Presentation Proceedings

This annual conference was held in Golden, Colorado, with the intent of bringing together solar technology experts to discuss current and future issues in PV reliability. Longer-lasting PV systems make lower-cost solar electricity and have less impact on the environment, human health, and natural resources.

This document collects talks that were presented at PVRW 2025. Click the talk titles in the following agenda to jump to each presentation. Not all talks listed in the agenda can be found in this document, as not all presentation files were provided to PVRW for inclusion in these proceedings.

The content and views contained herein are those of the individual authors only, and are not reviewed or endorsed by NREL.

August 2025

Access PVRW 2025 poster and presentation proceedings on Box

Chair:

Chris Deline

Committee:

Teresa Barnes
Ken Boyce
Jennifer Braid
Evelyn Butler
Kristopher Davis
Michael Deceglie
Tristan Erion-Lorico
Robert Flottemesch
Peter Hacke
Henry Hieslmair
Will Hobbs
Cara Libby
Danielle Merfeld
Christos Monokroussos
Colleen O'Brien
Gernot Oreski
Michael Owen-Bellini
Jon Previtali
Ingrid Repins
Laura Schelhas
Eric Schneller
Adam Shinn
Colin Sillerud
Nick de Vries
Allan Ward
Kent Whitfield

AGENDA – Tuesday, 4 March 2025

Check In / Breakfast: 7:30 am

8:30 AM

Session 1: Opening session
Session Chairs: Ingrid Repins, George Kelly

- Workshop Opening Remarks —Chris Deline, NREL *(8:30-8:45)*
- Terabase Mechanized PV System Installation —Matt Campbell, Terabase *(8:45-9:15)*
- The American Solar Manufacturing Renaissance: Maintaining the Momentum —MJ Shiao, American Clean Power *(9:15-9:45)*
- PowerMark Prize Announcement —John Wohlgemuth, PowerMark *(9:45-9:55)*

Break: 9:55 AM

10:25 AM

Session 2: Field results - Extreme Weather
Session Chairs: Will Hobbs, Brooke Stanislawski

- Assessing the Impacts of Extreme Weather Events on Photovoltaic Installations Using Remote Sensing Imagery —Kirsten Perry, NREL *(10:25-10:45)*
- Duke Energy's Extreme Weather Perspectives —Matt Pickett, Duke Energy *(10:45-11:05)*
- Survivability of Island PV Following Hurricane Beryl —Frank Oudheusden, Azimuth Advisory Services *(11:05-11:25)*
- Panel Discussion *(11:25-11:45)*

Lunch: 11:45 AM

Poster Session A: 12:45 PM

2:15 PM

Session 3: Issues from the Field
Session Chairs: Robert Flottemesch, Sanjana Kartik

- Field Testing Methods and Results —Jim Rand, Core Energy Works *(2:15-2:35)*
- Typical Rates of Module Anomalies Found in IR Inspections —Nathan Brunner and Charlie Davies, DNV and Raptor Maps *(2:35-2:55)*
- Notes from the Trenches —Penny Ladner, DNV *(2:55-3:15)*
- Panel Discussion *(3:15-3:35)*

Break: 3:35 PM

4:00 PM

Session 4: Module Manufacturing
Session Chairs: Teresa Barnes, Tristan Erion-Lorico

- US Manufacturing Overview —Teresa Barnes, NREL *(4:00-4:05)*
- Sensitivity of Material Selection for Glass-Backsheet Modules —Suchi Mitra, Heliene *(4:05-4:20)*
- An Update on Qcells' US Manufacturing and Reliability Testing —Max Koentopp, QCells *(4:20-4:35)*
- US Module Manufacturing and Hail Resistant Module Development —Hongbin Fang, LONGi *(4:35-4:50)*
- Panel Discussion *(4:50-5:20)*
- Awards from Poster Session A *(5:20-5:30)*

PVRW Mixer Sponsored by RETC, TÜV Rheinland, and VDE: 5:30 PM

AGENDA – Wednesday, 5 March 2025

Check In / Breakfast: 7:30 am

8:30 AM

Session 5: Module Reliability Science
Session Chairs: Ashley Gaulding, Colin Sillerud

- Breaking the Trend: Are Retro PV Module Designs a Cost-Effective Solution to Glass Reliability? —Jennifer Braid, SNL *(8:30-8:50)*
- Spontaneous Glass Breakage in Glass-Glass Modules —Ellie Palmiotti, NREL *(8:50-9:10)*
- Novel temperable glass for improved performance in solar applications —Alex Mitchell, Corning Incorporated *(9:10-9:30)*
- Panel Discussion *(9:30-9:50)*

Break: 9:50 AM

10:20 AM

Session 6: Module reliability - UVID
Session Chairs: Kaushik Roy Choudhury, Peter Hacke

- Accelerated UVID Testing and Comparison to Outdoor Testing —Archana Sinha, PVEL *(10:20-10:40)*
- UV + Damp Heat Induced Power Losses in Fielded Utility N-Type Si PV Modules —Ashley Gaulding, NREL *(10:40-11:00)*
- Performance and Degradation of PV Encapsulants for UV Induced Degradation Study —Dennice Roberts, NREL *(11:00-11:20)*
- Panel Discussion *(11:20-11:40)*

Lunch: 11:40 AM

Poster Session B: **12:40 PM**

2:10 PM

Session 7: PV System Insurance
Session Chairs: Nick de Vries, Leah Holton

- PV Risks and the Insurance Landscape —Mike Perron and Sandy Calvert, FM Global and Moore-McNeil *(2:10-2:30)*
- NatCat Modeling and Resiliency Considerations for Solar Property Insurance —Nicole Thompson, kWhAnalytics *(2:30-2:50)*
- Models, PMLs, and Insurance Sublimits —Lauren Carroll-Allan, CAC Specialty *(2:50-3:10)*
- Panel Discussion *(3:10-3:30)*

Break: **3:30 PM**

4:00 PM

Session 8: Inverters and BOS
Session Chairs: Colleen O'Brien, Michael Bolen

- More than One Side to the Story: a Forensics Dive into PV Connector Failures —Laurie Burnham, SNL *(4:00-4:20)*
- Uncapped Photovoltaic Connectors - A Combined Field and Chamber Study Verifies and Elucidates the Degradation —Dave Miller, NREL *(4:20-4:40)*
- Nominal Operating IGBT Temperature (NOIT), A Metric for Establishing Reliable Inverter Operations —Nick deVries, Silicon Ranch *(4:40-5:00)*
- Panel discussion *(5:00-5:20)*
- Awards from Poster Session B *(5:20-5:30)*

End of Wednesday Sessions

AGENDA – Thursday, 6 March 2025

Check In / Breakfast: 7:30 am

8:30 AM

Session 9: Next-Gen PV Reliability
Session Chairs: David Young, Silvana Ovaitt

- An Update on Perovskites Performance and Reliability Based on PACT's Testing —Michael Deceglie and Tim Silverman, NREL *(8:30-8:50)*
- Qualification Test Standards for Floating PV —Mauro Pravettoni, TII - Abu Dhabi *(8:50-9:10)*
- Reliability of TOPCon Solar Cells: Understanding Degradation and Recovery of Poly-Si/SiOx Passivating Contacts —Aditya Ratnapagol, NREL *(9:10-9:30)*
- UVID Initiates Metastability in the Dark: How to Properly Measure n-Type Modules —Todd Karin, PVEL *(9:30-9:50)*

Break: 9:50 AM

10:20 AM

Session 10: Trackers + hail
Session Chairs: Michael Deceglie, Sumanth Lokanath

- Effectiveness of Hail Stow in Photovoltaic Systems —Jon Previtali, VDE *(10:20-10:40)*
- Full-scale High Speed Wind Testing of Trackers —David Kresse, NexTracker *(10:40-11:00)*
- Fatigue Loading of Purlins for Single Axis Solar Trackers —Nat Healy and Scott Van Pelt, GameChange Solar *(11:00-11:20)*
- Panel Discussion *(11:20-11:40)*

Lunch: 11:40 AM

Poster Session C: 12:40 PM

2:10 PM

Session 11: System Analysis & Modeling
Session Chairs: Elsa Kam-Lum, Steven DiGregorio

- Repowering and Decommissioning Cost Model —Cara Libby, EPRI *(2:10-2:30)*
- Is Your Project Underperformance Caused by Unreliable Trackers? —Dan Chawla, Natural power *(2:30-2:50)*
- Energy at the End of the World: Renewable System Design for the South Pole —Amy Bender, ANL *(2:50-3:10)*

Break: 3:10 PM

3:40 PM

Session 12: Manufacturing and circularity
Session Chairs: Michael Kempe, Gernot Oreski

- Glass and Silicon Recovery from Solar Modules Using Laser Processing —Mool Gupta, UVA *(3:40-4:00)*
- Uncovering Reliability Risks in Advanced PV Modules: A Data-Driven Approach for Industry Guidelines —Mahyar Nezhad, Kiwa *(4:00-4:20)*
- Module Warranty Backstop by Munich Re —Ron Sastrawan, Munich RE *(4:20-4:40)*
- Panel Discussion *(4:40-5:00)*
- Awards from Poster Session C *(5:00-5:10)*
- Workshop Closing Remarks —Chris Deline, NREL *(5:10-5:20)*

Workshop Closes

Terabase

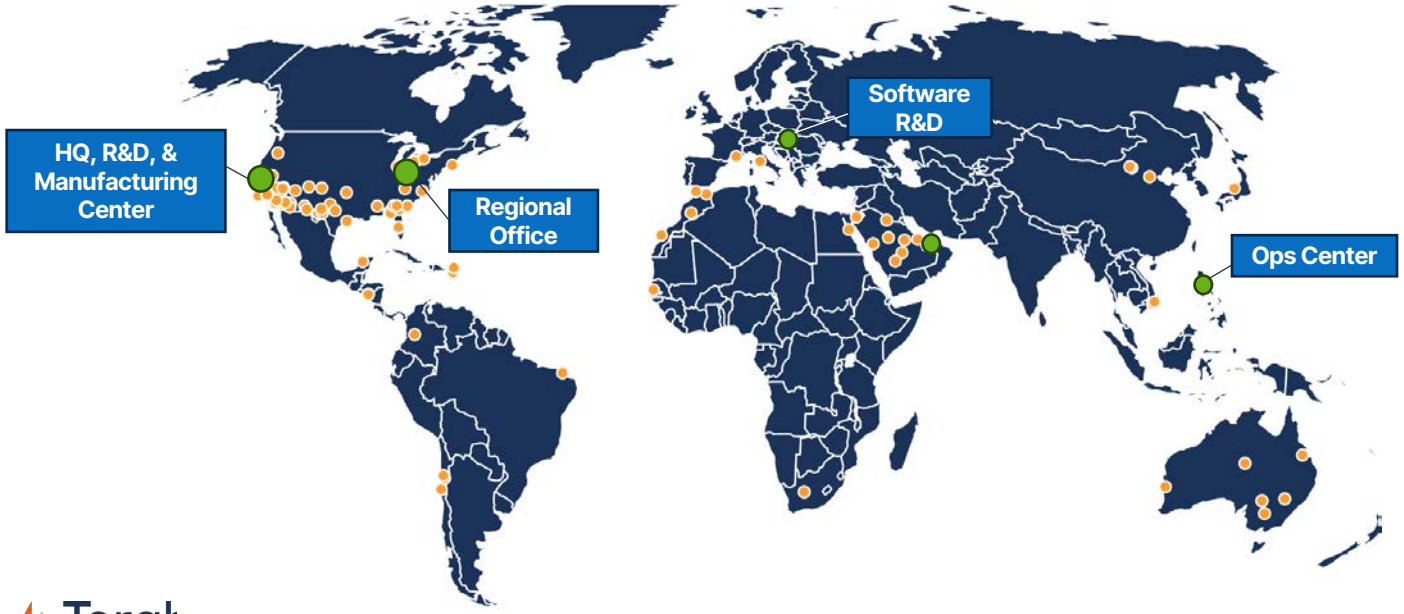
Mechanized PV System Installation

March 2025

About Terabase Energy, Inc.

Solar Technology for the Terawatt Era

- Transforming utility-scale solar with integrated solutions that **reduce costs, improve quality** and **unlock scalability**
- Founded in 2018, 160+ team members globally
- Extensive global customer base – Terabase is providing solutions for some of the largest solar power plants in the world



Investor Partners

Breakthrough Energy Ventures

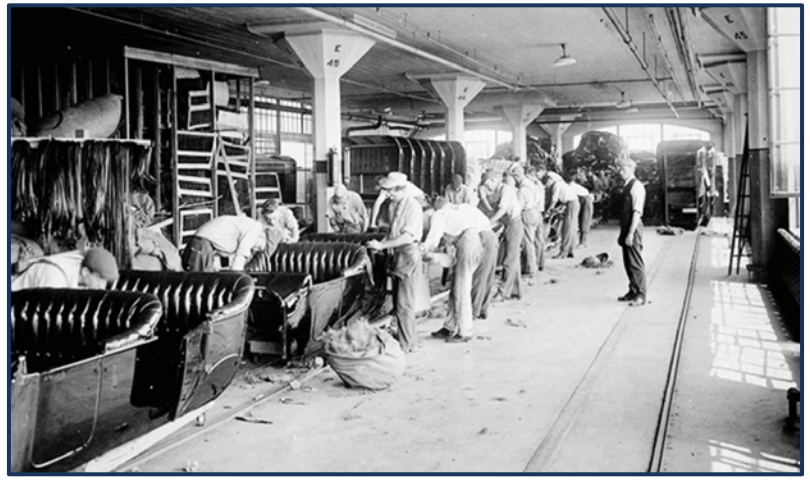
Prelude Ventures

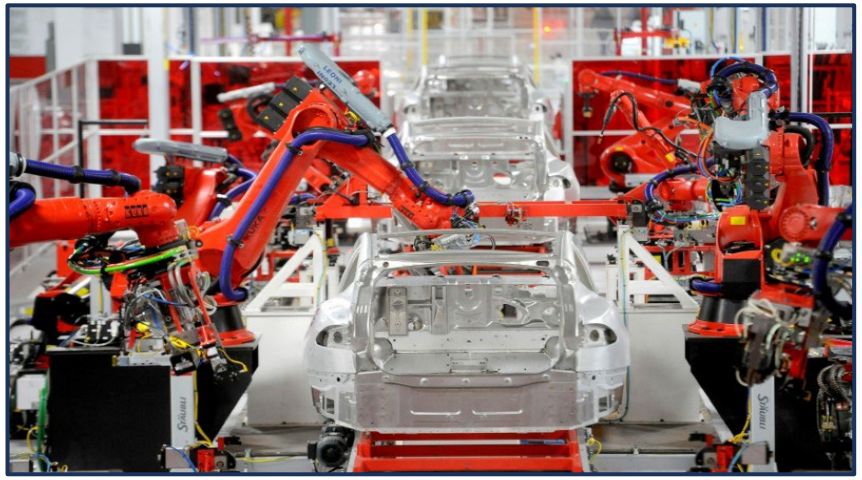
FIFTH WALL

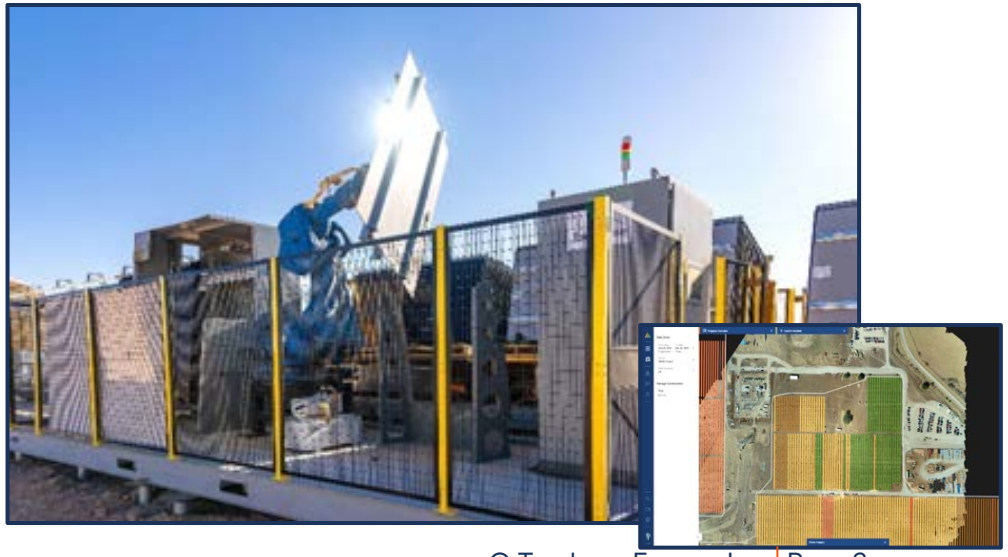
SJF VENTURES

POWERHOUSE

Terabase – Modernizing Solar Deployment







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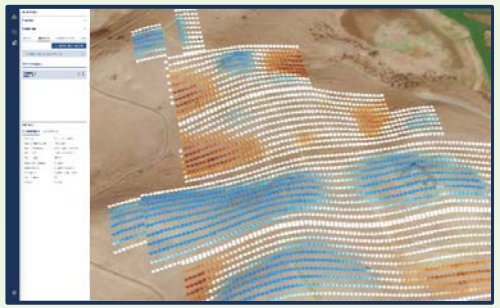
Terabase: The Platform for Solar Project Delivery

ENGINEERING | **CONSTRUCTION** | **OPERATIONS**

PlantPredict™
Pre-Construction Optimization



Construct™
Construction Management

Terafab™
Install Automation

SCADA
Plant Controls & EMS

Data capture

1+ Petabyte at the end of 2024

1TW of Plants simulated in 2024	14GW of Construction Digitized
107MW of Construction Automated	12GW of Plants Operational

Knowledge through data

AI Wisdom

© Terabase Energy, Inc.

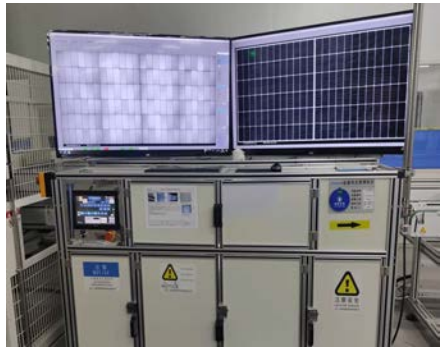
The Journey of the Module Today

© Terabase Energy, Inc.

Panel Manufacturing 21st Century Operations

Robot Manufacturing

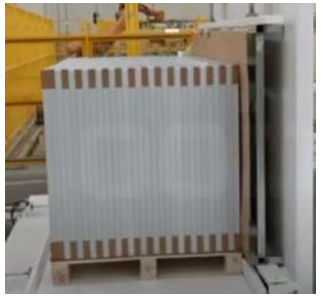
Flash Test



EL Inspection

Visual Inspection

Module Sort



Module Package

Module Ship

Depart by Truck

Module Installation – 20th Century Operations

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Onsite Module Handling Can Create Defects

© Terabase Energy, Inc.

Onsite Module Handling Can Create Defects – Not a Corner Case

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Onsite Module Handling

Trailer-Based Installation

Skid Steer Distribution

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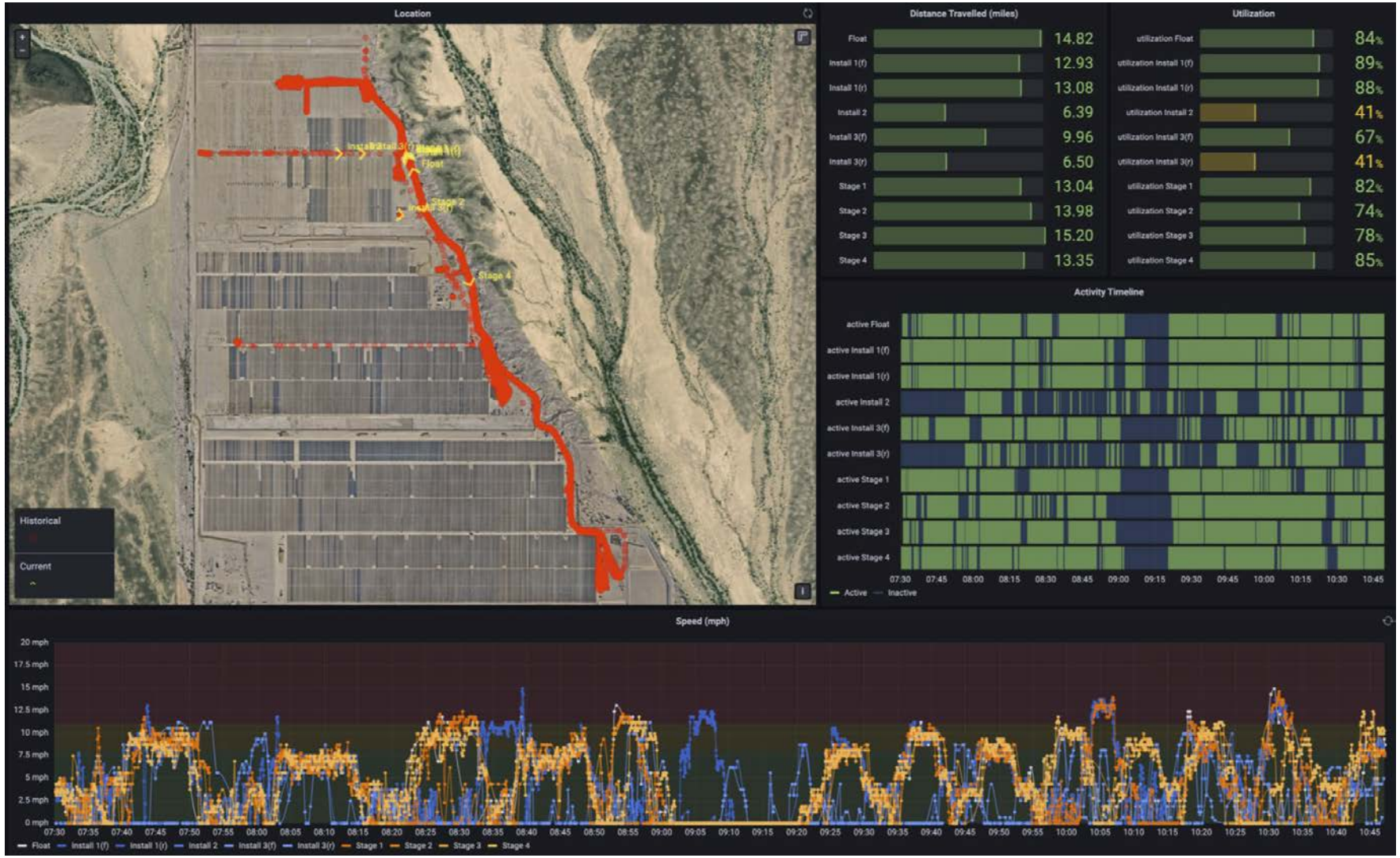
Module Staging Delivery Distance & Speeds



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Possible Sources of Module Defects

1. Modules mishandled (collision with torque tube / bracket / packaging/corner)
2. Dirt in connectors
3. Damage from palette placement on uneven ground
4. Damage from forklift/telehandler/skid steer handling
5. Flooding
6. Wiring / stringing mistakes
7. Shipping defects not found before installation (no incoming QC)
8. Factory defect escapes

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Possible Impact of Module Defects

1. Underperformance
2. Arcing / fires
3. EPC Inspection / remediation costs
4. Higher O&M costs
5. Warranty claim dispute
6. Safety

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Sample Quality Issues in Solar Construction

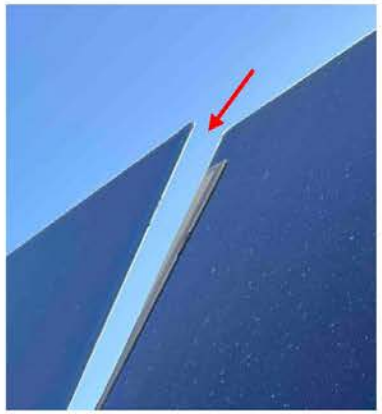
Module Cracking

Shipping Damage

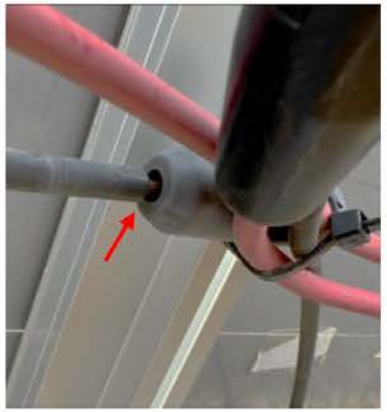
Missing Hardware

Broken Module Clip

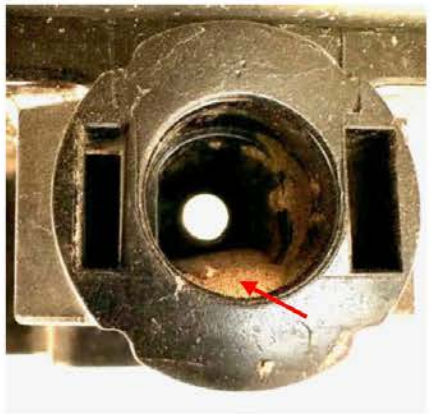
Tracker Misalignment



Module Misalignment



Cable Damage / Defects



Dust in Electrical Connectors

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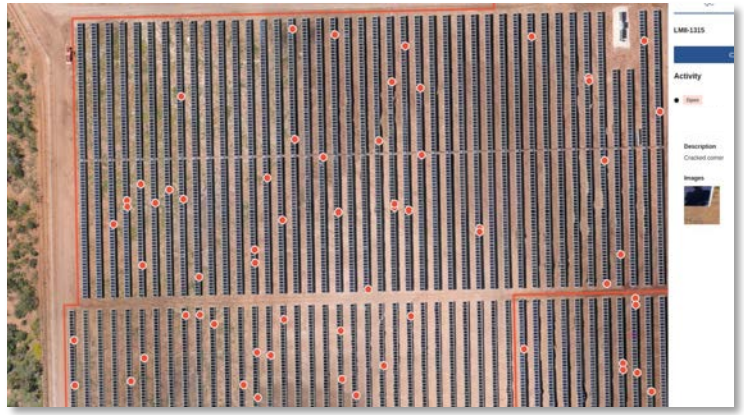
Automating Module Installation

© Terabase Energy, Inc.

Automation improves quality at a lower cost than traditional solar field construction and operations

Risks that are mitigated by Terabase:

- **Safety Risks:** Poor quality construction can lead to **1500V** electrical faults
- **Increased Costs:** Higher installation costs due to repairs, rework, and replacements
- **Project Delays:** Extended project timelines due to the need for correcting defects and rework, risk of delay penalties
- **Reduced Durability & Longevity:** Shortened useful life and increased maintenance and operational costs
- **Reduced Energy Production:** Poor quality construction can directly lead to performance shortfalls putting the project financial pro forma at risk
- **Higher Insurance Premiums:** Power plants with poor construction quality are at an increased risk of wildfires, leading to higher insurance premiums
- **Reputational Risk:** Loss of credibility and trust among clients, investors, and stakeholders
- **Lower Asset Value:** Poor quality construction can lead to lower market value and reduced attractiveness to buyers



Project Quality Defects

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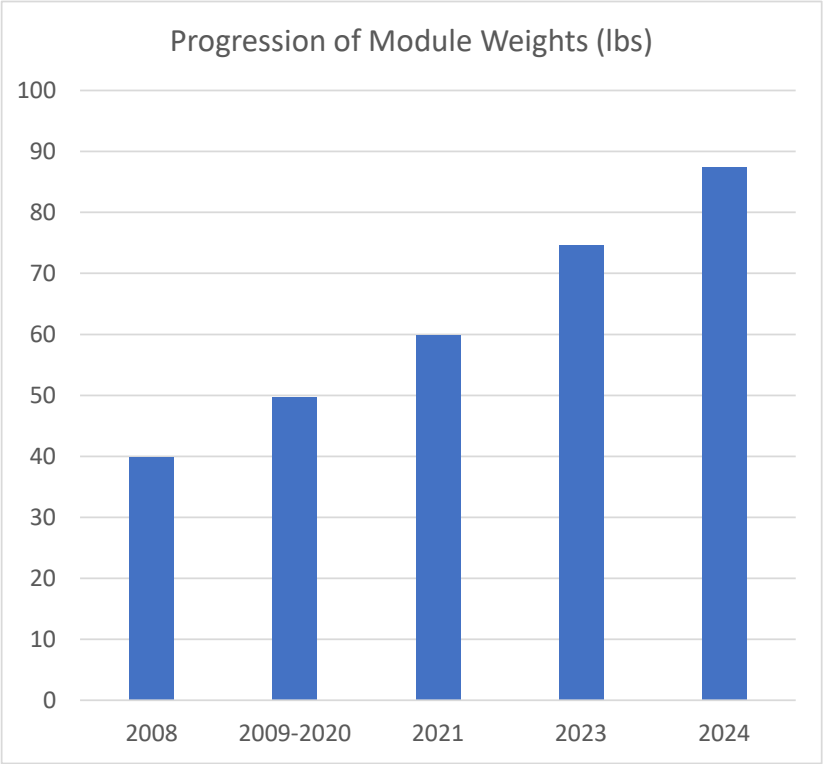
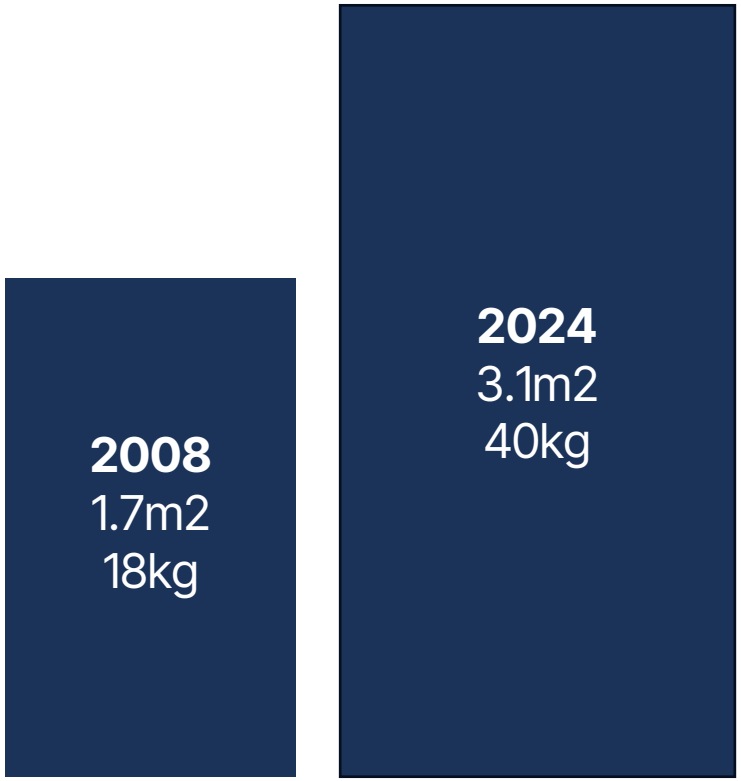
Automation Enables Larger Modules

Module sizes and weights have more than doubled, workers now need to lift over 15,000 pounds of panels during a typical shift





Typical Solar Panel Sizes

Worker height to-scale

© Terabase Energy, Inc.

Approaches to Mechanized Module Installation

Mechanical Assist	Mod Bot	Onsite Prefab	Offsite Prefab
• Eliminates heavy lifting – worker health & safety benefit • Could reduce module breakage	• Eliminates heavy lifting • Could reduce module breakage • Labor savings	• Brings factory benefits to field operations • High speed • Max scope • Minimize in-field operations	• Enables full factory automation in a controlled setting • Can serve multiple projects from one location
• Can be slower • Incompatible with some modules • Cost	• Speed and complexity of in-field automation • Still requires support operations • Capex requirements • Requires skilled support	• Requires delivering “tables” over tough field • Changes site logistics / space requirements • Capex requirements • Requires skilled support	• Lower shipping density may increase cost • Could require double handling / shipping • May lead to suboptimal racking design • Onsite logistics could still be a challenge

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Terafab: The Future of Solar Construction

Automated field factory for PV module + tracker assembly

- **Faster** construction: high throughput, 24/7
- Increased **productivity** alleviating worker shortage
- **Reduced product costs** through design for automation
- Improved **safety** and working conditions
- Improved **quality =** higher performance & lower cost

© Terabase Energy, Inc.

Terafab Robotic Construction System
High speed site data network
Delivery rovers
Automated Factory
Digital Command Center
Digital material management

Terafab Overview

Patents Pending

© Terabase Energy, Inc.

Terafab MES - Managing Project Robot Operations

Fab Design Simulate Install MES

The Terabase MES system manages onsite robotic operations in real time

Fab Design Simulate Install MES

Day Plan - Sept. 26, 2023

Return to Task

Log progress | Tools | Activate plan

Overview | Blue Team Workfront | Red Team Workfront | Stats | Orders

Search any field

Queue Rank	Name	Build Type	Status	Assembly Line	Field Crew
124	B55-S1-R12-T2 8-N	8-N	Assembling	Line 2 (North)	Red Team
125	B55-S1-R11-T2 8-N	8-N	Module Buffer	Line 2 (North)	Red Team
128	B55-S1-R10-T2 8-N	8-N	Build Queue	Line 2 (North)	Red Team
138	B54-S1-R8-T10 8-S	8-S	Assembling	Line 1 (South)	Blue Team
139	B54-S1-R7-T10 8-S	8-S	Module Buffer	Line 1 (South)	Blue Team
140	B54-S1-R6-T10 8-S	8-S	Build Queue	Line 1 (South)	Blue Team

Legend

Not started | Planned | In progress | Delivered | Installed | Blocked | Field Buffer

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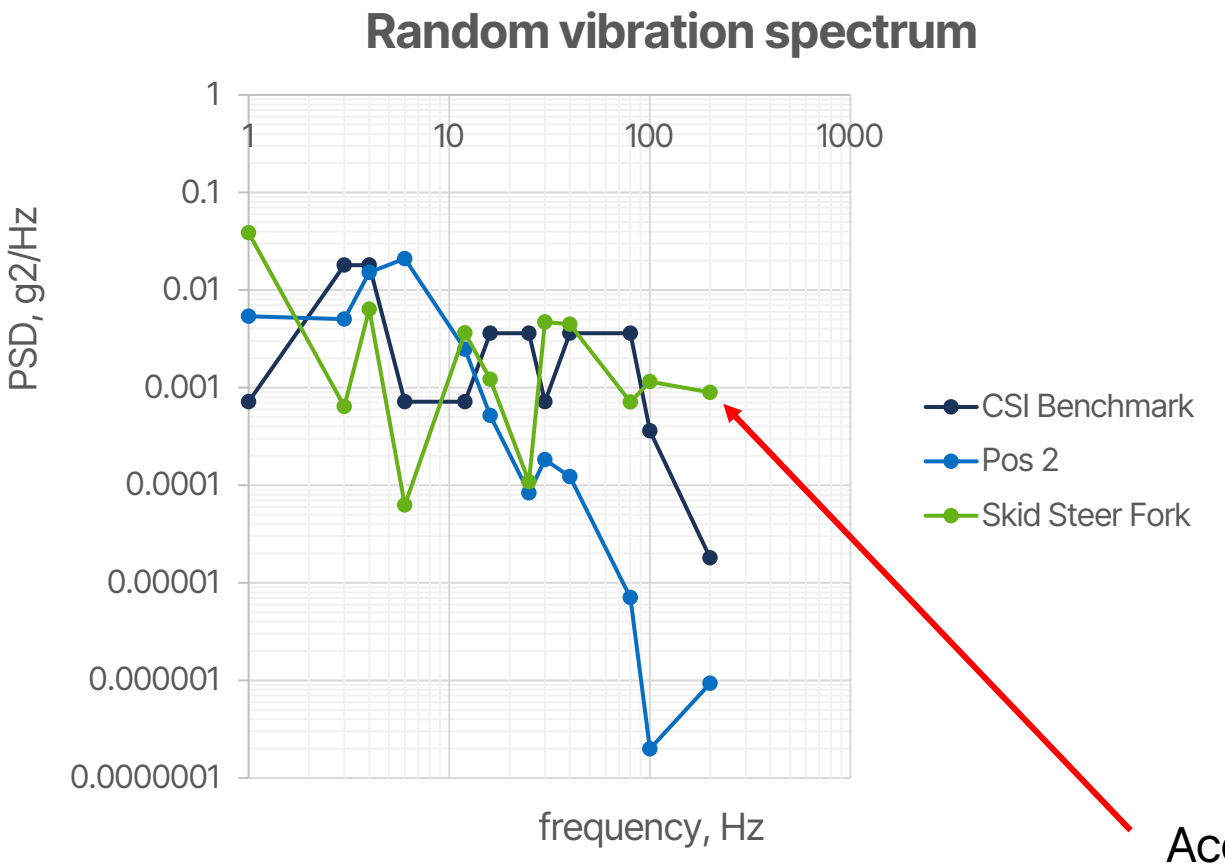
Terafab – Performance Dashboard

© Terabase Energy, Inc.

Terafab Reduces Module Transport Vibration

38% less shock energy than stick-build – zero module defects



Position	g_{RMS}	% of Bench
Benchmark	.542	
Forklift	.531	98.0%
Terabase	.336	62.0%

Accelerometer attached to Skid Steer Fork

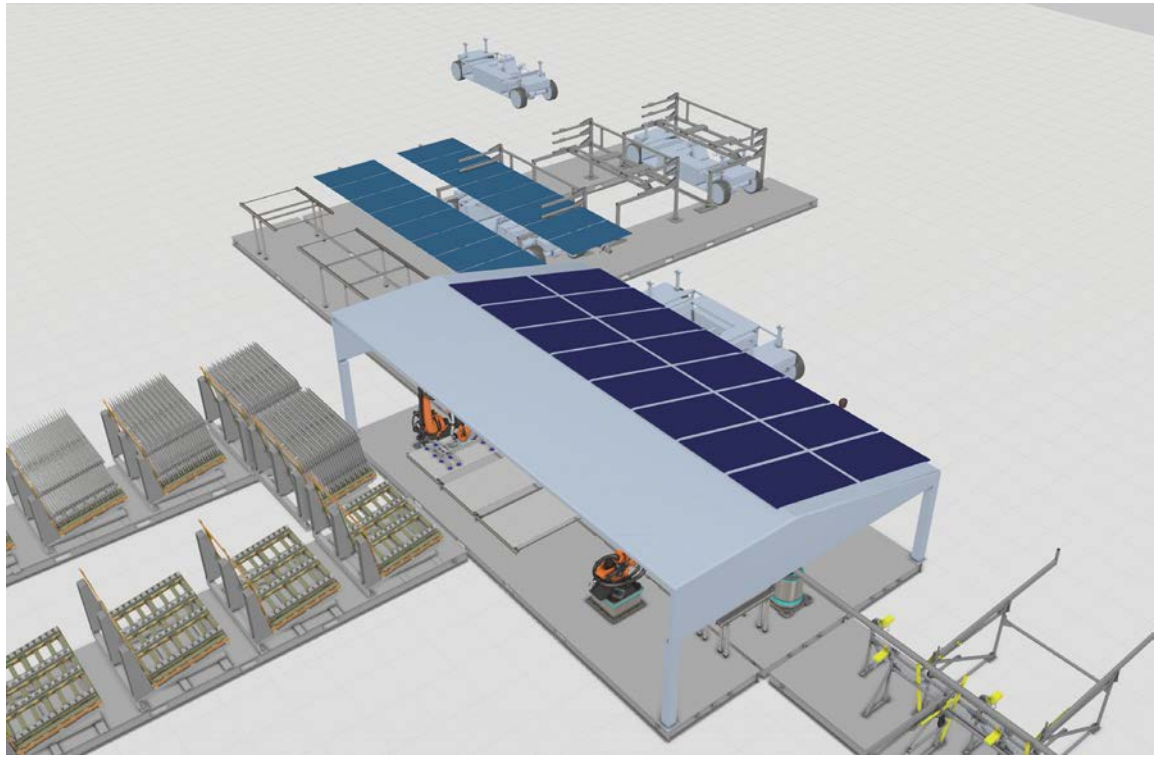
© Terabase Energy, Inc.

Terafab Roadmap - V2 Fully Automated Factory – Q3 2025

Process Control & Validation

Key V2 Benefits:

- 50%+ reduction in footprint over V1
- Less than 4 hours to set-up – easy to relocate across the site
- Fully automated table assembly
- 1MW+ / shift throughput
- Compatible with major module manufacturers
- Next gen rover architecture
- **In-line module QC inspection**



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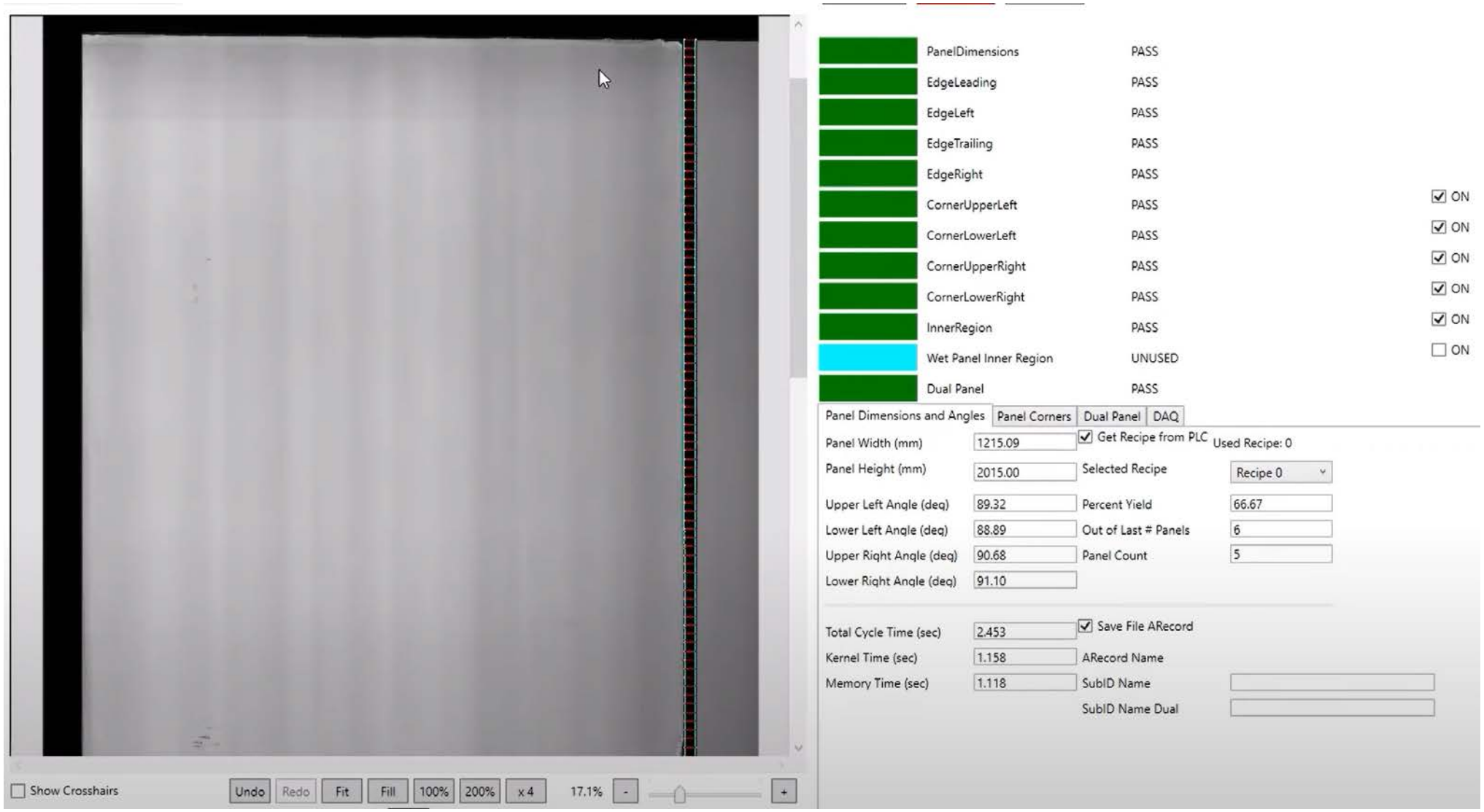
In-Line Module Inspection in Terafab V2



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The American Solar Manufacturing Renaissance: Maintaining the Momentum

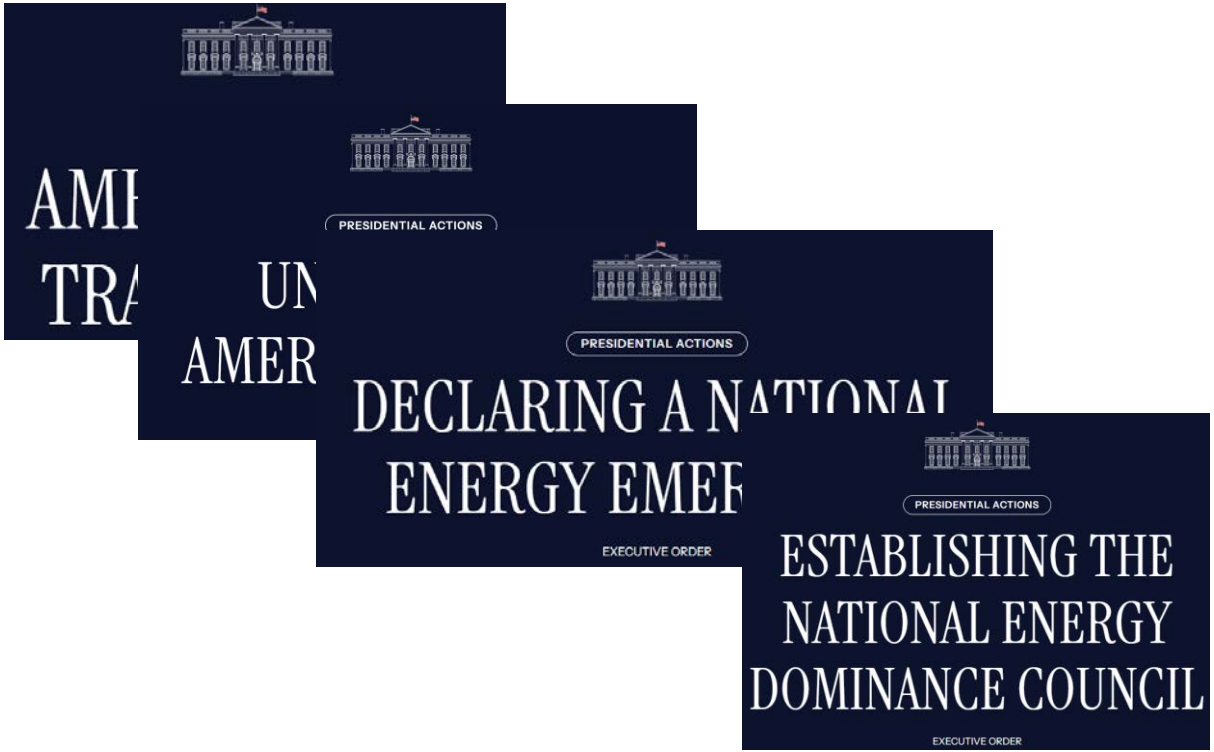
NREL PV Reliability Workshop
March 4, 2025 | Denver, CO

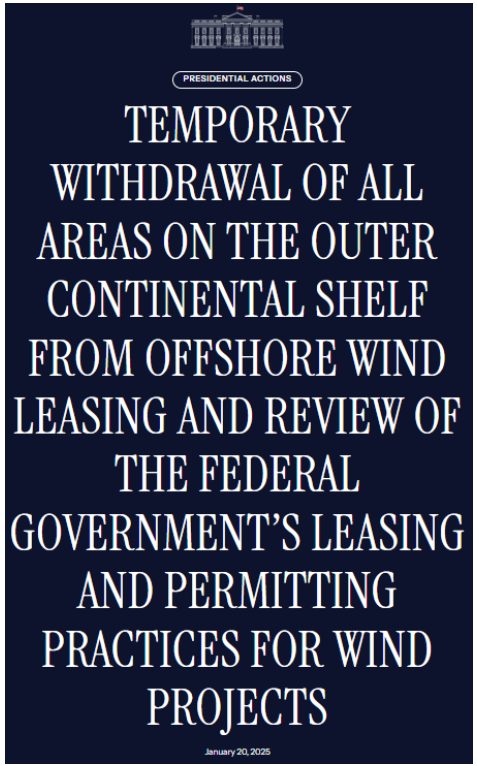
ABOUT

The leading voice for all clean energy technology

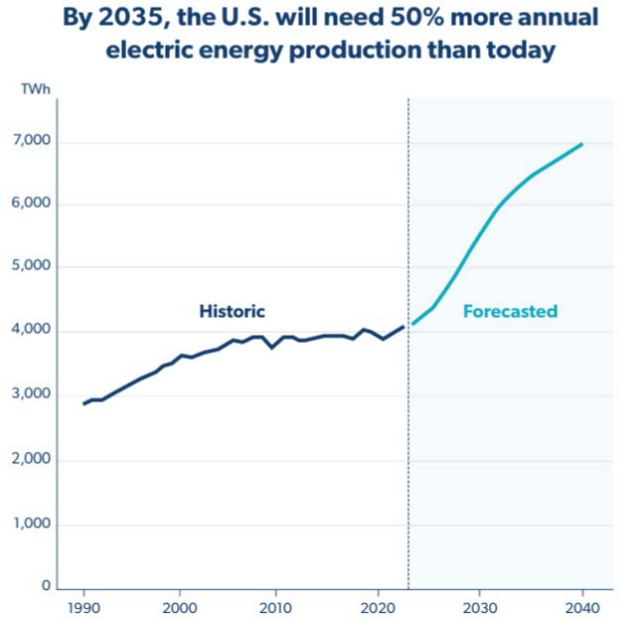
The American Clean Power (ACP) Association is dedicated to **meeting America's energy goals** and **strengthening the economy** through the growth of low-cost reliable domestic power.

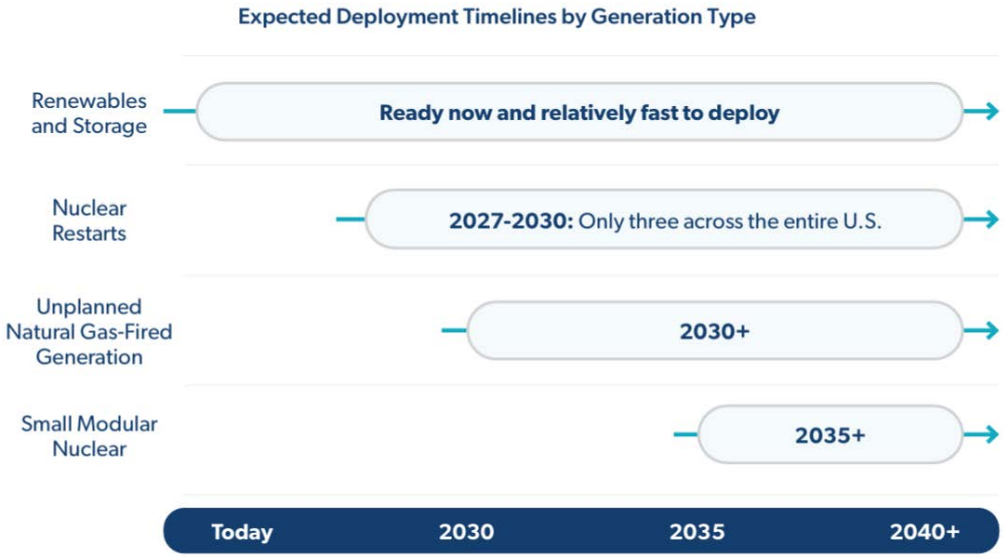
A flurry of Executive attention





How will we meet skyrocketing electricity demand?

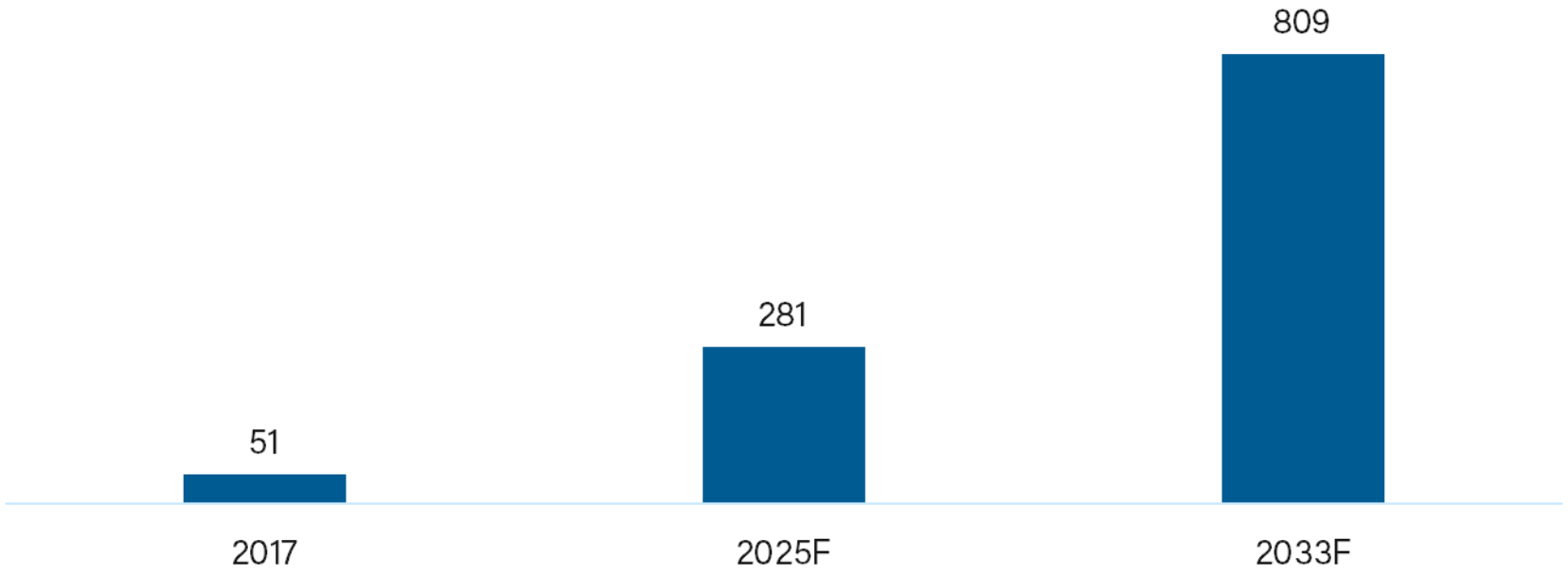




Source: ConservAmerica, Brattle Group: *A Wide Array of Resources is Needed to Meet Growing U.S. Energy Demand*

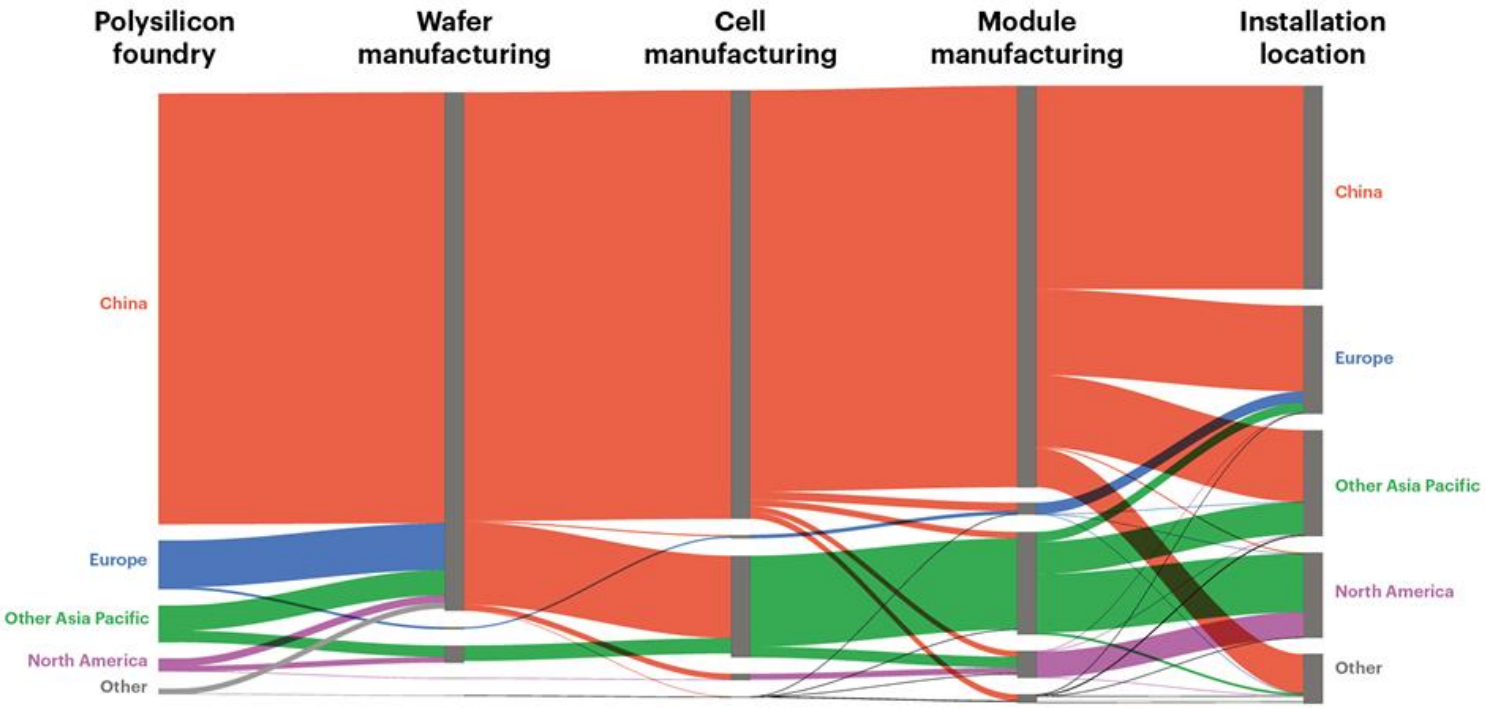
Solar deployments lead the way

Cumulative U.S. Solar Deployments and Forecast, GWdc



Source: BloombergNEF *1Q 2025 Global PV Market Outlook*

A global(?) solar supply chain



IEA. CC BY 4.0.

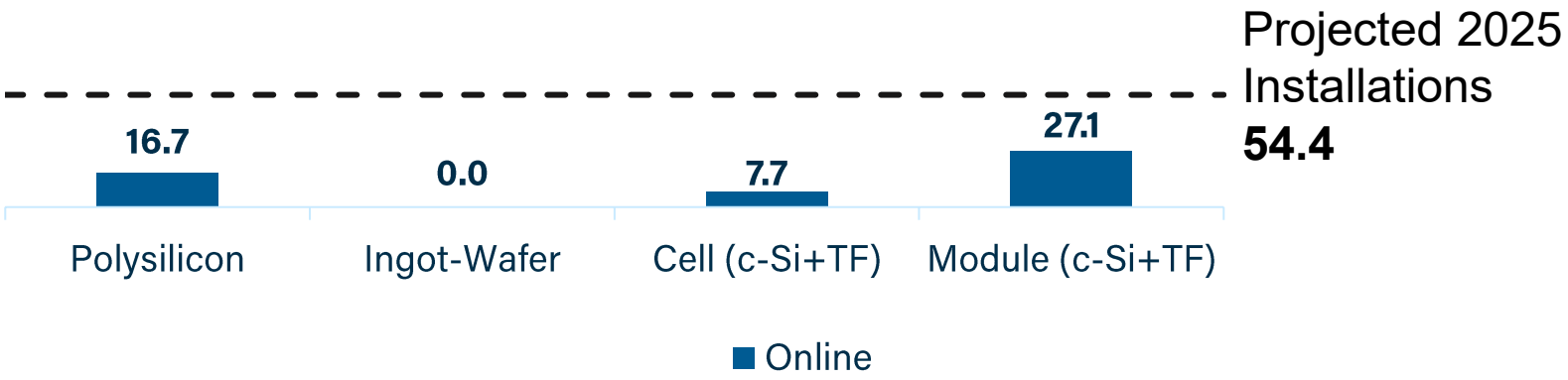
Note: Normalised values based on gigawatts equivalent of capacity.
Source: IEA analysis based on IEA (2022b).

The necessity of secure, resilient and more domestic solar supply chain

AMERICAN CLEAN POWER

- Mitigate supply chain disruptions
- Invest in the American economy
- Ensure cybersecure electricity generation
- Maintain American energy leadership

U.S. Solar Manufacturing Capacity (GWdc): Year End 2024



Source: Clean Energy Associates (capacity and status), BloombergNEF (Projected 2025 Installations), American Clean Power Association,

Trade, Tariffs, and Tax Credits: more complex than ever

AMERICAN CLEAN POWER

In Place

Solar 1 and 2 AD/CVD
SE Asia anticircumvention
Section 201 Tariffs
Section 301 Tariffs
UFLPA
45X Manufacturing PTC
Domestic Content Bonus

Underway

Solar 3 AD/CVD (SE Asia)
Mexico and Canada Tariffs
Steel and Aluminum Tariffs

In the Crosshairs

Section 232 Tariffs
Reciprocal Tariffs
IRA repeal
FEOC Restrictions
China Export Controls
CFIUS Revamp

Growing Pains

REUTERS

Solar company CubicPV scraps plans for US silicon wafer factory

PVTECH

Quality inspections reveal US solar modules among those with the highest defect rates

pv magazine

Meyer Burger cancels US solar cell plant, announces restructuring

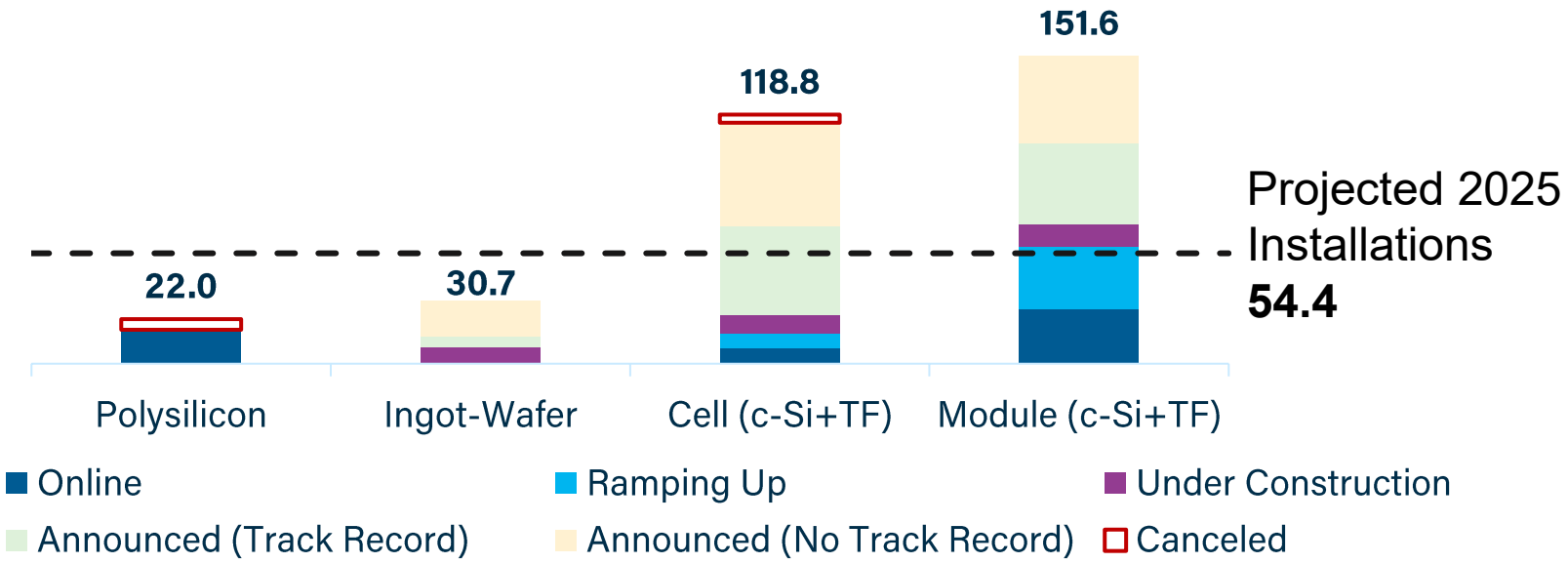
Solar Power World

More TOPCon patent infringement complaints filed in the United States

THE OKLAHOMAN

Construction of Oklahoma solar panel plant once celebrated by governor has been stalled

U.S. Solar Manufacturing Capacity (GWdc): 2025 and Beyond

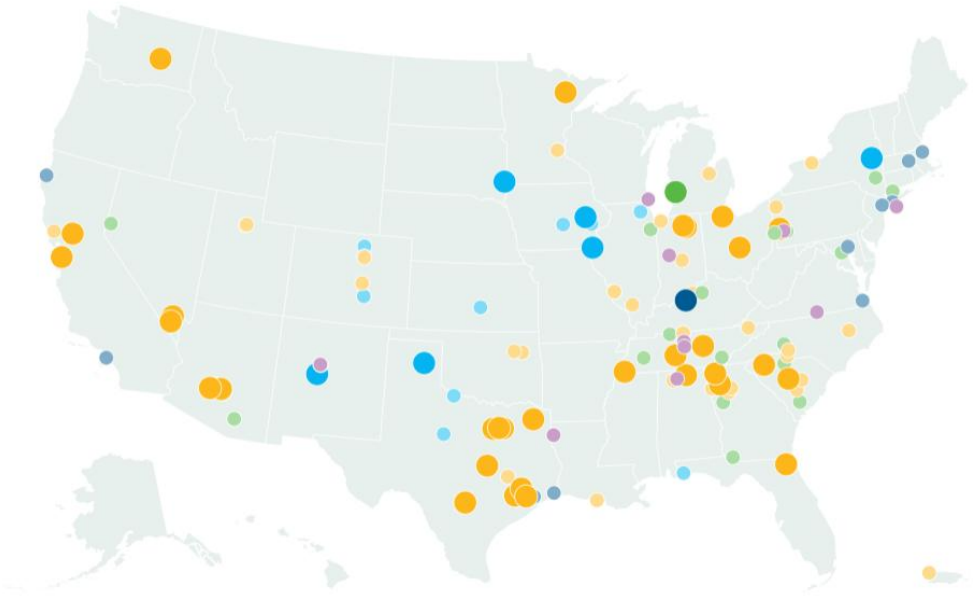


Source: Clean Energy Associates (capacity and status), BloombergNEF (Projected 2025 Installations), American Clean Power Association,

Clean energy manufacturing across the country

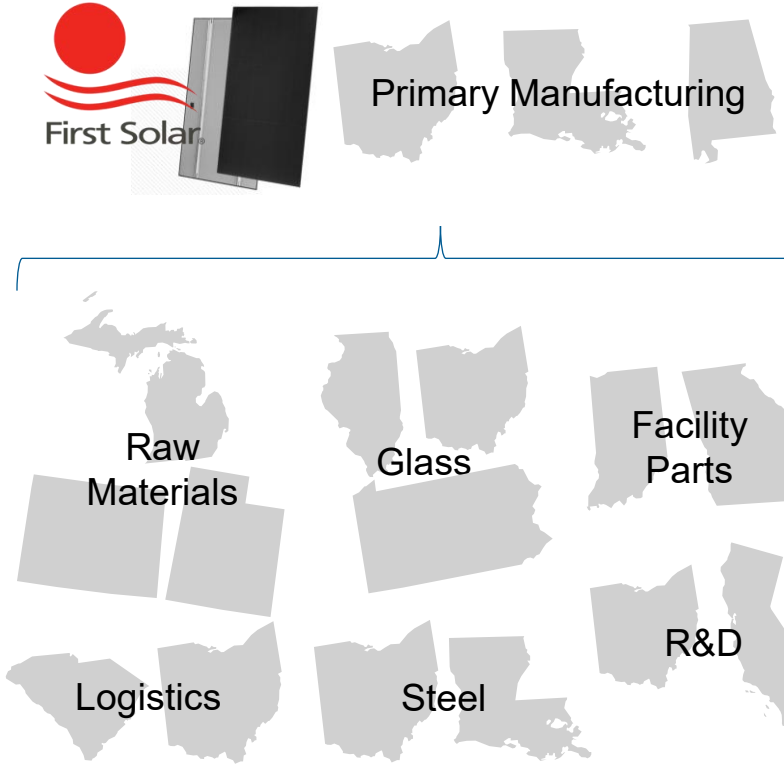
Domestic Solar, Wind and Grid Battery Manufacturing

- **193** primary component manufacturing facilities in operation
- **Nearly 100** primary component manufacturing facilities announced
- Supporting hundreds of additional domestic supply chain partners



Source: American Clean Power Association

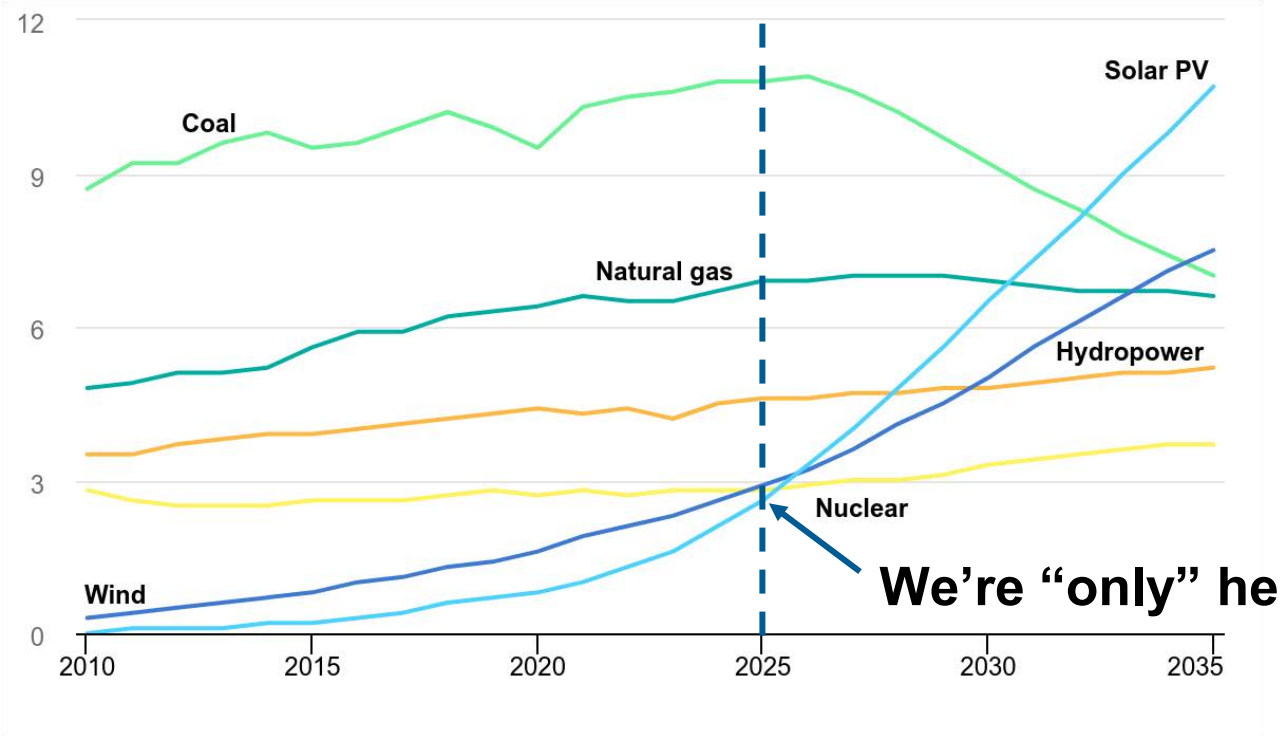
Beyond the Module: the supply chain multiplier



Source: First Solar, Nextracker

Just the start of the journey…

IEA Global Electricity Generation by Source (thousand TWh)



Source: IEA *World Energy Outlook 2024*

AMERICAN CLEAN POWER

Thank You!

POWERMARK PRIZE

2025 PowerMark Early Career Prize in Photovoltaic Reliability

POWERMARK PRIZE

- PowerMark Corporation has established an annual prize in Photovoltaic Reliability for an early-career scientist or engineer who has contributed in an outstanding and innovative way to the progress of photovoltaic reliability.
- Nominations accepted from thesis advisors, faulty members, supervisors, or colleagues.
- Received a number of strong nominations.
- Nominations were assessed by a review panel from the PowerMark Board of Directors.

POWERMARK PRIZE CONSISTS OF

- Public Announcement at the NREL PVRW.
- Certificate of Achievement
- $1000

And the winner is:

And the winner is:

Kirsten Perry

POWERMARK PRIZE

Kirsten is being recognized for development of innovative and impactful software tools and performance analysis, including:

- Developing a panel segmentation algorithm for correcting system metadata using machine learning and satellite imagery,
- Contributing four algorithms to publicly-available PVAnalytics software, and
- Deducing impacts of extreme weather on PV installations using satellite imagery.

Assessing the Impacts of Extreme Weather Events on Photovoltaic Installations using Remote Sensing Imagery

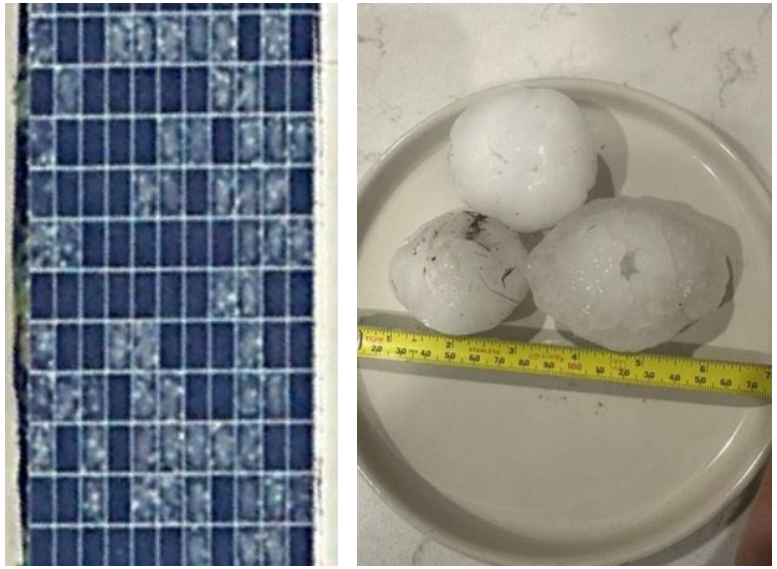
Kirsten Perry, Dirk Jordan, Quyen Nguyen
National Renewable Energy Laboratory
PVRW—Golden, CO
March 4th, 2025

Photo by Dennis Schroeder, NREL 55200

Introduction

- Previous research: time series analysis assessing extreme weather PV impacts [1]
- **This work: visible damage inspection via satellite imagery**
- **Only looking at visible damages here → non-visible damage could lead to increased degradation**
- Two storms:
  - Hurricanes Maria/Irma
  - Austin, TX September 2023 hailstorm: >$600 million damages [2]
- **Goal: fleet-scale damage assessment**
- Data Sources
  - Hailstorm: Google Earth/Google Maps API
  - Hurricane: NOAA Emergency Response Imagery [3]

Utility site heavily damaged by 180km/hr wind gusts from Hurricane Maria

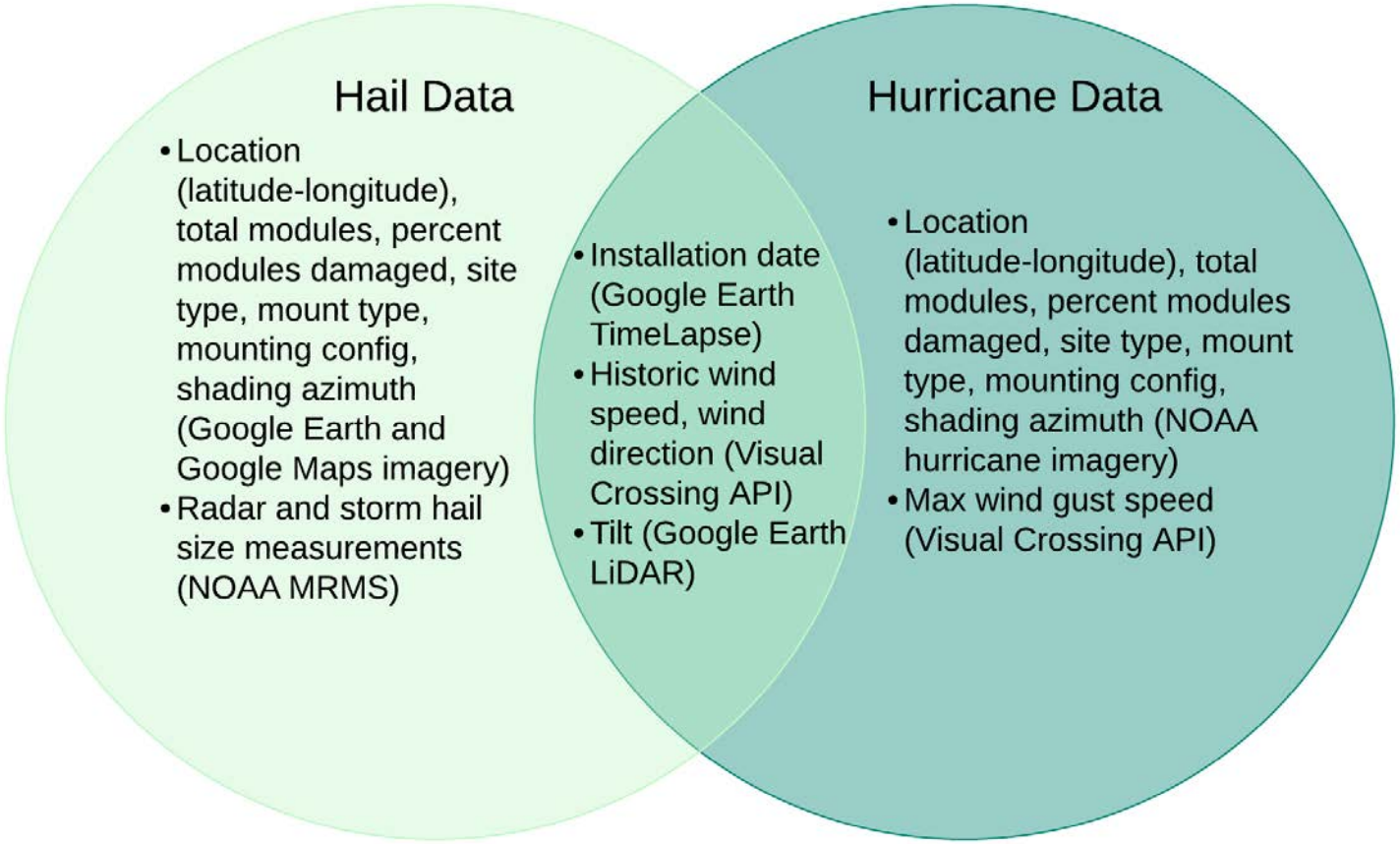


Hail-damaged modules; hail stones from Austin storm

[1] Jordan et al. "Extreme weather and PV Performance." Journal of Photovoltaics (2023)
[2] Segal, R. "September hail storm caused 600 million in damage to Austin area, NWS estimates." KXAN Austin (2023)
[3] NOAA NGS Emergency Response Imagery: Hurricane Maria. NOAA National Centers for Environmental Information (2017).

