then are prevented
- The premise that module level E-off switches improve safety must be validated.
- We need to widen the discussion and conduct the research with scientific rigor to support decisions!

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Precisely Right.

Danksagung

Gefördert durch:

Bundesministerium
für Wirtschaft
und Energie

aufgrund eines Beschlusses
des Deutschen Bundestages

The project “PV-Firebreaker” (FKZ:0325596) was sponsored by the Bundesministerium für Wirtschaft und Energie gefördert.

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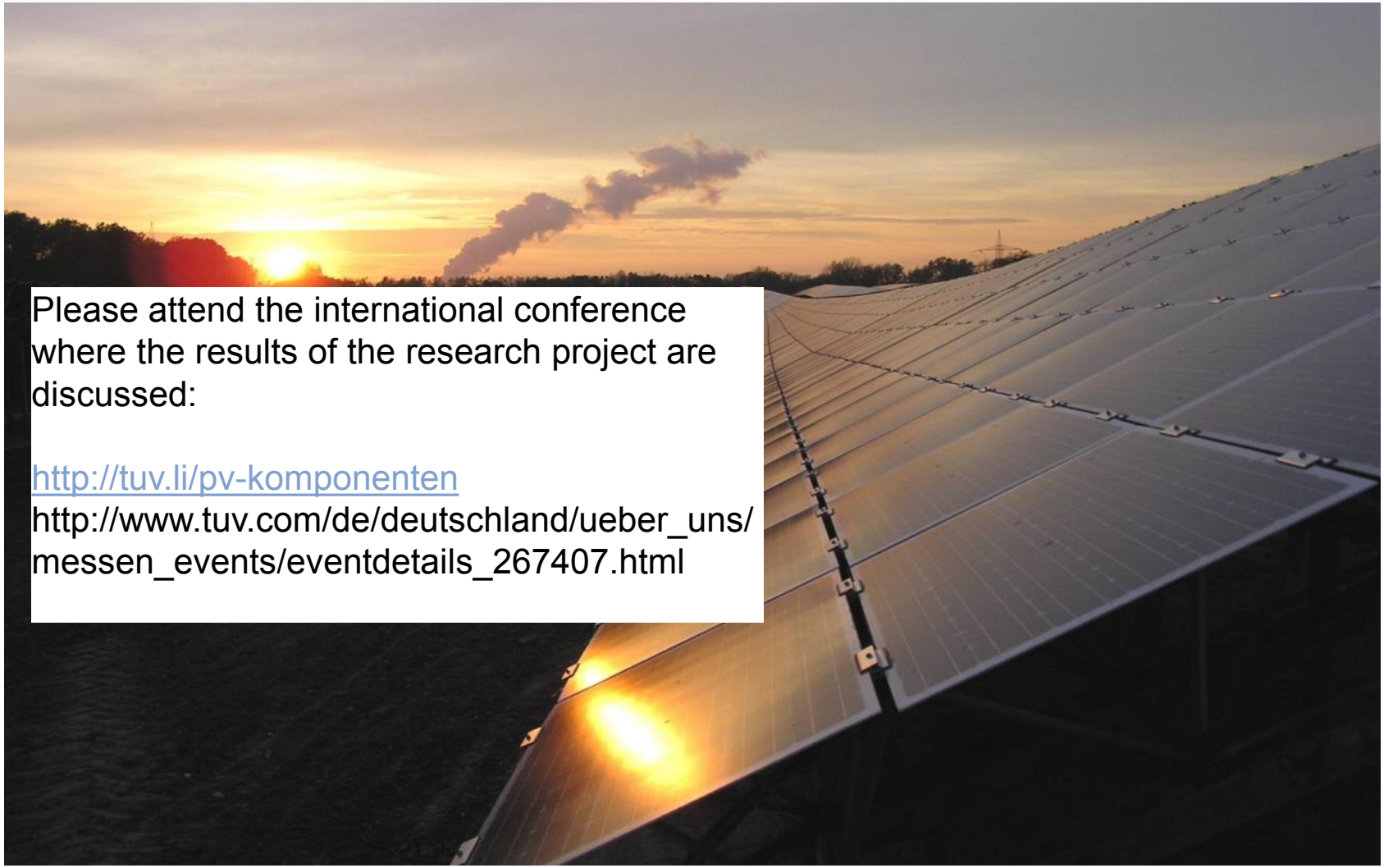
ENGINEERING TECHNOLOGY

SMA
SOLAR TECHNOLOGY

- Ralf-Martin Müller, Andreas Berghaus (Projektkoordination)
- Michael Slawik, Johannes Ellmann (Messergebnisse)

Thank you for your attention!



Please attend the international conference where the results of the research project are discussed:

http://tuv.li/pv-komponenten
http://www.tuv.com/de/deutschland/ueber_uns/messen_events/eventdetails_267407.html

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Precisely Right.

Fire Service Perspective 690.12 Rapid Shutdown

CA Matthew Paiss, IAFF Rep to NEC

NREL PV Reliability Workshop, Feb 25 2016

International Association of Fire Fighters

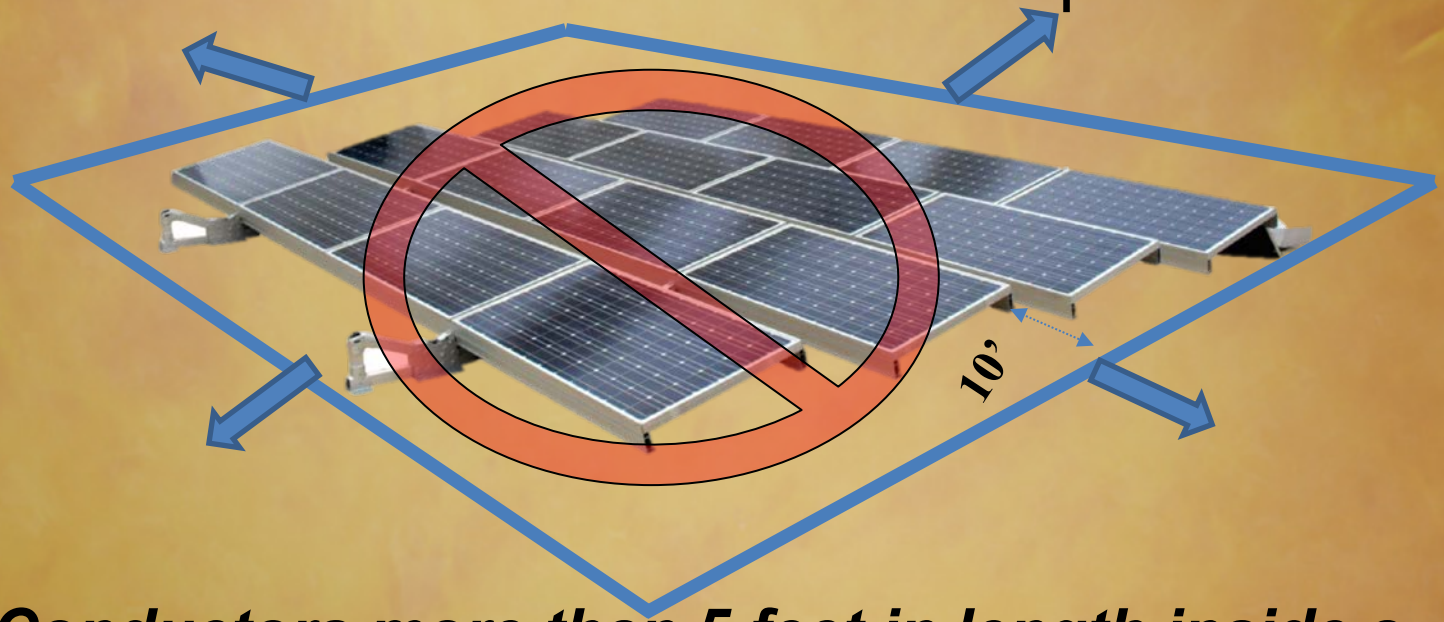
- Formed in 1918
- Today represents over 300,000 career fire fighters across North America
- 85% of the US population is protected by IAFF members.

"The IAFF is the driving force behind nearly every advance in fire and emergency services in the 20th century"

PV Safety & Rapid Shutdown (RSS)

690.12 Rapid Shutdown of PV Systems on Buildings (2014 NEC)

The area within a 10’ boundary of the array remains at Voc after main disconnect is opened.



“Conductors more than 5 feet in length inside a building, or more than 10 feet from a PV array are covered by 690.12”

Concern Examples

Inability to shut off array

- Accidental Contact with Damaged Array
  - *First Responders, Maint. Personnel, Property Owners, etc…*
- Unmonitored Systems (inverters offline)
  - *Re-ignition of energized damaged components*
  - *No O&M program in place for many systems*
- Contacting Qualified Technician
  - *Response time, still in business?*
  - *Liability in releasing property to occupants*

We see strange stuff

Supporters of IAFF Proposal

Fire Service – *1.2M Fire Fighters in US*
National Association of State Fire Marshals
California Office of the State Fire Marshal
International Association of Fire Chiefs
International Code Council (FLSS)
National Volunteer Fire Council

Insurance Industry
Zurich
FM Global
XL Group
Liberty Mutual

PV Fires & System Reliability

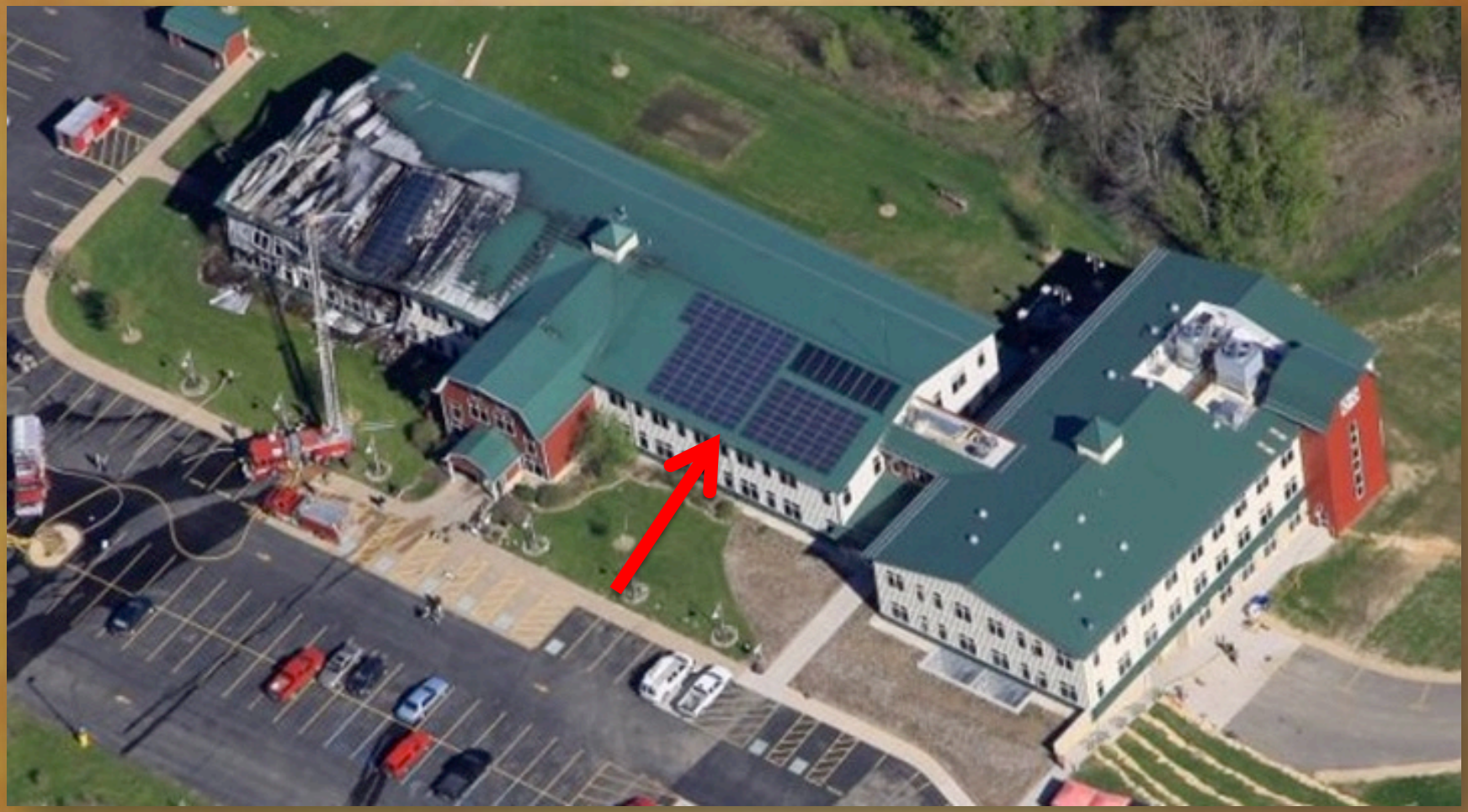
- Data only avail from media reports.
  - Often sensational & incomplete
  - Lack of industry cooperation = poor optics
  - There will be more fires in pre 2011 systems
  - Hoverboard fires damaging to ES industry

- Reliability research is needed to ensure new products do not decrease safety.
  - RSS Standard will need development funding

Case Study #11:
La Farge, WI May 2013

Metal Roof Energized by PV System

50Vdc ~ 100’ Away



Damage Hazards

Hail

Damage Hazards

Wind

Damage Hazards

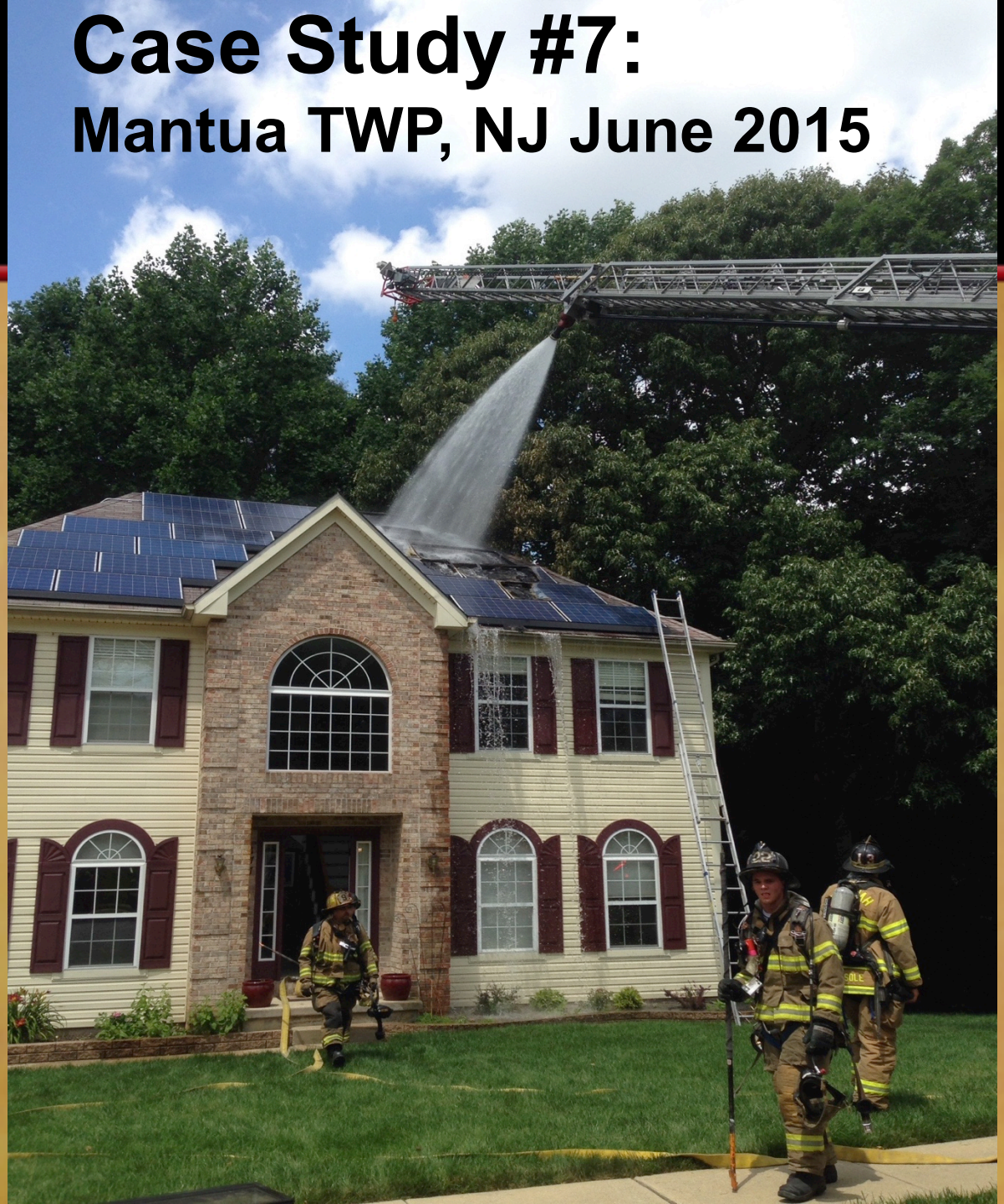
Mechanical

Damage Hazards

Rodent Damage

O&M (and plant) Gaps

Case Study #7:
Mantua TWP, NJ June 2015



NJ adopted 2011 NEC in 2012

- Was AHJ enforcing 690.11? (DC AFCI)

Did this inverter have DC AFCI?

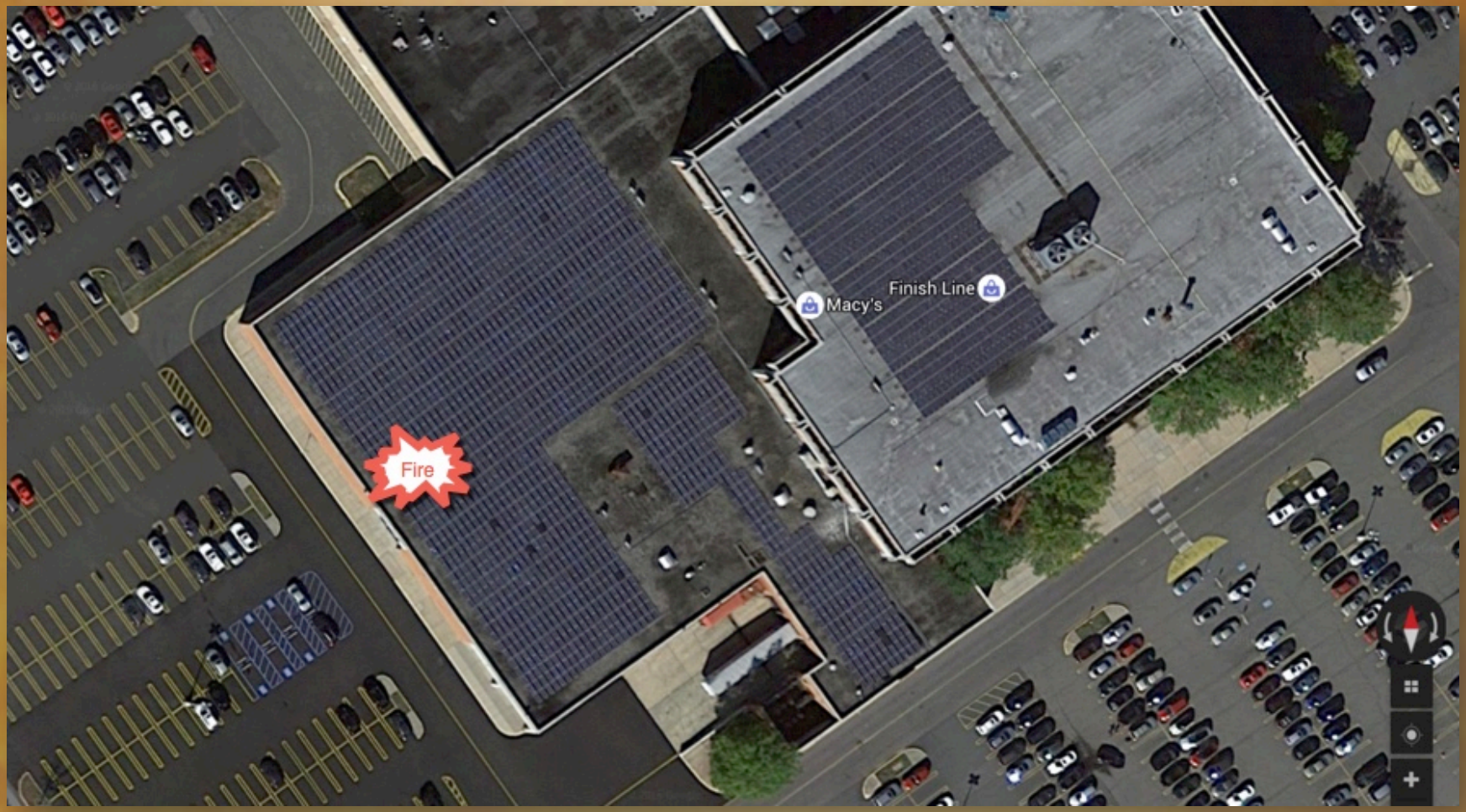
No? (Minor problem)

Yes? (Major problem)

Are undetected AF's occurring?

Case Study #11:
East Brunswick, New Jersey – Feb 2016

Cause Undetermined
GF or AF?



Fire Rated Roof?

IREC – 2016
Online PV Safety Training

IREC
Interstate Renewable Energy Council, Inc.

+

Free On-Line Learning Module
Coming to the IAFF Website Winter 2016

690.12 Rapid Shutdown of PV Systems on Buildings (2017 NEC)

- Most active proposal in terms of public comments and concern.
- Addresses all building mounted PV systems
- Delayed implementation to allow continued standards development

690.12 (B) Controlled Limits

(B) Controlled Limits.

The use of the term, array boundary, in this section is defined 305 mm (1 ft) from the array in all directions. Controlled conductors outside the array boundary shall comply with 690.12(B)(1) and inside the array boundary shall comply with 690.12(B)(2) .

690.12 (B)(1) Outside the Array

(1) Outside the Array Boundary.

Controlled conductors located outside the boundary or **more than 1m (3 ft)** from the point of entry inside a building shall be limited to **not more than 30 volts** within 30 seconds of rapid shutdown initiation. Voltage shall be measured between any two conductors and between any conductor and ground.

690.12 (B)(2)(a) Inside the Array

(2) **Inside the Array Boundary.**

The PV system shall comply with (a), (b), or (c):

(a) The PV array is listed and labeled or field labeled as a rapid shutdown PV array. Such a PV array is installed and used in accordance with the instructions included with the rapid shutdown PV array listing and labeling or field labeling.

690.12 (B)(2)(b) Inside the Array

(b) Controlled conductors located inside the boundary or not more than 1 m (3 ft) from the point of penetration of the surface of the building shall be limited to not more than 80 volts within 30 seconds of rapid shutdown initiation. Voltage shall be measured between any two conductors and between any conductor and ground.

690.12 (B)(2)(c) Inside the Array

(c) PV arrays with no exposed wiring methods, no exposed conductive parts, and installed more than 2.5 m (8 ft) from exposed grounded conductive parts or ground.

The requirement of 690.12(B)(2) shall become effective January 1, 2019.

(C) Initiation Device

(C) Initiation Device.

The initiation device(s) shall initiate the rapid shutdown function of all the PV system . The device **"off" position** shall indicate that the rapid shutdown function **has been initiated** for all PV systems connected to that device.

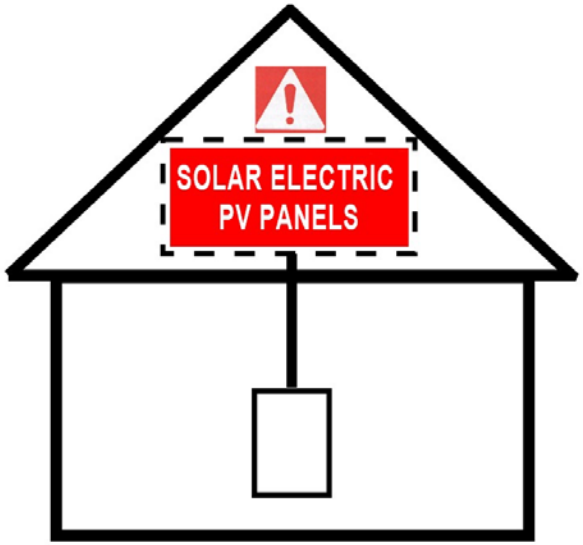
For one-family and two-family dwellings, an initiation device(s) shall be located at a readily accessible location **outside** the building.

Rapid Shutdown

2014 NEC Compliant Marking

SOLAR PV SYSTEM EQUIPPED WITH RAPID SHUTDOWN

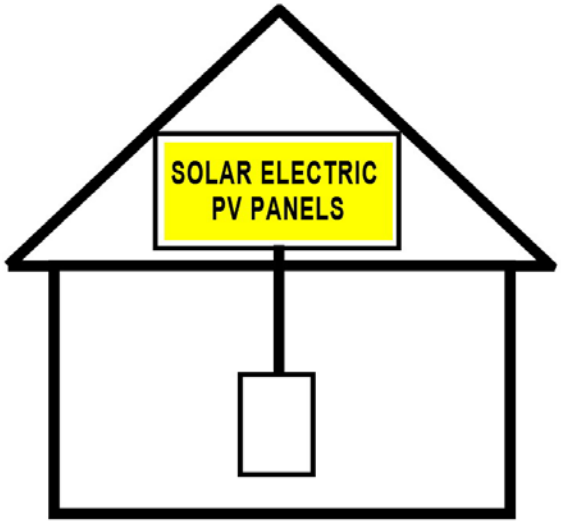
TURN RAPID SHUTDOWN SWITCH TO THE "OFF" POSITION, TO SHUTDOWN CONDUCTORS OUTSIDE THE ARRAY. CONDUCTORS WITHIN ARRAY REMAIN ENERGIZED IN SUNLIGHT



Rapid Shutdown
2017 NEC Compliant Marking

SOLAR PV SYSTEM EQUIPPED WITH RAPID SHUTDOWN

TURN RAPID SHUTDOWN SWITCH TO THE "OFF" POSITION TO SHUTDOWN PV SYSTEM AND REDUCE SHOCK HAZARD IN ARRAY



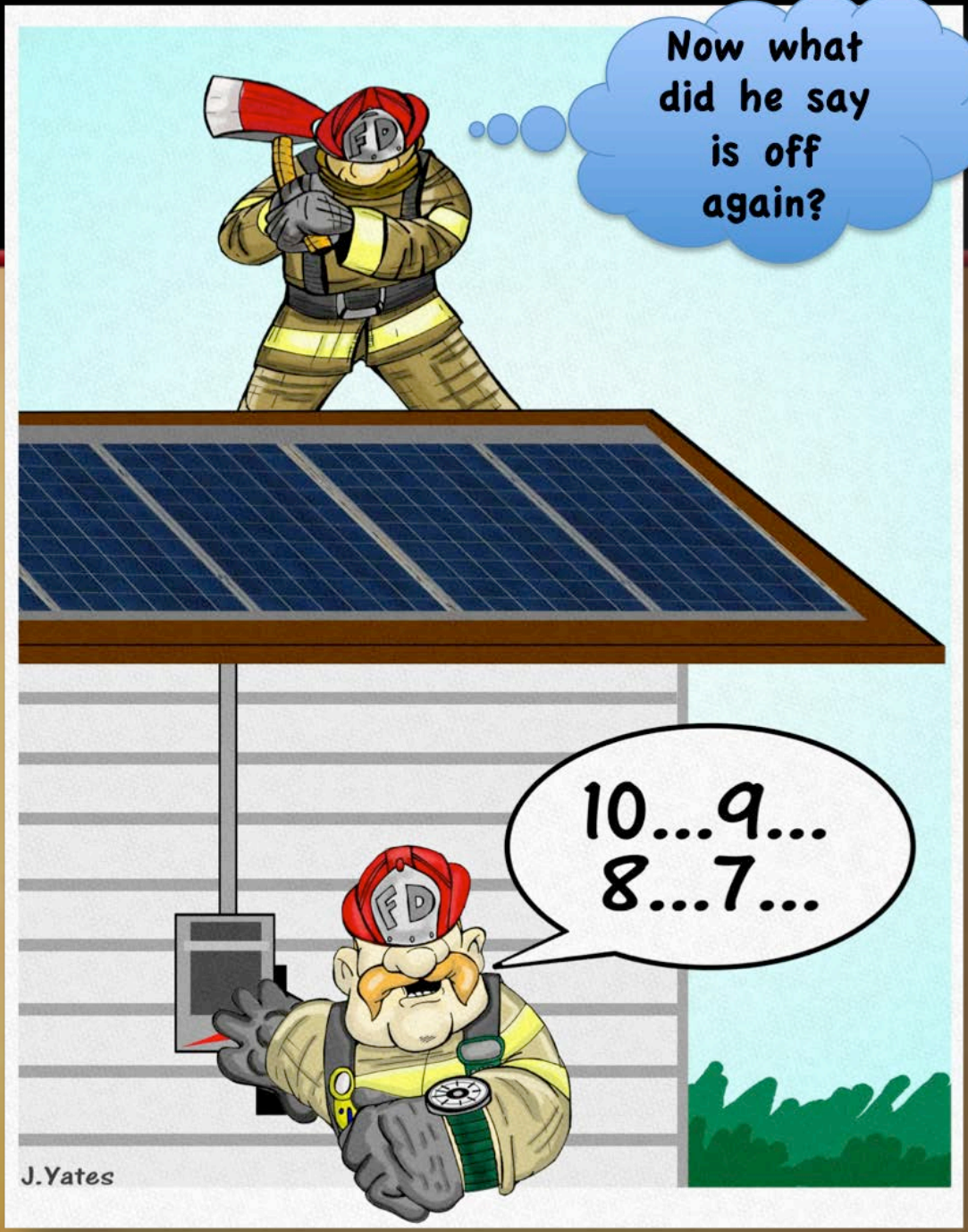
Conclusion

- 80Vdc intended as one of 3 options.
  - 30%-50% of resi systems installed today.
  - While not off, significant reduction of hazard from 600-1000Vdc.
  - Standard must address fail safe components.
- “Listed Rapid Shutdown Array” must present an equal or higher level of safety.
- Same language submitted to the 2018 IFC

Thank you.

CA Matthew Paiss,
IAFF Rep to NEC

mpaiss@gmail.com



Certifications and Standards related to NEC 690.12 Rapid Shutdown Components and Systems

Tim Zgonena

UL LLC

February 24, 2016

2014 NEC - 690.12 Intent

This system is intended to be used by fire fighters to reduce hazards of working around a electrically live PV array and its wiring. This article is intended to establish a safe perimeter around a PV array via functions such as an output disconnect or a function that attenuates or limits the PV array output power to a low level.

- PV Output
  - 30V
  - 10 seconds
- Perimeter
  - 10ft on surface
  - 5ft into building

What is a CRD?

- Certification Requirement Decision (CRD)

- Establishes published set of requirements to address the technical safety concerns in the absence of existing published requirements.
- Upon publication the CRD is required to be submitted to the STP for review and comment with intention to be included into the published standard.
- CRDs are useful tools for standards with fast growth like DG.

UL1741 CRD April 2nd 2015

2014 NEC 690.12 published before an equipment standard.

Product submittals led to a 16 page CRD for rapid shutdown equipment.

- Electrical Isolation Systems (EIS) and Electrical Output Attenuation Systems (EOAS).
- PVRSS that include PV Disconnect Functionality.
- Functionality can be built into PV BOS equipment – inverters, combiners, disconnects.

UL 2014 NEC
PV RSS Certification Categories

- **QIJS - Photovoltaic Rapid Shutdown Systems**
- **QIJW -Photovoltaic Rapid Shutdown System Equipment**
- **QIJW2 - Photovoltaic Rapid Shutdown System Equipment - Component**

Where are we now?

- Concurrent with the publication of the PV RSS CRD a corresponding UL1741 revision proposal was sent to the UL 1741 STP to start the consensus development process.
- That draft received many good STP comments.
- A large PV RSS industry task group lead by Larry Sherwood has been working on revising and modifying that UL proposal draft in preparation for the STP ballot.

Task Group Revising the UL CRD/ UL1741 SPT Draft Proposal for PV Rapid Shutdown Equipment and Systems

- **Protection of Emergency Personnel**
- **Status Indicators, Initiators and Reset Devices**
- **PVRSS that Includes PV Disconnect Functionality**
- **Operational Tests for PVRSS Verification of levels – Controlled Conductors.**
- **Verification Testing of PVRSS at Rated Extremes**
- **Power Supply Ride Through**
- **Inverters Certified as PVRSE**
- **PVRSS and PVRSE Functional Safety Using Solid State Controls**
- **Functional Safety Standards**
- **Conditions to be Addressed for a PVRSS/PVRSE**
- **Functional Safety Evaluation For PVRSS/PVRSE Using Solid State Controls**
- **Environmental Stress Testing (based on UL991)***
- **Ratings, Markings and Instructions.**

Larry Sherwood
Task Group Leader
"Chief Cat Herder"

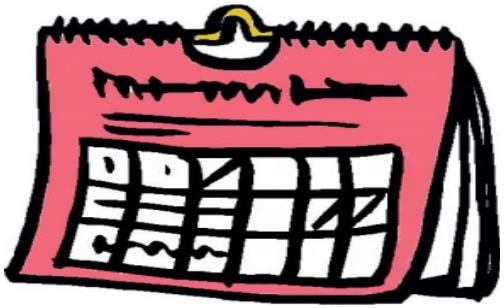
UL STP Timeline to Publish 2014 NEC PV RSS Requirements

- We anticipate the UL1741 task group will complete its work in March 2016 and sent back to the 1741 STP to start the CSDS ballot process.
- 45 days STP comment period on revised draft.

~ 15 days Task group review of STP comments. Make revisions and changes as task group deems necessary.

- 45 days STP Ballot on revised draft.
- ~ 15 days task group review and respond to STP comments and that may include revisions.
- Recirculate draft comment responses Minimum 2/3 affirmative votes to reach consensus.

Likely publication in mid 2016.



2017 Revisions to NEC 690.12

690.12 revision to include new requirements for rapid shutdown protection internal to a PV array. This is proposal requires the following options;

A) Listed PV array level protection system.
B) 80V, 30 Second Limit for controlled conductors internal to the array.
C) PV arrays with no exposed wiring methods, no exposed conductive parts, and installed more than 8ft from exposed grounded conductive parts or ground.

New Informational note to better explain possible implementations to reduce shock hazards by methods such as limiting access to exposed components that might become energized, reducing the voltage difference between energized components, limiting the electric current that might flow in an electrical circuit involving personnel with increased resistance of the conductive circuit, or by a combination of such methods.

New UL Standard to Address PV Array Protection Related to Rapid Shutdown

There is significant agreement and support from PV industry and fire fighters to develop a new consensus safety standard to address PV Rapid Shutdown Array protection.

While this effort can start and make good progress is critical that we do not make the same mistake again and assume we know the solution to an unknown question.

We need research to guide this effort!

New UL Standard for PV Rapid Shutdown Arrays

- Implementation / Solutions for 690.12 2017 will come in a variety of shapes and sizes.
  - Electrical
  - Mechanical
  - Installation based
  - Combinations there of

- This new standard will make use of the UL1741 electrical PVRS equipment requirements as well as other standards for PV modules UL1703, their installation UL2703, PV wiring UL9703 and more.

Goals for New PV RS Array Standard

- The new standard/requirements for PV array RS systems will be:
  - Science-based
    - FMEA what can failures lead to
    - HBSE
      - » identify hazards/concerns to be avoided,
      - » evaluate protective measures to reduce the risk, severity and probablity of such an event.
  - Written to address specific defined hazards and safety concerns.
  - Written to define specific normal and abnormal conditions of use.
  - Written to try to be implementation agnostic so as to allow for a range of product designs, concepts and innovations.

PV RS Array - Biggest Challenge

After 3 years of work on this rapid shutdown topic, there are still no clearly defined specific hazard conditions that need to be addressed to increase the safety before, during and after fighting fire on a building with PV.

1. Perform research to define what hazards PV RS needs to address. We need a consensus effort to specifically agree on the particular scenarios we are trying to address.
2. Use Science and Hazards Based Safety Engineering HBSE to develop requirements and tests to mitigate the hazards.
3. Movement to a solution that leverages technology in the most effective way for the PV and fire fighter communities.
4. This will help industry design, build, certify and sell products to reduce the hazards for fire fighters.

This New Challenge Needs Research to Determine what Specific Problems PVRS is Intended to Solve?

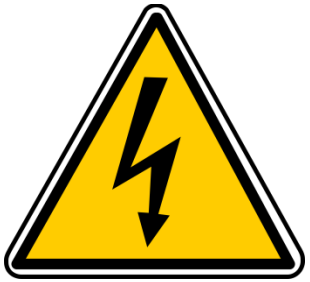
Identify and explore additional fire safety research and/or testing to better define the science upon which these requirements will be based.

1. Who needs protection?
2. Protection from what hazards?
3. Under what electrical and environmental conditions?

PV RS Voltage and Electric Shock

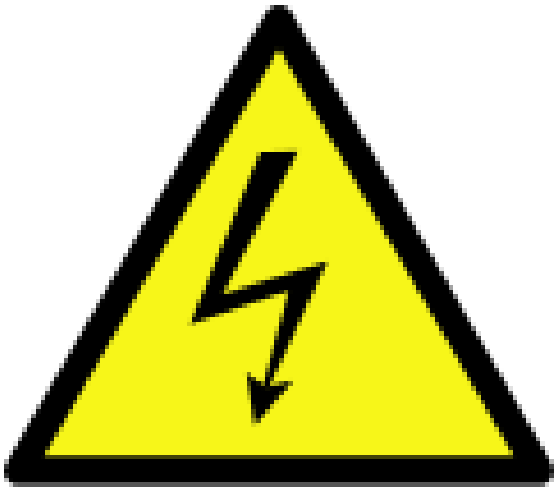
Location	DC Voltage
Dry	60Vdc
Wet (casual contact)	30Vdc
Wet Glove (large contact area)	< 30V (This limit needs more research)

We need to better define the FF interactions with different types of PV arrays.



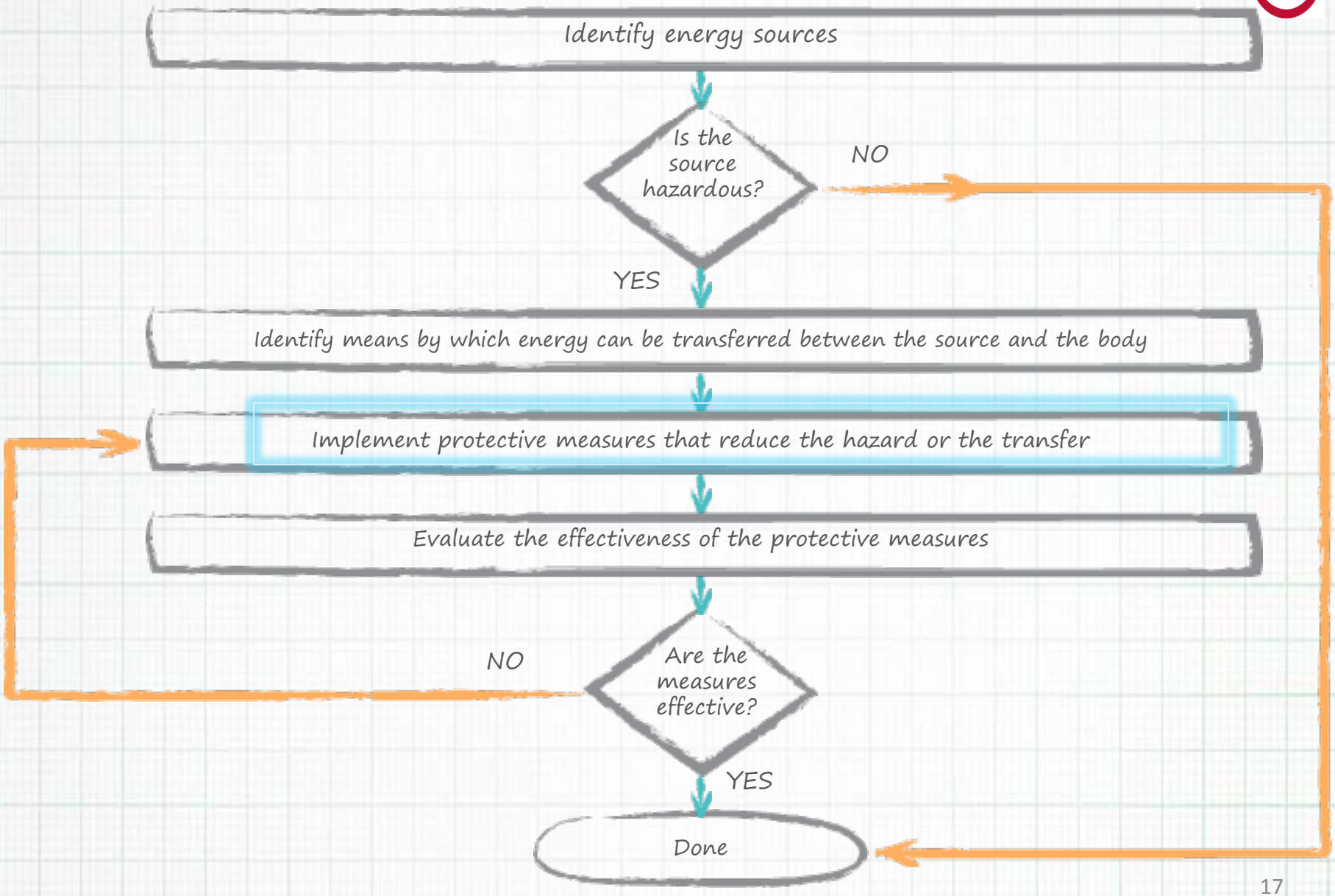
It Is Not Just the Voltage

While limiting voltage is <u>one</u> means to reduce electric shock hazards there are many other ways to reliably reduce shock hazards. This new standard will develop commonly applied other protection methods for this PV Array application in a manner that is based upon engineering and science.

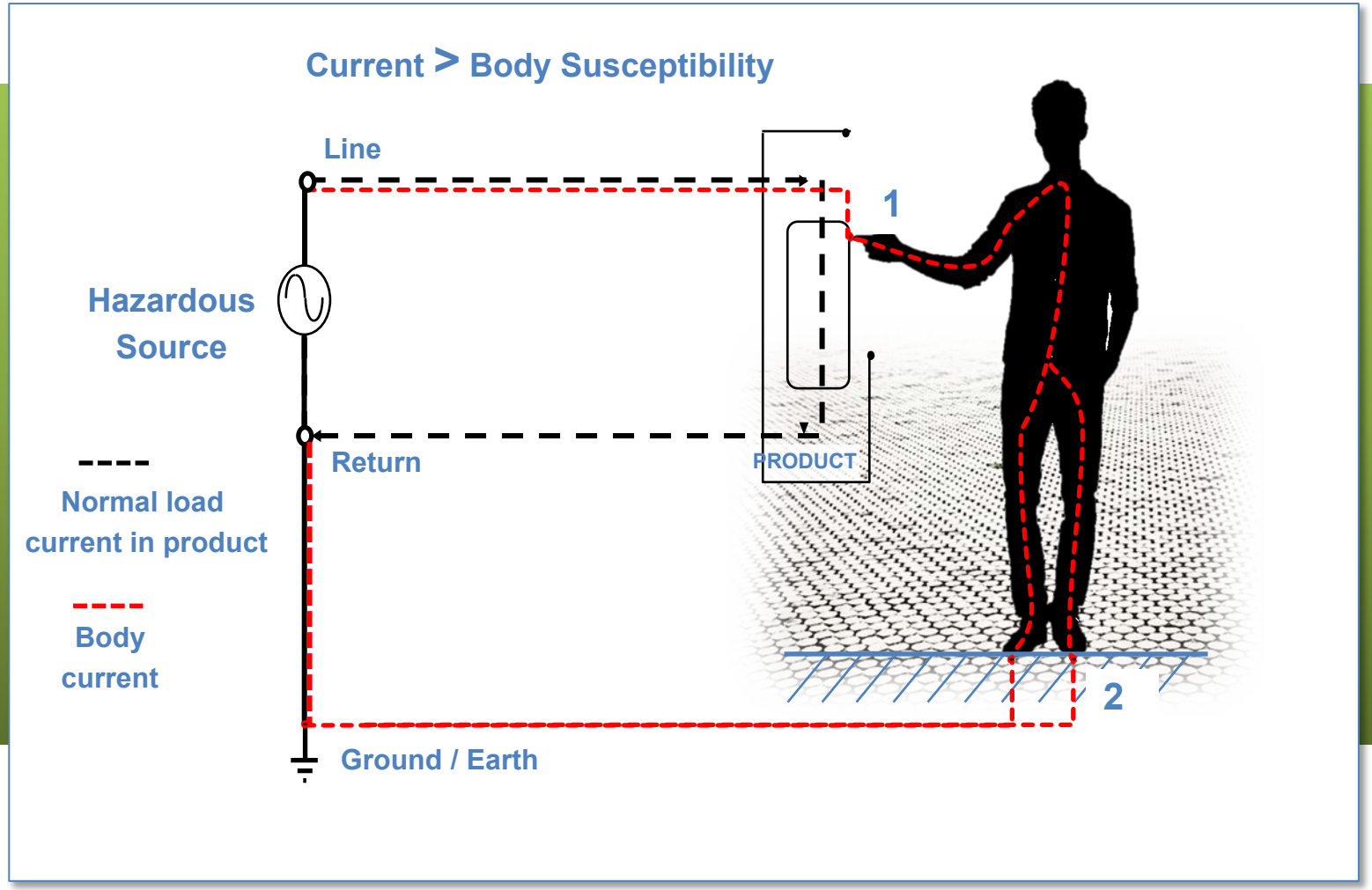


LOW VOLTAGE LABS

Hazard Based Protective Measures

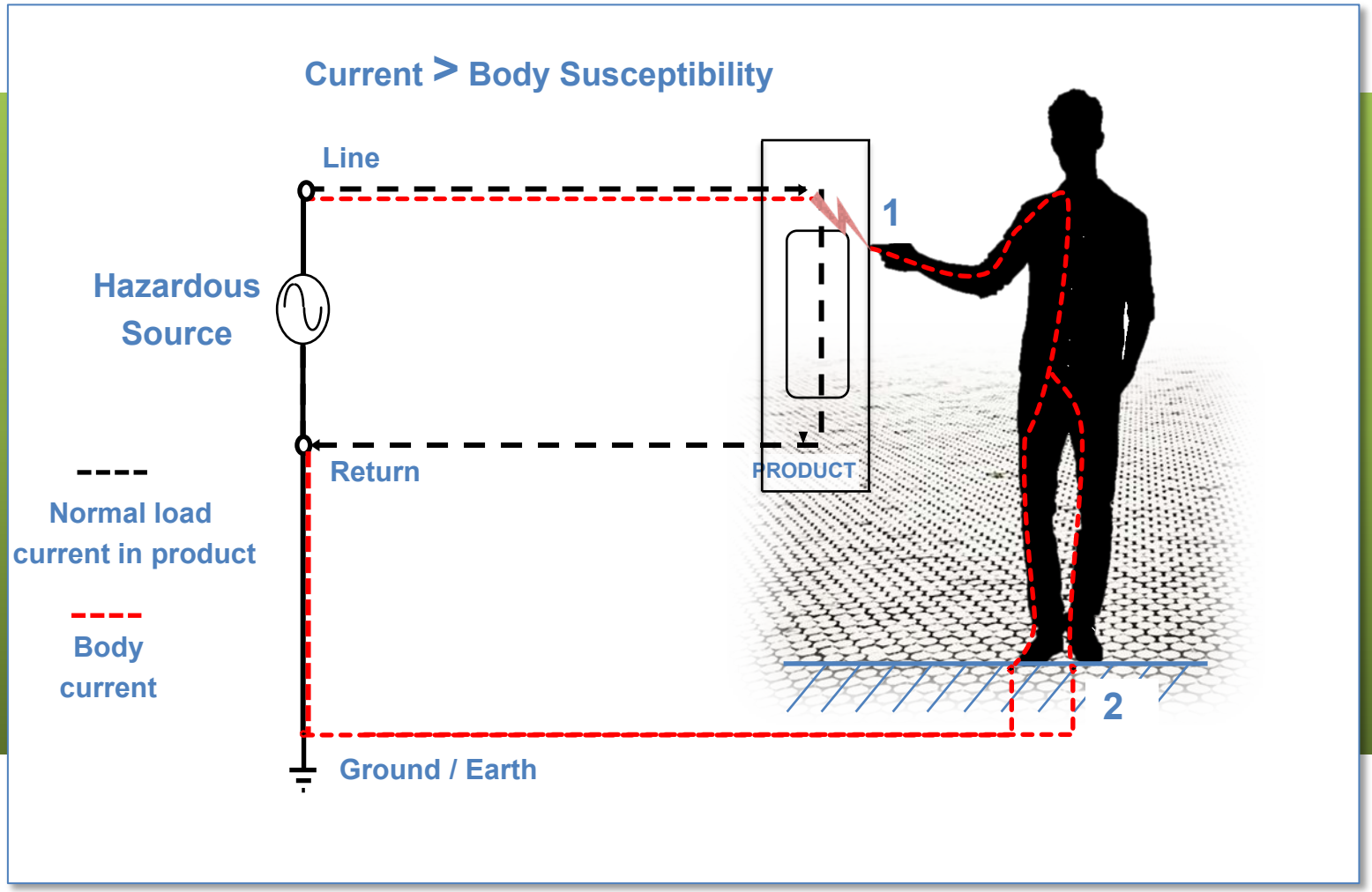


General Safety Objective: No Hazardous Body Current



Hazardous body current to be reduced by safeguards

General Safety Objective: No Hazardous Body Current



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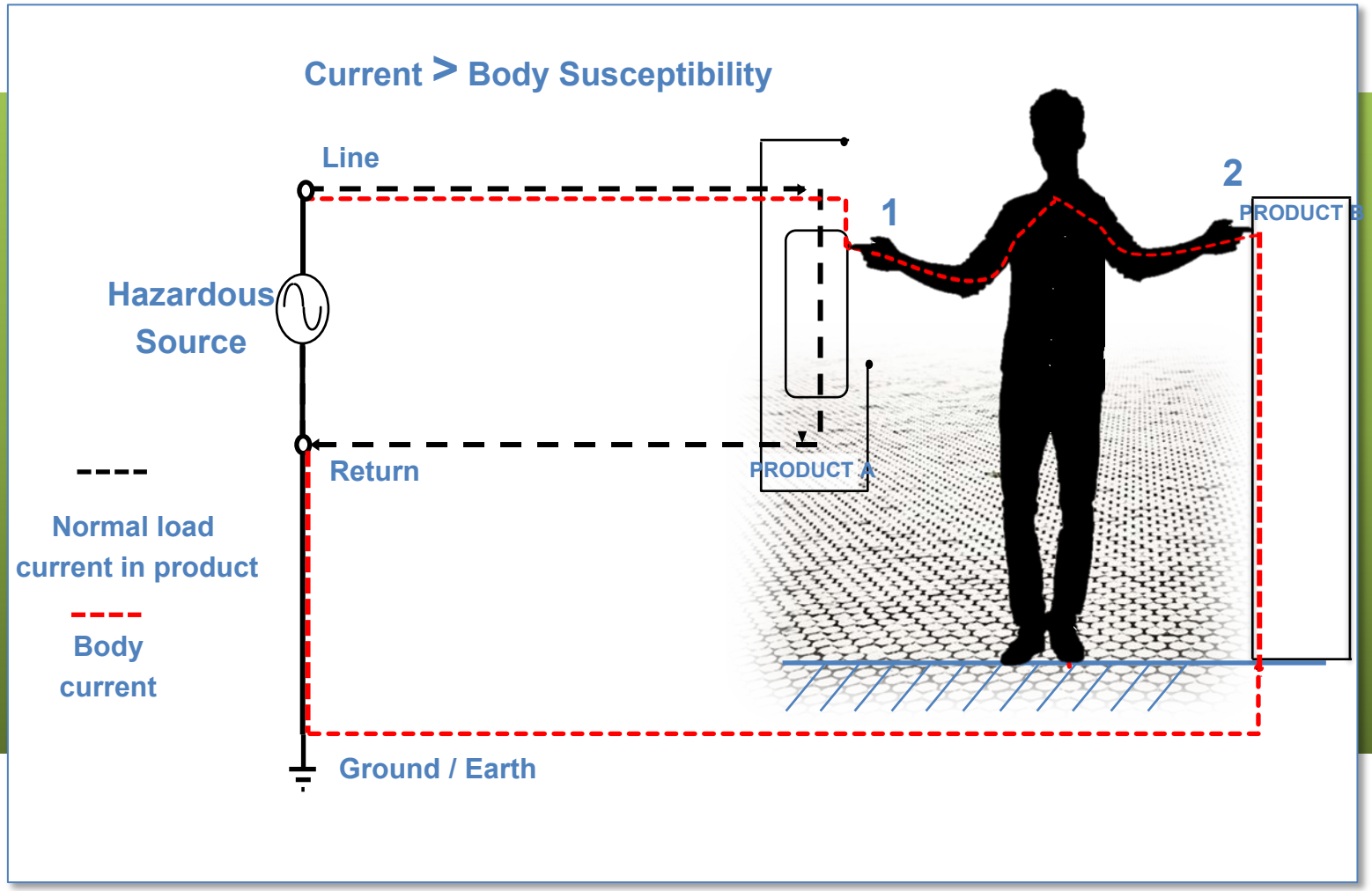