Methodology: Manual Labeling

- Manually labeled hail data set: 1211 sites
- Manually labeled hurricane data set: 48 sites*
- Venn diagram: System characteristics labeled by authors

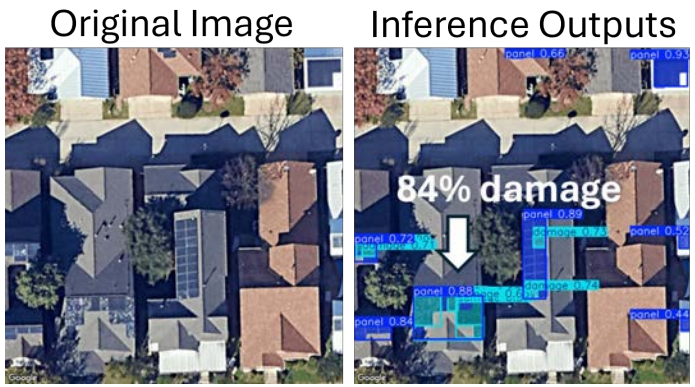


* This manual data set was taken from multiple hurricanes, including Maria, Dorian, Florence, Ian, Idalia, and Michael. All hurricane imagery is NOAA Emergency Response Imagery. Fleet-scale analysis is post-Maria/Irma only.

Methodology: Deep Learning Approach

- **Can we scale to a fleet-level analysis?**
  - **Yes, using deep learning!**
- Instance segmentation: YOLOv11
- Design of Experiments to tune models
- One model for identifying sites in Austin, another for finding sites in PR/US Virgin Islands
- Inference: >87k images of Austin, >630k images PR/US Virgin Islands

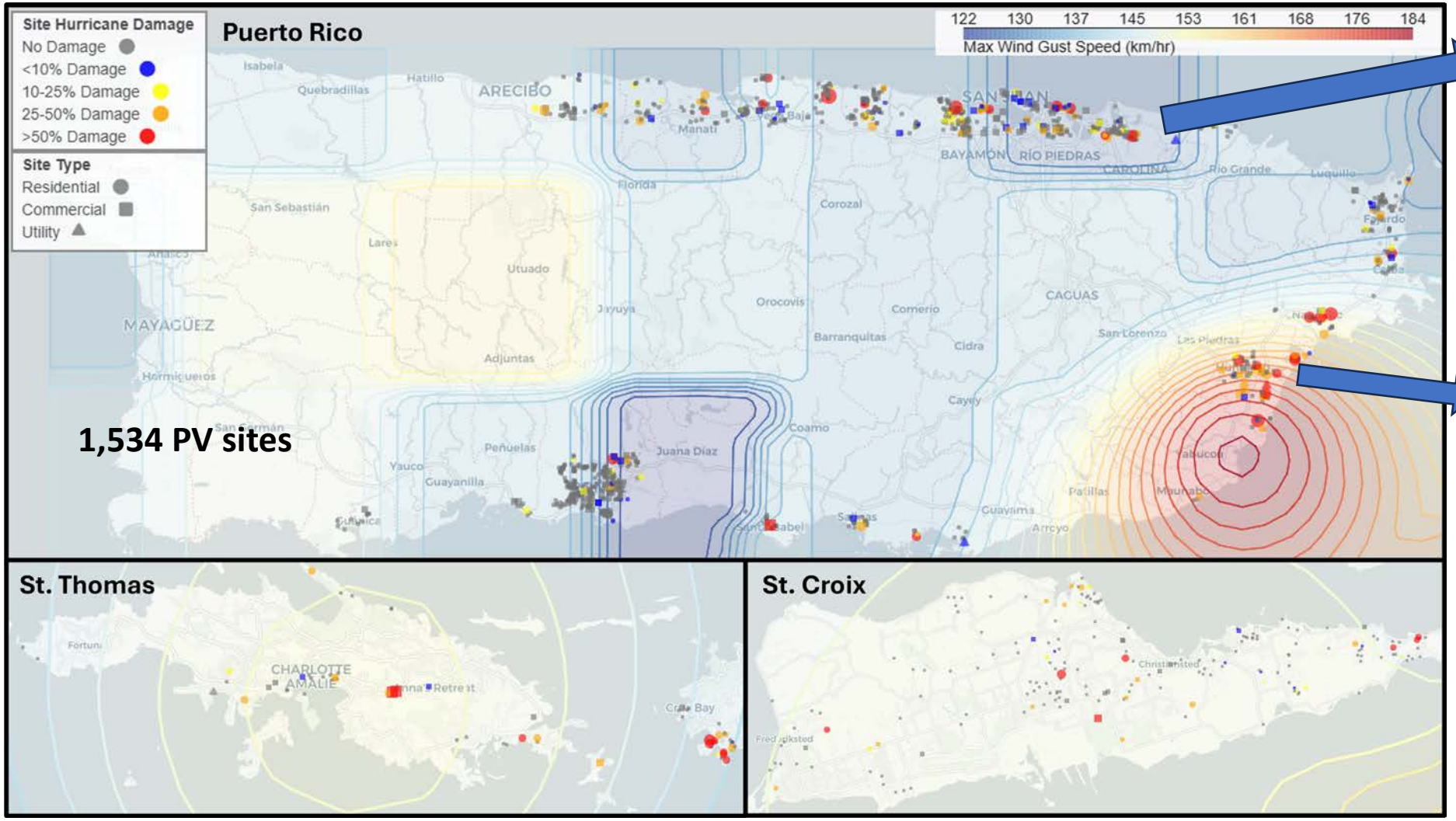
Pre- and post-storm imagery (with inference) of a PV install hit by Hurricane Maria



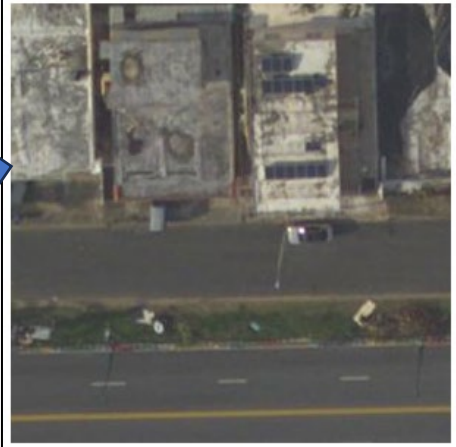
Hail model inference outputs, with panels in dark blue and hail damage in light blue

Train models on imagery data → Run model inference using gridded images of entire area → Locate all PV sites and damage from mask outputs

Visualizing the Data: Hurricane Maria/Irma



Site Coordinates: 18.419, -65.9626
Hurricane: Maria
Type: residential
Mount: rooftop
Percent Modules Damaged: 64.1%



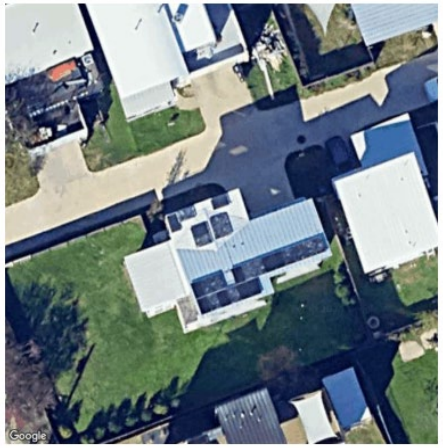
Site Coordinates: 18.159, -65.7622
Hurricane: Maria
Type: residential
Mount: rooftop
Percent Modules Damaged: 63.64%

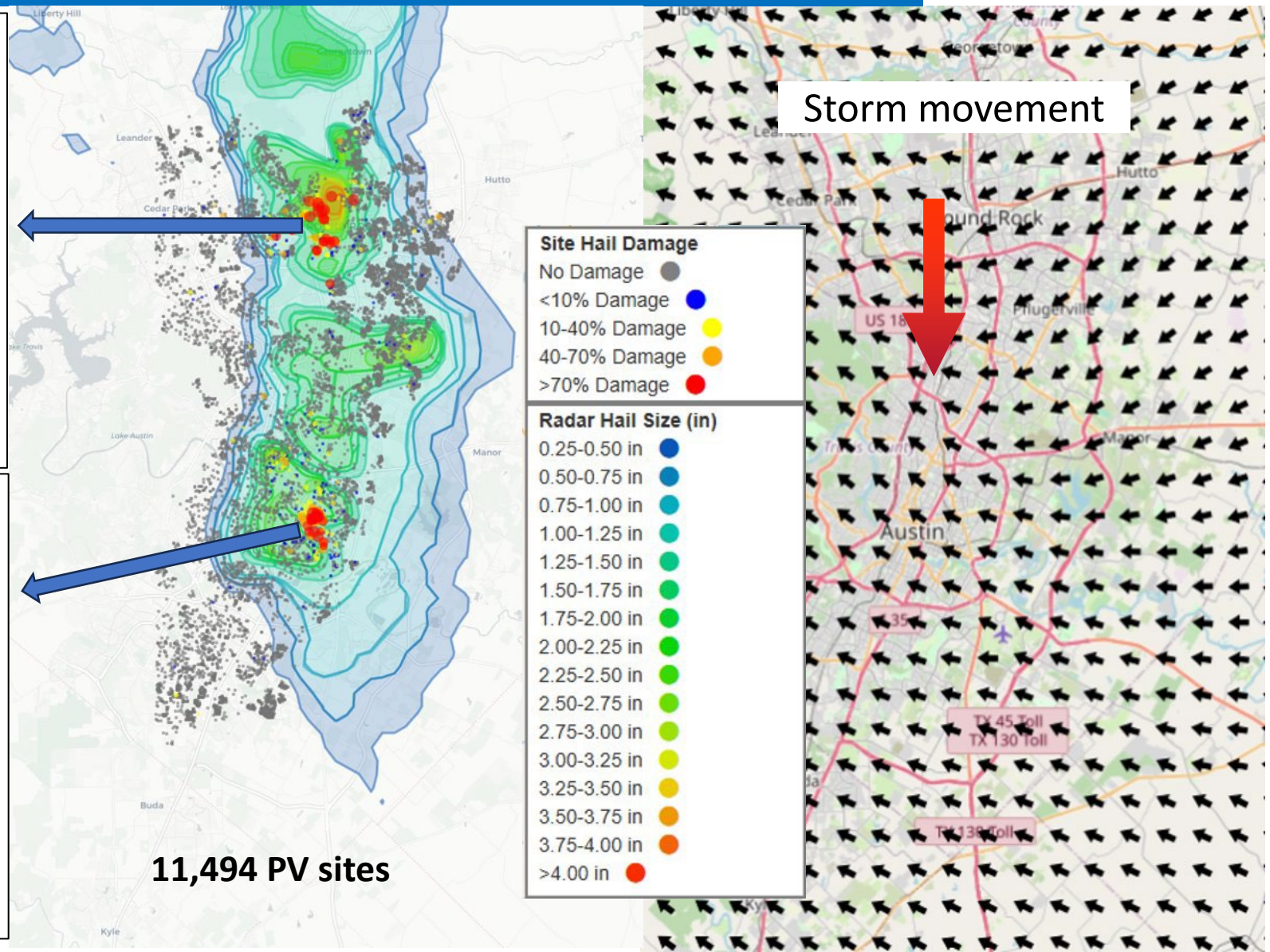
Visualizing the Data: Austin Hailstorm

Storm movement ≠ wind direction

Site Coordinates: 30.5226, -97.7011
Percent Modules Damaged: 72.01%
Max Hail Size (in): 3.25
Year Before Installation: nan

Site Coordinates: 30.2842, -97.6981
Percent Modules Damaged: 77.46%
Max Hail Size (in): 1.5
Year Before Installation: nan



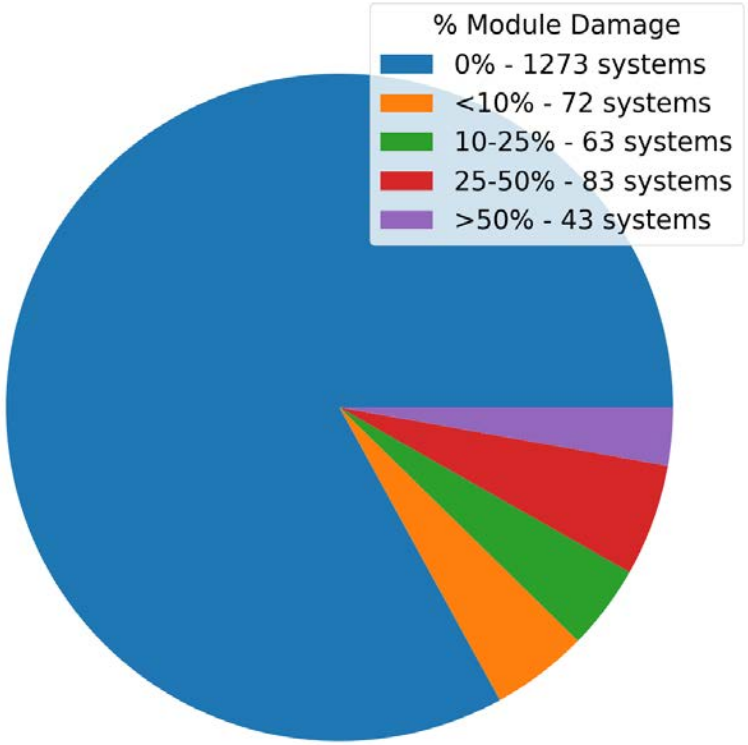


11,494 PV sites

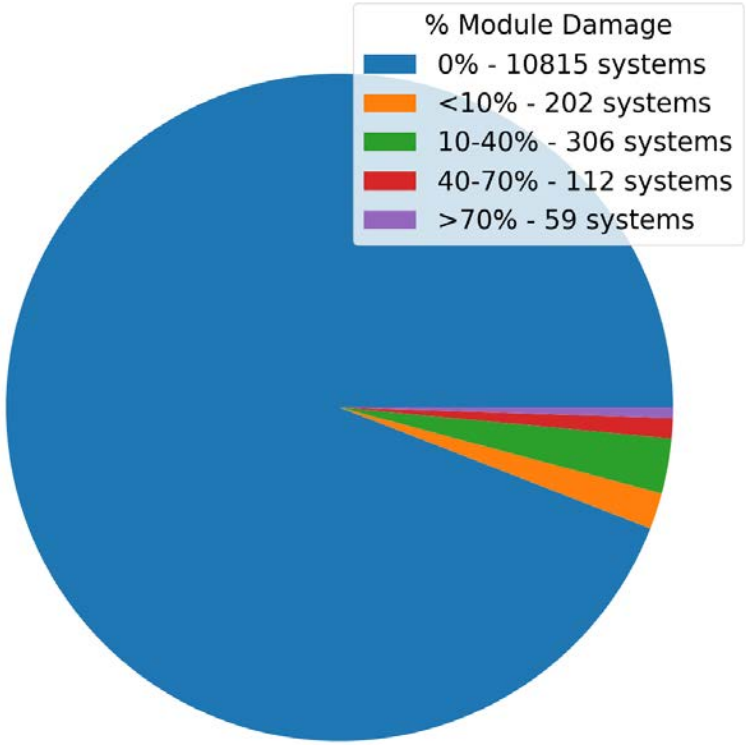
Results

- **So, just how much damage was sustained?**
  - 17% of installs damaged by Hurricane Maria/Irma
    - 2.8% of systems >50% damaged
  - 5.9% of installs damaged by Austin hailstorm
    - 0.5% of systems >70% damaged

Hurricane PV Damage, Maria and Irma

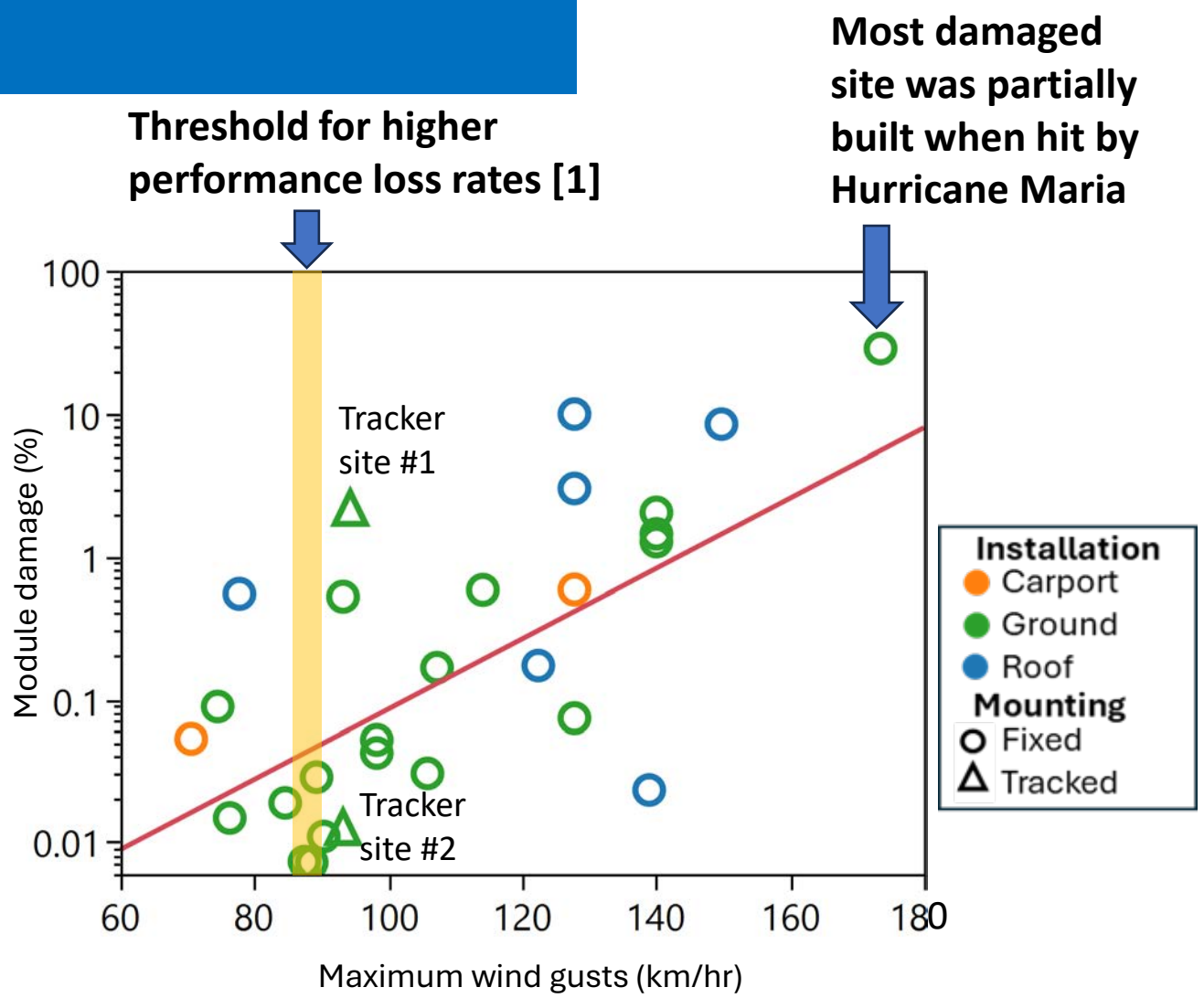


Hail PV Damage, Austin September 2023 Storm



Results: Hurricanes

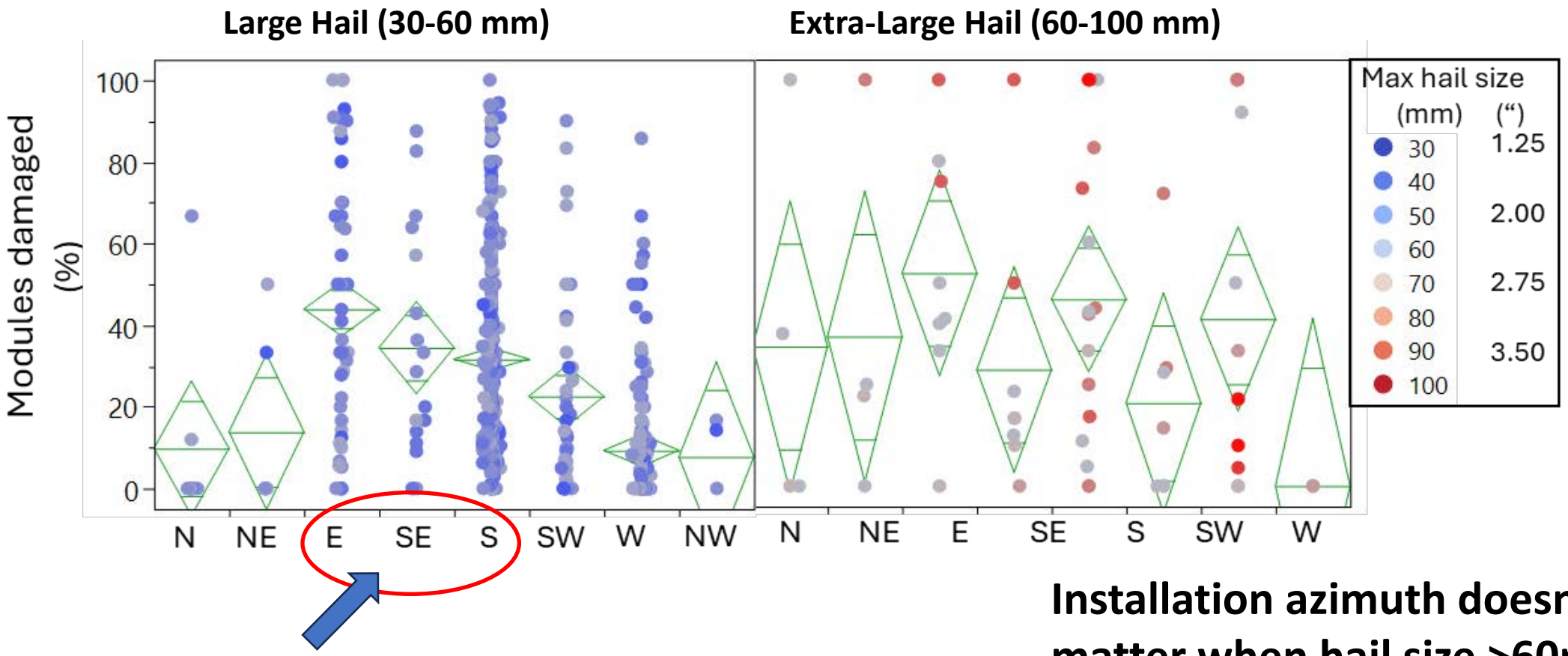
- Manually labeled data set
- Increasing module damage with increasing max wind gust speed
- Lots of noise → installation practices
- Two tracker sites: 2 km proximity, heavily damaged site had mounting issues
- Wind sheltering for minimally damaged sites under trend line



[1] Jordan et al. "Extreme weather and PV Performance." Journal of Photovoltaics (2023)

Results: Hail

Comparing PV installs with "moderate" tilt (20-40 deg)

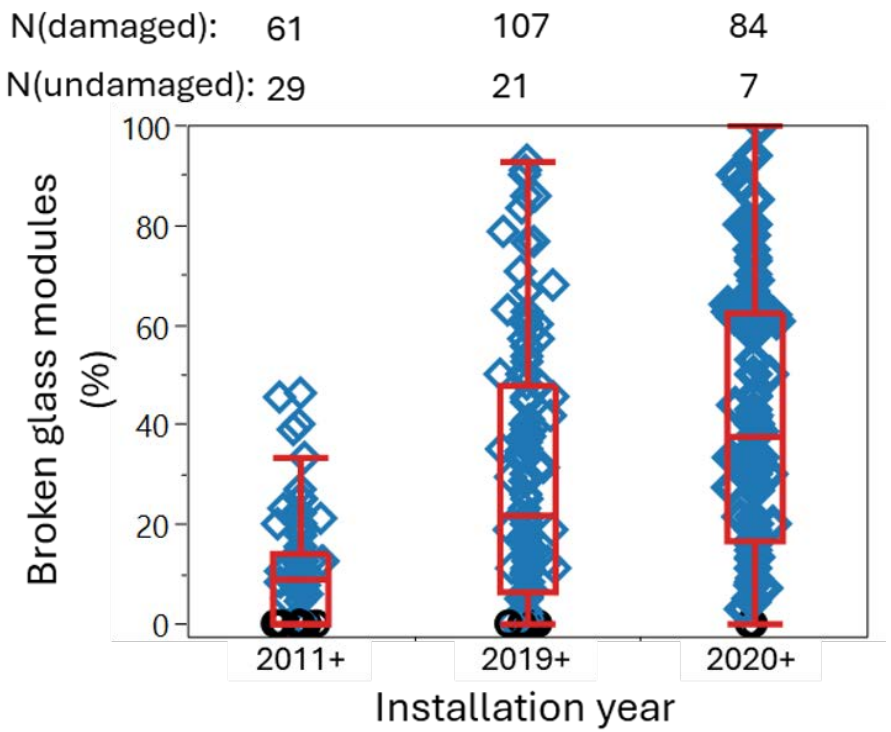


Directly facing wind direction in storm → higher damage

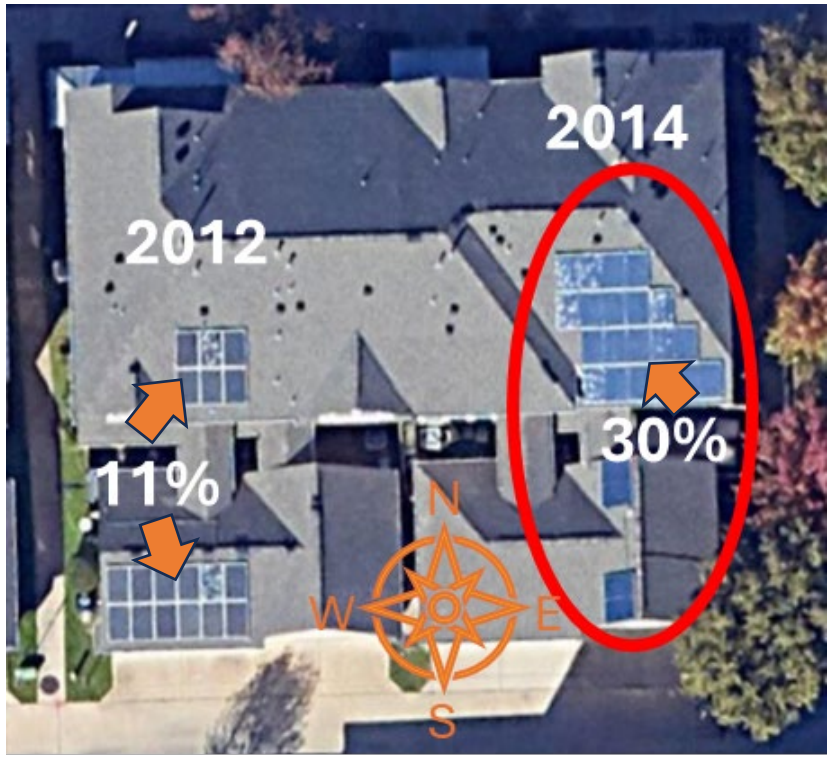
Installation azimuth doesn't matter when hail size >60mm → everything damaged

Results: Hail

- Manually labeled data set analyzed
- Module vintage found via Google Earth Timelapse
- Older module vintages more resilient
- Module glass thickness decreasing + size increasing could be cause



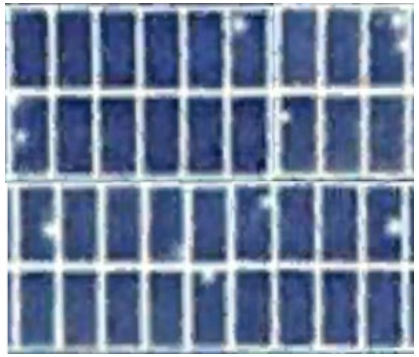
Test case: building with different module vintages



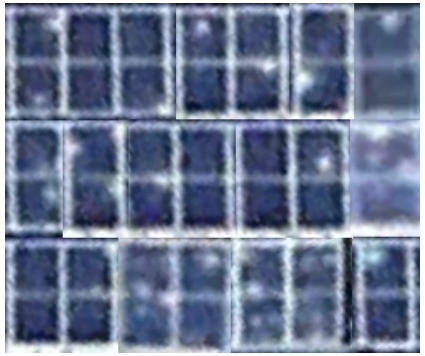
Results: Hail

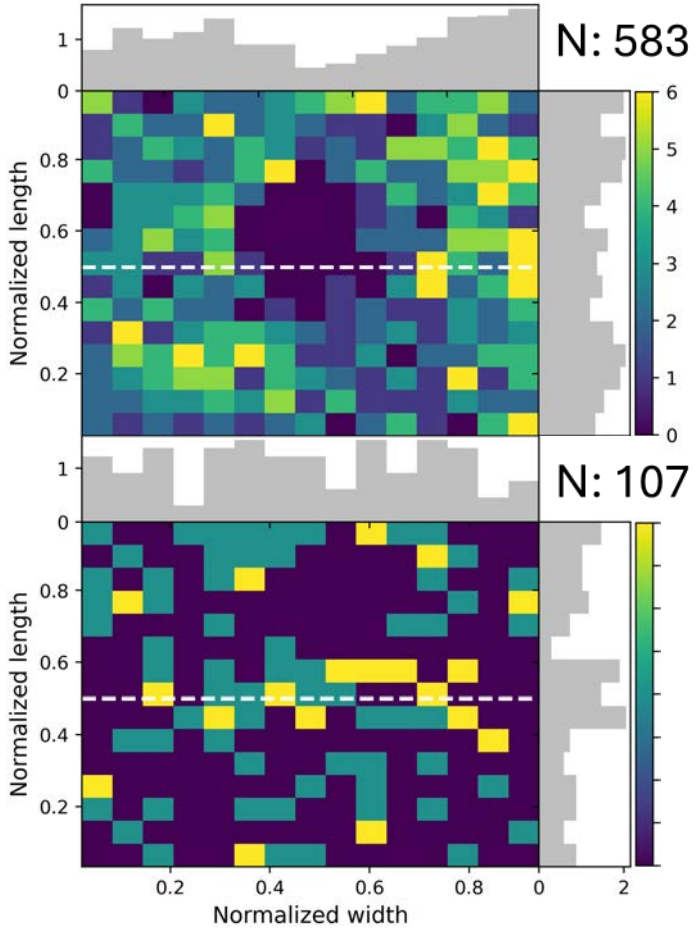
- Calculated approximate strike location for modules with 1-2 hail strikes
- 2D histogram of aggregated, normalized hail strike location across all modules
- More strikes along module perimeter + center junction box location (twin layout)
- Module center more flexible, perimeter more rigid

Traditional module layout



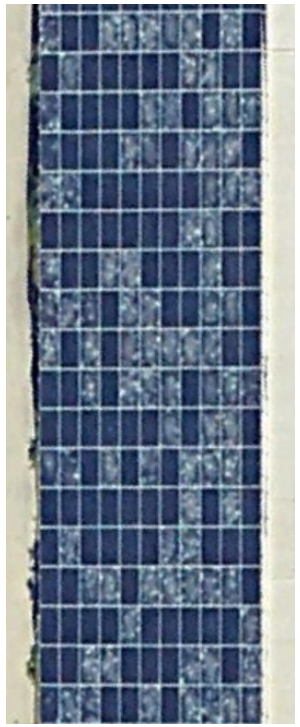
Twin module layout

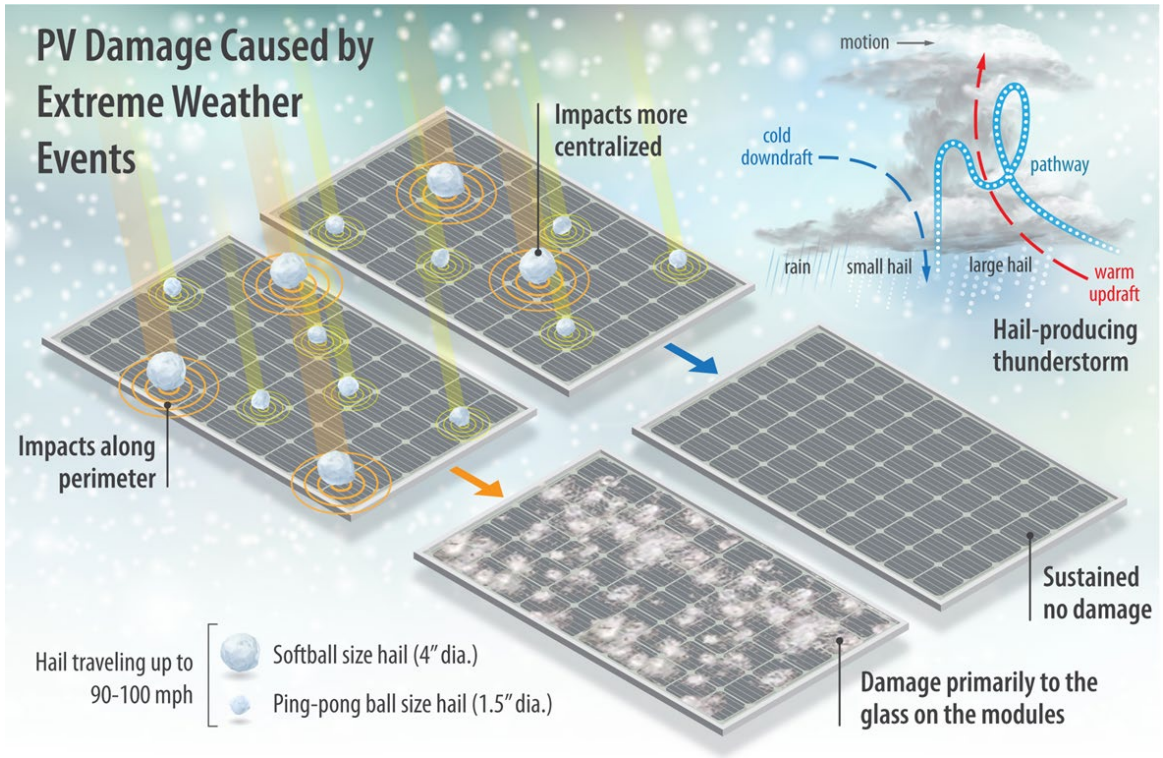


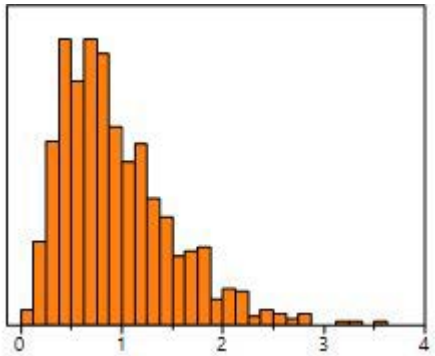


Results: Hail

- Theory explaining checkerboard pattern on hail-damaged installations
- Ground hail: gamma distribution with long tail
- Heterogeneous damage →smaller hail is preceded by larger hail along perimeter







Ground Distribution (Gamma): Long tail for large hail stones

Conclusion & Future Directions

- **Sometimes we heavily focus on the severely damaged sites, and forget the sites that aren't impacted**
- **With visual inspection, PV quite robust during extreme weather events**
- **Inevitable hail damage cutoff: >60 mm**
- **Open sourcing data & code**
- **Paper submitted to Progress in PV**

Panel-Segmentation (code currently in PR):

Thank you!

Contact:
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dirk.jordan@nrel.gov
quyen.nguyen@nrel.gov

www.nrel.gov

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NREL
Transforming ENERGY

Survivability of Island PV Following Hurricane Beryl

3.4.2025

Presented To: PV Reliability Workshop 2025

Frank Oudheusden - Azimuth Advisory Services

Chris Needham - Azimuth Advisory Services

AZIMUTH ADVISORY SERVICES

The Journey

About Us – Azimuth Advisory Services

Services:

- Technical Due Diligence
  - Trackers/Racking
  - BESS
- Damaged Site Assessments
  - Root Cause Analysis
  - Failure Mode and Effects Analysis (FMEA)
  - Site Remediation Development
- Market Analysis & AVL Strategy
- New Product Introductions
- Tracker & Racking Cost Reductions

Publications:

- Solar Under Storm 1 (2018)
- Solar Under Storm 2 (2020)
- Solar Under Storm 3 (May 2025)
- PV Magazine
- PVTech

www.azimuth-ventures.com

Frank Oudheusden

Manager

Frank holds a BS in Manufacturing Engineering from the Rochester Institute of Technology (RIT) in Rochester, NY

He is a co-founder of FCX Solar, an intellectual property development company.

He is a co-founder of Skyhook Solar, a start-up in Aspen, CO focused on last-mile solutions.

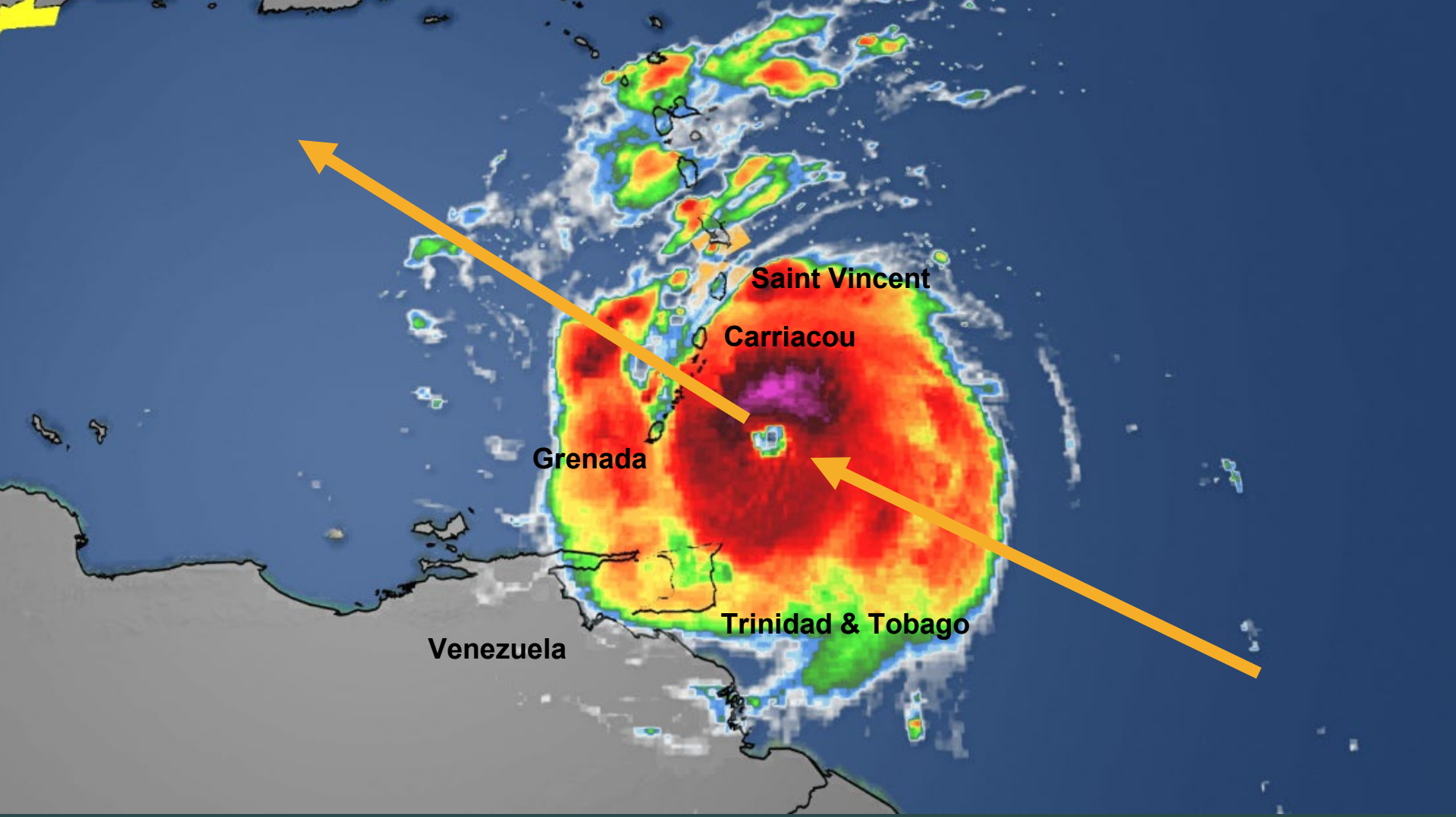
Chris Needham

Manager

Chris holds a BS in Aerospace Engineering from UIUC (University of Illinois Urbana Champaign) and an MS in System Optimization from Georgia Tech.

He is a co-founder of FCX Solar, an intellectual property development company.

He is a co-founder of Skyhook Solar, a start-up in Aspen, CO focused on last-mile solutions.



7/1/24 @ 6:19pm UTC

Category 4: 140mph sustained winds

4
4
4
4
4
4
5
5
5
4
4
3
3
3
3
2
1
Tropical Storm

Island 1

Alma’s Island

Modules Overhanging the Roof Edge. Image courtesy of Marc Lopata, Solar Island Energy

Takeaways from Island 1

- ☐ Erosion Control
- ☐ Top-Down Clip Module Attachment
- ☐ Tek Screws & Aluminum T-Slots
- ☐ Topographical Factors
- ☐ Issues Not Caught By Technical Due Diligence
- ☐ Large Format Modules with Insufficient Allowable Pressures
- ☐ Combiner/Recombiner Box Wind Load Assessment

✅ E-W fixed tilt system architecture is good for low latitude and high irradiance sites.

Island 3

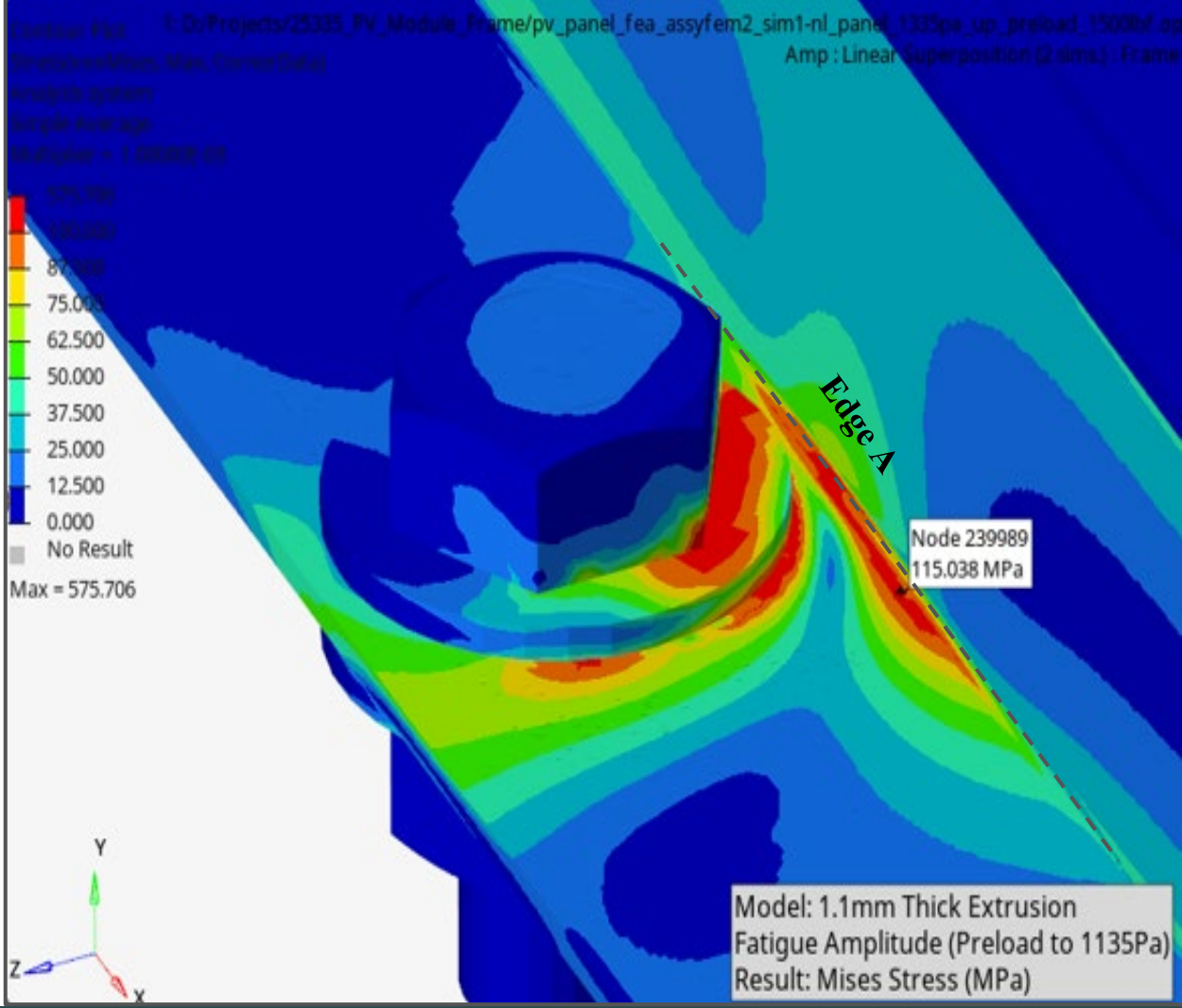
Henry & Giancarlo

Takeaways from Island 3

- ✅ Erosion Control
- ✅ Non-Shared Top-Down Clip Module Attachment
- ✅ No Tek Screws & Aluminum T-Slots
- ☐ Kz Topographical Factors – Missed in Due Diligence
- ☐ System Testing Not Best-in-Class
- ☐ Wind Pressure Considerations on Inverter Pad Walls, Combiner Boxes, etc.
- ☐ Single Post vs. Dual-Post Design
- ☐ Analysis for Shifting Winds & Circular Storms
- ☐ No Vibration Resistant Fasteners – Loose Fasteners Around Site
- ✅ 72-Cell Modules with Appropriate Pressure Ratings
- ✅ E-W fixed tilt system architecture is good for low latitude and high irradiance sites.

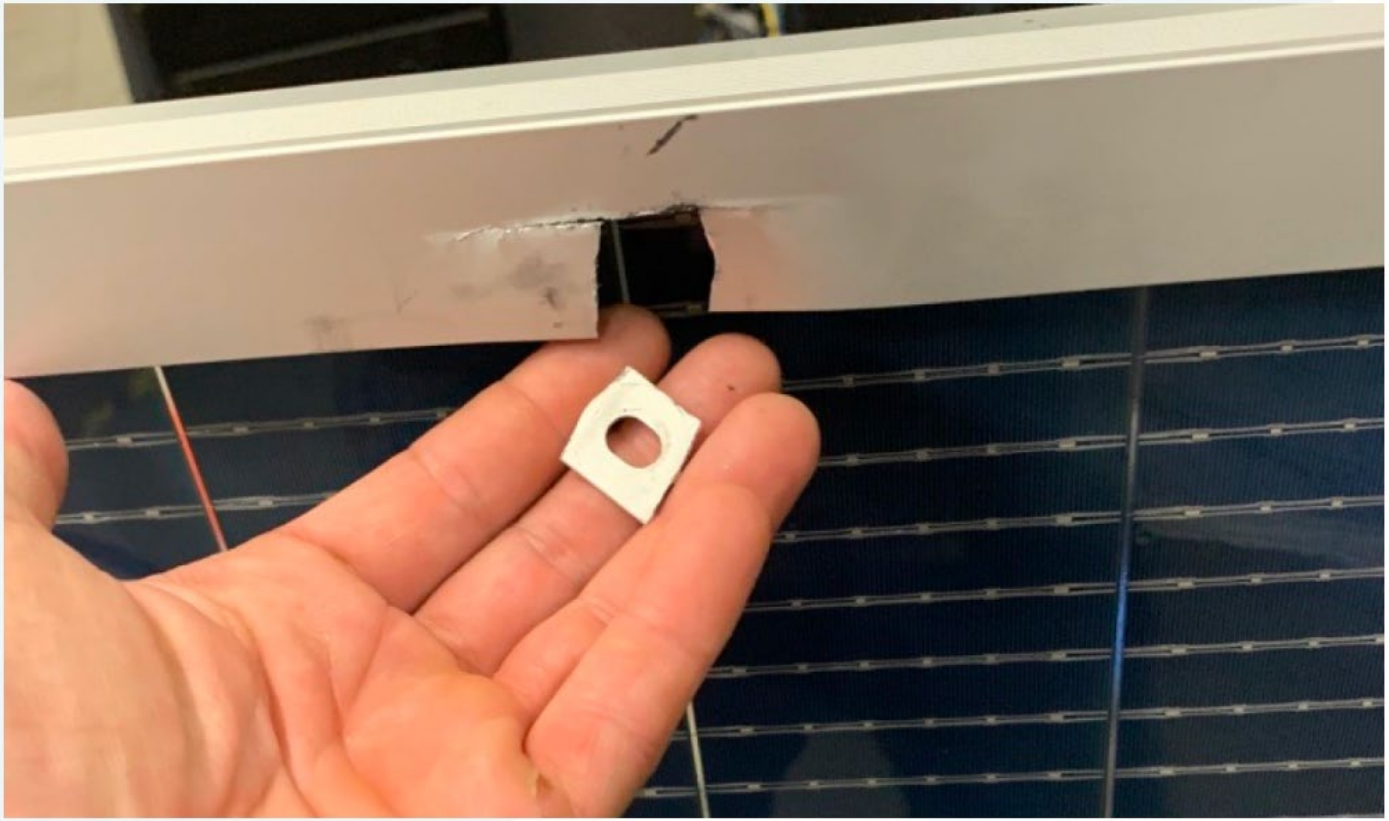
Island 2

Testbed Island

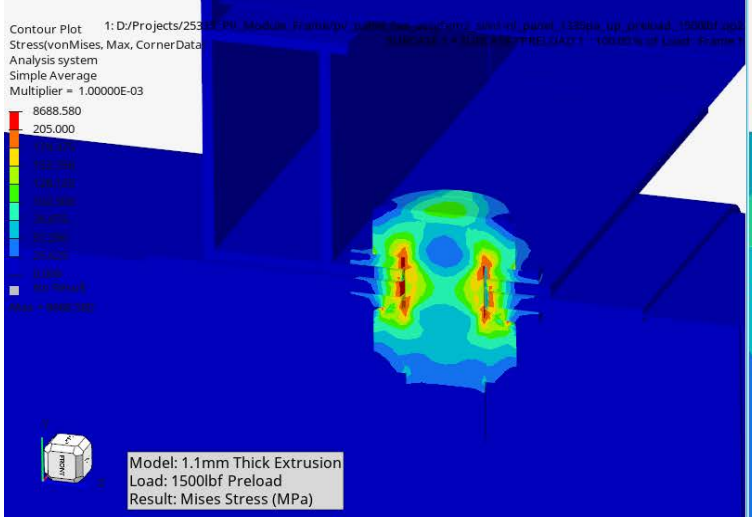

Amp : Linear Superposition (2 sims) - Frame
75.000
62.500
50.000
37.500
25.000
12.500
0.000
No Result
Max = 575.706
Edge A
Node 239989
115.038 MPa
Y
Z
X
Model: 1.1mm Thick Extrusion
Fatigue Amplitude (Preload to 1135Pa)
Result: Mises Stress (MPa)

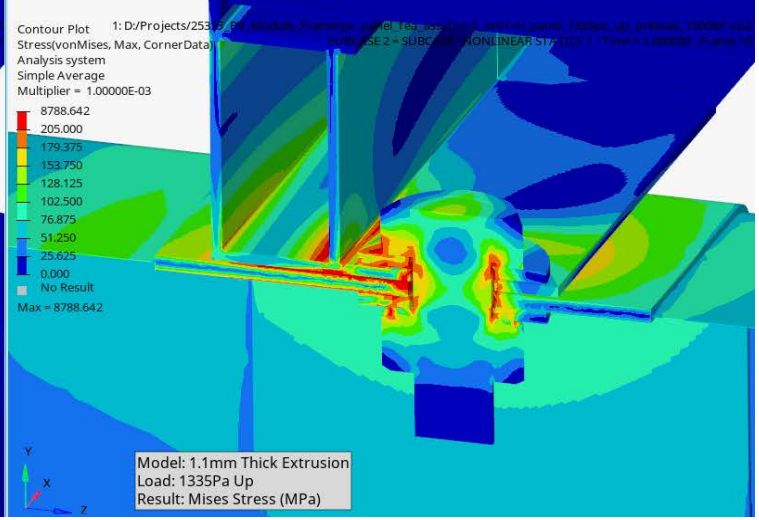
Cyclical Loading Results

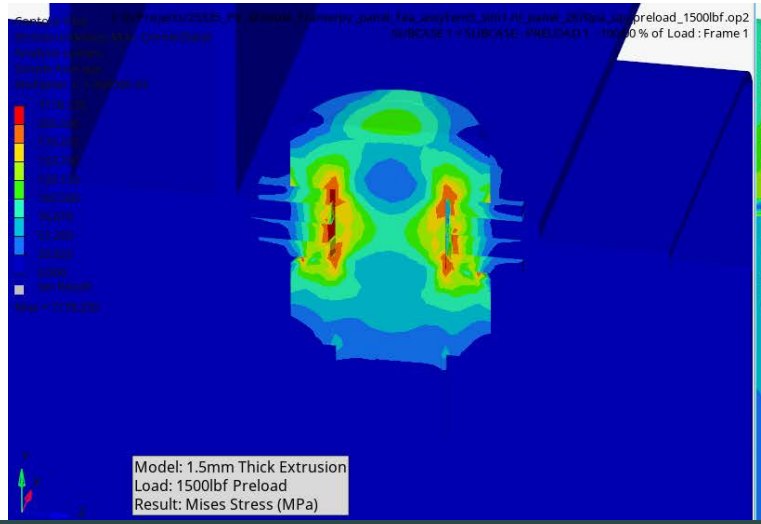
Fatigue Life 2 Elements from Edge A (Cycles)	
Model	Applied Load
	607

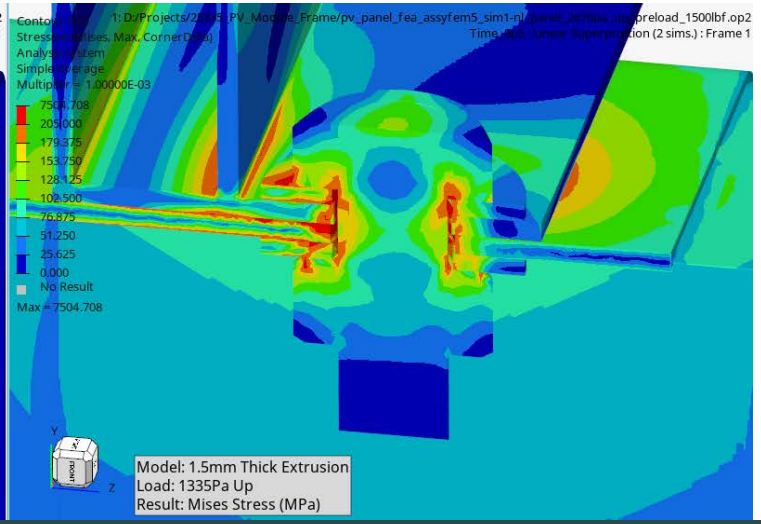


The module frame failed following static mechanical load testing at ±1800 Pa and dynamic mechanical load for 1000 cycles at ±1000 Pa. The failure occurred on DML cycle #962.


Contour Plot
Stress(vonMises, Max, CornerData)
Analysis system
Simple Average
Multiplier = 1.00000E-03
8688.580
205.000
Model: 1.1mm Thick Extrusion
Load: 1500lbf Preload
Result: Mises Stress (MPa)


Contour Plot
Stress(vonMises, Max, CornerData)
Analysis system
Simple Average
Multiplier = 1.00000E-03
8788.642
205.000
179.375
153.750
128.125
102.500
76.875
51.250
25.625
0.000
No Result
Max = 8788.642
Model: 1.1mm Thick Extrusion
Load: 1335Pa Up
Result: Mises Stress (MPa)

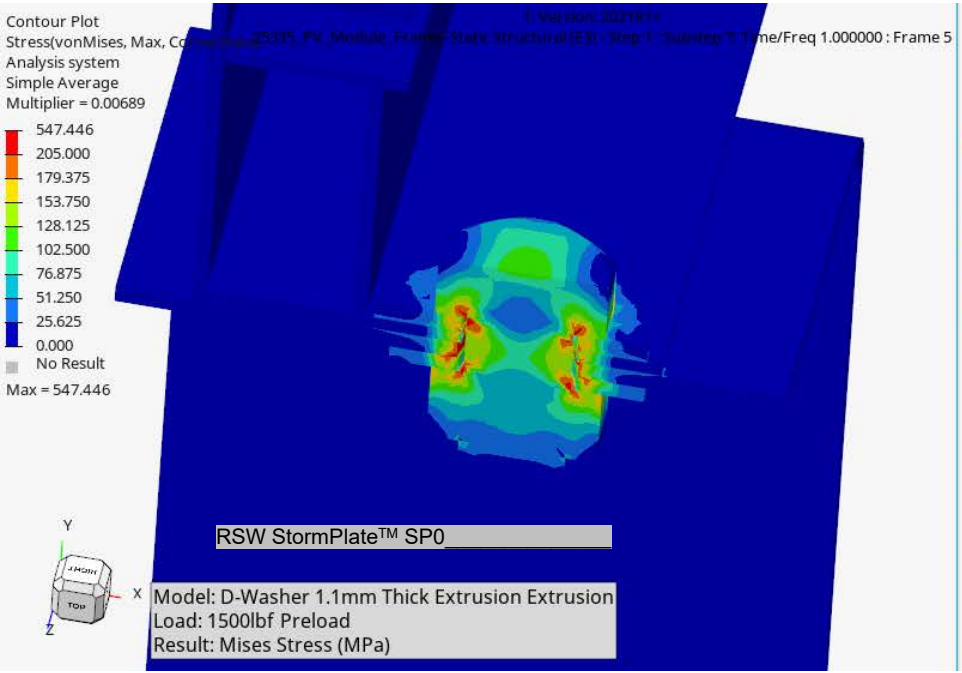

Model: 1.5mm Thick Extrusion
Load: 1500lbf Preload
Result: Mises Stress (MPa)

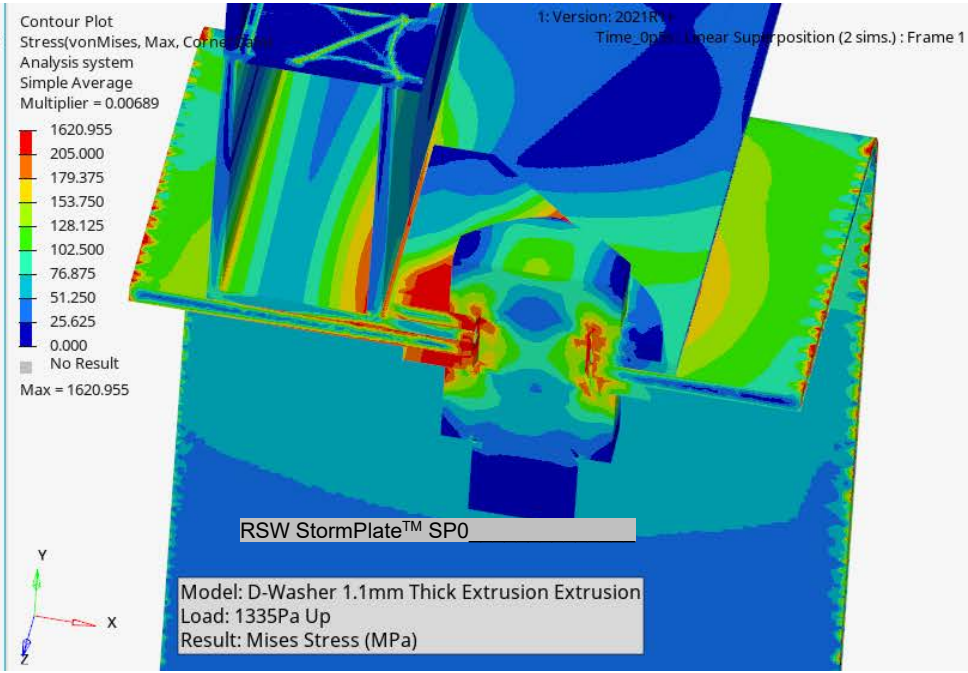

Analysis system
Simple Average
Multiplier = 1.00000E-03
7504.708
205.000
179.375
153.750
128.125
102.500
76.875
51.250
25.625
0.000
No Result
Max = 7504.708
Model: 1.5mm Thick Extrusion
Load: 1335Pa Up
Result: Mises Stress (MPa)

Cyclical Loading Results

Fatigue Life 2 Elements from Edge A (Cycles)			
	Applied Load		
Model	**1068 Pa** 40% Rated	**1335 Pa** 50% Rated	
			607

RSW StormPlate™ SP0





Cyclical Loading Results

Fatigue Life 2 Elements from Edge A (Cycles)			
	Applied Load		
Model	**1068 Pa** 40% Rated	**1335 Pa** 50% Rated	
	198,427		607
			283,169

Thank You.

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AZIMUTH
ADVISORY
SERVICES

Field Testing Methods *and* Results

Jim Rand, Mason Reed • Core Energy Works

EPRI Robert Flottemesch,
Joe Karas, Wayne Li
CEW AJ Hendricks,Andrew Cooper
Lightsourcebp
T. Pananos, J. Martinez
KIWA/PI Berlin
NREL Martin Springer

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Core Energy Works' Experience with Field Testing Modules

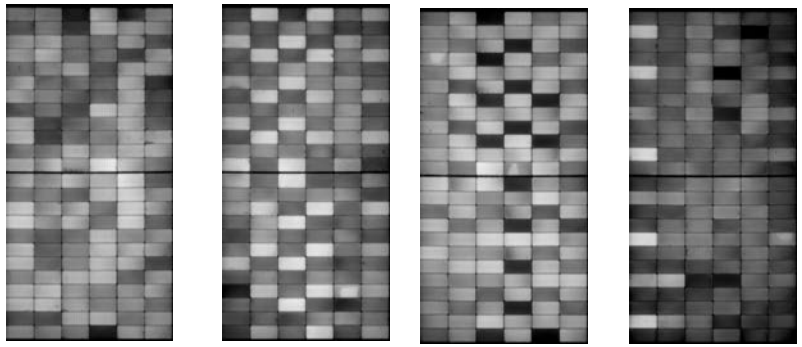
Metrics

- >450 Sites Visited
- ~50,000 Field IV Measurements
- ~75,000 Field EL Images

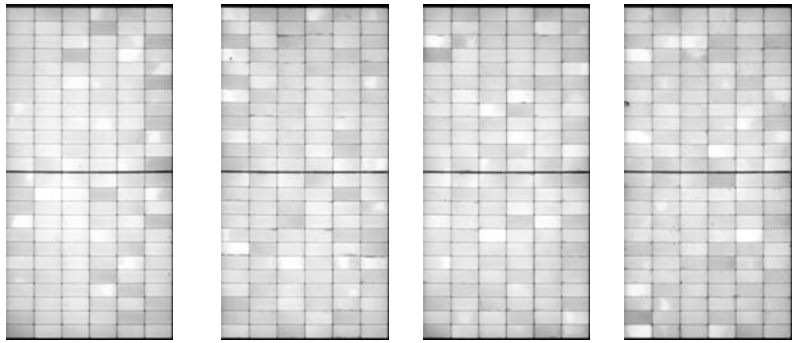
OM and PM Locally

Focus on Module Performance and Reliability

550W Dropped ~8%



545W Dropped ~5%



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Field Testing and Results

Ranging from Practical to the Esoteric

- How do you get samples from the field to the lab?
- How do you determine bifacial module degradation rates?
- Can hail do internal damage to glass/glass modules?
- How do you find a ground fault?

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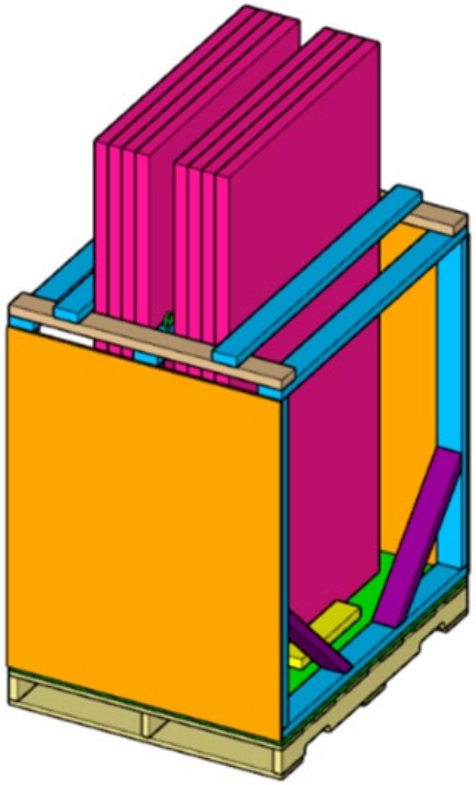
Field Testing and Results

Ranging from Practical to the Esoteric



- How do you get samples from the field to the lab?

  CEW Sample Crate – Simple and Inexpensive

- How do you determine bifacial module degradation rates?
- Can hail do internal damage to glass/glass modules?
- How do you find a ground fault?

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CORE
ENERGY WORKS

Old School Horizontal Stacking

Damage due to shifting (w/o packaging corners)
Modern modules are so long that special pallet jacks are needed

2 Broken Modules in this stack

Expensive Custom Crates

- Expensive
- Single module size
- Long lead time
- Big and hard to manage

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CEW Sample Crate

Advantages

- Accommodates Most Modules
- Stable to Load and Unload
- Easily Assembled
- Readily Available Parts
- Inexpensive
- Handled with Conventional Pallet Jacks
- Can be Lifted on a Truck Lift Gate

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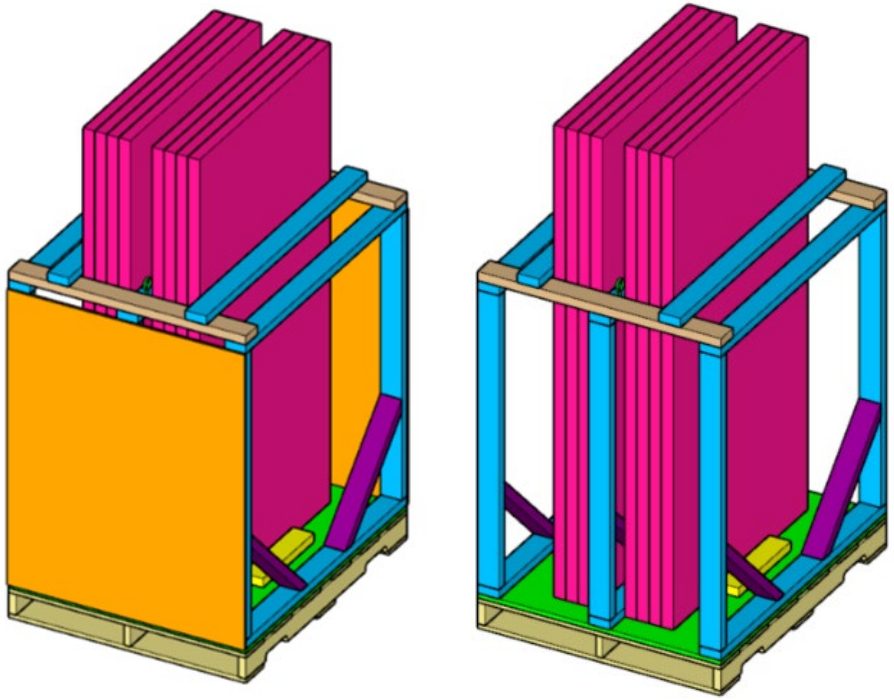

Cut Part Description	Stock Material	Part Cut Size	Quantity	function
ORANGE: 1/2" plywood - 40x48"	1/2" plywood	40x48"	2	used to connect and stiffen the 3 vertical wall assemblies
PURPLE: 2x4 - 24" 45° angle brace	2x4	24"	6	used to stiffen vertical wall assembly
YELLOW: 2x4 - 24" bottom kick plate	2x4	24"	2	used to constrain bottom of modules from kicking out during shipment
BLUE: 2x4 - 48"	2x4	48"	14	used is vertical wall construction (QNTY 12) and for modules constraint after loading (QNTY 2)
BROWN: 2x4 40"	2x4	40"	2	wall cross-tie (used to connect three vertical wall assemblies)
GREEN: 3/4" plywood - 40x48"	3/4" plywood	40x48"	1	pallet floor
EYELET FOR BUNGEE	steel	~1" opening (purchase zinc plated wood screw)	2	woodscrew eyelet for bungee use during loading
48'"x40" standard pallet	hard wood	purchased assembly	1	pallet

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Field Testing and Results

Ranging from Practical to the Esoteric

- How do you get samples from the field to the lab?
  CEW Sample Crate – Simple and Inexpensive
- How do you determine bifacial module degradation rates?
  Testing Bifacial Modules in the Field
- Can hail do internal damage to glass/glass modules?
- How do you find a ground fault?