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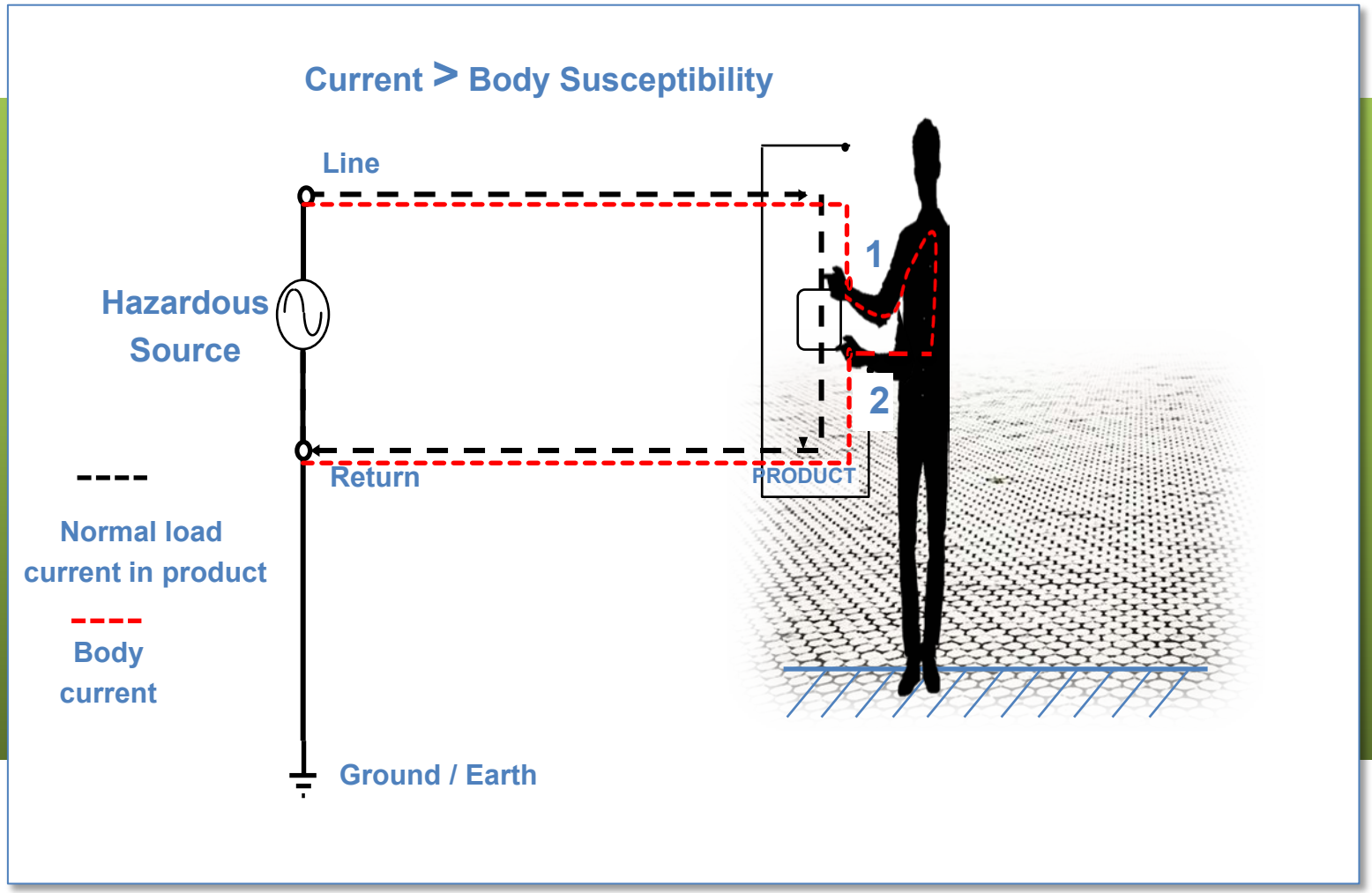


Hazardous body current to be reduced by safeguards

Mitigate Electric Shock Injury by Reduction of Energy Transfer to a Person

Safeguard Categories

1. Equipment
2. Personal
3. Site
4. Behavioral

Safeguard Mechanisms

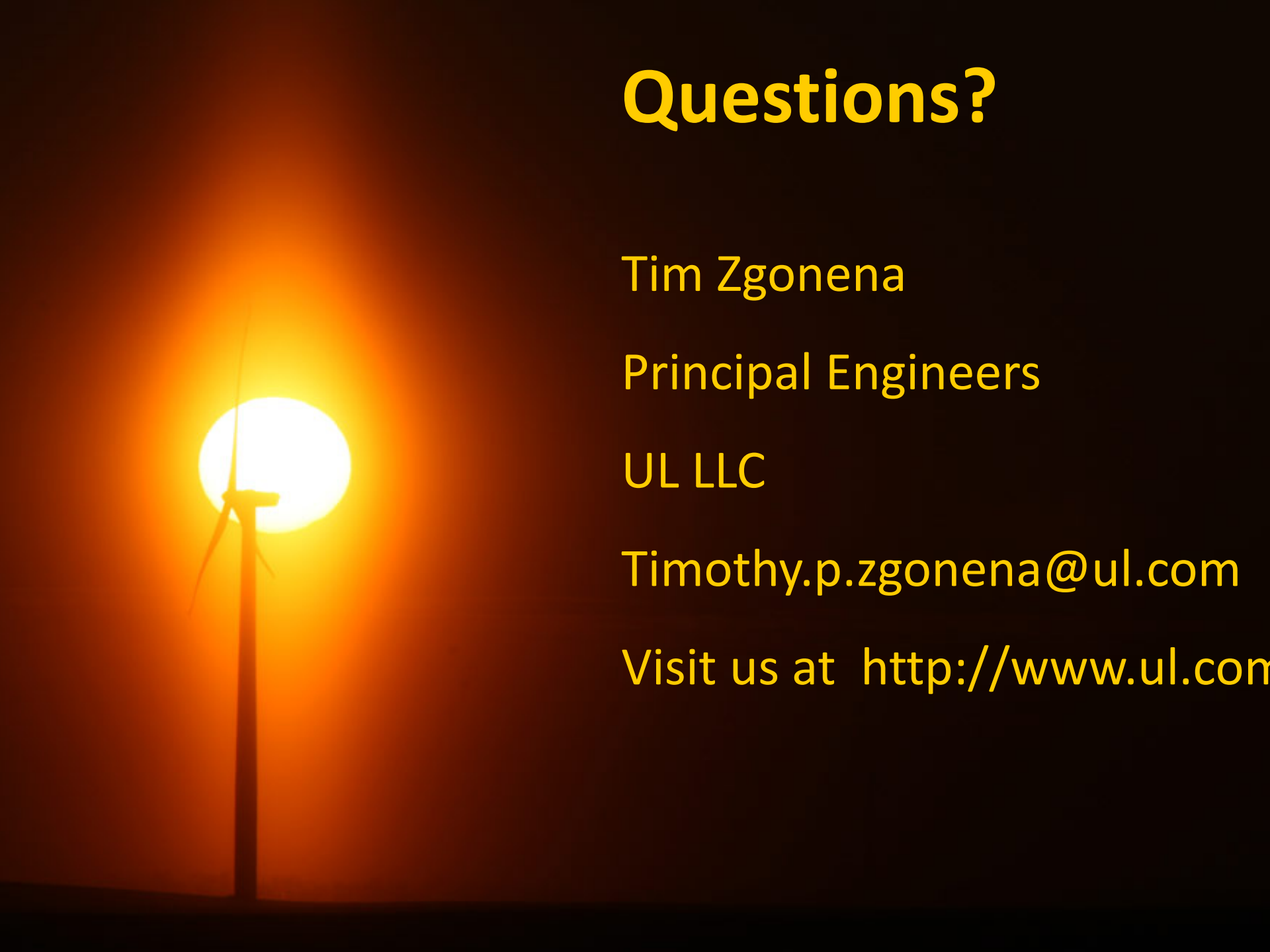
1. Disconnection
2. Attenuation
3. Impedance
4. Deflection
5. Containment
6. Isolation

New UL Standard for PV Rapid Shutdown Arrays

- Implementation / Solutions for 690.12 2017 will come in a variety of shapes and sizes.
  - Electrical
  - Mechanical
  - Installation based
  - Combinations there of
- This new standard will make use of the UL1741 PVRS equipment requirements as well as other standards for PV modules UL1703, their installation UL2703, PV wiring UL9703 and more.

Path Forward for New UL PVRS Standard

- Complete 1741 PVRS requirements.
- Start up 2017 PVRS task group calls.
- Develop a STP for the new standard expand from 1741 electrical task group to include experts from PV, racking and wiring groups.
- What can we do & What can we not do?
- Research to expand on UL's original PV Fire report.
- Task group efforts
- Voltage and current safety limits for this application.
- Develop educational material Do's and Don'ts



Questions?

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Visit us at http://www.ul.com

Photovoltaic Arc-Fault Detection and Mitigation

Exceptional service in the national interest

Sandia National Laboratories

Jay Johnson
Sandia National Laboratories, Albuquerque, NM

System Reliability Session
PV Module Reliability Workshop

25 February 2016
Golden, CO

SAND2016-1470 C

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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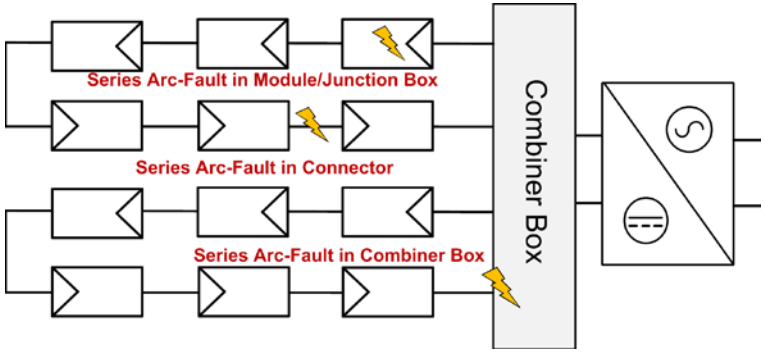
Presentation Outline

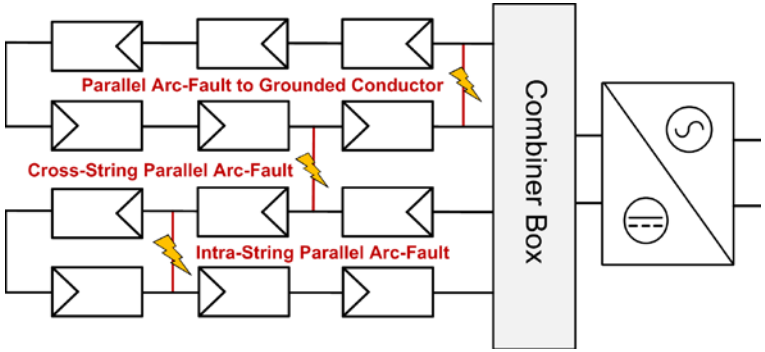
- PV Arc-Fault Types and the National Electrical Code
- Arc Detection Methods
- Arc-Fault Product Requirements in UL 1699B
- AFCI Limitations and the Tigo Energy Survey
- Conclusions

Arc-Fault Types

- 2011 and 2014 *NECs* require **series** arc-fault protection in PV installations above 80 V
- Types of arc-faults
  - Series Arc-Fault – Arc from discontinuity in electrical conductor
  - Parallel Arc-Fault – Electrical discharge between conductors with different potentials
  - Arcing Ground Fault – Parallel arc-fault to the equipment grounding conductor



Series Arc-Faults



Parallel Arc-Faults

Most Inverters Have Series AFCIs

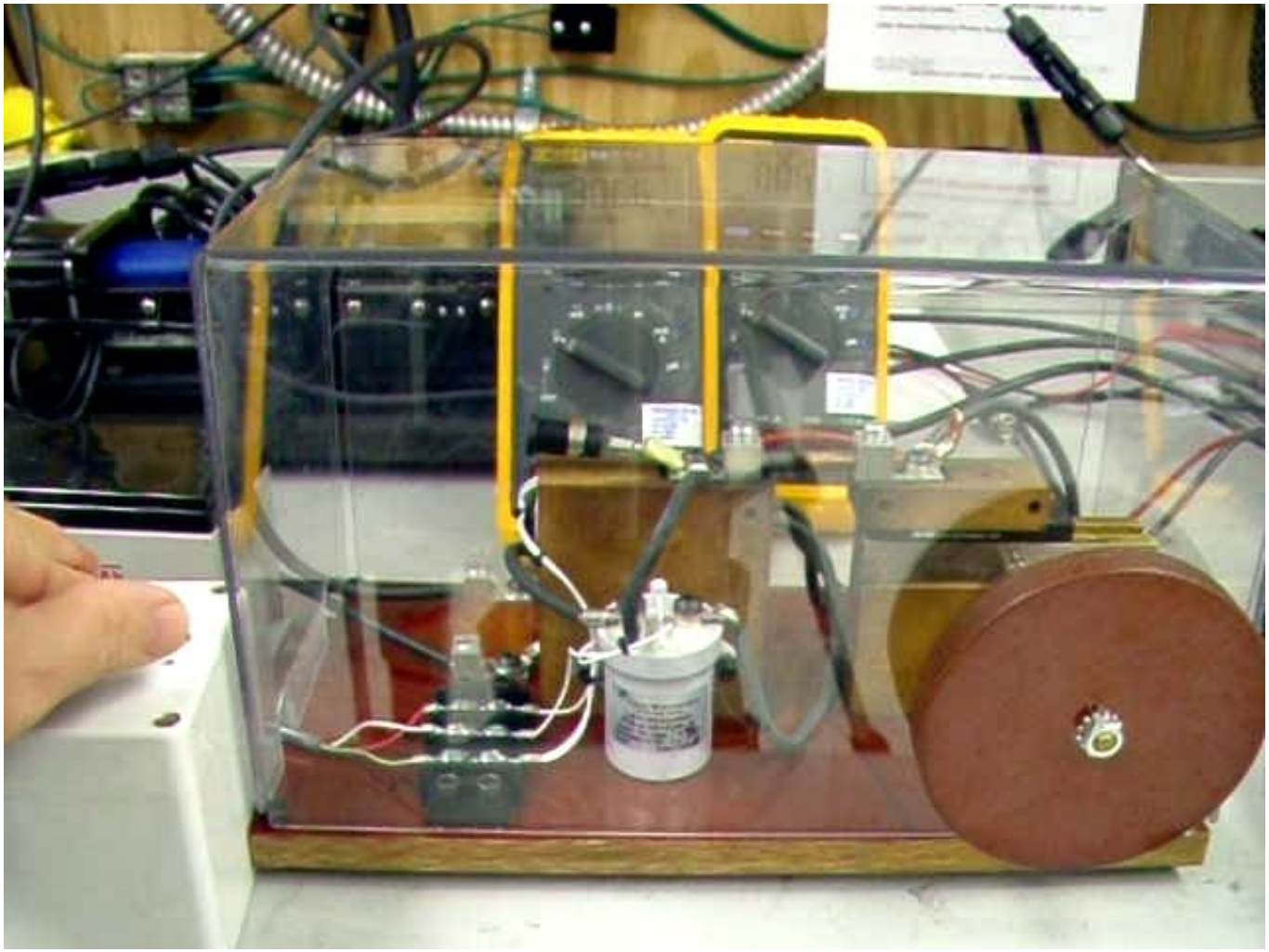
- Joe Schwartz, “2016 Single and 3-Phase String Inverter Specifications” SolarPro 9.1, Jan/Feb 2016.

Manufacturer	Model	Integrated Disconnects and Combiners			
		DC disconnect standard	AC disconnect standard	Fused combiner standard	Arc-fault protection
ABB	UNO-2.0-I-OUTD-S-US-A	yes [4]	no	no [4]	yes [4]
ABB	UNO-2.5-I-OUTD-S-US-A	yes [4]	no	no [4]	yes [4]
ABB	UNO-7.6-TL-OUTD-S-US-A	yes [4]	no	no [4]	yes [4]
ABB	UNO-8.6-TL-OUTD-S-US-A	yes [4]	no	no [4]	yes [4]
ABB	PVI-3.0-TL-OUTD-S-US-A	yes [4]	no	yes [4]	yes [4]
ABB	PVI-3.6-TL-OUTD-S-US-A	yes [4]	no	yes [4]	yes [4]
ABB	PVI-3.8-TL-OUTD-S-US-A	yes [4]	no	yes [4]	yes [4]
ABB	PVI-4.2-TL-OUTD-S-US-A	yes [4]	no	yes [4]	yes [4]
ABB	PVI-5000-TL-OUTD-US-A	yes [4]	no	yes [4]	yes [4]
ABB	PVI-6000-TL-OUTD-US-A	yes [4]	no	yes [4]	yes [4]
ABB	TRIO-20.0-TL-OUTD-S1-US-480-A	yes [4]	no	yes [4]	yes [4]
ABB	TRIO-27.6-TL-OUTD-S1-US-480-A	yes [4]	no	yes [4]	yes [4]
Chint Power Systems	CPS SC14KTL-DO/US-208	yes	yes	yes	option
Chint Power Systems	CPS SC20KTL-DO/US-480	yes	yes	yes	option
Chint Power Systems	CPS SCA23KTL-DO/US-480	yes	yes	yes	option
Chint Power Systems	CPS SCA28KTL-DO/US-480	yes	yes	yes	option
Chint Power Systems	CPS SCA36KTL-DO/US-480	yes	yes	yes	option
Delta	SOLIVIA 3.0 TL	yes	no	yes	yes
Delta	SOLIVIA 3.8 TL	yes	no	yes	yes
Delta	SOLIVIA 5.2 TL	yes	no	yes	yes
Delta	SOLIVIA 6.6 TL	yes	no	yes	yes
Delta	SOLIVIA 7.6 TL	yes	no	yes	yes
Fronius USA	GALVO 1.5-1	yes	no	no	yes
Fronius USA	GALVO 2.0-1	yes	no	no	yes
Fronius USA	GALVO 2.5-1	yes	no	no	yes
Fronius USA	GALVO 3.1-1	yes	no	no	yes
Fronius USA	PRIMO 3.8-1	yes	no	no	yes
Fronius USA	PRIMO 5.0-1	yes	no	no	yes
Fronius USA	PRIMO 6.0-1	yes	no	no	yes
Fronius USA	PRIMO 7.6-1	yes	no	no	yes
Fronius USA	PRIMO 8.2-1	yes	no	no	yes
Fronius USA	PRIMO 10.0-1	yes	no	yes	yes
Fronius USA	PRIMO 11.4-1	yes	no	yes	yes
Fronius USA	PRIMO 12.5-1	yes	no	yes	yes
Fronius USA	PRIMO 15.0-1	yes	no	yes	yes
Fronius USA	SYMO 10.0-3 208/240	yes	no	yes	yes
Fronius USA	SYMO 12.0-3 208/240	yes	no	yes	yes
Fronius USA	SYMO 10.0-3 480	yes	no	yes	yes
Fronius USA	SYMO 12.5-3 480	yes	no	yes	yes
Fronius USA	SYMO 15.0-3 280	yes	no	yes	yes
Fronius USA	SYMO 15.0-3 480	yes	no	yes	yes
Fronius USA	SYMO 17.5-3 480	yes	no	yes	yes
Fronius USA	SYMO 20.0-3 480	yes	no	yes	yes
Fronius USA	SYMO 22.7-3 480	yes	no	yes	yes
Fronius USA	SYMO 24.0-3 480	yes	no	yes	yes
Ginlong	Solis-2.5K-2G-US	yes	no	no	yes
Ginlong	Solis-3K-2G-US	yes	no	no	yes
Ginlong	Solis-3.6K-2G-US	yes	no	no	yes

Manufacturer	Model	Integrated Disconnects and Combiners			
		DC disconnect standard	AC disconnect standard	Fused combiner standard	Arc-fault protection
Ginlong	Solis-4K-2G-US	yes	no	no	yes
Ginlong	Solis-4.6K-2G-US	yes	no	no	yes
Ginlong	Solis-5K-2G-US	yes	no	no	yes
Ginlong	Solis-1P6K-3G-US	yes	no	no	yes
Ginlong	Solis-1P7K-3G-US	yes	no	no	yes
Ginlong	Solis-1P7.6K-3G-US	yes	no	no	yes
Ginlong	Solis-1P8K-3G-US	yes	no	no	yes
Ginlong	Solis-1P9K-3G-US	yes	no	no	yes
Ginlong	Solis-1P10K-3G-US	yes	no	no	yes
Ginlong	Solis-6K-US [6]	yes	no	no	option
Ginlong	Solis-10K-US [6]	yes	no	no	option
Ginlong	Solis-15K-US	yes	no	no	option
Ginlong	Solis-20K-US	yes	no	no	option
Ginlong	Solis-25K-US	yes	no	no	option
Ginlong	Solis-30K-US	yes	no	no	option
Ginlong	Solis-36K-US	yes	no	no	option
Ginlong	Solis-40K-US	yes	no	no	option
HiQ Solar	TrusString TS208-5k75	yes [7]	yes [7]	no	yes
HiQ Solar	TrusString TS480-8k	yes [7]	yes [7]	no	yes
Ingeteam	INGECON SUN 1Play 2.8TL U M	option	no	no	yes
Ingeteam	INGECON SUN 1Play 3.3TL U M	option	no	no	yes
Ingeteam	INGECON SUN 1Play 5TL U M	option	no	no	yes
Ingeteam	INGECON SUN 1Play 6TL U M	option	no	no	yes
Ingeteam	INGECON SUN 3Play 18TL U M480	option	no	option	yes
Ingeteam	INGECON SUN 3Play 24TL U M480	option	no	option	yes
Ingeteam	INGECON SUN 3Play 40TL U M480	option	no	option	yes
KACO new energy	1502xi [8]	yes	yes	no	no
KACO new energy	2502xi [8]	yes	yes	no	no
KACO new energy	3502xi [8]	yes	yes	no	no
KACO new energy	5002xi [8]	yes	yes	no	no
KACO new energy	6400xi	yes	no	yes	no
KACO new energy	7600xi	yes	no	yes	no
KACO new energy	6400M [8]	yes	no	yes	no
KACO new energy	7600M [8]	yes	no	yes	no
KACO new energy	2.0 TL1	option	no	option	yes
KACO new energy	3.0 TL1	option	no	option	yes
KACO new energy	4.0 TL1	option	no	option	yes
KACO new energy	5.0 TL1	option	no	option	yes
KACO new energy	XP10U-H4	option	option	option	no
KACO new energy	10.0 TL3 US	option	option	option	yes
KACO new energy	32.0 TL3 M1	yes	yes	no	no
KACO new energy	40.0 TL3 M1	yes	yes	no	no
KACO new energy	50.0 TL3 M1	yes	yes	no	no
KACO new energy	32.0 TL3 M3 [12]	yes	yes	no	no
KACO new energy	40.0 TL3 M3 [12]	yes	yes	no	no
KACO new energy	50.0 TL3 M3 [12]	yes	yes	no	no
Schneider Electric	CL18000 NA	option [4]	no	option [4]	option [4]
Schneider Electric	CL25000 NA	option [4]	no	option [4]	option [4]

Manufacturer	Model	Integrated Disconnects and Combiners			
		DC disconnect standard	AC disconnect standard	Fused combiner standard	Arc-fault protection
SMA America	SB 3000-US	yes	no	yes	option
SMA America	SB 3800-US	yes	no	yes	option
SMA America	SB 4000-US	yes	no	yes	option
SMA America	SB 5000-US	yes	no	yes	yes
SMA America	SB 6000-US	yes	no	yes	yes
SMA America	SB 7000-US	yes	no	yes	yes
SMA America	SB 8000-US	yes	no	yes	yes
SMA America	SB 3000TL-US	yes	no	no	yes
SMA America	SB 3800TL-US	yes	no	no	yes
SMA America	SB 4000TL-US	yes	no	no	yes
SMA America	SB 5000TL-US	yes	no	no	yes
SMA America	SB 6000TL-US	yes	no	no	yes
SMA America	SB 7000TL-US	yes	no	no	yes
SMA America	SB 7700TL-US	yes	no	no	yes
SMA America	SB 9000TL-US	yes	no	no	yes
SMA America	SB 10000TL-US	yes	no	no	yes
SMA America	SB 11000TL-US	yes	no	no	yes
SMA America	STP 12000TL-US	option [17]	no	option [17]	yes
SMA America	STP 15000TL-US	option [17]	no	option [17]	yes
SMA America	STP 20000TL-US	option [17]	no	option [17]	yes
SMA America	STP 24000TL-US	option [17]	no	option [17]	yes
SMA America	STP 60-10-US	option [17]	no	option [17]	no
SolarEdge	SE3000A-US	yes	yes	no	yes
SolarEdge	SE3800A-US	yes	yes	no	yes
SolarEdge	SE5000A-US	yes	yes	no	yes
SolarEdge	SE6000A-US	yes	yes	no	yes
SolarEdge	SE7600A-US	yes	yes	no	yes
SolarEdge	SE10000A-US	yes	yes	no	yes
SolarEdge	SE11400A-US	yes	yes	no	yes
SolarEdge	SE9KUS	yes	yes	no	yes
SolarEdge	SE10KUS	yes	yes	no	yes
SolarEdge	SE14.4KUS	yes	yes	yes	yes
SolarEdge	SE20KUS	yes	yes	no	yes
SolarEdge	SE33.3KUS	yes	yes	yes	yes
Sungrow	SG30KU	yes	option	yes	yes
Sungrow	SG36KU	yes	option	yes	yes
Sungrow	SG60KU	yes	yes	yes	yes
Sungrow	SG60KU-M	yes	yes	yes	yes
Yaskawa (Solectria)	PVI 3800TL	yes	no	yes	yes
Yaskawa (Solectria)	PVI 5200TL	yes	no	yes	yes
Yaskawa (Solectria)	PVI 6600TL	yes	no	yes	yes
Yaskawa (Solectria)	PVI 7600TL	yes	no	yes	yes
Yaskawa (Solectria)	PVI 14TL	yes	yes	yes	yes
Yaskawa (Solectria)	PVI 20TL	yes	yes	yes	yes
Yaskawa (Solectria)	PVI 23TL	yes	yes	yes	yes
Yaskawa (Solectria)	PVI 28TL	yes	yes	yes	yes
Yaskawa (Solectria)	PVI 36TL	yes	yes	yes	yes

DC Arc-Fault Experiment

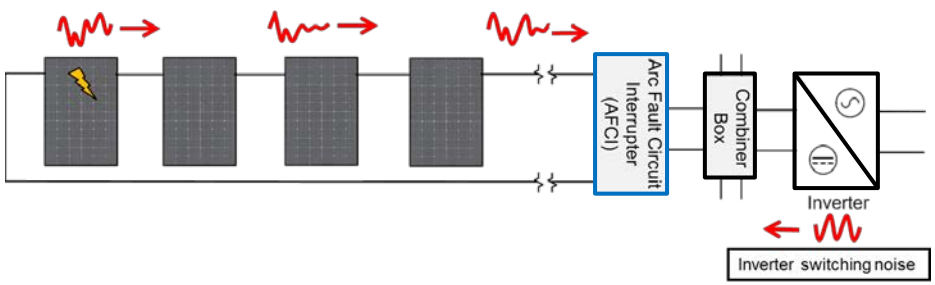


Arc-Fault Detection

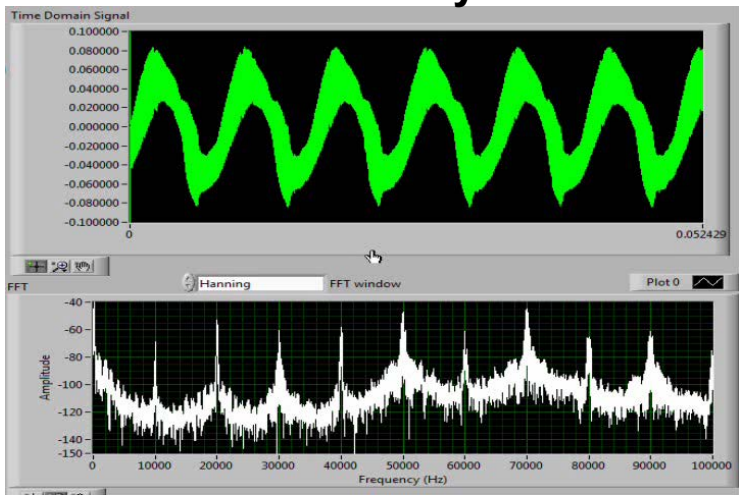
The **conducted noise** on the PV DC conductors is often **used to identify** when series **arcing** occurs in PV systems.

- Generally **frequency domain techniques are used** to trigger the interrupting device.
- Time-based methods have been proposed, but susceptible to noise.
- New techniques using wavelets and learning algorithms are actively being researched.

Series arcing conducted noise propagating through the DC-side of the PV array



Arcing noise propagating through the array

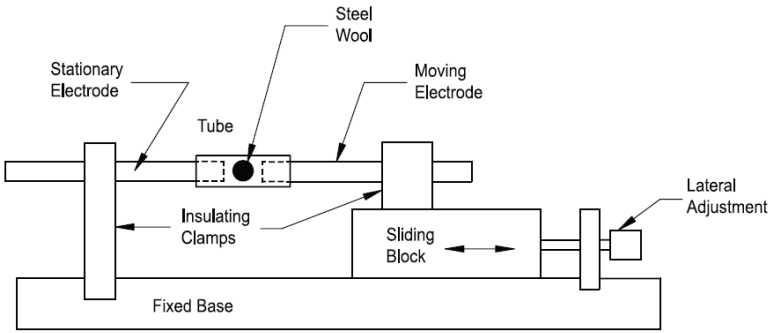


Arc-Fault Certification Standard

- Arc-fault circuit interrupters are listed using **Underwriters Laboratories (UL) 1699B**, "*Outline of Investigation for Photovoltaic (PV) DC Arc-Fault Circuit Protection*"
  - Not a standard yet! Needs to be improved and voted on by the UL Standards Technical Panel (STP) to make UL 1699B an ANSI standard.
  - STP continues to refine the test procedures, test configurations, and number/types of experiments.
- At highest level: UL 1699B needs to verify AFCIs trip when they should and not trip when they shouldn't.
  - The Sept 2013 STP meeting identified the following areas for development:
    - DC power supplies for PV simulation. Need realistic test circuits.
    - Arc generation methods. Need realistic arc-faults to detection tests.
    - Test circuit parameters (e.g., ballast resistors, capacitors). Need realistic test circuits.
    - Unwanted tripping tests. Must check AFCIs for operation on different PV arrays.

Arc-fault generation in UL 1699B

- Currently UL 1699B requires the arc to be created with a tuff of steel wool between the ¼” Cu electrodes
- Electrodes are set to a fixed gap
- 4 tests are required with arc powers between 300-900 W



Arc Powers

Trip Times

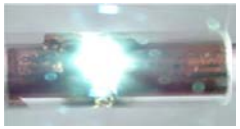
Arcing current (amps)[a, d]	Arcing voltage[b] (volts)	Average Arcing Watts [a]	Approximate electrode, inches (mm) [b]	Max time (sec) [c]
7	43	300	1/16 (1.6)	2
7	71	500	3/16 (4.8)	1.5
14	46	650	1/8 (3.2)	1.2
14	64	900	1/4 (6.4)	0.8

Trip times verified in K.M. Armijo, J. Johnson, R.K. Harrison, K. E. Thomas, M. Hibbs, A. Fresquez, “Quantifying photovoltaic fire danger reduction with arc-fault circuit interrupters,” Progress in Photovoltaics: Research and Applications, 2014, doi: 10.1002/pip.2561.

Alternative arc-fault generation methods

The following variables were parameterized:

Arc Power



100 W

300 W

Sheath Material

Polycarbonate

PET

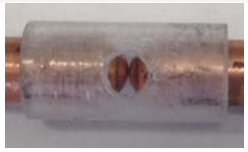
Nylon 6,6

Electrode Diameter

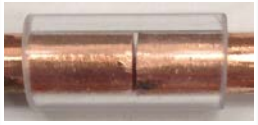
1/8 inch

1/4 inch

Electrode Tip

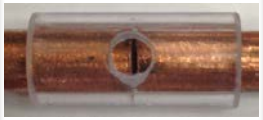


Rounded Tip

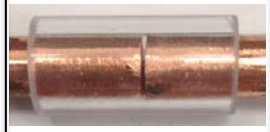


Flat Tip

Hole for O_2 Ingress

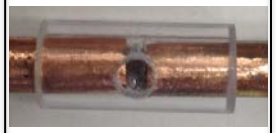


Hole

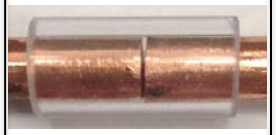


No Hole

Steel Wool Igniter



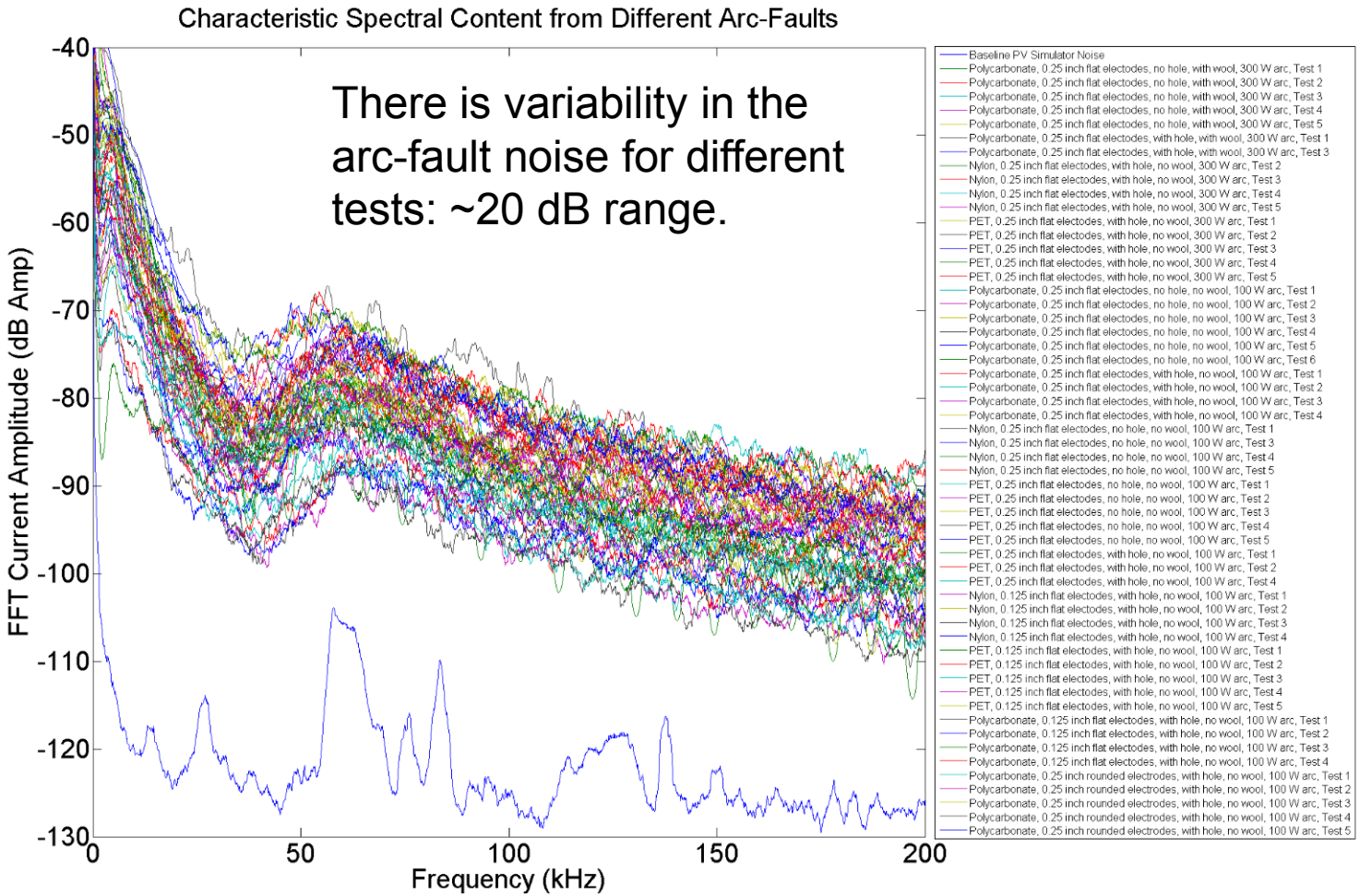
Steel Wool



No Steel Wool

Test Number	Arc Power	Polymer	Electrode Diameter	Electrode Tip	Hole	Steel Wool
1 (UL 1699B)	300 W	Polycarbonate	1/4”	Flat	No	Yes
2	300 W	Polycarbonate	1/4”	Flat	Yes	Yes
3	300 W	Polycarbonate	1/4”	Flat	No	No
4	300 W	Polycarbonate	1/4”	Flat	Yes	No
5	300 W	PET	1/4”	Flat	Yes	No
6	300 W	Nylon 6,6	1/4”	Flat	Yes	No
7	100 W	Polycarbonate	1/4”	Flat	No	No
8	100 W	Polycarbonate	1/4”	Flat	Yes	No
9	100 W	Nylon 6,6	1/4”	Flat	No	No
10	100 W	Nylon 6,6	1/4”	Flat	Yes	No
11	100 W	PET	1/4”	Flat	No	No
12	100 W	PET	1/4”	Flat	Yes	No
13	100 W	Polycarbonate	1/4”	Round	Yes	No
14	100 W	Polycarbonate	1/8”	Flat	Yes	No
15	100 W	PET	1/8”	Flat	Yes	No
16	100 W	Nylon 6,6	1/8”	Flat	Yes	No
17	300 W	Polycarbonate	1/8”	Flat	Yes	No

Arc-Fault Noise at Initiation



- SNL Recommendations for arc detection experiments:
  - Larger (1/4”) diameter electrodes. “Pull-apart” generation method (no steel wool). A hole in polymer sheath. Do not use rounded electrode tips. 300 W power.

J. Johnson, K.M. Armijo, “Parametric Study of PV Arc-Fault Generation Methods and Analysis of Conducted DC Spectrum,” 40th IEEE PVSC, Denver, CO, 8-13 June, 2014.

AFCI Unwanted Tripping

- Problems for manufacturers:
  - Expensive retrofits/redesigns
  - Damaged reputation
  - Loss of business
- Problems for PV owner:
  - Lost energy production – can go days (or months) before manually reset
  - If unwanted faults continue, the owner may remove the AFCI
    - No longer code-compliant
    - Safety feature designed to prevent fires, is no longer operational
      - Life and property at risk
- UL standard should address unwanted tripping to establish a minimum bar for market entry.

Unwanted Tripping Field Experiences

Unwanted Tripping Situation	Evidence
1. Downward power step change.	Manufacturer experienced tripping when a portion of the array was disconnected. Sandia witnessed unwanted tripping when PV simulator irradiance is stepped down and when switching between the simulator and real PV.
2. Upward power/current step change.	Manufacturer has seen high frequency noise when PV systems are energized in the middle of the day.
3. Capacitive coupling (in conduit) from dissimilar PV inverters.	Manufacturer discovered this problem and developed a new AFCI algorithm to address the issue.
4. Conducted DC/DC converter noise on the PV system.	Sandia has seen this with prototype AFCIs.
5. AC noise propagating to the DC with transformerless inverters.	University of Berne reported problems with elevators injecting noise on the AC side and causing DC tripping. A manufacturer stated a PV system on a parking garage would trip when the lights turned on.

J. Johnson, K.A. Armijo, M. Avrutsky, D. Eizips, S. Kondrashov, Arc-Fault Unwanted Tripping Survey with UL 1699B-Listed Products, 42nd IEEE PVSC, New Orleans, LA, 14-18 June, 2015.

Sandia/Tigo AFCI Experiments

- Tests replicate unwanted tripping experiences in the field
  - 1 arc-fault test
  - 1 masking test ("hiding" the arc-fault)
  - 7 unwanted tripping tests

- Completed 9 experiments with 10 products at Tigo Energy's Lab in Los Gatos, CA
  - 5 PV inverters (all NRTL-listed)
  - 1 charge controller (unlisted)
  - 1 combiner box (unlisted)
  - 3 stand-alone AFDs (1 NRTL-recognized)

J. Johnson, K.A. Armijo, M. Avrutsky, D. Eizips, S. Kondrashov, Arc-Fault Unwanted Tripping Survey with UL 1699B-Listed Products, 42nd IEEE PVSC, New Orleans, LA, 14-18 June, 2015.

Unwanted Tripping Experiments

Sandia National Laboratories

ARC-FAULT CIRCUIT INTERRUPTER AND ARC-FAULT DETECTOR ARCING, MASKING, AND UNWANTED TRIPPING RESULTS

			Arc Detection Tests		Masking Tests		Unwanted Tripping Tests									
AFCI Product	UL 1699B Compliance	Product Specs	1. Arc-fault Generation at Different Power Levels		2. Masking with Inductance/Capacitance		3. Unwanted Tripping with Inductance/Capacitance in Circuit		4. Loading Condition I							
			100-200 W*	300 W^	L#	C#	L#	C#	Power Supply#	Tigo Optimizers$	Inverter E$	Inverter F$	Inverter G$	Inverter H$	Inverter I$	Charge Controller J$
A	Unrecognized	Stand-Alone AFD Product	✓	✓	Masked 234 W arc with 994 µH, ran indefinitely	Masked continuous arc with 1.5 µF	✓	✓	✓	✓	Trip on startup period	Trip on startup and normal operation	Trip on inrush and startup period	Trip on inrush	Trip on startup and operation	✓
B	Unrecognized	Stand-Alone AFD Product	✓	✓	Masked 234 W arc with 994 µH, ran indefinitely	Masked continuous arc with 1.5 µF	✓	✓	✓	✓	Trip on startup period	Trip on startup period	Trip on inrush and startup period	Trips when using power supply	Trip on startup and operation	✓
C	Recognized	Stand-Alone AFD Product	169 W (36 V, 4.7 A), 30+ seconds, pull apart	✓	Masked 234 W arc with 994 µH, ran indefinitely	Masked continuous arc with 1.5 µF	✓	✓	✓	✓	✓	✓	✓	✓	Trip (only once)	✓
D	Unlisted	8-string Combiner Box with AFCI	169 W (36 V, 4.7 A), 30+ seconds, pull apart	298 W (42 V, 7.1 A), 20 sec, steel wool, Inv. I	Masked 234 W arc with 994 µH, ran indefinitely	Masked continuous arc with 1.5 µF	✓	✓	✓	✓	✓	✓	✓	✓	Trip (only once)	✓
E**	Listed	3.8 kVA, 1ϕ, inverter with transformer	102 W (16 V, 6.4 A), 20+ seconds, pull apart	328 W (40 V, 8.2 A), 20 seconds, pull apart	Masked arc with 994 µH	Masked continuous arc with 1.5 µF	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
F**	Listed	8.2 kVA, 1ϕ, TL inverter	✓	324 W (38.6 V, 8.4 A), 7 sec, steel wool	✓	✓	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
G	Listed	3.0 kVA, 1ϕ, inverter with transformer	✓	✓	Masked arc with 994 and 127 µH	Masked continuous arc with 1.5 µF	✓	✓	Would run only with inductors	✓	N/A	N/A	N/A	N/A	N/A	N/A
H	Listed	4.2 kVA, 1ϕ, TL inverter	✓	✓	Tripped when inductor installed	Tripped when capacitor installed	Tripped with 994, 127, and 82 µH	Tripped with 1.5 µF	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
I	Listed	5.5 kVA, 1ϕ, TL inverter	169 W (36 V, 4.7 A), 30+ seconds, pull apart	298 W (42 V, 7.1A), 20 sec, steel wool	N/A	N/A	N/A	N/A	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
J	Unlisted	14.4 kVA, 1ϕ charge controller	✓	N/A	N/A	N/A	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
Recommended for Manufacturer Testing			✓	✓	✓	✓	✓	✓	✓	✓	Test using as many inverters, converters, and charge controllers as possible for stand-alone devices.					
Recommended for UL 1699B Inclusion			✓	✓	Test with 1 mH unless otherwise specified by the mfr.	Test with 3 mF unless otherwise specified by the mfr.	Test with 1 mH unless otherwise specified by the mfr.	Test with 3 mF unless otherwise specified by the mfr.	✓	✓	Test using 1 single phase inverter, 1 three-phase inverter, 1 converter, and 1 charge controller for all stand-alone devices going to be UL 1699B recognition.					

^ Test currently in the UL 1699B Outline of Investigation.
* Tests added to the UL 1699B Outline of Investigation in November, 2014.
# Tests not included in the UL 1699B Outline of Investigation.
$ Only a single 1-phase or 3-phase inverter, converter, or charge controller is used as the load in the current version of Loading Condition I.
** These products are from the same manufacturer.

J. Johnson, K.A. Armijo, M. Avrutsky, D. Eizips, S. Kondrashov, Arc-Fault Unwanted Tripping Survey with UL 1699B-Listed Products, 42nd IEEE PVSC, New Orleans, LA, 14-18 June, 2015.

Unwanted Tripping Experiments

Sandia National Laboratories

ARC-FAULT CIRCUIT INTERRUPTER AND ARC-FAULT DETECTOR ARCING, MASKING, AND UNWANTED TRIPPING RESULTS (CONTINUED)

			Unwanted Tripping Tests																
AFCI Product	UL 1699B Compliance	Product Specs	5. Loading Condition II – DC Disconnect ^	6. Loading Condition III – Irradiance Change*	7. Frequency Sweep with Coupling Transformer#	8. Inductive Coupling between Arrays				9. AC-DC Coupling				10. Broadband Noise Injection			11. Injected Inverter Signatures with Coupling Transformer		
						Inverters F, G, H#	Inverters F, G, I#	Inverters F, G, Charge Controller J#	Inverters E, G, H#	Paper Shredder #	Shop Vacuum #	Bench Grinder #	Relay on AC load#	50 ms#	100 ms#	150 ms#	Noise A#	Noise B#	Noise C#
A	Unrecognized	Stand-Alone AFD Product	✓	Tripped when 1/2 PV array is connected	Square wave tripped at 100 kHz, 133 kHz, 1-10 kHz; 73 & 76 kHz Trip with Inv. F			On J DC system		✓	✓	✓	Tripped with Power Supply	N/A	N/A	N/A	N/A	N/A	N/A
B	Unrecognized	Stand-Alone AFD Product	✓	✓	Square wave tripped at 1 and 2 kHz for many Inv.; Sine wave tripped 3-10 kHz			✓ On J DC system		✓	✓	✓	Tripped with Power Supply	N/A	N/A	N/A	N/A	N/A	N/A
C	Recognized	Stand-Alone AFD Product	✓	✓	Square wave tripped at 2kHz with Inv. E, 12-14 kHz trips with Inv. H			✓ On J DC system		✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
D	Unlisted	8-string Combiner Box with AFCI	✓	✓	✓			✓ On J DC system		✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
E**	Listed	3.8 kVA, 1ϕ, inverter with transformer	✓	Tripped when 1/2 PV array is disconnected or resistance added	✓				✓	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
F**	Listed	8.2 kVA, 1ϕ, TL inverter	✓	Tripped when 1/2 PV array is disconnected or resistance added	✓	✓	✓	✓		✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
G	Listed	3.0 kVA, 1ϕ, inverter with transformer	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
H	Listed	4.2 kVA, 1ϕ, TL inverter	✓	✓	✓	✓			✓	✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
I	Listed	5.5 kVA, 1ϕ, TL inverter	✓	✓	N/A		✓			✓	✓	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A
J	Unlisted	14.4 kVA, 1ϕ charge controller	✓	✓	Square wave tripped at 1-2 kHz and 4 kHz			✓		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Recommended for Manufacturer Testing			✓	✓	✓	✓	✓	✓	✓	Test as many devices as possible.			✓	✓	✓	✓	✓	✓	✓
Recommended for UL 1699B Inclusion			✓	✓	✓ (With sine wave injection)	Test with same devices from Loading Condition I							✓	✓					

^ Test currently in the UL 1699B Outline of Investigation.
* Tests added to the UL 1699B Outline of Investigation in November, 2014.
# Tests not included in the UL 1699B Outline of Investigation.
** These products are from the same manufacturer.

J. Johnson, K.A. Armijo, M. Avrutsky, D. Eizips, S. Kondrashov, Arc-Fault Unwanted Tripping Survey with UL 1699B-Listed Products, 42nd IEEE PVSC, New Orleans, LA, 14-18 June, 2015.

Conclusions/Recommendations

- Difficult to balance detection sensitivity with resistance to unwanted tripping.
- 9 detection, masking, and unwanted tripping experiments were conducted on 10 AFD/AFCI products.
  - 6 of the products passed UL 1699B and are UL-recognized or UL-listed.
  - AFCI/AFD issues with all products.
  - 1 inverter product did not experience unwanted tripping.
- Recommend manufacturers complete more comprehensive unwanted tripping experiments.
- Recommend UL 1699B STP adopt some of these experiments to improve products entering the market.

J. Johnson, K.A. Armijo, M. Avrutsky, D. Eizips, S. Kondrashov, Arc-Fault Unwanted Tripping Survey with UL 1699B-Listed Products, 42nd IEEE PVSC, New Orleans, LA, 14-18 June, 2015.

Questions?

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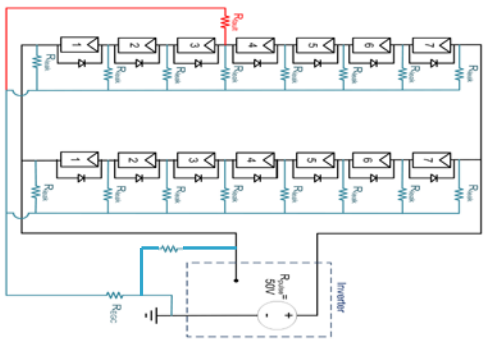

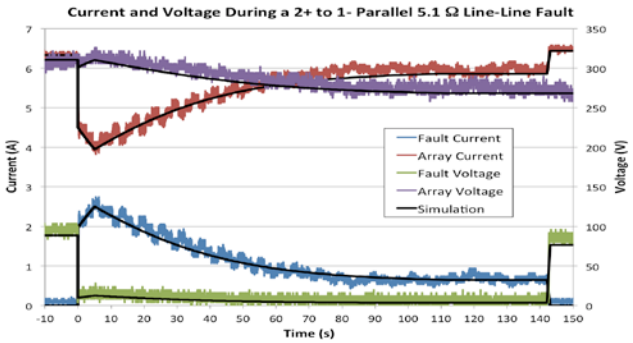

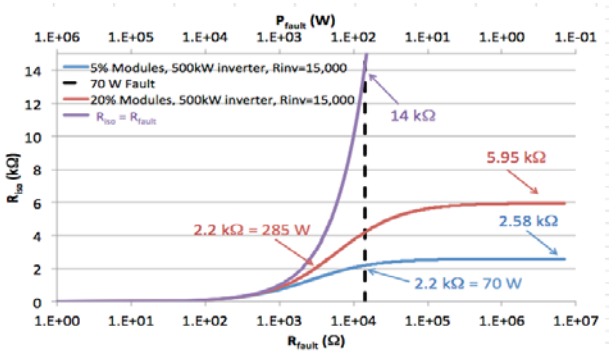

Ground Fault Detection and Mitigation

Jack Flicker

Jay Johnson

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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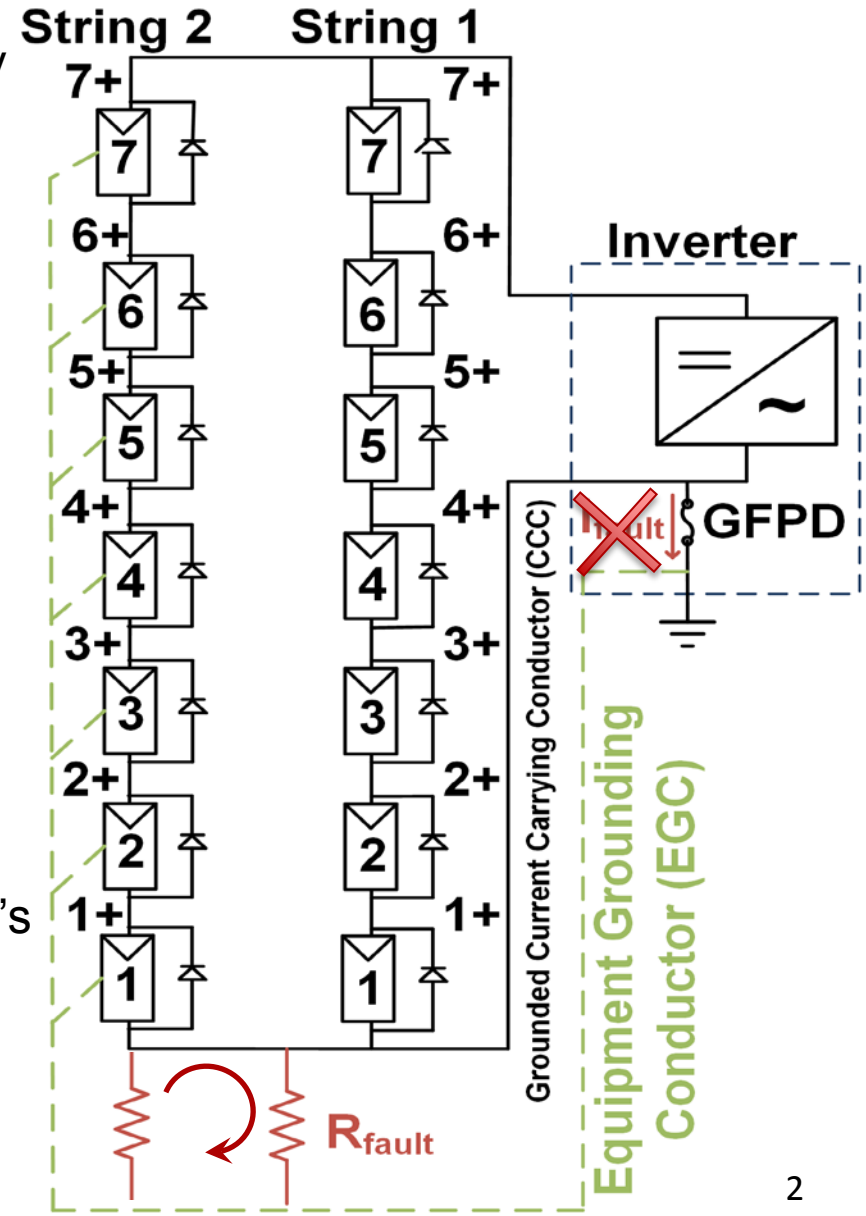
Ground Faults

- Electrical pathway between one or more array conductors and earth ground
  - Mechanical, electrical, or chemical degradation of PV components, or mistakes during installation
- Ground fault protection device (GFPD) is used to detect ground fault currents
  - Historically (in the U.S.) has been a fuse
- Fuses have detection blind spot
  - → Caused multiple latent ground faults
  - → Undetected fault persists for an extended period (either on CCC or elsewhere)
  - → Fault current is too low to trip the inverter's GFPD fuse
  - → Second ground fault occurs in the array, fault current will bypass the fuse
  - → Has cause multiple fires



Motivation

- Solar ABCs steering committee investigated ground faults and the ground fault detection blind spot
  - Concluded that fuse-based GFDI designs vulnerable to faults in the grounded current-carrying conductor

- Number of alternative technologies have been suggested:

  Decreasing Fusing sizes

  Isolation monitoring (R_{iso})

  Residual Current Detection (RCD)

  Current Sense Monitoring/Relay (CSM/R)

- Little experience with these technologies in U.S. systems
- Range of detectable ground faults depends on thresholds
  - All detection methods register leakage current as a type of fault
  - Balance between detection window and unwanted tripping
- What are proper detection thresholds above maximum leakage current?

  All Meteorological, Configurational, Electrical Conditions

Goal: find appropriate thresholds to balance system performance, reliability, and safety….

Decreasing Fuse Size

- Worst-case is when the fault location is on the grounded CCC
- Current division between the fault path and CCC path is heavily dependent on small internal resistances of the conductors.