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Black Out Boards – V3.2

Basic Concept

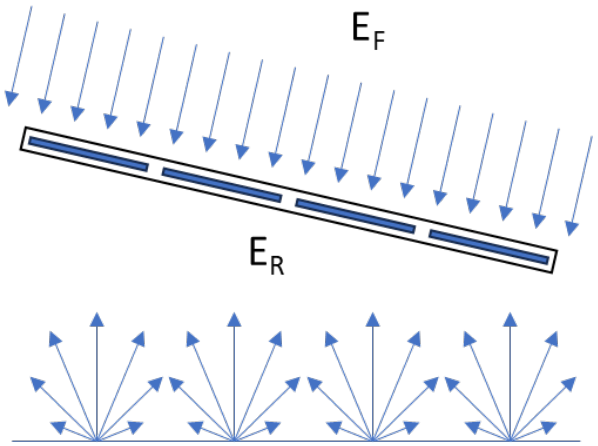
1. Back Irradiation is very non-uniform in space and time.
2. Nameplate Ratings (and warranties) are based on front illumination
3. Eliminating Back Irradiation
   - Repeatable
   - High Signal to noise

1. Test the module as it operates in the field, front and back irradiation

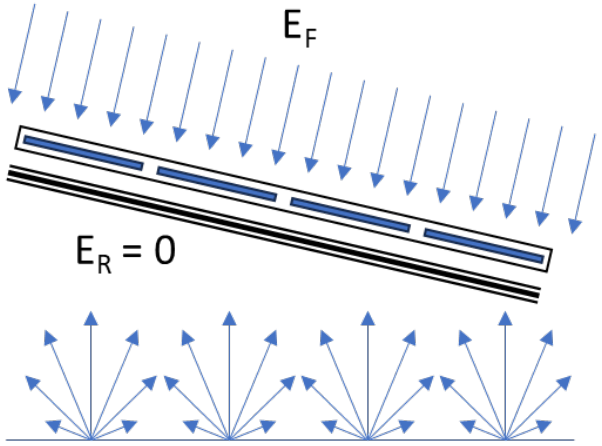
2. Test the module the back irradiation blocked

3. Utilize an instrumented control to analyze the results

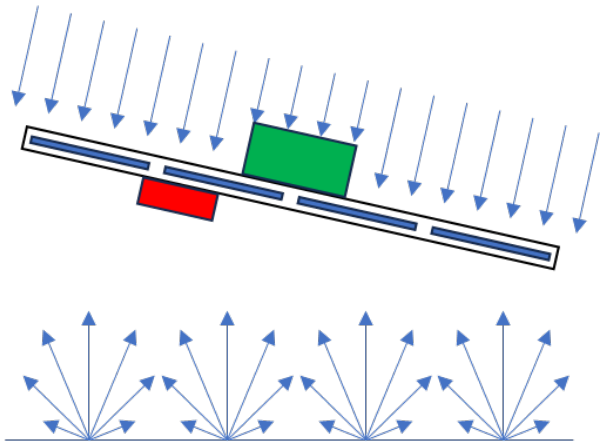
Bifacial Condition



Frontside Condition



Instrumented Reference



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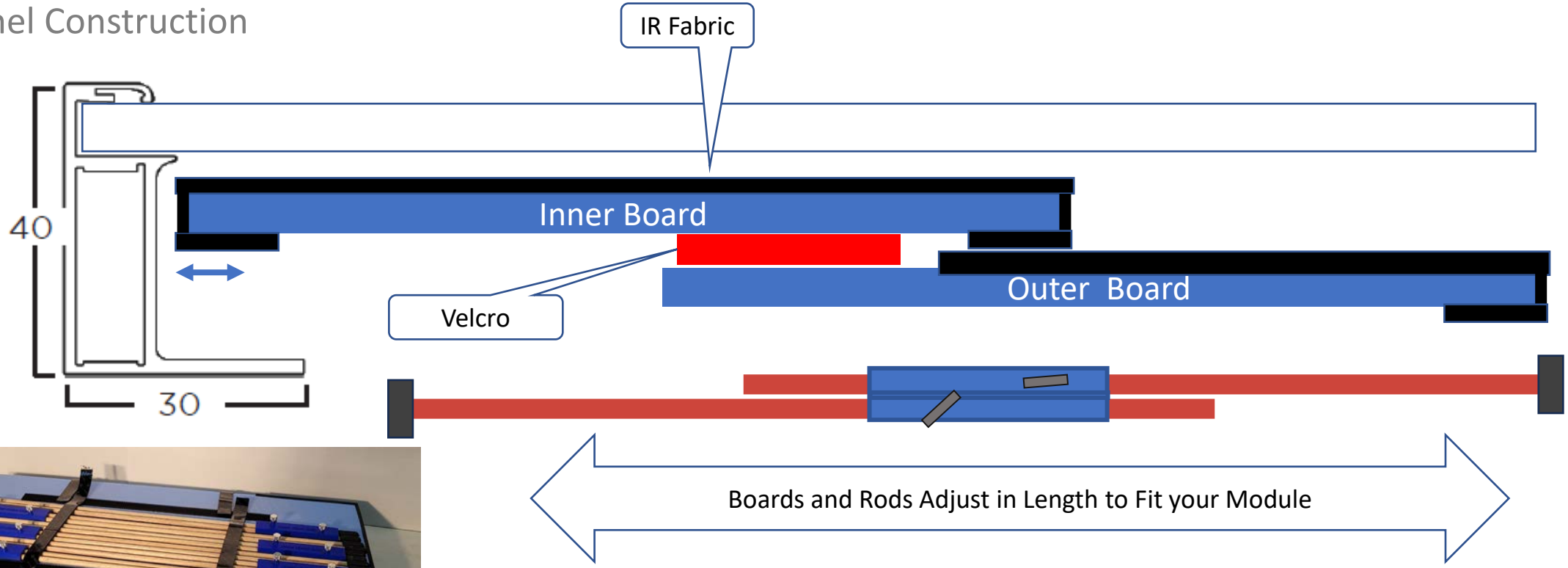
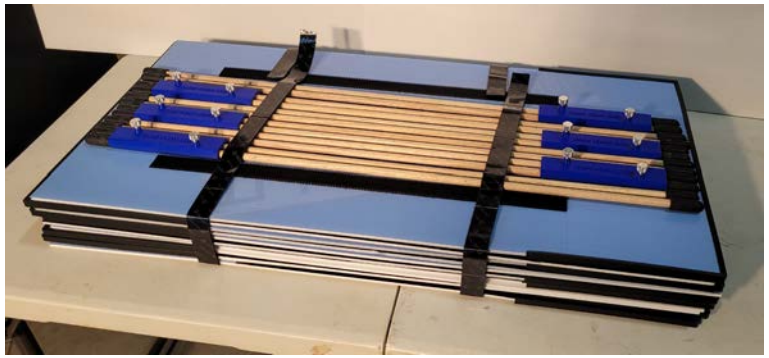
Black Out Boards – V3.2

Panel Construction





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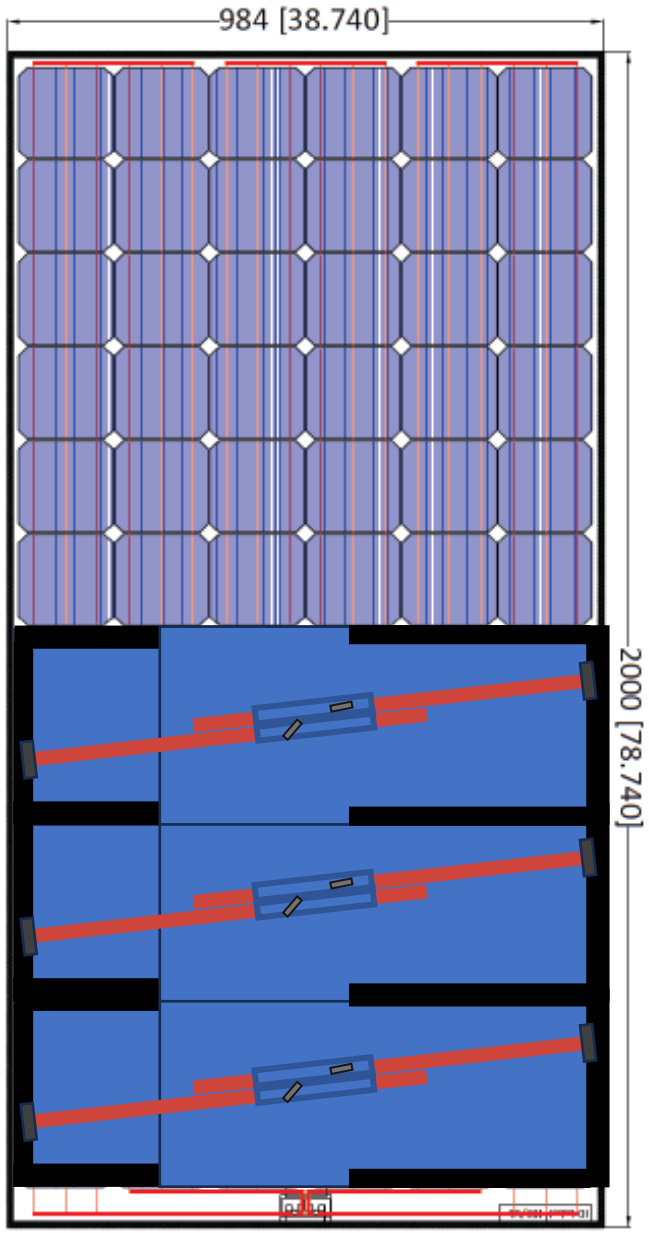
Black Out Boards – V3.2

Boards in Use



Advantages

1. Boards are easily and quickly transported and used.
2. Applicable to wide range of module sizes.
3. Greater than 100 tests in a few hours around solar noon.
4. Fault tolerant. Small “leaks” do not impact the results.
5. The use of the instrumented control accounts for temperature changes.
6. Traditional IV curve equipment can be used.

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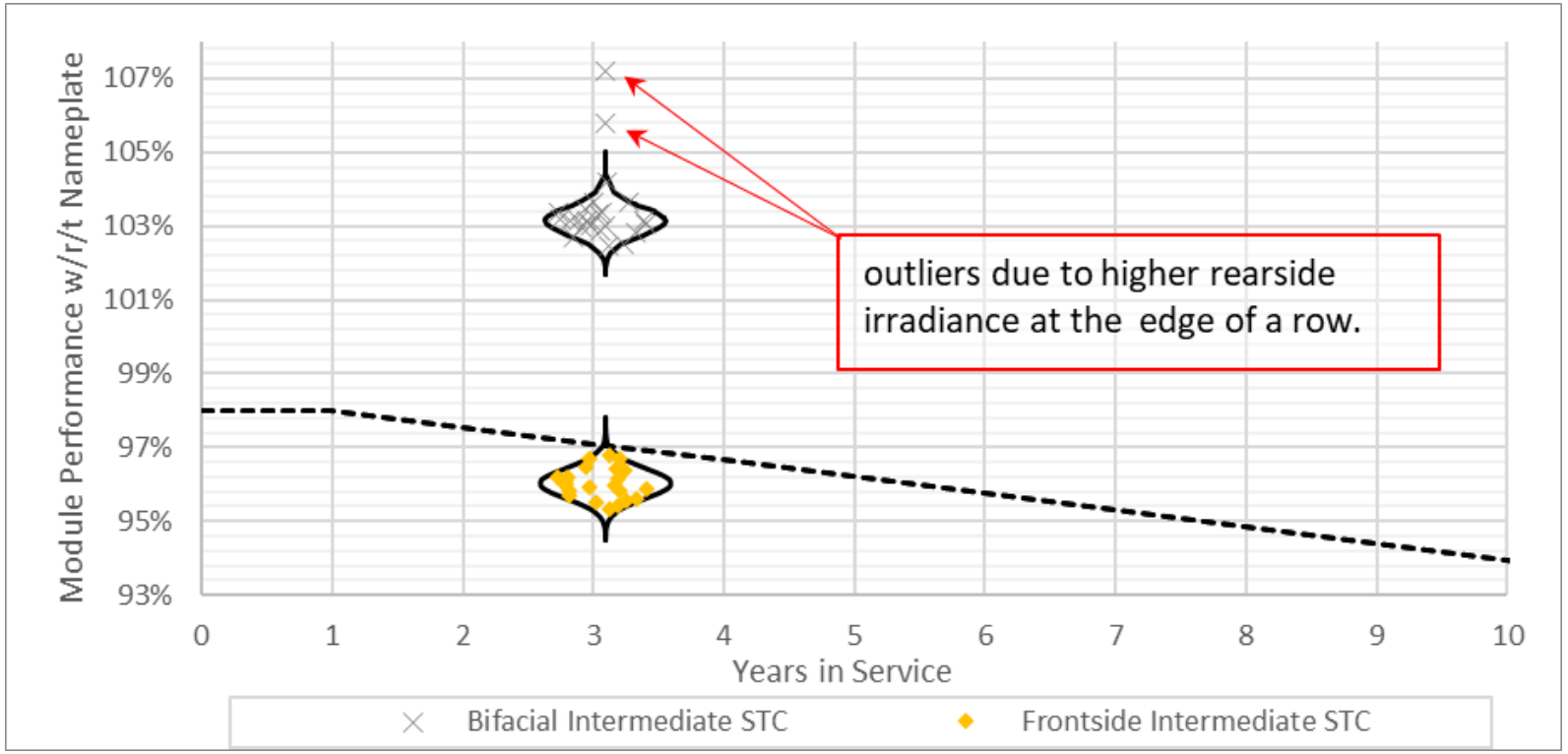
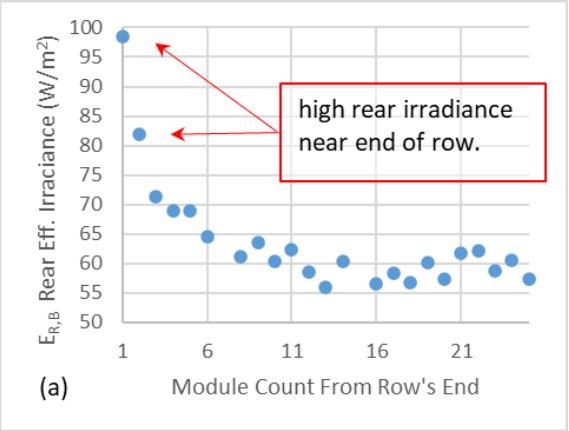
Black Out Boards – V3.2

Example Results

~ 7% Gain due to Backside Irradiance on this site

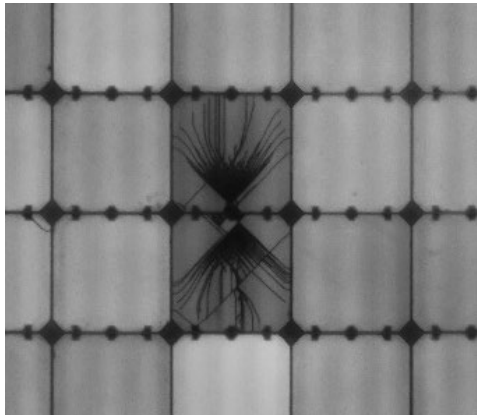


Example of how Backside Irradiance Varies



Field Testing and Results

Ranging from Practical to the Esoteric



- How do you get samples from the field to the lab?
  CEW Sample Crate – Simple and Inexpensive
- How do you determine bifacial module degradation rates?
  Testing Bifacial Modules in the Field
- Can hail do internal damage to glass/glass modules?
  Sadly, yes. But there could be a silver lining
- How do you find a ground fault?

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Hail Damage

A 2019 Case Study and Lab Trials

February 2020

James Rand, Chris Thompson, Mason Reed, AJ Hendricks, Andrew Cooper
Paul Donley, Duke Energy

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Hail Damage on Glass/Glass vs Glass/Polymer Modules

Module Construction	Location	Year of Module Mfg	# Modules on Site	# Modules Insp/Tested	Undamaged	Glass Breakage	Internal Cracking
Glass/Polymer	Mid Atlantic	~2008	19,950	19,950	48.5%	30.4%	21.1%
Glass/Glass	South	~2020	650,000[1]	901	44.7%	45.4%	10.0%
Glass/Polymer	Northern Plains[2]	~2020	4,600	4,600	47.4%	17.3%	35.3%
Glass/Glass	Northern Plains[2]	~2020	1,600	1,600	45.1%	45.8%	9.1%

[1] Huge Range of Damage on this site, from 0% glass breakage to 93% in different sub arrays, this is a very sample selection dependent result
[2] These different module types were both on the same array in the same storm

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Front vs Back Glass Breakage

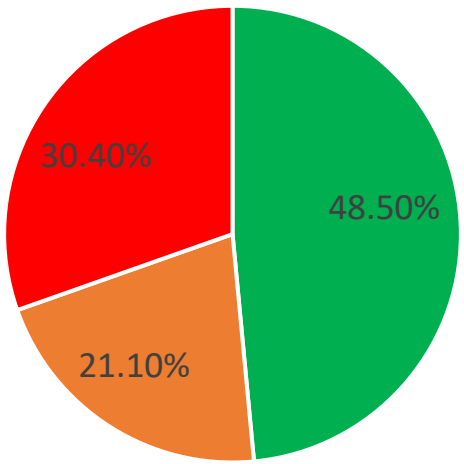
- Glass/Glass

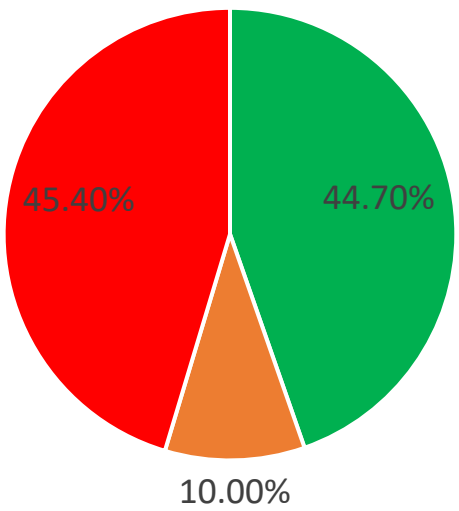
  You can Crack Solar Cells

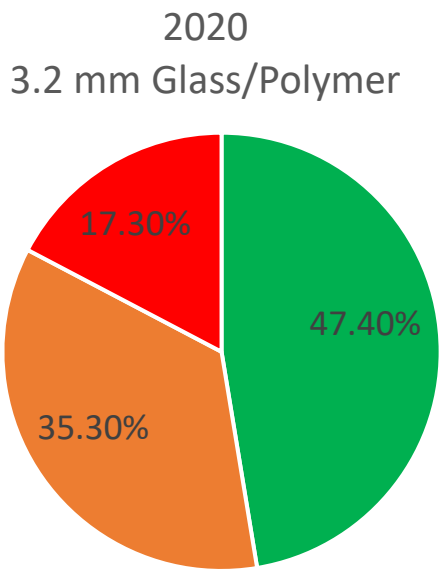
  Energy $_{\text{Break Glass}}$ < Energy $_{\text{Crack Cell}}$

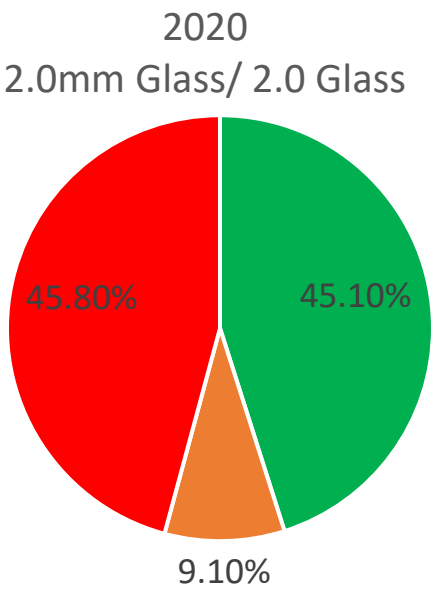
  Energy $_{\text{Break Back Glass}}$ < Energy $_{\text{break Front Glass}}$

A small study (168 modules) found that back glass broke at a 58% higher rate than front glass.









■ Undamaged ■ Internal Cracking ■ Glass Breakage

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Front vs Back Glass Breakage

- Glass/Glass

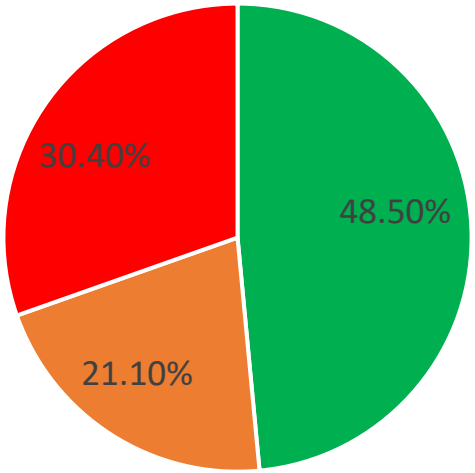
  You can Crack Solar Cells

  Energy $_{\text{Break Glass}}$ < Energy $_{\text{Crack Cell}}$

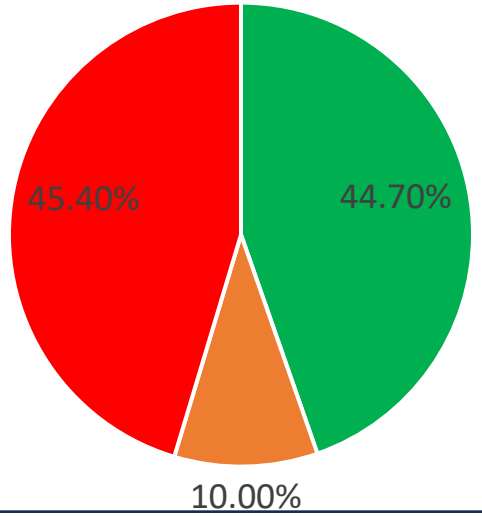
  Energy $_{\text{Break Back Glass}}$ < Energy $_{\text{break Front Glass}}$

A small study (168 modules) found that back glass broke at a 58% higher rate than front glass.

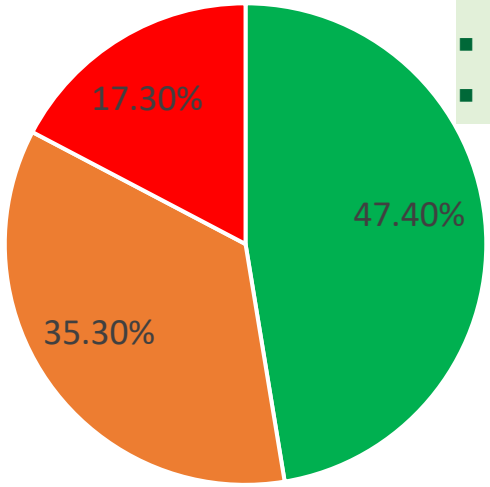
2008
Traditional 3.2mm Glass/Polymer



2020
2.0mm - Glass/Glass

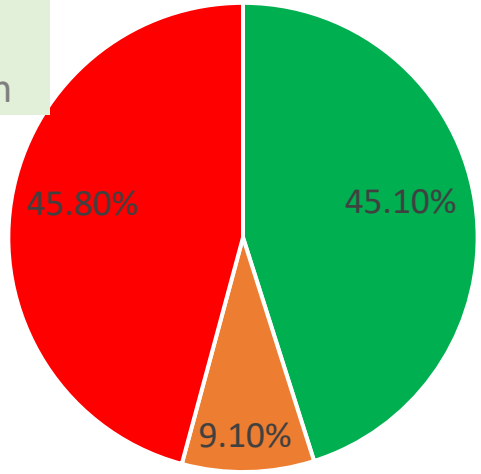


2020 3.2 mm Glass/Polymer



- Same Storm
- Same Racking
- Same Location

2020 2.0mm Glass/ 2.0 Glass



■ Undamaged ■ Internal Cracking ■ Glass Breakage

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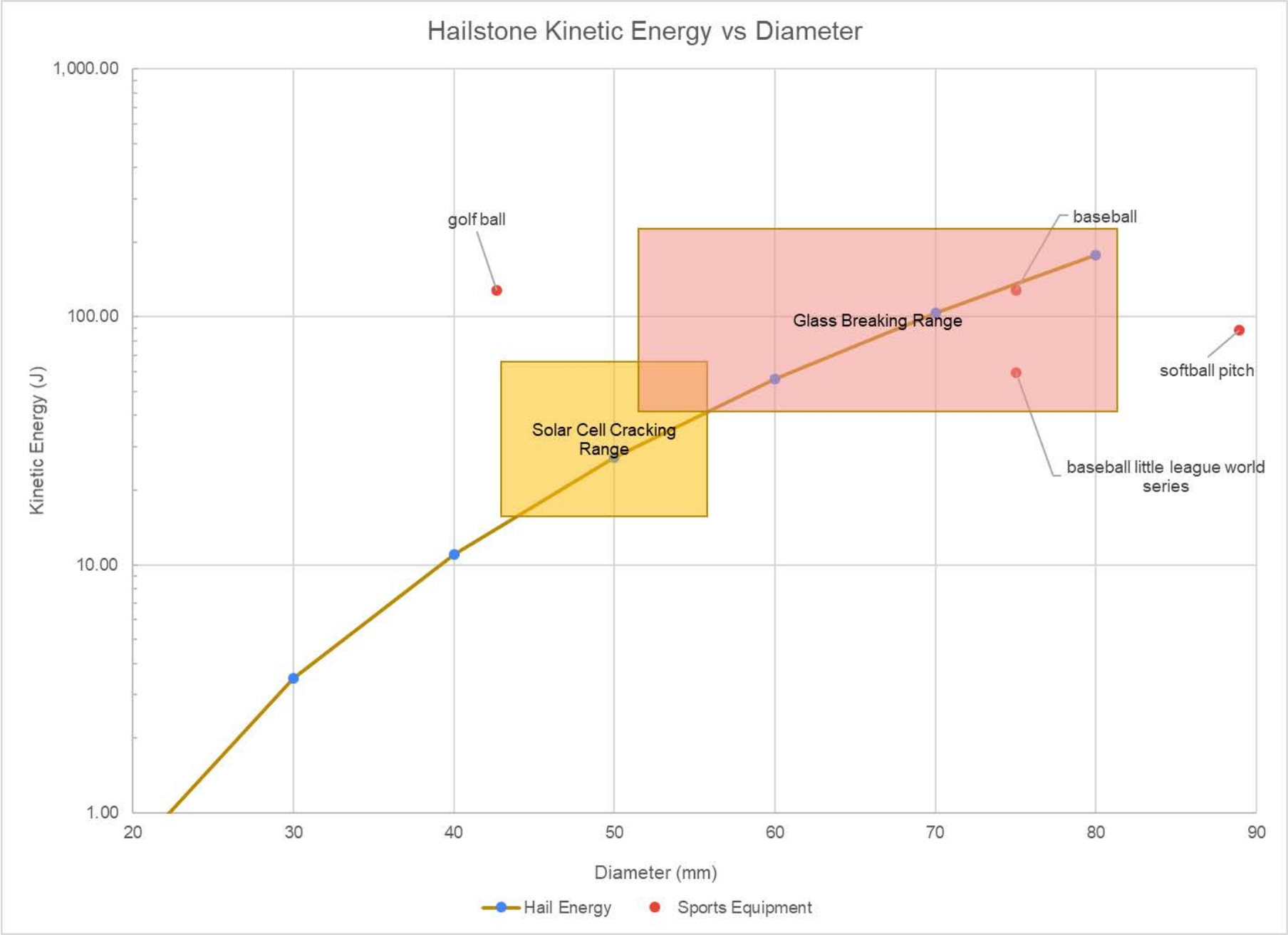
Natural Behavior of Hail Balls



Reference: VKF, Association of Public Insurance Companies Test Specification No. 00a.

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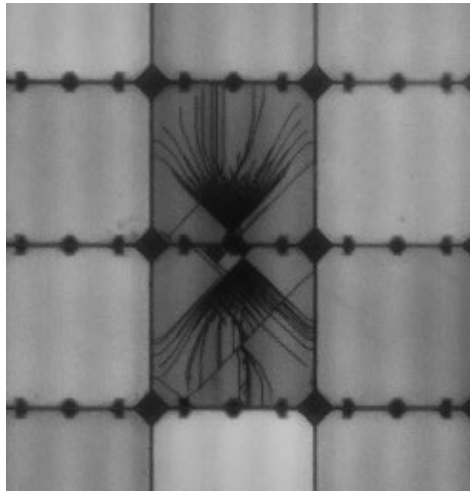
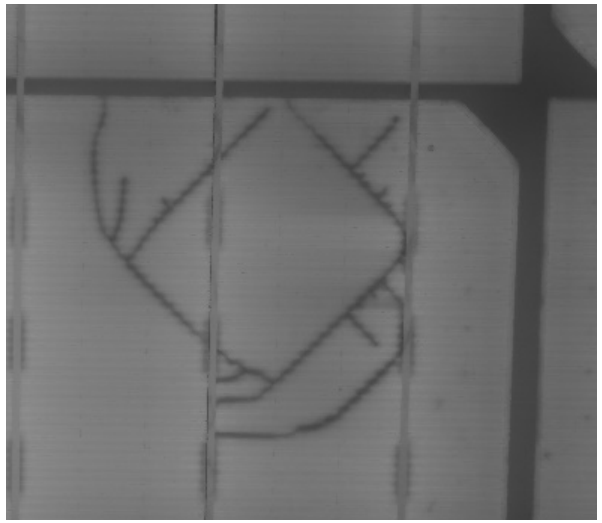
Glass/Polymer VS Glass/Glass vs Modules

- More Internal Damage
- More Potential for Performance Impact
- 100% Testing by EL Required?

- Less Internal Damage
- Less Potential for Performance Impact
- More Glass Breakage – Back and Front
- Is Only Sample EL needed?



Typical Glass/Polymer Hail Strike Damage



Typical Glass/Glass Strike Damage

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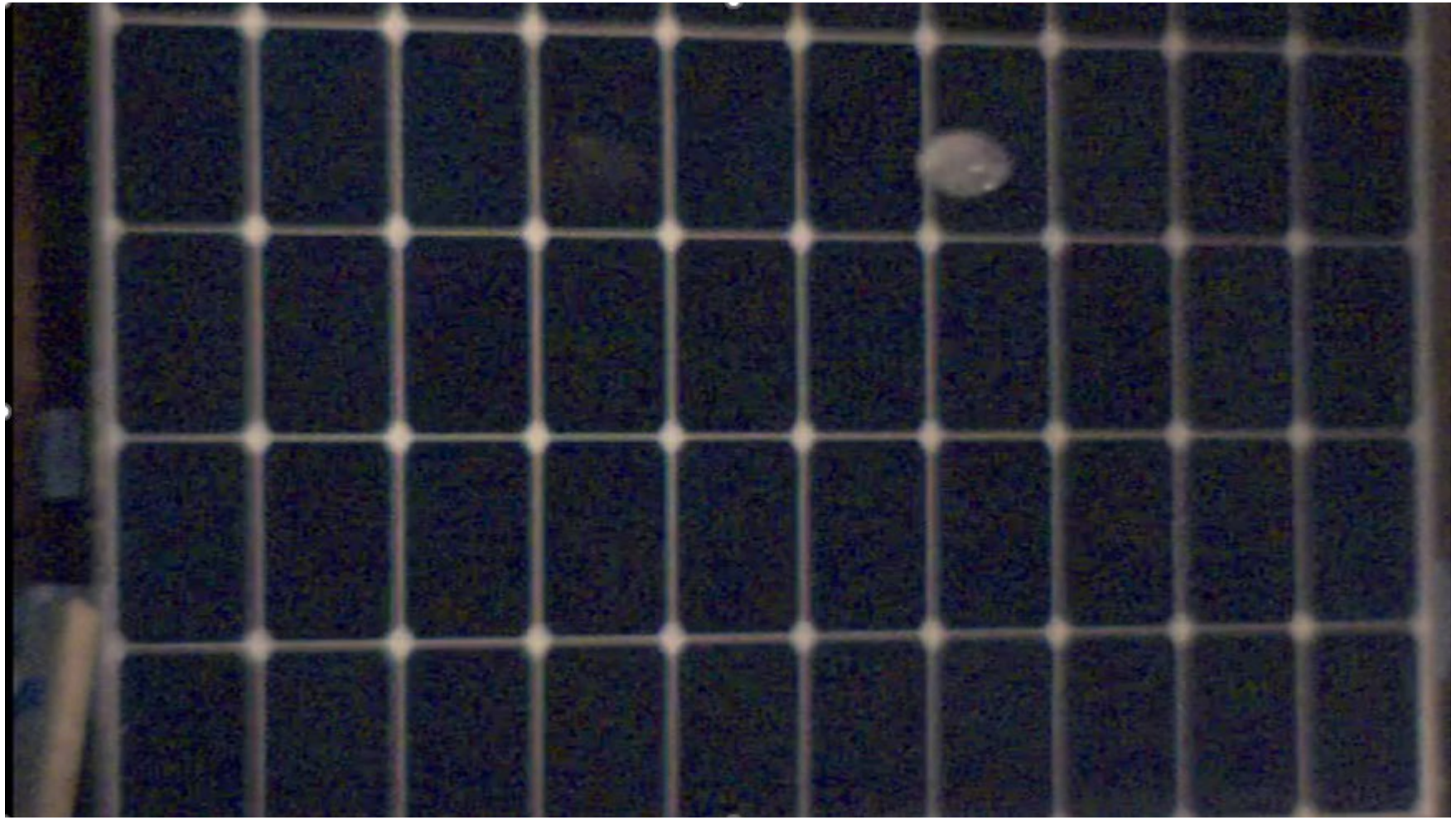
Emulating Hail Damage in the Lab

- 2” Hail Ball
- 31 Joules
  - Threshold to Cell Cracking
  - Performance Impact



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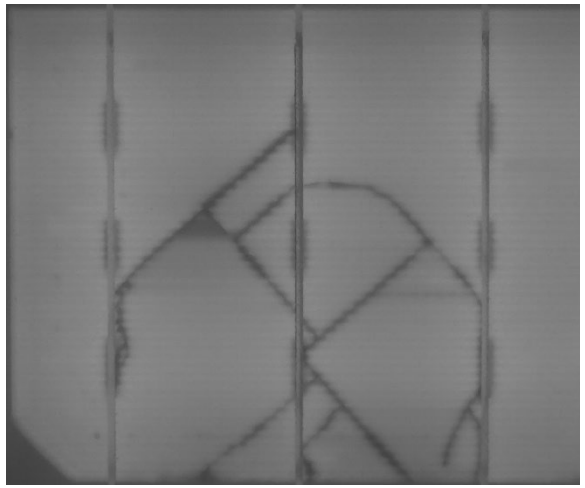
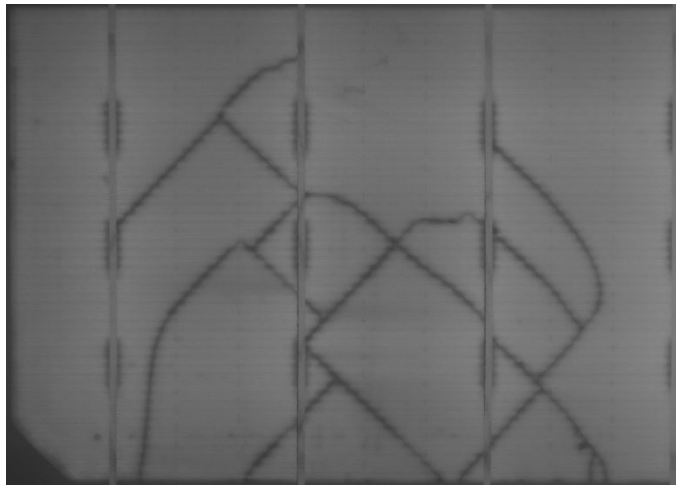
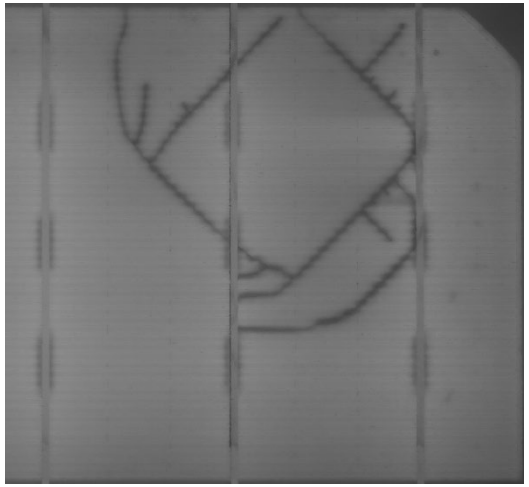
Internal Hail Damage on Glass/Glass

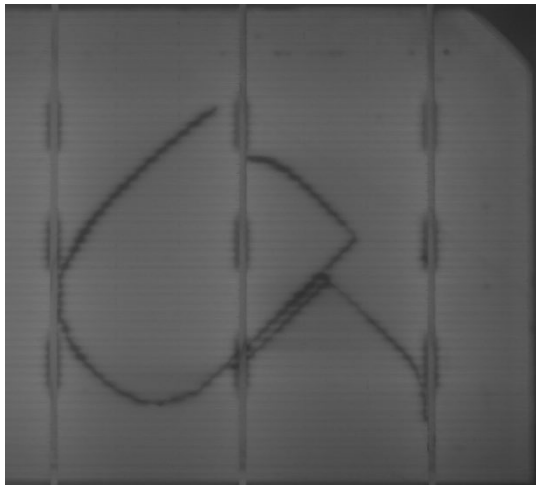




Novel Crack Pattern

- An uncracked center
- The appearance of curved cracks that are short cracks changing direction at each gridline intersections
- More typical dendritic cracking coming from the center feature





In one detailed study of 901 EL images glass/glass modules:

- 10% had internal damage
- Of the internally damaged modules
  - 75% had these novel crack patterns
  - 93% impacted only 1 solar cell per module
  - They are not that damaged

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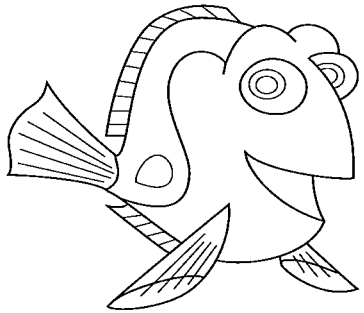

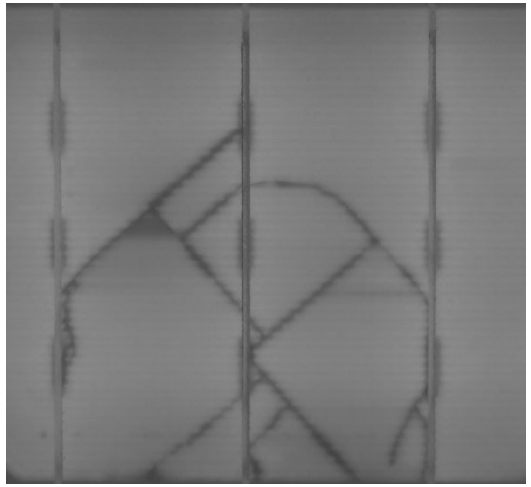

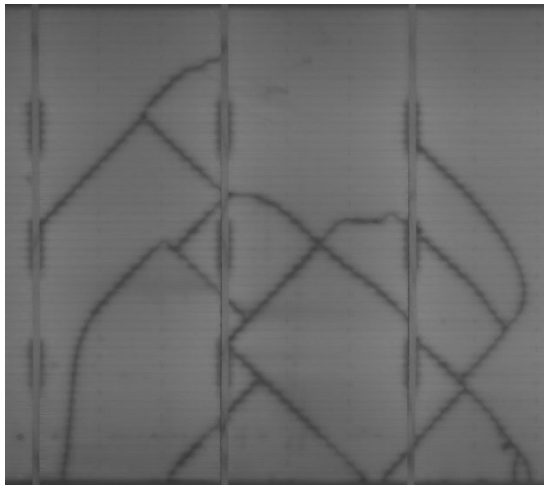

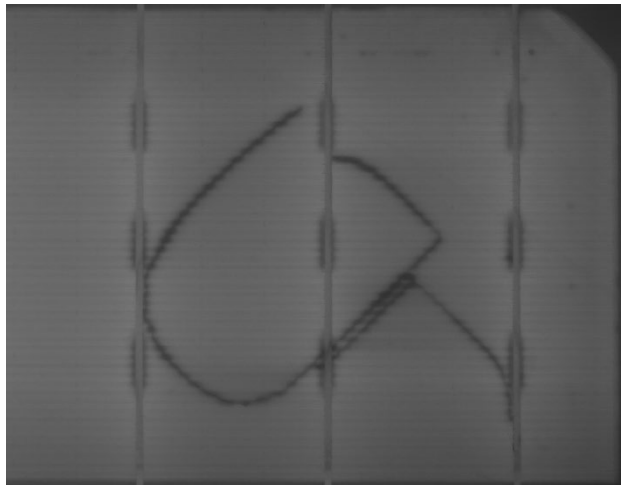

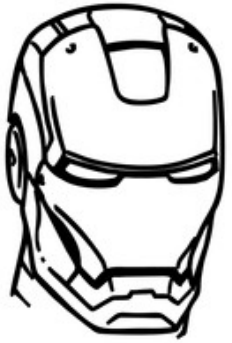

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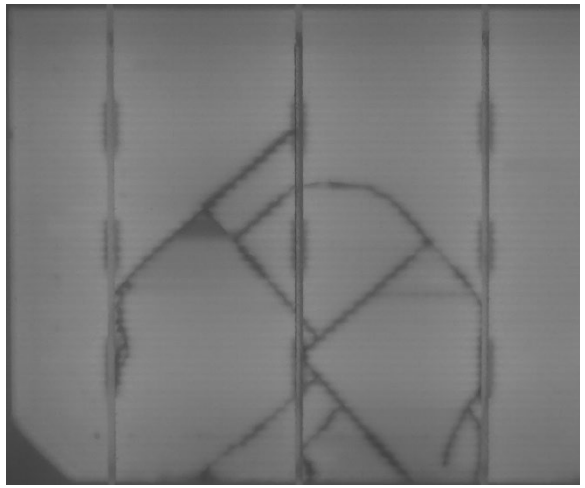
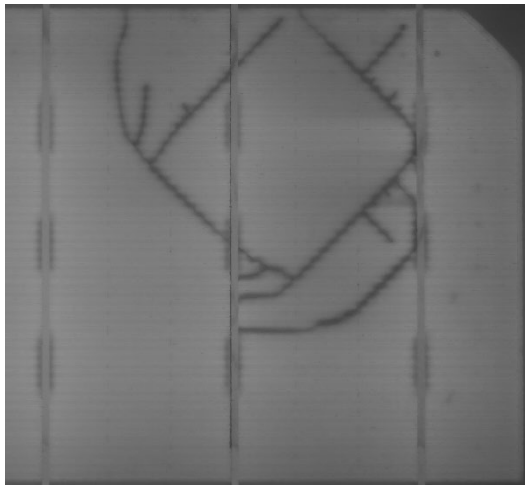
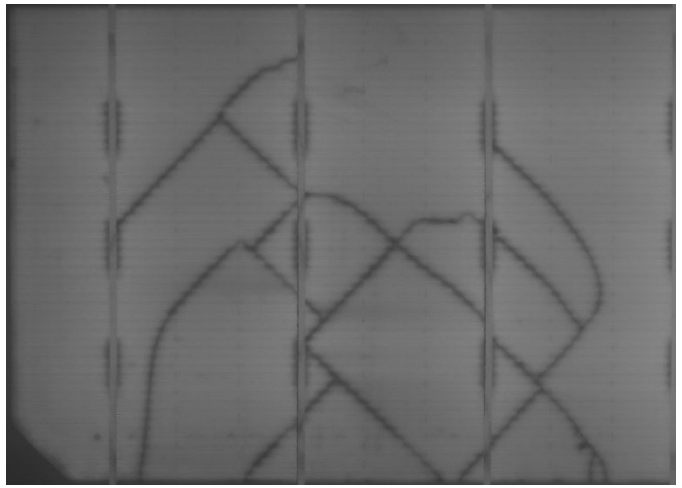
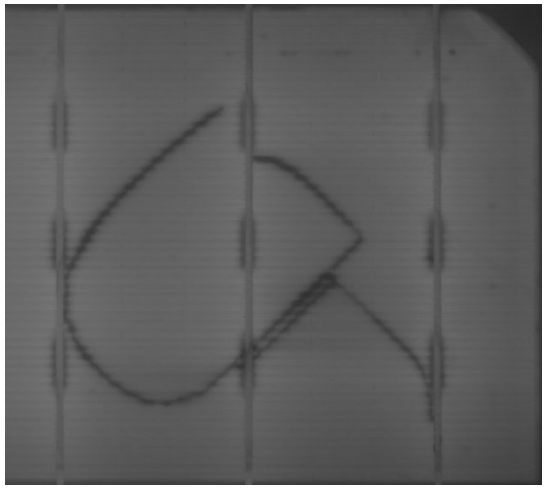




Halo Cracks





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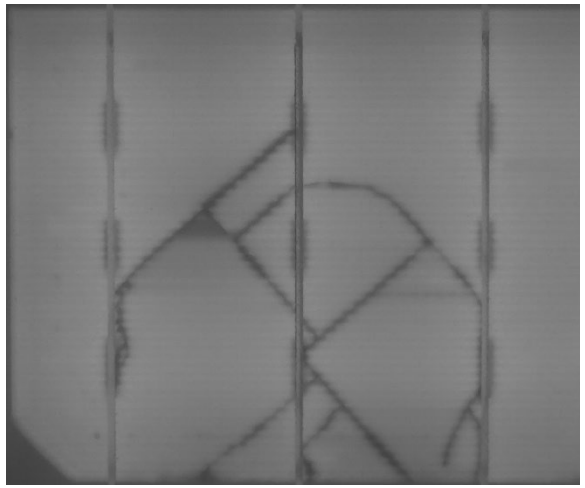
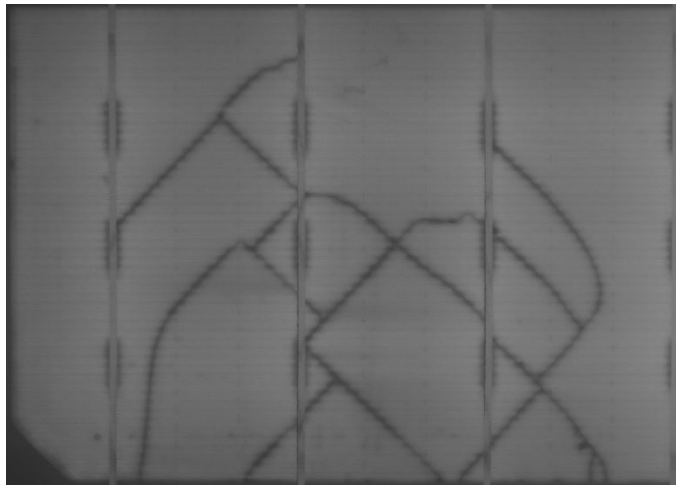
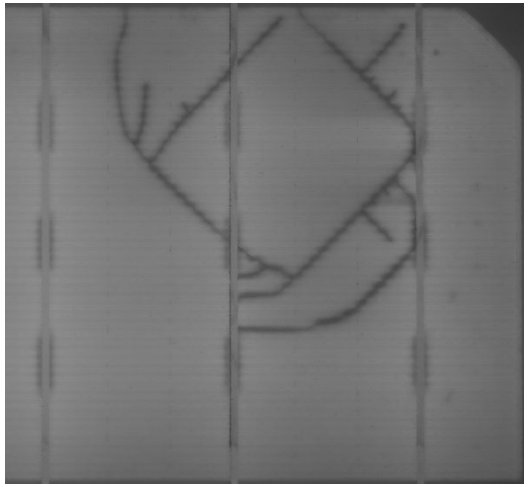
Internal Hail Damage on Glass/Glass

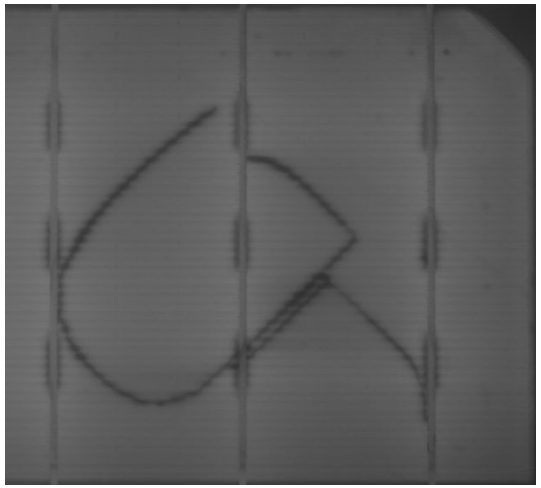




Novel Crack Pattern – Halo Cracks

- Can Internal Damage on glass/glass modules be considered benign?
- Will visual inspection alone be sufficient to remediate a site hit by hail?





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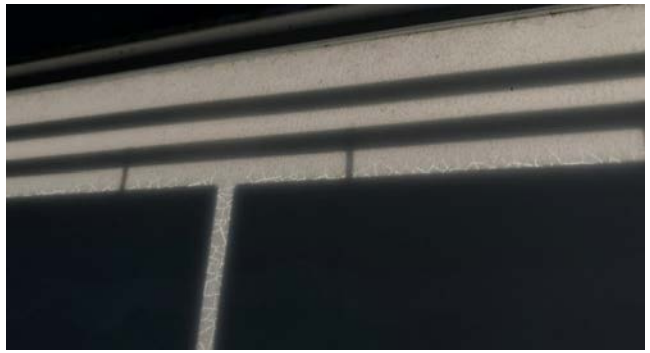
Field Testing and Results

Ranging from Practical to the Esoteric



2024 Poster on Inner Layer Cracks

- How do you get samples from the field to the lab?
  CEW Sample Crate – Simple and Inexpensive
- How do you determine bifacial module degradation rates?
  Testing Bifacial Modules in the Field
- Can hail do internal damage to glass/glass modules?
  Sadly, yes. But there could be a silver lining
- How do you find a ground fault?
  Partial Immersion Wet Insolation Test

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Ground Faults

Nemesis of the OM Team
Work when the Modules are Wet

Set up Wet Insulation Testing in the Field

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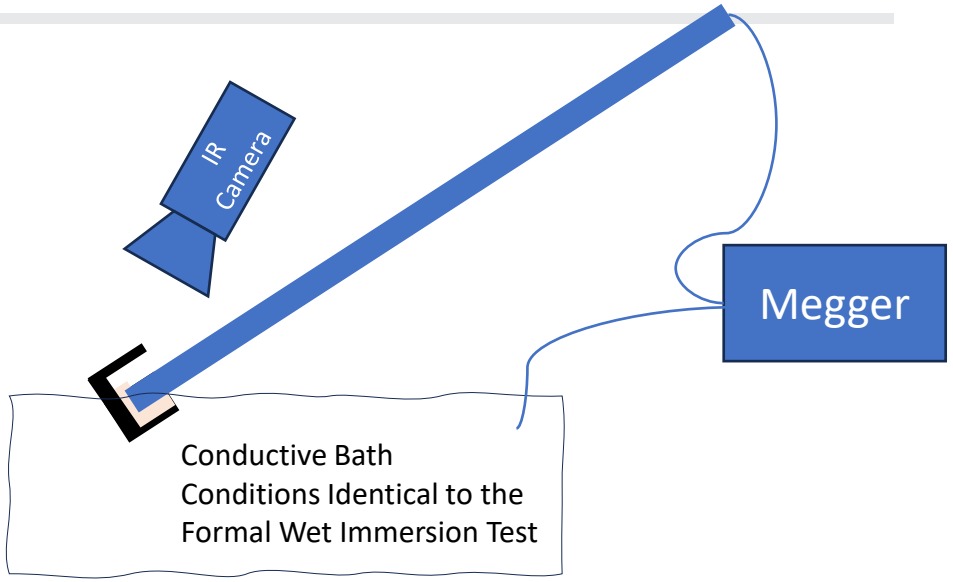
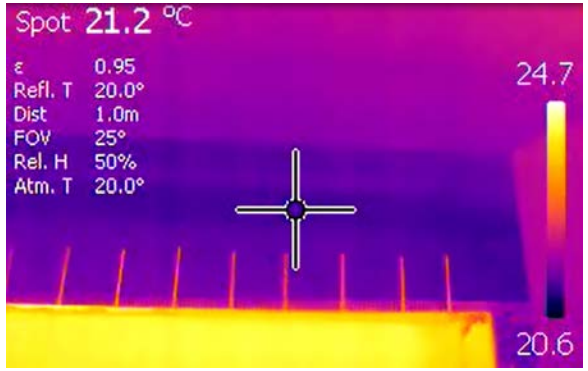
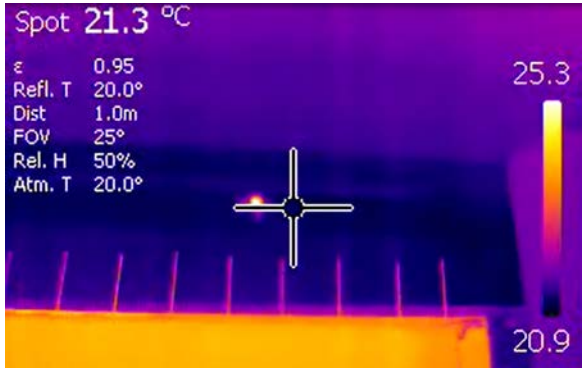
Partial Immersion Wet Insulation Test

Utilize the local heating produced by the Megger to identify the fault!
Localize the defect with an IR camera in moments.

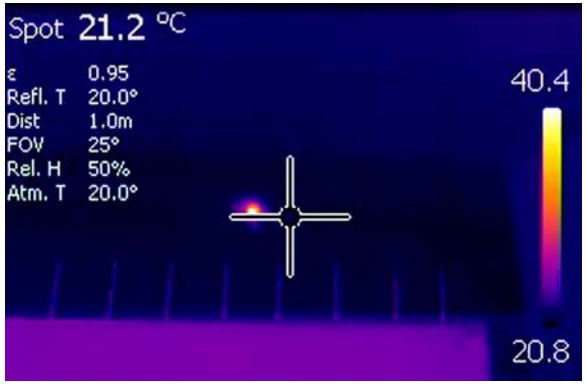




Start



7 Sec



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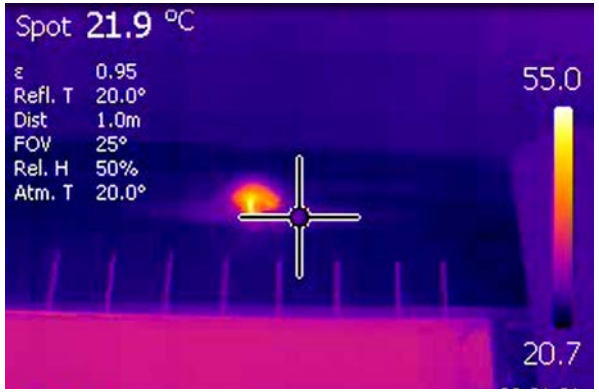

20 Sec

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ENERGY WORKS

Core Energy Works' Experience with Field Testing Modules

- Metrics

  >450 Sites Visited
  ~50,000 Field IV Measurements
  ~75,000 Field EL Images

- Core Expertise is Module Performance and Reliability
- OM and PM Locally
- Combiner Box Testing
- Inverter Evaluations
- IR Imaging by Drone

jim.rand@coreenergyworks.com • 610 416 7771
mason.reed@coreenergyworks.com

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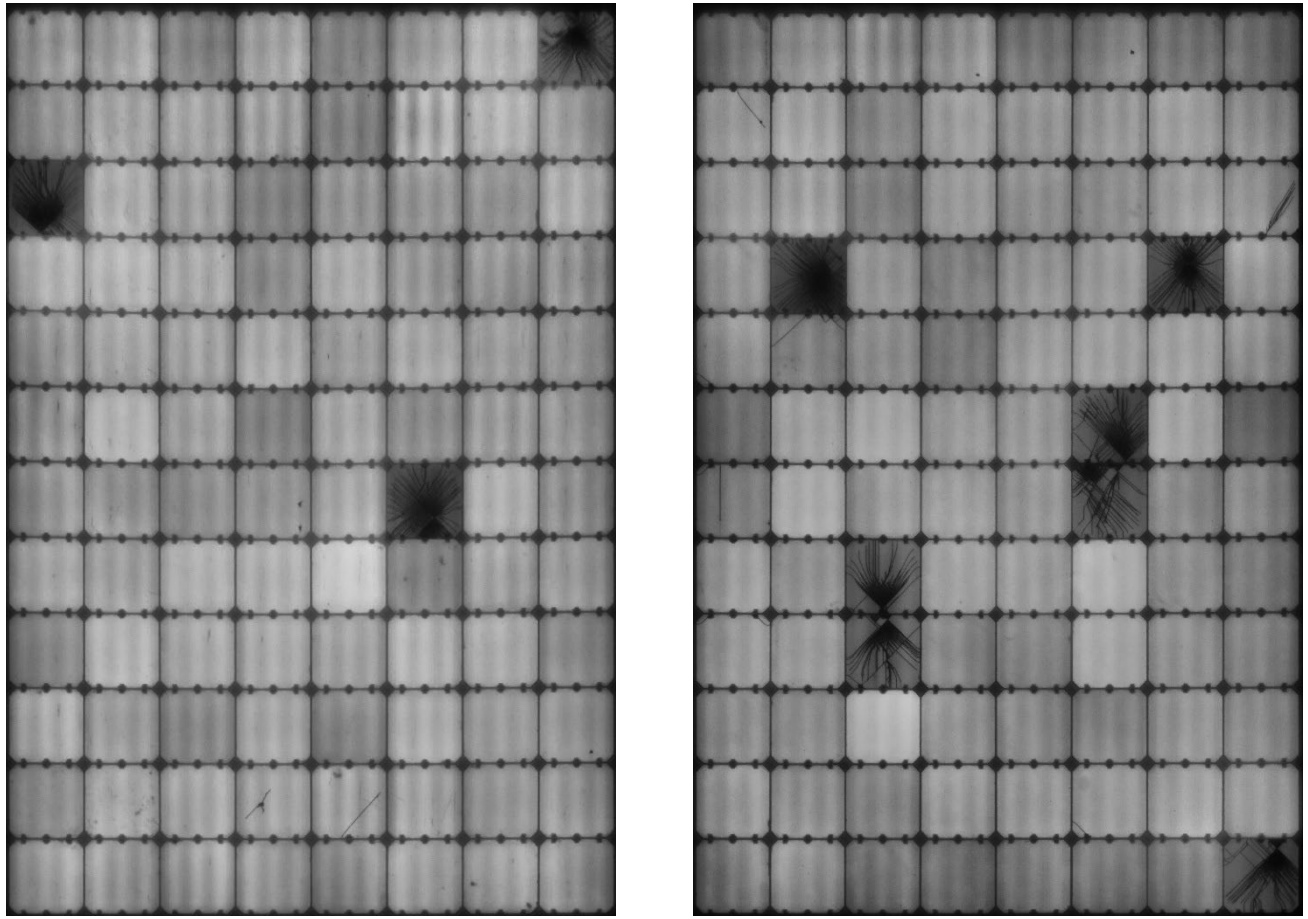
El Images & Classification

Typical Glass/Polymer



“Storm Damage”

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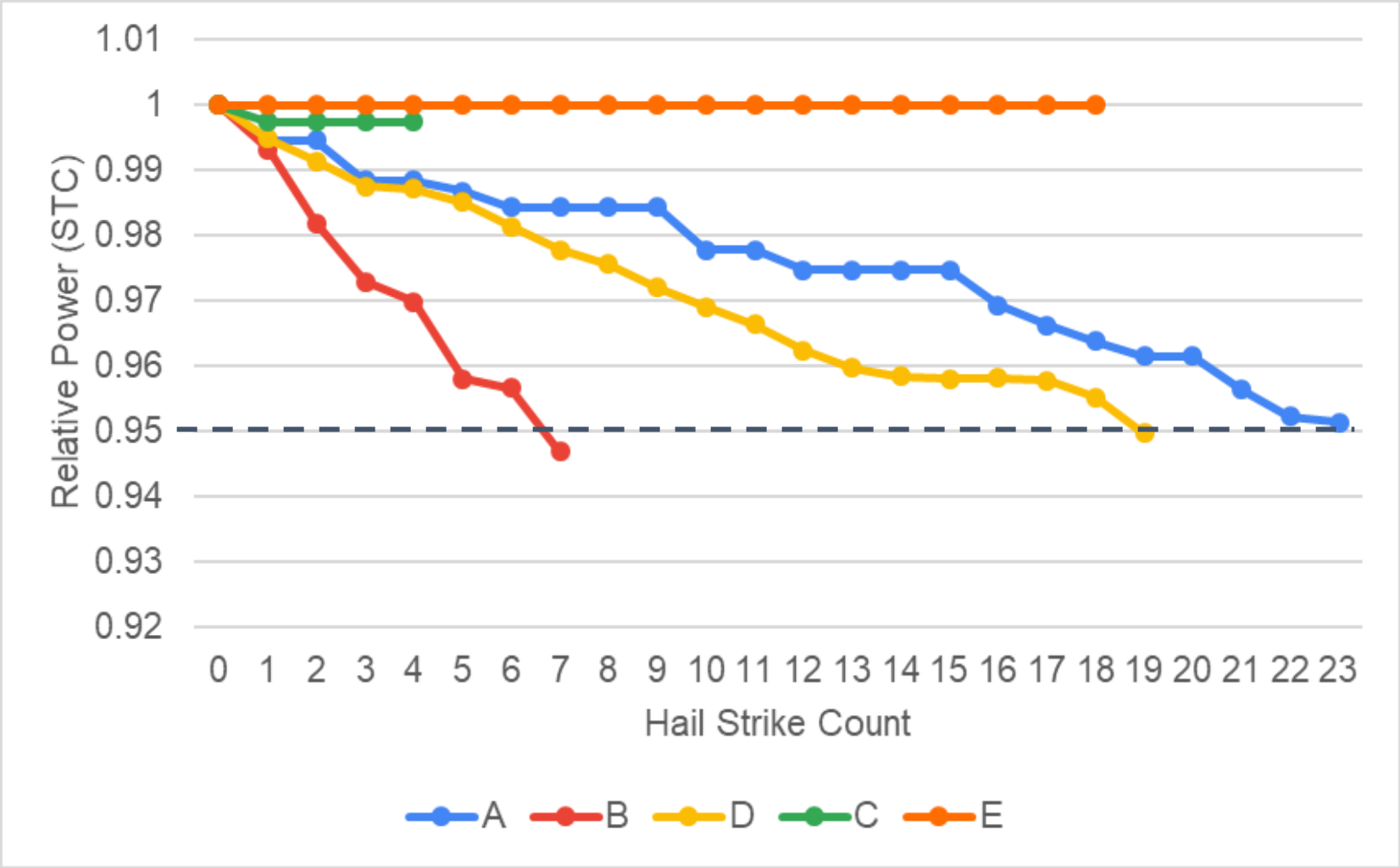
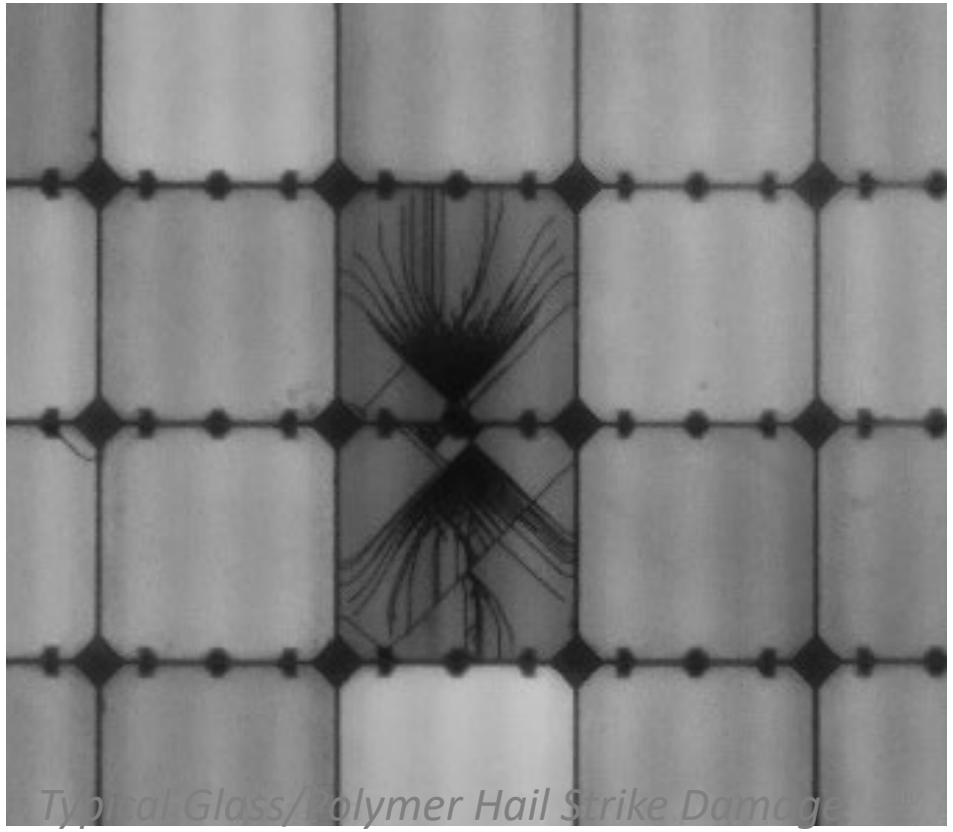
Impact of a Hail Storm on Performance

All Glass/Polymer



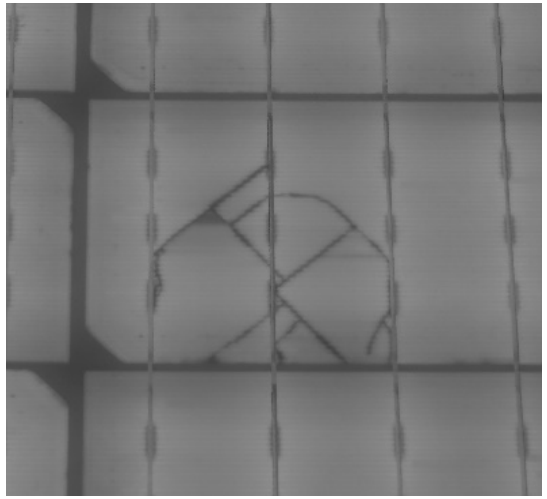
Internal Hail Damage on Glass/Glass

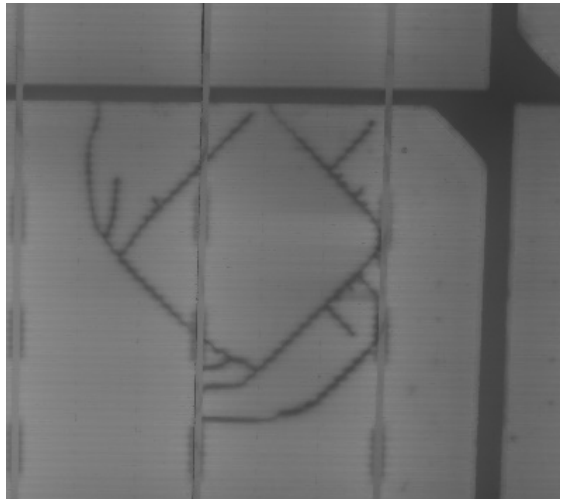
Typical Glass/Polymer Hail Strike Damage



Typical Glass/Polymer Hail Strike Damage

Typical Glass/Glass Strike Damage





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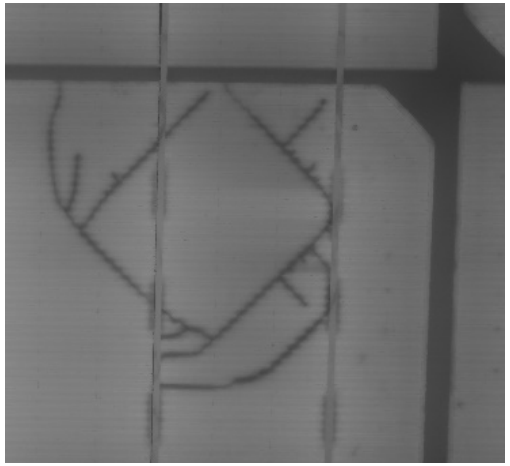
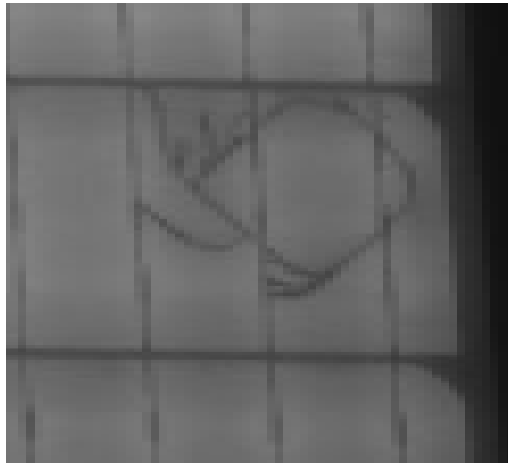
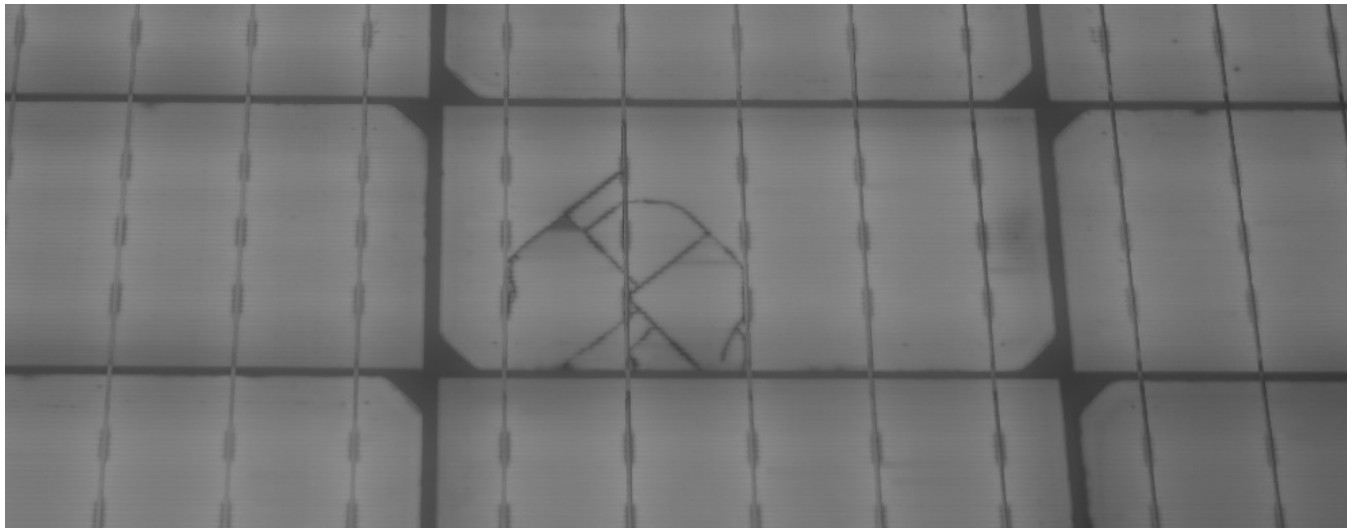
Internal Hail Damage on Glass/Glass

- An uncracked center
- The appearance of curved cracks that are short cracks changing direction at each gridline intersections
- More typical dendritic cracking coming from the center feature







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WHEN TRUST MATTERS

Notes from the trenches

Observations from DNV site visits

Penny Ladner, April Jeffries, Henry Hieslmair

04 March 2025

Introductions

Penny Ladner background

- Was construction manager on solar and wind projects
- Performing construction oversite and site visits since age 18
- 73 site visits while at DNV

Purpose of site visits

- Construction: Monitor construction progress, quality, project status, often for verification of reaching milestones (MC, SC)
- Operational: Verify quality and operational practices, often for due diligence for Project M&A or troubleshooting underperformance

Goal of this talk

- To raise awareness of construction quality issues

About DNV

DNV is the world's largest independent energy and renewables advisory firm.

We have over 2500 energy experts.

More than 1000 are focused on renewables.