  Problem: resistance of the fuse is inversely related to the fuse rating

  → low trip ratings can have significant resistances (e.g. 0.1A = 85.5 Ω)
- Decreasing fuse rating increases fuse resistance

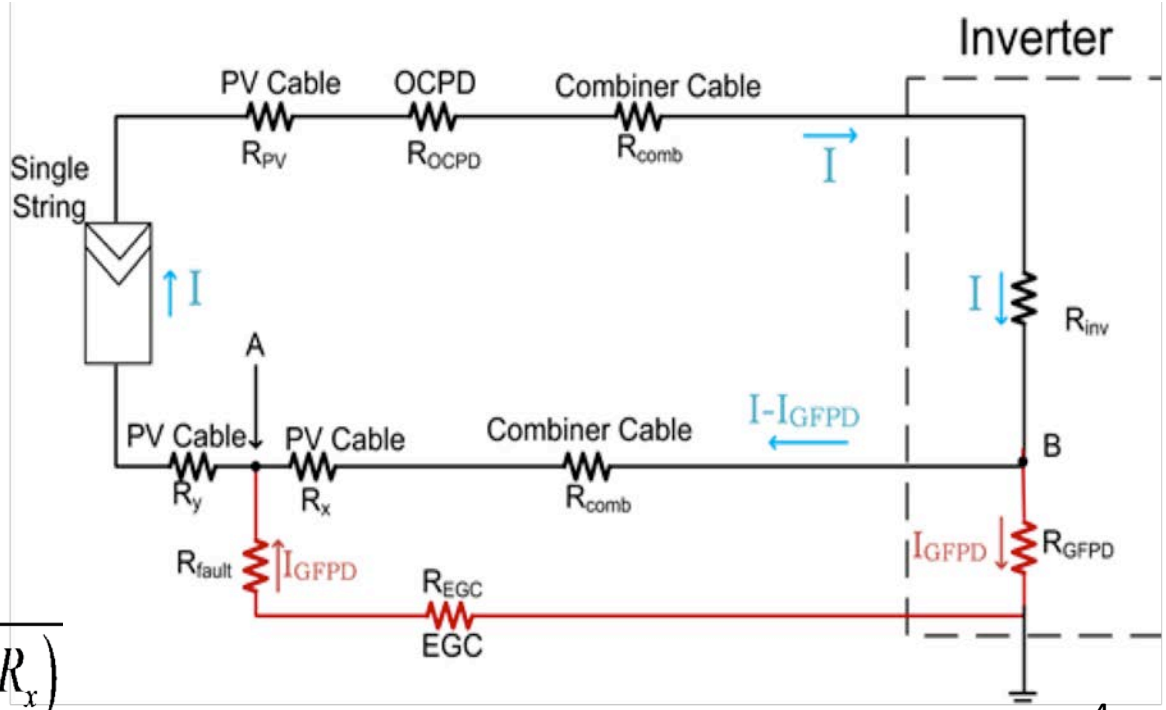
  → Decreases I_{GFPD}

  → Decreases fuse sensitivity
- 600 V below 250 kW

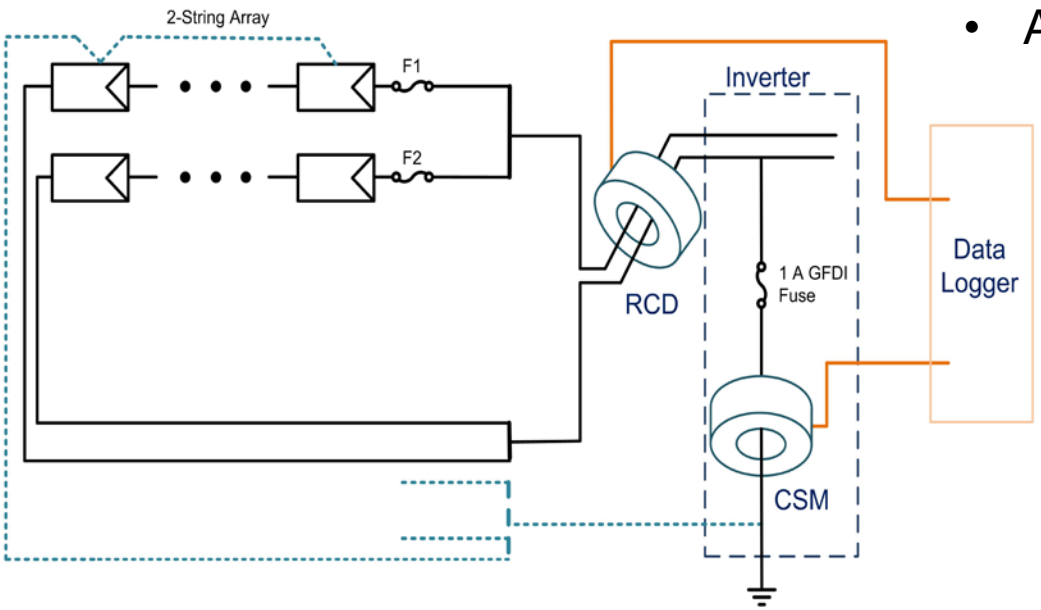
  → 1A fusing
- Higher voltage and power

  → may require a 2 A fuse

$$I_{GFPD} = \frac{I_{mp} \cdot \left(R_{comb} + R_x\right)}{\left(R_{GFPD} + R_{EGC} + R_{fault} + R_{comb} + R_x\right)}$$



CSM/RCD Measurements



- Array leakage is a function
  - module/inverter technology
  - BOS components
  - array layout
  - meteorological conditions

→ Creating guidelines for thresholds challenging
  → too low = unwanted tripping
  → too high = safety issue

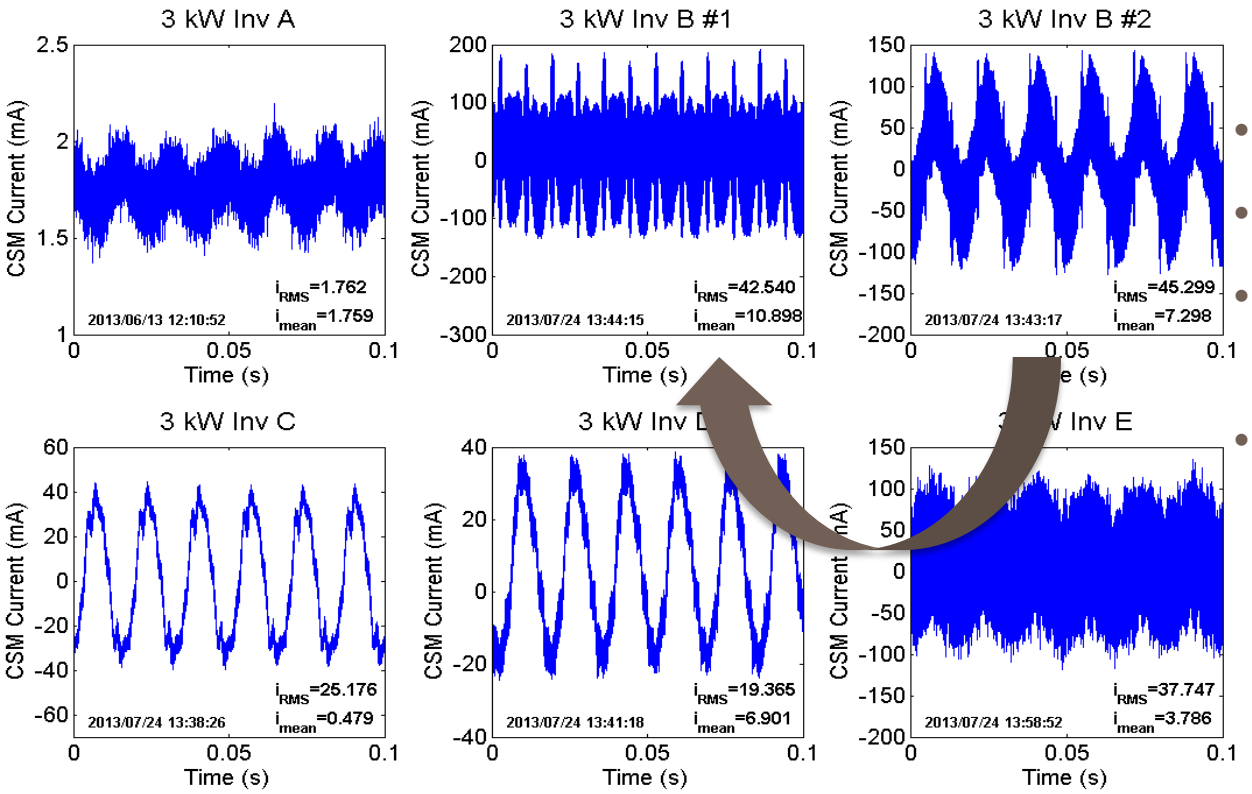
- CSM monitors current flow through ground bond (CT or shunt)
- RCD monitors differential current flow in the positive and negative CCCs
  - Excessive signal assumed due to ground fault → monitor trips

- Trip point settings are freely selectable
- Does not modify the conductive pathway being monitored

→ Maintains the inverter certification listing even after retrofit

→ Trip points can be tailored to individual systems

CSM/RCD Measurements



- Identical 3 kW inverters
- Identical 2.4 kW arrays
- Identical meteorological conditions
- Visually different waveforms
  - But I_{RMS} within 4 mA

- CSM leakage data
- 10 kHz for 0.1 s
- Tektronix TCP303 CTs

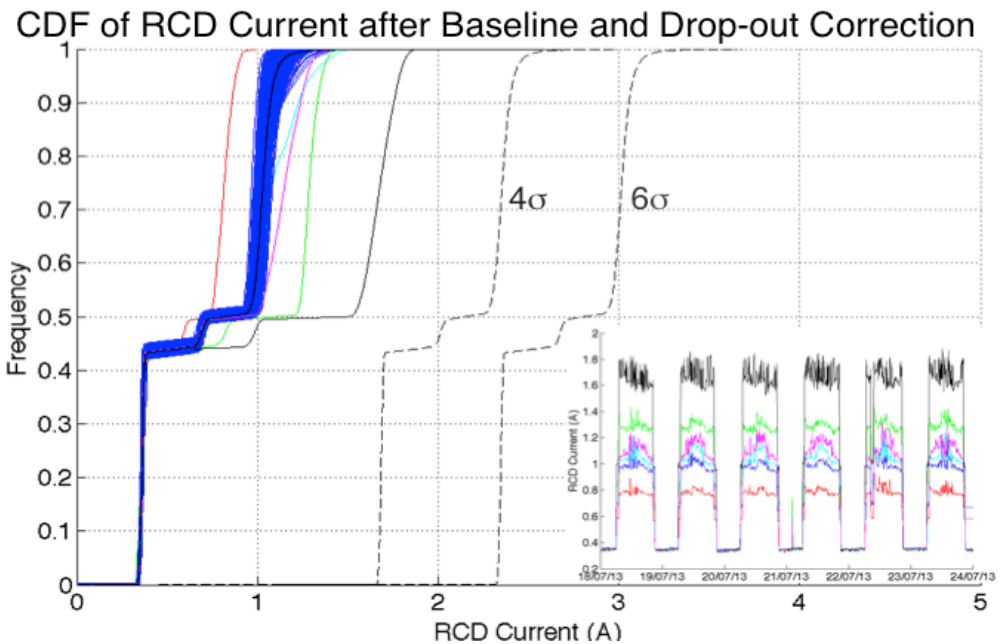
- 6 residential 3kW PV inverters
- Switching noise varies widely
  - High frequency component highly variable

CSM/RCD Measurements

- Sandia worked with utility-scale PV operator to collect system leakage values
  - 340 500 kW co-located inverters in a desert environment
  - One-minute intervals for over a year (1 January 2013 to 3 August 2014)
  - Each inverter has a GFPD fuse rated at 5 A to protect against ground faults

- Corrected CDFs of all 340 RCDs for the time period of data collection
  - baseline deviations
  - data dropouts

Frequency	Average	4σ	6σ
99	1.1825	2.5067	3.1688
99.9	1.6437	2.9679	3.6300
99.99	1.8028	3.1270	3.7892
99.999	1.8752	3.1994	3.8616
99.9999	2.4891	3.8133	4.4754
99.99999	2.8759	4.2001	4.8623
99.999999	3.6827	5.0069	5.6690



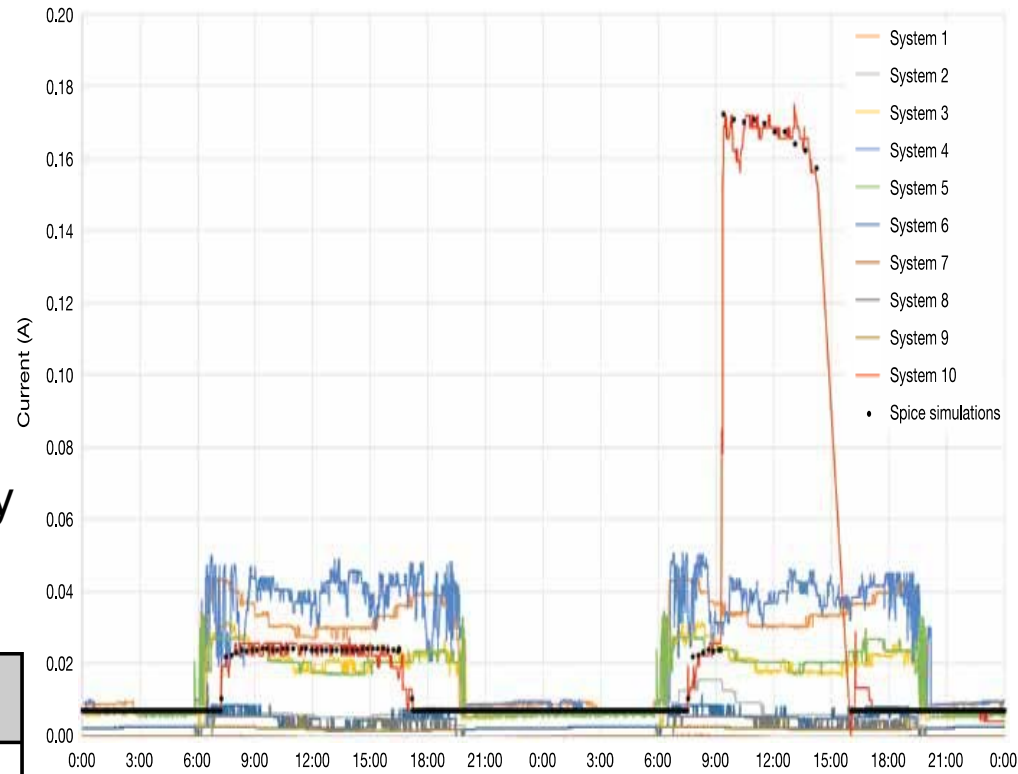
- 5 A → 2.5 A with 6-9's confidence that any single measurement lower than setpoint
- 0.5 trips/inverter/year for single, raw 1-minute data
- Number could be reduced further through more advanced data analysis techniques
  - data windowing, averaging, data error correction, step change analysis

CSM/RCD Measurements

- Since 2013, Sandia worked with a major EPC firm
  - Retrofit central inverters with CSM devices
    - 331 central inverters (109 MW)
    - Aggressive ground fault trip setting of 100 mA

- Fuse solution
  → 9 thermal events in 6-year period
- CSM solution with 100mA setting
  → 0 fires in 3 years
  → detected 20 ground faults
  → Many would have persisted indefinitely with fuse GFPD
- 9 unwanted trip events
  → Thunderstorm, noise (dc/ac), faulty equipment
  → Solutions developed to mitigate

	Fuse-based GFPD (6 years)	Post-CSM retrofit (3 years)
Ground-fault detections	--	20
Nuisance Trips	--	9
Fires	9	0



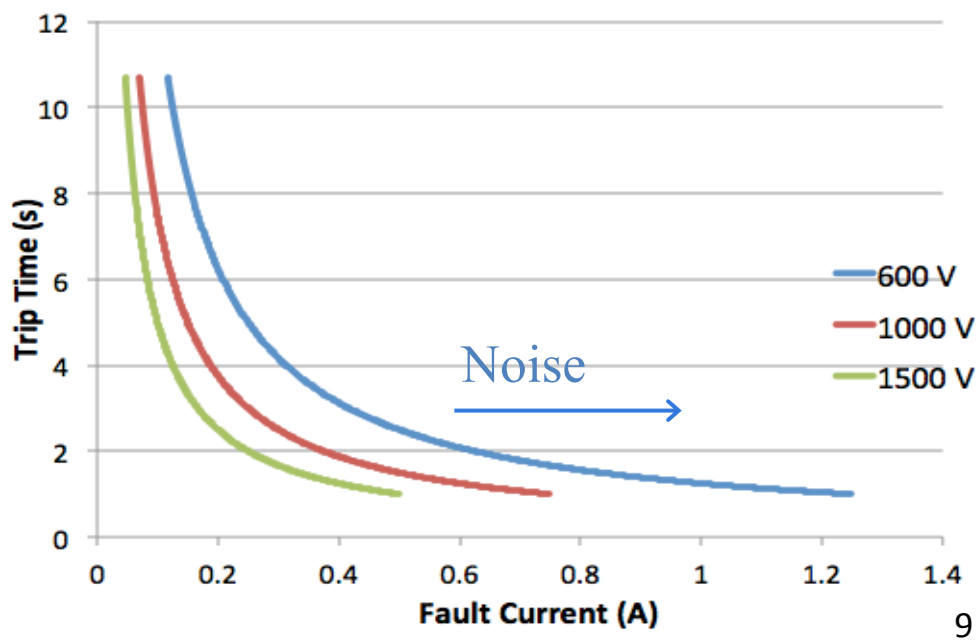
CSM/RCD Recommendations

- IEC 60364-4-42: max power that can be dissipated without risk of a fire is 70 W/750 J
  → possible to formulate a trip time vs. fault power curve for any PV system
  → presence of noise necessitates shifting curves by max amount of leakage

- Subsecond noise characteristics over the entire normal operating regime should be recorded
  - Max noise plus margin (*e.g.* 50%) added to set point for optimal threshold
  - Due to the variability from unit-to-unit, ideally done for every unit.

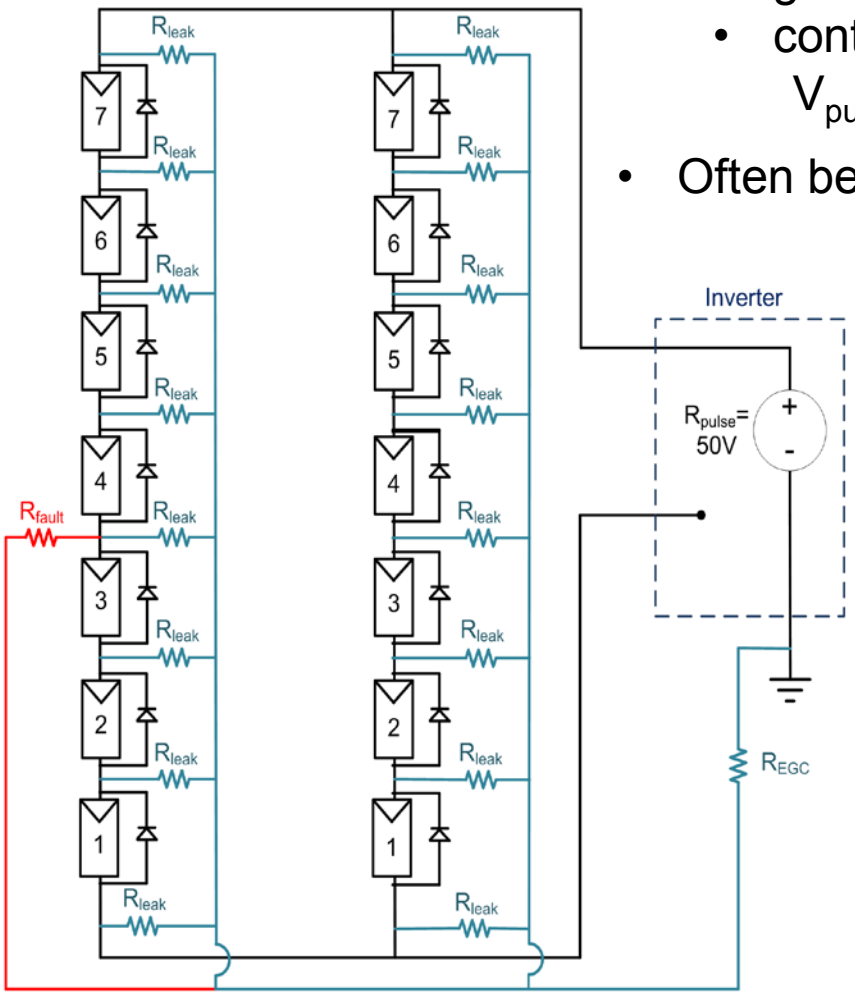
$$t_{RCD\_trip}(s) = \begin{cases} \text{No trip} & \text{for} \quad P_{fault} < 70 + N \text{ W} \\ \dfrac{750}{I_{fault} \cdot V_{oc}} & \text{for} \quad 70 + N \text{ W} \le P_{fault} < 750 + N \text{ W} \\ 1 & \text{for} \quad P_{fault} \ge 750 + N \text{ W} \end{cases}$$

where $N = \max\left(I_{noise} \cdot V_{oc}\right)$



Isolation Monitor (R_{iso})

- R_{iso} measurements on ungrounded systems
  - grounded systems which temporarily unground
  - continuous monitoring possible by superimposed V_{pulse} on nominal DC bus
- Often before the inverter begins to export power
  - "morning check"



- Inject voltage pulse (~50 V)
  - using an external power source
  - isolation calculated from current draw

$$R_{iso} = \frac{V_{applied}}{I(V_{applied}) - I(V=0)}$$

If R_{iso} < threshold, isolation monitor trips

R_{iso} Simulations

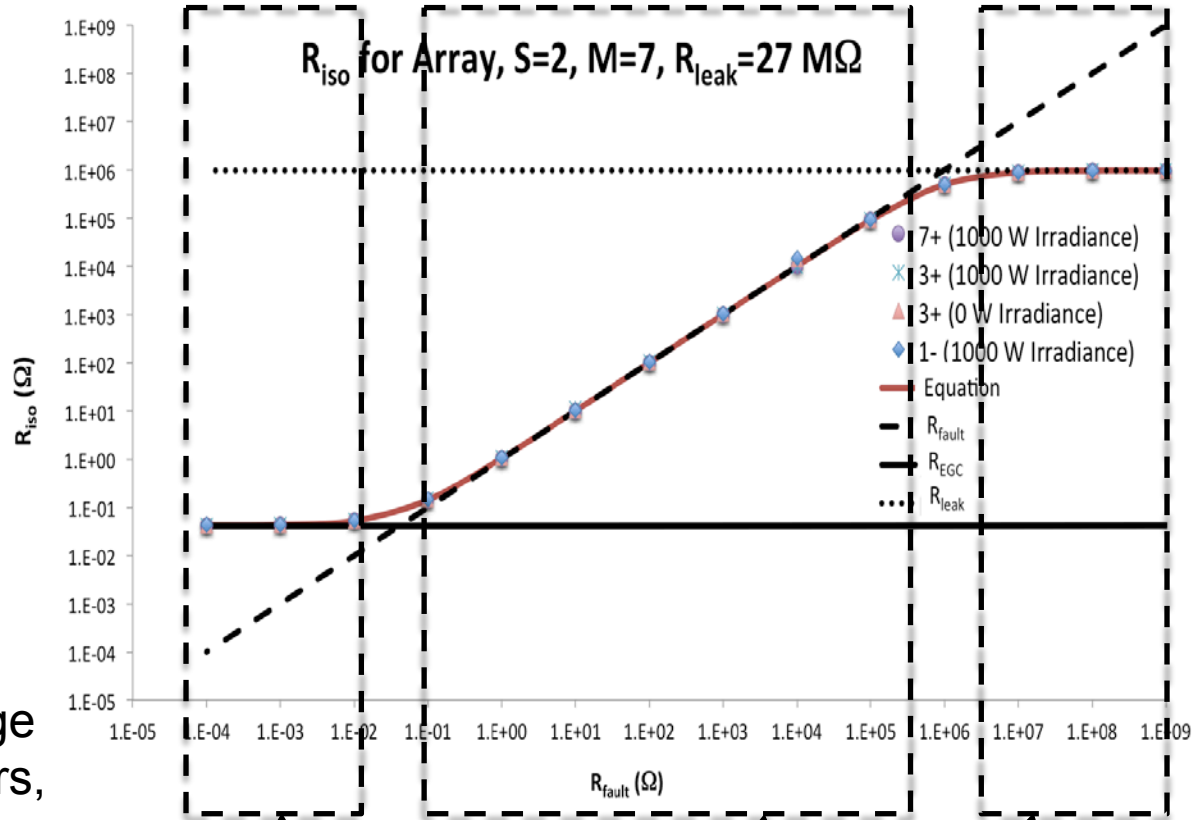
R_{iso} modeled as S*M resistor array

S = # strings

M = modules/string

$$R_{iso}^{array} = \frac{1}{\left(\frac{S \cdot M}{R_{leak}} + \frac{1}{R_{inv}} + \frac{1}{R_{fault}}\right)} + R_{EGC}$$

- Slight deviations due to voltage drops across parasitic resistors, bypass diodes, and/or module photodiodes
- Validated by measurements on 750 and 3 kW systems (PVSC 2015)



R_{iso} dominated by R_{EGC}

R_{iso} dominated by R_{fault}

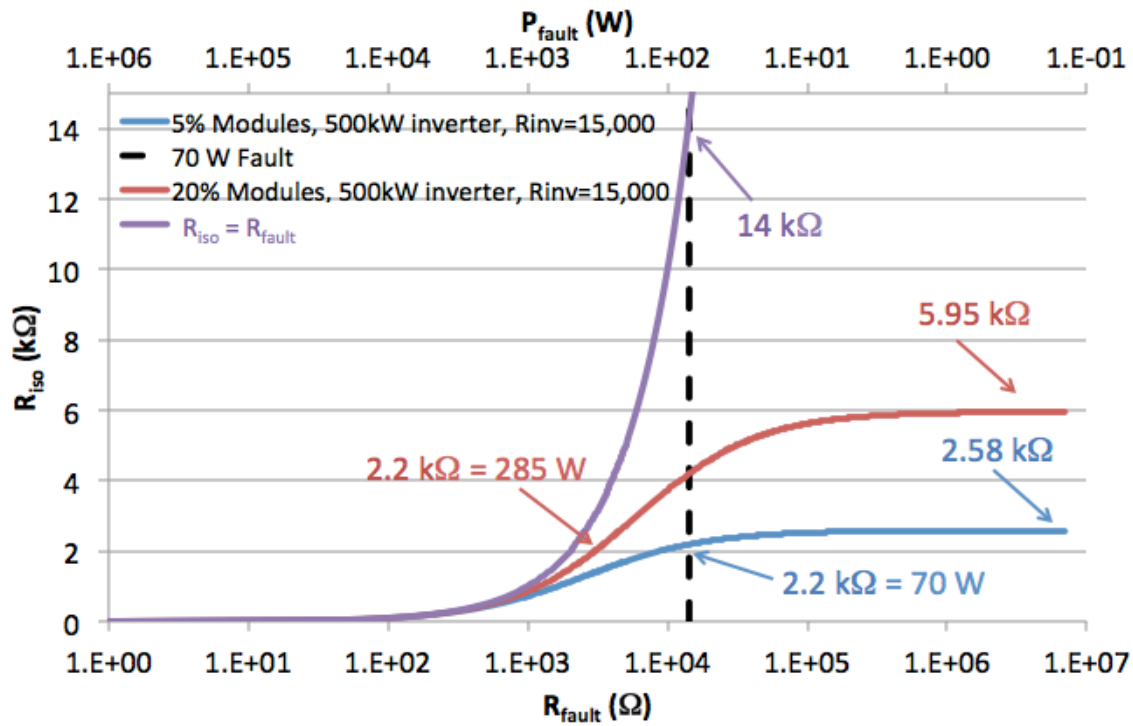
R_{iso} dominated by Leakage (module and inverter)

J. D. Flicker, and J. Johnson. "Electrical Simulations of Series and Parallel PV Arc-Faults" *Proceedings Photovoltaics Specialists Conference (PVSC)*, pp 3165-3172, 2013.