DNV

Primary issue: Inexperienced labor

- Unskilled/inexperienced labor is a widespread problem
- Inadequate training and quality control at sites
- Poor construction undermines all upstream reliability and quality efforts
- Many pushing towards automation because of this problem

Poor cable management

Finding:

- Cables resting on top of the rotating tracker gear drive shaft
- Cables rubbing against a pile

Risk:

- **Major safety risks** as cable insulation will wear; electrical hazards and potential faults and fires
- **Reduced availability**
- **Equipment damage**

Mitigation:

- DNV requests further inspections and locations to identify occurrences of dc cable dangerous practices including resting and crossing the driveline

Cables resting on tracker drive shaft

Cables rubbing against pile

Wrong polarity

Finding:

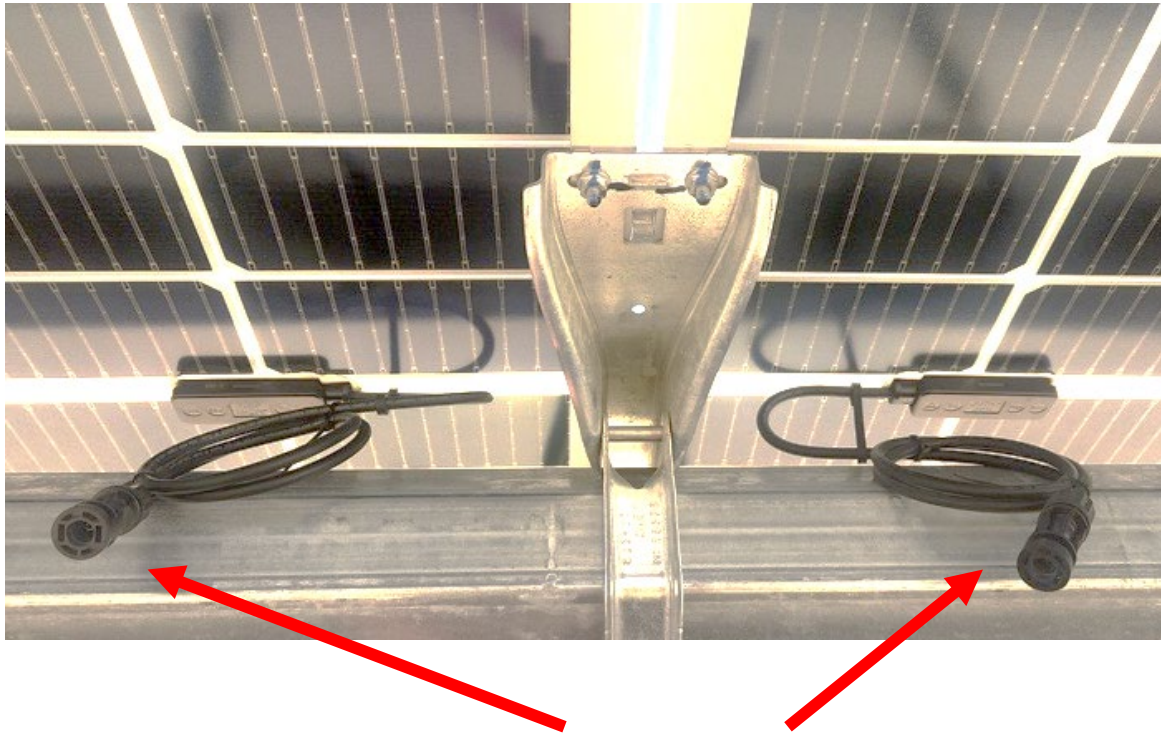
- Module crew installed modules on tracker with arbitrary rotation leading to polarity mismatch

Risk:

- **Some may try to stretch cables to reach opposite cable connection**
- **Major safety risks**
- **Equipment damage**

Mitigation:

- Had to review all modules, remove and reinstall reversed modules. Put the project $400k over budget and 2 weeks behind



Same polarity

Over-excavation around piles

Finding:

- Over trenching at piles due to grounding rings. Observed deflection and twisting of the piles
- Damaged due to excavation equipment

Risk:

- **Equipment damage:** unstable foundation for arrays
- **Structural integrity compromised**
- **Tracker downtime**
- **Schedule delay**

Mitigation:

- Re-compaction may be possible but additional piles may be necessary to reinforce

Over-excavation around inverter pad

Finding:

- Over excavation around inverter pad

Risk:

- Equipment damage: unstable foundation for inverter pad, damage to inverter
- Reduced availability

Mitigation:

- Re-compaction

Missing or damaged J-box covers

Finding:

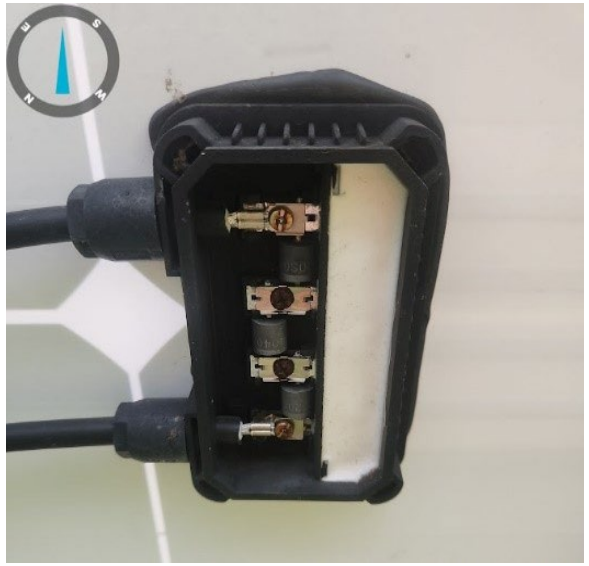
- Missing J-box covers for over a year due to costs

Risk:

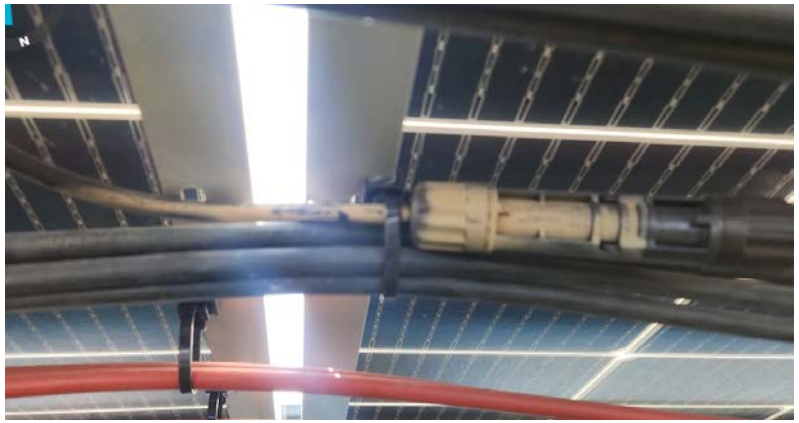
- Equipment damage
- Safety risk
- Ground fault
- Availability

Mitigation:

- Re-attach covers via manufacturer’s guidance



Water ingress in connectors



Finding:

- Staged modules were left sitting in standing water, thereby compromising the electrical components of the connectors

Risk:

- Safety
- Availability

Mitigation:

- Replace all connectors

Summary/Take Aways

- Need a good quality control manager on site
- Need good training program for workers
- Cost pressures cause shortcuts that become reliability issues
- Poor construction practices can undermine upstream quality efforts

- By the way: using union labor does not guarantee trained workers

Thank You

www.dnv.com

DuraMAT
Durable Module Materials Consortium

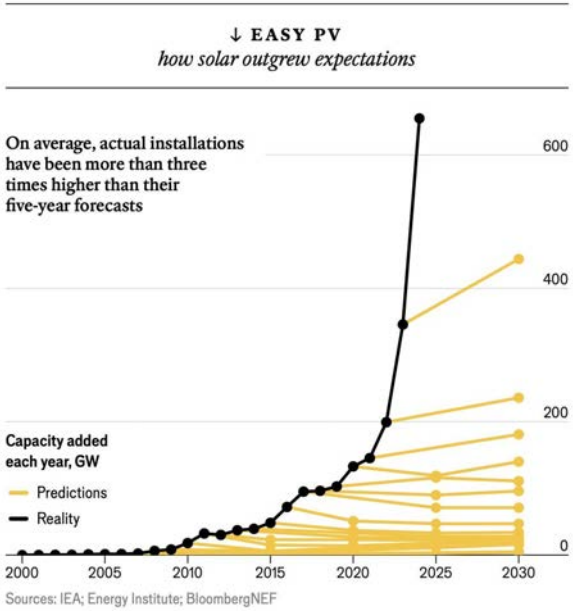
US PV Manufacturing and Deployment

The awesome Teresa Barnes

U.S. DEPARTMENT OF ENERGY
NREL
Sandia National Laboratories
BERKELEY LAB

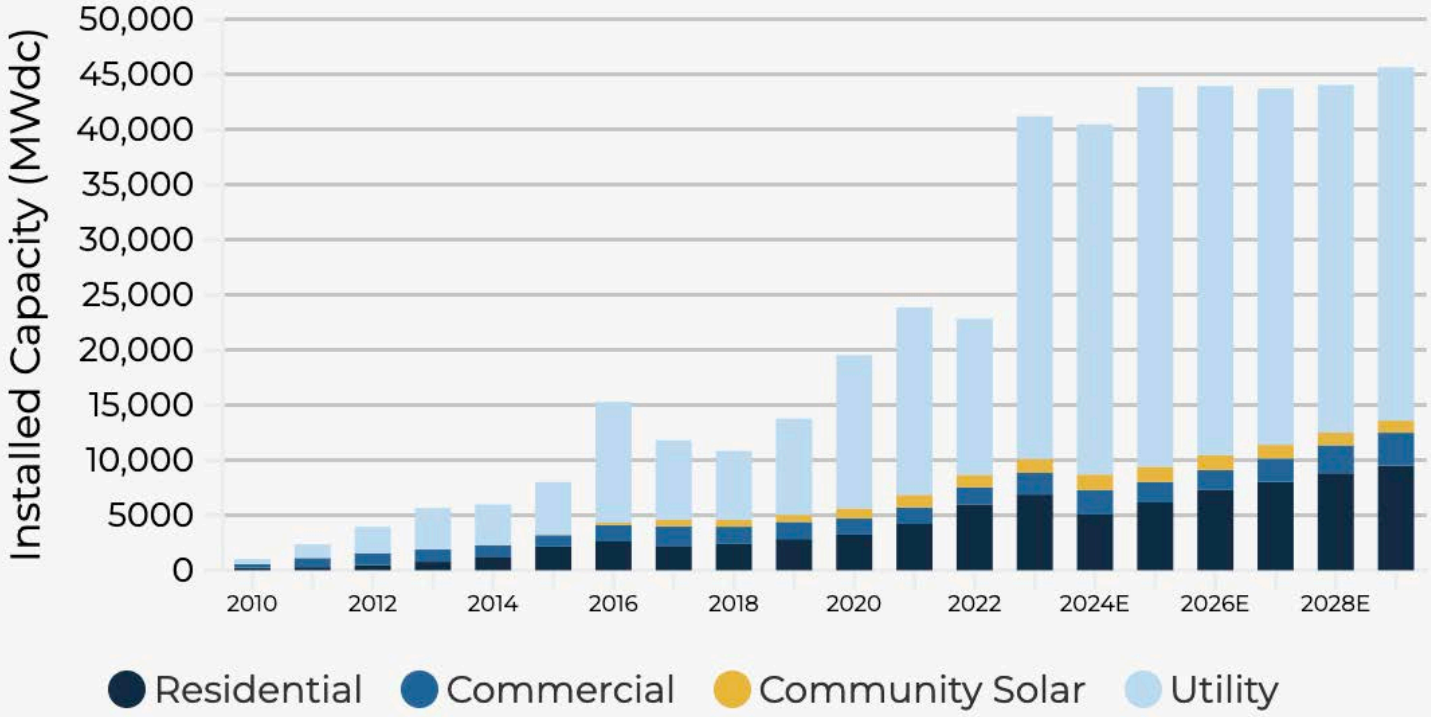
Predictions are hard

Global energy predictions ALWAYS underpredict PV deployment



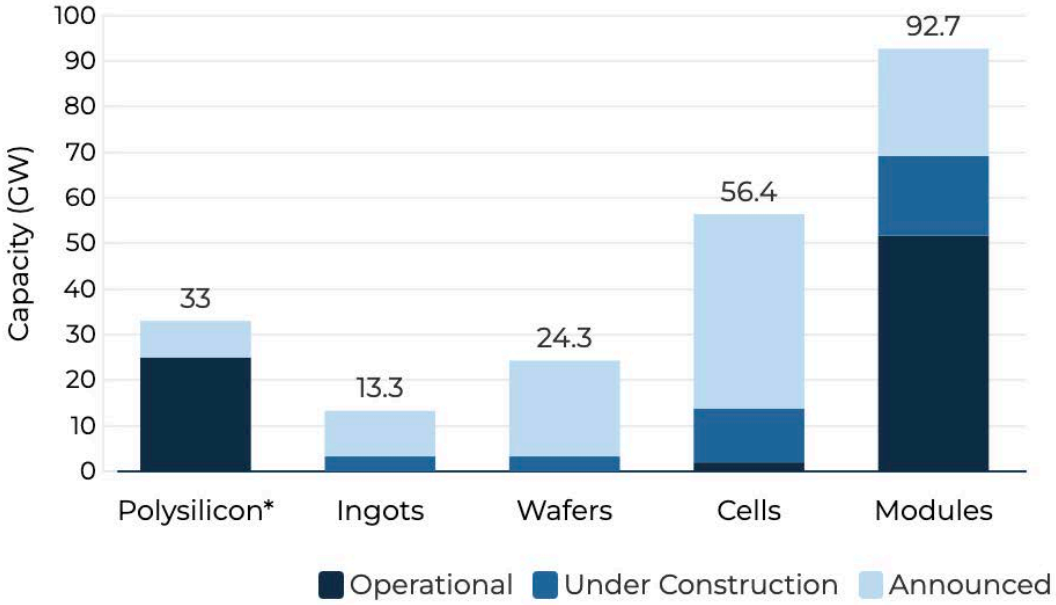
Economist comparison of IEA predictions vs. real deployment numbers

U.S. Solar PV Deployment Forecast



Source: SEIA/Wood Mackenzie Power & Renewables U.S. Solar Market Insight Q4 2024

Total U.S. Module Supply Chain Capacity
by Component and Status



Source: SEIA Solar and Storage Supply Chain Dashboard, February 2025
*Polysilicon values have been converted to GW using NREL's assumption of 2.0 g/W

SEIA Solar Energy Industries Association®

DuraMAT
Durable Module Materials Consortium

U.S. DEPARTMENT OF ENERGY

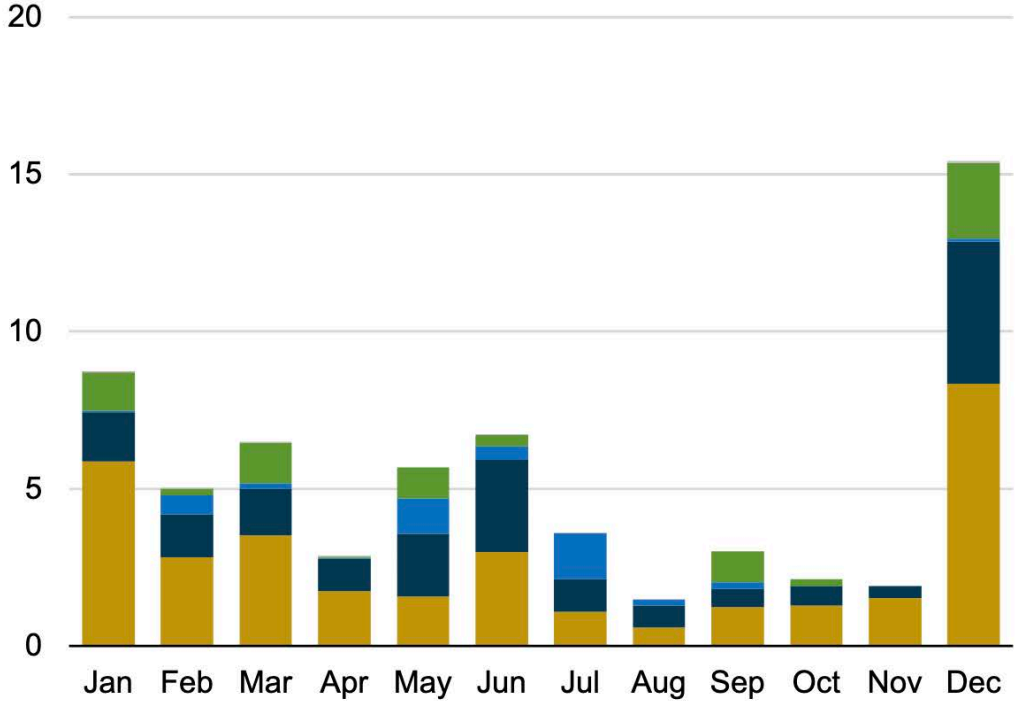
NREL

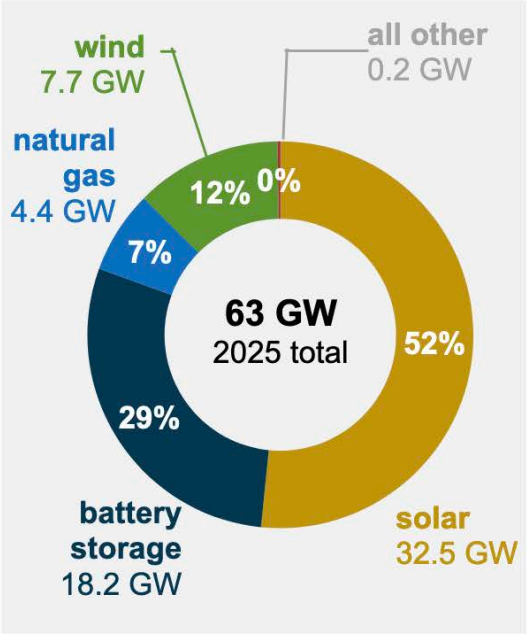
Sandia National Laboratories

BERKELEY LAB

U.S. planned utility-scale electric-generating capacity additions (2025)

gigawatts (GW)





Data source: U.S. Energy Information Administration, *Preliminary Monthly Electric Generator Inventory*, December 2024

PV Reliability Workshop | 4th -6th March 2025 | Denver, Colorado

HELIENE

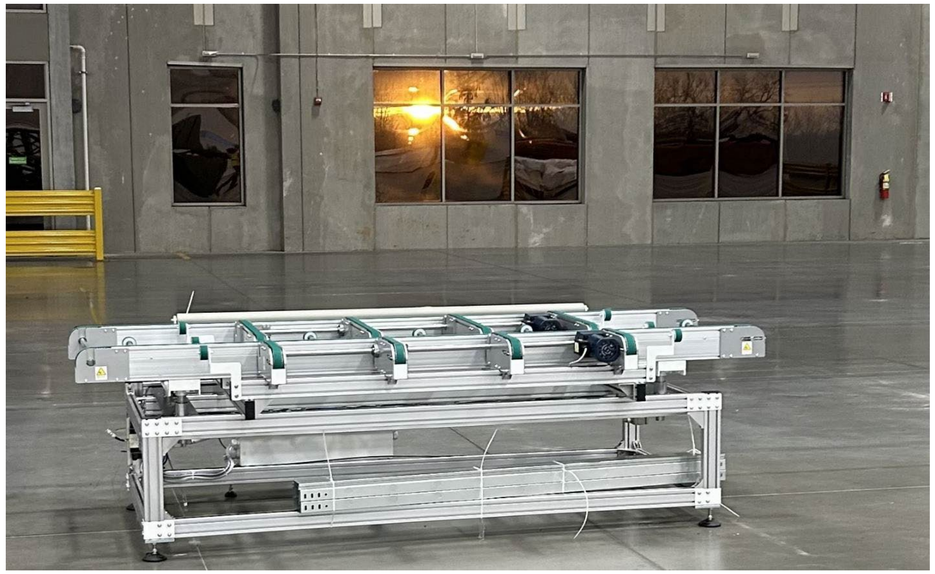
Sensitivity of Material Selection for Glass-Backsheet Modules

Suchismita Mitra, Dmitry Andronikov, Nadeem Haque
March 4th, 2025

About Heliene Inc., USA

Manufacturing in USA

- Line 1 - 300 MW/yr, Mountain Iron, MN
- Line 2 - 500 MW/yr, Mountain Iron, MN
- Line 3 - 500 MW/yr, Rogers, MN- Production from Q2 2025
- Potential Capacity of Rogers, MN facility upto ~1.6 GW/yr



The sun rising on the first conveyor placed for Line 3, Rogers, MN

Heliene Inc., Mountain Iron, MN

©Heliene

About Heliene Inc., Canada

Canada, Headquarters, R&D, Testing Facility

- Testing capability for large area modules (156HC, 144HC)
  - IV, EL tester
  - Mechanical Load, Frame Pull, Wet Leakage, High Pot, Reverse Current Overload, Hotspot, Cell tester, Gel content, PCT*, UVID*, Damp Heat**, PID**
  - Outdoor test set up
- Quality and Reliability of Existing materials
- R&D with new materials

**For mini-modules, **To be commissioned*

R&D Facility, Sault Ste. Marie, Canada

… and many more!

©Heliene

Growth of Solar Module Manufacturing in the US

Significant Increase

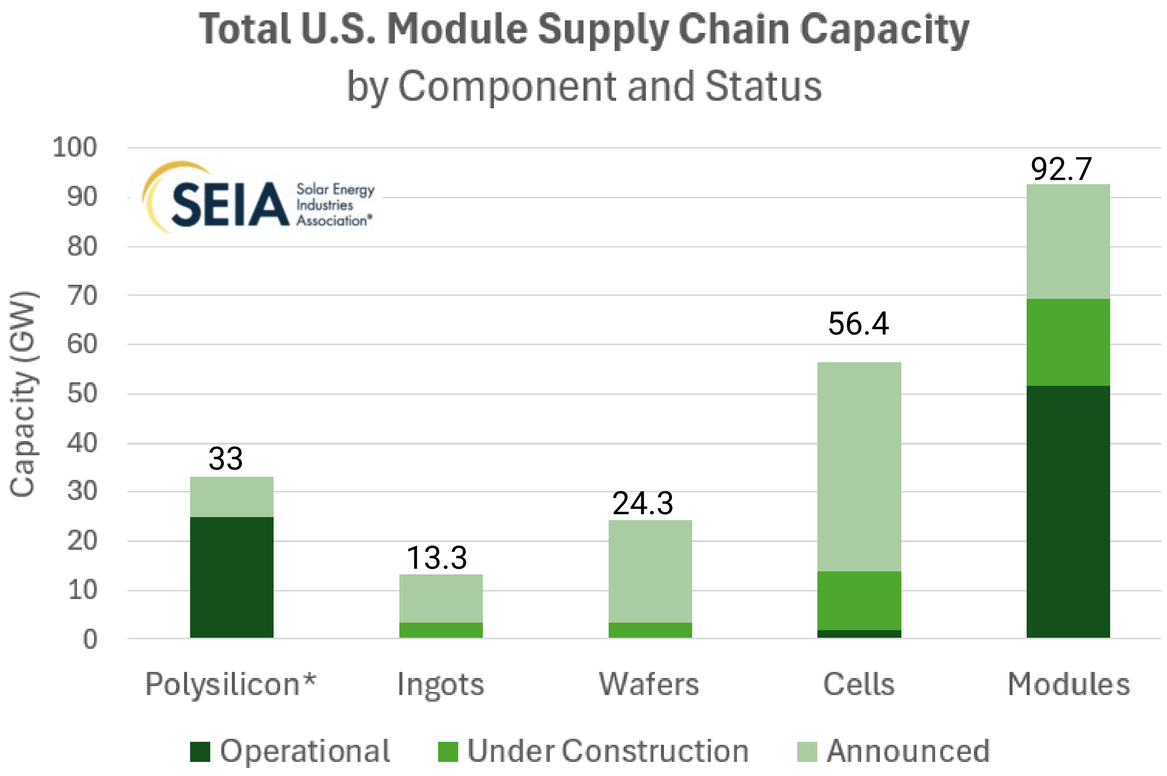
- Currently 51.7 gigawatts (GW) of domestic module manufacturing capacity

Domestic Manufacturing of Raw Materials

- Domestic production of critical materials such as backsheets, encapsulants, and solar cells
- This shift supports supply chain stability and reduces dependency on foreign sources

US Materials Already in Use*	US Sources Identified
Backsheet	Interconnects (Tabbing and Busbars)
Encapsulant	Potting Material
Frame	
Silicone	
Junction Box, Cable, Connector	
US PERC Cells	

*More sources being developed



Source: SEIA Solar and Storage Supply Chain Dashboard, February 2025
*Polysilicon values have been converted to GW using NREL's assumption of 2.0 g/W

©Heliene

Sensitivity of Materials in Glass-Backsheet Modules

Heliene focuses on efficient and reliable Glass-Backsheet (G/B) modules.

Glass Backsheet vs. Glass-Glass Modules:

- Glass-Backsheet modules are 12% lighter than Glass-Glass modules leading to easier handling
- Better PID & Hail performance, Better manufacturability, Lower Operating Temperature
- Glass-backsheet modules currently exhibit a higher percentage of domestic content compared to glass-glass modules, as identified through safe harbor calculations.

Reliability Data Gap:

- Absence of comprehensive reliability data for Glass-Backsheet bifacial TOPCon modules

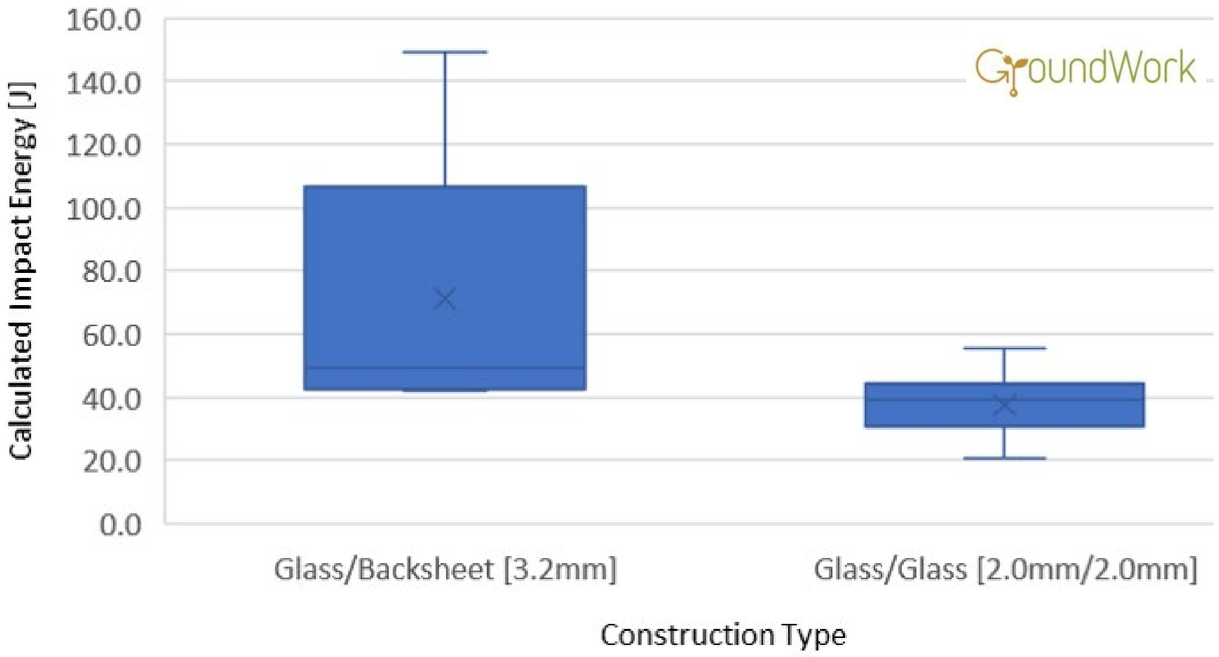
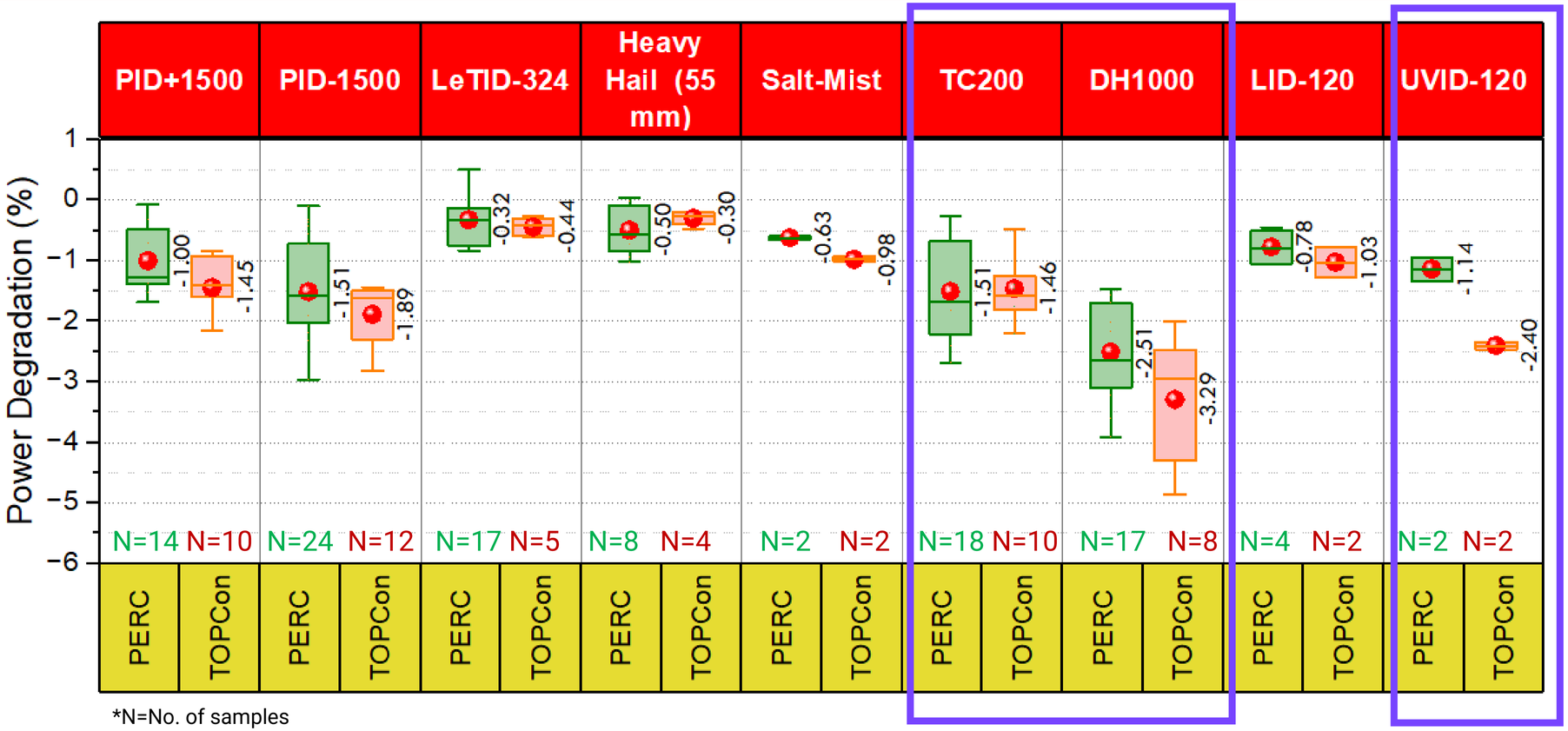


Fig. Impact Energy at Glass Failure
(Ref: CFV labs, Alburquerque, NM)

©Heliene

TOPCon & PERC G/B modules-A comparison



*N=No. of samples

- Comparable performance of PERC and TOPCON modules
- PERC ~10 busbars, TOPCon ~16 busbars: Difficult to manufacture with thinner busbars
- TOPCon sensitive to moisture: This makes it more important to select the correct materials

- LID 40 kWh: 3 cycles, total exposure 120 kWh
- PID +1500/-1500 V, 192 hours, 85 ℃, 85% RH
- LeTID 162 hours,75℃, Applied current (Isc-Imp): 2 cycles
- MLT 5400/-2400 Pa, 3 cycles
- Heavy hail: 55 mm
- Salt Mist: Method 6
- Data Source:
  - TUV SUD: 156HC, 144 HC (LID, PID, LeTID, MLT, Hail, Salt Mist), 132HC(LID, PID,LeTID), 108HC (LID, PID,LeTID, MLT)
  - PVEL PQP: 144 HC (PID, LeTID)
  - CFV 144HC (LID, PID)
  - Intertek: TC200, DH1000
- Red circles show the mean value
- Total number of modules tested :161

©Heliene

Bill of Materials (BOM) description

TOPCon Cells		Encapsulant pairs			Backsheets		
C1(F)	Foreign	PEv 1(F)	POE + Low acid EVA	Foreign	BS 1(F)	Kpf	Foreign
					BS 2(D)	Coating type	
			POE + Low acid EPE	Foreign	BS 3(D)	Laminated	

Baseline BOM

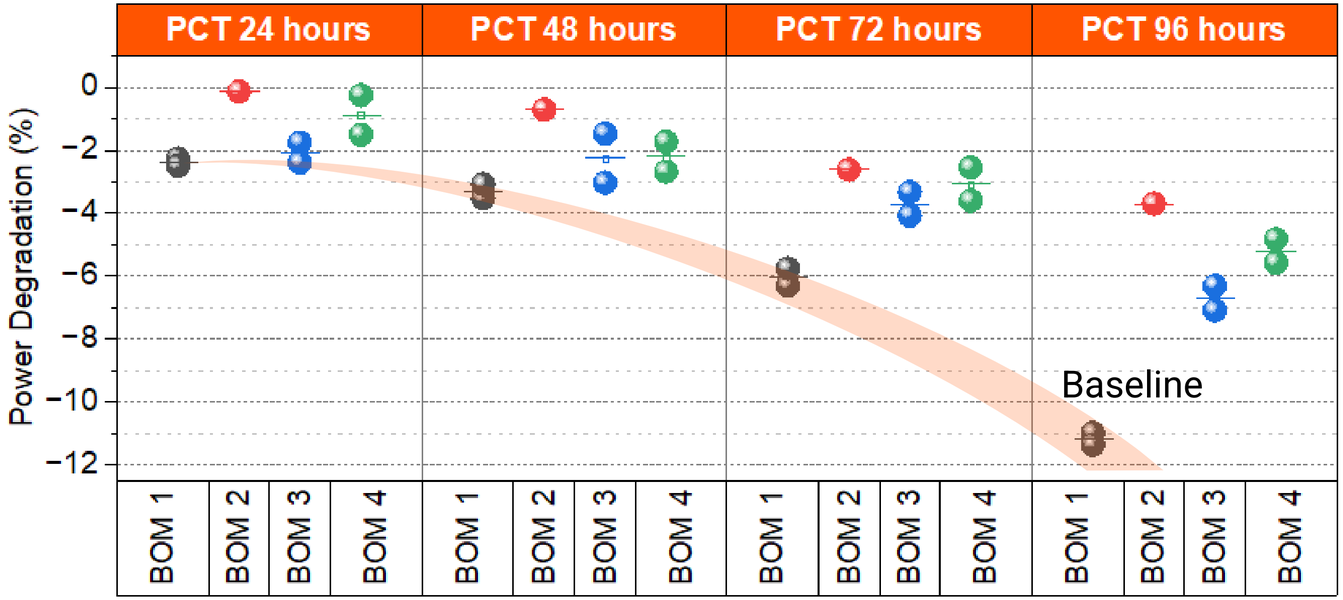
BOM 1: C1(F)+PEv 1(F)+ BS 1(F)

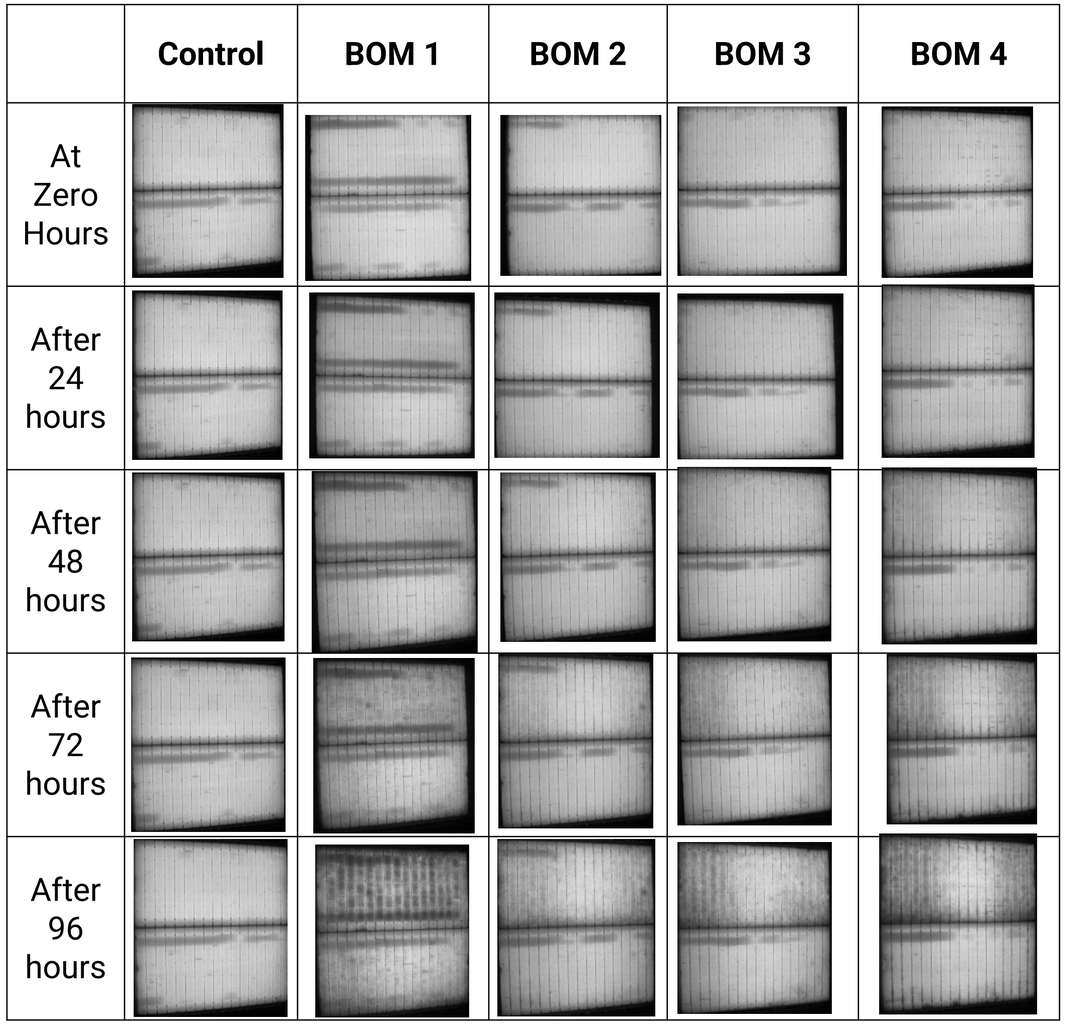
©Heliene

Sensitivity to Encapsulants

Pressure cooker testing (PCT) @120℃, 100% RH on mini-modules
~quick test for infant failures and material quality

BOM #	BOM Combination
BOM 1	
BOM 2	C1(F)+ PEv 2(F)+ BS 1(F)
BOM 4	C1(F)+ PEv 4(D)+ BS 2(D)





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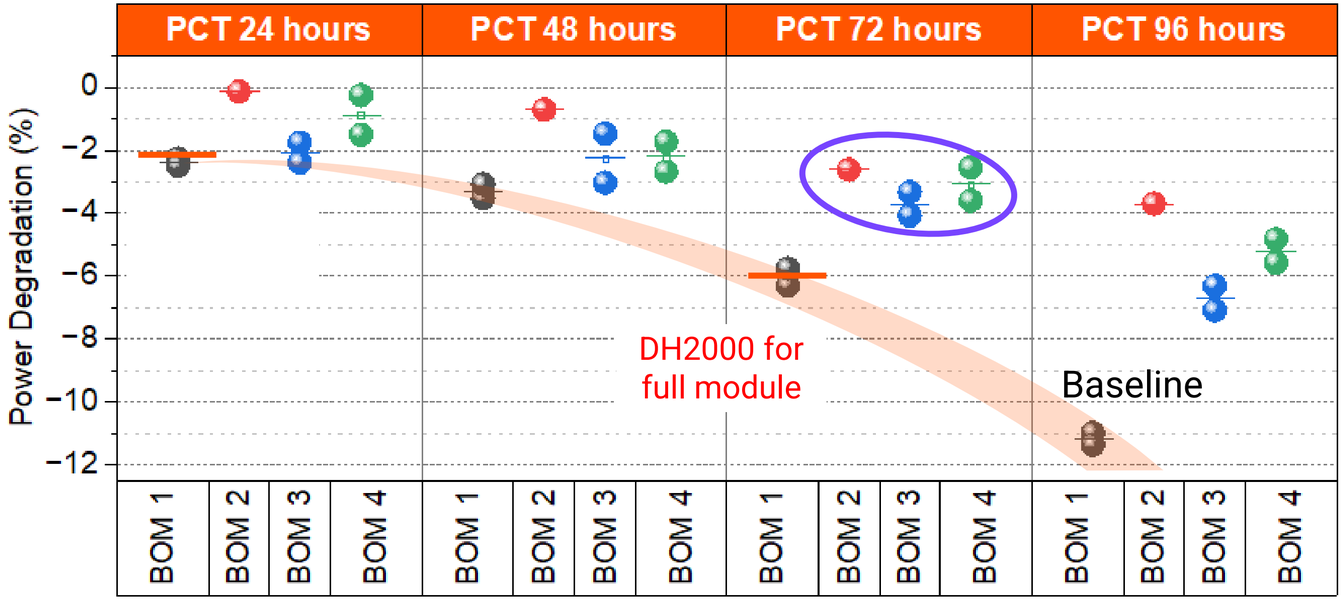
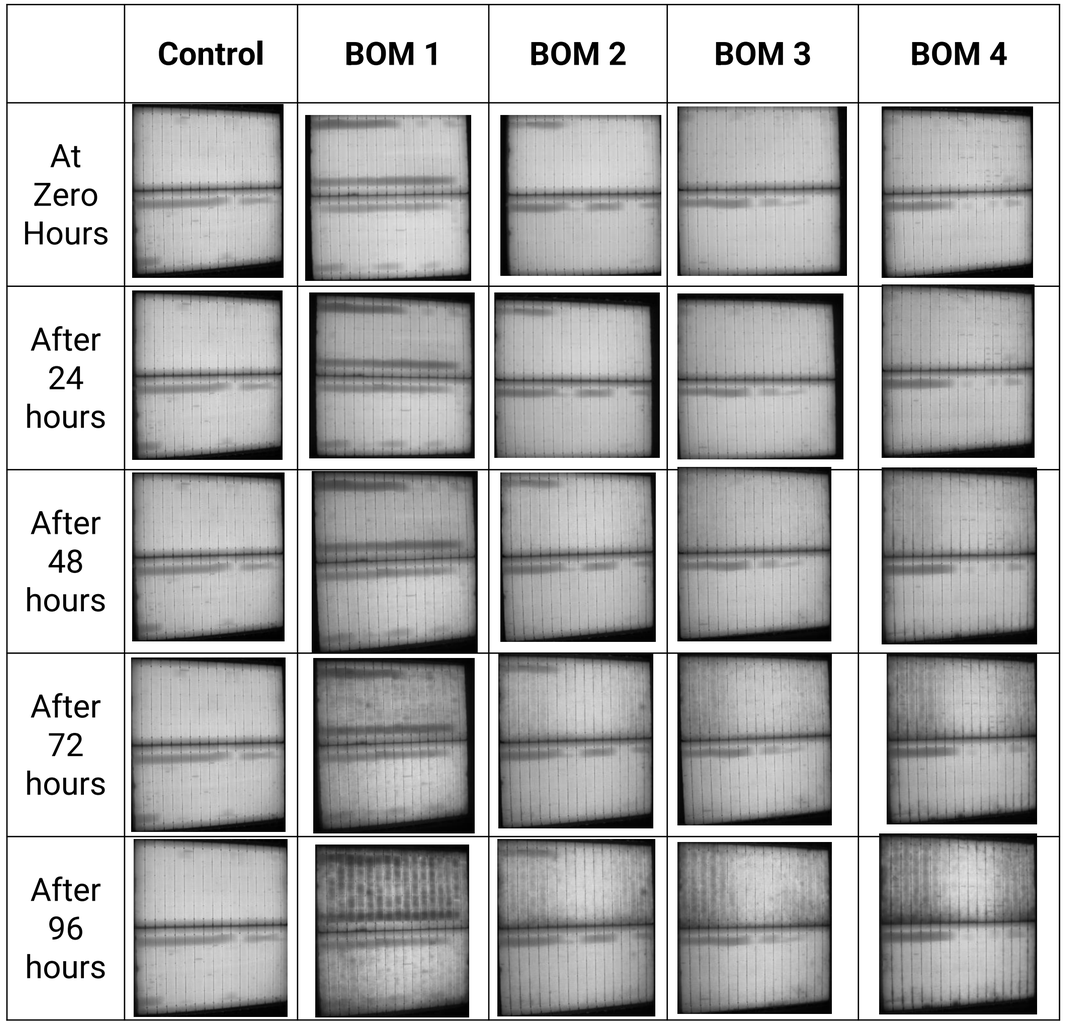
Sensitivity to Encapsulants

Pressure cooker testing (PCT) @120℃, 100% RH on mini-modules
~quick test for infant failures and material quality

BOM #	BOM Combination
BOM 1	
BOM 2	C1(F)+ PEv 2(F)+ BS 1(F)
BOM 4	C1(F)+ PEv 4(D)+ BS 2(D)



Combination of domestic materials performs at par with the materials from leading foreign manufacturers



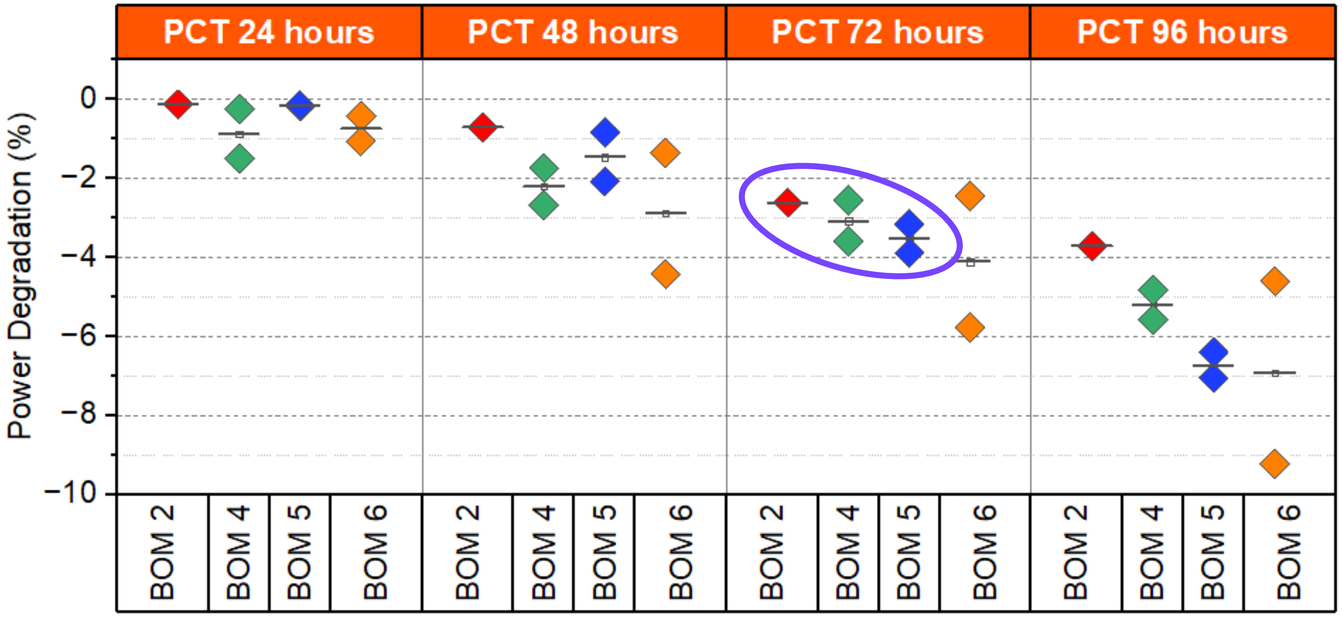
©Heliene

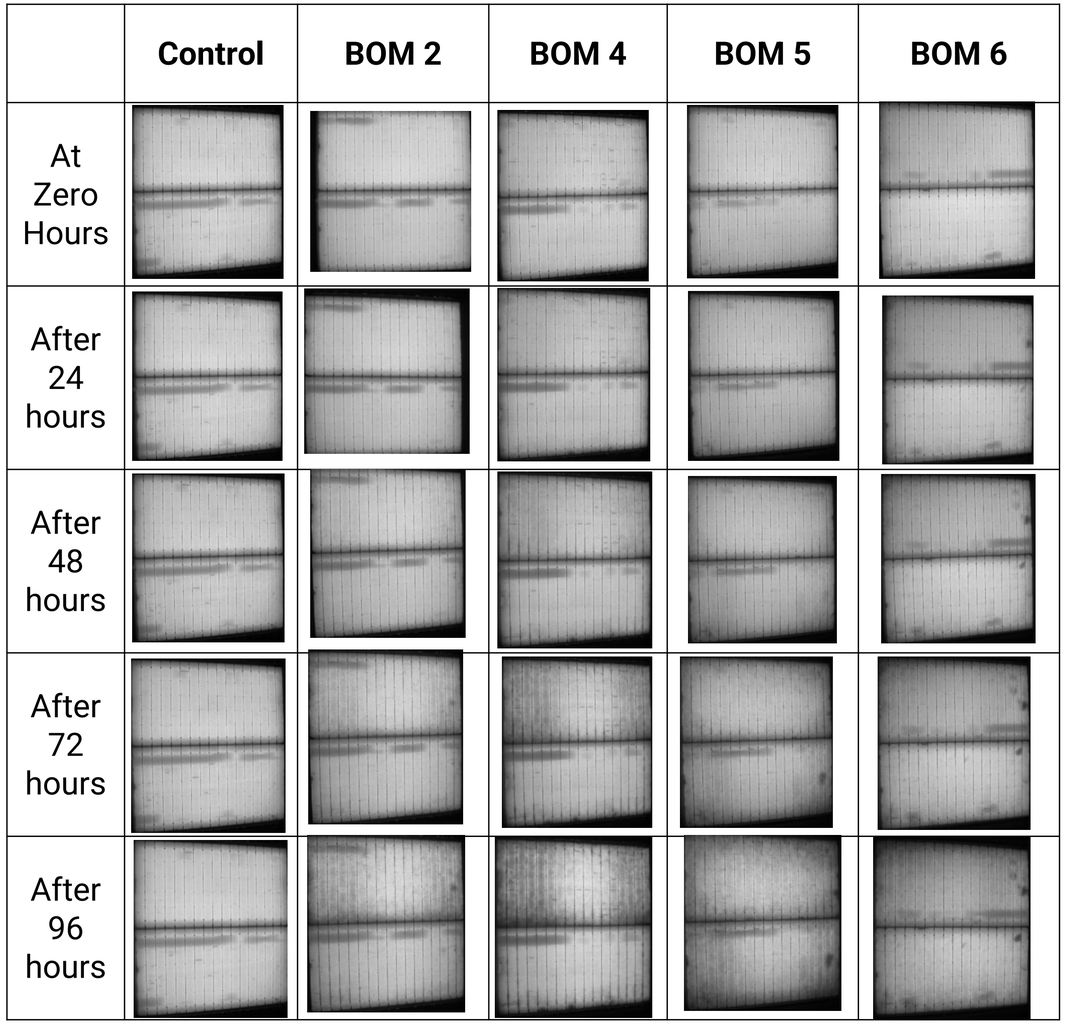
Sensitivity to Backsheets

Objective:

- PCT test with same encapsulant pair but different backsheet

BOM #	BOM Combination
BOM 2	
BOM 4	C1(F)+ PEv 4(D)+ BS 2(D):Coating
BOM 6	C1(F)+ PEv 2(F)+ BS 4(D):Co-extruded





©Heliene

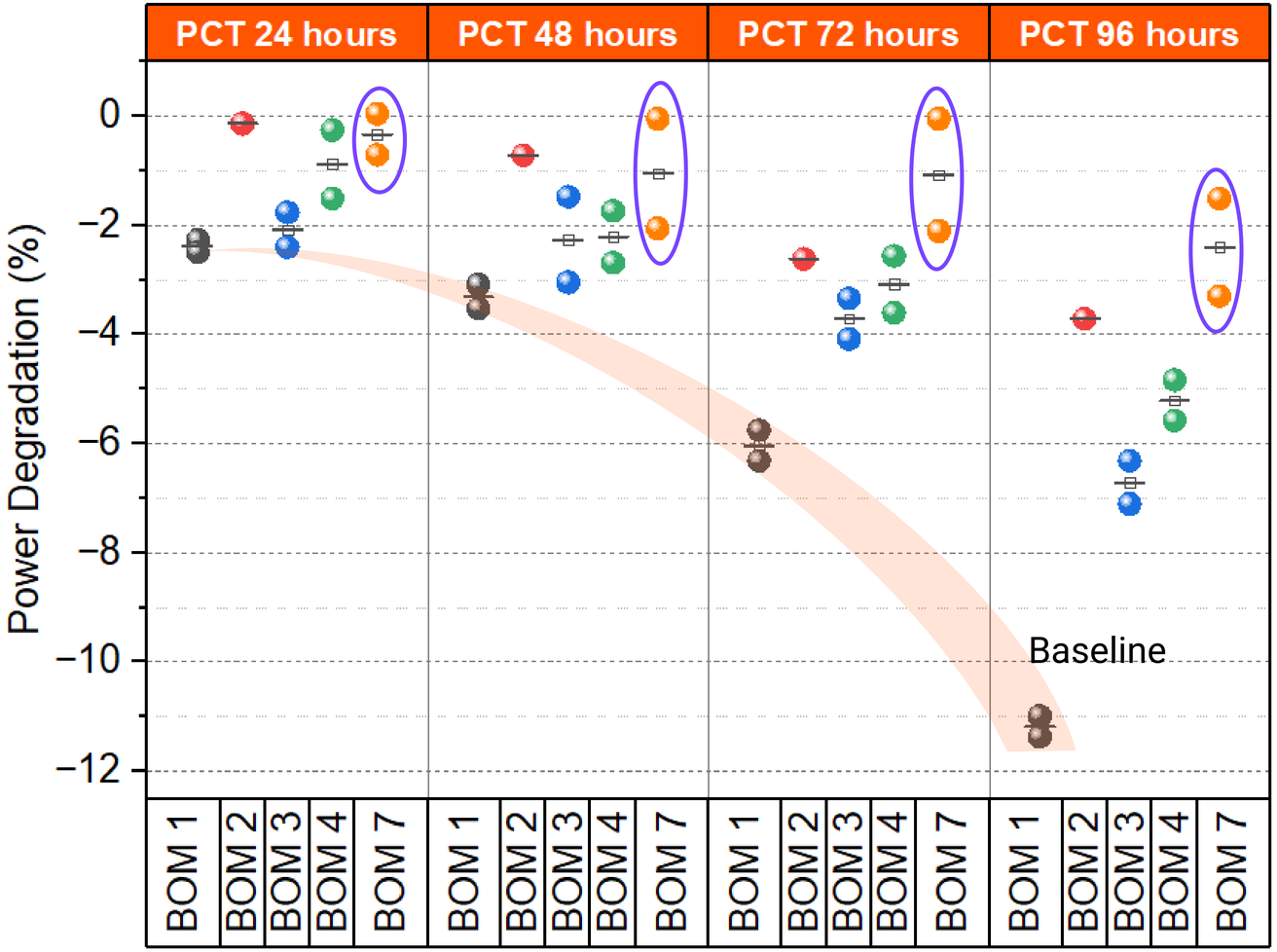
Performance of backsheets with high moisture barrier

Water Vapour Transmission Rate (WVTR)

- Steady state rate at which water vapor permeates through a film at specified conditions of temperature and relative humidity (usually at 38℃ 90%RH)

BOM 7: PEv 2(F)+ Backsheet with low WVTR

- Average WVTR of backsheets <2.5 g/m^2.day
- Low WVTR backsheets <0.005 g/m^2.day



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Summary

- Heliene is actively performing R&D to evaluate the reliability of TOPCon and PERC Glass-Backsheet bifacial modules
- US manufactured raw materials for Glass-Backsheet modules perform at the same level as foreign materials from leading manufacturers
- Low WVTR backsheets (<0.005 g/m².day) show promising results for Glass-Backsheet TOPCon bifacial modules

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Acknowledgement

•We thank everyone involved in Engineering team for their essential support in conducting the experiments.

•We express our gratitude to everyone at Heliene for their assistance throughout the process.

•We acknowledge the suppliers for providing the latest products available in the market.

•We sincerely thank our lab partners (CFV, RETC, PVEL, NREL, TUV SUD, Intertek Lake Forest, Intertek Sanghai)

For further details contact: smitra@heliene.com

For job openings, please check: https://heliene.com/openings/

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HELIENE

Thank you

An Update on Qcells' US Manufacturing and Reliability Testing

Max B. Koentopp l Hanwha Qcells R&D Center Germany

PVRW 2025 l Golden, CO March 5th, 2025

Hanwha

Hanwha is South Korea's seventh-largest business group with a diverse portfolio that includes innovative businesses in the areas of energy, ocean, aerospace, finance, and retail & services.

Aerospace, Energy & Materials, Finance, Retail & Services

Main Industries

Total Sales (2023)

$ 61.3 Billion

Total Assets (As of 2023)

$ 181.2 Billion

Founded in

1952

Domestic Affiliates

103

As of end of 2023

Global Networks

776

As of end of 2023

Fortune Global 500 Ranking

372

(As of 2024)

Business Enterprise Ranking in South Korea

7

(Total asset basis, as of end of 2023)

(Source: Hanwha Profile 2024)

Complete Energy
Solutions Provider

Qcells is a renowned complete energy solutions provider in solar cell and module, energy storage, downstream project business and energy retail.

Solar
Cell & Module

Residential System
Solutions

C&I Distributed
Energy Solutions

Utility Scale
Energy Solutions

Qcells has a long history and deep know how in the solar industry.
Our technology is regularly recognized as top quality and our brand is the top choice for global customers.
With our expertise, we are now moving forward in providing complete energy solutions
for every energy market segment including the residential, C&I and utility sectors.

qcells

Qcells in the US market

No.1 Market Share and Brand

Market Share NO

EUPD RESEARCH TOP BRAND PV MODULES USA 2025

- Market leader in residential (since 2018) and commercial (since 2019) solar module segments in the U.S.
  **Wood Mackenzie Power & Renewables U.S. PV Leaderboard
- EUPD Research Top Brand PV – U.S. for four consecutive years.
- Ranked No.1 Solar Panel Brand by SolarReviews

Solar Hub

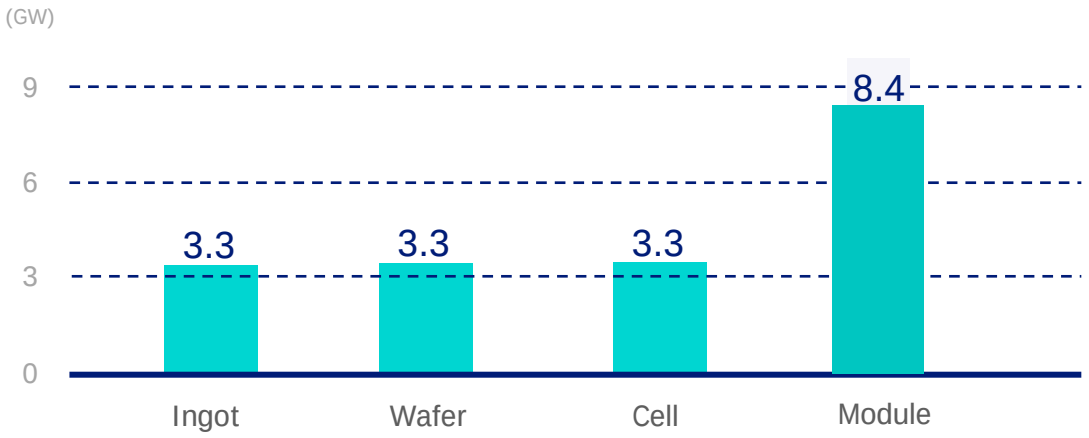
Dalton Factory

- Area: 300,000 m²
- Capacity : Module 5.1GW

Cartersville Factory

- Area: 1.3 million m²
- Capacity : Ingot/Wafer/Cell/Module each 3.3GW

Complete Solar Supply Chain



- Invested over $2.8 billion to establish a fully integrated solar supply chain in the U.S.
- New Georgia facility to manufacture 3.3GW of ingots, wafers, cells and finished modules respectively
- Total solar module production capacity in the U.S. 8.4GW
- When fully ramped, between the Dalton and Cartersville factories Qcells will employ nearly 4,000 people

Dalton GA module manufacturing facility

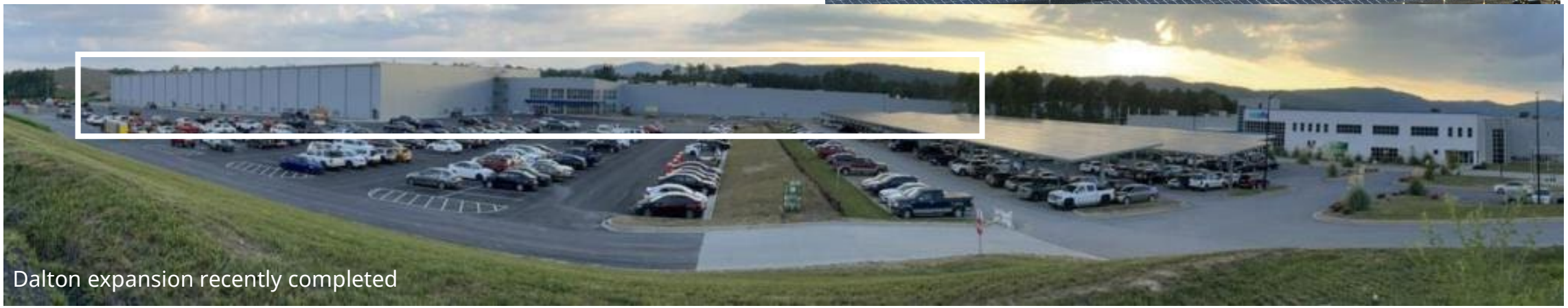
MAY 30, 2018 — Dalton Plant Announcement

SEPT. 26, 2019 — Grand Opening

MAY 26, 2022 — Expansion Plan announcement

Q4 2023 — Completion of the expansion

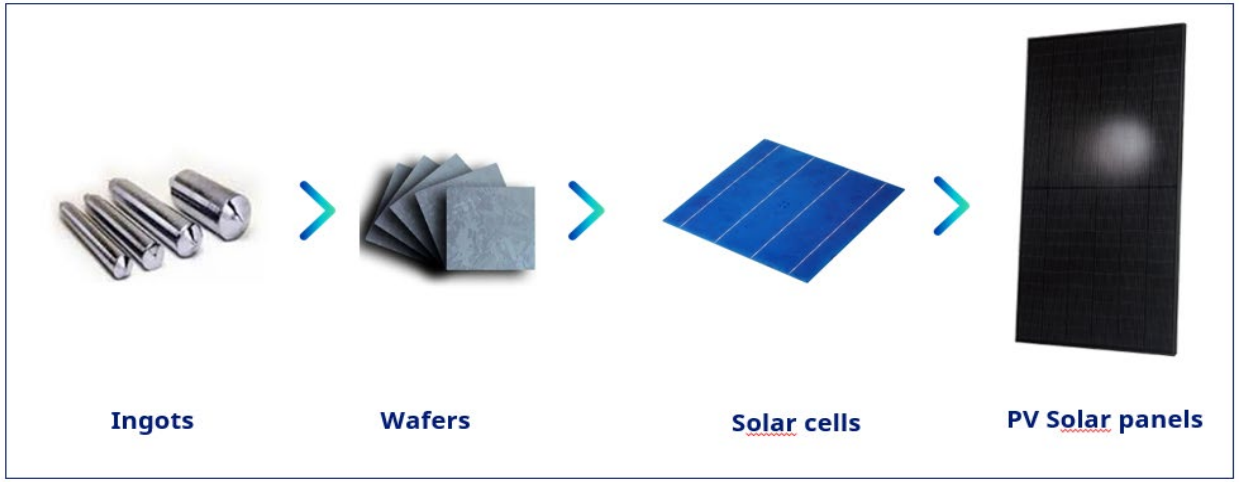
- In 2019, the Dalton factory started with total module capacity of 1.7 GW
- Dalton factory now has total module capacity of 5.1GW



Dalton expansion recently completed

Cartersville, GA manufacturing facilities

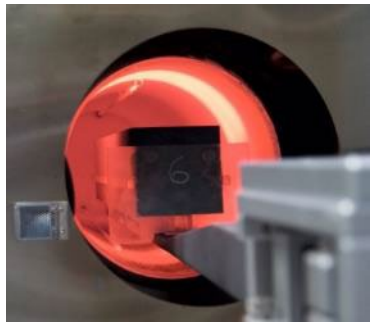
- New factory announced March 2023 as a part of Hanwha's multi-billion dollars investment in US
- Total capacity **3.3 GW** of ingots, wafers, cells, and modules

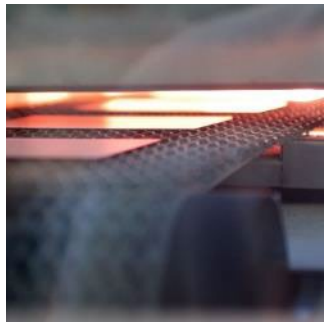


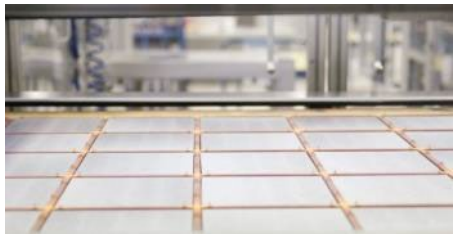
Manufacturing in Georgia US:

- **4,000** total clean energy jobs
- **8.4 GW** module production capacity
- **3.3 GW** ingot, wafer, and cell capacity when fully ramped

R&D Setup In Germany







R&D Center
– Advanced Solar PV Research –

Development of next generation solar cell & module & system technologies & manufacturing processes

About 200 people in R&D

Pilot Line
– For cell and modules –

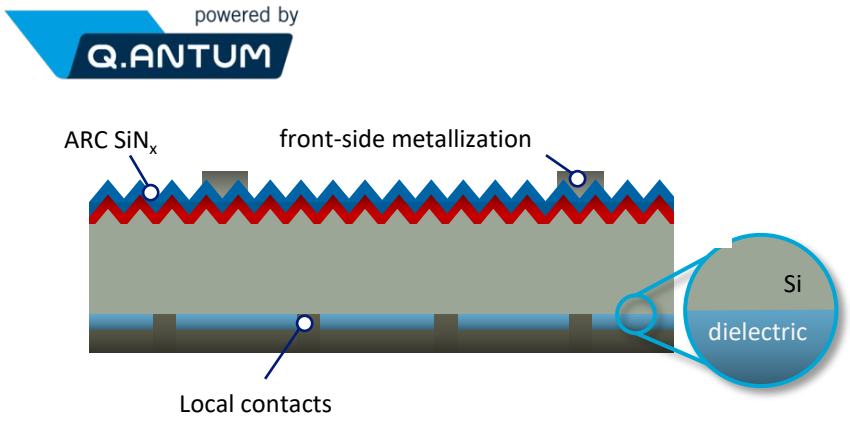
Mass production relevant tools
Rapid transfer to production

Mass Production
– Superior Support–

Global support

Qcells Silicon Technology – Evolutionary Development Approach

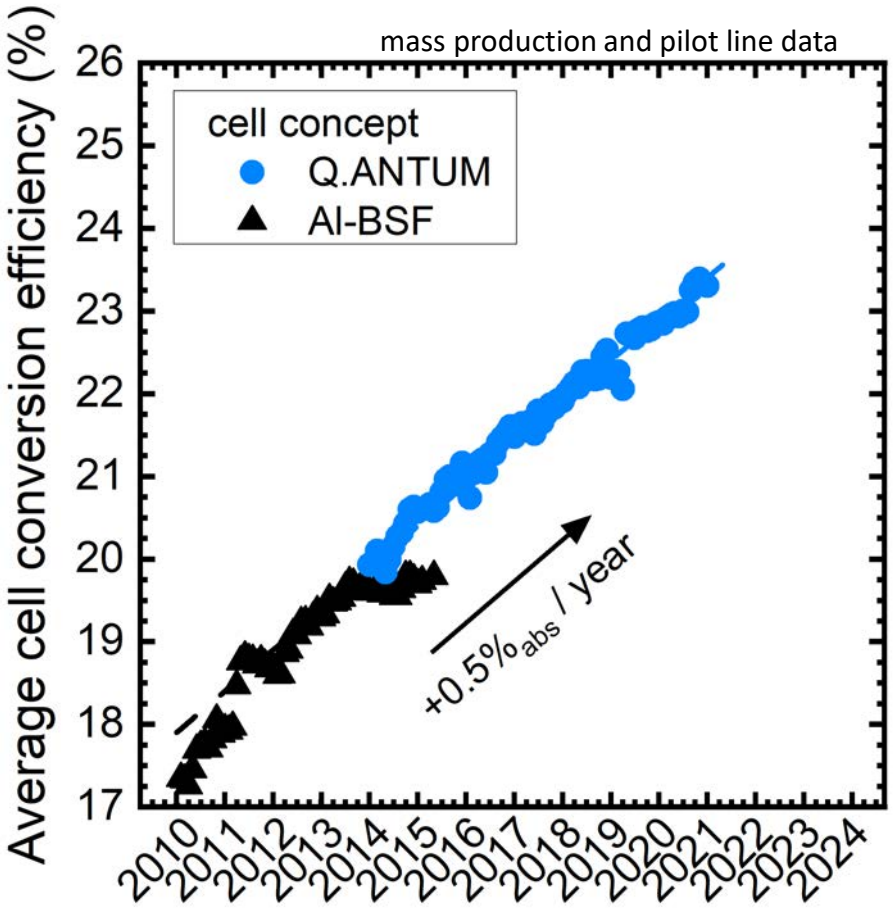
Evolutionary cell development



- texture
- diffusion
- edge isolation
- dielectrics + ARC
- LCO + metallization

Q.PEAK:
Q.ANTUM[1-4] technology

- PERC-like structure with additional features
- Patent-protected components
- Lean & cost-effective process (ARC module optimized, screen print, …)
- Effective suppression of degradation effects (PID, LID, LeTID)

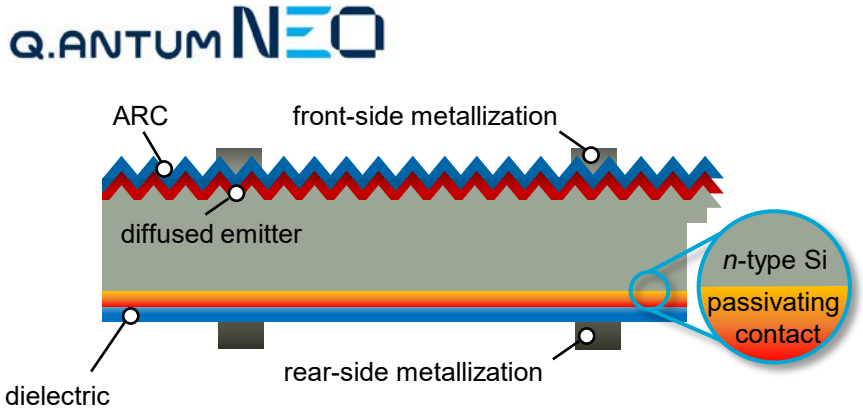


Q.ANTUM has efficiency headroom > 24 %

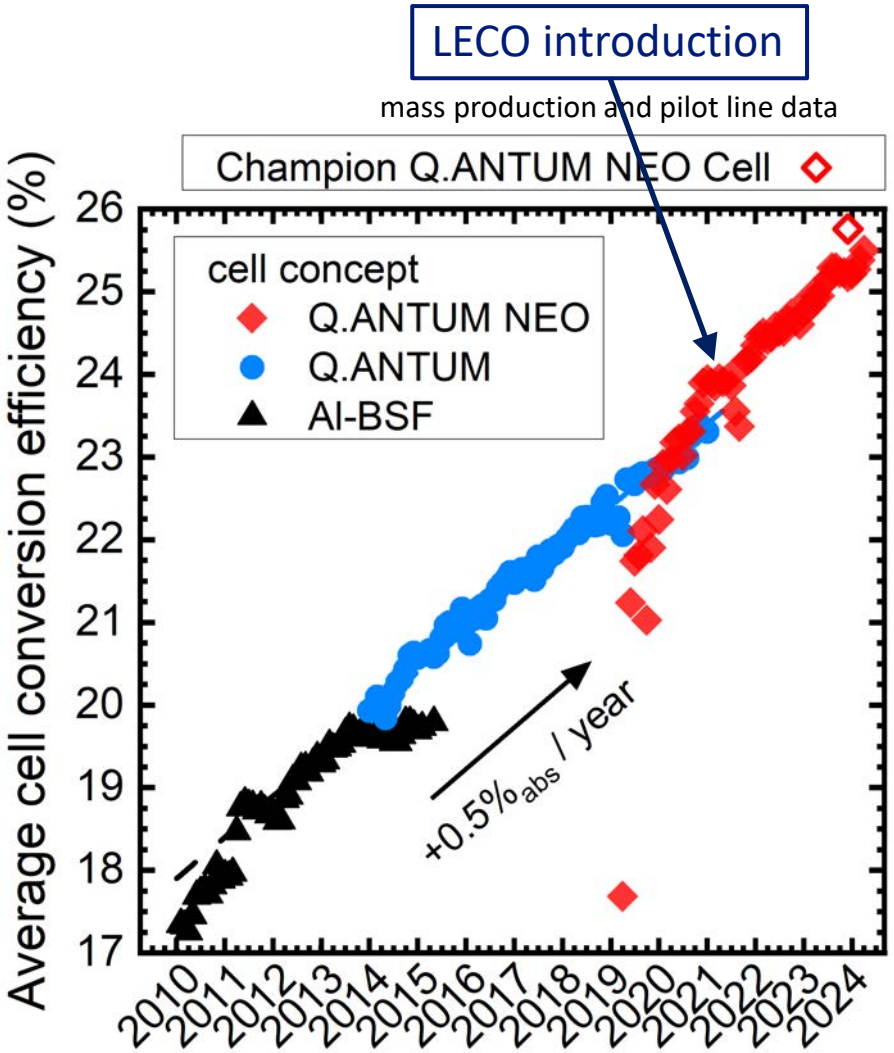
[1] P. Engelhart *et al.* in Proc. 26th EUPVSEC, 821-826, Hamburg, Germany, 2011.
[2] A. Mohr *et al.* in Proc. 26th EUPVSEC, 2150-2153, Hamburg, Germany, 2011.
[3] F. Fertig *et al.*, Energy Procedia, vol. 124, pp. 338–345, 2017.
[4] F. Kersten *et al.*, Energy Procedia, vol. 124, pp. 540–546, 2017.

Qcells Silicon Technology

Evolutionary cell development



- texture
- diffusion
- edge isolation
- passivating contact
- clean
- dielectrics + ARC
- metallization
- LECO



Q.TRON based on
Q.ANTUM NEO[1-2] technology (TOPCon based)

- Passivating rear-side contact
- *n*-type
- Lean & cost-effective process (ARC module opt., screen print, …) w/ 2 add. steps vs. Q.ANTUM + LECO
- Possible to retrofit existing lines
- Compatible module technology
- Effective suppression of degradation effects (PID, LID, LeTID)

Q.ANTUM NEO has efficiency headroom > 26 %

[1] J. Müller et al., Silicon PV 2021.
[2] F. Fertig et al., IEEE PVSC 2021.

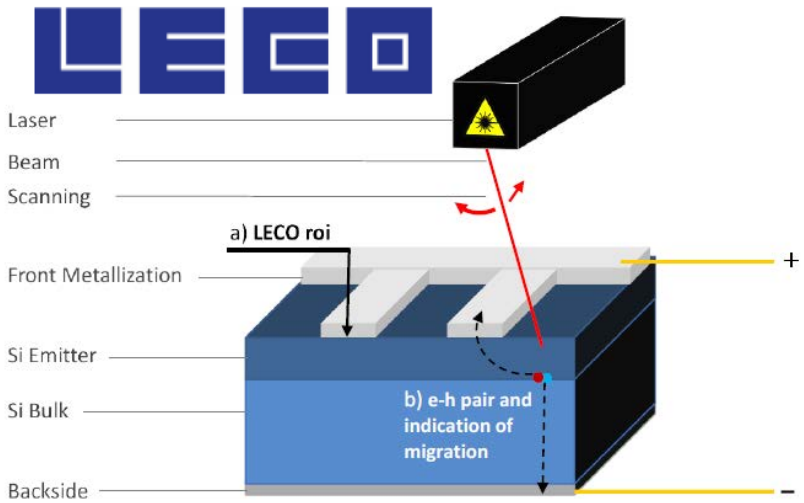
LECO – Laser Enhanced Contact Optimization

Qcells Silicon Technology

LECO Process[1]

- Laser scans over the cell while reverse bias is applied
- Free carriers are forced through small interface areas between contact and silicon

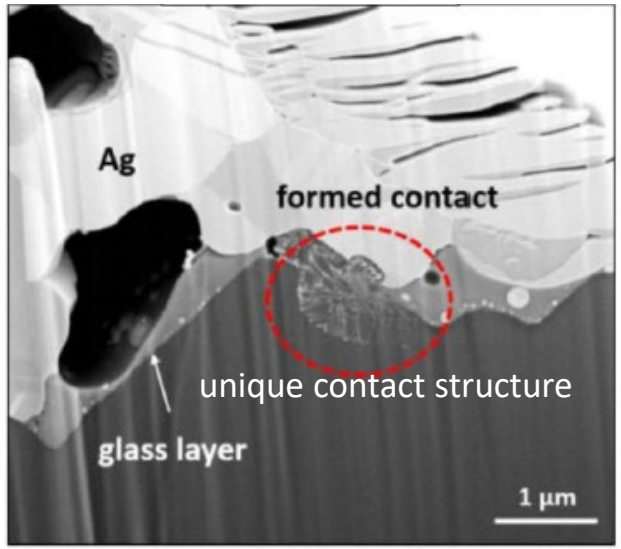
→ A unique contact structure is formed named CFC – Current Fired Contact



[1] E. Krassowski, WCPEC 2022

Qcells and Cell Engineering joint forces[2,3]

- LECO was developed by CE (Cell Engineering GmbH) since 2016
- Tool in pilot line at Qcells in 2018
- Qcells became 100 % shareholder of CE in October 2022
- IP granted in several countries like EU, China, US, India…
- Qcells and CE are committed to defend its IP to ensure fair and lawful use of LECO



[2] S. Großer et. al, doi: 10.1109/JPHOTOV.2021.3129362

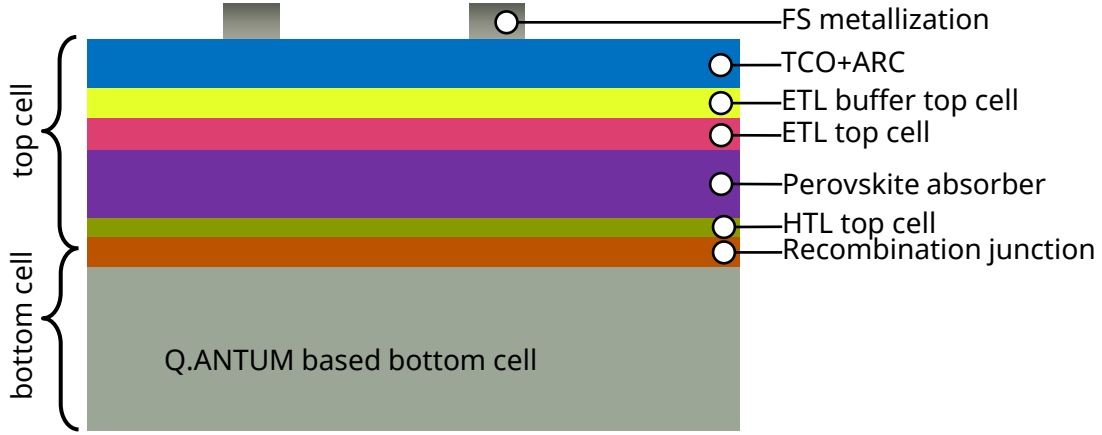
[1] E. Krassowski et al., EUPVSEC 2021.
[2] J. Müller et al., CSPV 2023.
[3] A. Mette et al., SiPV 2024.

Qcells Tandem Technology

Initial tandem results & cooperations

powered by Q.ANTUM

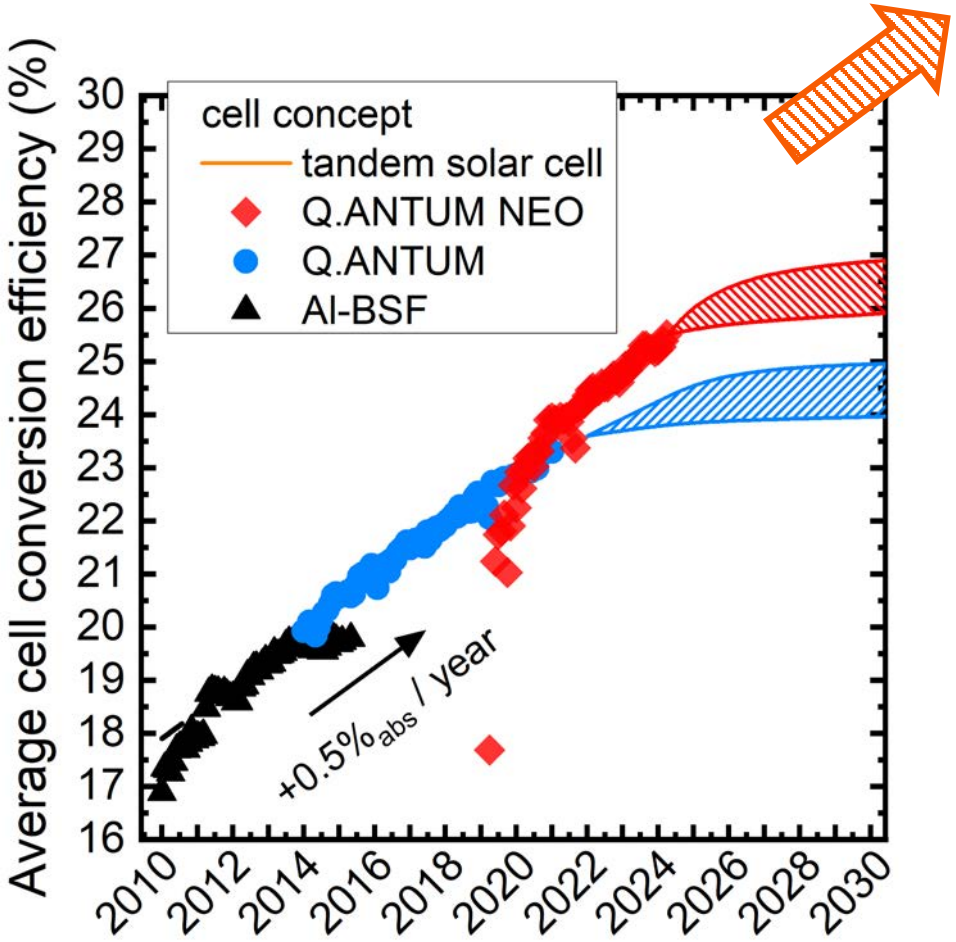
perovskite top cell



2-terminal perovskite-on-silicon tandem solar cell

Overcome practical limit of silicon solar cells

- Bottom cell based on Q.ANTUM technology
- **29.9 % solar cell efficiency** (certified by ESTI), V_{OC} > 1.93 V in close cooperation with HZB[1]
- **First time presentation of Qcells-internal tandem development results** including **record efficiency of 28.6% on full-size M10 wafer next week → Qcells talk by F. Fertig at PV CellTech on March 11**



2T tandem based on Q.ANTUM bottom cell has efficiency headroom > 30 %

[1] B. Li et al., EUPVSEC 2023.