R_{iso} Trip Point Recommendations

- Can derive an R_{iso} trip threshold vs. system size for maximum allowable fault power dissipation (P_{fault})
- R_{iso} has a dependence on system size (P_{inv}) → find R_{iso} trip points vs. system size

$$R_{iso}^{array} = \frac{1}{\left(\frac{P_{inv} \cdot \left(\frac{P_{DC}}{P_{AC}} \right)}{R_{leak} \cdot 1000 \cdot \eta} + \frac{1}{R_{inv}} + \frac{P_{fault}}{V_{oc}^2} \right)}$$



Assume worst case= leakiest modules/inverter?
R_{leak} = 40 MΩ•m², R_{inv} = 15kΩ, η = 5%, V_{oc} = 1000 V

What if someone puts on better modules?
R_{leak} = 20 MΩ•m², R_{inv} = 15kΩ
η = 20%, V_{oc} = 1000 V

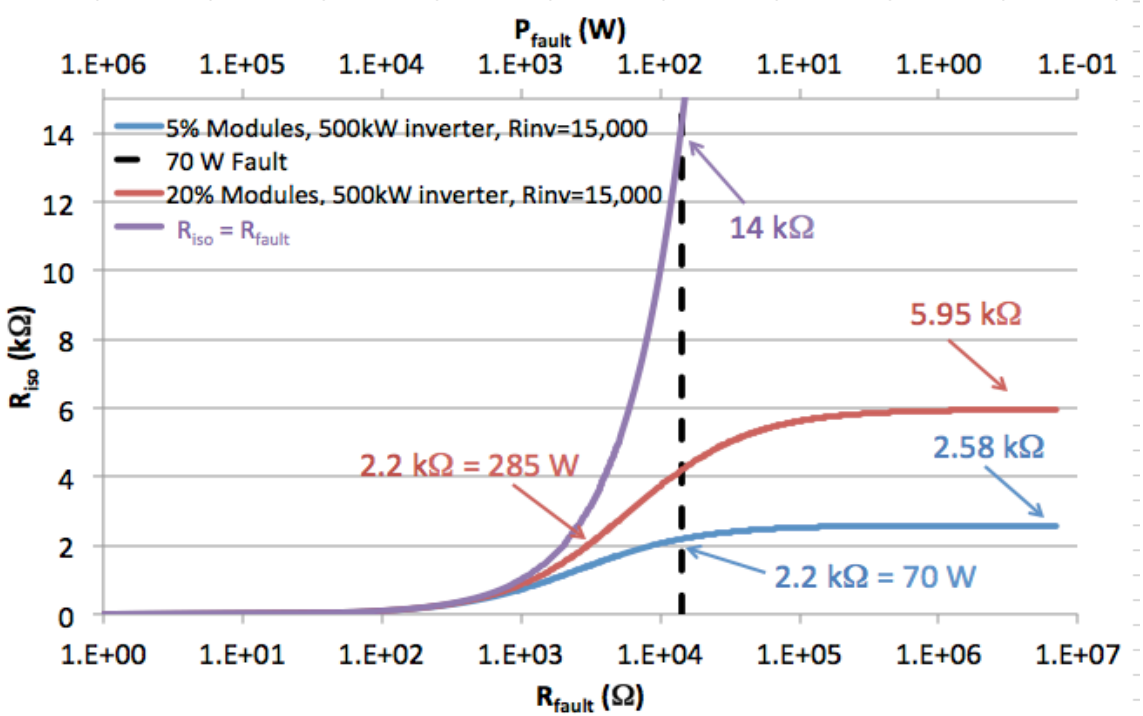
More overhead → less unwanted tripping
But R_{iso} trip point → unsafe condition (P_{fault} > 70 W)

What if you assume best case
→ least leaky modules/inverter?
$R_{iso} \approx R_{fault}$

Safe if installer puts on leaky modules/inverter, but unwanted tripping issues

R_{iso} Trip Point Recommendations

- Assuming "bad" modules (low R_{mod}/η) leads to potential safety issues if better modules are installed. Assuming "good" modules leads to possible unwanted tripping issues if worse modules are installed
- Some array state knowledge is necessary for accurate trip point
  - **No one-size-fits-all solution** to solve both safety and unwanted trip issues
  - May need to move to **range of values** that can be set by qualified technician
  - Recommend "best case" scenario and allow qualified installer to adjust **down**



Envelope of R_{iso} trip settings: ~2.2 kΩ (worst case) to ~14 kΩ (best case)

$$R_{iso}^{array} = \frac{1}{\left(\frac{P_{inv} \cdot \left(\frac{P_{DC}}{P_{AC}} \right)}{R_{leak} \cdot 1000 \cdot \eta} + \frac{1}{R_{inv}} + \frac{P_{fault}}{V_{oc}^2} \right)}$$

Summary

Decreased Fuse Size:

- Larger internal resistances decrease fault current
- Optimize GFPD rating vs. resistance to maximize detection window
  - Decrease rating to 1 A for systems <250 kW, 2 A for systems >250 kW

CSM/RCD:

- Array leakage can vary widely from system to system
- Trip-time vs. fault current curve shifted to higher current trip settings
  - shifted by the maximum measured subsecond switching noise
  - over the normal operating regime
  - plus a margin (*e.g.* 50%)

Isolation Monitoring:

- Default R_{iso} trip settings based on system assumptions may cause problems
  - leaky systems → potential safety
  - well-isolated systems → possible unwanted tripping issues
- Default R_{iso} trip setting cannot be determined *a priori*
- Allow for a range of R_{iso} thresholds that can be determined on a case-by-case basis
  → By qualified technician
  → Part of array commissioning?

Acknowledgements

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Considerations and structured approach for selecting and deploying climate specific polymerics for wire management means

Sumanth Lokanath – Manager Systems Reliability

NREL PV Module Reliability Workshop Feb 2016, Colorado, USA

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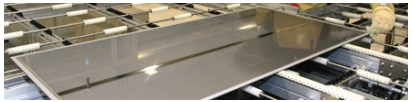
History of Leadership Across Entire Solar Value Chain

First Solar

1st global module recycling program



1st to break $1/watt cost barrier

1st to produce 1GW in single year

World record 21.5% cell

World record 18.2% module

1999 … 2005 … 2007 2008 2009 2010 2011 2012 2013 2014 2015

Acquired EPC & project DEV

World's largest PV plants

Proprietary plant controller

TetraSun

Acquired disruptive x-Si technology

Financed ~11B solar plants

Industry leading tracker technology

State-of-the-art Operations Center

Integrating into the global energy mix

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Outline

- Typically used wire management (polymeric) components in photovoltaic plants
- Risk Analysis – Wire Management Driven Risks in PV systems
  - FMEA [Failure Mode Effects Analysis] – Bottoms Up Approach
  - FTA [Fault Tree Analysis] – Top Down Approach
- Suggested Approach to Mitigate Risks
  - Application Guidance
- Zn from Galvanization as a Stressor.
  - Developing the correlation between Field and Lab Tests
- Introducing the UCET [Universal Chemical Exposure Test] and application of the Test
- Design for Reliability – Environmental Considerations
  - Chemical Exposures in the Use Environment
  - Material Selection Criteria and suggested approach
- Summary

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Source: Best Practices for Wire management, Systems Reliability, First Solar.

Typically used polymeric wire management components in photovoltaic plants

Cable Ties are used predominantly. Different types of polymeric clips exist.

Metallic solutions are new entries. Some may have coated polymeric materials.

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Source: Goggle image search – "wire management in PV"

FMEA – Wire Management Risks

A Failure Modes Effects Analysis (FMEA) and Fault Tree Analysis was completed to evaluate Wire Management Risks [Wire Ties and Edge Clips].

FMEA: Effects of failures and their underlying causes are identified and prioritized based on
- Severity,
- Occurrence and
- ability to detect before failure.

The S x O metric is used to rank the risks as illustrated (e.g. 1 = low, 10 = high).

Safety critical risks are lower on the risk cube, followed by performance impacts.

Also the severity of the fire and shock hazards and power loss increase as the point of defect is higher up the aggregation chain of the DC collection system (module, string, array).

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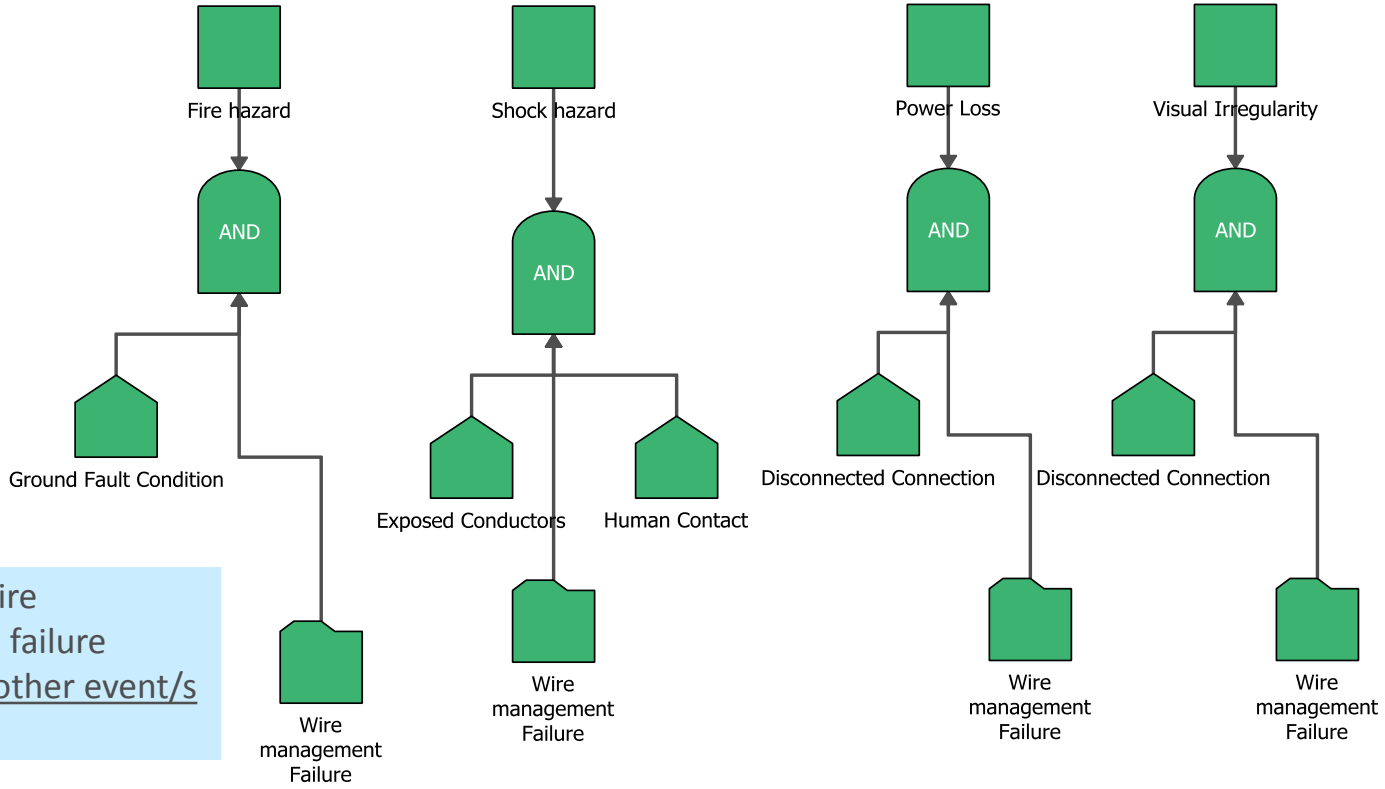
Source: Best Practices for Wire management, Systems Reliability, First Solar.

FTA – Fault Tree Analysis – Wire Management Risks



* Failure = Wire management failure probability* <u>other event/s probabilities</u>

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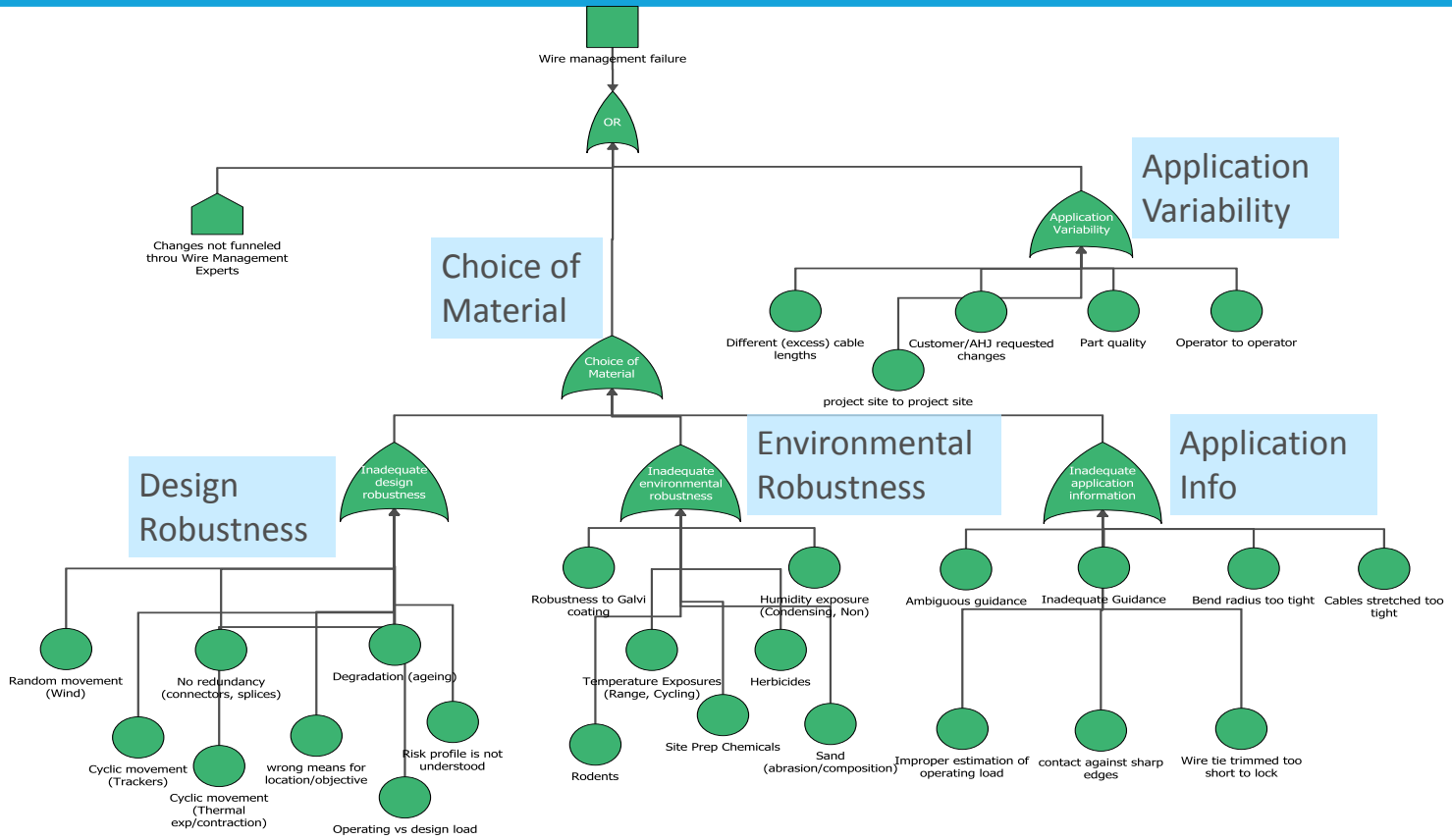
Source: Best Practices for Wire management, Systems Reliability, First Solar.

FTA – Fault Tree Analysis – Wire Management Risk Causes



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Source: Best Practices for Wire management, Systems Reliability, First Solar.

FMEA – Wire Management Risks

Low
Moderate
High
Extremely high

Severity (Across) Occurrence (Down)	1	2	3	4	5	6	7	8	9	10
1	L	L	L	L	L	L	L	L	L	L
2	L	L	L	L	L	M	M	M	M	M
3	L	L	L	M	M	M	M	M	M	M
4	L	L	M	M	M	M	M	H	H	H
5	L	L	M	M	M	M	H	H	H	H
6	L	L	M	M	M	H	H	H	H	H
7	L	M	M	M	H	H	H	H	E	E
8	L	M	M	H	H	H	H	E	E	E
9	L	M	M	H	H	H	E	E	E	E
10	L	M	M	H	H	H	E	E	E	E

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FMEA – Wire Management Risks

** Scored on Wire management failure probability only.

High Risk (SOi > 60)		Moderate Risk (35 ≤ SOi ≤ 60)		Low Risk (SOi < 35)	
Causes	**Effects**	**Causes**	**Effects**	**Causes**	**Effects**
Improper Material Selection (S=10; O=7)	Arcing	Improper Material Selection (S= 6-10; O= 4-7)	Power Loss --> String connector OC. Loss of Tracker function,	Improper Material Selection	Arcing (module connector)
Excessive loading (S=10; O=7)	Fire (Ground Fault) Shock	Excessive loading (S= 6-10; O= 4-7)	Power Loss Fire Loss of Fn (Trackers)	Excessive loading	Power Loss
Cables on Sharp Edges; Pinched Cables (S=10; O=7)	Shock	Documentation (S= 7-10; O= 5-7)	Power Loss Fire Loss of Fn (Trackers)	Documentation	Connector corrosion
		Slack (S=10, O=4)	Fire	Slack	Immersion Shock
		Spacing (S=8, O=4)	Regulatory (Spacing)	Short lengths/tight	Power loss
		Thermal Expension (S=10, O=4)	Fire (module connector)	Tie cut short	Short to ground

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Source: Best Practices for Wire management, Systems Reliability, First Solar.

FMEA & FTA – Wire Management Risks

Risk Analysis - Conclusions

Key themes that span all risk categories are identified.
From this it is clear that improved guidance is very important related to.

A. Proper material selection

B. Methods to properly manage the loading and

C. Application / Installation Guidance
- to address cable routing to avoid sharp edges,
- slack/tight/pinched cables/connections,
- thermal expansion impacts,
- proper use of the connector locking sleeve
- cable tie installation guidance
- connector management (dust, flood plane)
- Avoid sharp bend radius

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Source: Best Practices for Wire management, Systems Reliability, First Solar.

Suggested Approach to Mitigate Risks

Risks	Things to Consider
Application / Installation	Human factors introduce wider variance of noise factors Guidance/training may not be adequate with multiple crews/shift changes Technical competence of installer Installation tools may not have been calibrated **Suggest having a detailed training program and release / certification for work**.
Load Capacity	Weight of cable Number of conductors in bundle Cyclic loading due to wind/tracker movement Loading due to snow/ice 25 year life span **Need pragmatic usable guidance.**
Material Selection	Exposure to chemicals Contact with galvanized metal Ambient temperature Relative humidity 25 year life span **Need to design for environment and reliability.**

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Source: Best Practices for Wire management, Systems Reliability, First Solar.

Suggested Approach to Mitigate Risks

Risks	Things to Consider
Application / Installation	Human factors introduce wider variance of noise factors Guidance/training – Important with multiple crews/shift changes Technical competence of installer Provide pragmatic and practical guidance Installation tools may not have been calibrated **Suggest having a detailed training program and release / certification for work.**
Load Capacity	Weight of cable Number of conductors in bundle Cyclic loading due to wind/tracker movement Loading due to snow/ice 25 year life span **Need pragmatic usable guidance.**
Material Selection	Exposure to chemicals Contact with galvanized metal Ambient temperature Relative humidity 25 year life span **Need to design for environment and reliability**

Source: Best Practices for Wire management, Systems Reliability, First Solar.

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Suggested Approach to Mitigate Risks

Training of Contractors/Installers
Construction audits and quality checks
Installation Guidelines

- Detailed drawings with illustrations and notes + Contractor Training
- Follow wire management drawings provided by engineering
    - Do not install on or near sharp edges
    - Do not over torque cable tie
    - If possible, install to avoid direct sunlight
    - Avoid too much tightness, allow some slack (1/2” loop)
    - With Edge Clips, avoid lateral loading on edge clips
    - Ensure edge clips are fully inserted onto metal structure
    - Avoid Sharp Bend Radius
    - Avoid kinking the cable

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Source: Best Practices for Wire management, Systems Reliability, First Solar.

Suggested Approach to Mitigate Risks

Risks	Things to Consider
Application / Installation	Human factors introduce wider variance of noise factors Guidance/training may not be adequate with multiple crews/shift changes Technical competence of installer Installation tools may not have been calibrated **Suggest having a detailed training program and release / certification for work.**
Load Capacity	Weight of cable Number of conductors in bundle Cyclic loading due to wind/tracker movement Loading due to snow/ice 25 year life span De-rate **Need pragmatic usable guidance.**
Material Selection	Exposure to chemicals Contact with galvanized metal Ambient temperature Relative humidity 25 year life span **Need to design for environment and reliability.**

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Source: Best Practices for Wire management, Systems Reliability, First Solar.

Suggested Approach to Mitigate Risks

Maintain suggested cable bend radius;
Avoid kinks in cable; Avoid sharp bend radius

De-rate Appropriately for the Load

Choose appropriate rated means for use
Apply a minimum of 2x safety margin for loading considering
- Cyclic loading due to wind, thermal cycling
- Cyclic loading due to movement of tracker
- Additional loading in cold regions due to snow and ice
- Life expectation should be >25 years in the field (or replacement interval)

Detailed Drawings - Map locations with right BOM.

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Source: Best Practices for Wire management, Systems Reliability, First Solar.

Suggested Approach to Mitigate Risks

Risks	Things to Consider
Application / Installation	Human factors introduce wider variance of noise factors Guidance/training may not be adequate with multiple crews/shift changes Technical competence of installer Installation tools may not have been calibrated **Suggest having a detailed training program and release / certification for work.**
Load Capacity	Weight of cable Number of conductors in bundle Sharp bend radius Cyclic loading due to wind/tracker movement Loading due to snow/ice 25 year life span **Need pragmatic usable guidance.**
Material Selection	***Contact with galvanized metal*** ***Use Environment Stress*** ***Exposure to chemicals*** UV, Ambient temperature, Temperature Cycling Relative humidity **Need to design for environment and reliability.**

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Source: Best Practices for Wire management, Systems Reliability, First Solar.

Case Study – Cable Ties failing prematurely in field (<1 year)

- A site in the US desert southwest climate experienced mass systemic failure of cable ties within 1 year of deployment. These were of Nylon 6.6 material.
- Examination of those cable ties still on system indicated conditions to be very fragile, with ties breaking with a gentle tug by hand.
- The failure analysis concluded that in the presence of corrosive ingredients at or near line artifacts, or under deposits, can cause stress corrosion cracking, eventually leading to the tie failure. The combined action of corrosion and stresses present leads to the observed failures of the present ties. **ZnCl from the galvanization is one of the leading drivers of this failure.**

  To reproduce failure in lab, Nylon 6.6 material cable ties were immersed into solutions of various Zn concentrations.
- What is the relevant field exposure concentration of ZnCl?

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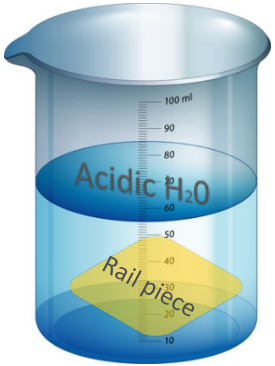
Experiment for Zn concentration estimation

- What is the maximum amount of Zn ions that can be leached into the solution from galvanized rail?

Soak Solution	1 inch x 1 inch (ca. 25mm x 25mm) **Zinc coated rail** in solution [ml]	1 inch x 1 inch (ca. 25mm x 25mm) **Zinc coated rail** in solution [ml]	1 inch x 2 inch (ca. 25mm x 50mm) **Zinc coated rail** in solution [ml]	Notes
Deionized water (DI) at 40°C	100	200	100	ICP - OES* of solution to evaluate trace metals
0.1M Hydrochloric Acid (HCl) at 40°C	100	200	100	**Baseline** and final measurement at **four weeks.**

* ICP-OES Inductively Coupled Plasma – Optical Emission Spectrometry

- Substrate to solution ratios are captured
- Effect of acid rains and other mode of wetness (rain, dew, washing etc.) are captured.
  - pH of DI water ~6 and 6.5
  - pH of 0.1M HCl is 1
- We have tested from 0.03 sq.cm/ml to 0.13 sq.cm/ml (a difference of up to 4 times) and found saturation is independent



Source: Materials Reliability, First Solar.

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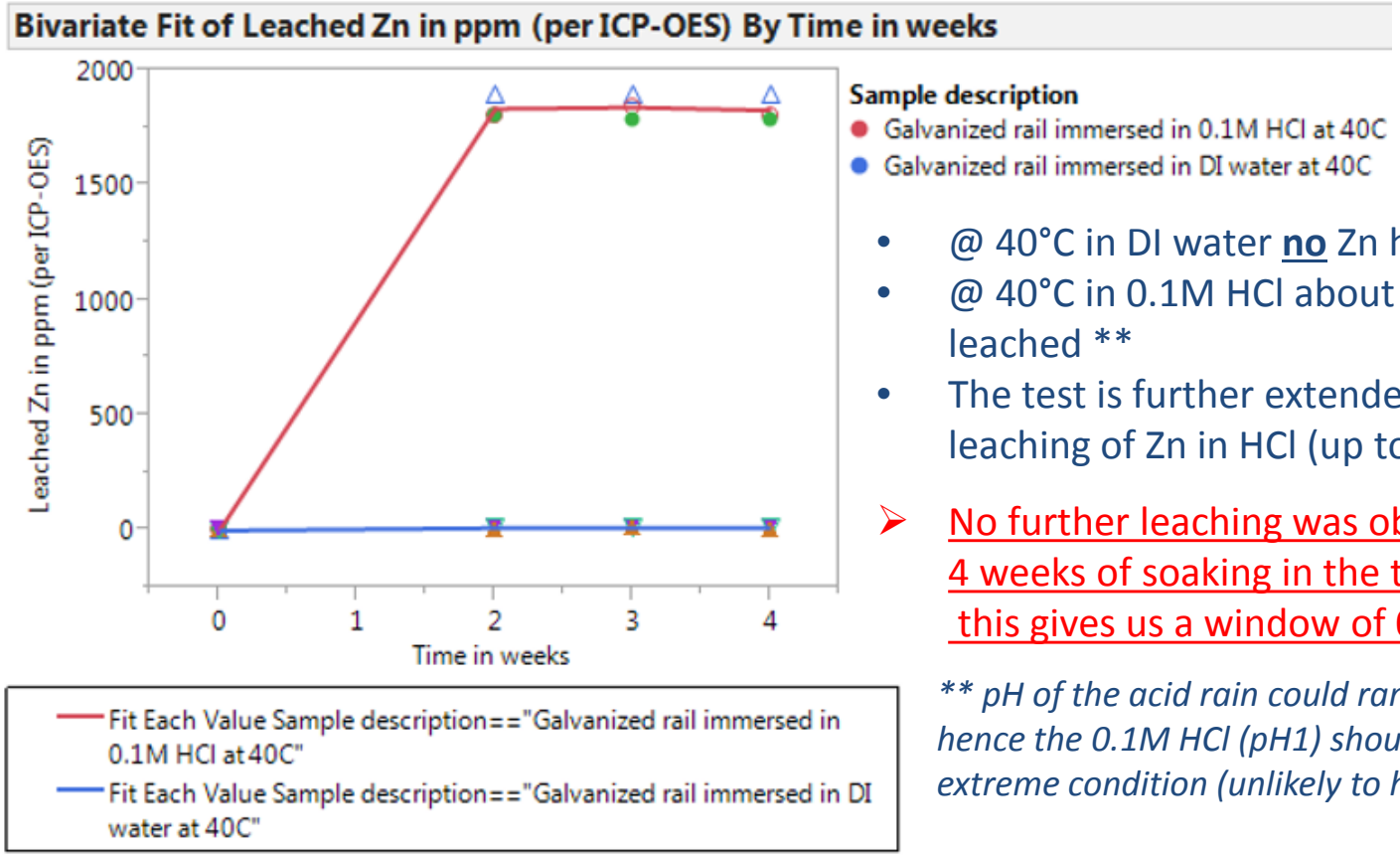
Leached Zn concentration as measured by ICP - OES



- @ 40°C in DI water **no** Zn has leached into the water
- @ 40°C in 0.1M HCl about **1800ppm** of Zn has leached **
- The test is further extended to verify further leaching of Zn in HCl (up to 4 weeks): saturation

➢ No further leaching was observed after 4 weeks of soaking in the test solution – this gives us a window of **0 to 2000ppm** of Zn

*** pH of the acid rain could range between 4 and 5.5 – hence the 0.1M HCl (pH1) should be considered an extreme condition (unlikely to happen in the field)*

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Source: Materials Reliability, First Solar.