Ensuring Superior Quality And Reliability

Quality Controlled PV
TÜVRheinland CERTIFIED
www.tuv.com
ID 1111232615

Part 1: Initial qualification

- Test thoroughly
- Over 40 individual, realistic and harsh tests
- Based on IEC TS 63209 extended stress testing
- Additional Qcells tests for new failure modes
  - UVID
  - Extended hail du
  - LETID

Part 2: Monitoring of production

- Test continuously
- Random sampling of production to guarantee consistent product quality and durability
- Sampling supervised by independent TÜV Rheinland experts
- TÜV Rheinland ... for reliability tests in

Part 3: Monitoring of material & supplier

- Ensure and continuously monitor incoming material quality in mass production via material fingerprints
- Specialized tests to immediately detect variations in component & material quality
- Check of supplier via audits and change control

UNIQUE IN THE PV INDUSTRY:

- Comprehensive third-party oversight via TÜV Rheinland representative on site
- Continuous monthly monitoring of mass production w/ random third party sampling
- Continuous monitoring of material & supplier
- IEC 63209 extended qualification already included for all products
  → no need for third party sampling
- **Outlook**: extend quality reporting (EQR) bankability program by TÜV with built-in bankability testing of mass production

Long term durability of product verified

Modules will meet warranty promises

High quality of production verified

All supplied modules have same high quality

High quality of used material verified

No unexpected issues in the field

Where We Test: Our Module Test Centers

Germany - one of the largest module labs in the world

- Total area 2.300 m²
- About 90 module tests per day
- More than 20 climate chambers (DH, TC, HF,…)
- light soaking chambers, UV chambers
- 2 flasher lines (incl. EL, dry & wet insulation, high pot. test)
- 1 full module size LED solar simulator for Tandem

Additional large module test centers

supervised by Germany MTL

- **Eumseong (Korea)**
- **Cartersville (USA)**

CTF agreement with TÜV Rheinland

- Permanent on-site presence of a TÜV Rheinland representative at all labs
- Independent supervision of testing procedures
- In-house certification and qualification of products

Aligned qualification and testing procedures

- German R&D center defines testing procedures
- aligns procedures between across test labs
- Performs regular audits and trainings

Development of test methods for new failure modes

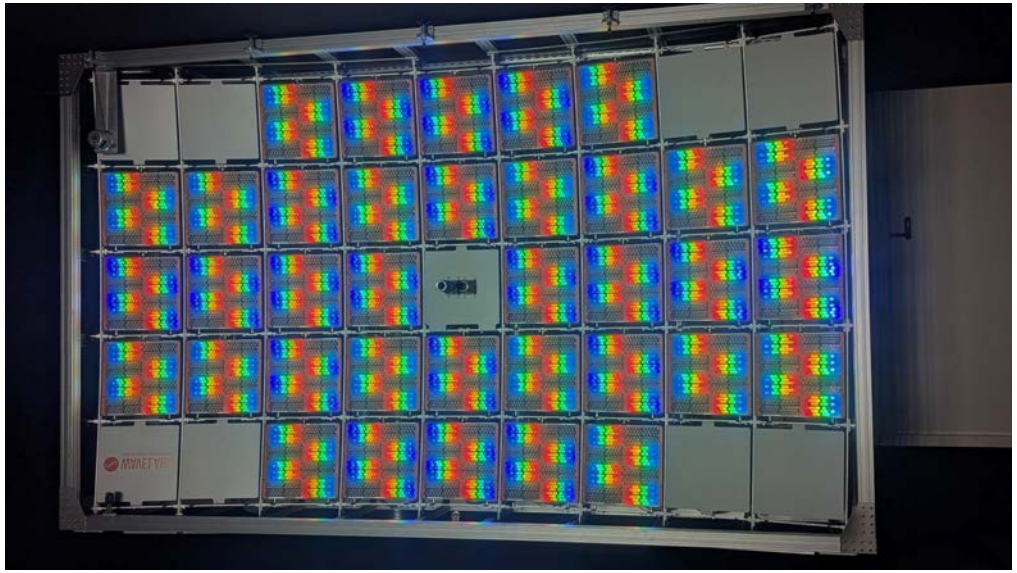
- German R&D continuously develops testing procedures for new failure modes
  e.g. PID, LETID, BO-LID, UVID, component qualification tests
- Roll-out of testing procedures to all sites

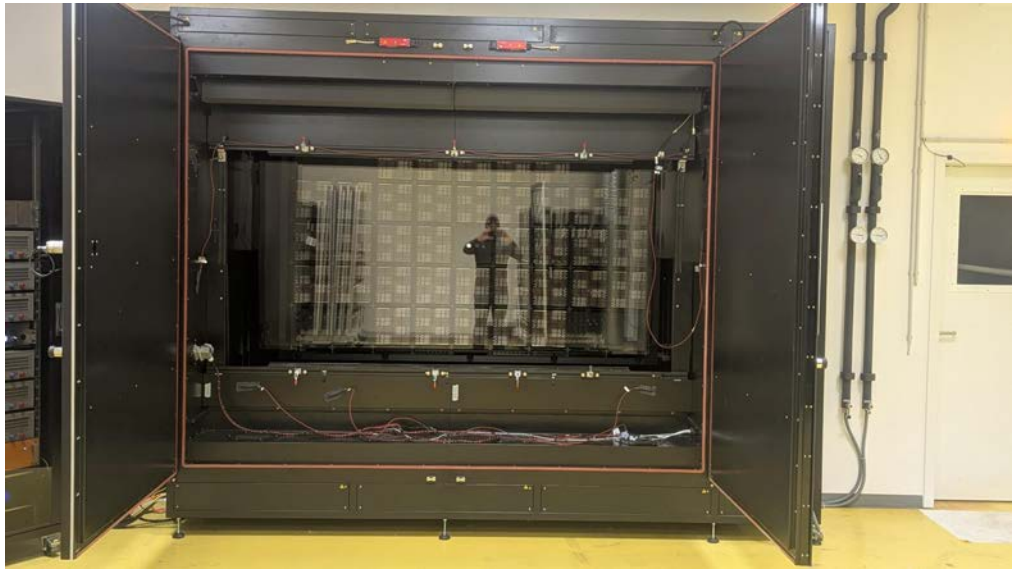
Regular update of qualification requirements

qcells

Measuring Tandem modules – new LED solar simulator in GER

- Power determination of Si-PVK Tandem modules is challenging
  - Slow-moving ions
  - Metastabilities
  - Mpp-tracking
  - Spectrum matching
- Constant light tuneable module size LED simulator with temperature controlled chamber



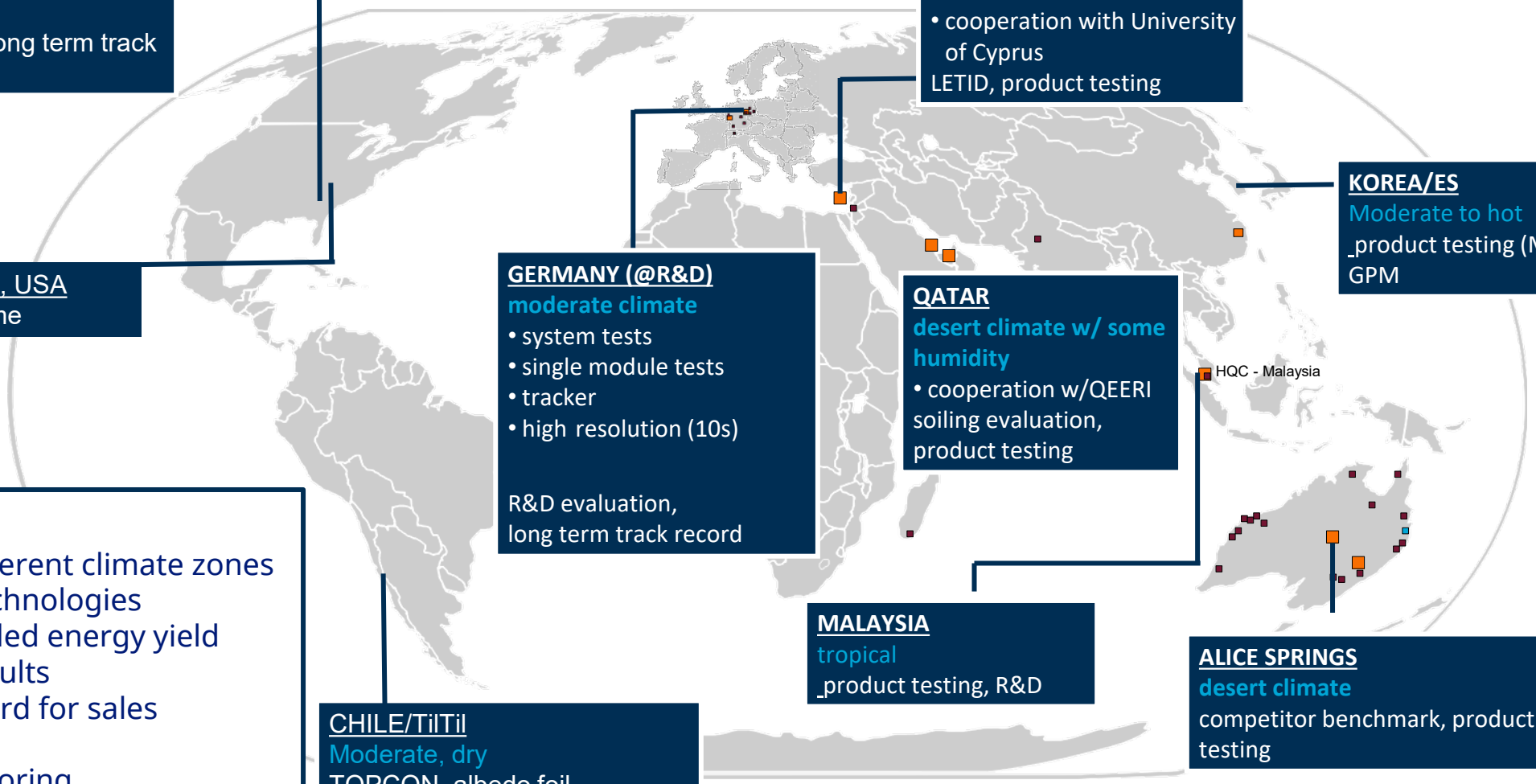


New Module Test Center in Cartersville, GA

- **Operational since August 2024**
- **CTF status with TÜV Rheinland**
- **Local TÜV representative supervising testing**
- **Used for BOM qualification and certification**
- **Quality monitoring**
- **Continuous improvement and product development**

- 5 climate chambers
- Flasher, EL, wet leakage, insulation
- Hail testing
- Mechanical load testing, module breakage testing
- Hot spot testing
- Other safety and performance tests required for certification
- Extension currently ongoing, new chambers to arrive this year

Global Outdoor Test Facilities



GEORGIA, USA
product testing, long term track record, R&D

NORTH CAROLINA, USA
TOPCON, steel frame

CYPRUS
Hot sea climate
• cooperation with University of Cyprus
LETID, product testing

GERMANY (@R&D)
moderate climate
• system tests
• single module tests
• tracker
• high resolution (10s)

R&D evaluation,
long term track record

QATAR
desert climate w/ some humidity
• cooperation w/QEERI
soiling evaluation,
product testing

KOREA/ES
Moderate to hot
product testing (MLPE), GPM

MALAYSIA
tropical
product testing, R&D

ALICE SPRINGS
desert climate
competitor benchmark, product testing

CHILE/TilTil
Moderate, dry
TOPCON, albedo foil

Targets

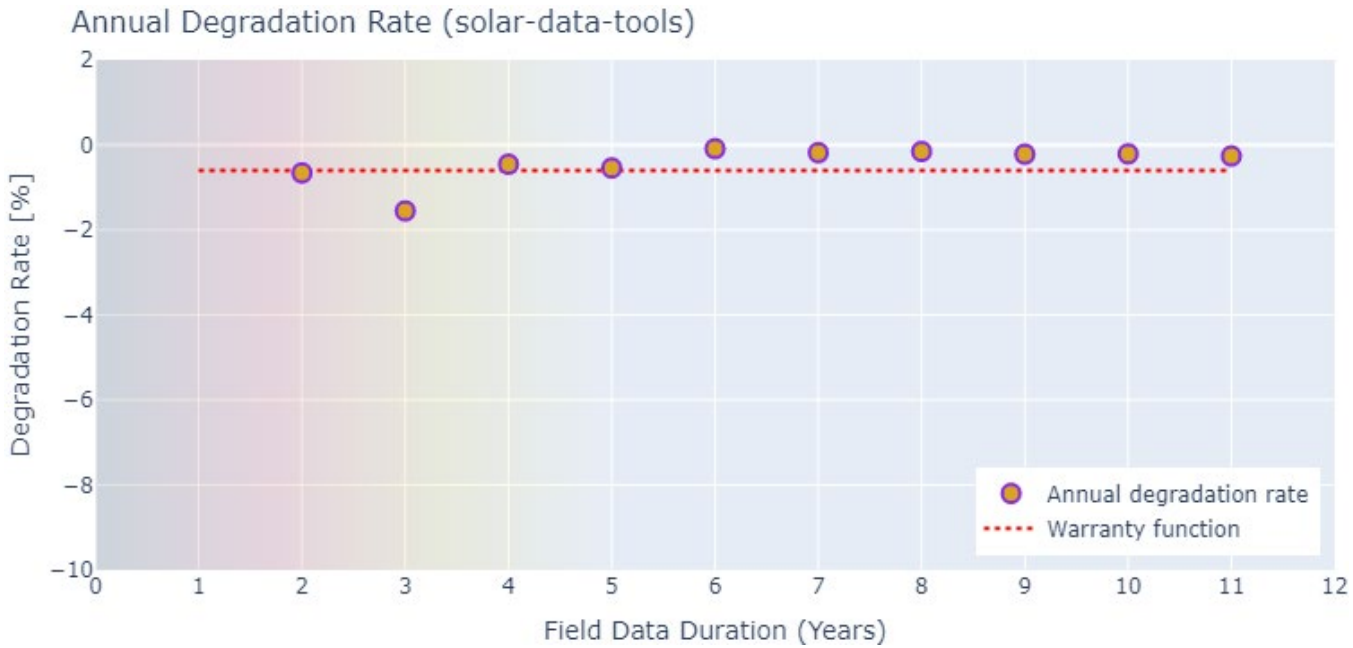
- Reliability data in different climate zones
- Evaluation of new technologies
- Verification of modelled energy yield with real outdoor results
- Long-term track record for sales
- Degradation rates
- Product safety monitoring

qcells

Long Term verification: Degradation rates

- Monitoring of performance of relevant product generations
- Solar-data-tools used for degradation rate determination
- **oldest system from 2012** **-0.26% / a**
  11 c-Si modules

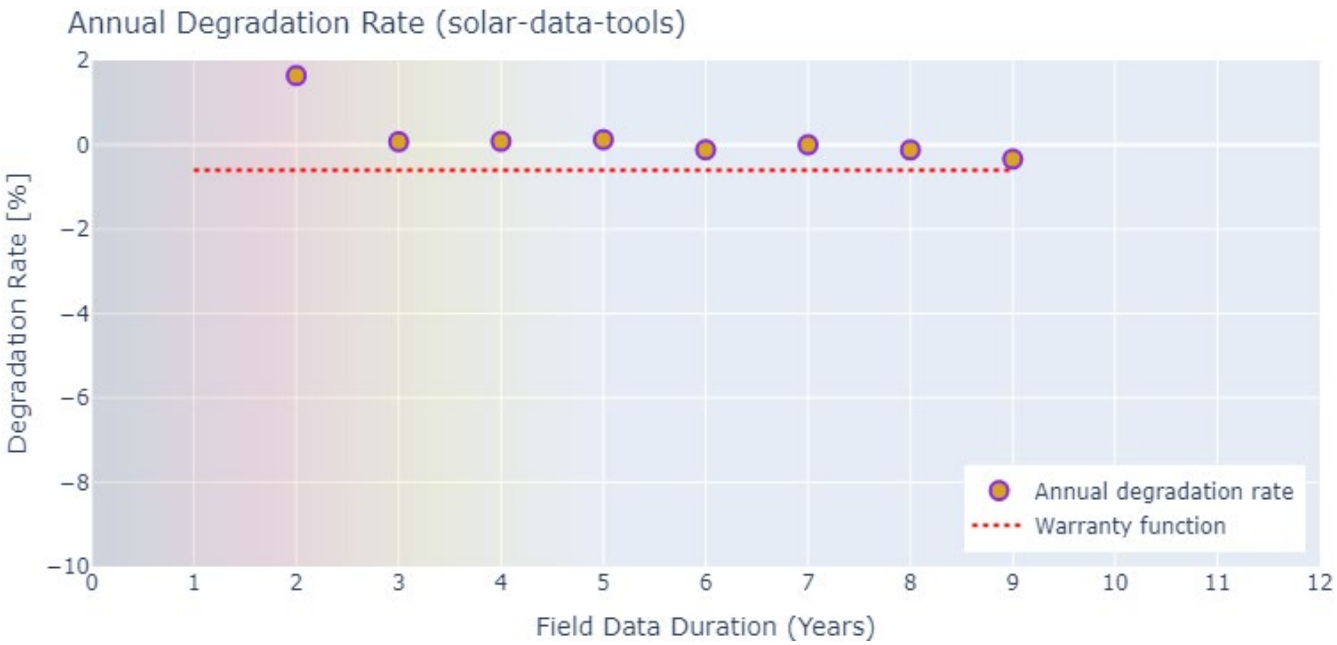
Location:
Bitterfeld, Germany



Long Term verification: Degradation rates

- Monitoring of performance of relevant product generations
- Solar-data-tools used for degradation rate determination
- oldest system from 2012 -0.26% / a
  11 c-Si modules
- **oldest Q.ANTUM system from 2013 -0.34% /a**
  10 early Q.ANTUM modules

Location:
Bitterfeld, Germany



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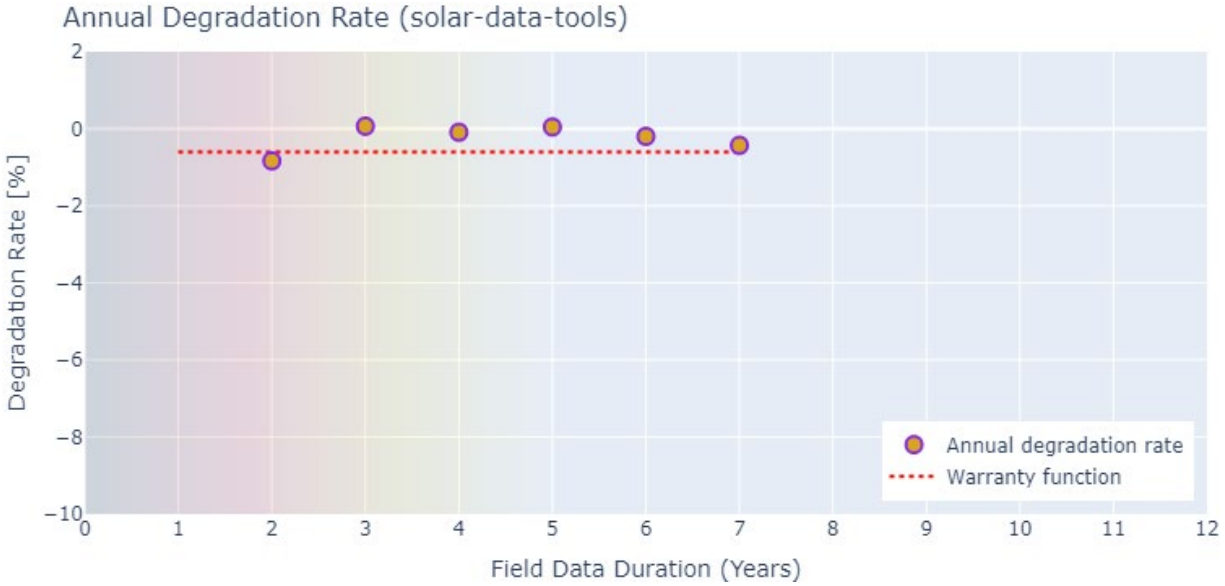
Long Term verification: Degradation rates

- Monitoring of performance of relevant product generations
- Solar-data-tools used for degradation rate determination
- oldest system from 2012 -0.26% / a
  11 c-Si modules
- oldest Q.ANTUM system from 2013 -0.34% /a
  10 early Q.ANTUM modules
- **Q.ANTUM system from 2015 -0.43% / a**
  10 Q.ANTUM modules from mass production

Location:
Bitterfeld, Germany

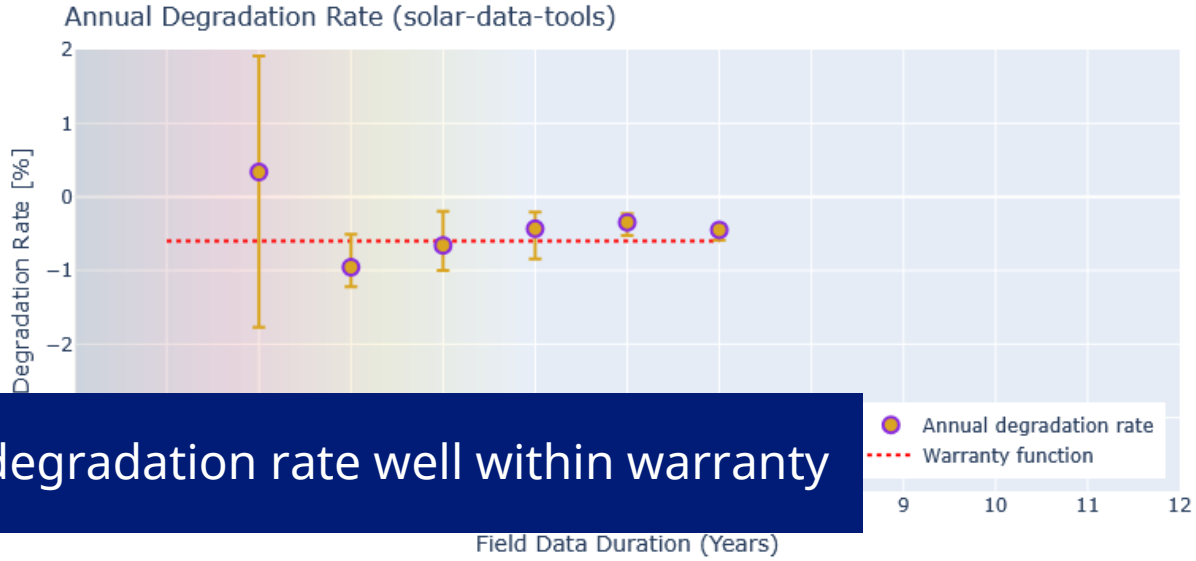


qcells

Long Term verification: Degradation rates

- Monitoring of performance of relevant product generations
- Solar-data-tools used for degradation rate determination
- oldest system from 2012 -0.26% / a
  11 c-Si modules
- oldest Q.ANTUM system from 2013 -0.34% /a
  10 early Q.ANTUM modules
- Q.ANTUM system from 2015 -0.43% / a
  10 Q.ANTUM modules from mass production
- **Q.ANTUM system from 2017 -0.45 %/a**
  hot climate in Cyprus

Location:
Cyprus
mediterranean
climate



Very stable performance observed with degradation rate well within warranty

qcells

Conclusion

- US manufacturing
  - 8.4GW module production capacity in US
  - >3GW fully integrated production - ingot, wafer, cell, module
  - $2.8bn investment

- Tandem record results on full M10 wafer to be presented next week at PV Celltech

- Superior reliability program of Qcells
  - most extensive and stringent testing scheme available to date
  - constant third party oversight and presence of TÜV Rheinland engineers at all test labs
  - independent and random onsite testing of running mass production
  - regular material fingerprint analysis and monitoring
    examples : EVA, backsheets, metal pastes
  - dynamically updated based on industry requirements
  - extension to a full bankability program in progress

- Qcells monitors performance of its products in test fields around the globe
  - more than 12 years of field data show stable performance of Qcells products

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Quality Controlled PV
www.tuv.com
ID 1111232615

Qcells Advanced Yield Security

25 YEARS Warranty Product & Performance

DuraMAT
Durable Module Materials Consortium

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

Breaking the Trend:
Are Retro PV Module Designs a Cost-Effective Solution to Glass Reliability?

Jen Braid, Norman Jost, James Hartley, Michael Shimizu, Steven DiGregorio, Cliff Hansen
Sandia National Laboratories

2025 PV Reliability Workshop, 5 March 2025

U.S. DEPARTMENT OF ENERGY | DuraMAT | NREL | Sandia National Laboratories | BERKELEY LAB

PV module glass is breaking at an alarming rate

pv magazine

Glass breakage – a growing phenomenon in large-scale PV

MONDAY, 20. NOVEMBER 2023

4:00 PM – 5:00 PM GMT, LONDON | 5:00 PM – 6:00 PM CET, BERLIN, PARIS, MADRID | 11:00 AM – 12:00 PM EST, NEW YORK

Spontaneous glass breakage on solar panels on the rise

The National Renewable Energy Laboratory noted an increase in spontaneous glass breakage in solar panels. The PV Module Index from the Renewable Energy Test Center investigates this and other glass-related trends in solar manufacturing.

JUNE 24, 2024 RYAN KENNEDY

Larger, thinner… and weaker?

With hailstorms in Australia and the United States severely damaging solar arrays – including "golf-ball sized" hail at the 350 MW Fighting Jays project in Texas in March 2024 – insurers are raising premiums and reducing or canceling hail coverage. Everoze Partner Simon Mason discusses the challenges the industry faces in minimising its hail risk exposure.

IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 15, NO. 2, MARCH 2025

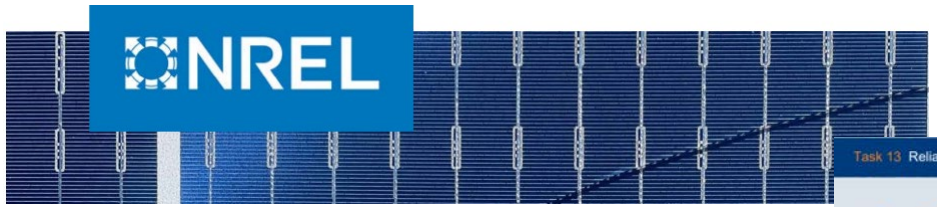
Growing Panes: Investigating the PV Technology Trends Behind Frequent Early Failures in Modern Glass–Glass Modules

PVTECH

PV modules are getting weaker—how should the industry respond?

By Colin Sillerud, CFV Labs

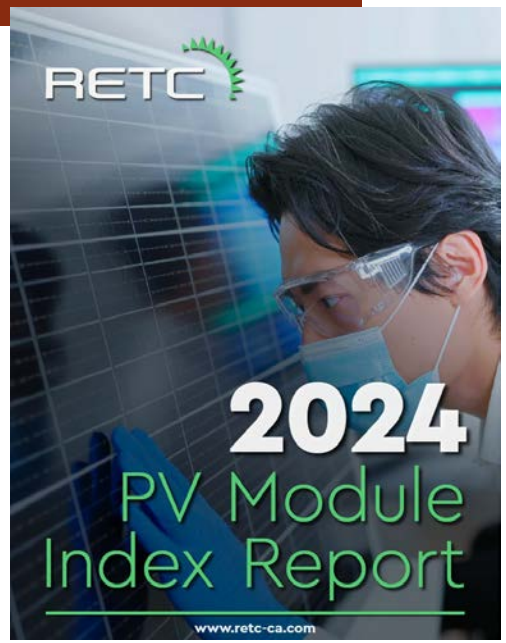
September 16, 2024



Tough Break: Many Factors Make Glass Breakage More Likely

Timothy J Silverman,[1] Elizabeth C. Palmiotti,[1] Martin Springer,[1] Nick Bosco,[1] Mike Deceglie,[1] Ingrid Repins,[1] and Ashley Gaulding[1]

National Renewable Energy Laboratory



Task 13 Reliability and Performance of Photovoltaic Systems

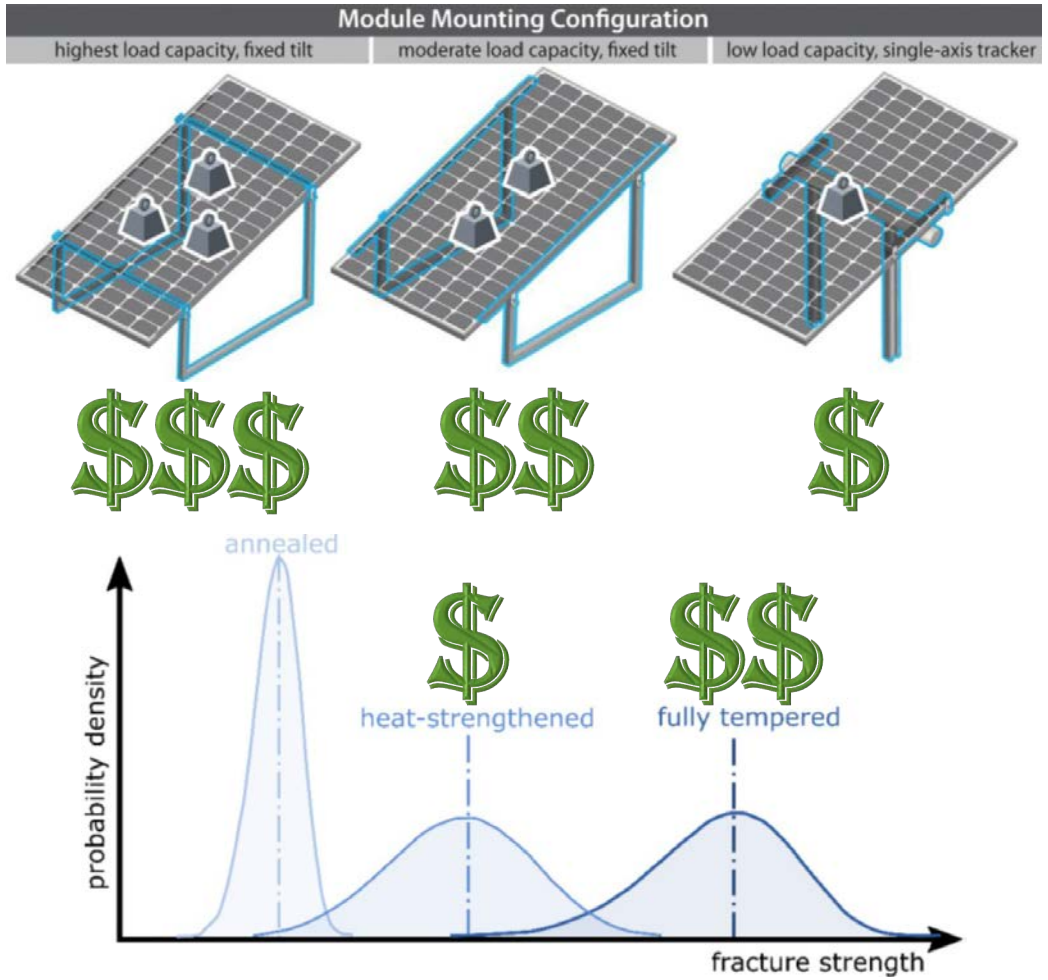
PVPS

Degradation and Failure Modes in New Photovoltaic Cell and Module Technologies

2025

Why are PV modules breaking?

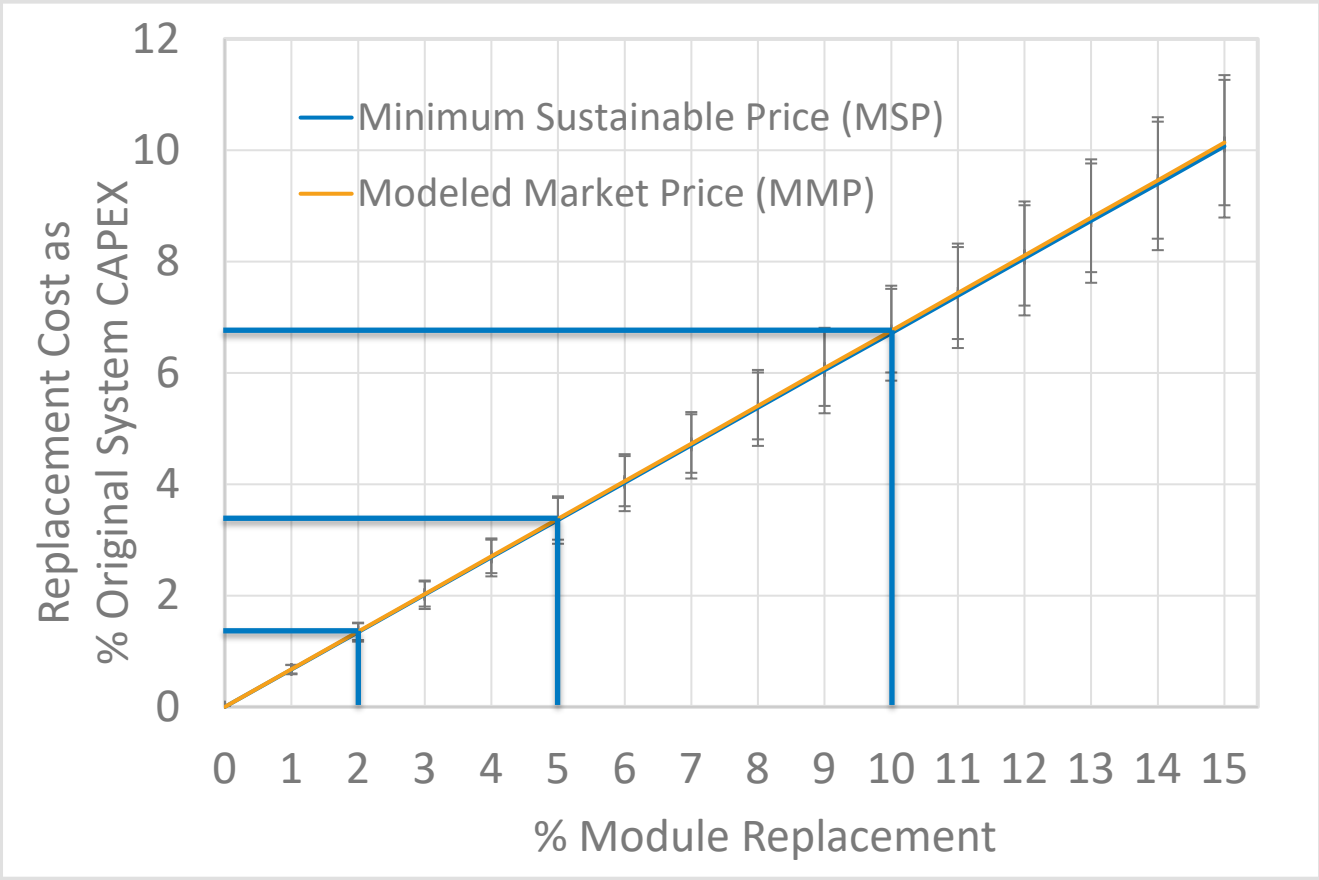
- Mechanical load imposes stress on an object exceeding its fracture strength
- Mechanical load & stress on glass are increasing
- Fracture strength of glass is decreasing
- What is driving these changes?
- Costs of changes to the module or racking to mitigate breakage < costs incurred by module breakage



Palmiotti, Elizabeth C., et al. "Growing Panes: Investigating the PV Technology Trends Behind Frequent Early Failures in Modern Glass–Glass Modules." *IEEE Journal of Photovoltaics* (2025).

How much do module mechanical failures cost?

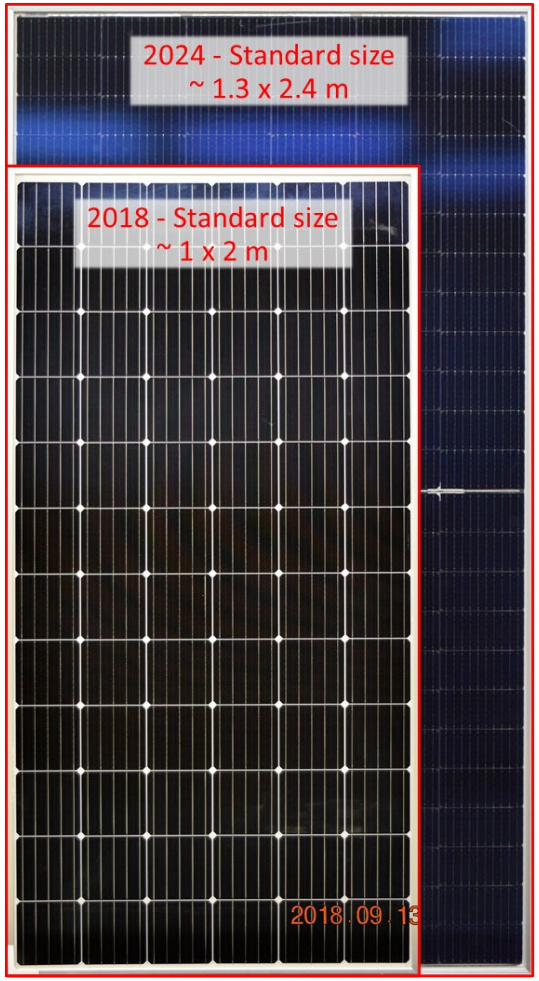
- Some utility-scale PV plants are reporting up to 10% spontaneous glass breakage
- Costs for replacement of broken PV modules include:
  - Inspection and location of broken modules
  - Replacement module cost
  - Mechanical and electrical labor costs

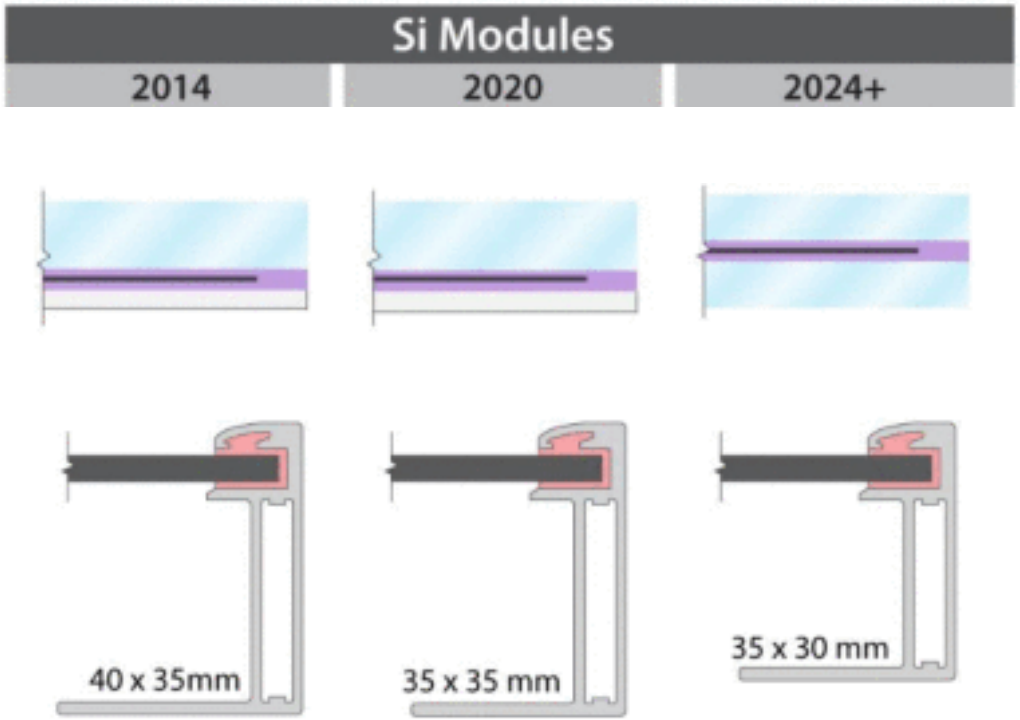


Possible solutions to PV mechanical reliability

- Smaller modules
- Thicker glass
- Glass/backsheet
- Thicker frame

Sillerud, Colin. “PV Modules Are Getting Weaker—How Should the Industry Respond?” *PV Tech*, 16 Sept. 2024.





Palmiotti, Elizabeth C., et al. "Growing Panes: Investigating the PV Technology Trends Behind Frequent Early Failures in Modern Glass–Glass Modules." *IEEE Journal of Photovoltaics* (2025).

Smaller PV modules

Module Type	# Cells	Front Glass	Back Sheet	Module Height (m)	Module weight (kg/m^2)
2mm G/G Baseline	**72**	2mm	2mm glass	**2.27**	**11.5**
2mm G/G Smaller	**60**	2mm	2mm glass	**1.89**	**11.5**
3.2mm G/B Smaller	**60**	3.2mm	Polymer	**1.89**	**9.9**

- Module variants compared to PV System Cost Benchmark utility-scale module in a 100 MW system
- Module and system cost considerations:
  - Front/backsheet materials
  - Module size and weight (mounting, shipping)
  - Manufacturing and installation labor (fixed per module)
  - SBOS materials (less module area per row)

Basore, Paul A., et al. "2024 Solar Photovoltaic System Cost Benchmarks." https://www.energy.gov/eere/solar/solar-photovoltaic-system-cost-benchmarks.

Smaller PV modules: Costs

Module Type	Module Cost ($/kW$_{DC}$)	% Increase Module Cost	System CapEx ($/kW$_{DC}$)	% Increase System CapEx
2mm G/G Baseline	336	-	1118.5	-
	340.01	**1.19**	1179.49	**5.45**
			1183.78	**5.83**

- Smaller modules result in a slightly higher module cost per kW$_{DC}$
  - Fixed manufacturing labor cost per module
- System cost per kW$_{DC}$ increases by much more
  - Installation labor is fixed per module
  - Less module area per tracker row due to smaller size

PV modules with thicker frames

Module Type	# Cells	Front Glass	Back Sheet	Module Height (m)	Module weight (kg/m^2)
2mm G/G Baseline	72	2mm	2mm glass	2.27	**11.5**
2mm G/G Thick Frame	72	2mm	2mm glass	2.27	**12.0**
3.2mm G/B Thick Frame	72	3.2mm	Polymer	2.27	**10.4**

- Thicker module frames add weight and cost to the module
- Modeled ~33% increase in cost and material
- Assuming extruded aluminum frames

PV modules with thicker frames: Costs

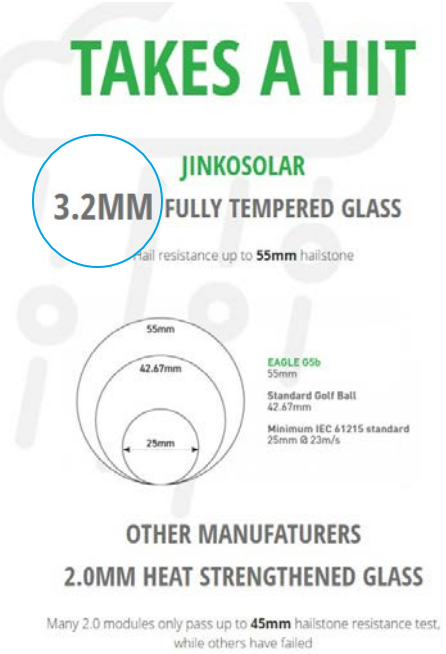
Module Type	Module Cost ($/kW$_{DC}$)	% Increase Module Cost	System CapEx ($/kW$_{DC}$)	% Increase System CapEx
2mm G/G Baseline	336	-	1118.5	-
	343.69	**2.29**	1127.6	**0.81**
			1131.89	**1.19**

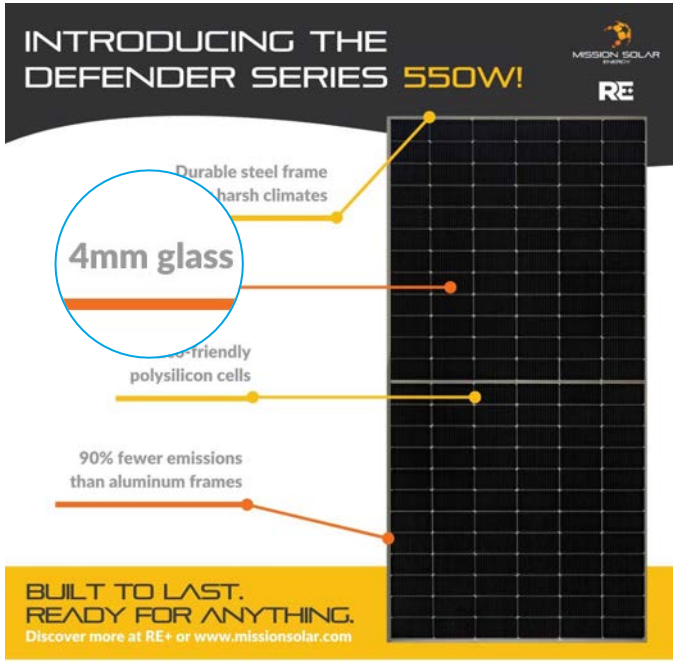
- Thicker module frames add more module cost per kW$_{DC}$ when compared to making modules smaller
- The impact on system cost per kW$_{DC}$ is lower than smaller modules, due to lower overall SBOS and installation costs.

Hail-resistant PV modules

Module Type	# Cells	Front Glass	Back Sheet	Module Height (m)	Module weight (kg/m^2)
2mm G/G Baseline	72	2mm	2mm glass	2.27	**11.5**
3.2mm/2mm G/G	72	3.2mm	2mm glass	2.27	**14.5**
4mm G/B	72	4mm	Polymer	2.27	**11.9**

Hail-resistant modules have thicker front glass, but similar form factor



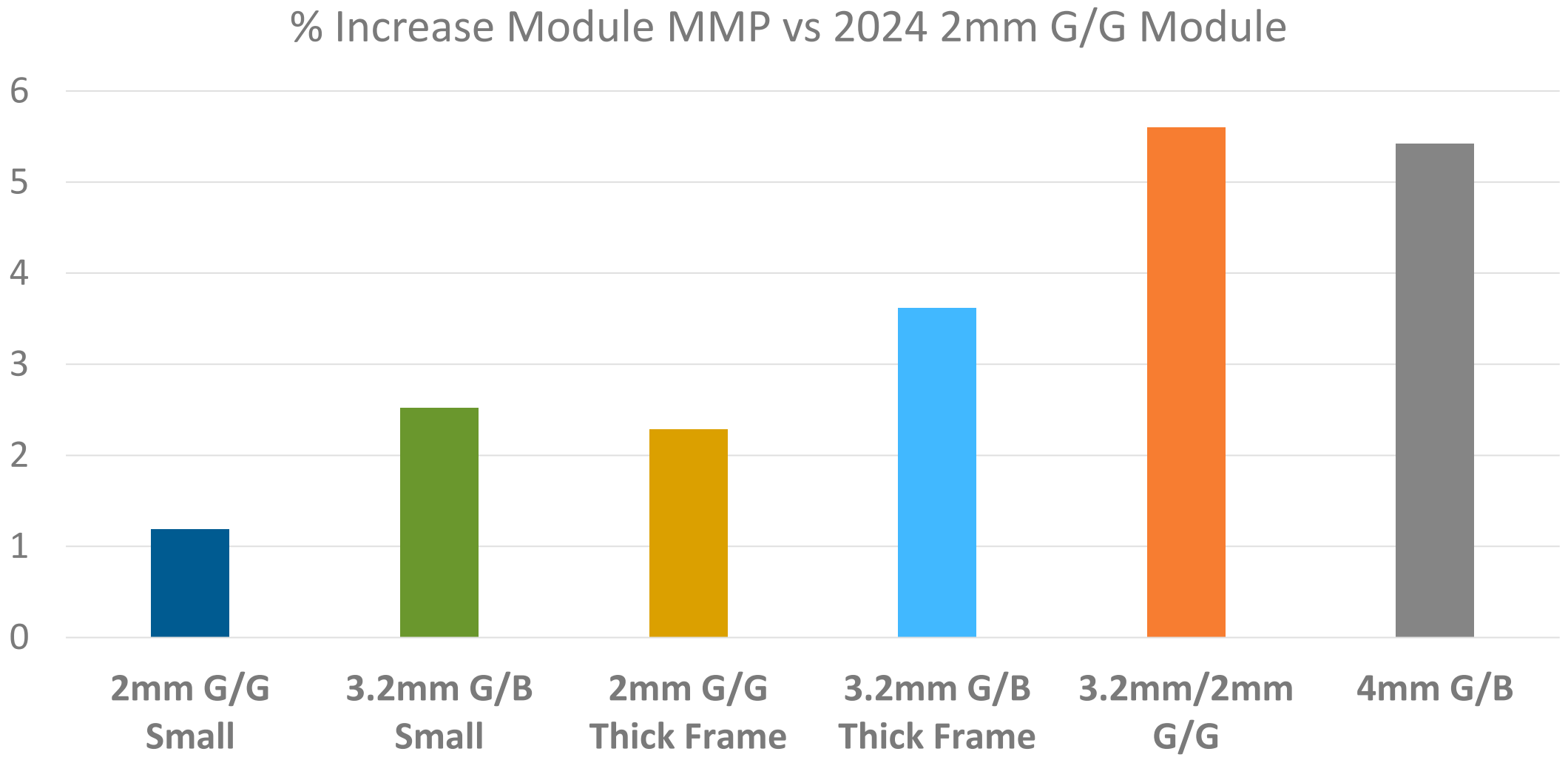


Hail-resistant PV modules: Costs

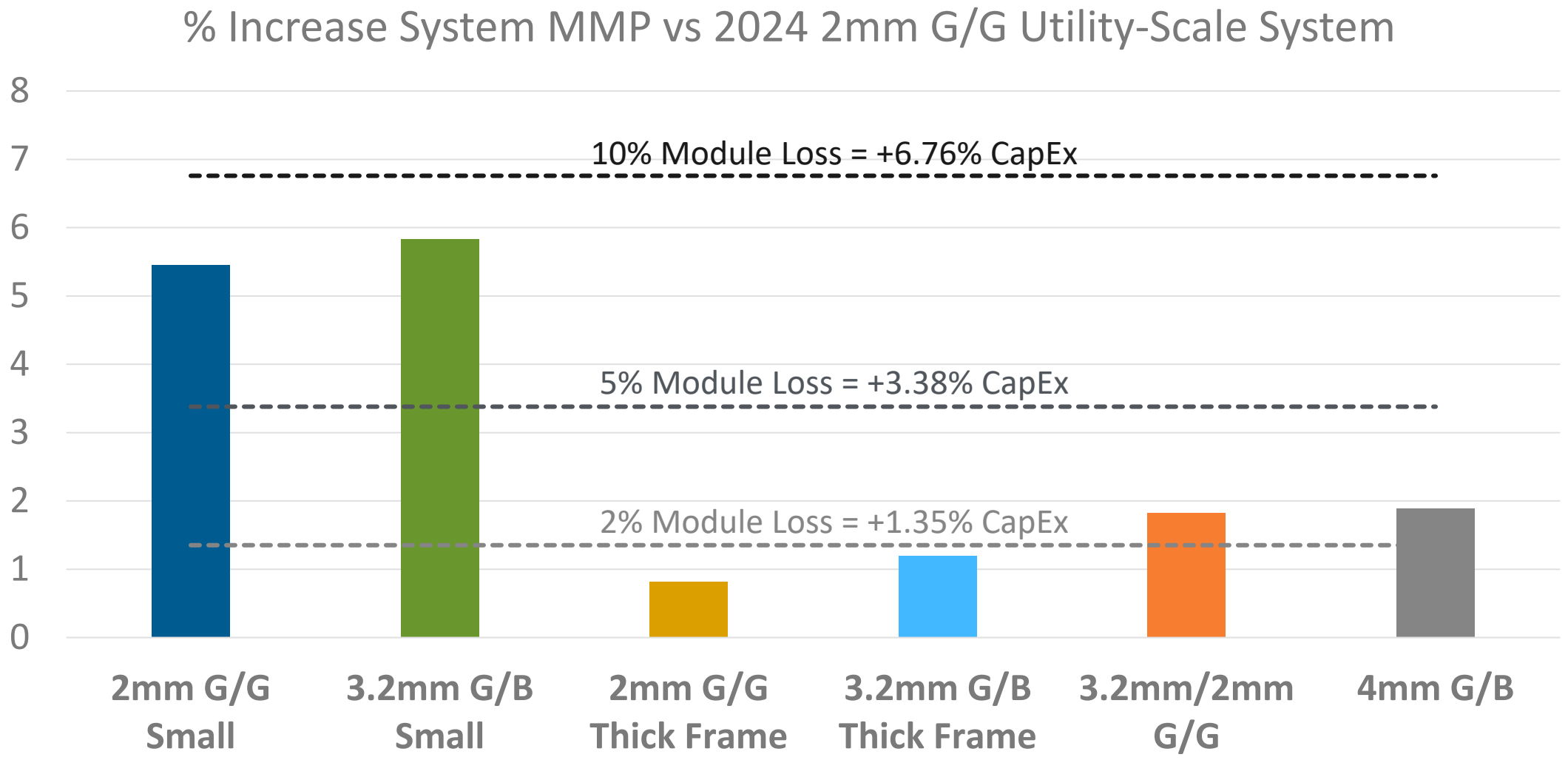
Module Type	Module Cost ($/kW$_{DC}$)	% Increase Module Cost	System CapEx ($/kW$_{DC}$)	% Increase System CapEx
	336		1118.5	-
			1138.99	**1.83**
			1139.61	**1.89**

- Hail-resistant modules are the costliest of all module designs
- The associated increase in system cost is still modest compared with smaller module sizes

Robust PV Module Cost Viability

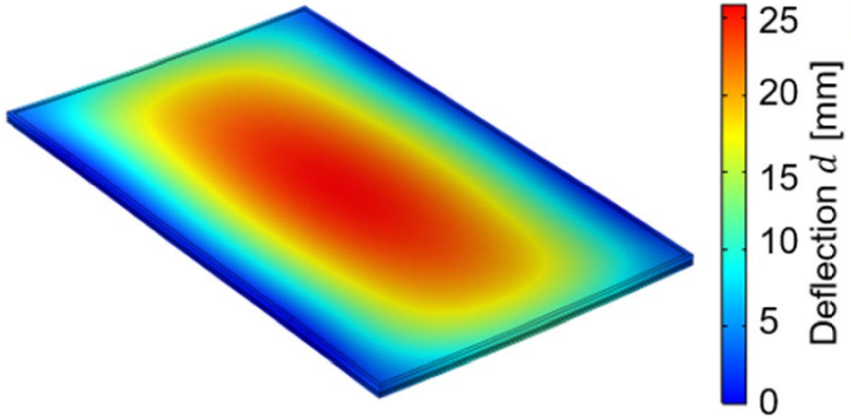


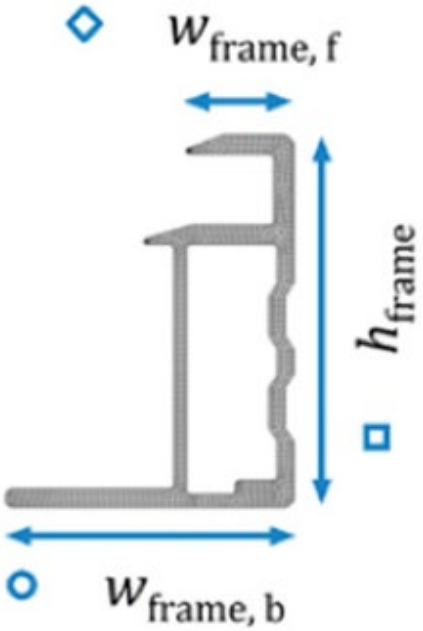
Robust PV Module System Cost Viability

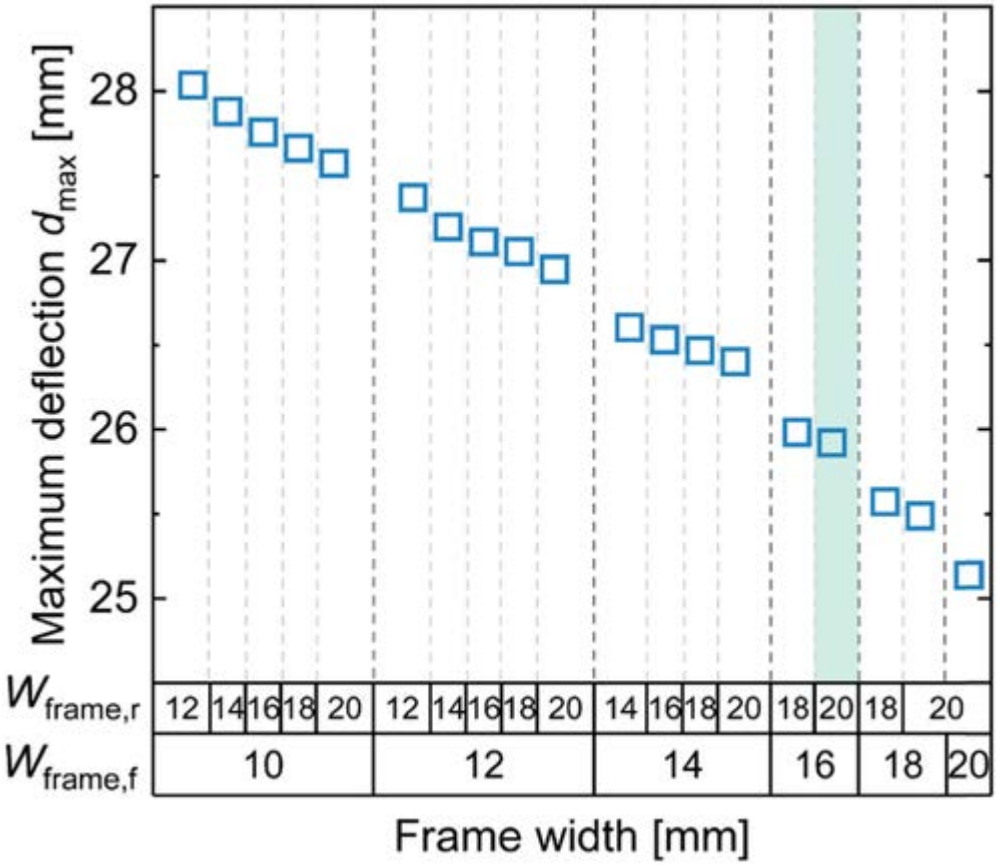


Will cost-effective changes prevent glass breakage?

Prior FEA studies have shown that thicker frames reduce module deflection



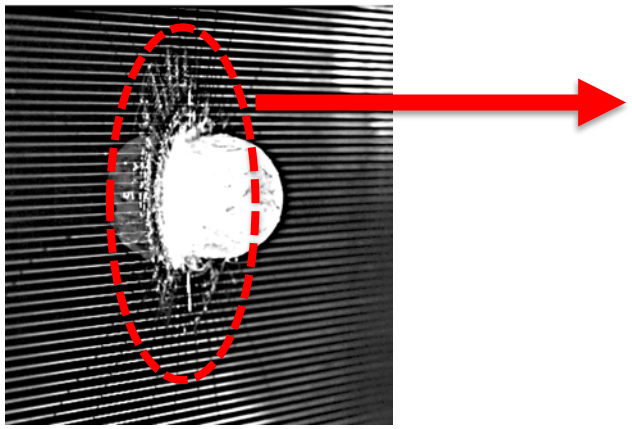


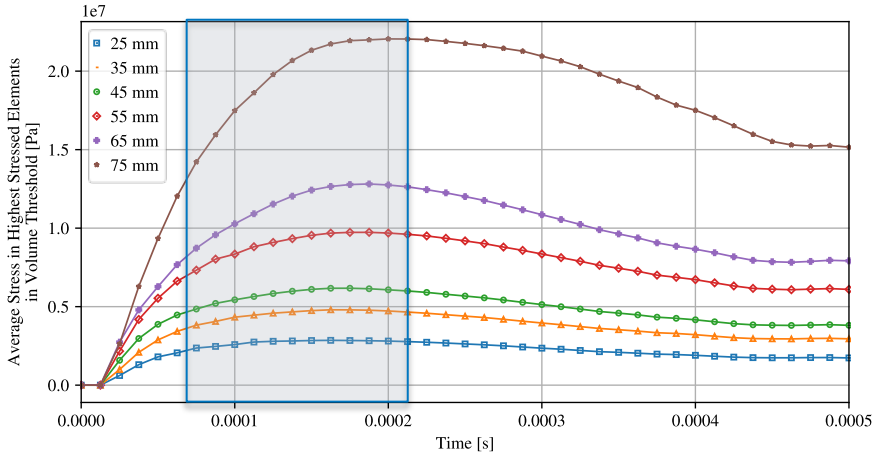


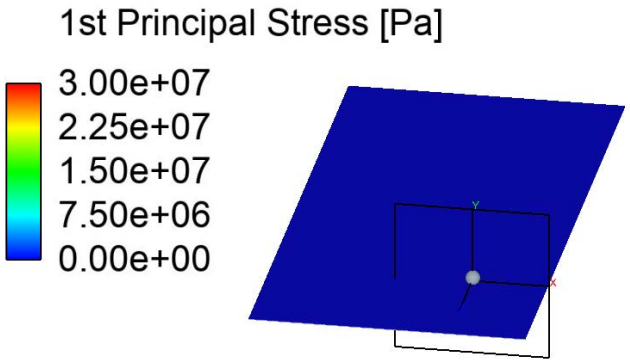
Tummalieh, Ammar, et al. "Holistic design improvement of the PV module frame: Mechanical, optoelectrical, cost, and life cycle analysis." *Progress in Photovoltaics: Research and Applications* 30.8 (2022): 1012-1022.

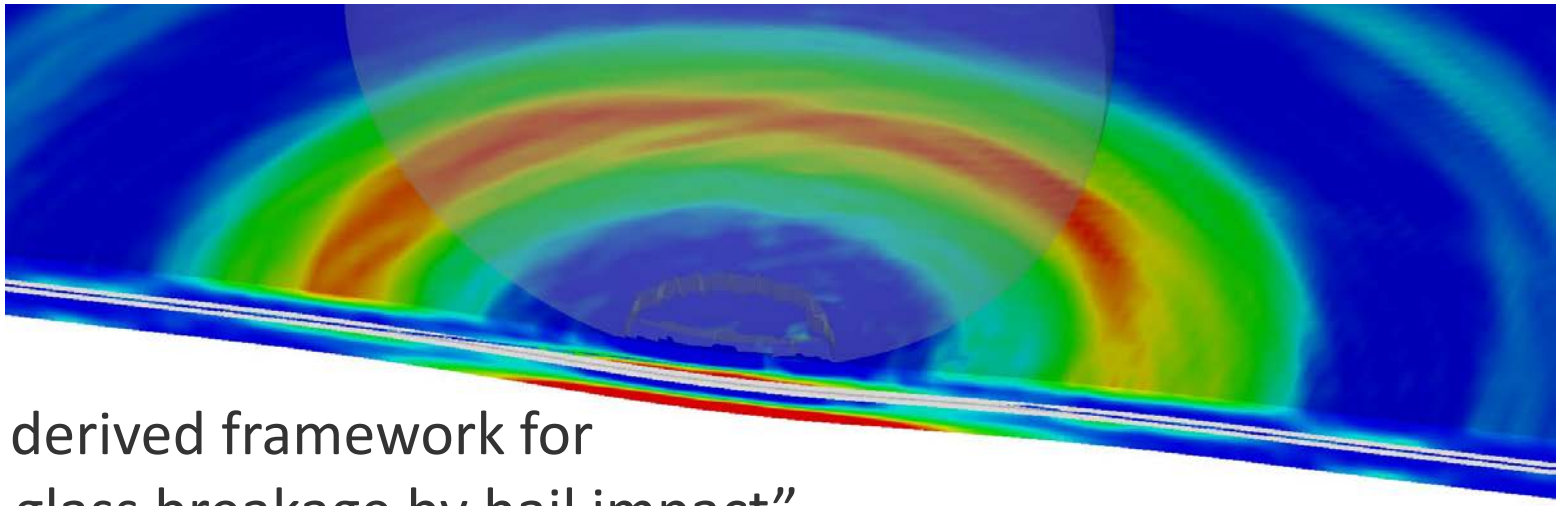
FEA evaluation of PV module hail impacts

Glass breakage from hail typically results from stress imposed at the impact site



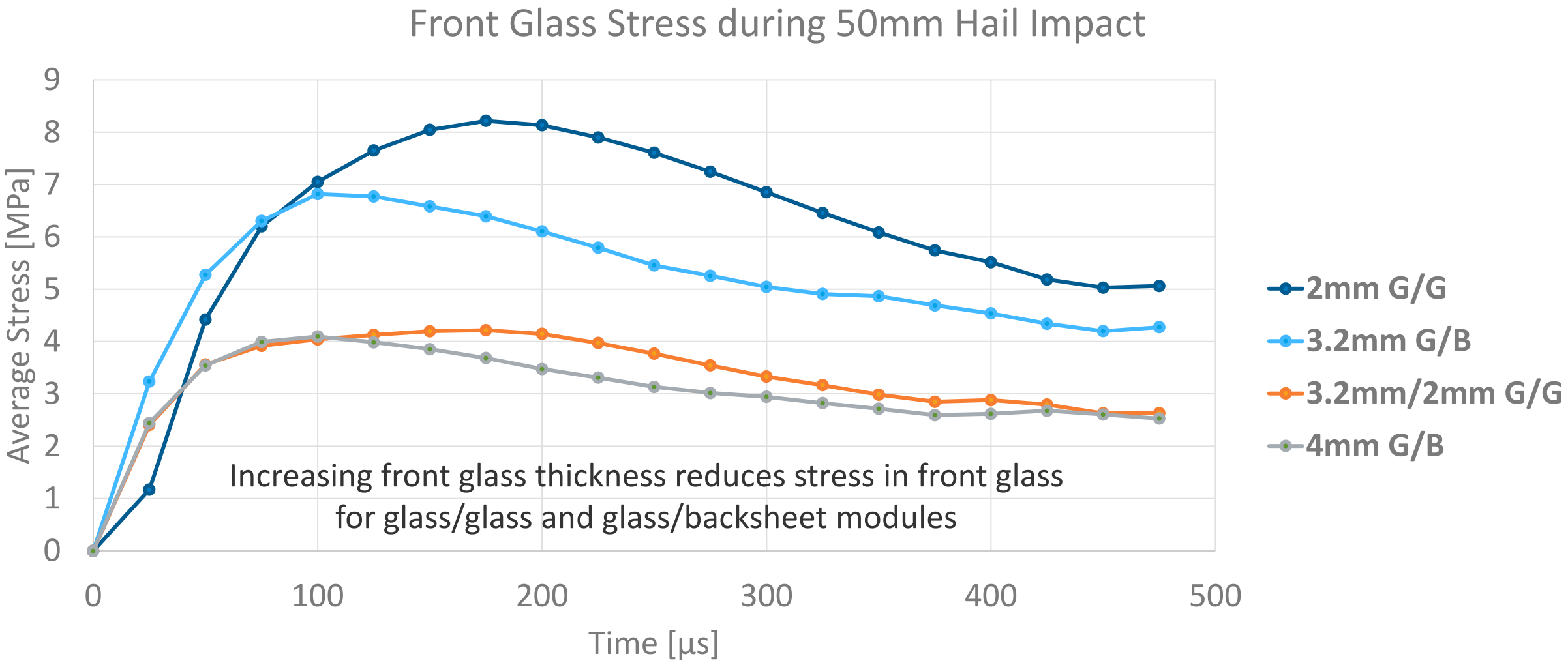




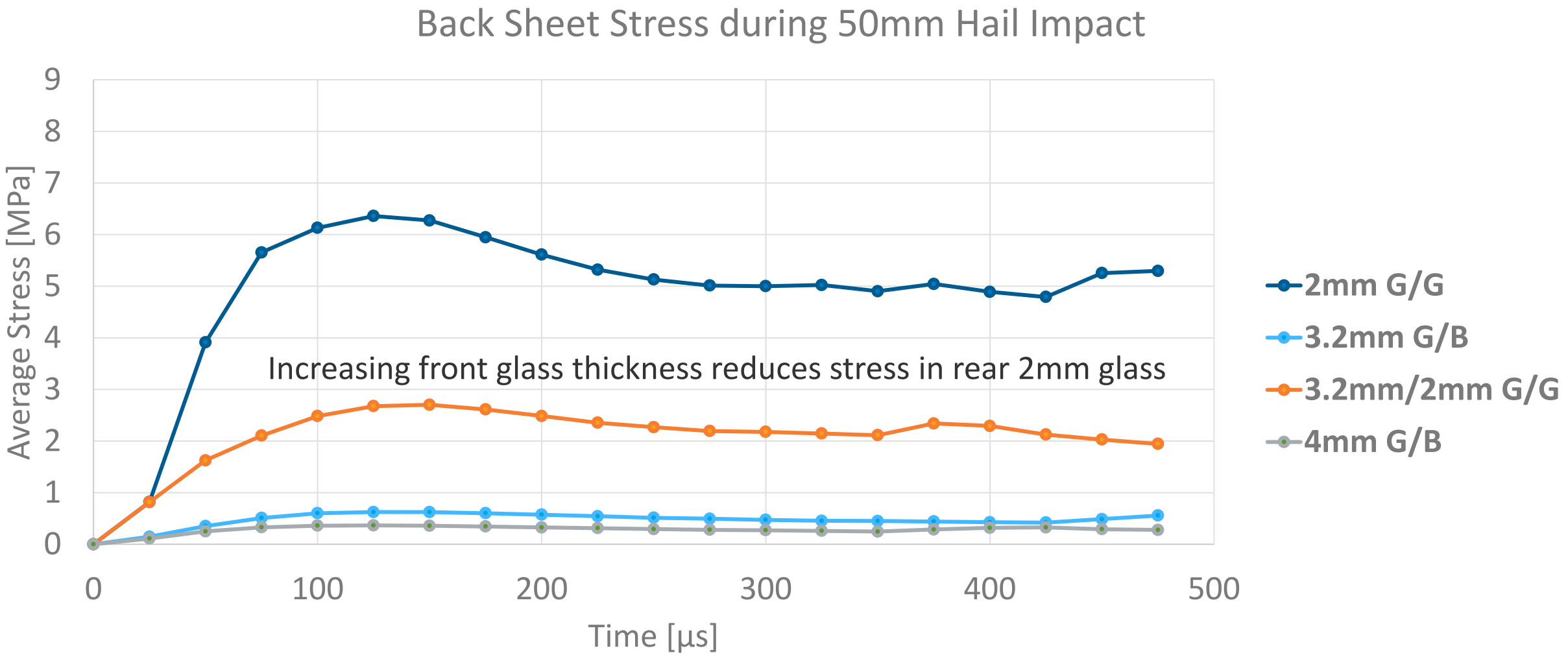


See poster 124: "A computationally derived framework for predicting probability of PV module glass breakage by hail impact"

Mechanical viability of hail-resistant modules

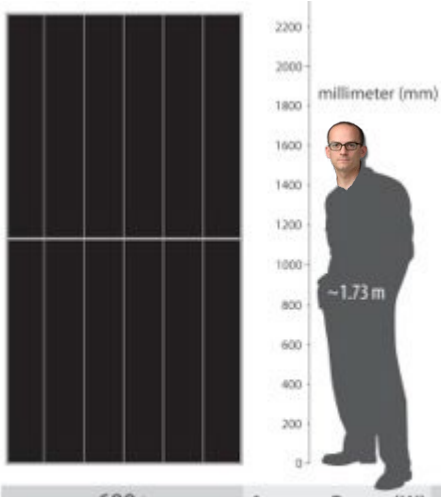


Mechanical viability of hail-resistant modules

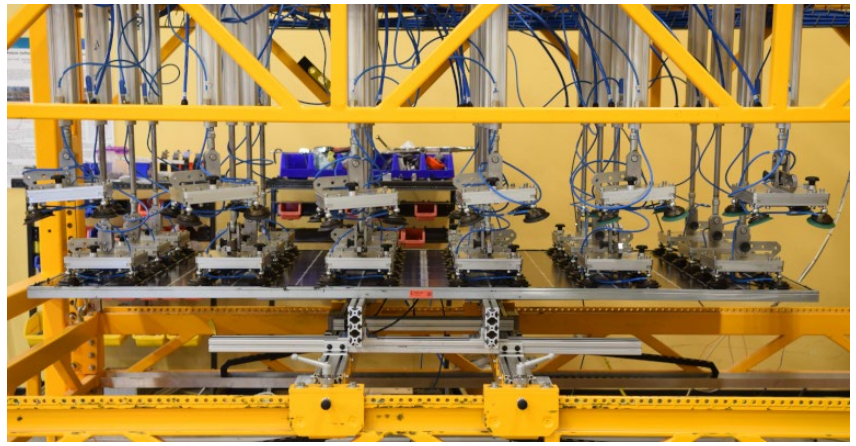


Conclusion: PV modules (probably) aren't too big*!