What we know today?

- At **5000ppm** of Zn – Nylon 6.6 parts **fail**
- **500ppm** of Zn – Nylon 6.6 parts **pass**
- The maximum Zn that can be leached from G90 galvanized rail is **2000ppm**

- **2000ppm of Zn = 4g/L of $ZnCl_2$**

➢ Based on this we recommend using 2000ppm of Zn (i.e. 4g/L of $ZnCl_2$) as a standard test concentration *(for testing very extreme conditions)*

➢ If we see failure in the above said extreme condition then we will need to do further testing to assess real world scenarios
(*tests at around acid rain pH, and drip tests for instance)*

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Source: Materials Reliability, First Solar.

Design for Reliability - Environmental Considerations

Chemical Exposures in PV:

- ❑ **Site Preparation Chemicals (Items 1-4)**
- ❑ **Site Management Chemicals (Item 5)**
- ❑ **Contact with Galvanization (slide 18-21)**

Examples of Site Preparation and Site Management Chemicals:

Chemicals			
Application order	Trade name	Concentration	Purpose
1	AQUA-TEX		The Aqua-Tex is a surfactant that was utilized as part of the watering process.
2	POLY-TEX	See below	Poly-Tex is used to prevent wind kickup.
3	CHLOR-TEX	See below	The roads are covered with the Chlor-Tex at final stabilization.
4	ECCO-TEX	See below	Ecco-Tex is used prior to module installation.
5	MILESTONE HERBICIDE		Used to prevent weed growth
6	S and ZnCl		These are contaminants found in the galvanized zinc coating.

Weed growth reduction

Surfactant: watering process
Dust reduction
Road stabilization
Insecticide

Each of them is used in Chemical Concentrations as specified by the manufacturer.

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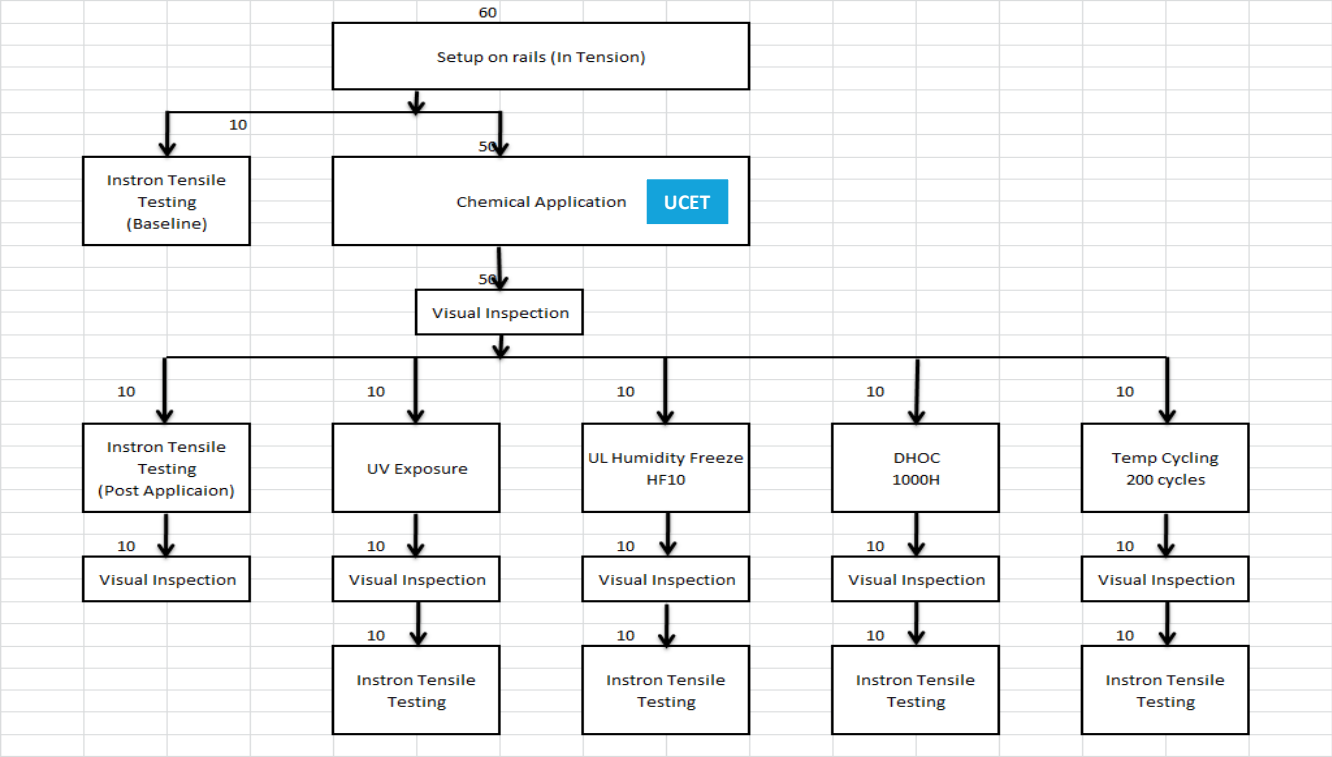
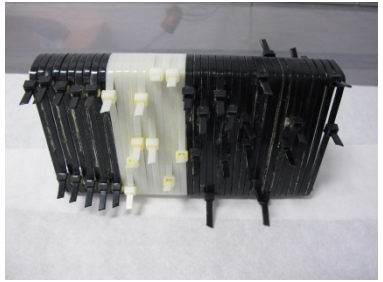
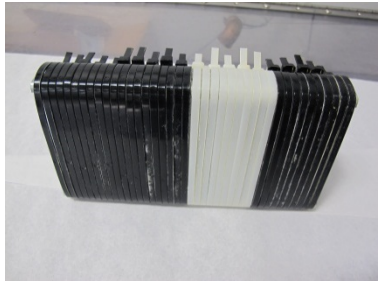
Source: Best Practices for Wire management, Systems Reliability, First Solar.

Suggested Approach to Mitigate Risks – Testing for Reliability

TEST Sequence for evaluating Chemical Robustness of Polymeric Wire Management Means (Cable Ties)
The primary measurement is failure rates and degradation in tensile strength of the wire management means as they progress through various combinations of stress exposures as illustrated in figure below.







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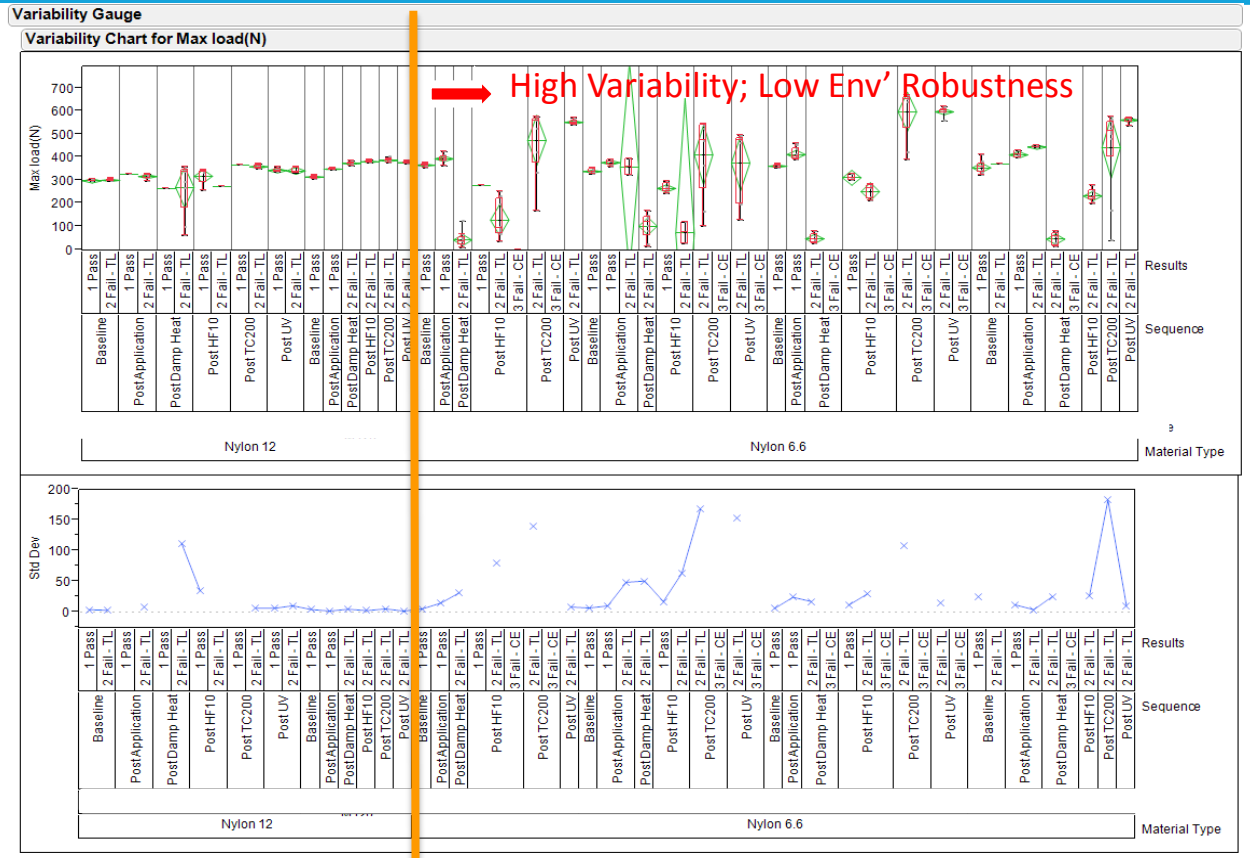
Source: First Solar Systems Reliability – Wire management Qualification Sequence.

Wire Tie Qualification – Test Results



Legend	Interpretation
No Break	No Breakage Found
Break - TL	Breakage due to tension (load)
Break - CE	Breakage due to chemical exposure

- **Conclusions**
- Chemical exposures can cause cable ties to fail (Nylon 6.6)
- Temperature and UV exposure risks are lower compared to humidity. High humidity exposures causes cable ties to fail prematurely
- Nylon 12 is a superior polymer to Nylon 6.6 from a chemical robustness standpoint.
- Nylon 12 also has a better performance to Temperature variations (TC 200) and also high humidity conditions (HF10)

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Source: Systems Reliability Test Laboratory, First Solar.

UCET – Universal Chemical Exposure Test

A UCET can be used to evaluate robustness of materials against chemicals in the operating environment.

Test Conditions and Chemicals used:

Chemical	Bath Temp. (C°)	Exposure Time (h)	Curing Temp. (°C)	Curing Time (h)
10:1 H2SO4:HNO3 (acid rain)	40	72,0	N/A	N/A
Ammonium hydroxide (3%)	RT	48,0	N/A	N/A
AQUA-TEX(5X)	RT	0,5	40	168
AQUEOUS NaCl SOLUTION(5%)	55	168,0	N/A	N/A
CHLOR-TEX(1X)	RT	0,5	40	168
ECCO-TEX(5X)	RT	0,5	40	168
MILESTONE HERBICIDE(10X)	RT	0,5	40	168
NaOH (5X)	RT	1,0	N/A	N/A
POLY-TEX(5X)	RT	0,5	40	168
TAP WATER	55	168,0	N/A	N/A
ZnCl2 (2000ppm of Zn)	**RT**	**0,5**	**40**	**4**

Within UCET, every test is performed independently on different samples and material sensitivities can be exposed.

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Source: Materials Reliability, First Solar.

Design for Reliability - Environmental Considerations

Climate classification	Mean value of the annual extreme values of temperature and humidity		
	Low temperature (°C)	High temperature (°C)	Highest absolute humidity (g × m–3)
Tropical	5	45	35
Arid	-10	50	30
Temperate	-20	40	30
Cold	-50	45	25

Tropical

UV: High (>4)
Moisture: High (>4)
Heat Cycling: Low (<2)

Arid

UV: High (>4)
Moisture: Low (<2)
Heat Cycling: High (>4)

Temperate

UV: Low (<2)
Moisture: Medium (≤4,≥2)
Heat Cycling: Medium (≤4,≥2)

Cold

UV: Medium (≤4,≥2)
Moisture: Medium (≤4,≥2)
Heat Cycling: Low (<2)

Step 1: Identify the climate classification for the site based on IEC 60721-2-1 standard (Top left)

Step 2: Identify the key stressors of polymeric wire management means for the classification. (Table in left)

Step 3: Look up the ranking level for the stressor in the appropriate climate. (Table in left)

Step 4: Rank the stress level on the polygon in next slide

Step 5: Select the type of polymeric material that meets the needs.

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Source: Best Practices for Wire management, Systems Reliability, First Solar

Design for Reliability - Environmental Considerations

Choose the correct material for the application

Nylon 6.6

These cable ties are heavily used in market place.

Pros

- relatively inexpensive compared to Nylon 12 and stainless steel
- product is readily available in numerous sizes, lengths and has load carrying capabilities
- product is readily available by multiple suppliers

Cons

- internal test results show high humidity + high temperature can result in degradation in the nylon material; Multiple replacements over lifetime.
- contact with galvanized metals can result is degradation in the nylon material
- life expectation requires multiple replacement for 25year design life

Nylon 12

Pros

- test results show the material is more robust than the Nylon 6.6 in typical "Solar duty" environmental conditions
- test results show the material is more robust to contact with galvanized metal (ZnCl2 exposure)
- should last much longer than expected 6.6 lifetimes, 0-1 replacements

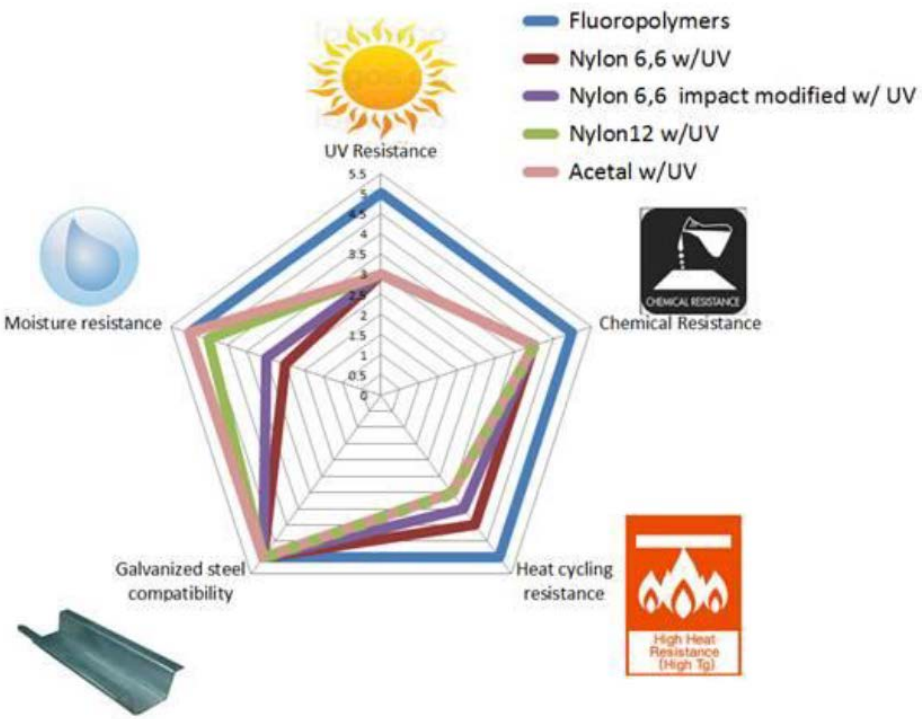
Cons

- more expensive compared to Nylon 6.6
- not as readily available as Nylon 6.6
- does not come in all sizes required by market place currently

Other Materials : Acetal, Flouropolymers etc.

- **Supply Constraints and Costs are restrictive**.

Figure 3: Material Selection according to environmental conditions (chart provided by Hellermann Tyton)



Source: Best Practices for Wire management, Systems Reliability, First Solar.; Chart courtesy of Hellerman Tyton.

Summary

- We have illustrated through risk analysis the importance of planning the wire management means considering the criticality of potential failure modes and optimizing lifetime costs.
- Specifically for risk mitigation, due consideration should be given to
  - Selection of the right material for the application
  - Proper estimation of the load to be managed and appropriate selection of means
  - Considerations of the operating environment, human and installation factors
- We also illustrate the chemical and other primary stressors experienced by wire management means and a structured selection approach considering the effects.
- We suggest the use of Nylon 12 material as the material of choice for wire ties based on chemical and environmental experience. It offers the best balance of cost, performance and reliability for free field applications.

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  - Hellerman Tyton

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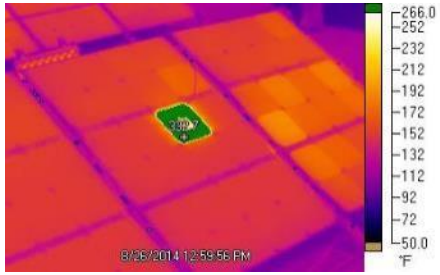
Polymer Encapsulated Photovoltaic Solar Panel Abusive Testing

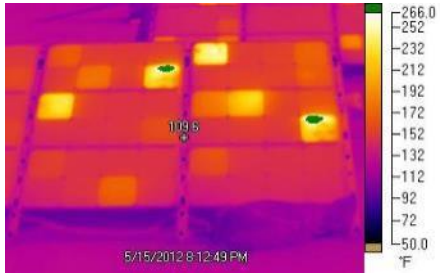
Overview

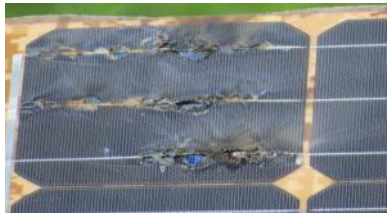
The USMC utilizes photovoltaic solar panels to power equipment such as laptops, radios, battery chargers, and lighting in austere locations. **Weight, volume,** and **transportability** are key attributes of such panels.

To reduce weight and volume and improve transportability for expeditionary applications, specialized panels employing polymer encapsulation on semi-rigid or flexible backings and lightweight composite deployment structures have been evaluated. Crystalline silicon, amorphous silicon, and CIGS are the common semiconductor types.

However, the transition from glass and metal framing to polymers has introduced unique stability and safety issues that were discovered in testing.







Clockwise from bottom left: Traces burning under short circuit, partial shading heating, short circuit heating

Solar Panel Abusive Testing

In 2014, Carderock experienced a fire at a solar test facility that originated from a prototype solar array. The root cause was determined to be short circuiting with partial shading.

Carderock has developed abusive test procedures aimed specifically at polymer encapsulated panels to uncover potential performance and safety design issues:

- Short circuit at high irradiance and temperature
- Partial shading at high irradiance and temperature
- Partial shading with short circuit

Electrical design, materials selection, and **manufacturing processes** were all found to have strong impacts on panel performance and safety.

Lessons Learned

- Short circuit leads to pronounced heating effects on panels with crystalline silicon cells
- Partial shading leads to localized heating
- Partial shading under short circuit is the most abusive condition
- Heating is most pronounced at high irradiance and high temperature
- Sufficient bypass diode layout and internal insulating layers improves panel survivability:
  - Additional specialized polymer layer reduces or eliminates severe heating and fires
  - Addition of bypass diodes reduces heat generation in shaded cells

Tech POC: Matt Huffman, NSWC Carderock, 301-227-4206

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US DoD Expeditionary Solar Power Needs

Overview

The DoD utilizes specialized photovoltaic solar panels to power equipment such as laptops, radios, battery chargers, and lighting in austere locations.

Solar is best suited for low power scenarios such as observation posts and combat operations centers, where saving fuel provides the greatest logistical benefits and where silence is a major operational benefit.

However, the needs and constraints of the DoD for expeditionary power vary significantly from commercial needs and constraints.

Advanced GREENS array (AISPCA), 1680W in 296lbs (5.68W/lb*)

* Values include deployment structure

Early GREENS array (ISPCA), 1720W in 620lbs (2.77W/lb*)

SPACES array, 80W in 6.3lbs (12.7W/lb)

Commercial Vs. Expeditionary Solar

Metric	Commercial	Expeditionary
Installation	Predictable, planned installation	Set up in diverse, challenging environments
Setup Time	Not typically critical	Must be rapidly deployed and recovered
Number of Deployments	One Time	Many lifetime deployments
Voltage Configuration	High voltage	Low voltage
Mounting	Typically heavy, robust structures	Low weight AND physical robustness
Environmental Conditions	Known global location and weather	Can be deployed in many locales
Setup Personnel	Well-trained, specialized for solar	Minimally trained, have other focuses
Weight Metric	6.1W/lb	15.3W/lb to 22.9W/lb
Volume Metric	106W/ft^3	629W/ft^3

Current DoD Approach

- Combine high efficiency solar cells with lightweight polymer encapsulation to reduce panel weight & volume
- Deployment methods are adaptable, quick, and easy, and structures are optimized for weight & volume
- Incorporate adjustable deployment angle, MPPT, and bypass diodes to maximize solar array effectiveness
- Solar is used where it provides the most benefit in expeditionary, tip-of-the-spear situations, NOT at large bases, where tactical generator power is widely available
- GREENS ISPCA: ~17% efficiency, mono-Si
- GREENS AISPCA: ~16% efficiency, mono-Si (~double W/lb to ISPCA)
- SPACES: ~4% efficiency, CIGS
- Future goals/targets:
  - GREENS: Prototype a-Si array delivers reduced weight and increased power (10.5W/lb deployed, ~84% improvement) at the cost of aerial power density
  - SPACES: Prototype a-Si array delivers reduced weight and increased power (22.9W/lb deployed, ~80% improvement)
  - Gallium Arsenide may improve all power density metrics, but has been perceived as cost prohibitive

Tech POC: Matt Huffman, NSWC Carderock, 301-227-4206

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Considerations for Useful Life for Utility, Commercial and Residential Solar Photovoltaic (PV) Power Plants

Rounak A. Kharait, Mark Reusser, Heidi Larson, P.E., John W. Graff, Ph.D.

Background

What is the expected useful life for a PV system?

There has been a significant increase in the installation and operation of PV projects. As a result, lenders and investors have inquired on the expected useful life of PV systems, especially as it relates to acquisitions or refinancing transactions.

The answer is not simple, as there is limited field data from assets with a meaningful operating period. In the absence of field data, other aspects of system development, design, and operation must be relied upon in order to form an opinion on the expected useful life of a PV system.

Estimated Useful Life (EUL)

Technical EUL

> Proposed Definition: The expected period of time during which 90 percent of the overall PV system is operating at or above 80 percent of expected output.

Major PV System Equipment and Considerations

Modules

Module technology and construction – crystalline or thin film, glass & back sheet, or glass on glass

Accelerated Life time testing (ALT) conducted by module manufacturers to measure degradation and durability

Module manufacturers provide performance warranties

Inverters

Inverter technology – string, microinverters, or central inverters

Inverter manufacturers also conduct ALT and provide equipment warranties

Inverter components may be tested for mean time between failure (MTBF)

Mounting/Tracking System

Types of mounting –
> Ground mount: fixed tilt (piles), fixed tilt (ballasted), carport or single axis tracking
> Roof mount: anchored or ballasted

For both mechanisms load bearing capacity is important

Structure should be able to withstand prescribed wind and snow loads

For tracking system, O&M of motor drive, bearing housing, etc.

String Inverters	> Used in residential/commercial projects/utility scale projects > Mid-size units and capacity, some components field replaceable
Microinverters	> Used in residential projects/commercial projects > Small units (one per module), failed units are replaced (not repaired)
Central Inverters	> Used in utility scale projects > Large units ranging over 2 MW-AC capacity, field repairable

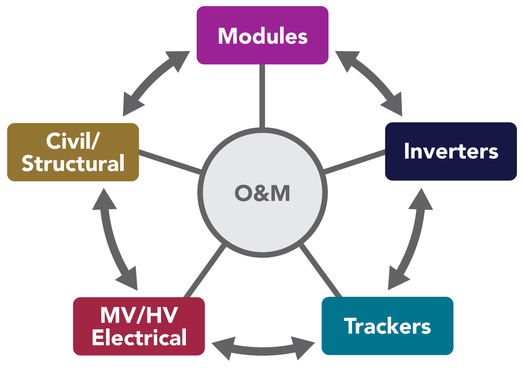
Economic EUL

> Proposed Definition: The period of time during which the revenue and benefit generated by a PV system exceeds the cost of ownership.

> Definition provided for reference, some items that factor into economic useful life are the power purchase agreement, depreciation, tax credits, etc.

Industry Standards

> While an industry definition of PV plant EUL may not be fully standardized and accepted, we offer the above working definition for the purpose of this poster.



> EUL of the PV plant is interdependent as shown, with operation and maintenance (O&M) of all equipment being of prime importance.

> Major equipment is developed upon a basis for design life:
  > Key equipment components are tested to determine MTBF
  > Replacement intervals may be recommended
  > Standard warranties include:
    > 10 years product, 25 years performance for modules
    > 5 years for central inverters, 10 years for string inverters, 10+ years for microinverters
    > 5+ years for mounting systems

> Industry has begun to explore technical equipment options, construction methods, and O&M best practices for the purpose of extending the EUL.

Key Considerations in Evaluating Technical Useful Life

Site Considerations

> Atmospheric conditions:
  > Thermal cycling, heat and humidity
  > Dynamic loading from wind and snow ***(increasing area of focus)***
  > Corrosion from air natural composition (such as salt fog) or contaminates

> Geotechnical concerns that could impact construction quality, including corrosion from soil natural composition or contaminates (ground mount)

> Roof construction, quality, and condition (roof mount)

> Landfill cap condition (landfill systems)

Design and Equipment

> Design basis included in the engineering and construction contracts

> Design basis for major equipment proposed for a system
  > Module reliability continues to be an industry focus
  > Wide range of inverter design topologies and architectures ***(increasing area of focus)***
  > Adequacy of wind tunnel testing for mounting systems ***(increasing area of focus)***

> Provision and term of equipment warranties

> Corrosion calculations (ground mount)

> Expected remaining service life of roof (roof mount)

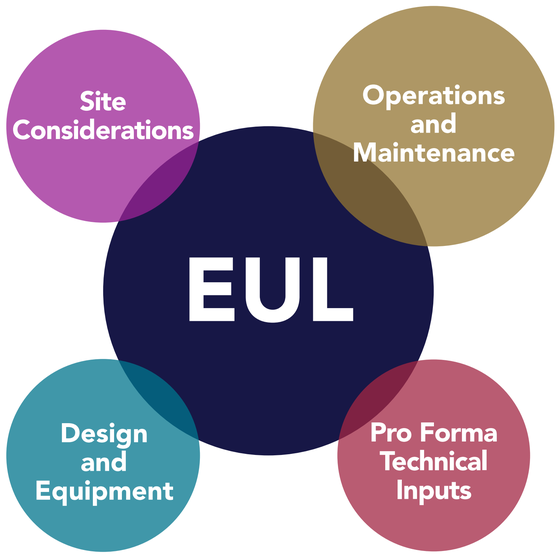
> DC system design and voltage

> DC and AC system cabling including exposure to ambient conditions; quality of connectors, insulation, and conduit; methods for wire management

> AC system equipment has applications beyond PV and proven field history ***(area of limited focus)***

> Performance of similar equipment/systems in similar climates ***(increasing area of focus as more historic data becomes available)***

> Evolving trends in equipment and design, potential for avoiding obsolesce by designing flexibility in integration ***(increasing area of focus)***



Operations and Maintenance

> Scope and budget included for O&M

> Number of years included in the O&M budget

> Routine and preventative maintenance provisions (pre and post warranty)
  > Module replacements
  > Inverter refurbishments/repair/replacement
  > Cabling replacement/repair

> Spare parts inventory and arrangements for additional procurement

> Major maintenance plans and reserve budget

> Consideration of any historical budget data ***(increasing area of focus)***

> Consideration of obsolesces - Technical feasibility of obtaining replacement equipment, possibility of plant cannibalization, potential for full sub-system replacement

Pro Forma Technical Inputs

> Assumed system degradation rate (especially post module warranty)

> Assumed availability/uptime
  > Potential for decreased availability in later years due to replacements/repairs
  > Additional potential for decreased availability for roof mount due to roof replacement/repairs

Implications and Impact

The expected useful life for a PV system is dependent on project-specific factors. While there is no set criteria for establishing the expected useful life, it is important to consider the combined influence of various aspects – with the current primary focus on O&M, design basis, and technology. As the PV industry continues to evolve, key considerations may be adjusted or re-prioritized, especially as more operating data and performance records become available to the industry.

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REC Component Reliability Studies:

Extended Reliability of PV Connectors

*C.W.J. Ho[1], A. Tan[1], T.C. Tan[2]

[1] Failure Analysis & Customer Assurance, REC Solar Pte Ltd.

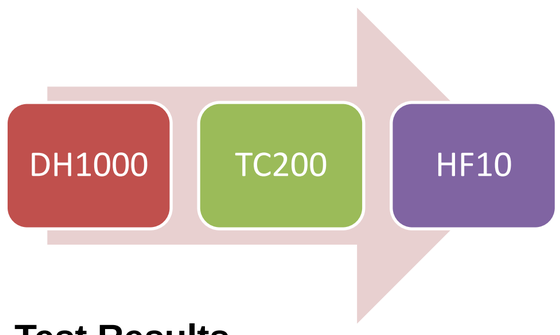
[2] Quality Assurance & Performance Management, REC Solar Pte Ltd.

Abstract

One of the most commonly encountered field failures in the industry is faulty connectors resulting in common failures like R_{iso} error in PV system or burnt connectors etc. Multiple designs of cable connectors are obtained to undergo reliability & durability studies. Combined Cycle Test, CCT, (DH1000, TC200, HF10) is selected as primary indoor test (instead of 2xIEC or 3xIEC etc.) to mimic harsh environmental conditions in the field. Several failure modes were observed like cracked connectors, loosening of cable gland, resulted in wet leakage current test failures. Further investigation showed weak plastic welding resulted in connectors to crack easily along welded joints and optimized tightening torque force help to mitigate loosening of connectors to certain extent. In addition, oxidation of metallic contacts (Failure analysis showed due to non-uniform & insufficient Sn coatings) have also been detected which may lead to hot connectors/burnt connectors in the field.

REC Reliability Test Regime

Primary Test Sequence



Connectors Tested

5 types of connectors selected for studies : *A, B, C, D, E*. (Connector *A,B,C* have similar design. *D&E* connectors have additional anti-loosening feature.)

Test Results

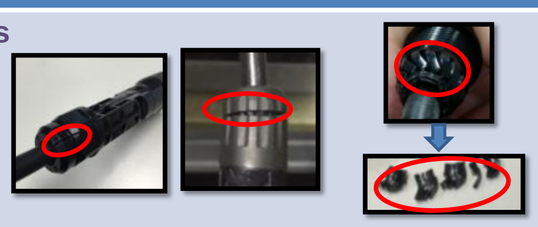
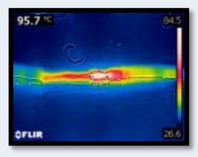
Samples	Connector type	Test Failures (%) Visual Inspection	WLT	Contact Resistance
Before improve*	A	0%	58%	0%
	B	0%	40%	20%
	C	33%	50%	0%
	D	0%	0%	100%
	E	0%	0%	100%
After improve**	A	0%	0%	0%
	B	0%	0%	0%
	C	0%	0%	0%

* Multiple failures detected initially after CCT. Failures are similar to field failures.

** Pass all test measurements. CCT could be used as a qualification test regime to improve reliability & durability of connector design

(Note: Target to continue for 2 X CCT to understand the potential failure mode and material limitation.)

Connector Failures

Field failure	CCT failure mode and analysis
Riso error in PV system due to faulty connectors Corrosion due to water ingression	Cracks  Loose Cable Gland
Hot connector / Burnt connector 	Oxidation of Metallic Contacts Discoloration & friction lines IR Image (Hot connectors)

Improvement Actions on failures observed :

1) Visual Inspection failure due to cracked connectors – Change to more durable polymer resin (Polymer with Fiberglass additives).

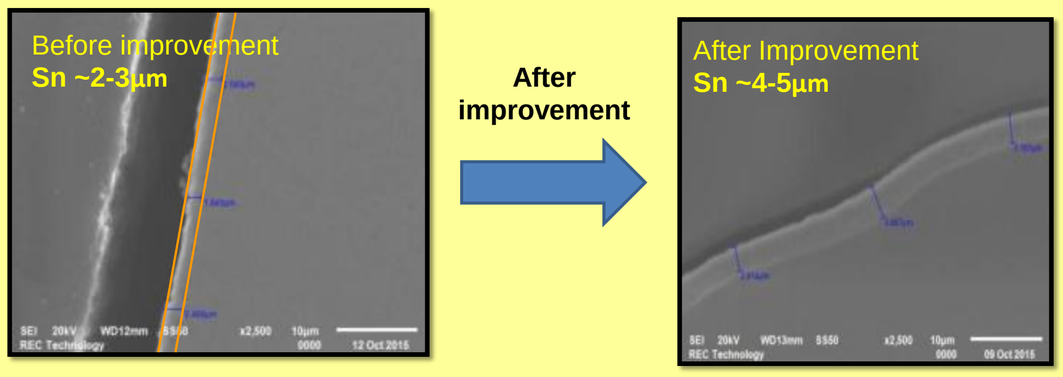
2) Wet leakage current test (WLT) failure - Change to more durable polymer resin & increase in tightening torque.

(Note: WLT failure can be restored by tightening of cable gland).

3) High contact resistance – Improve on Sn coatings thickness & uniformity on metal contacts.

(Note: Other electroplating methodology to improve Sn coating uniformity under exploration. Cause behind high contact resistance for connectors D & E not studied.)

SEM analysis of Sn coating thickness on metallic contacts:



Design Recommendations: Connector glands with anti-loosening feature and sufficient gap for thermal expansion & contraction.

Conclusion

Combined Cycle Test is an effective test to uncover potential weak points of connectors. Different types of connector failures are observed which includes cracked connector parts, loosening of connector gland and corrosion of metallic contacts that coincides with field failures reported. Less aging resistant polymer resin used resulted in increase in the ease of connector cracking after CCT. Loosening of cable gland occurs due to insufficient tightening torque during manufacturing. However, such failures can be restored by tightening of the cable gland. High contact resistance is found to be due to non-uniform and thin Sn coating (<4µm) on metallic contacts which leads to higher chance of corrosion. All connectors are able to pass CCT after improvement actions are implemented. In future, two cycle of CCT will be used to further study the weaknesses of connectors manufactured.

*Email: John.ho@recgroup.com

Rooftop PV Systems and Firefighter Safety

Greg Ball[1], Jason Fisher[2]

[1]DNV GL, [2]Solar City

ABSTRACT

This paper summarizes findings from a DNV GL study of rooftop PV systems and firefighter safety. The study's scope included:

1) Literature review focused on firefighting issues specific to PV
2) In-depth firefighter interviews covering rooftop operations, concerns and decision making processes with respect to PV
3) Failure Mode and Effects Analysis (FMEA) based evaluation of various methods of shock-hazard reduction.

BACKGROUND

The 2014 edition of the National Electrical Code (NEC) instituted requirements in Article 690.12 for "rapid-shutdown" functionality: the ability to effectively de-energize specific PV system circuits that would otherwise remain energized by the sun after utility power is cut to the building.

The 2014 requirements apply to circuits outside the boundary of the PV array, but the draft 2017 NEC includes requirements to reduce shock hazard inside the array. The original 2017 draft was an effective mandate for module level control devices. However the 2nd draft allows alternative means listed to a rapid shutdown array standard. The hard work now falls to standards developers and the PV & firefighter industries to determine the objectives and requirements for reducing shock hazards in arrays.

FIREFIGHTER SURVEY OBJECTIVES

The study sought to advance the conversation between the PV and firefighter industries by addressing these key questions:

1. **What are the firefighter operations that put them at risk of electrical shock?**
2. **What are the specific shock scenarios created by these operations?**
3. **How do the risks, both real and perceived, impact tactical decisions?**
4. **How would enhanced protection in the array impact those tactical decisions?**
5. **What are the expectations for fire-damaged arrays, or for verifying components are de-energized?**

FIREFIGHTER ROOFTOP OPERATIONS

Vertical Ventilation:
Cutting a hole in the roof above the hottest part of the fire to allow trapped smoke and hot gasses to rise out of the building.

Short window of opportunity to safely execute.

Additional Commercial Building Operations:

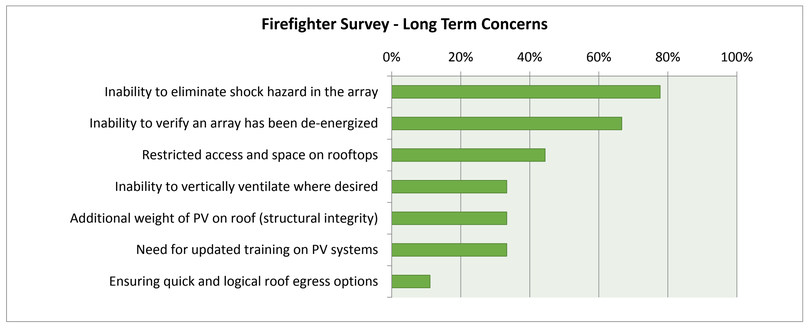
Trenching – a "trenched" ventilation hole used as a firebreak to prevent spread of fire to other parts of the building

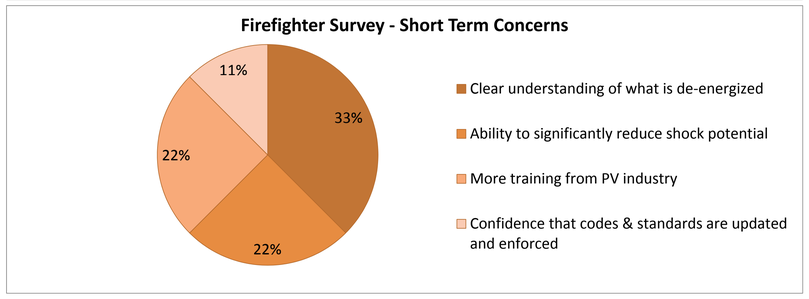
Probing (or "sounding") – a tactic used to determine the progress of the fire and damage in a building. One method is to pound the roof with the blunt side of an axe to determine softness.

FIREFIGHTER SURVEY FINDINGS

The presence of a rooftop PV array adds additional risk factors that impact decision making of incident commanders:

- Access (available maneuvering space)
- Trip or slip hazards, particularly with poor visibility
- Roof structure integrity due to the additional weight of PV
- The risk of inadvertent electrical shock, should a firefighter come in contact with damaged array components, or accidentally cause damage to the components
- The level of perceived electrical hazard risk by individual firefighting units and incident commanders.





KEY SURVEY TAKEAWAYS

- Clear knowledge of what is and what is not energized is vital.
- Respondents do not expect rapid shutdown functions to work under damaged equipment conditions; will treat as energized
- Indication and verification is not full proof
- Enhanced array protection should be pursued to reduce risk of accidental shock and to improve operational decision-making
- Firefighters should not intentionally interact with the array due to the limitations and uncertainty of de-energization.
- The survey did not reveal rationale for mandating a specific solution for reducing electrical hazards within array.

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[4] NFPA NEC (2014): National Electrical Code

ACKNOWLEDGEMENTS

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FMEA: SHOCK SCENARIOS AND SHOCK REDUCTION METHODS

DNV GL developed FMEAs for Residential and Commercial rooftops with PV. Risks identified from the specific firefighter operations are evaluated along with a variety of mitigation options. The FMEA incorporates severity of failure, probability of failure, and effectiveness of mitigation to provide relative scores for the mitigation options. The product of the three scores is called the Risk Priority Number (RPN), and the lower the RPN value, the better the outcome. Cases included arrays with no damage and arrays with an existing single point of failure.

Severity Score (1-10)		Occurrence Score (1-10)		Detection Score (1-10)	
10	All Cases	5	Moderate	6	Risk to personnel
		3	Low	4	Reduced risk
		1	Extremely Low	2	Low risk

Residential FMEA Table Undamaged Array Case

#	Electrical Shock Risk Scenario	Probability	Mitigation Impact of.... 2015 IFC			2015 IFC + 2014 Array RSS			Module level control (80V)			Floating System, single point (Inverter)			Floating System, combiner box level			Floating System, string level (1-pole)			Floating System, string level plus string disconnect from each other (2-pole)			Floating System, conductors are proximity and access limited			Floating System, conductors mechanically protected		
	Undamaged Array		O	D	RPN	D		RPN	D		RPN	D		RPN	D		RPN	D		RPN	D		RPN	D		RPN	D		RPN
1a	Fall on array, conductive tool punctures module glass or inter-module wiring, additional contact with module frame or grounded structure* (via skin, damaged glove or boot)	*Moderate*	5	6	300	6	3	300	4	2	200	4	2	200	2	1	100	2	1	100	2	1	100	2	1	100	2	1	100
2a	Fall on array, conductive tool punctures string wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)	*Moderate*	5	6	300	6	3	300	2	1	100	4	2	200	2	1	100	2	1	100	2	1	100	2	1	100	2	1	100
3a	Fall on array, conductive tool damages electrical dc component (combiner, inverter, e.g.) and contacts aggregated circuits, additional contact with grounded structure) via skin, damaged glove or boot)	*Low*	3	6	180	6	3	180	2	2	60	4	3	120	4	3	120	2	3	60	2	3	60	4	3	120	4	3	120
4a	Fall on array, single conductive tool damages/cuts two separate string/field circuit conductors, contact via skin or damaged gloves.	*Low*	3	6	180	6	3	180	2	2	60	4	3	120	4	3	120	4	3	120	2	3	60	2	3	60	2	3	60
5a	Fall on array, conductive tools in both hands or grab/damage two separate circuit conductors, contact via skin or damaged gloves.	*Extremely Low*	1	6	60	6	1	60	2	2	20	6	1	60	6	1	60	6	1	60	4	2	40	2	2	20	2	2	20
6a	Hose fitting punctures glass or damages conductor insulation and contacts circuits, additional contact with damaged gloves/boots via wet hose and grounded surface.	*Extremely Low*	1	6	60	6	1	60	2	2	20	2	1	20	2	1	20	2	1	20	2	1	20	2	1	20	2	1	20
7a	FF pulls on intermodule wiring with damaged gloves, additional contact with module frame or grounded structure.	*Low*	3	6	180	6	3	180	4	2	120	4	2	120	4	2	120	4	2	120	2	3	60	2	3	60	2	3	60
8a	FF cuts intermodule wiring with tool, additional contact with module frame or grounded structure.	*Extremely Low*	1	6	60	4	1	40	2	2	20	4	1	40	4	1	40	4	1	40	2	1	20	2	1	20	2	1	20
9a	FF pulls on string/field wiring with damaged gloves, contact between circuit poles.	*Extremely Low*	1	6	60	6	1	60	2	2	20	6	1	60	6	1	60	6	1	60	6	1	60	2	2	20	2	2	20
10a	FF cuts string/field wiring with tool, contact between circuit poles.	*Extremely Low*	1	6	60	4	1	40	2	2	20	4	1	40	4	1	40	4	1	40	2	1	20	2	2	20	2	2	20
		Average	2	6	144	5.6	1	140	2.4	2	64	4.2	2	98	3.8	2	78	3.6	2	72	2.6	2	54	2.2	2	54	2.2	2	54
		Maximum	5	6	300	6	3	300	4	2	200	6	2	200	6	2	120	6	2	120	6	2	100	4	2	120	4	2	120

FMEA Summary Results for Residential and Commercial Rooftop

Risk Category	SUMMARY: Max Mitigation RPN Scores for 2015 IFC +								
	2015 IFC	2014 Array RSS	Module level control (80V)	Floating System, single point	Floating System, combiner box level	Floating System, string level (1-pole)	Floating System, string level plus string disconnect from each other (2-pole)	Floating System, conductors are proximity and access limited	Floating System, conductors mechanically protected
Residential (Undamaged)	300	300	200	200	120	120	100	120	120
Residential (Single Point Failure)	300	300	200	300	200	180	120	180	180
Commercial (Undamaged)	300	300	200	200	120	120	100	120	120
Commercial (Single Point Failure)	300	300	200	200	180	180	120	180	180

CONCLUSIONS

- FMEA demonstrates several mitigation methods are capable of providing comparable shock hazard reduction, and are aligned with general methods identified in the NEC:
  - ❖ limiting access to energized components
  - ❖ reducing the voltage difference between energized components, and
  - ❖ limiting circuit current with increased resistance of the conductive circuit.
- 2015 IFC access and 2014 Rapid Shutdown Requirements (RSS) do not provide sufficient mitigation
- Floating an array with a single ground disconnection is not sufficient in a single point failure case
- Module level control, multiple ground and circuit disconnection, and access limited & mechanically protected conductors are all capable of meeting acceptable scores.
- DNV GL recommends supplemental testing to the UL Firefighter tests that were conducted in 2011.
  - ❖ Better replication of shock scenarios as defined here
  - ❖ Tests of residual charge in floating circuit(s)
- Further detailed study is needed to validate or clarify results from this high level study.

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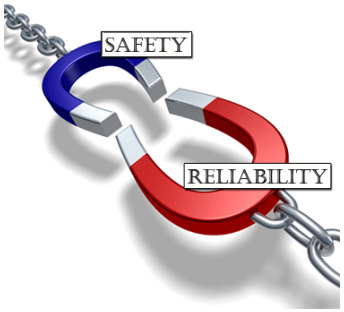
The Changing Dynamics of Inverter and Electronic BOS Reliability

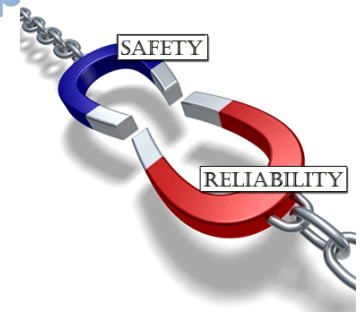
Ward Bower: Ward Bower Innovations LLC

2016 NREL Module Reliability Workshop

February 23-25, 2016

Lakewood, CO





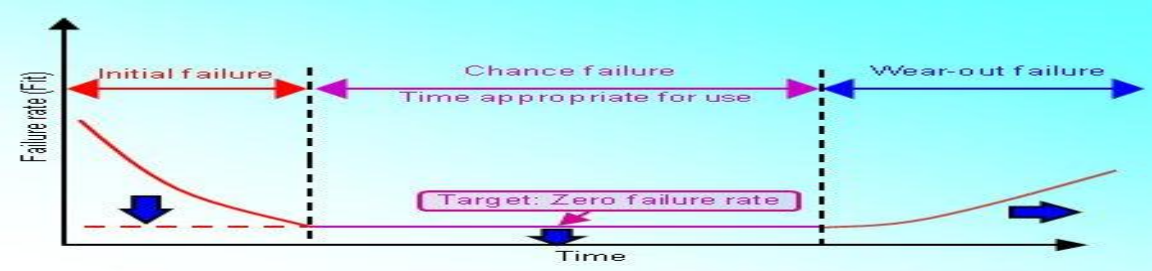
ABSTRACT

The required functionalities of inverters and increasingly other electronic BOS components are changing almost on a weekly basis. The changes offer many challenges and opportunities. Very high reliability is now critical where life-safety is concerned. Reliability will be a major deciding factor for successful commercialization. New or updated standards, codes and certifications are required for the complexities associated with new life safety requirements. High reliability for mandated functions will be the norm to address concerns beyond just performance. Inverters and BOS equipment must be evaluated for very reliable operations as well as long-term reliability equal to PV modules.

New Required Roles Where High Reliability Must be Addressed

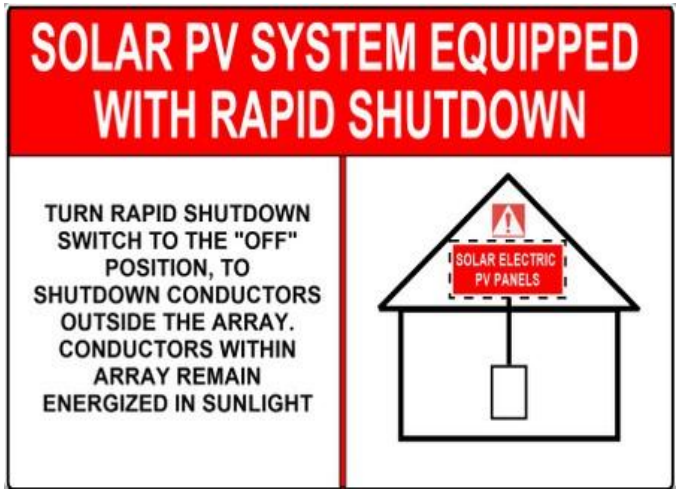
Category	Priority Requirements	Technical Barriers and Needs
First Responder Safety	NEC Article 690.12	Environments, Lifetimes, Materials, Testing, Standards, Compatibilities
Arc Fault Detection	NEC Article 690.11, UL1699b update	Extreme Environments, Compatibilities
Microgrids Backup /Resiliency	IEEEP2030.7 and others in process	State and Utility Mandates, Standards, Compatibility
Distributed Generation	CEC Rule 21 (Power Quality /Support)	Mandates, Standards, System Compatibilities
Communications for Safety	Fail Safe, Many Disparate Standards	Compatibility, Reliability Standards, Interference

You Can't Get

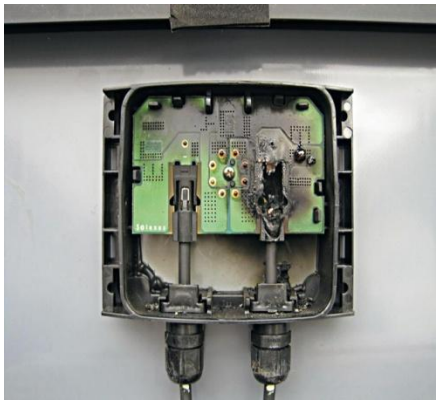


Around This!

The New Reasons For High Reliability



Module Level Electronics Likely!

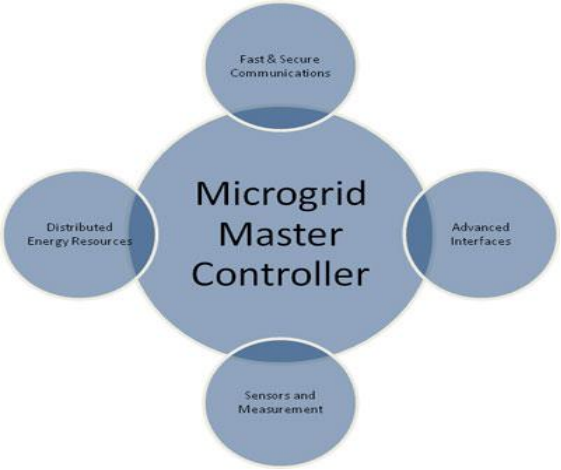


Arc Fault Detection in Severe Environments

Resilience requires Reliability

"US rooftop solar capacity could increase 5-fold (to 50GW) by 2016:" Deutsche Bank

50GW = 20M Module Level Electronic Devices



Microgrids for Reliability

Steps Necessary to Improve Reliability

Present Situation	Needs and Concerns	How to
Section 690.12 of the 2017 NEC requires safer voltages within the PV array.	Methods to reliably provide PV close-to-the-source (<80V_{dc}*) voltages and low power with rapid shutdown. Lifetimes equivalent to PV is needed Less than 30V_{dc} is preferred by IAFF	Develop and certify high reliability, long lifetime methods for safe rapid shutdown for firefighters. This will most likely require close-to-the-source electronics. Inverters and BOS must include methodologies for dealing with legacy PV systems .
The new language for Article 690.12 for 2017 from the NFPA fire safety task group requires module-level control or a listed PV array.	The PV industry needs cost effective, reliable, long lifetime,, rapid disconnect products integrated into a listed array that do not compromise system reliability or lifetime.	Identify advanced materials for designs that use reliable highly integrated circuits, digital topologies and secure communications. Fast track standards and qualified facilities to provide certification, reliability and lifetime assurances.
The language adopted for the 2107 NEC was done with the understanding that the concerns over reliability could be addressed before 2019. Industry-wide verifiable progress must begin.	There is no program to accelerate development of rapid shutdown products. Standards addressing the wide variety of technology options, system sizes or initiation methods and devices are just beginning.	Advanced electronic designs using wide band-gap materials for temperature environments of rapid shutdown devices that can be used in highly integrated packages. The new package designs must be weather resistant and minimize discrete components or individual semiconductor devices.
The safe operation of legacy systems (installed prior to the 2017 NEC) that also may lack both adequate ground fault protection and arc fault mitigation.	Legacy systems will require retrofits that may compromise operations. Retrofitting systems with the rapid shutdown devices must void the listings, certifications and warranties already in place.	Include additional monitors to detect abnormalities and operations that indicate component, wiring and interconnect weaknesses. This will require periodic testing. Place signs to indicate firefighting preferred methods and dangers. Rapid shutdown must be reliable for fires originating outside of the PV.

Engineering Priorities Needed to Improve Electronic Reliabilities

Needs	Methodologies	Timeframes
Design for High Reliability and Long Lifetimes	Quality Assessment, FMEAs, Subassembly Testing	2-3 Years
Determine Critical Material properties critical failures	Quality Assurance Programs, Material Compatibilities	1 Year and Relentless Ongoing Studies
Accurate Modeling Programs	Reliability Programs	2-3 + Years
Update Failure Models	Catalog Relevant Devices	Ongoing
Life cycle reporting from monitoring	New Monitoring Methods and Software	2-4 Years and Ongoing
List and Prioritize Critical Anomaly Conditions	Monitoring Fielded Systems with Engineering FMEA	1-3 Years and Ongoing
Remaining Useful Life Assessment	Monitoring and Materials Studies	2-5 Years and Ongoing

Summary
Electronic BOS Reliability

- Very High Reliability of Inverters and Safety Related Balance-of-System must become the normal practice in the near future
- The Highest Priority for Inverters & BOS today is for Rapid Shutdown and Arc Fault Detection
- Applications for DG, Microgrids are next and will require reliability that Utilities & Owners can count on.

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