- *based on CapEx savings vs. replacement costs
- But they probably shouldn't get any bigger.
- As suggested by IEA PVPS Task 13, test labs, and others, **TEST MODULE AND RACKING COMPONENTS TOGETHER**
- Thicker frames are cost-effective for providing more mechanical rigidity in the array and preventing glass failure
- Hail-resistant module designs with thick front glass may be worth the investment in hail-prone regions



600+	Average Power (W)
2.8	Area (m²)
37.8	Weight (kg)



NREL
Transforming ENERGY

Spontaneous Glass Breakage in Modern Utility Glass-Glass Modules

Elizabeth Palmiotti, Timothy Silverman, Martin Springer, Nick Bosco, Michael Deceglie, Ingrid Repins, Ashley Gaulding

Photovoltaic Reliability Workshop (PVRW)
March 4-6, 2025

Photo by Dennis Schroeder, NREL 55200

NREL/PR-5K00-93391

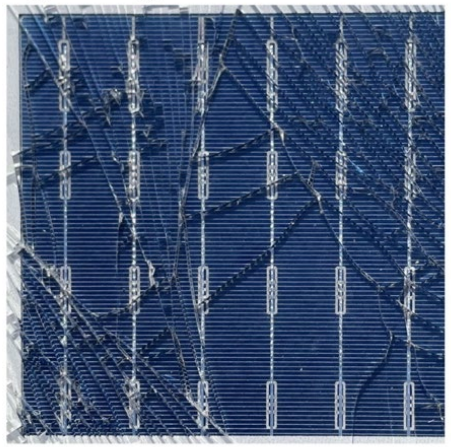
As modules change, so do reliability concerns

- PV module technology and design have changed rapidly
  - Increased area
  - Bifaciality
  - Glass/Glass architecture
  - Thinner glass
  - Thinner frames

Rise of a new failure mechanism: spontaneous glass breakage

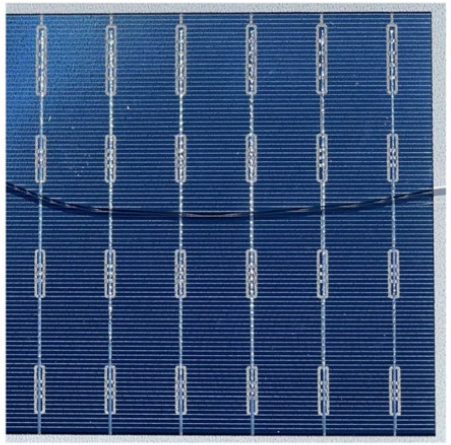
- Module glass is breaking spontaneously
  - 1-2% of modules breaking in sites under 2 years old
- Broken glass is a safety concern
  - Arc, fire, and shock hazards
- Low-energy fracture patterns
  - Not reproducible
  - Not captured by current testing standards
- The great equalizer
  - Different module sizes, manufacturers, clamps, trackers, locations

high-energy fracture



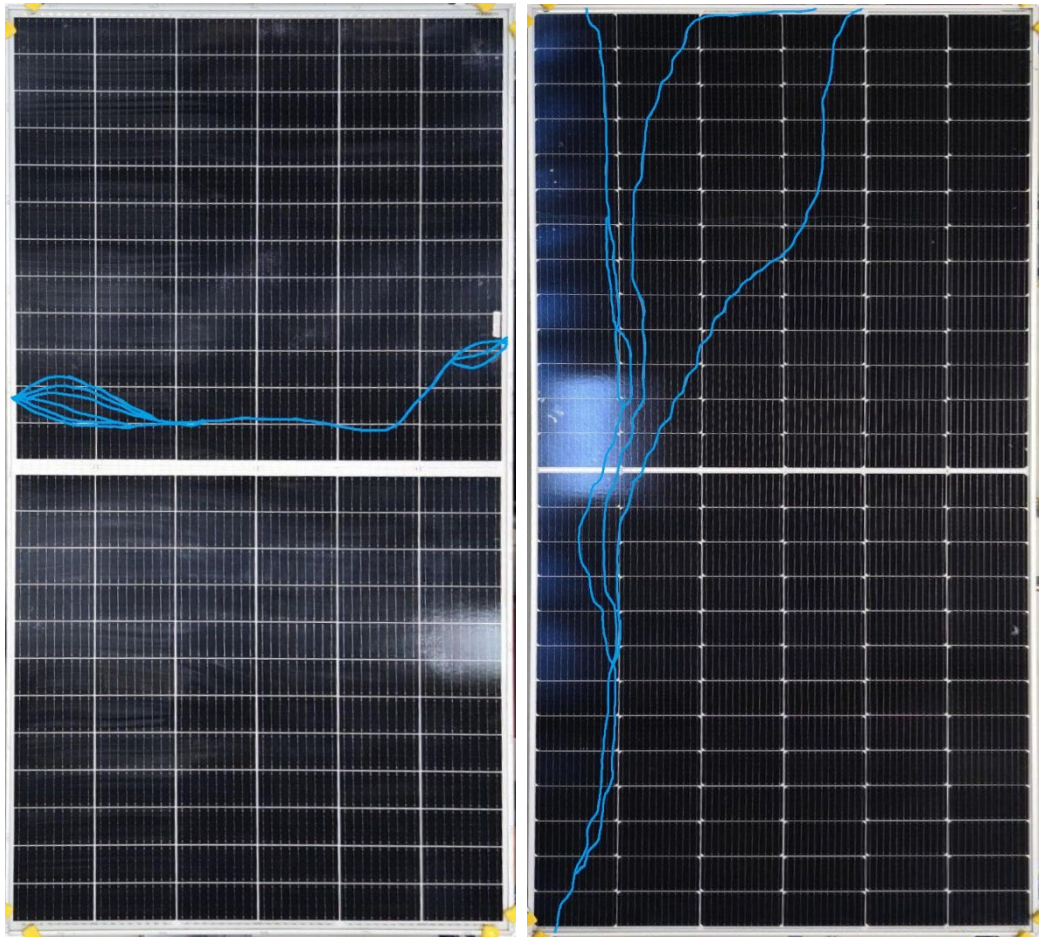
100 mm

low-energy fracture



100 mm

Different low-energy fracture patterns

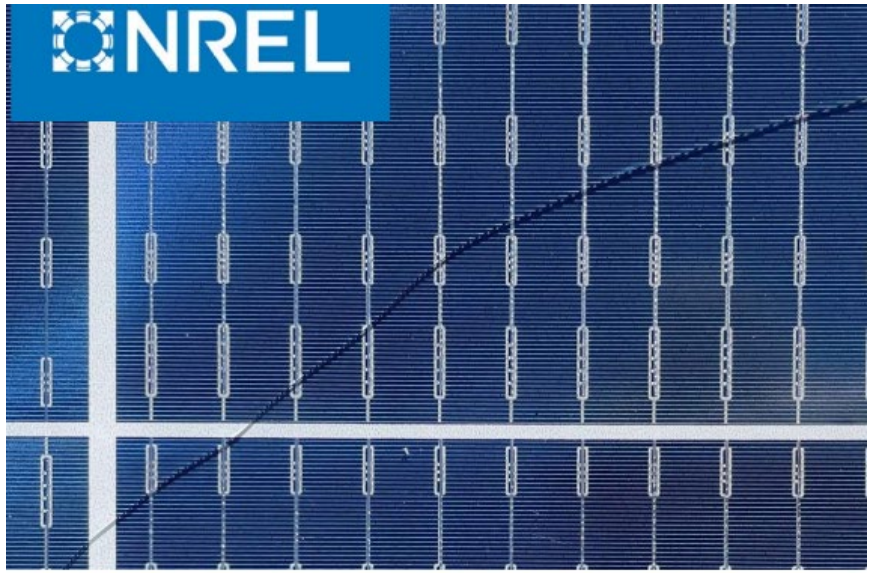


- Glass breaks by brittle fracture
  - Glass strength determined by distribution of microscopic flaws
  - Adding defects or stress increases chance of breaking
  - Thin, large glass has lower tolerance for defects

- Different combinations of defects or stress may result in different fracture patterns and likelihood of fracture

There are many risks putting PV glass on the brink of breakage

tinyurl.com/tough-break



Tough Break: Many Factors Make Glass Breakage More Likely

Timothy J Silverman,[1] Elizabeth C. Palmiotti,[1] Martin Springer,[1] Nick Bosco,[1] Mike Deceglie,[1] Ingrid Repins,[1] and Ashley Gaulding[1]

RISKS

- Reduced glass strength
- Edge pinch
- Surface and edge flaws
- Inadequate support of module
- Glass contact with frame

Risk:
Reduced Heat Strengthening

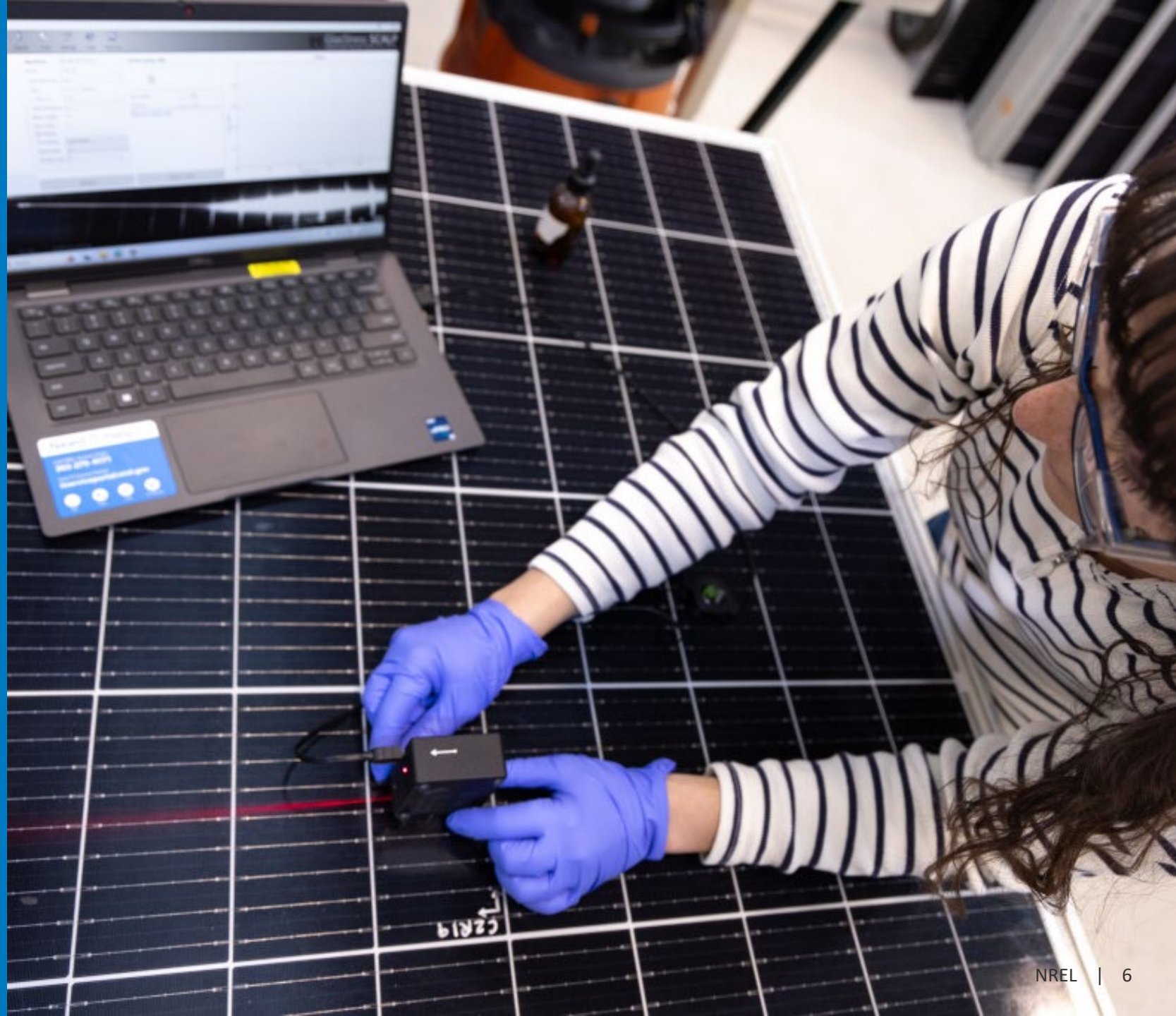
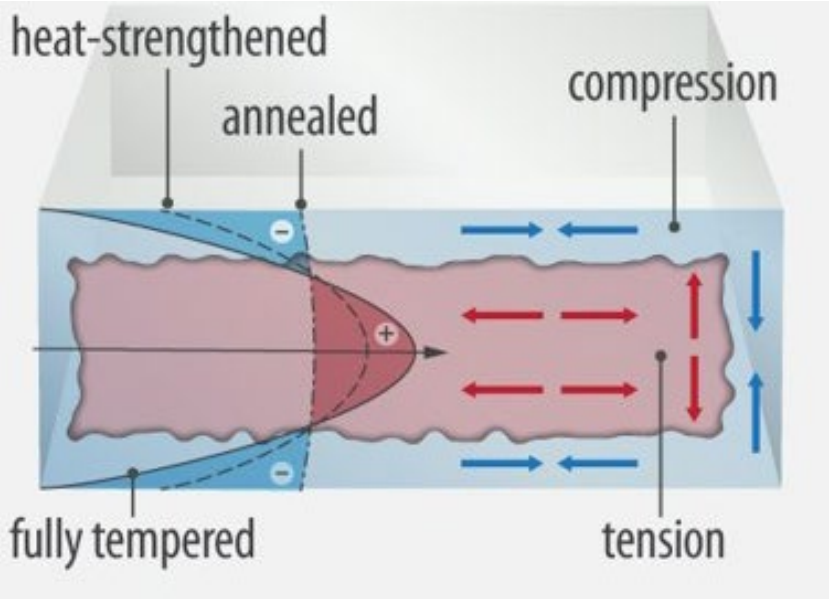
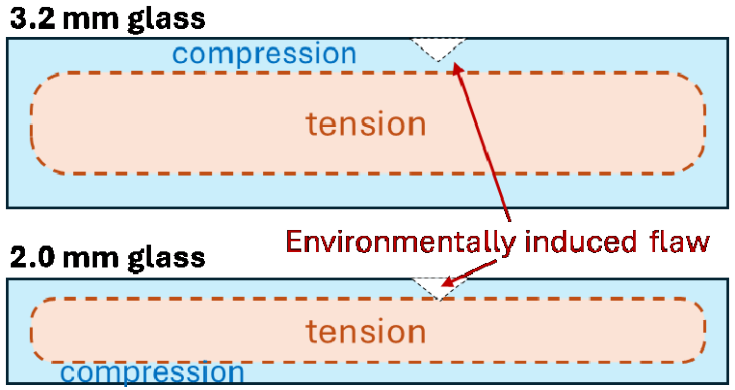


Photo by Agata Bogucka / NREL

Glass heat strengthening



E. C. Palmiotti et al., *IEEE Journal of Photovoltaics,* 2025, doi: 10.1109/JPHOTOV.2025.3526170.



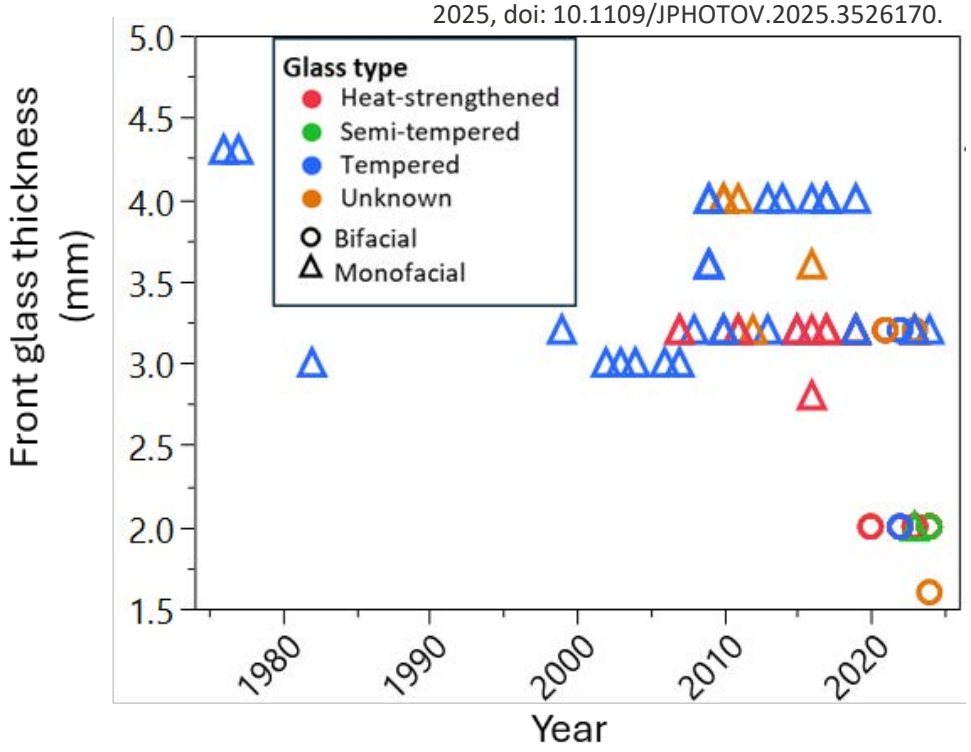
- Heat treatments introduce compressive surface stress that squeezes flaws together
  - Makes it harder for flaws to open
  - Open flaws can propagate into cracks

- Thinner glass has a thinner compressive region
  - Less tolerance to deep flaws

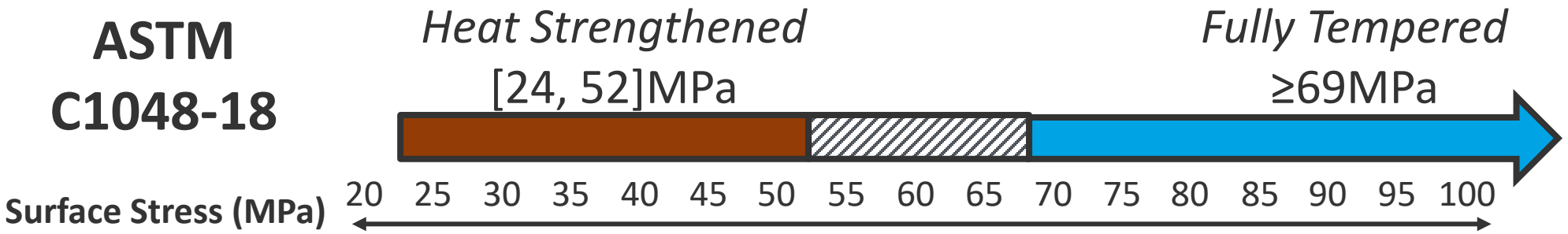
Quantification of glass surface stress

- No specific PV glass standards
  - Variability in datasheets
    - Most do not cite a standard
  - ASTM C1048-18 most relevant
    - "Standard Specification for Heat-Strengthened and Fully Tempered Flat Glass"

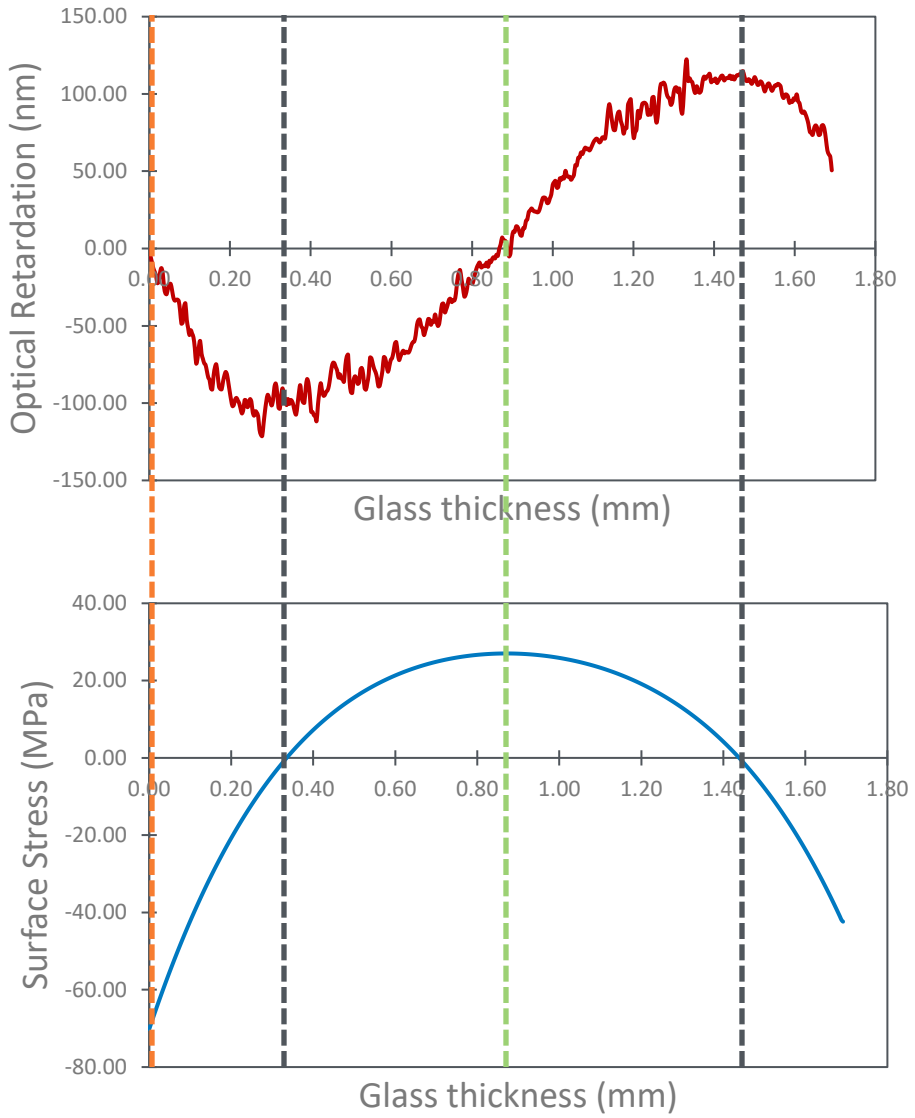
E. C. Palmiotti et al., *IEEE Journal of Photovoltaics*, 2025, doi: 10.1109/JPHOTOV.2025.3526170.

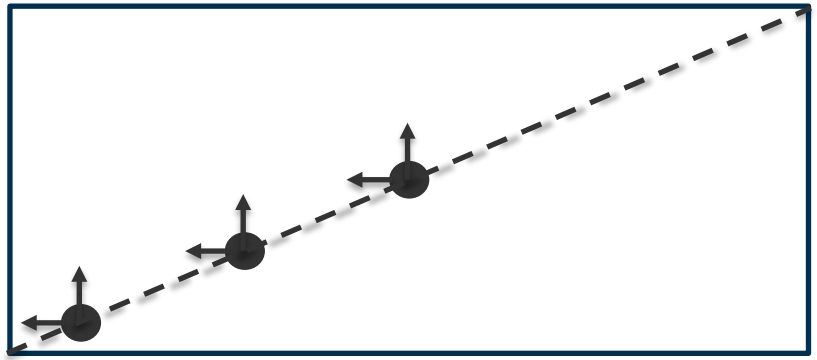


ASTM C1048-18



How do we measure surface stress?



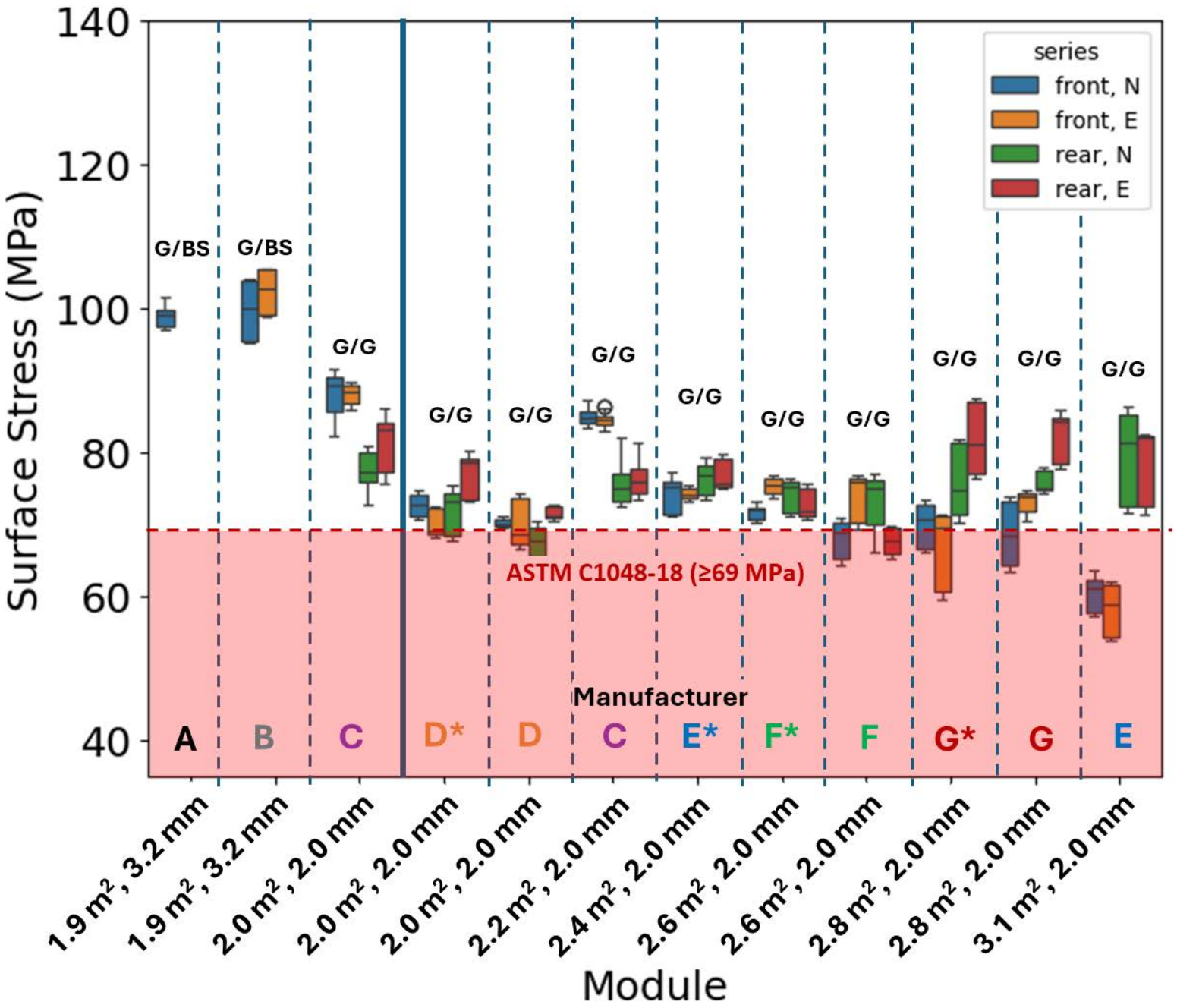


- Scattered light polariscope (SCALP)
  - Measures depth-dependent stress in glass
  - Some technique needed to measure PV glass
    - Glass texture and metallization reflections

Reduced strengthening in 2.0mm glass

- 3.2mm and 2.0mm glass are fully tempered
- Lower surface stress in 2.0mm glass
  - Impacts fracture pattern

- **Surface stress is a *continuum.*** Resist temptation to draw a threshold value!

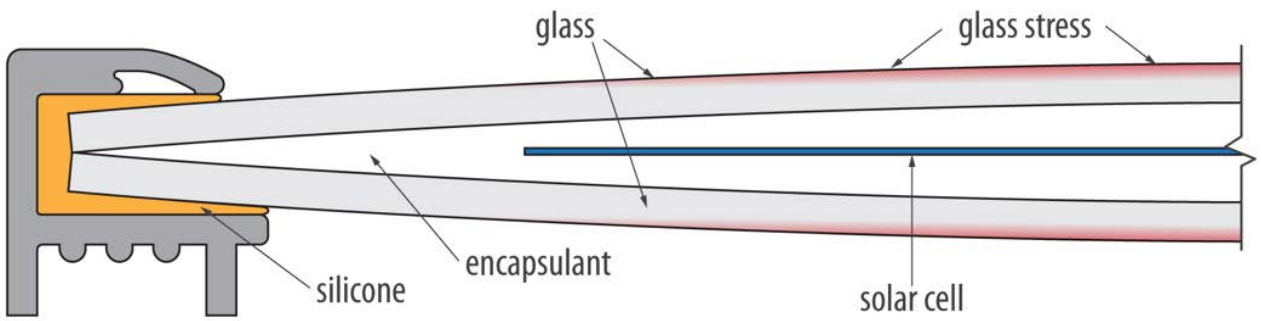


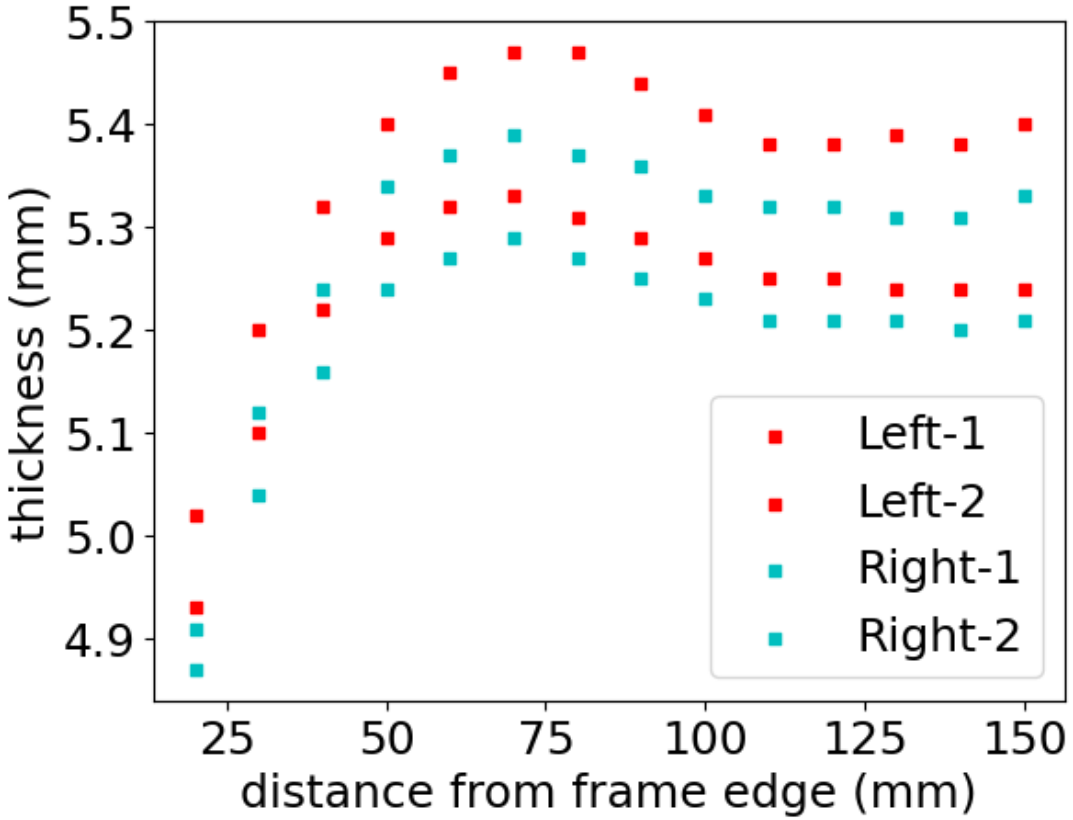
Risk:
Edge Pinch

Photo by Agata Bogucka / NREL

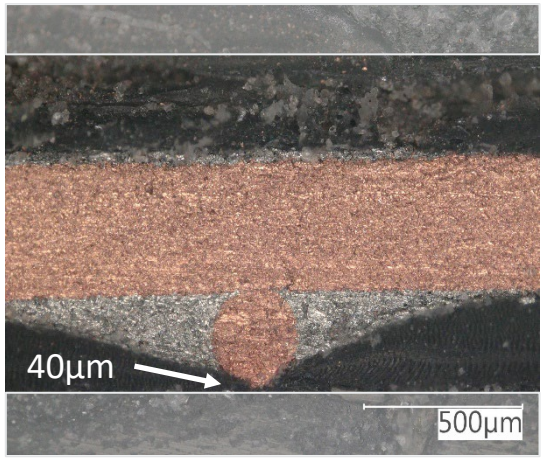
Measured c-Si glass-glass modules have edge pinch

- Measured edge pinch in all investigated c-Si modules so far
- Edge pinch causes bending of both sheets of glass
- Results in tensile stress on outside of the glass
  - Reduces glass strength
  - Increases risk of flaw growth

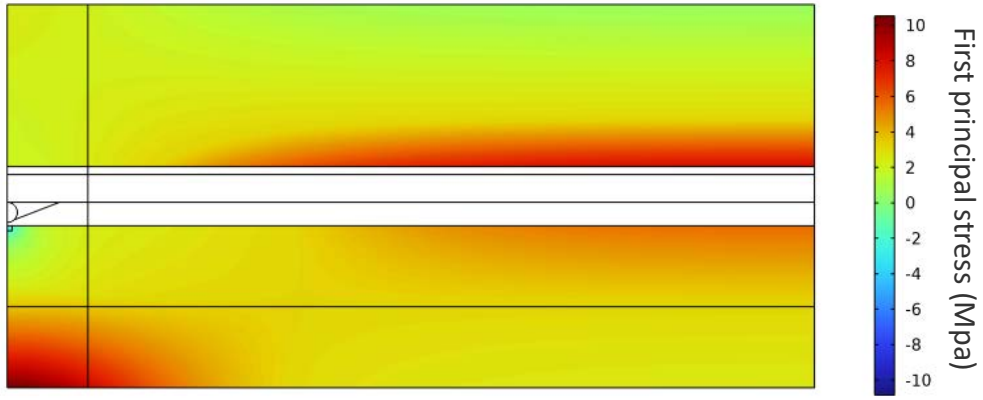




Edge pinch risk compounded by insufficient encapsulant between glass and busbar ribbon

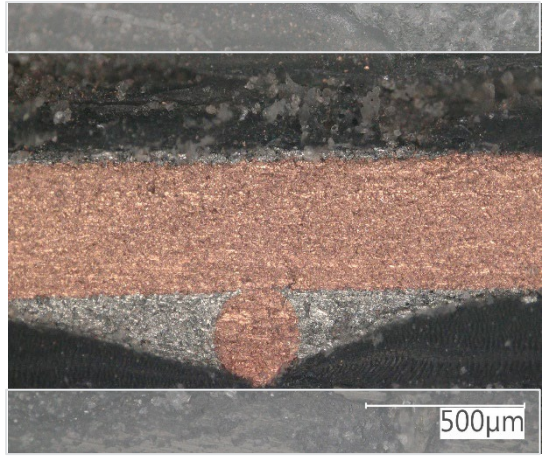


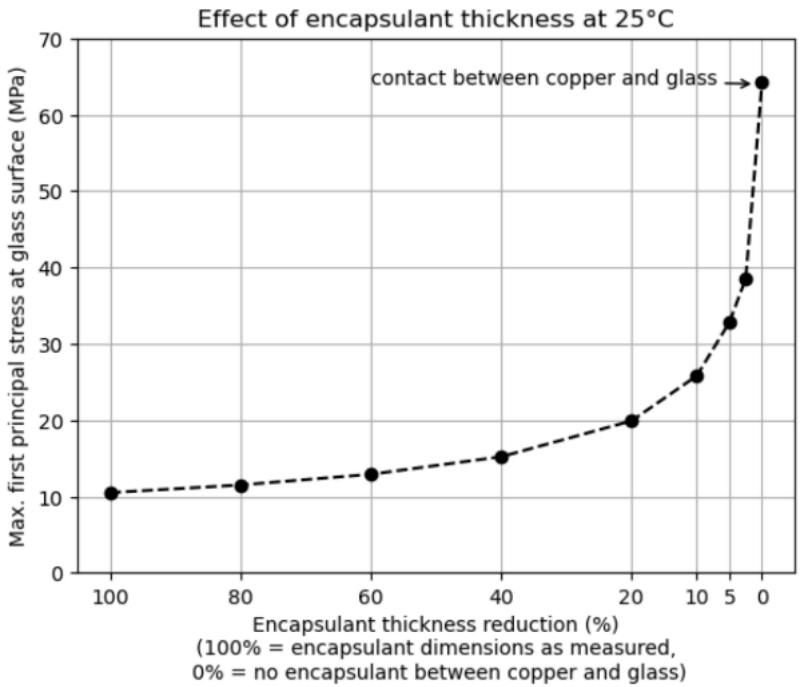
Post-Lamination

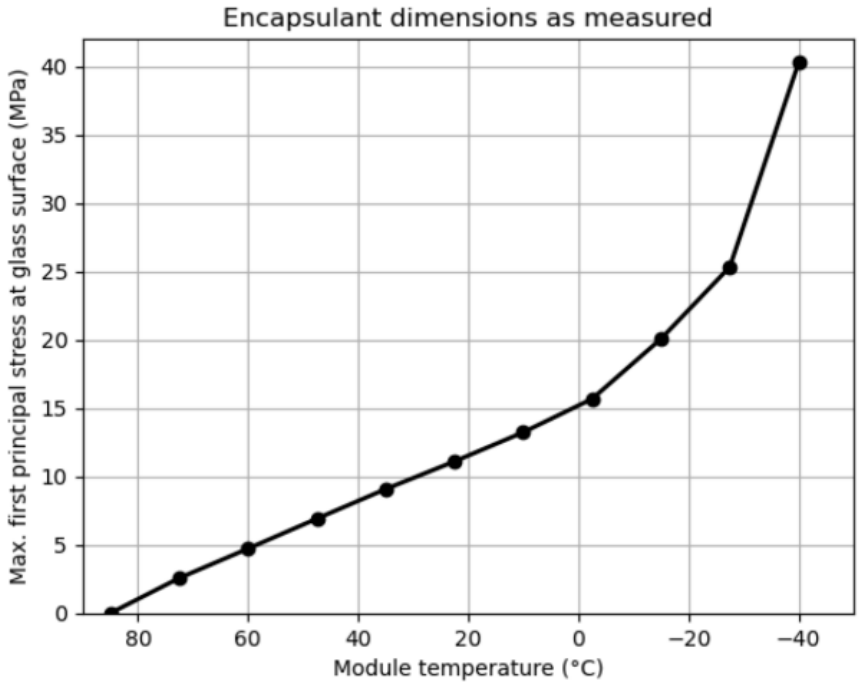


Glass and metal contact during lamination adds *more* stress to glass

Edge pinch risk compounded by insufficient encapsulant between glass and busbar ribbon





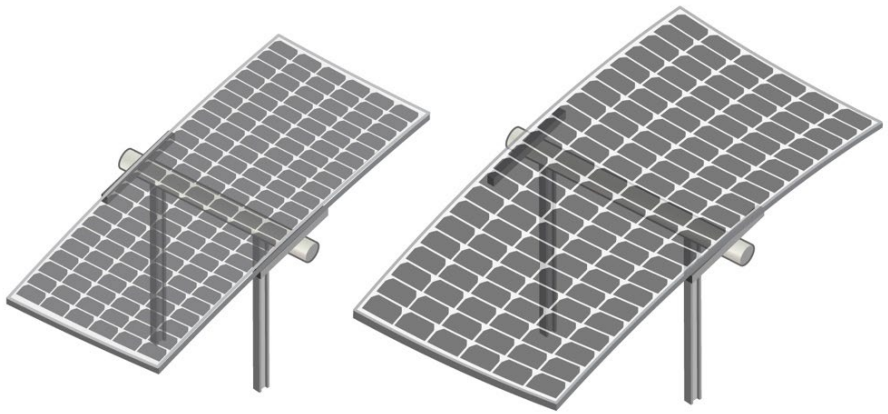


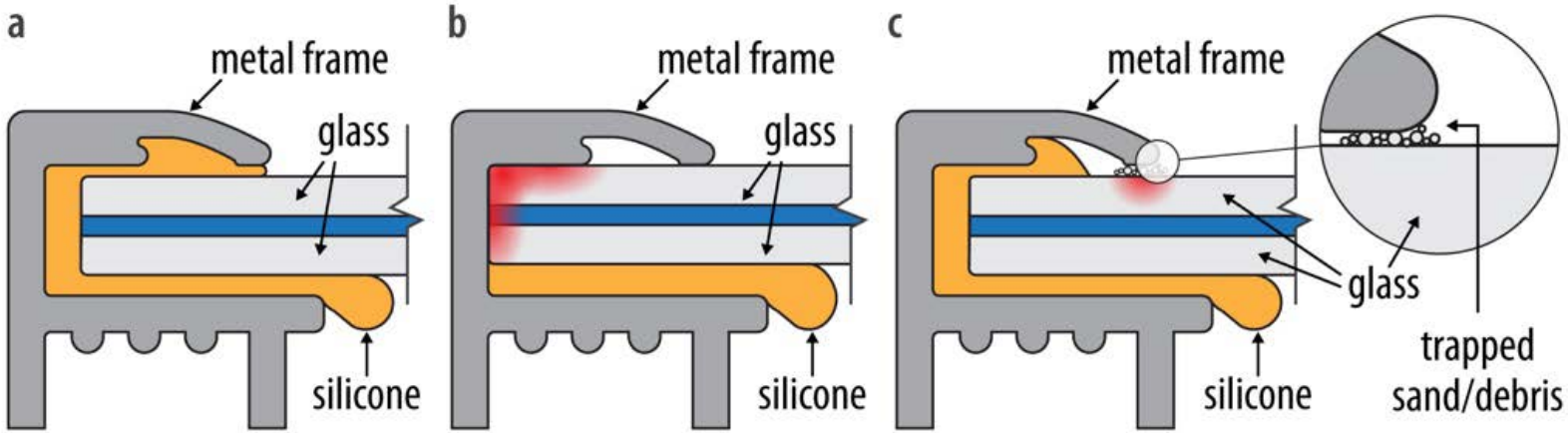
Stress increases with *decreasing* encapsulant thickness and *decreasing* module temperature.

More stress puts the glass at greater risk for fracture!

Additional Risks:

-Surface and edge flaws
-Inadequate support
-Contact with frame





Tough Break

NREL

Tough Break: Many Factors Make Glass Breakage More Likely

Timothy J Silverman,[1] Elizabeth C. Palmiotti,[1] Martin Springer,[1] Nick Bosco,[1] Mike Deceglie,[1] Ingrid Repins,[1] and Ashley Gaulding[1]

National Renewable Energy Laboratory

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

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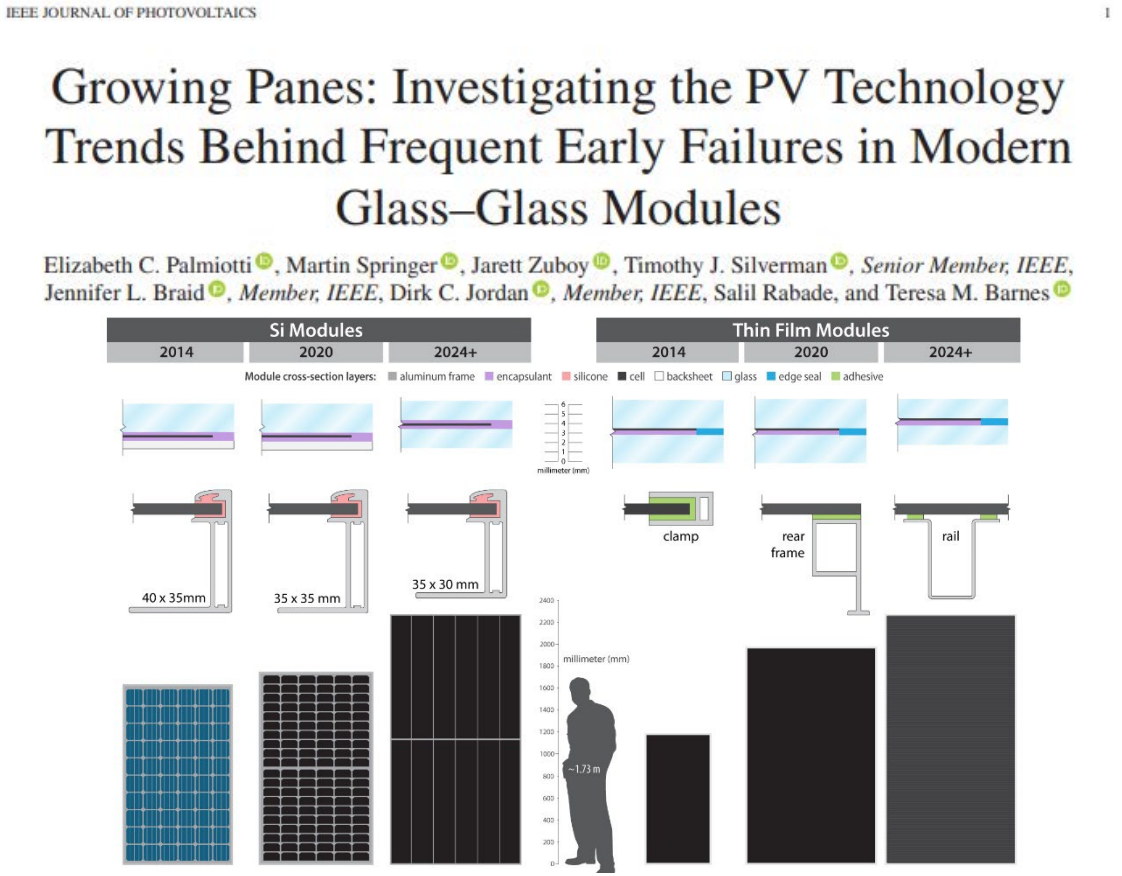
Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5K00-91695
November 2024

tinyurl.com/tough-break

Growing Panes

DuraMAT
Durable Module Materials Consortium



IEEE JOURNAL OF PHOTOVOLTAICS 1

Growing Panes: Investigating the PV Technology Trends Behind Frequent Early Failures in Modern Glass–Glass Modules

Elizabeth C. Palmiotti, Martin Springer, Jarett Zuboy, Timothy J. Silverman, *Senior Member, IEEE*, Jennifer L. Braid, *Member, IEEE*, Dirk C. Jordan, *Member, IEEE*, Salil Rabade, and Teresa M. Barnes

tinyurl.com/growing-panes

Sock puppet account's solutions to minimize risks

@PVreliabilitynerd

- Reduced glass strength
  - Maximize surface stress for glass thickness
- Edge pinch
  - Eliminate all edge pinch
- Surface and edge flaws
  - Fully polish the edge
  - Establish a criterion and inspect the edge
- Inadequate support
  - Stop making modules so big
  - Return to deep frames with thick walls
- Glass contact with frame
  - Have sufficient silicone between the frame and laminate
  - Establish a criterion and survey silicone distribution

Help us help you!

- Are the puppet's solutions reasonable asks? Are they cost prohibitive?
- How do you set acceptable risk levels?
- How do you decide where to compromise?

- What does the community need? What type of output(s) are useful?
  - Actual recommendations and thresholds
  - Factory inspection documentation
  - IEC standards
  - Academic papers

Thank you!

Elizabeth.Palmiotti@nrel.gov

www.nrel.gov

The authors thank Rachael L. Arnold and Aubrey Jackson for experimental contributions to this presentation.

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office (SETO) agreement no. 52785. Funding provided as part of the Durable Module Materials Consortium 2 (DuraMAT 2) funded by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Office, agreement number 38259. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes

Publication Number NREL/PR-5K00-93391

NREL
Transforming ENERGY

PV Reliability Workshop 2025

Accelerated UVID Testing and Comparison to Outdoor Testing

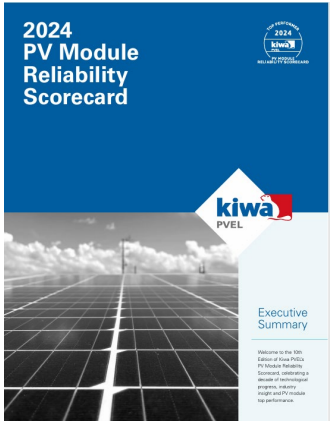
Archana Sinha, Jean-Nicolas Jaubert, Todd Karin (Kiwa PVEL)
Dana B. Kern (NREL)

Mar 5, 2025

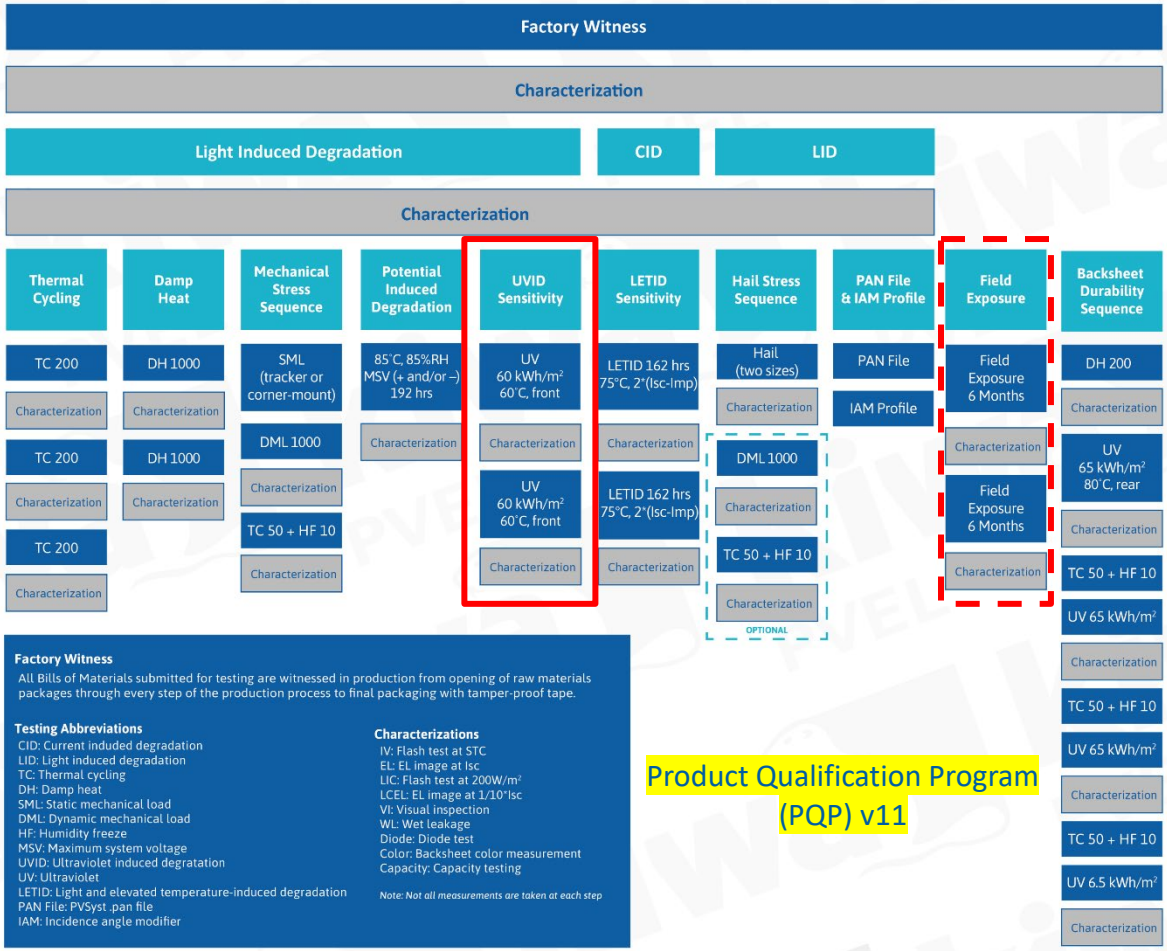
We Create Trust

About Kiwa PVEL

- Independent lab for PV Module **Performance and Reliability Testing.**
- Developed PQP test sequences.
- Releases PV Module Scorecard every year.
- Lists “Top Performer” for their superior test results.



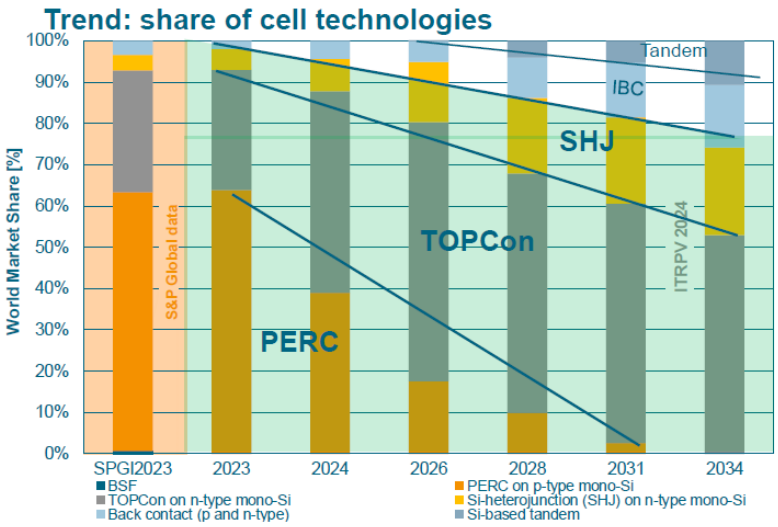
TOP PERFORMER 2024 kiwa PVEL PV MODULE RELIABILITY SCORECARD



Product Qualification Program (PQP) v11

Solar PV Market Shift and UVID Concern

- Rapid adoption worldwide of n-type silicon cell topologies (TOPCon, HJT, xBC, …).
  - Higher efficiency due to better metallization scheme and improved passivation quality.
  - UV transparent encapsulants for current gain.
- Marketed with improved first year (-1%) and annual degradation rates (<-0.4%).
  - Kiwa PVEL's testing shows resiliency to LID and LETID.
- Higher **vulnerability to UV-induced degradation (UVID)** due to increased cell sensitivity to UV radiation (280-360 nm).
  - Negative impact on energy yield, reliability and bankability.



Source: ITRPV 2024

Kiwa PVEL's UVID Testing

- Testing **large-size industrial modules**.
- Outdoor preconditioning for LID stabilization.
- UV Testing with front-side exposure only.
- Exposure dose **120 kWh/m²** of UV (280-400 nm) when using metal-halide lamps or **55 kWh/m²** when using UV fluorescent lamps.
  - Equivalent to 1-2 years of outdoors, depending on location.
- Operating conditions: **module temperature 60°C ± 5°C**, under **short-circuit (SC) condition.**
  - *Historical testing results under UVF bulbs that contribute very little to the current generation.*
- Characterization include visual inspection, I-V at STC and low irradiance, high & low-current EL, wet leakage current test.

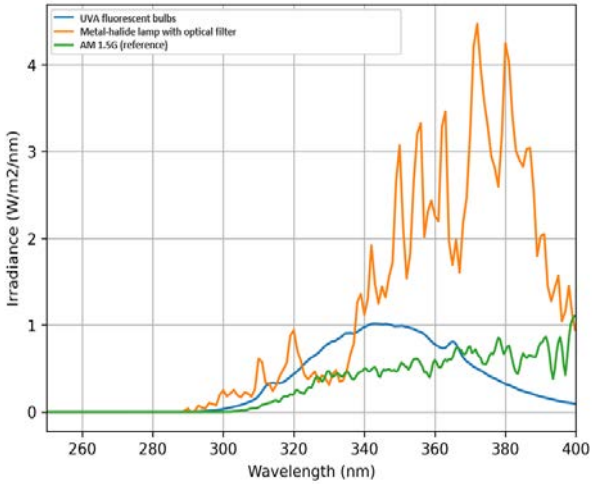
UVID Sensitivity

UV 60 kWh/m² 60°C front

Characterization

UV 60 kWh/m² 60°C front

Characterization



New UV Chambers at Napa Lab

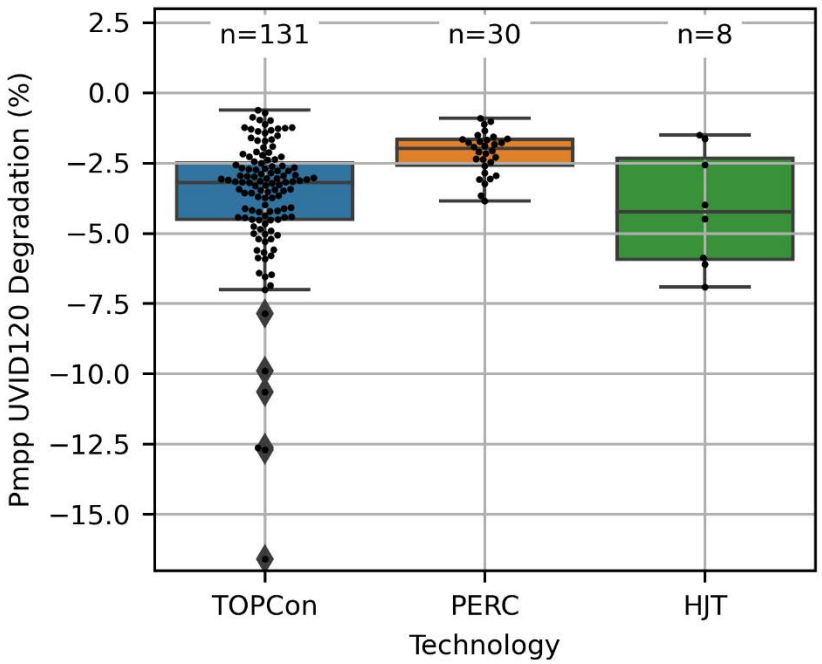
- Added two new UV chambers equipped with high-power UVF bulbs.
- **Higher UV intensity**, faster turnaround time.
- **In-house design and built from scratch.**
- Each chamber can accommodate **8 large-size modules (max. 2.7 m x 1.6 m)**.
- **Enhanced uniformity and control** over UV exposure conditions.
- **In-situ monitoring** of module temperature and UV irradiance at module test plane.

UVID Test Results: Variation with Cell Technology

- More than 85 BOMs evaluated, 2 modules per BOM.
  - 75% of them are TOPCon.

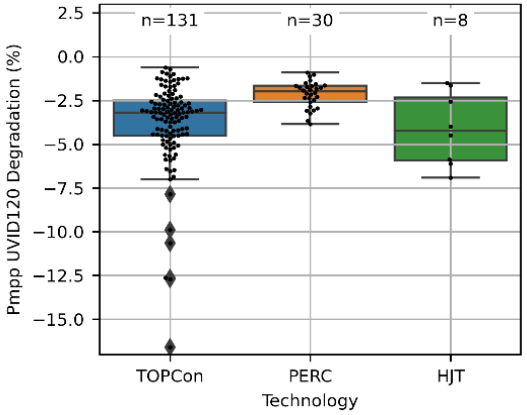
- Power degradation varies with cell technology.
  - TOPCon: range -0.6% to -17%, **median -3.1%**.
  - HJT: range -1.5 to -7%, **median -4.2%**, limited samples.
  - PERC: **median -2.2%.**

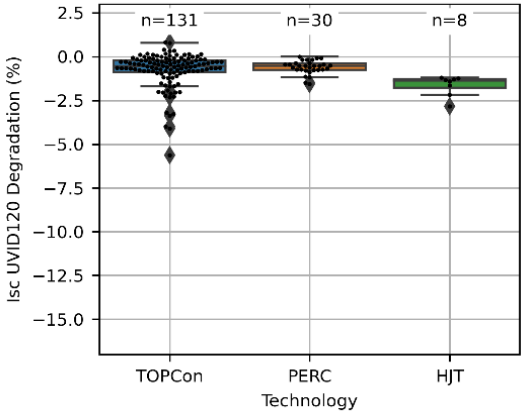
- UVID power loss is higher in n-type modules than p-type modules.
  - **N-type modules are more UVID-sensitive.**

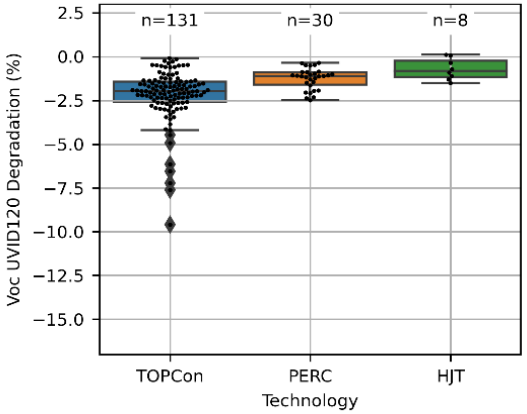


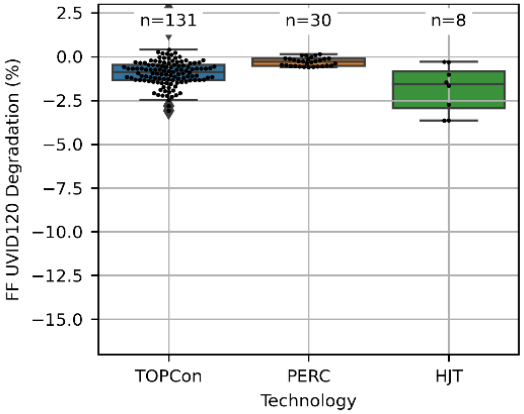
Degradation in I-V Parameters

- TOPCon:
  - **Voc** is the most affected parameter → ***passivation loss***
  - Few BOMs showed greater Isc & FF losses → ***mismatch loss***
- HJT:
  - **Isc and FF losses** are significant → ***front TCO layer degradation***
  - Voc is fairly stable
- Different UVID failure mechanisms occurring concurrently in different cell types.





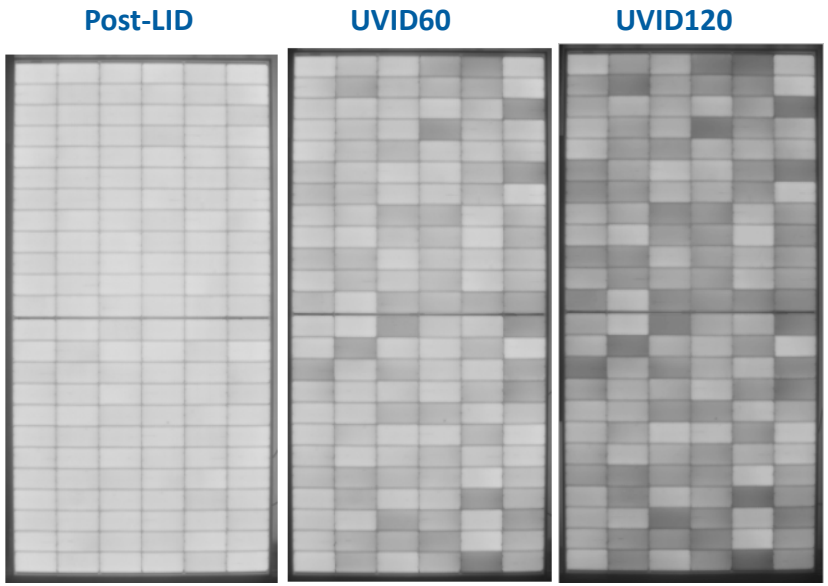




Degradation is Heterogeneous

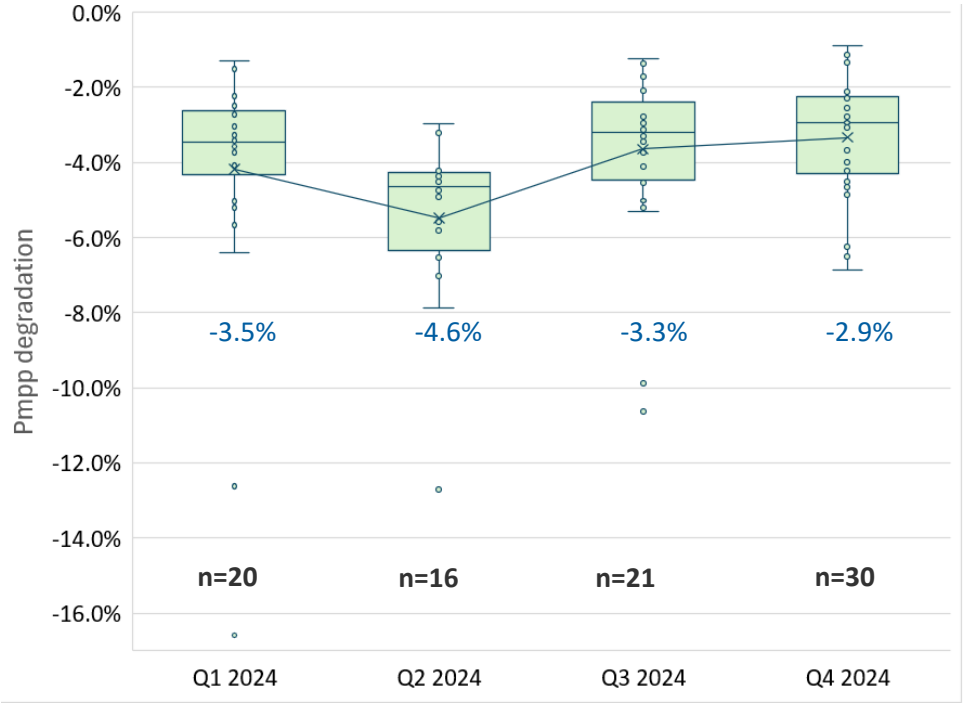
- Checkerboard pattern in EL images.
- Cells degrade **randomly** within the module, with no distinct pattern with position.
- Verified the pattern has **no correlation to the light non-uniformity** in the chambers.
- Possibly due to **variation in front cell passivation thickness** (critical parameter) during process quality control.

- Testing based on one-cell sample is not sufficient.
  - Test multiple cells
  - Perform batch testing



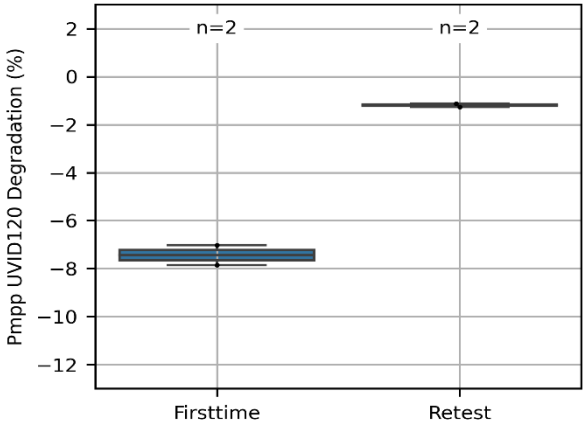
UVID Testing Timeline: Cell Processes Improvement

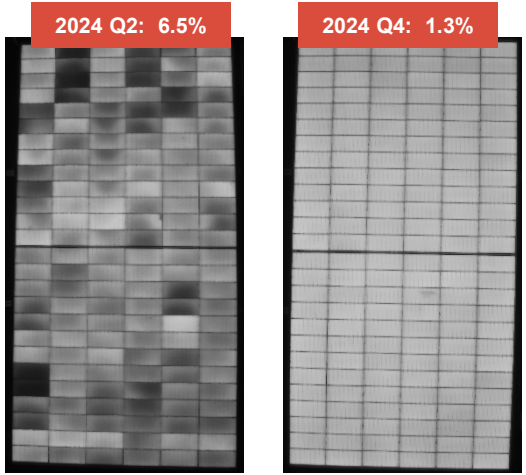
- Post-UVID120 power loss against samples production time (factory audit).
- Only results for TOPCon BOMs shown.
- Samples from Q1-Q2 showing worst results than Q3-Q4.
- **Less samples with excessive >-5% power loss in recent quarters.**
- Slight improvement in median power loss.
- Some manufacturers nailed it down (<-2% loss).



UVID Mitigation at Cell Level

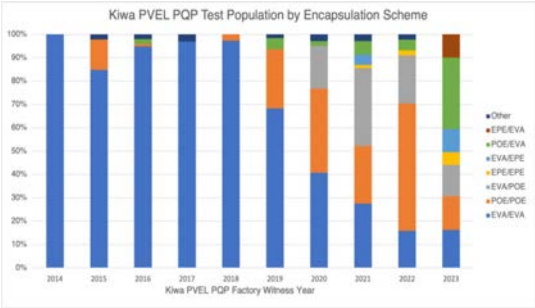
- Tier-1 cell manufacturer.
- First project tested in 2024 Q2, retest in 2024 Q4 with same BOM.
  - TOPCon cells in G//G construction.
  - EPE/EVA encapsulation scheme, standard recipe.
- From worse to best-in-class.
  - Original samples Pmax degradation -7.6% (average), strong checkerboard pattern.
  - Retest samples degraded by only-1.4% (average), no EL defects.
- Earlier discussion with manufacturer, pointed out to **front cell ARC/passivation layer process controls**.
- Two other projects with similar excellent results after recent UVID retests.

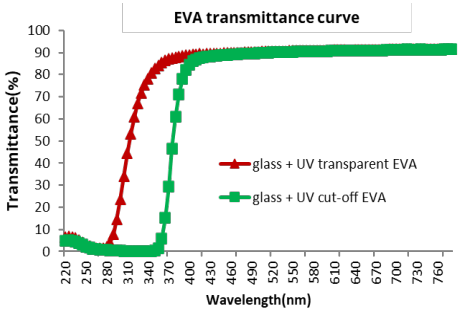


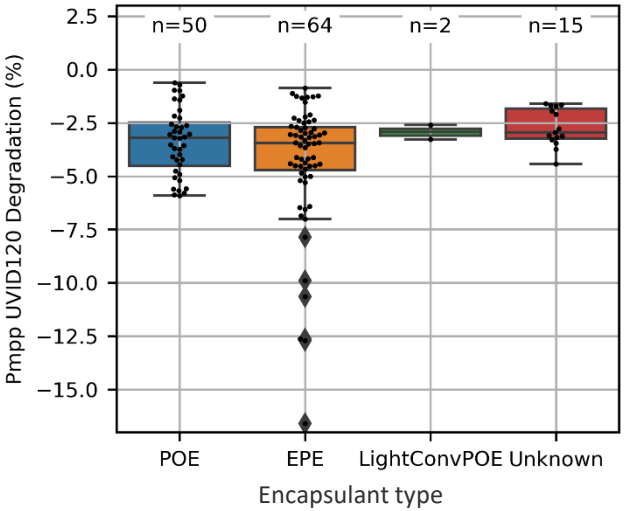


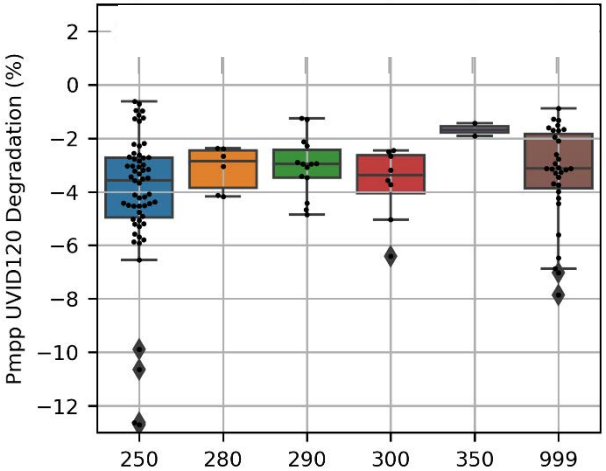
Role of Encapsulant

- TOPCon modules with varying encapsulant type.
- Base resin is not important, but **additives and UV cut-off wavelength are critical**.
  - Degradation increases with lower cut-off wavelength.
  - Higher degradation with UV transparent encapsulants.





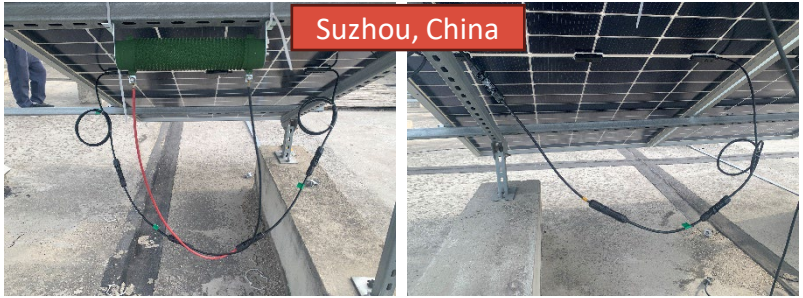




"999" refers to Unknown

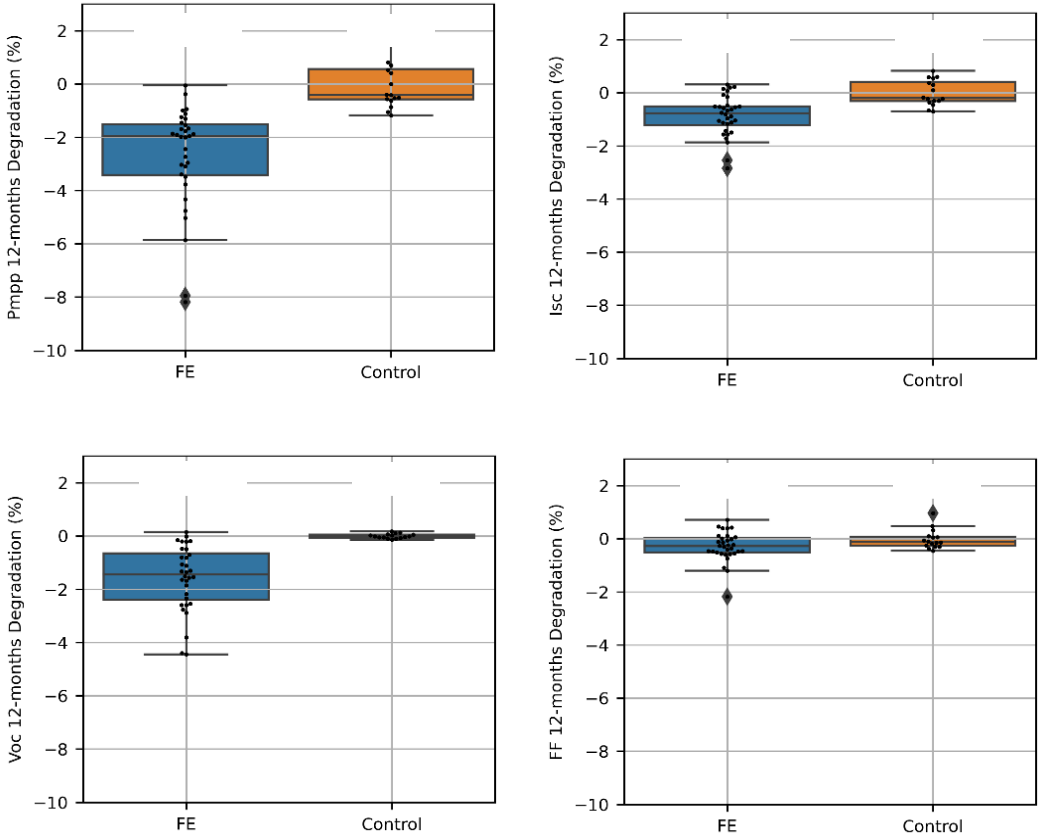
Outdoor Testing

- Modules installed at different sites in the US and China under MPP and SC operating conditions.
  - Field exposed (FE) modules under PQP are under MPP and performance is evaluated after 6 month and 1-year.
  - Test modules installed in China are monitored on monthly basis.
- PQP FE projects are only shown.
- No separate LID is performed.
  - Power degradation is calculated with respect to intake characterization
- Modules are cleaned regularly to minimize the energy yield loss due to soiling.



Field Degradation

- PQP FE modules performance are evaluated for all technology modules.
- Total 16 BOMs. 2 test modules and 1 control per BOM.
- Significant degradation (**median -2%, highest -8%**) in fielded modules after 1 year of installation in Davis, CA.
  - **Mainly due to UVID**. Higher Voc loss in test modules. Isc and FF losses are lower.
  - Control modules exhibited stable performance.
  - LID and LETID combined Pmax loss is <-1% (refer PQP Scorecard 2024).

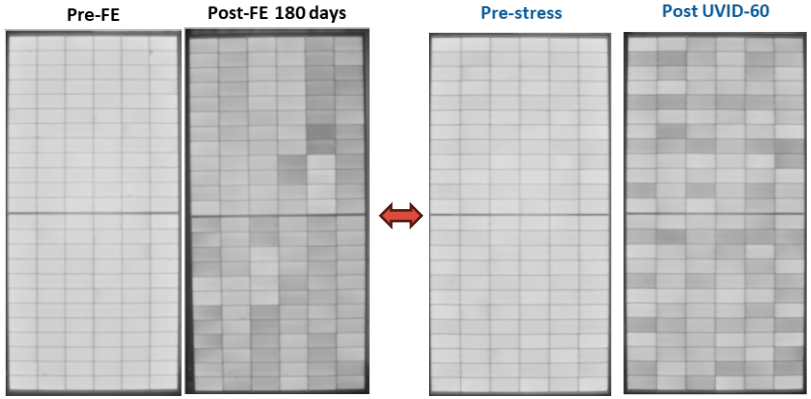


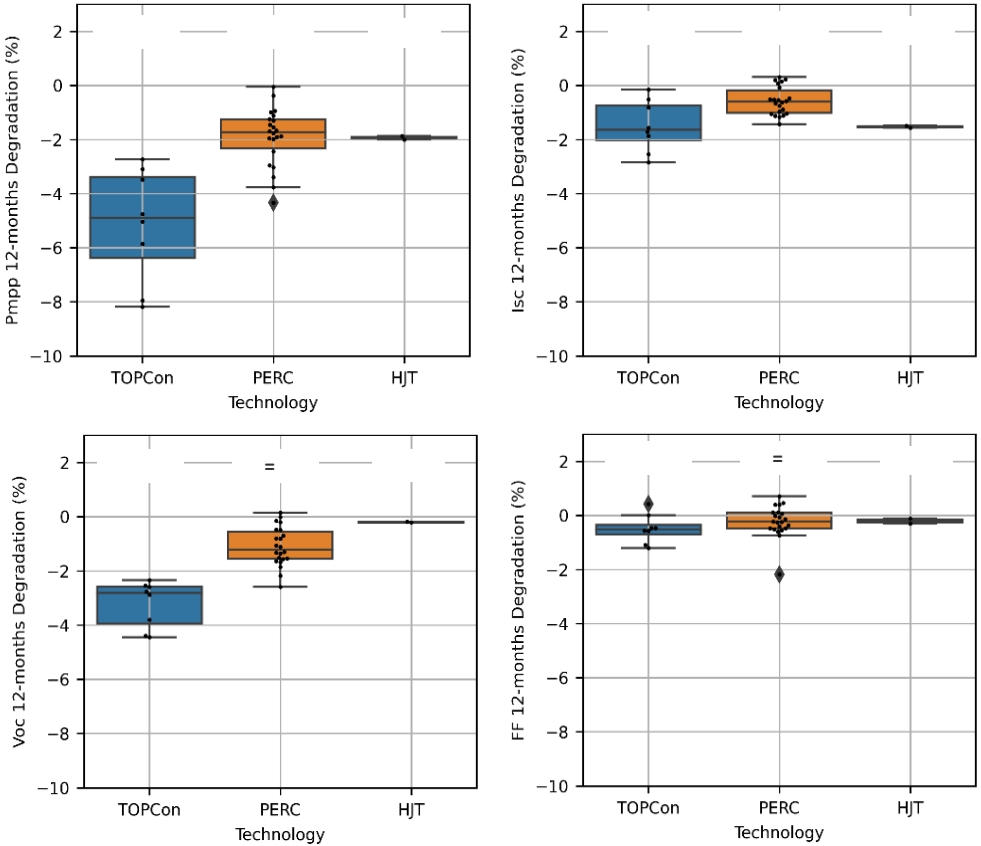
Comparison Field and Lab Testing

- Like chamber test, TOPCon FE modules degraded dramatically after 1-year.
- Similar checkerboard patten in FE module.
- **UVID is a real field-reliability problem.**

Outdoor field exposure

Indoor chamber test

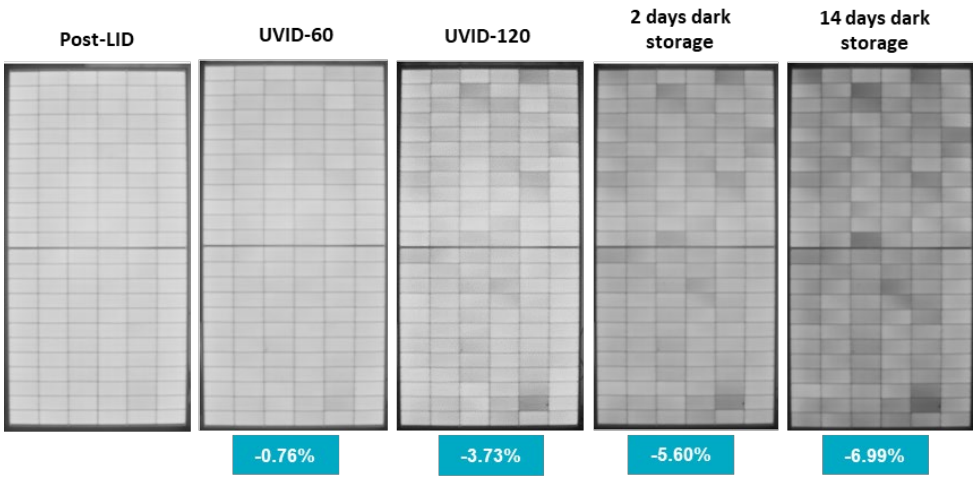




UVID/Dark Degradation and Metastability Issues

- TOPCon modules stored in dark after end of the test exhibited significant power degradation – **signs of metastability exist**.
- Experimented different recovery methods and results are very promising.

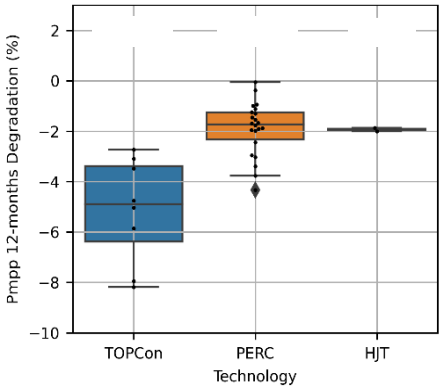
Step#	Pmp%	Voc%	Vmp%	Isc%	Imp%	FF%
Post-LID						
UVID-60	-0.76	-0.84	-1.02	0.60	0.31	-0.52
UVID-120	-3.73	-2.31	-3.24	-0.17	-0.45	-1.29
After 2 days dark storage	-5.60	-3.39	-4.98	-0.47	-0.60	-1.83
After 14 days dark storage	-6.99	-4.18	-5.66	-1.28	-1.42	-1.68



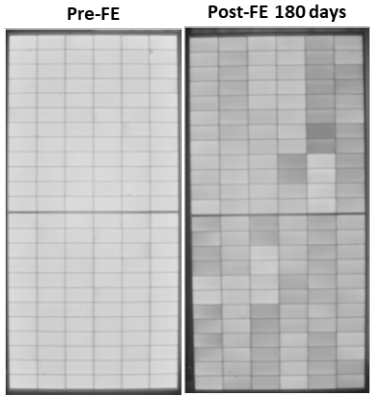
Todd's presentation: **Mar 6 (Thurs), 9.30 am**
UVID Initiates Metastability in the Dark: How to Properly Measure n-Type Modules

Key Takeaways

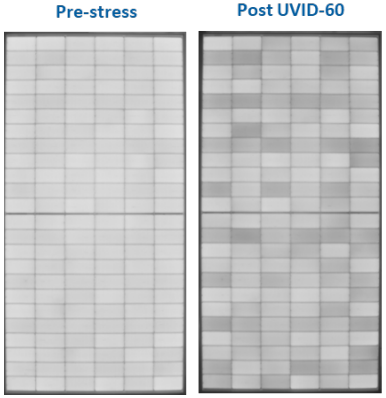
- UVID is a big **reliability challenge for n-type modules**, which exists in the field as well and significantly increase risk of exceeding first year degradation (<-1%).
- Kiwa PVEL has enhanced UV test capacity, please contact us if you'd like to test your modules.
- Recent UVID testing showed lesser modules are exceeding power loss >-5%.
- Some manufacturers have understood on how to control the UVID at cell level.

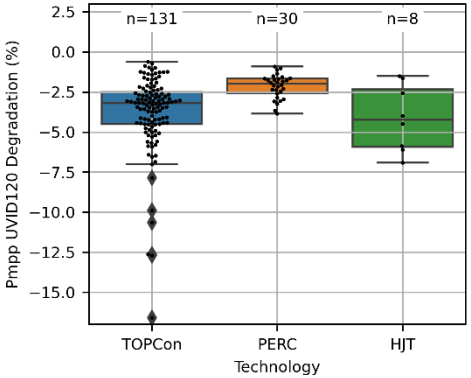


Outdoor field exposure



Indoor chamber test





Thank you!

- *Funding provided by the Durable Module Materials Consortium 2 (DuraMAT 2), an Energy Materials Network Consortium funded by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Office agreement number 38259. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.*

- Kiwa group partners
  - PVEL test facilities in the US and China
  - PI Berlin for Factory audit

- For collaboration and any queries, please contact us.

kiwa PVEL

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Renewable Energy

PV Risks and the Insurance Landscape

Insurance Overview & Lender's Perspective

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Presented at PV Reliability Workshop (PVRW)

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The Renewable Energy Insurance Market

- Introductions
- How Property Insurance Works – Overview (Mike Perron)
- Large Losses impacting the property insurance market (Sandy Calvert)
- Solar Insurance Market Overview & History (Mike Perron)
- Insurance Market – Moore-McNeil perspective
  PV Solar projects - Property (Sandy Calvert)
- Recent History of the Renewables Insurance Market (Mike Perron)
- Insurance Due Diligence overview
  PV Solar projects - Property (Sandy Calvert)
- PV Solar – Large Insured Losses (Mike Perron)
- Lender / Investor Perspective
  Property Insurance – Solar Projects (Sandy Calvert)
- Conclusion - Solar Insurance
  Suggested Path Forward (Sandy Calvert & Mike Perron)

Introductions

MOORE MCNEIL

Moore-McNeil, LLC

MOORE MCNEIL

- *Independent* Insurance Consultants (not a broker)
- Established in 2005 (HQ in Nashville, TN)
- Acquired by Alliant early 2009
- Consultants Across U.S.
- Team of 25+ including support staff (includes ee's with background in risk management, insurance brokerage and finance)
- Sandy Calvert and Haney Swidan have run the day-to-day operations of the company since 2014 and lead deals

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WHAT DO WE DO

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Insurance review and due diligence services

- Primary function of our business

Form of services began in late 80's

- Insurance review (quotes, binders, policies, etc.)
- Risk review (insurance emphasis)
- Contract review (insurance emphasis)
- Establish minimum insurance standards (debt / equity)
- Provide insurance report for closing (debt / equity)
- Coordinate insurance documentation for closing

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- Over 200 years of Property Insurance History
- Mutual insurer – owned by our clients
- Membership Credits and Resilience Credits to Mutual Members
- Large Policyholders Surplus affords us flexibility
- Ability to deploy Large Insurance Capacity (over $1b on many risks)
- Broad Coverage
- Strong Client Retention / Long Term Partnership (67% of our clients > 10 years)
- 60k+ Locations in over 145 countries
- Engineering Expertise
- Rapid insurance claims response
- Newly formed Renewable Energy Group in 2024 on non-mutual basis
    - Research & Engineering Expertise
    - Market-Competitive, stable capacity
    - Customized Solutions, Strong Partnerships

What are we doing?

- FM Global is responding to a growing industry and a rapidly changing risk landscape by launching a new business unit focused exclusively on Renewable Energy.
- We're leaning in on our business model to support our clients with one of the most significant challenges of our time – the transition from fossil fuels to renewable energy.
- Our product offerings are powered by proven science and loss prevention engineering capability and are designed to help our clients protect their purpose and reach their financial and sustainability goals.
- From design through operation, we're here to help today's leaders accelerate their energy projects with ease and confidence.

Why are we doing it?

- Our clients need our guidance more than ever to design, build and operate renewable energy assets that are reliable for the long term.
- The goal is to influence owners, operators, and manufacturers to design and build for resilience and to help guide our clients through a successful energy transition.
- In addition, as countries around the world issue new regulations and emissions-reduction targets, growth in the renewable energy industry accelerates even more.
- More than 50% of our energy clients are already investing in renewable energy. In fact, renewable energy is shaping the future of every industry worldwide.
- As our clients expand in utility-scale renewable energy, they are looking to us for reliable, resilient solutions.
- As renewable energy efficiencies continue to improve, production costs for renewables will continue to decline, contributing to growth and demand.
- The industry is challenged by risks associated with rapidly evolving technologies and increased vulnerability to loss events, particularly climate-related events.
- Together, we can lead the charge to protect today for a better tomorrow.

How Property Insurance Works Overview

How Insurance Works - Intro

“Hello, I’d like to buy some property insurance, RIGHT NOW!”

How Insurance works: Coverage overview - “The Chain Rule”

The chain rule

The chain rule helps us evaluate whether a loss is covered.

The chain rule lists conditions that should be present in order for a loss to be considered covered. If a step (or link) is missing from the chain, the loss likely does not meet the requirements of a covered loss. This useful tool should be used in conjunction with the specific terms and conditions of the Policy.

Property Damage

A discrete event of physical loss or damage
↓
to insured property
↓
from a risk of loss
↓
where no exclusions apply,
↓
the policy covers
↓
the defined loss.

Time Element

A discrete event of physical loss or damage
↓
to described property
↓
from a risk of loss
↓
where no exclusions apply,
↓
which causes an interruption of business operations,
↓
the policy covers
↓
the defined loss
↓
for the defined period of liability.

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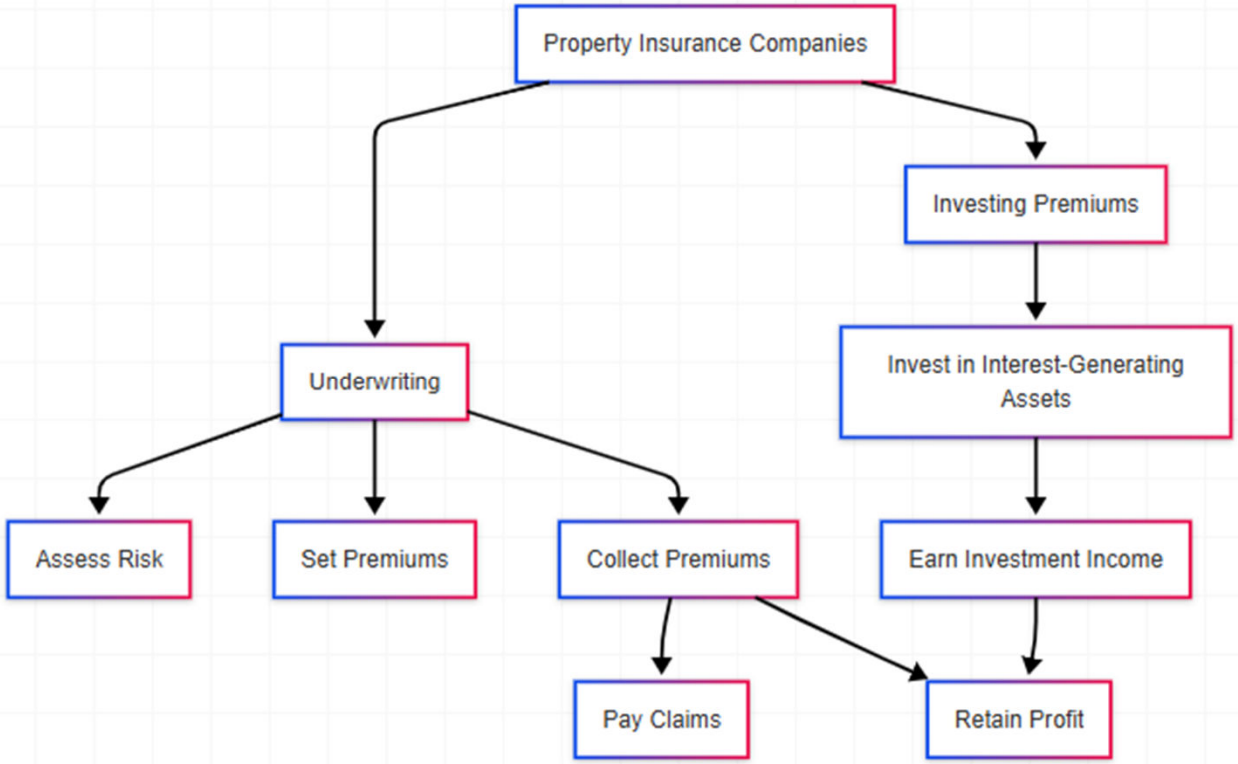
Simplified Property Insurance Process



- Insurers collect the premiums
- Insurers invest the premiums – earn interest (Float)
- Insurers Pay claims

Insurers look to ultimately have **pure** loss ratios in the 65% range, so they can pay expenses and earn a profit

AOP Perils: Common perils in Property insurance policies

Common Perils

- Fire and smoke
- Explosion
- Vandalism and malicious mischief
- Damage from Vehicles
- Theft
- Falling objects
- Power surges
- Etc.

NAT CAT Perils: Primary & Secondary Perils

Primary Perils

- Earthquakes
- Hurricanes (Typhoons)
- Tsunamis
- Extreme Tropical Cyclones

Secondary Perils

- Floods (Some consider this a primary peril)
- Wildfires
- Severe Convective Storms
  - Derechos
  - Tornados
  - Hail
  - Lightning (sometimes a primary Peril)
  - etc.

"Hi, does my property insurance policy cover flood?"

Large Losses impacting the property insurance market

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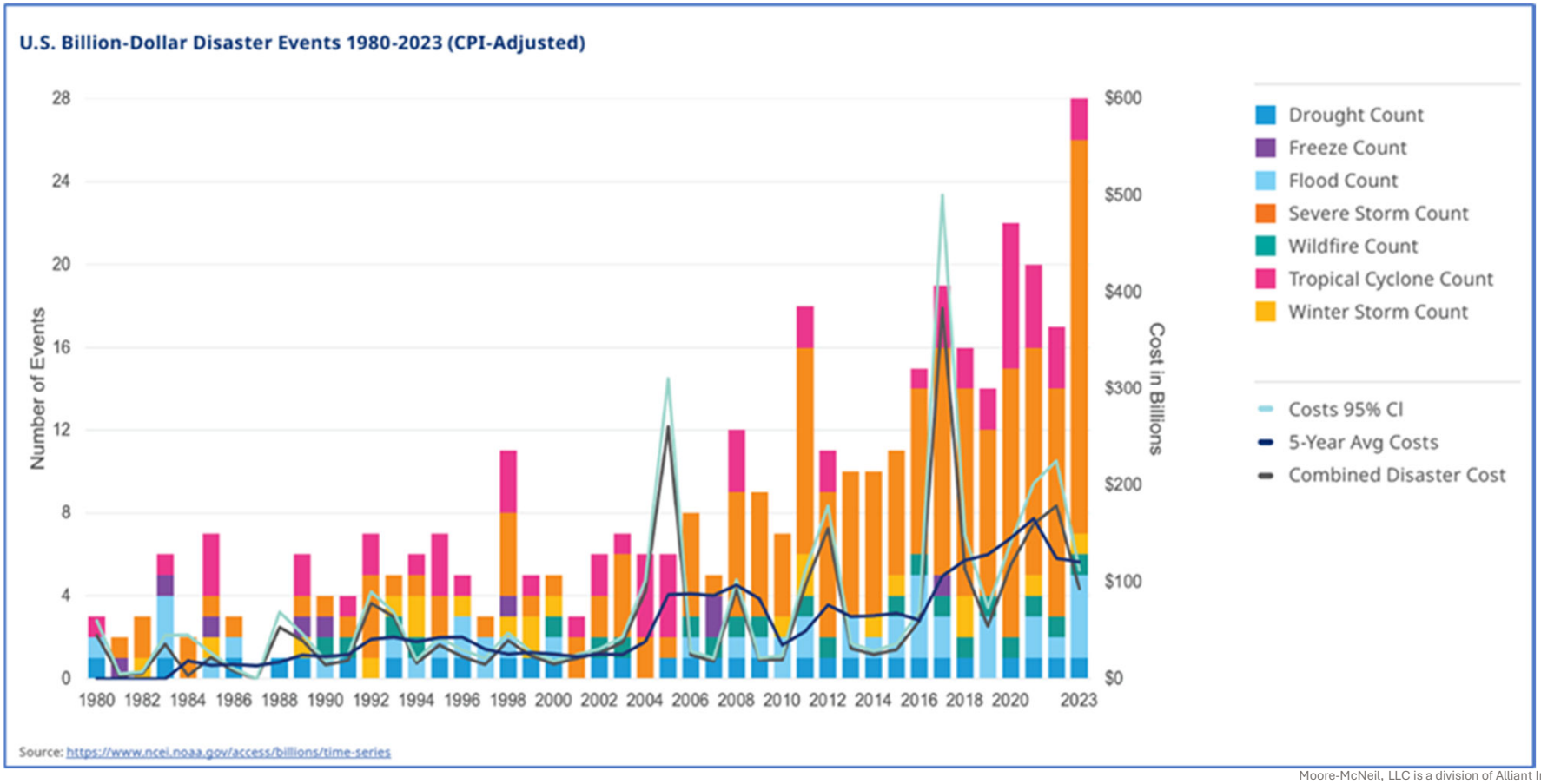
US Billion Dollar Events 1980 – 2023



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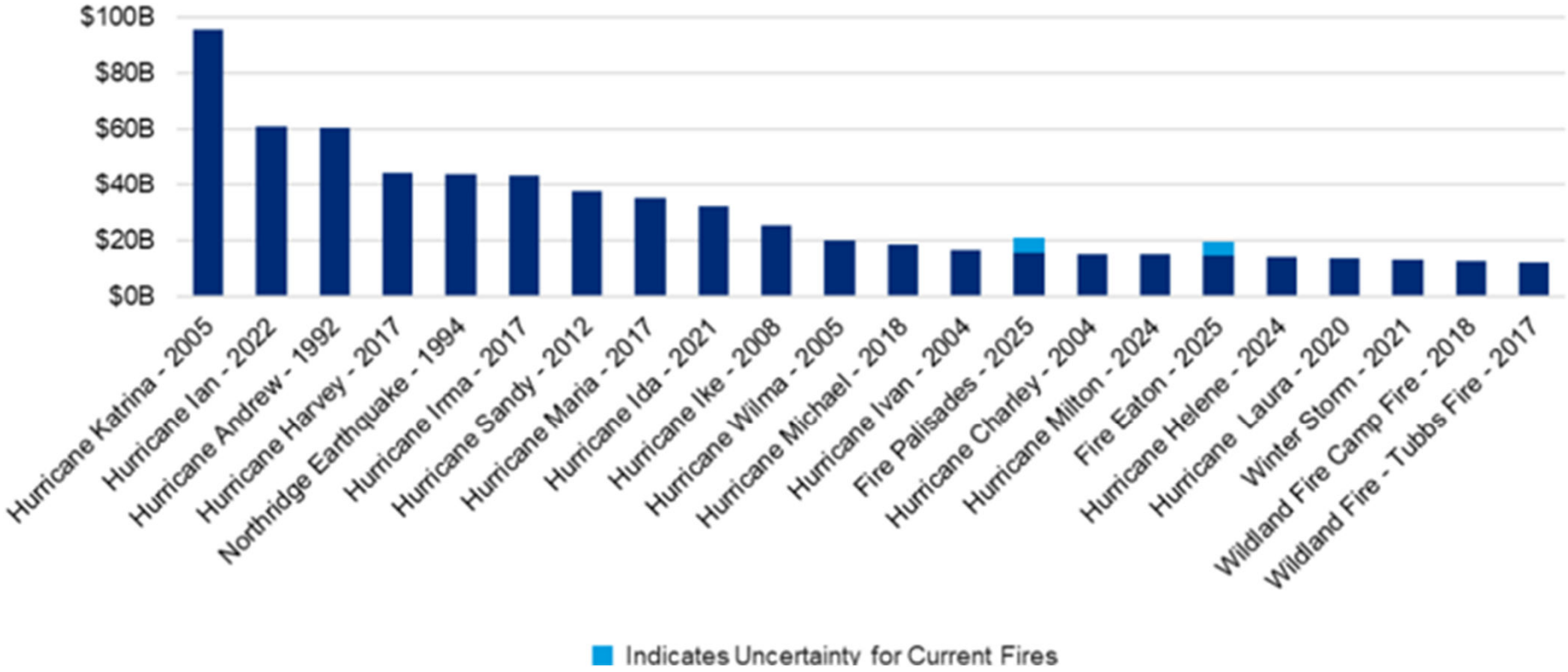
Largest Losses (Descending)



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2024 Billion-Dollar Weather Events

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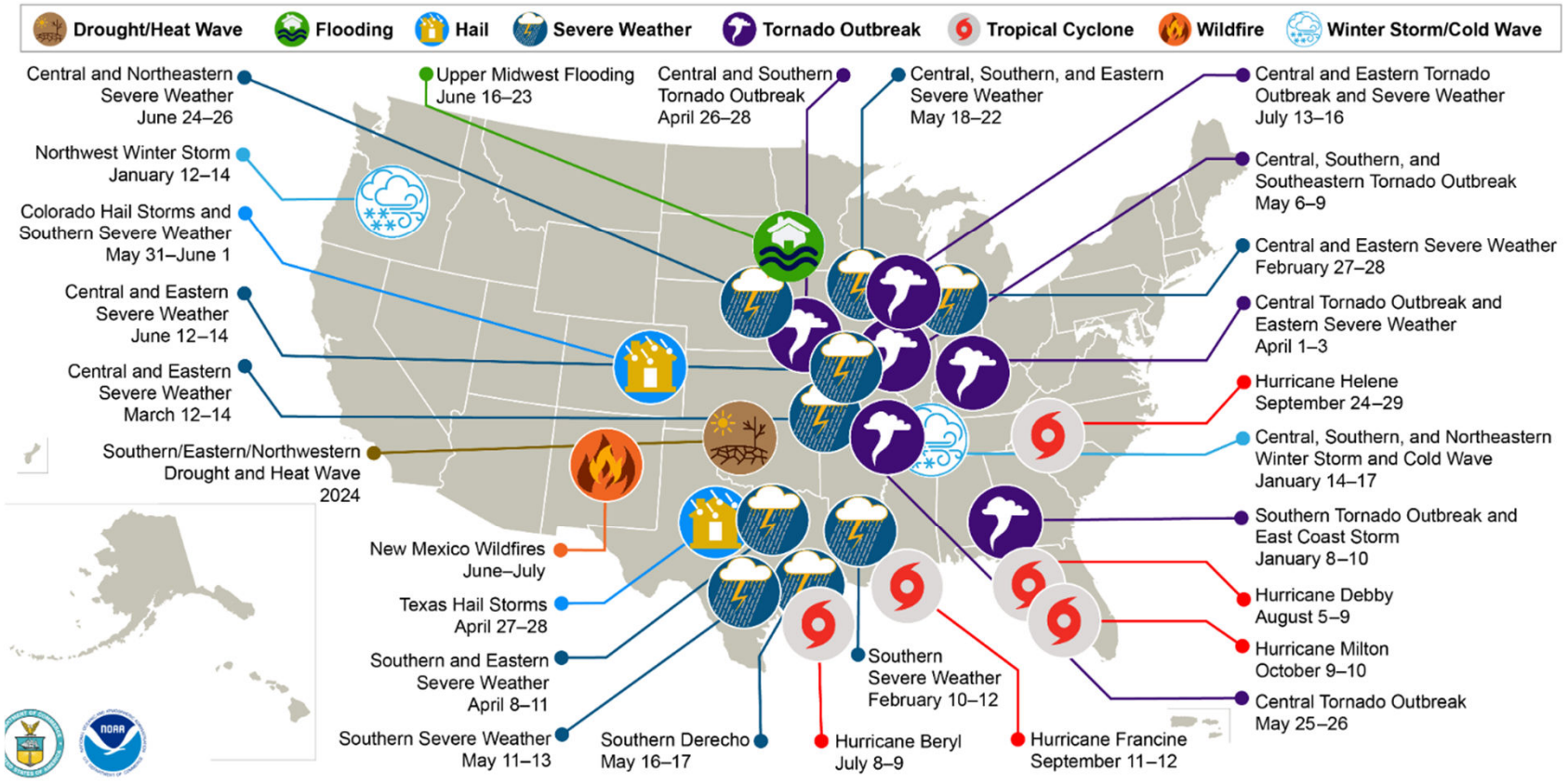
U.S. 2024 Billion-Dollar Weather and Climate Disasters



*This map denotes the approximate location for each of the **27 separate billion-dollar weather and climate disasters that impacted the United States in 2024.***

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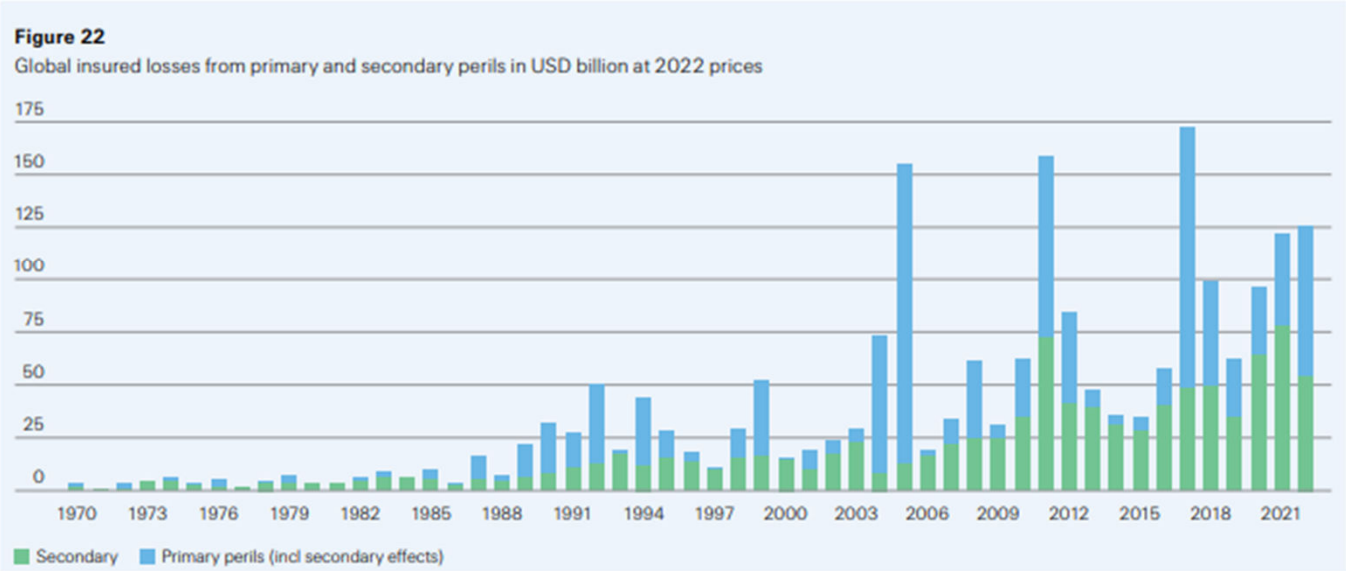
Secondary Perils in general property market

- 59% of global insured natural catastrophe losses in 2023 were from “secondary perils” ($63 billion)
- We don’t have sufficient models for many of these perils (Wildfire, severe convective storm, etc.)
- From 1992 to 2024, the average annual growth trend of losses has been 5–7%
- From 2017, average annual insured losses from natural catastrophes have been above $110 billion.
  - The previous five-year average was $52 billion
  - Expectation of $100 billion annually
- From 2017-2022, the re/insurance industry has paid out $650 billion for weather-related natural catastrophes claims



Swiss Re Sigma Report 2022 & 2024 https://www.swissre.com/institute/research/sigma-research/sigma-2024-03-world-insurance-global-resilience.html

Solar Insurance Market Overview & History

Recent History of Renewables Insurance Market 2010's – Soft Market

The tax credit system means lenders are only entitled to repayments from the profits of projects.

In the soft market, lenders and their advisors were able to request and receive the limits of coverage requirements, leading to:

- Low deductibles
- Low Cat pricing

Buyers were "on the hook" for these terms and conditions for a number of years

In the 2010s high insurance capacity resulted in:

- Relatively low insurance premiums
- Inability of some insurers to pay losses
- Insurers leaving the market (CNA, RSA, Pioneer)
- Less choice for lenders
- Reduced capacity in a growing market

Recent History of Renewables Insurance Market 2020 – 2023 Hard Market

The 2010s led to a different reality in the 2020s:

- Less capacity
- Stricter terms and conditions

Lenders are not in the business of taking on insurance risk, including NAT CAT risks, however, insurance was no longer available for the limits desired on a *commercially reasonable* basis. Insurers wanted higher deductibles and began reducing limits offered.

It is critical that brokers, clients, lenders and their consultants should better collaborate together to proactively anticipate market changes.

Exceptions from old contracts will need to be agreed, increasing the risk of missing renewal dates and being out of compliance or uninsured.

Recent History of Renewables Insurance Market 2023 – 2025 Market in Transition / Stabilization

- Capacity returns with ample capacity available
- Modest pricing relief on many deals along with improved terms and conditions.
- Multi-year deals / Low claims bonus common
- Rates start to decrease
- Markets more comfortable with broader forms / manuscript coverages on large programs
- Gap between lender requirements and capacity available at commercially reasonable pricing remains large.
- California Wildfires in early 2025 have gotten insurers again focused on wildfire hazards. Some feel California exposure has peaked, with new concerns in other western states.
- Markets beginning to cap CAT for areas thought to be nonCAT prone given some losses in unexpected areas

MGAs and brokers looking to find alternative solutions to bridge gap between CAT coverage available and CAT Coverage needed.

- Improved modeling available, though insurers skeptical given past results
- Push towards more resilient design has mixed results
  - Some measures can't easily change – clients have dedicated utilizing chosen (often 2mm bifacial) panels for several years into the future
  - Firms building in severe hail zones such as Texas building with trackers having auto-stow capability and higher angle trackers
  - No large push towards thicker glass or chemically treated glass from clients yet, which could provide further credit.

Insurance a significant portion of operating income for PV Solar [1]

Industry	Insurance Cost in % of Operating Income (low)	Insurance Cost in % of Operating Income (high)
Manufacturing	2-5%	10-15%
Construction		8-12%
Retail	2-4%	6-10%
Transportation	3-5%	7-11%
Chemicals	3-6%	8-12%
Petrochemicals	4-7%	10-15%
Energy Industry	3-6%	9-13%
Thermal Power Generation	3-6%	10-15%
Utility Scale Solar	25% in 2019 (from NREL), before market hardened; at least 30% now (from Marsh Podcast [2])	>30%

In a related statistic, as someone mentioned at PVRW meeting 3/4/25, ROI on fossil fuel plants Is in 15% range, while ROI on renewables is in 5-7% range.

[1] https://content.naic.org/sites/default/files/inline-files/2022-Annual-Property-%26-Casualty-%26-Title-Insurance%20Industries-Analysis-Report.pdf
[2] https://tinyurl.com/a5kwh8yc and https://tinyurl.com/2f264drp

Insurance is reactive - appetite changes (examples)

When	What	Result	Comments
1980s	A slew of explosions in paper mills involving black liquor recovery boilers	• Several leading insurers choose not to continue insuring paper mills • Rates rise and deductibles increase; more focus on risk control	In time, engineering measures were developed that significantly reduced the number of explosions
2002	Insurers raised rates on hurricane insurance after paying out significant losses	• Citizens Insurance founded. State funded. Provides more affordable insurance but most do not believe it to be sustainable.	Most believe that Citizens is undercapitalized and will require government backstop should a large event occur.
2016	Power outage shuts potline at steel mill smelter in Victoria, Australia.	• Aluminum in piping freezes, making for expensive repair • Some insurers choose to no longer insure aluminum smelting operations	Reinsurance of the area of concern helps insurers to continue providing coverage to clients
Circa 2017	US Concentrated Solar projects encounter significant operational challenges and losses	• Renewable Energy Insurers stop offering coverage for concentrated solar projects (CSP)	Lack of growth in the sector and perceived financial challenges among the reasons insurers exited CSP risks
2018	Palisades Fire and then Kincade Fire (2019)	• PG&E Bankruptcy • Insurers now significantly limit liability coverage for wildfire where power lines exposed	Buying wildfire coverage continues to be very challenging for utilities; industry mutuals AEGIS & EIM lead the way.
2019	California Wildfires	• Home Insurers paying out $2 in losses for every $1 in premium they collect • Several insurers chose to no longer write homeowners business in California	Some insurers left the market, particularly if they were unable to raise rates
2022	3 hailstorms caused > $100m in insured damage to Texas solar farms	• GCube advised at a PVTech conference they were “out” on Texas solar projects for hail coverage until the industry figures things out (Stowing / resilience) • Continued fragmentation of marketplace – more insurers sharing each risk • Largest insurer on largest 2024 hail event had 15% share and $50m sublimit	Good for the short term, but not sustainable approach for longer term.
January 2025	California Wildfires cause an estimated $30b in damage significant homes;	• Carriers will need significant premium increases to continue writing California homeowners business, or they will leave the state (As others have) • In some cases, California has denied carriers raising rates • Insurers now have renewed concerns about wildfire exposures in other western states and Canada in the way fires have developed in California	If California doesn’t allow insurers to raise rates, more insurers will leave

Insurance is reactive - coverage restrictions

Event	Insurance Community response
WTC attack (2001)	• Insurers excluded terrorism from property policies • Stand-alone terrorism insurance market developed • Government initiated TRIA government backstop for terrorism events, protecting insurers
NotPetya cyber attack (2017)	• Cyber limitations in coverage (including for "ensuing loss")
Subsea cable failures account for 70–80% of offshore wind insurance claims (2017)	• More focus on qualified contractors, better information on seabeds, and cables sourced quickly and handled properly
Midway hail event damages large solar project, including microcracking damage (2019)	• Hail sublimits introduced • Hail deductibles introduced (% of TIV*) • Microcracking restrictions added • Rates increased for hail-exposed risks • Carriers more closely managed hail capacity offered in Texas and other areas
Wildfire events during COVID damages renewable energy projects (2020)	• Protective Safeguards Endorsements on property policies added limiting coverage if vegetation not maintained below certain thresholds
Cost to rebuild higher than expected (2020)	• Valuation wording in policy reduced to reflect values reported
Winds damaged projects at lower windspeeds than expected (2021)	• Limitations on coverage for certain panels (especially 2p trackers) • Redefining windspeed threshold for Severe Convective storm
3 large hail losses May-June (2022)	• Higher rates for hail-exposed zones, particularly Texas • Insurers further reduced hail capacity offered; more fragmented insurance programs shared by many insurers, driving up price • Continued market fragmentation
Obsolescence of panels and other equipment	• Obsolescence wording and "Agreed Amount" type wording in policies

* TIV = Total Insured Value at site that sustained the loss

Renewable Energy Insurers over the years
Large portfolios with heavy CAT exposure

Period (approx.)	Insurers taking >50% line share	Insurers taking >20% line share	Insurers taking follow lines (not an exhaustive list)
2000-2011	GCube	Various if needed	Munich RE, RSA, CarbonRE, Lloyds, etc.
2011-2013	GCube, PERse	GCube, PERse	Munich RE, AIG, etc.
2013-2020	GCube, PERse, AXIS	Munich RE, AIG, Liberty, Swiss RE, HDI, HSB, Travelers, etc.	Lloyds, if needed
2020-2024	-	GCube, PERse, AXIS, AIG, AEGIS, etc. *	Zurich, Swiss RE, Munich RE, HDI, Liberty, Travelers, Hartford, Lloyds, kWh Analytics, NARDAC, Starr, Aviva, etc.
2024-present	-	GCube, PERse, AXIS, AIG, AEGIS, Aviva, FM*	Zurich, Allianz, Swiss RE, Munich RE, HDI, Liberty, Travelers, Hartford, Lloyds, kWh Analytics, NARDAC, Starr, Chubb, Mapfre S.A., SCOR, Markel Corporation, AXA XL Group, Beazley, Hiscox, etc.

- Several insurers would have exited renewable energy risks if not for corporate ESG initiatives
- Carriers also staying in the market now because renewables growing very quickly (as is premium volume)
- Fragmented market where all insurers take small lines on risks will not support sustainable market over time (58 insurers shared the Moss Landing event; largest line on the largest 2024 Texas hail event was 15%)
- More focus needed by all parties on risk mitigation, where there has been little focus.
  - Insurance company engineers well trained in fire protection risks, but exposure to solar projects is weather related
  - Few engineering surveys done at solar farms, and such surveys have little value either to insurers or clients when focus is in wrong place
  - Collaboration between OEMs, insurers, brokers, banks and clients has increased, and all are more interested in better risk engineering
- A more efficient and sustainable market will include insurance programs being shared by fewer insurers taking significant line sizes (>20%)
- **Ultimately, we want resiliently designed assets that can withstand the weather events that occur where the sites are built; when this is done, carriers can offer more capacity and banks can accept less.**

* Carriers limited on what they can offer often by CAT and especially hail capacity needed on risk

Insurance Market – Moore-McNeil perspective
PV Solar projects - Property

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General Risk Mitigation

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Insurance

- Broadest Coverage Available
- Highest Limits Available
- Lowest Deductibles

Non-Insurance

- Reserve Accounts
- Manufacturer / Supplier Warranties
- Long Term Service Agreements (planned / unplanned maintenance)
- Contractual Risk Transfer (e.g., risk of loss, indemnifications)
- Liquidated Damages
- Proven Technology
- Credit Worthiness/Experience of Equipment Manufacturers & Suppliers
- Credit Worthiness/Experience of Contractors

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Primary Insurance Objectives

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- Insure Against Key Property and Liability Exposures
- Meet Lender / Tax Equity Requirements
- Meet Project Contract Requirements
- Protect Lenders, Tax Equity Investors and Sponsor Equity
- Balanced Approach (i.e., Cost vs. Risk)
- Secure Carriers (e.g., A.M. Best A-, X or S&P A or higher)
- Payment of Claims

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Catastrophic Peril Coverage

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- Meaningful coverage is available
- Some large Sponsors using Captives able to obtain significant coverage, including SCS in Texas – e.g., up to $100M.
- CAT coverage (especially in high hazard areas) will come at a price
- How much coverage is enough? That depends.
  - What is the Investors'/Lenders' risk tolerance
    - How much can the Project lose?
    - Deductibles
    - Module Costs?

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The 1/500-year event

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- MM uses the 1/500-year event (ABS PL and mean value) as a very conservative event or that the chance of occurring is very low. Its not that it happens once every 500 years. There is a 1 in 500 chance of the event happening in any given year. We then adjust upward (125%) to reflect volatility or uncertainty. MM used 125% to approximate 2 standard deviations.

- ABS uses the mean1/500-year event (PL) and the 90% confidence interval (PML). That doesn't mean it is the worst event you can imagine (it is a very conservative number reflecting 1.65 standard deviations around the mean).

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Lloyds Premiums and Loss Ratios (Power Gen)

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Fiscal Year	Gross Premium	Current Loss Ratio
2022	$ 530,460,000	56.2%
2021	$ 540,540,000	66.1%
2020	$ 510,300,000	46.1%
2019	$ 462,420,000	74.4%
2018	$ 560,700,000	82.1%
2017	$ 530,460,000	91.90%

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Status of the Renewables Property Market - 2025

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- Last few years
  - Reduced CAT Coverage: Coverage desired is no longer available to fully protect owners and lenders against extreme weather events
  - Unreliable CAT modeling: Even sophisticated modeling for hail risk generates results that are unreliable, frequently underestimating possible damage in worst case event
  - Rising insurance rates - Increased insurance costs impact viability of some projects without relocating the project or making the project more resilient.
  - Incomplete / non-concurrent coverage - Some programs cannot secure fully subscribed coverage, and often programs are non-concurrent (different terms and conditions among insurers)
- Recent market developments
  - Prices are stabilizing. Some large, loss free accounts have achieved decreases at renewal.
  - Terms and conditions improving
  - Even CAT constrained accounts are seeing some improvement.
  - More capacity = More competition = Better terms / pricing
  - Captive insurance and master programs add stability. Aggregation of risk is an issue for some.
  - Still enough supply, even in TX, with excess coverage "at a price" – Will this change?
  - Less erosion of coverage / more concurrency for limits and deductibles
  - New policy forms - Some insurers seeking to include depreciation in payout or include CAT within series loss wording - MM and Stance pushing back

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Loss Limits vs Replacement Cost

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- Strong case to be made for use of loss limit vs. replacement cost value to establish overall policy limit
- Historically, full replacement cost available at a low cost. Insurers charging for capacity (i.e., limits) regardless of risk.
- All-risk rates roughly .17 per $100 value for non-CAT exposed Projects and up to .55 per $100 value for CAT exposed Projects (i.e., PV in Texas) – This is before cost of Excess CAT cover.
- Reducing all-risk limit frees up capital to purchase additional CAT coverage
- MM believes Investors/Lenders should consider loss limit approach equal to 2xs the MFL and/or 100% of investment (whichever is greater) or agreed minimum

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PV Solar – Large Insured Losses

Some of the Largest Renewable Energy Losses

Year	Location	Event	Insured Amount Paid
2016	Texas Solar project under construction	Hail	$100m (est'd)
2019	Midway Solar	Hail	$75m
2020	Various Wildfires – California & Pacific Northwest (mainly solar)	Wildland Fire	Several multi-million-dollar losses, some of which exceeded $10 million
2022	3 Texas Solar projects	Hail	$110m (Est'd)
2023	Various California Wildfire & Wind losses (mainly solar)	Wildland fire / wind	Up to $100m
2024	Iowa Wind projects	Tornado	$50m (Est'd)
2024	CSP facility – Noor Energy1 (Construction) Dubai UAE	Flooding destroyed heliostats	>$300m (Est'd)
2025	Moss Landing (Vistra) - California	BESS fire – inside building	$400-$500m (Est'd)

Hail losses dominate the solar insurance marketplace

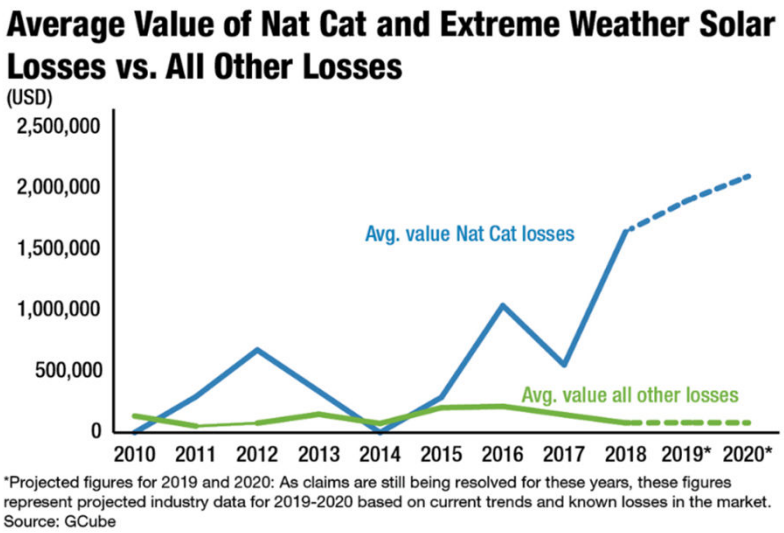


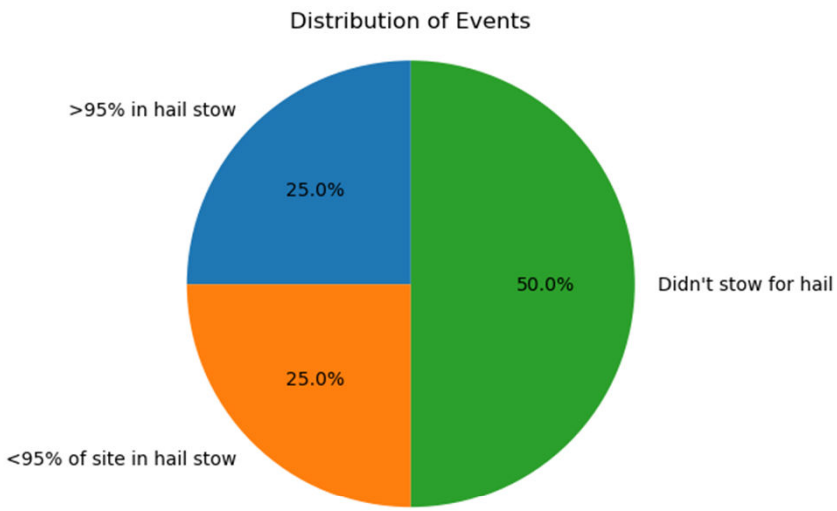
Image: Gcube Insurance

- GCube noted that Hail events represented 2% of events, but 54.2% of solar losses in 2023 [1]
- Swiss RE advised that Hail events represent 3% of events but 60% of solar losses in 2024 [2]

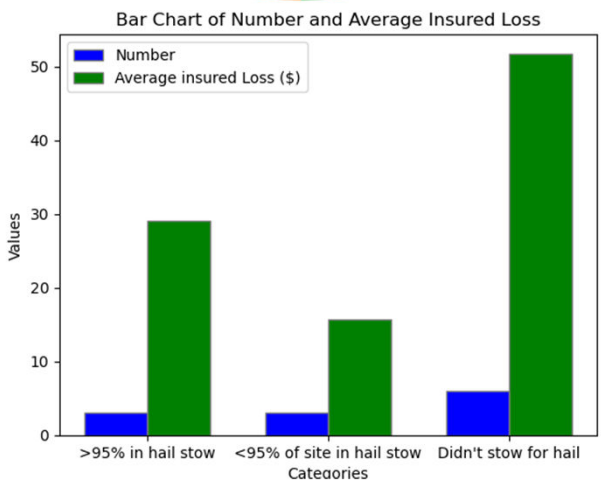
"Hail damage risk is undermining the security of solar power as a prominent clean energy solution," said Fraser McLachlan, chief executive officer of GCube Insurance. "We therefore have an overriding imperative to develop solutions to this challenge and restore our ability as insurers to provide the sector with long term risk underwriting."

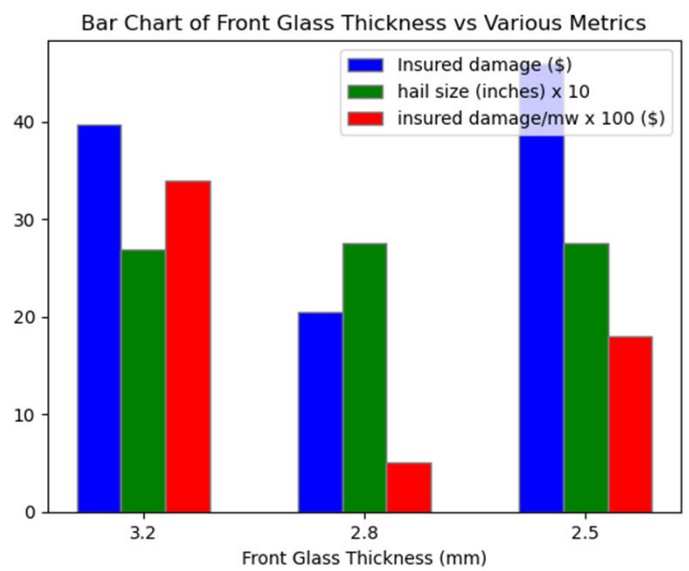
[1] https://www.pv-magazine.com/2023/12/07/hail-damage-accounts-for-about-half-of-all-solar-facility-loss-claims-says-gcube/
[2] https://www.swissre.com/institute/research/topics-and-risk-dialogues/climate-and-natural-catastrophe-risk/climate-change-solar-power.html

Data from 12 large hail events 2016-2024 impacting PV solar projects



Front Glass Thickness (mm)	Insured damage ($)	hail size (inches)	insured damage/mw x 10 ($)
3.2	39.72	2.69	3.4
2.8	20.5	2.75	0.5
2.5	46.0	2.75	1.8





Takeaways:

1) Many projects with large losses didn't stow

2) Though glass thickness and composition is really important, stowing is perhaps as important

Why didn't the projects stow / fully stow (Actual or possible)?

- Software related issues
  - Software Error (various)
  - Computer system "timed out" before stow protocols could be sent to entire solar farm; portions of the solar farm failed to stow
  - Tracker system instruction to stow panels was password protected. Personnel were unable to find / input password quickly enough to stow the project before storm arrived
  - System had been stowed for wind inadvertently in advance of potential hailstorm. Tracker system had 15-minute wait to input change to hail stow
  - Default stow position for certain trackers set to "flat", unless project owner specifically requests otherwise.
  - Some trackers not tracking. In several events, most trackers stowed defensively as designed, but a portion of the site failed to stow. Non-stowed panels sustained much more severe loss than those defensively stowed.
- Configuration faulty / incomplete
  - Part of site operational, but stowing not yet configured. Stowing not yet configured when system was operating
  - System not fully stowed at time hail impacted site (perhaps not properly installed)
  - Hailplates triggering stowing panels located at perimeter of site – not providing sufficient time to stow panels before storm hit (Possible system not yet functional / connected.
- Project lost power and therefore ability to stow in advance of storm
- Project stowed in Construction Mode (lower angle than hail stow) rather than higher angle (hail mode)

Bottom line for insurers – lack of trust that the sites will stow when a storm arrives. More emphasis on stowing is needed. Autostow and higher stow angles helps, but more emphasis needed to ensure projects stow every time. Clients have big opportunity to differentiate themselves on stow design / stow protocols. Once this is tested and shown to work, insurers will differentiate rates. Industry needs to think of stow tests akin to how buildings conduct sprinkler acceptance tests.

Hail losses and premium collected

- The U.S. Energy Information Administration (EIA) estimates by EOY 2024, the US had a total installed and operational utility-scale solar capacity of approximately **110.3 gigawatts (GW)**
- Additionally, there was about **32.5 GW** of utility-scale solar capacity under construction in 2024, expected to become operational in 2025, as reported by the Solar Energy Industries Association (SEIA)
- To estimate the replacement cost value for these solar assets, we used an average construction cost of **$1.588 billion per gigawatt (GW)** [1]. This results in an estimated replacement cost of **$175.2 billion** for the installed capacity and **$51.6 billion** for the under-construction capacity.
- Let's assume an average rate of $0.20/$100 of insured value for operational solar, and a rate 15% higher for solar under construction. This would suggest there is just under **$500m of premium** spent for US utility scale solar risks (Actually premium will be higher because rates are higher in areas subject to severe NAT CAT events; these figures are solely for comparative purposes)
- The loss figures noted earlier suggest insurers are paying out in the $100m range in recent bad hail years for the largest losses.
- There are other smaller losses not counted here, as well as losses for other energy risks that impact insure profit margins

Bottom line – though these losses have been painful for insurers, by taking smaller line sizes in CAT-exposed zones and reducing sublimits, insurers have protected their bottom line. However, this comes at the expense of clients and banks taking on more risk than they would otherwise choose. Not the solution.

[1]. https://www.edisonenergy.com/blog/insurance-costs-for-clean-energy-projects-are-rising-heres-what-buyers-need-to-know/

Lender / Investor Perspective Modeling of PV Solar Projects

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What about the NAT CAT Models?

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- RMS – generally used for earthquake and named windstorm and sometimes flood
- AIR – commonly used tool for flood
- SwissRe – CATNET – good for general risk ID
- VDE – Runs a complicated hail model specifically designed for solar risks
- CoreLogic – on the same order as RMS
- None of these particularly good for forecasting hail. All are pulling on NOAA observed data except VDE which uses NEXRAD satellite data along with NOAA data

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Conclusion:
Solar Insurance - Suggested Path Forward

What is the solution?

- Renewables is a highly technical market. **Expertise/experience** of both insureds and developers/contractors is fundamental. **Insurers too.**
- There is ample capacity to get solar projects insured, but more work is needed to develop sustainable projects; a fragmented marketplace has little incentive to do that. Strong **insurers need to set the bar for projects to be built resiliently.**
- **Collaboration** in the form of sharing more information between industry stakeholders including **owners, developers, EPCs, operators, banks and insurers** is key.
- The industry must put **more standards** in place pushing towards resilience. FM can help in developing standards and has begun doing so, collaborating with OEMs.
- More focus on risk control / **sites** "fit for purpose" **to handle extreme weather events** where solar farms built – more resilient glass (chemically treated glass, thicker glass) and reliable tracker systems with automated stow protocols.
- Strong hail stow programs to mitigate loss implemented **every time**, with testing done prior to operations, and monthly thereafter, with **annual testing witnessed by owner, operator, Tracker OEM and an informed independent third party who documents test results and action items to address.** This should be **akin to a sprinkler test in a new building.**
- The sustainability of the market relies on writing each risk individually. Some are better than others at differentiating risk. More than ample capacity is available to complete most programs, often utilizing capacity in small pieces from those that do little to differentiate risks. Clients want **strong insurers offering significant capacity with stable terms, conditions and pricing.**

Renewable Energy

Thank You.
Any Questions?

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PVRW: Photovoltaic Reliability Workshop

Insurance 101:
P&C Insurance Basics, Models, PMLs, and Sublimits

Lauren Carroll-Allan

Vice President, Power & Renewables

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March 4-6, 2025

AGENDA

1. CAC Specialty & Cirrus Advisers
2. Property & Casualty Insurance Basics
3. Introduction to Natural Catastrophe Modeling
4. How Models Inform Insurance Sublimits

1 CAC Specialty & Cirrus Advisers

About CAC Specialty

CAC Specialty is an industry-leading specialty broker offering comprehensive broker and advisory expertise across industry, product and program specialties.

1,000+ Clients Added In Last 3 Years

500+ Employees

Largest Team: CAC Natural Resources

Key Facts

- Employer of choice for top industry talent displaced in a rapidly consolidating brokerage marketplace
- Privately held and employee-owned
- The largest industry vertical within CAC Specialty is Natural Resources with more than 80 associates and an average industry tenure of ~15 years
- Priorities and investments:
  - Transaction risk and tax equity resources in the renewable energy and oil and gas industries for developers, sponsors and tax equity investors
  - Strong leadership commitment to technology, data and analytics

About Natural Resources

- CAC NR is the largest industry practice within CAC Specialty.
- Our expansive platform brings decades of industry expertise and exemplary client service to the power and renewables sector.
- Our professionals are thought leaders – driving innovative products and solutions to a constantly-evolving energy landscape. By design, our team manages all client deliverables within our industry practice group, creating a client-first service model that drives best-in-class results.

Differentiators

1 Specialties in Oil & Gas, Metals & Mining, Power & Renewables, and Surety

2 More than 65 seasoned insurance brokers with an average industry tenure of ~15 years, including four former risk managers from NRG Energy, SunEdison, and Pattern Energy

3 Historical insurance placements exceeding $2.5 billion in premium within the energy sector

4 Teammates with decades of experience representing over one third of the total US power & utility generating capacity in the US

5 Claims settlements and negotiations exceeding $2 billion with licensed loss adjusters on staff

6 Market-leading Battery Energy Storage Loss Control program; staff engineer who is current Chair for NFPA 855 Battery Storage Standards Committee.

7 Deep independent domestic, London, Bermuda and international market relationships and unencumbered access to specialty wholesalers

8 Dedicated renewable energy consulting platform bringing extensive project finance expertise and a track record of successfully negotiating complex energy transactions

Power & Renewables

Technology Expertise

Organizations with power generation and renewable assets face unique challenges in the insurance market. CAC Natural Resources is a specialized brokerage with extensive experience designing and implementing construction and operational risk transfer programs for a wide range of traditional, renewable and prototypical technologies, including the following:

- Advanced Composting
- Anerobic Digesters
- Battery Energy Storage
- Biodiesel
- Biomass
- Cogeneration
- Combined Cycle Natural Gas
- Data Centers
- Electric Transmission and Distribution Lines

- Hydroelectric
- Hydrogen
- Nuclear
- Geothermal
- Landfill Gas
- Onshore Wind
- Offshore Wind
- Simple Cycle Natural Gas
- Solar
- Wastewater Treatment
- Water Filtration

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Cirrus ADVISERS

RENEWABLE ENERGY RISK & INSURANCE CONSULTING

Cirrus was launched by a team of seasoned renewable energy insurance experts who saw a need to help the industry more accurately project and plan for insurability considerations, thereby enabling a faster and more profitable global energy transition.

The Cirrus consulting platform was designed to provide renewable energy projects with analytics, modeling, risk mitigation and insurance market intelligence tools, all under one roof, to better inform critical project and portfolio-level insurance and risk management decisions. The Cirrus team brings a holistic view to the development process that can't be replicated by engineering, lender consulting or natural catastrophe modeling offerings alone.

UNDERSTANDING THE IMPACTS OF RISK

- Insurance costs are a significant financial burden on renewable energy projects, and the long-term profitability of a project requires a sounder understanding of insurability & project risk profile.
- Incorporating accurate insurance projections from Cirrus yields substantial benefits over the life of the project.
- Cirrus provides critical insight into project-specific natural catastrophe exposures associated with a project or portfolio's geographic footprint.
- Technology and loss-control mitigation factors are accounted for when determining accurate Probable Maximum Loss (PML) returns and aggregation assumptions.
- Cirrus' exclusive renewable energy specific Natural Catastrophe modeling capabilities drive smarter analytical outcomes for the project / portfolio.

2 Property & Casualty Insurance Basics

Types of Insurance

FIRST PARTY COVERAGES

Covers the named policy holder ("insured") against damages or losses suffered by the policy holder to his person or property

- ✓ "All Risk" Property
- ✓ Business Interruption
- ✓ Builder's "All Risk" (BAR)
- ✓ Delay in Start Up (DSU)
- ✓ "CAT" – Earthquake, Flood, Hail, Wildfire & Windstorm
- ✓ Ocean & Inland Marine Cargo
- ✓ Drone Physical Damage
- ✓ Contingent Marine Cargo DSU
- ✓ Cyber
- ✓ Crime
- ✓ Automobile Physical Damage

THIRD PARTY COVERAGES

An insurance policy purchased for protection against the claims of another; also commonly referred to as casualty insurance

- ✓ General / Products Liability
- ✓ Automobile Liability
- ✓ Employers Liability
- ✓ Umbrella / Excess Liability
- ✓ Directors & Officers Liability
- ✓ Employment Practices Liability
- ✓ Fiduciary Liability
- ✓ Cyber Liability
- ✓ Foreign Liability
- ✓ Pollution / Environmental Liability
- ✓ Professional Liability / Errors & Omissions
- ✓ Drone Liability

Property Insurance

"All Risk" Property Insurance:

- Property Insurance provides coverage to protect against the risk of loss to **tangible property**. The policy provides coverage for **property damage to property** caused by a covered cause of loss (typical perils include such losses as a result of **fire, mechanical and electrical breakdown, wind, lightning, hail, explosion, flood, earthquake, etc**.).
- EXAMPLES OF PROPERTY SUBJECT TO POTENTIAL LOSS:
  - Office property
  - Development (Safe Harbor) property
  - Property in transit
  - Property being installed or under construction
  - Operational facility

Builder's "All Risk" Insurance:

- Provides coverage for the same perils as an "All Risk" Property policy (fire, testing and commissioning, wind, lightning, explosion, flood, earthquake, etc.) but the coverage applies to the facility **while it is under construction or installation**, and covers the interest of contractors, suppliers and subs.

Business Interruption:

- Covers **loss of revenues** suffered by a business when its premises or facility suffers a **covered property loss**, and the loss causes a slowdown or suspension of its operations. Coverage applies during the time required to repair or replace the damaged property.

Delay in Start-Up:

- Business interruption coverage that applies to a facility during construction or installation when a covered loss causes a **delay in the expected commercial operations date** of the facility. Does not include contractor delays. Also referred to as ALOP (advance loss of profits) insurance.

Casualty Insurance (Third-Party Liability)

Commercial General Liability:

- Insurance issued to businesses to protect against legal liability (third party) claims that arise out of the company's premises or operations including coverage for:
  - Bodily Injury & Property Damage: for bodily injury or property damage occurring on **your premises**.
  - Products & Completed Operations: for bodily injury or property damage that arises from a **product you design, install or sell**.
  - Personal Injury: provides protection against accusations of **libel** or **slander** that may arise from a written publication or a verbal statement that is made.

Automobile Liability:

- Insurance that protects the insured against financial loss because of legal liability for **automobile-related injuries to others** or **damage to their property** from use of an auto. Coverage can apply for liability arising out of vehicles owned by the company or employees driving their own (or rented) vehicles for business use.

Workers' Compensation:

- Benefits provided as mandated by state law and **provided by an employer to an employee** (or the employee's family) due to **job-related injury** including death, resulting from an accident or occupational disease. Benefits are paid are based on no-fault benefits prescribed by state law.

Employer's Liability:

- Provides coverage to the employer for liability to employees (or their family) for work-related bodily injury or disease, other than the liability imposed on the employer by workers' compensation law.

Excess / Umbrella Liability:

- Provide **additional liability limits** in excess of the limits provided in the underlying insurance (excess of general liability, auto liability and employer's liability).

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Claim Example: the Perfect Storm

One Storm – 5 Insurance Claims:

1. » Property Damage
2. » Loss of Revenue
3. » 3rd Party Property Damage
4. » 3rd Party Pollution Cleanup
5. » Professional or Errors & Omissions Liability – Drainage Design

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3 Introduction to Natural Catastrophe Modeling

How Catastrophe Models Work

Catastrophe models assess the potential impacts of a hazard on a portfolio by generating loss estimates and other metrics which quantify natural catastrophe risk. Models are calibrated & validated using historical claims data from a variety of sources to ensure they are robust & accurate. Below are the three main model components that come together to provide a holistic view of risk.

Hazard

Event Generation, Local Intensity

Incorporates the latest science understanding of each peril. An event set is generated to represent a complete range of potential catastrophe activity. Local intensity is calculated at each geographic location in the analyzed exposure.

Vulnerability

Damage Estimation

The latest engineering science is used to develop vulnerability functions which account for a building's construction type, occupancy type, and other characteristics. Realistic damage estimates for each location and event are made based on these functions.

Financial

Insured Loss Calculation

After calculating estimated losses at each location, the financial module will aggregate losses to different levels (e.g., event total). It also calculates losses at additional financial perspectives when insurance programs are applied.

Vendors in the Market

Several catastrophe modeling software providers exist in the insurance market. These companies have developed a variety of solutions that are used in assessing and managing natural catastrophe risk.

CAC Group currently licenses and uses catastrophe modeling software from **Verisk** and **Moody's RMS**.

Verisk
(formerly AIR Worldwide)

An industry leader in catastrophe modeling, Verisk's Touchstone software can be used to analyze a portfolio's risk across numerous regions and perils. Touchstone provides analytics so users can understand a portfolio's loss potential, hazard features, and exposure accumulations.

Moody's RMS

Moody's RMS is another industry leader in catastrophe modeling. Among a comprehensive suite of solutions is Risk Modeler, home to the Moody's RMS catastrophe models. Risk Modeler supports a large range of peril models, and it is tailored to help users understand, quantify, and manage risk.

Other Vendors

Other catastrophe model vendors include Karen Clark & Company, CoreLogic, and KatRisk. Each vendor has established their own unique view of risk backed by the experts, science, and data that is available to them.

Key Terms & Acronyms

Average Annual Loss (AAL)

a long-term average representing an expected loss amount per year given annual losses follow a uniform distribution (equal loss amount every year)

Exceedance Probability (EP)

the likelihood that losses in the upcoming year will be at least a given amount; can also be calculated as 1/Return Period

Probable Maximum Loss (PML)

the largest potential loss amount corresponding to a specific return period

Return Period

a frequency measure representing the average number between years (i.e. out of the 10,000 total years) that a loss of a certain size occurs; can also be calculated as 1/EP

Standard Deviation (SD)

the likelihood that losses in the upcoming year will be at least a given amount; can also be calculated as 1/Return Period

Ground Up Loss

the total financial amount of loss without considering deductibles; if deductibles are present, it can also be viewed as the sum of retained losses and gross losses

Gross Loss

the financial amount of loss ceded to the insurer; the total loss less any deductibles and limits

Retained Loss

the financial amount of loss the insured retains; the amount of loss less than any deductible and greater than any limit

4 How Models Inform Insurance Sublimits

How Nat Cat Models Inform Insurance Sublimits

- Financing parties commonly use 125% of the 500-year PML value as the **minimum** sublimit for nat cat perils.
- Example: 125% of $10,687,228 results in a minimum sublimit of $13,500,000 for Severe Thunderstorm (aka Severe Convective Storm):

Ground Up Losses

Return Period	All Perils	Earthquake	Hurricane	Inland Flood	Severe Thunderstorm	Wildfire	Winterstorm
10,000	155,339,676	10,701,394	1,595,509	0	155,339,676	116,714	0
5,000	25,567,866	1,422,225	925,935	0	25,567,866	116,714	0
1,000	13,463,580	0	156,396	0	13,463,580	85,074	0
500	10,692,273	0	77,070	0	10,687,228	85,074	0
250	8,570,846	0	0	0	8,497,096	85,074	0
200	7,310,390	0	0	0	7,211,549	85,074	0
100	5,093,753	0	0	0	5,030,091	0	0
50	2,715,926	0	0	0	2,689,856	0	0
25	1,190,711	0	0	0	1,173,147	0	0
10	213,828	0	0	0	210,443	0	0
5	83,357	0	0	0	80,243	0	0
AAL	252,765	1,446	611	0	250,216	491	0
SD	1,859,250	109,232	20,584	0	1,855,969	6,722	0

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Challenges with Using Nat Cat Models to Determine Insurance Sublimits

- Verisk and RMS are not “fit for purpose” when it comes to modeling solar projects; e.g., they cannot take into account glass thickness or panel tilt angle when calculating PMLs.
  - The VDE model is the only one in the industry that can incorporate empirically validated panel and tracker attributes into PML calculations for Hail risk.
- Models use different data sets and methodologies, so can produce differing results.
- Although 125% of the 500-year PML is a minimum expected limit, it is common for financing parties to require higher limits in the case of large loan values or highly exposed locations.
- Financing parties tend to think the more insurance the better in order to transfer risk, whereas underwriters tend to want to limit their exposure.
- Modeled PMLs are important datapoints, along with many other underwriting considerations, used in broking a comprehensive but realistically-priced insurance program for a project.

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About CAC Group

CAC Group is a leading insurance broker and advisor that provides expertise and placement capabilities across the spectrum of insurance and capital markets. The entity comprises CAC Specialty, an industry leading specialty broker, CAC Agency, a P&C, personal lines and employee benefits broker, and CAC Capital, a structured solutions group that specializes in the convergence of insurance and capital markets. Collectively, CAC Group serves large corporations, small to medium enterprises as well as individuals.

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More than One Side to the Story: a Forensics Dive into PV Connector Failures

Laurie Burnham, Steven DiGregorio and Bruce King,
Sandia National Laboratories

PVRW 2025 – 5 March 2025

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

SAND#

This material is based on work supported by the U.S. Dept of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Numbers 38531 and 52774.

Project Background

3-year DOE-funded project FY 2025 - FY 2027

"Connector Reliability Across the US Solar Sector"

Team:
- Laurie Burnham, co-PI
- Bruce King, co-PI
- Steven DiGregorio
- Tap Lolla, Wayne Li
- Andy Walker, Vignesh Ramasamy, Jal Desai

Sandia

EPRI, NREL

"Advanced Diagnosis and Accelerated Testing of Balance of System Components for Utility-Scale PV Installations"

Team:
- David Miller, PI

NREL

Sandia
NREL, EPRI

"National Lab Center for PV Electrical Balance-of-Systems Reliability"

Project Tasks:

1. Site inspections
2. Accelerated testing
3. Experimental field testing
4. Forensics: micro-scale and macro-scale
5. Techno-economic analysis
6. Outreach and information sharing

Sandia National Laboratories

NREL NATIONAL RENEWABLE ENERGY LABORATORY

EPRI ELECTRIC POWER RESEARCH INSTITUTE

A Few Connector Myths

- All MC4 connectors are the same (as in 100% compatible)
- The biggest problem is connector mismatch
- Installation errors are the smoking gun

Connector Facts

PV connectors are:

- Critical to PV plant efficiency and a leading cause of plant under-performance
- Numerically the largest BoS component at PV power plants (many points of failure)
- Of unknown lifetime and variable unknown manufacturing quality
- No one smoking gun; failures likely to increase (MTTF is dropping)
- Safety is a big concern and the costs of failure are significant
- Best practices lacking; standards, while improving, fall short
- A lot of finger pointing

But it's more than just the connectors…

Industry Survey

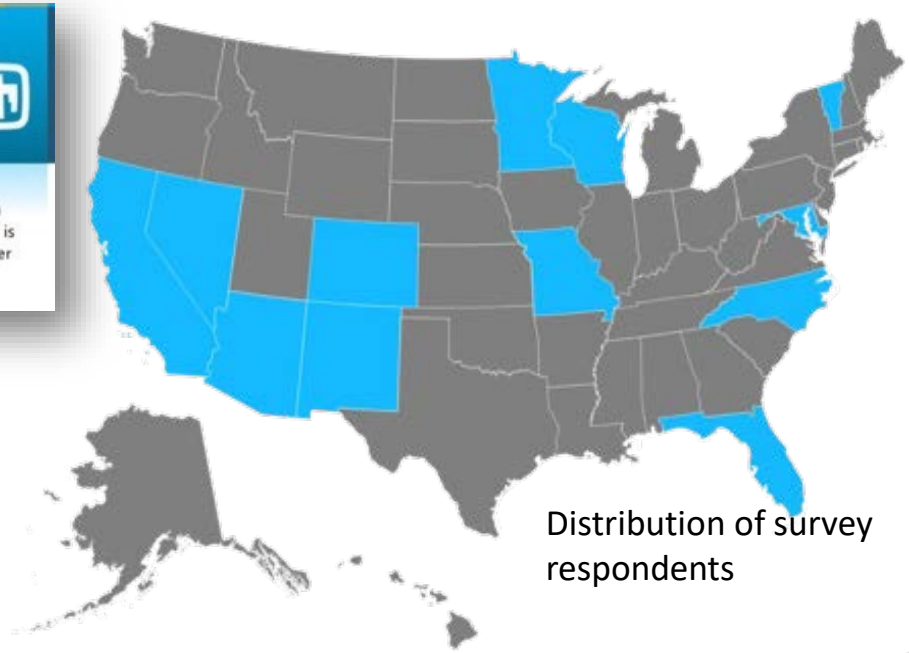
Sandia National Laboratories

Sandia PV Connector Questionnaire

Purpose
This questionnaire will gather information to support a research study on fielded photovoltaic (PV) connectors across the United States. The study is led by Sandia National Laboratories (Sandia) and is funded in part or in whole by the US Department of Energy Solar Energies Technology Office, under Award #38531.

50% of top ten EPCs

High rate of return = 60% / 88%



Distribution of survey respondents

80% acknowledged having connector problems.

"I have a plant now that is going to require an entire module connector replacement in the 1st quarter. **The connectors are cracking and breaking at an alarming rate** causing ground faults"

"MC-4 type connectors not seating securely resulting in thermal expansion/contraction and potential arc fault. **Significant effort to remediate … a 10MW AC plant."**

"Whole scale replacement of a ~20MW site due to connector thermal event ties to a **batch quality control issue** with the rolled springform inside the connector not always fitting snugly to the mating connector."

Sandia's Field Campaign

Project Objectives:
To visit and inspect PV power plants across the US
Work conducted by Laurie Burnham and Bruce King

Pre-Site:
Negotiate an NDA

Onsite Activities:

- Visual inspections
- Current measurements
- Site metadata
- Talk with field crews

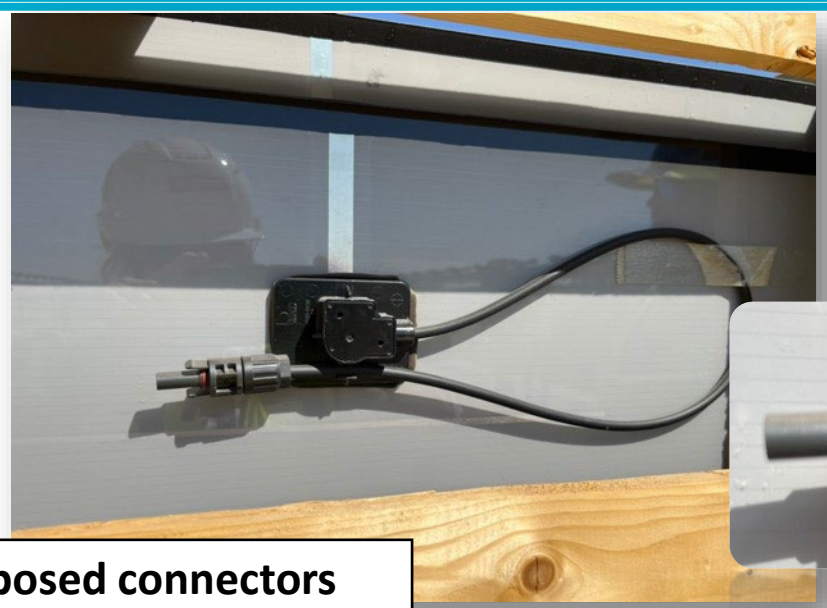
Post-Site:

Share our findings with the asset owner

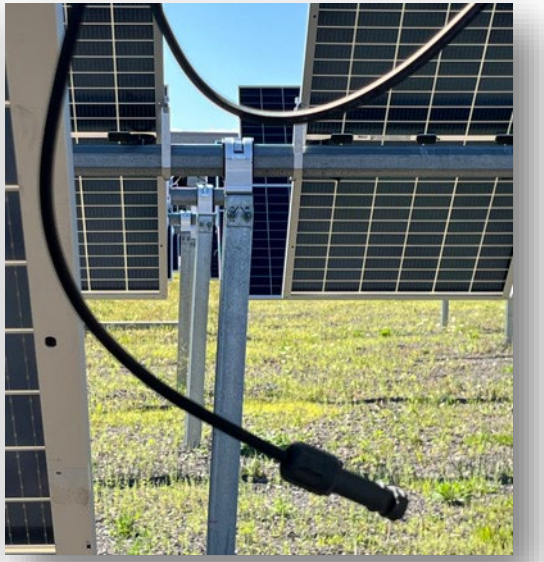
Poor Installation Practices

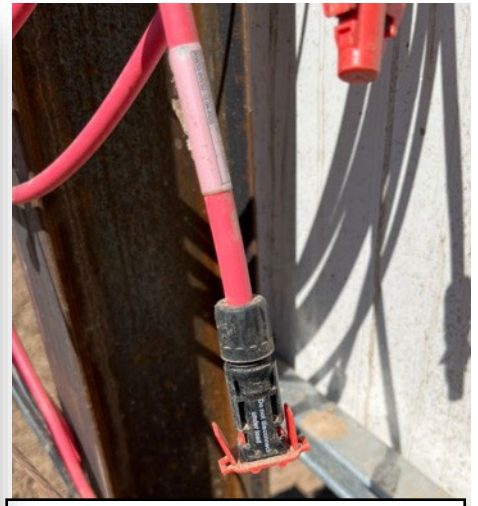
Problem #1 : Uncapped Connectors

Dusty construction sites



Exposed connectors

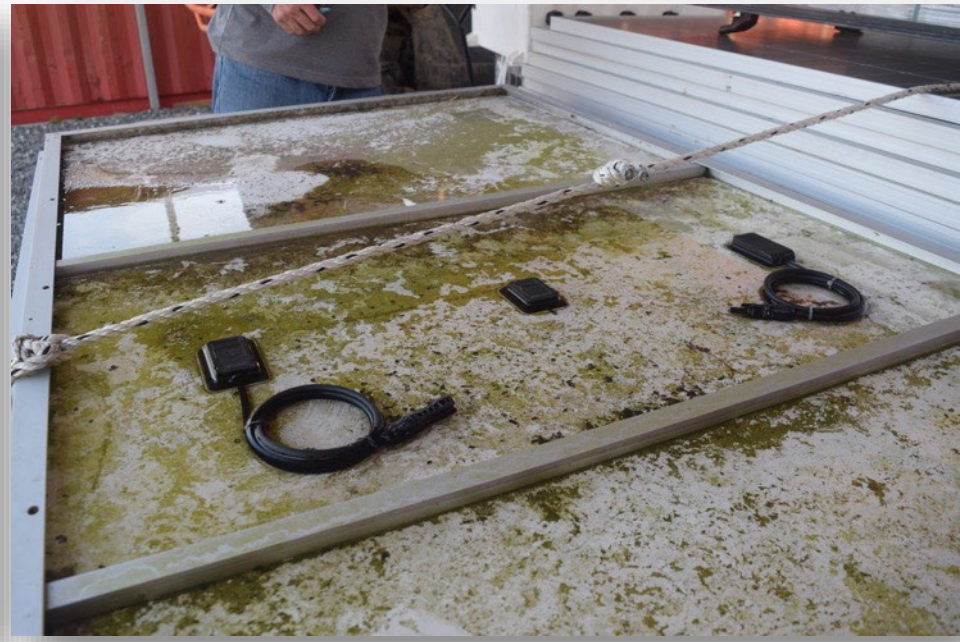




Protective end caps

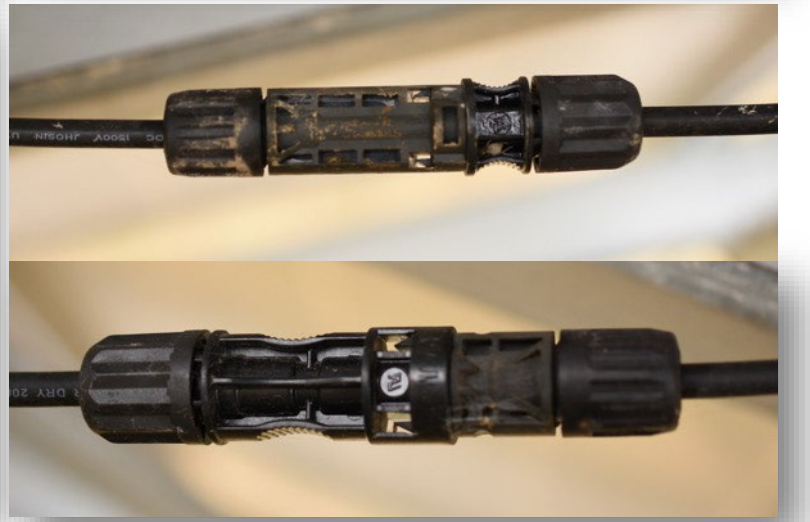
Poor Installation Practices, con't.

Problem #2 – Improper storage/handling of modules

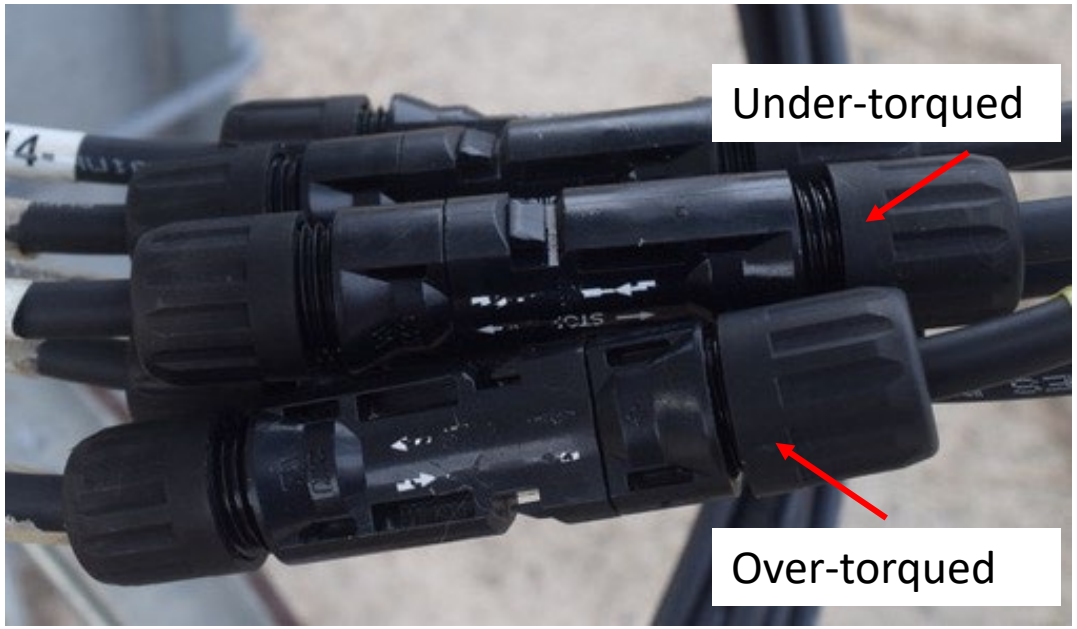


Poor Installation Practices– Module to Module Connectors

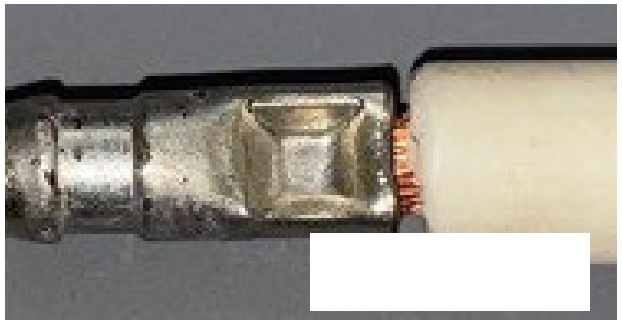
Problem #3 – Improper installation of module-to-module connectors

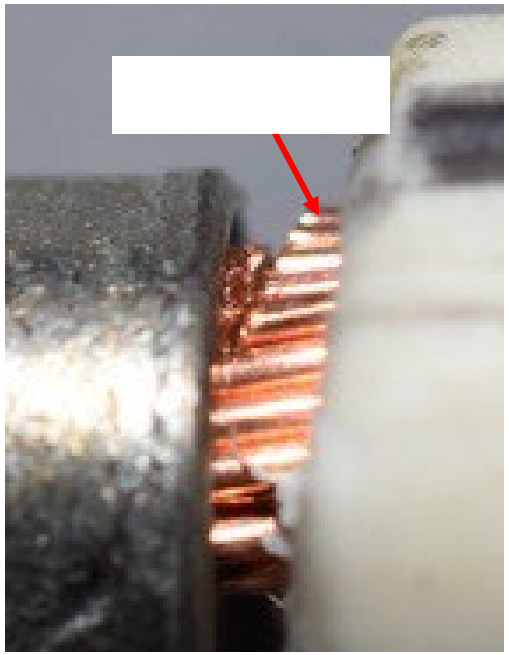


Field-Made Connectors (on the Home Runs)

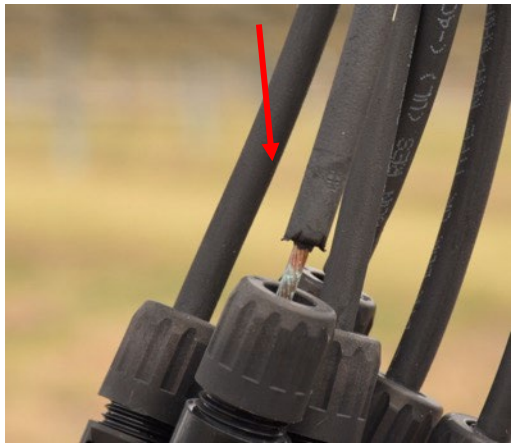


Bundled connectors can cause cascading thermal event



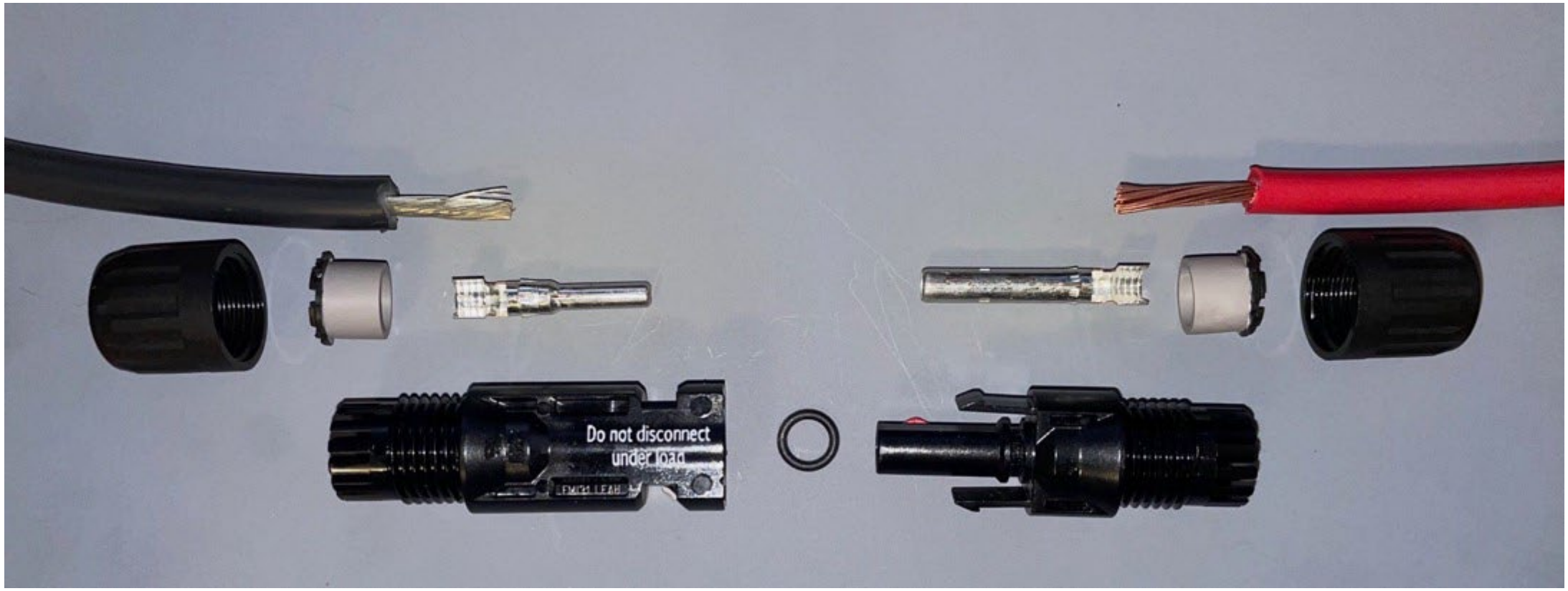


Wrong strip tool?
Exposed wire



Installation Problem #2 -- Complexity

Connectors have lots of little parts



Installation Problem #3 – Unrealistic Specifications

Unrealistic installation requirements?

STÄUBLI

MA231 (de_en) Montageanleitung	MA231 (de_en) Assembly instructions
PV-Kupplungsstecker PV-KST4/...-UR	**PV male cable coupler PV-KST4/...-UR**
PV-Kupplungsbuchse PV-KBT4/...-UR	**PV female cable coupler PV-KBT4/...-UR**

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Cable gland assembly ... 10
Mating and disconnecting the cable coupler
- without safety lock clip PV-SSH4 ... 11
- with safety lock clip PV-SSH4 ... 11
Notes on installation ... 12
Technical data ... 13
Notes ... 14 – 16

Kupplungsbuchse/Female cable coupler

PV-KBT4/2.5...-UR
PV-KBT4/6...-UR
PV-KBT4/10...

PV-KBT4/5...-UR
PV-KBT4/BII-UR

Kupplungsstecker/Male cable coupler

PV-KST4/2.5...-UR
PV-KST4/6...-UR
PV-KST4/10...

PV-KST4/5...-UR
PV-KST4/BII-UR

Optional
PV-SSH4
Sicherungshülse/Safety lock clip

(siehe/see www.staubli.com/re-downloads.html --> MA252)

Verschlusskappen/Sealing caps

PV-BVK4 32.0716 — **PV-SVK4** 32.0717

1/16

STÄUBLI

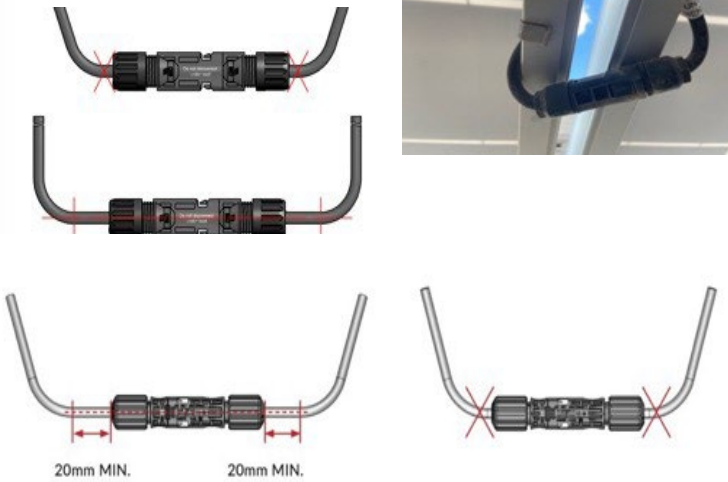
Notes on connectors and components storage

Stäubli recommends to store connector components at a preferably constant temperature range between –30°C and +60°C and relative humidity of less than 70%.
The components must not be exposed to moisture due to direct rainfall, condensation, etc.
Ensure that individual components do not get into contact with acids, alkalis, gases, acetone or any other aggressive chemical substances, which might impact the material performance.
Once all these storage conditions are met the components could be stored up to two years behind manufacturing.

General notes on installation

- Unmated connectors must be protected from environmental impact (moisture, dirt, dust, etc.) with sealing caps (socket order no. 32.0716; plug order no. 32.0717).

Bending Radius



- Refer to cable manufacturer's specification for minimum bending radius of cable.

Installation Problem #4 – Manufacturer Requirements

Connector manufacturers specify proprietary tools and have detailed instructions. 110.3(B) of the NEC states:
"Equipment that is listed, labeled, or both, shall be installed and used in accordance with any instructions in the listing or labeling."

haisstronica 25PCS Solar Crimping Tool Kit, 20 Pairs MC4 Connectors AWG14-10(2.5/4/6mm²) with Stripper and Spanners for Solar Panel PV Cable Installation

Visit the haisstronica Store

4.8 ★★★★★ 15 ratings

100+ bought in past month

$45.99

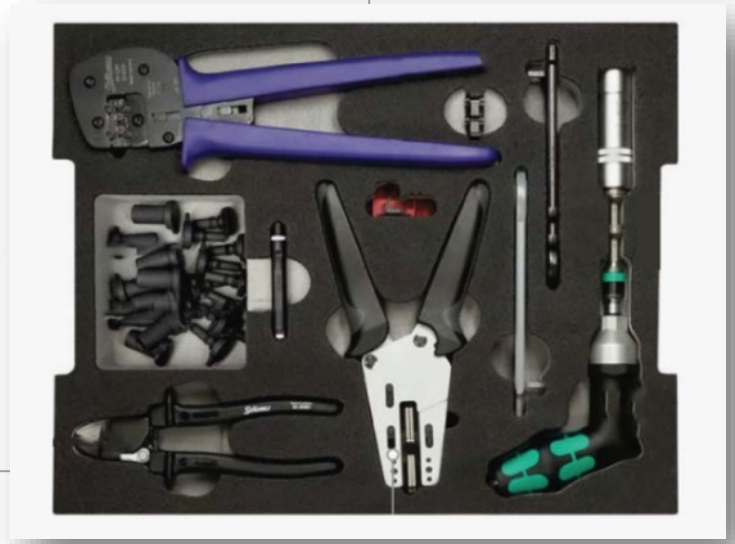
Staubli MC4 Tool Kit

STÄUBLI

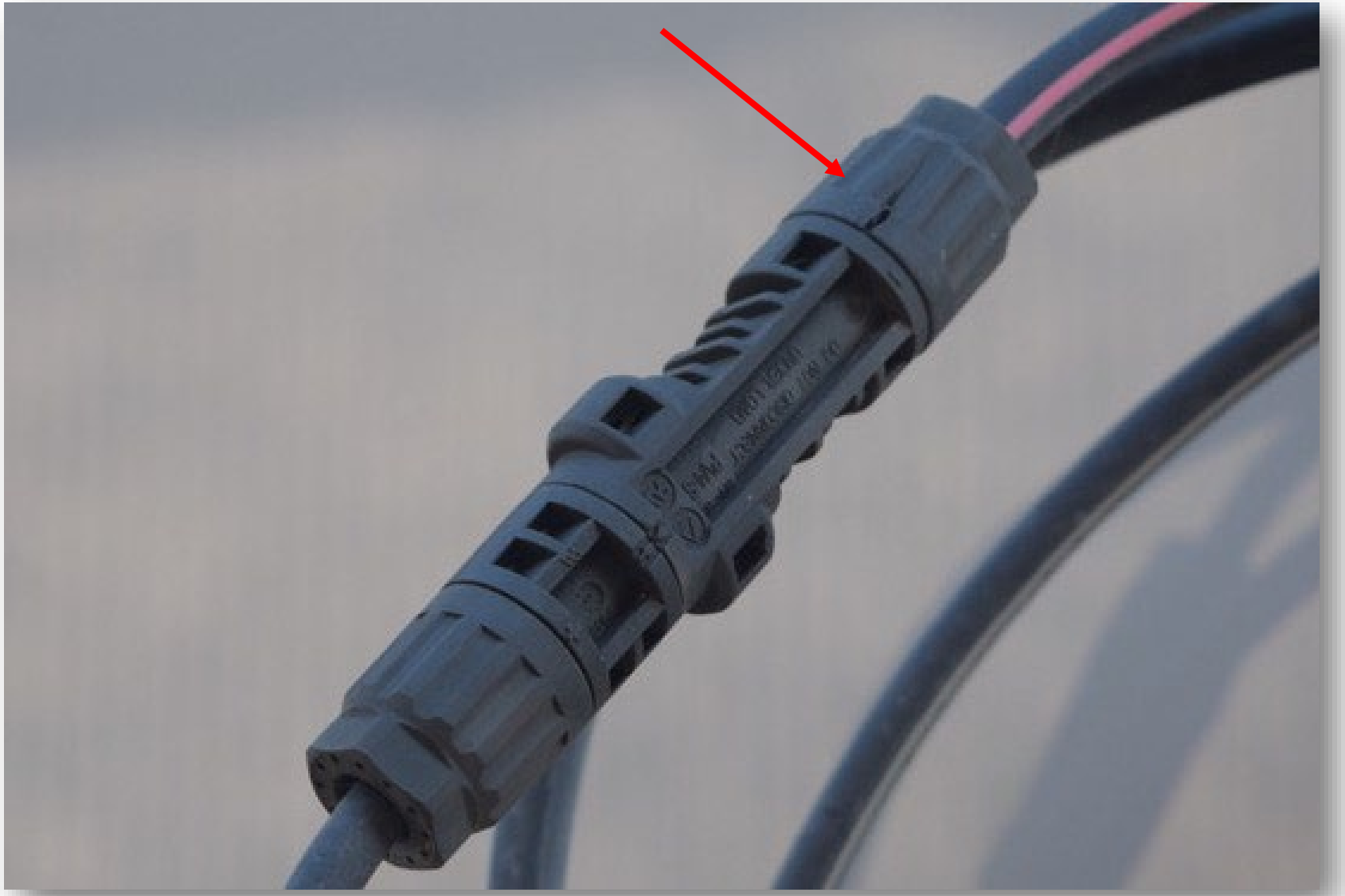
$1,041.10

SKU#: 32.6128-22100

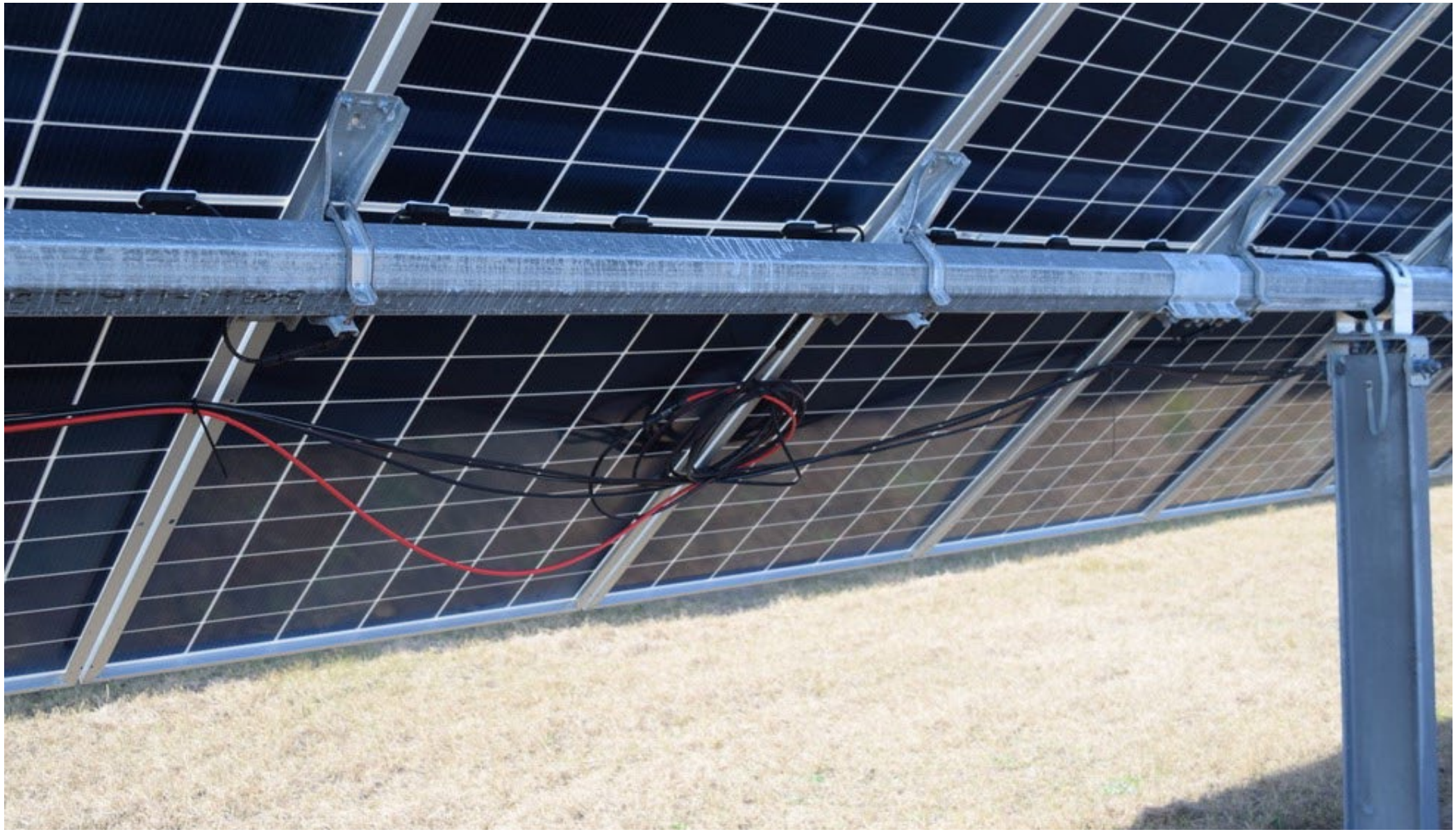
Staubli MC4 Tool Kit



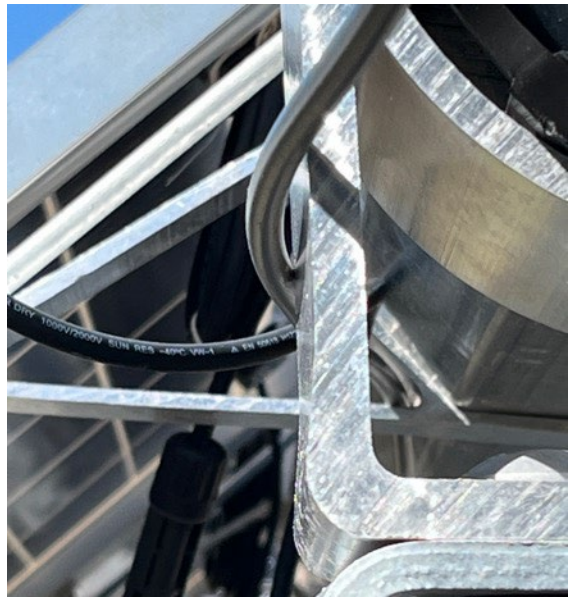
Other Problems – Home Run Connectors

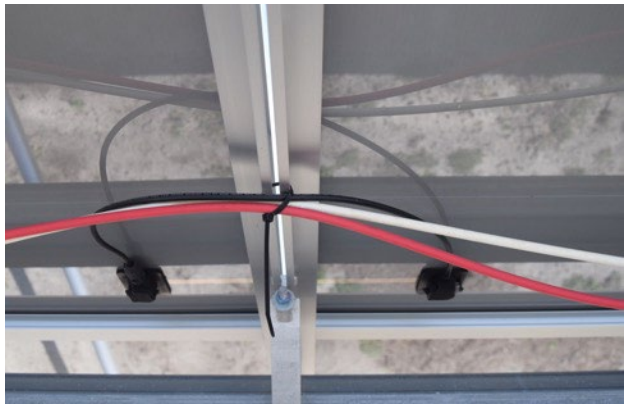


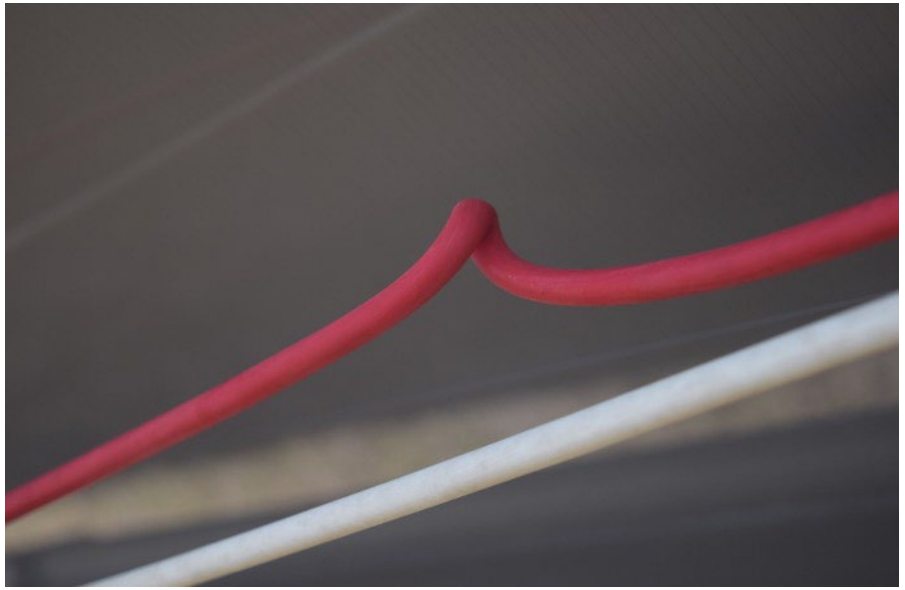
Cable Management

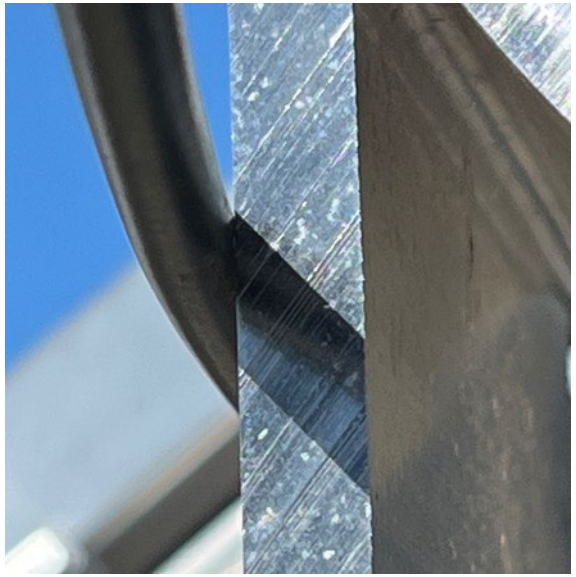


Cables and Cable Ties









Wire Hangers

Part II
Steven DiGregorio

Field-Harvested Connector Initiative

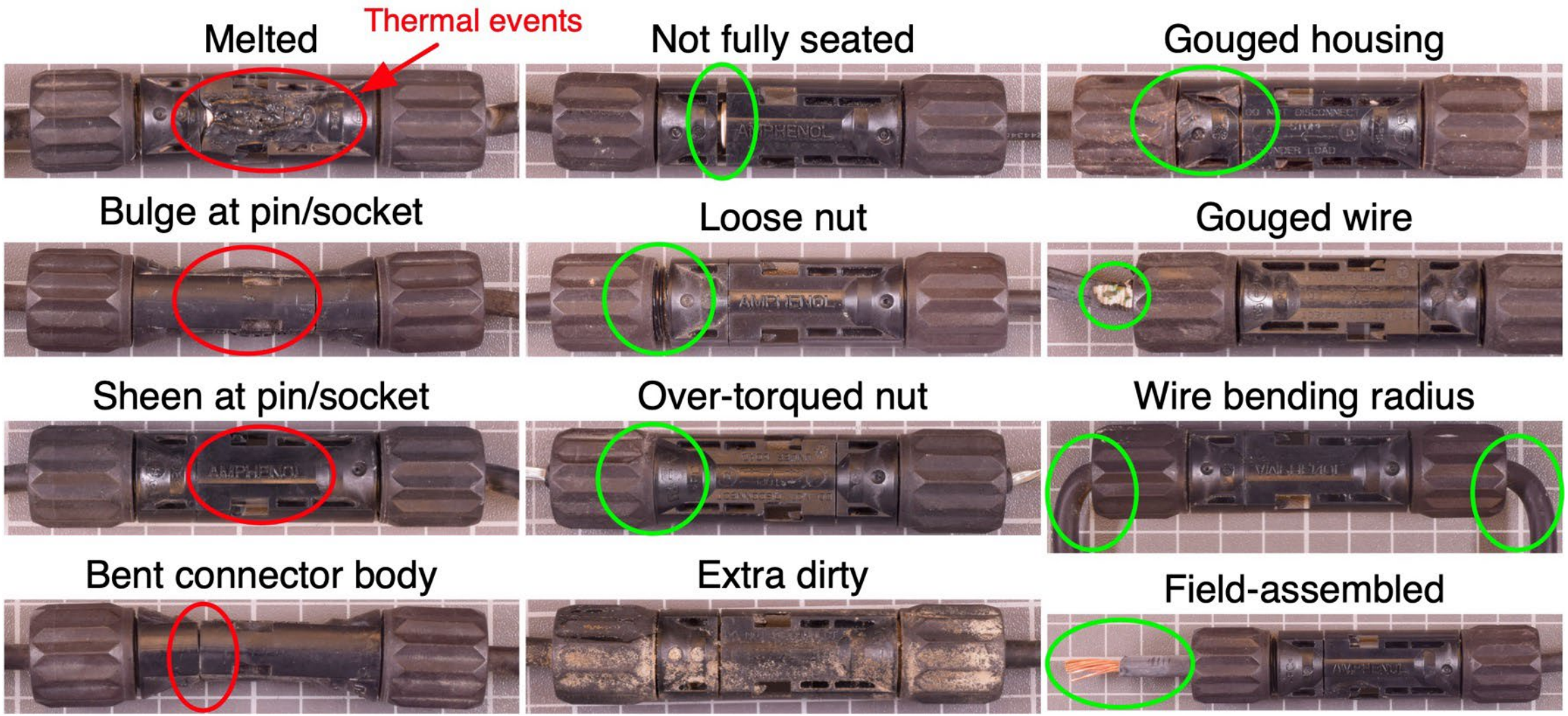
- To date, industry partners have provided thousands of connectors removed from systems for analysis
- Objectives
  - Identify and quantify connector failures
  - Test common perceptions (ex. field-assembly and cross-mating)
  - Inform standards and best practices for improved reliability
- Approach
  - Collect diverse, high-volume populations of fielded connectors
  - Gather metadata (age, climate, system configuration)
  - Characterize each connector at Sandia with a 4-step process

Step 1: Barcoding & Wire Stripping

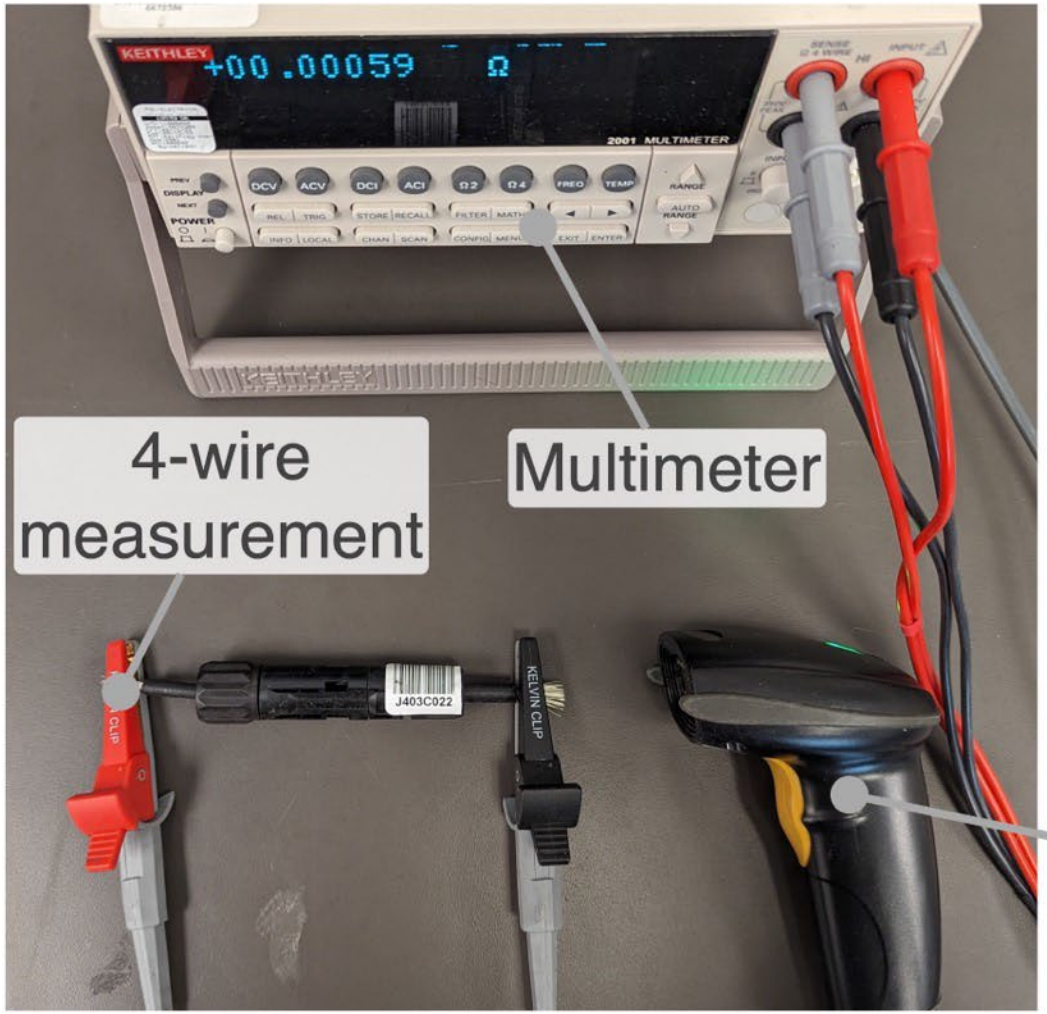
As-arrived

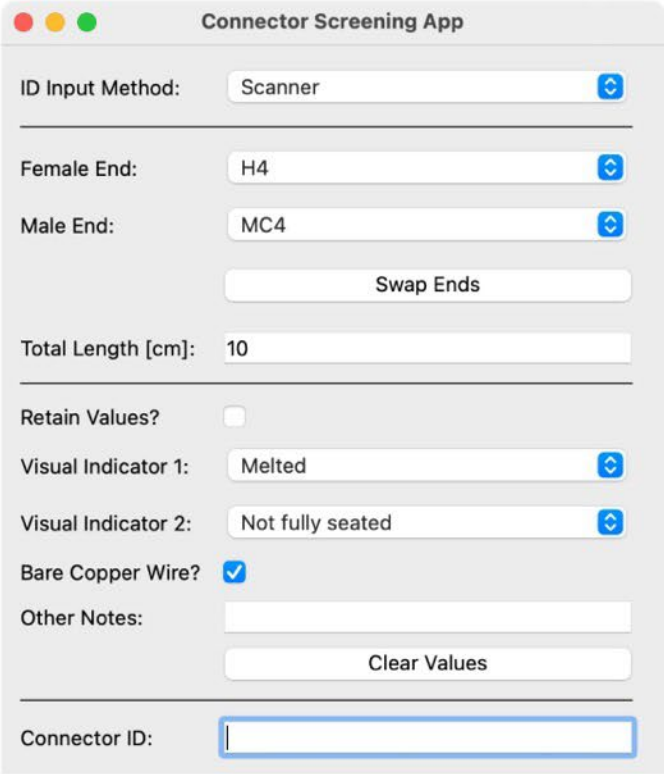
Barcoded and Stripped

Step 2: Visual Inspection



Step 3: Resistance Measurement





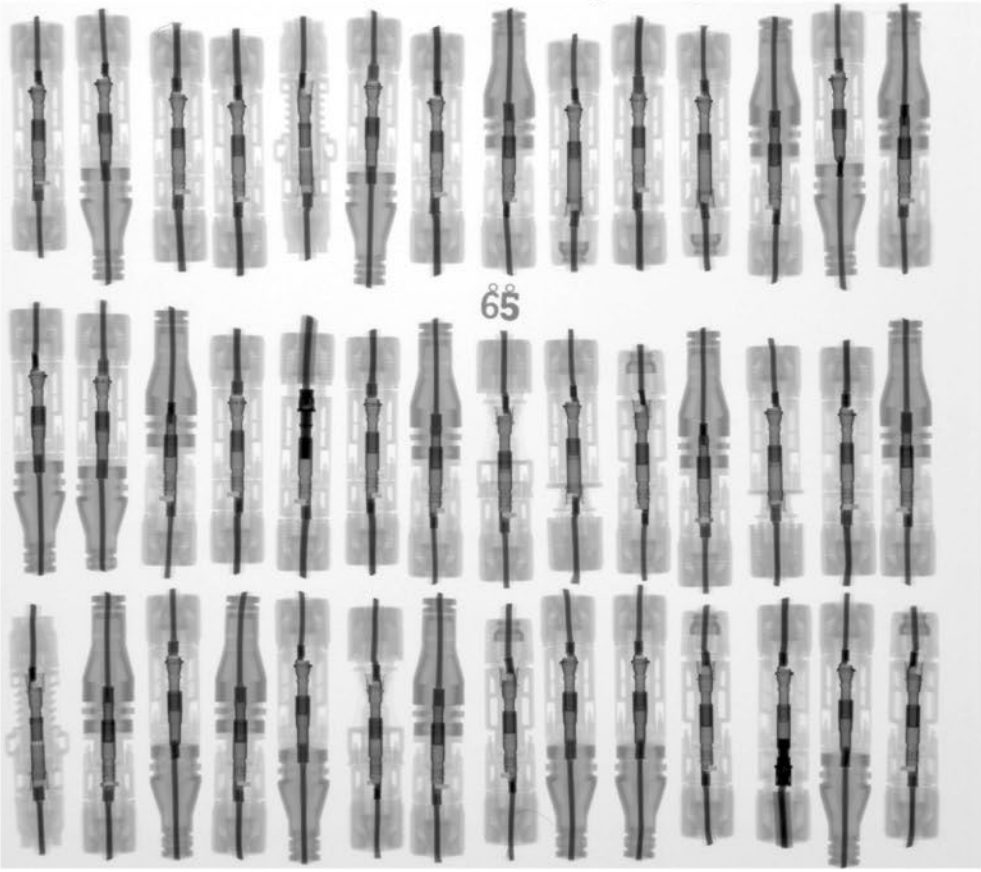
Custom control app

Scanning barcode initiates measurement

Step 4: X-ray Imaging

42 connectors arranged on foam board

Corresponding X-ray Image



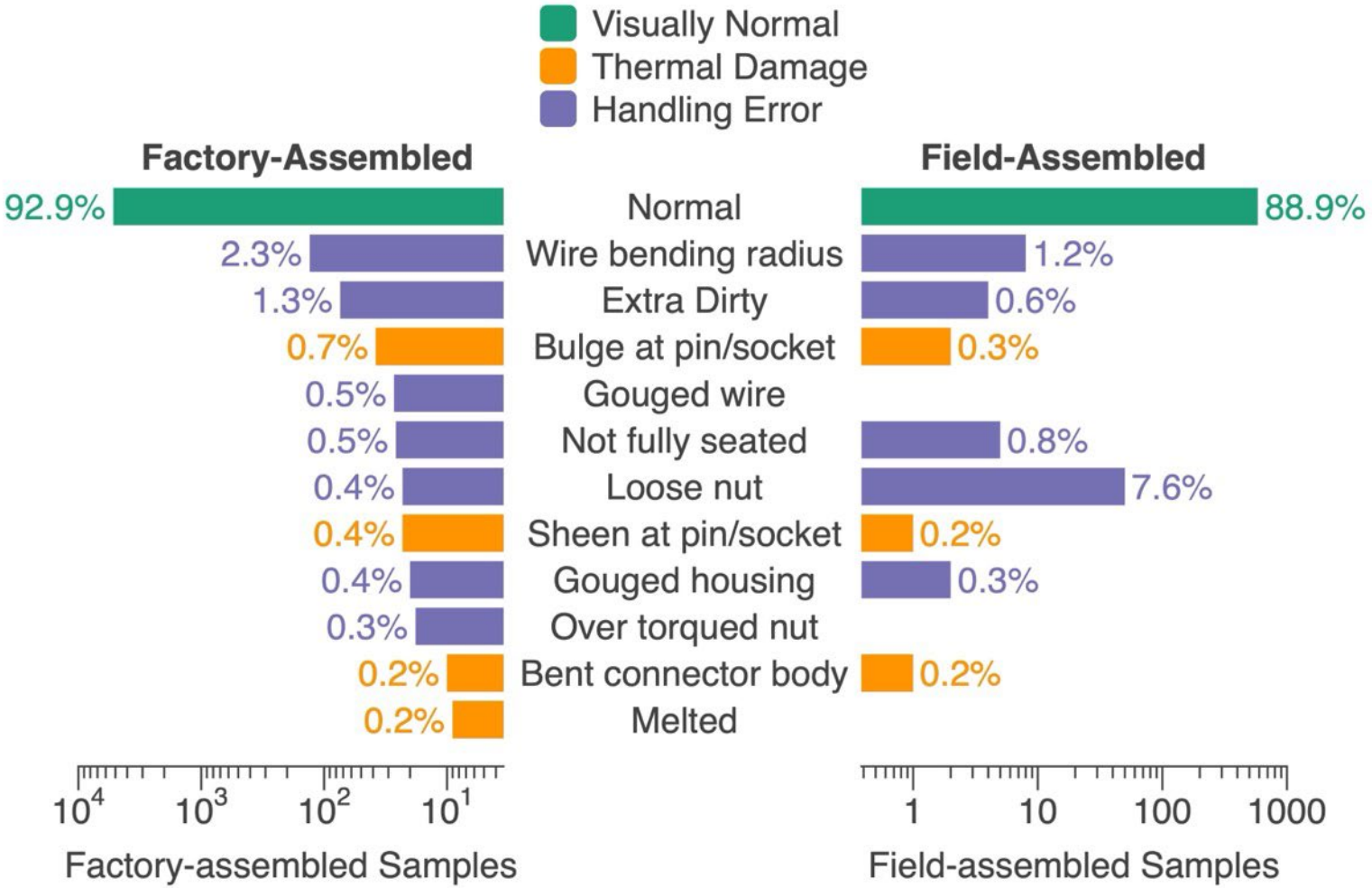
- Poster covers more details on X-ray methods (Poster #39 on Thursday)

Pilot Study of 6248 Connectors

- Provided by a rooftop solar installer
- Used to develop and test our methodology
- Conclusions may not represent the entire PV industry
- Result can inform commercial and utility analysis

Frequency of Inspection Categories

- Majority of connectors were visually normal
- Thermal events uncommon (only 9 melted samples)
- Loose nuts
  - 7.6% of field connectors
  - 0.4% of factory connectors



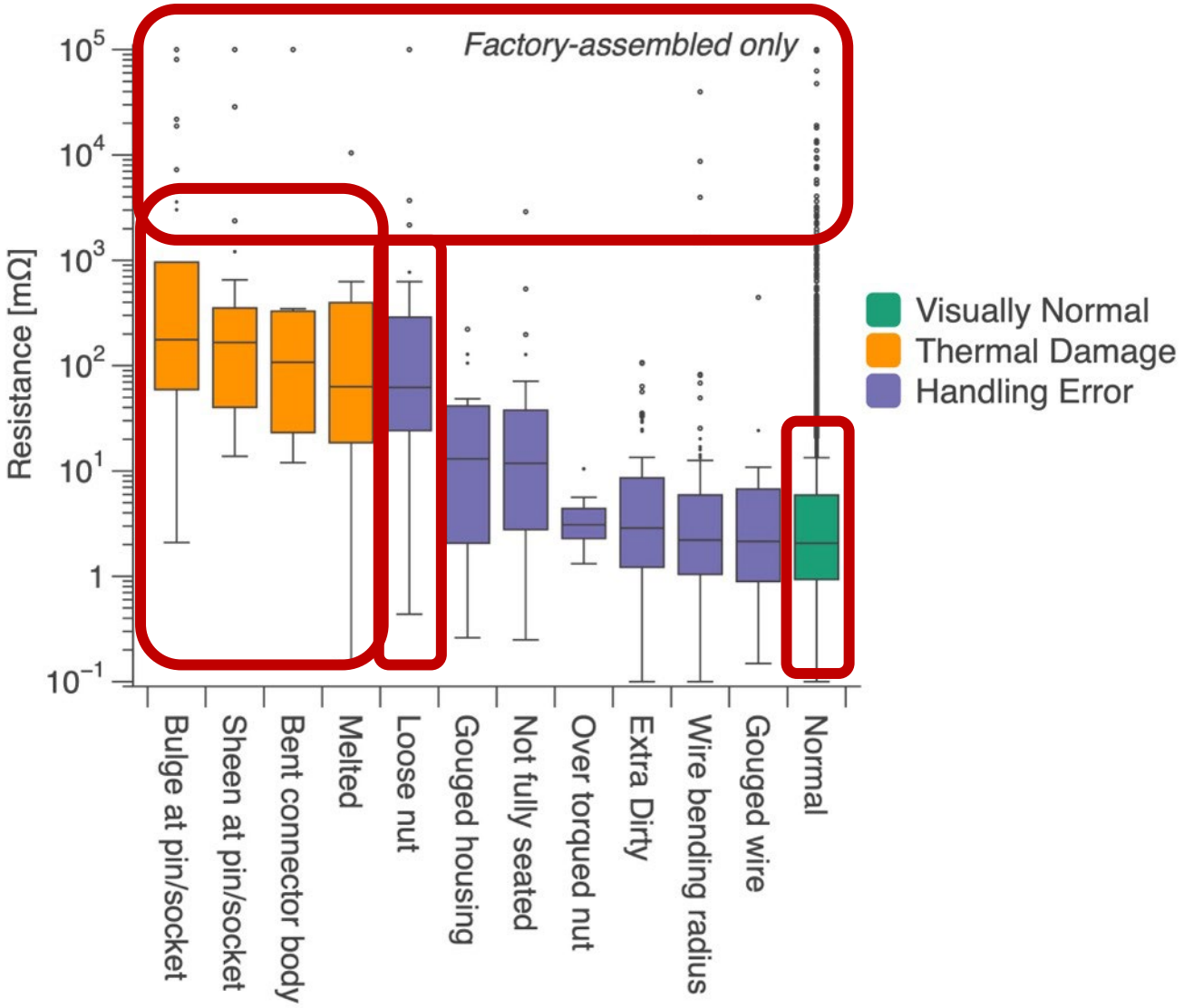
Resistance Ranges of Inspection Categories

Highest resistance:
Samples with thermal damage

Lowest resistance:
Visually normal connectors

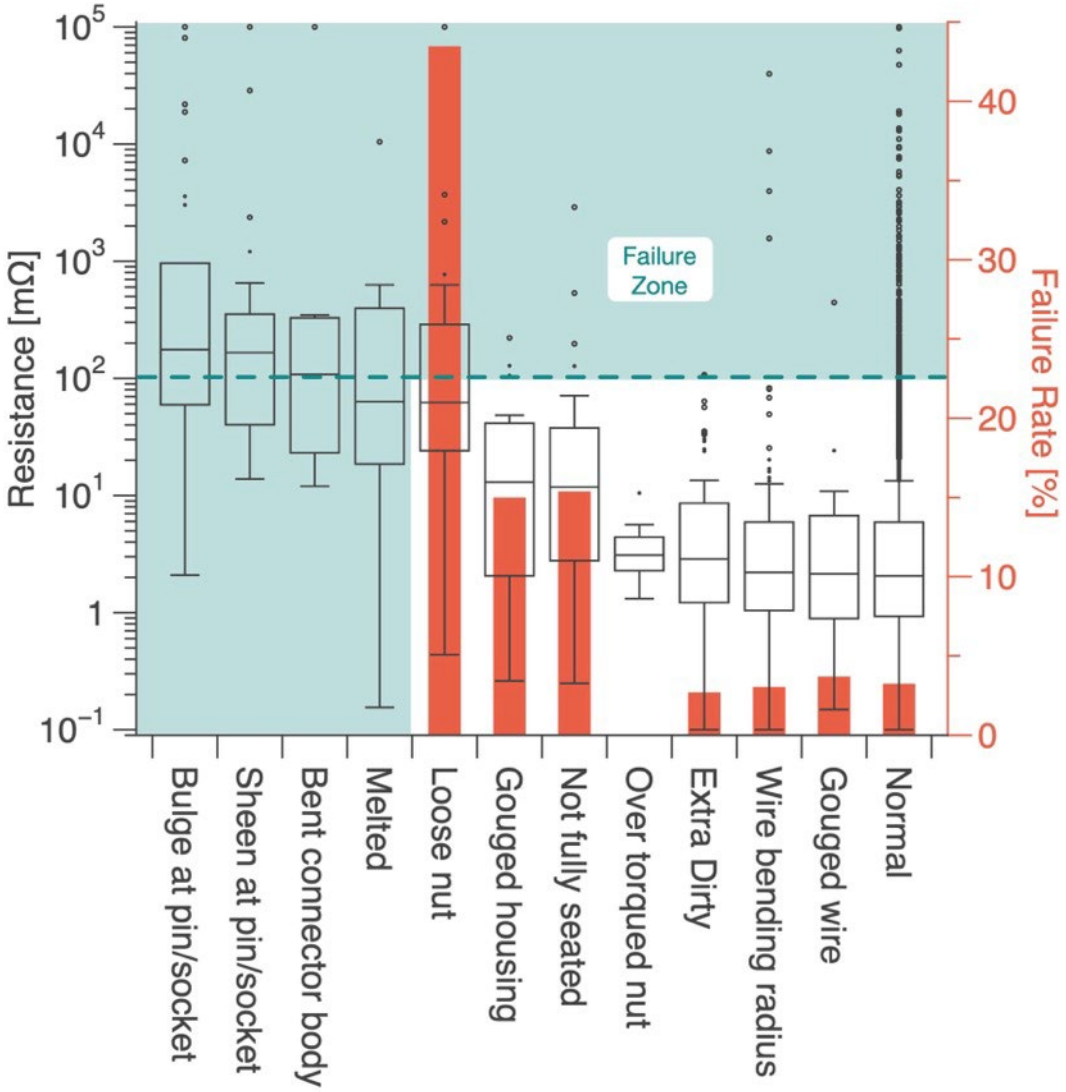
Critical installation error:
Loose nuts

Need to consider outlier values (establish failure criteria)

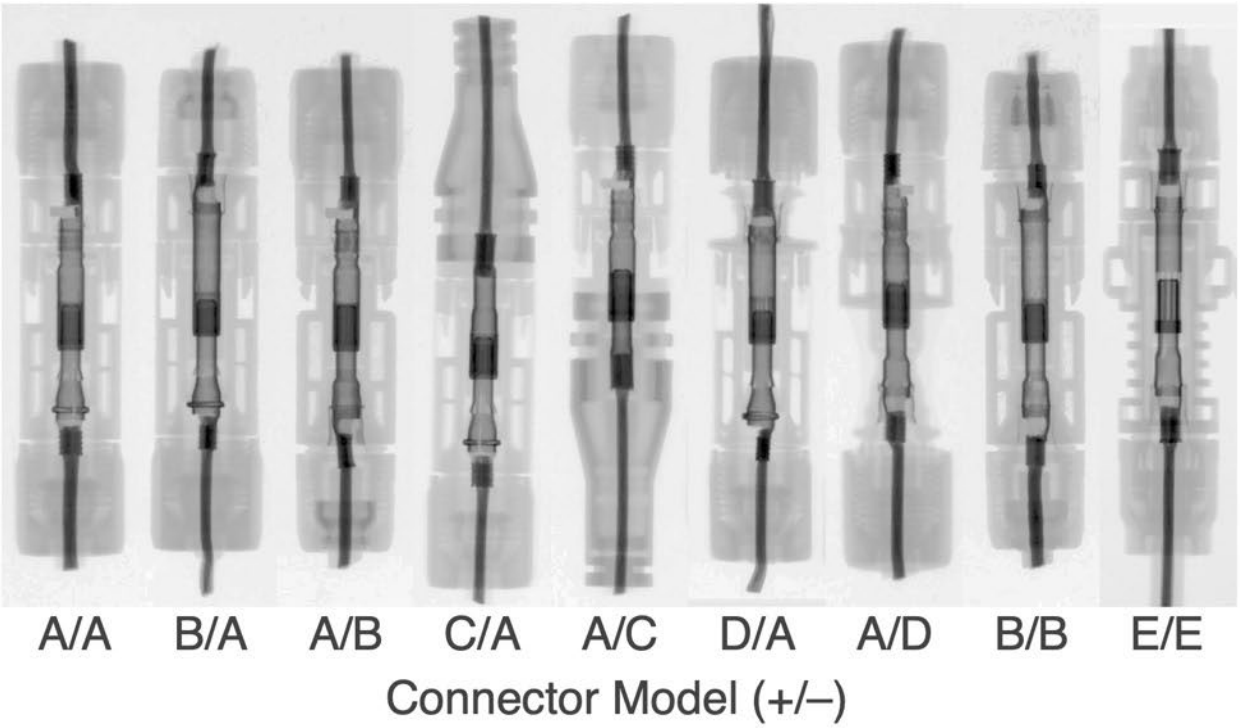


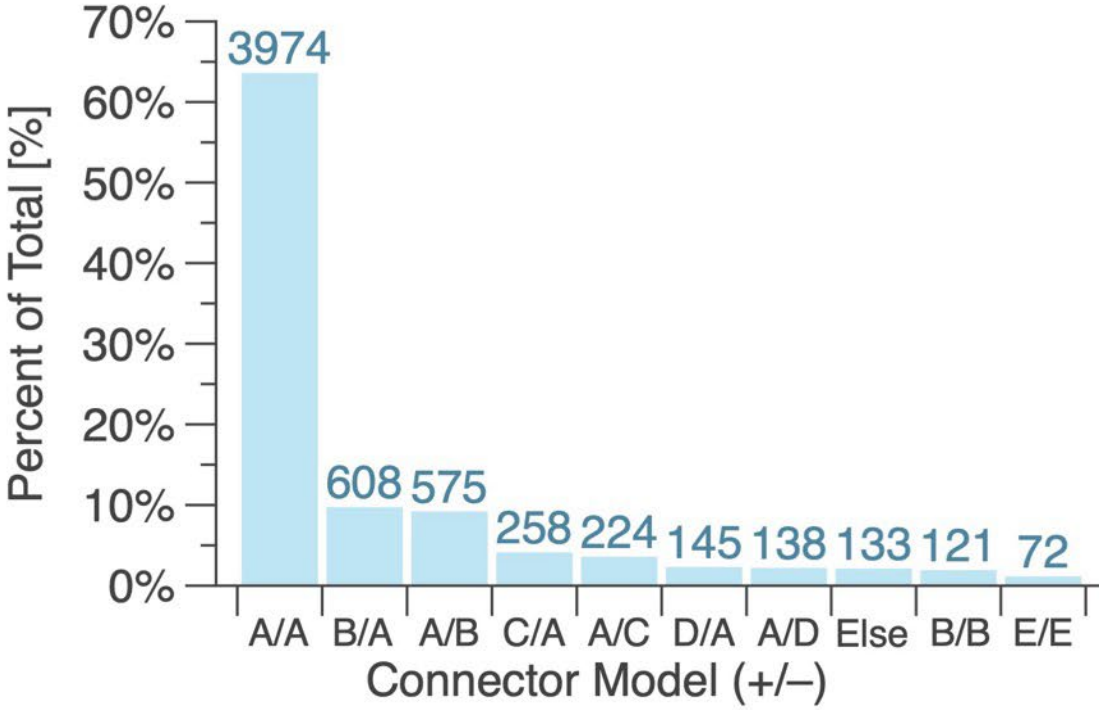
Establishing a Pass/Fail Criteria

- Conservative failure criteria:
  1. Resistance > 100 mΩ or
  2. Thermal damage
- Calculated failure rate for each category
- Connectors with loose nuts failed 43% of the time



Connector Models for Analysis

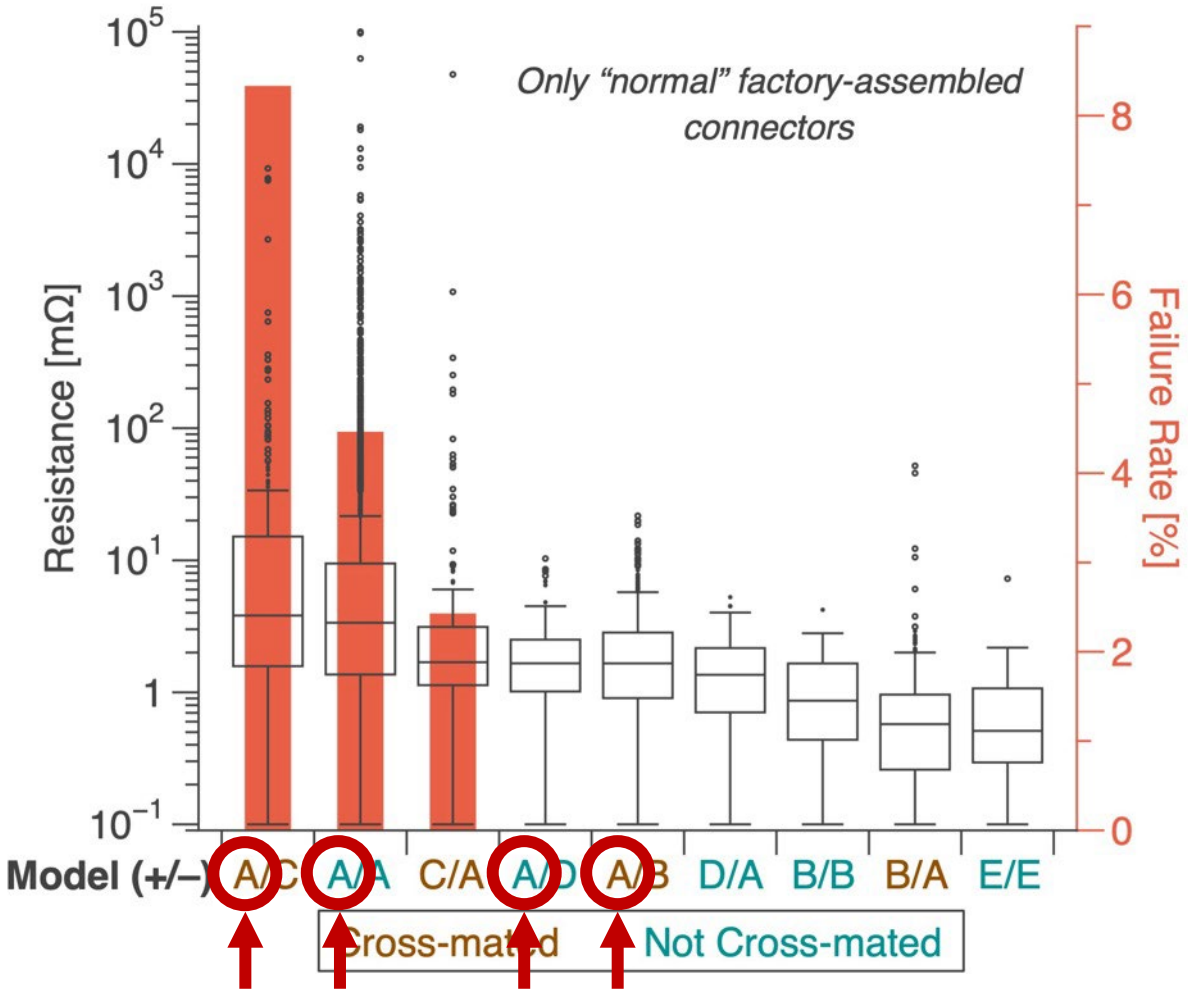




- Five different models (labelled A-E)
- Nine different positive/negative model combinations
- Model A/A connectors more prevalent (63% of total)

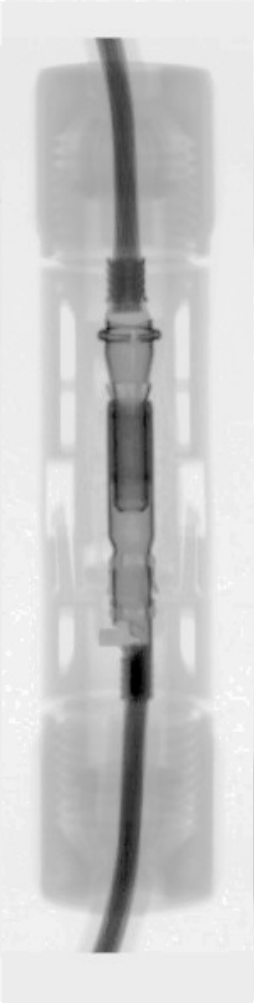
Resistance and Failure Rates vs. Connector Model

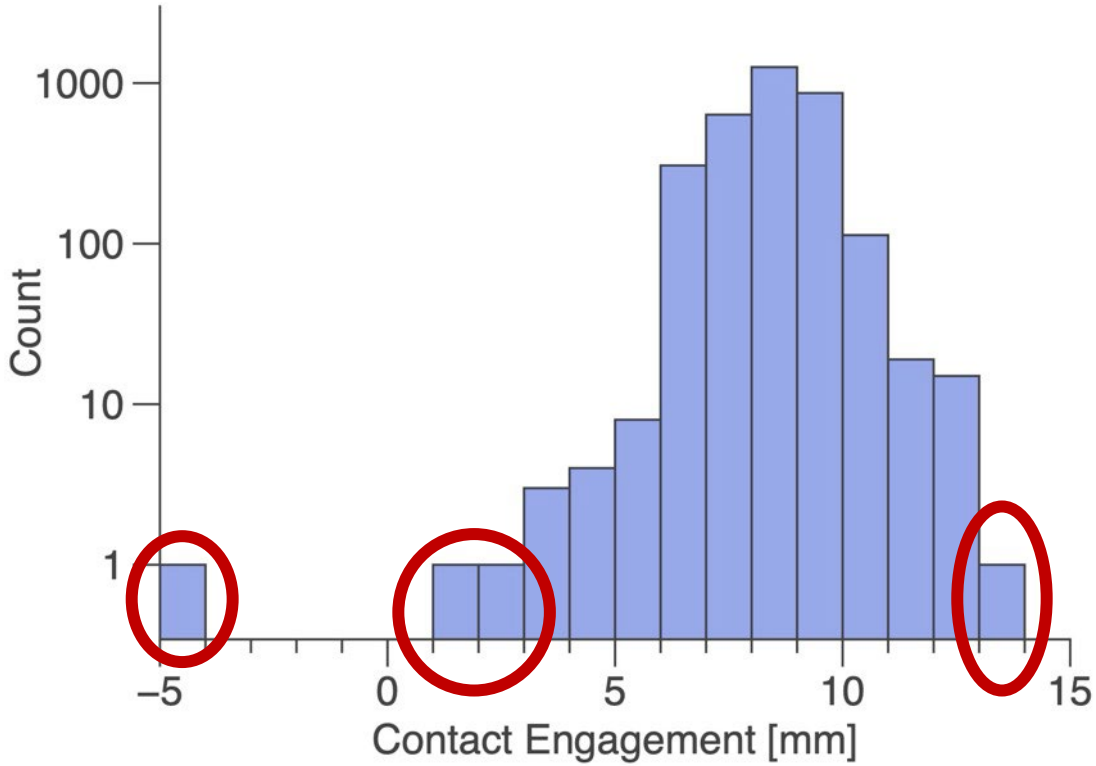
- Median resistance range from from 3.8 mΩ to 0.5 mΩ
- Cross-mating does not necessarily correlate with poor performance
- Avoiding cross-mating does not guarantee good performance
- 4/5 worst performers had a positive model A connector (potential design flaw)

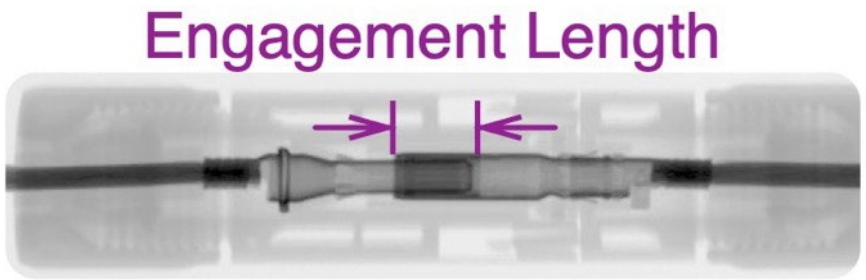


Contact Engagement Length Analysis

Contact Separation



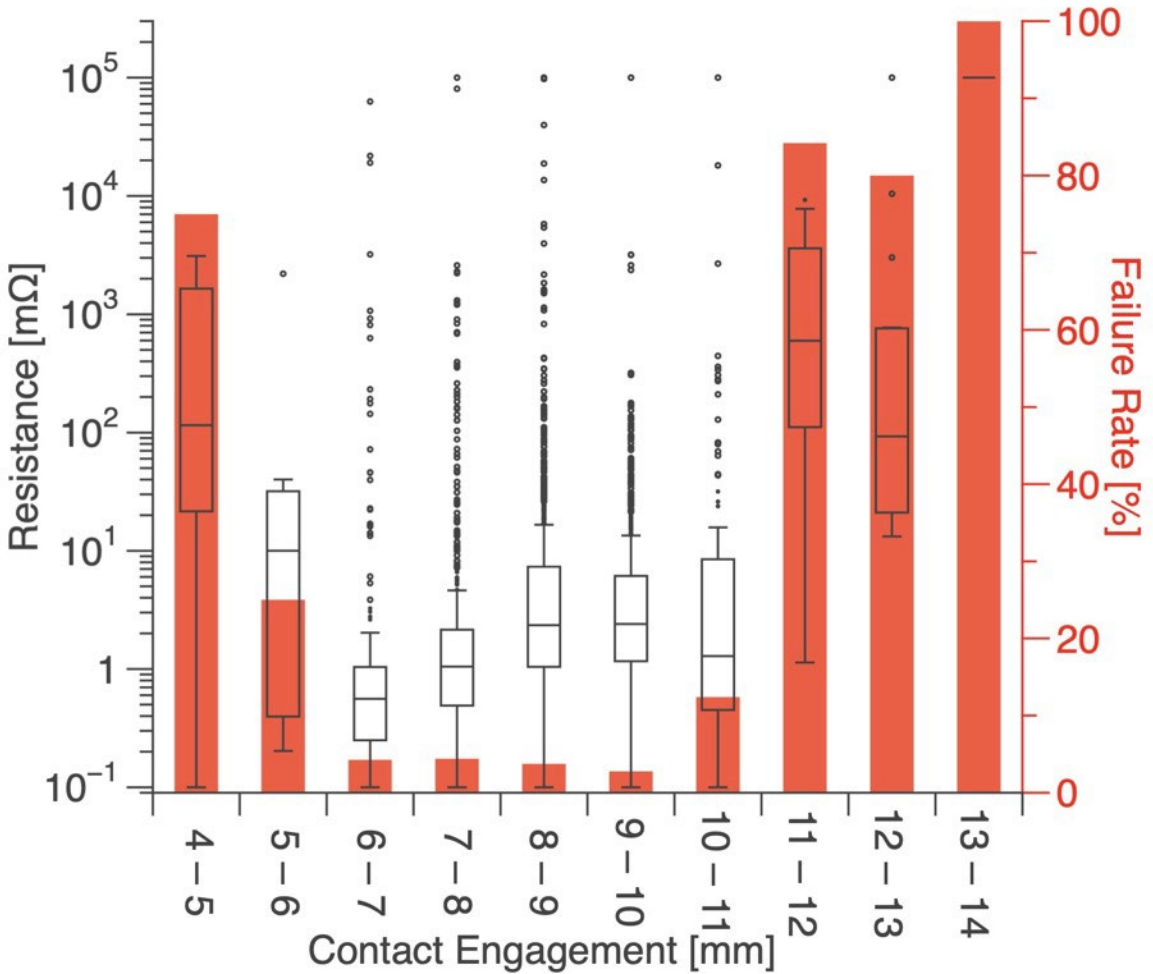




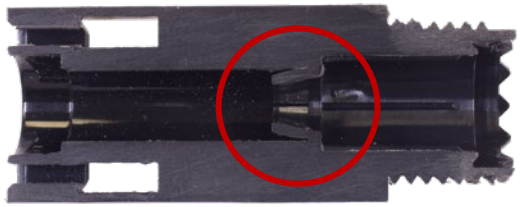
- X-ray revealed significant variation in contact engagement length

Impact of Contact Engagement Length

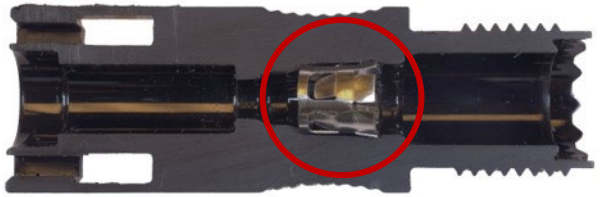
- Contact engagement length matters
  - Optimal range: 8 ± 2 mm
  - Both under and over engagement are problematic
- Reason for variation
  - Contact displacement within housing
  - Efficacy of different contact retainer designs
  - See poster #39 on Thursday for more details



Plastic Contact Retainer



Metal Contact Retainer



Conclusions

- Developed and demonstrated methodology for failure analysis of large connector quantities
- Data collected can illuminate the state of connector issues and inform actionable improvements
- Paper in prep. on the rooftop connector results
- Future work: use capabilities to characterize utility populations

Project Summary

Take-aways:

- Quality is a concern on the manufacturing side but installation is likely the most critical and difficult-to-control variable
- Connectors are not the only problem; cables matter too
- Failure rates are likely to increase
- Beware of assumptions; when in doubt contact the national labs

Moving forward, the Sandia project aims to:

- Link manufacturing and installation defects to failure mechanisms;
- **identify the installation errors that are the most consequential;**
- Quantify degradation rates and failure occurrences at the power-plant level
- Expand our economic analysis
- Create a National Lab Center for information sharing, including early failure warnings, best practices, etc.

Please support this effort:

- We need data
- We need connectors
- We need site access
- We need need your feedback and expertise

Questions?

lburnha@sandia.gov

Installation Problem #1 -- Mismatch

- 4mm connectors are commonly known as “MC4s” or “MC4 compatible.” True on Amazon; true for module m’facturers.
- The problem? MC4s are a Staubli-branded connector and NOT compatible with other brands.

Amazon.com
www.amazon.com/shop/mc4+connectors

Mc4 Connectors - Huge Selection & Great Prices

Read customer reviews & find best sellers. Free, easy returns on millions of items.

Parts Express MC4 Male/Female Solar Panel Cable…

$2.00

solarpowerco… , 2+

5.0 ★★★★★ (1)

MC4 Solar Connector Male and Female Set 30A, f…

$6.25

elliottelectronicsup…

4.6 ★★★★½ (12)

Male/Female Set of MC4…

$3.99

Titan WNC

Get by 9/24

Tycon Systems Inc. MC4-…

$3.50

DigiKey

30-day returns

Male and Female MC4 Connectors

$1.50

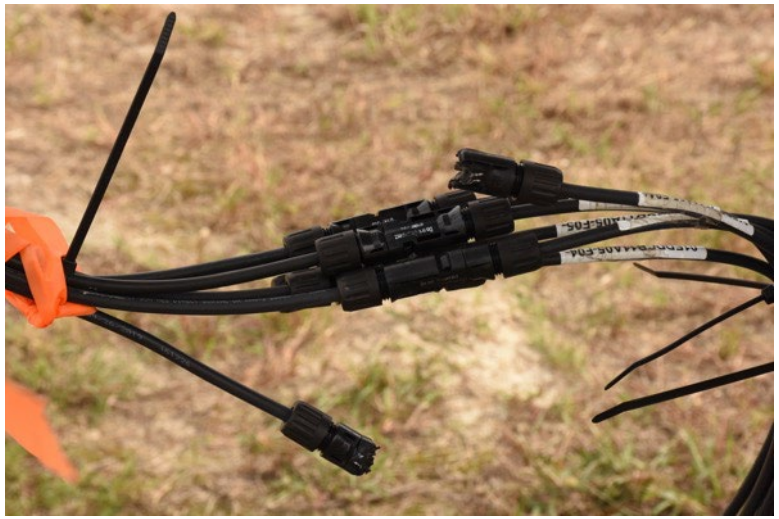
SanTan Solar

4.6 ★★★★½ (60)

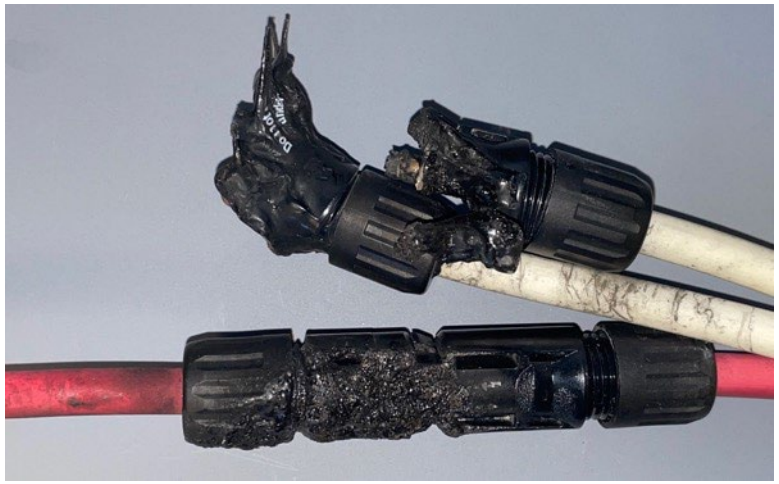
Field-Made Connectors (on the home runs)

- Numerous examples of seal failures at the end nut
- Evidence of cable insulation “pullout”…..short stripping or shrinkage?
- Incipient cable corrosion in some cases
- Almost certainly accompanied by water ingress into housing
- Not a matter of “if”….a matter of “when”

Cable Management (Home Runs)



- Runaway resistive heating at pin-sleeve contact
- Bundled home run harnesses can put adjacent connectors at risk
- Emerging thermal damage may not be easy to identify
- Blocks with failed strings are offline...no current = no heat
- Identification by maintenance crews often most reliable



Connector Facts

PV connectors are:

- Critical to PV plant efficiency and a leading cause of plant under-performance
- Of unknown lifetime
- Numerically the largest BoS component at PV power plants (many points of failure)
- No one smoking gun; failures likely to increase
- Costs of failure are significant
- Best practices lacking; training curricula do not include connectors (lots of opportunity)
- Standards, while improving, fall short
- A lot of finger pointing

Field connectors—at a minimum—are costing the industry $XX.
Numerically the most numerous PV BoS component at PV power plants
Critical to PV plant performance and a leading contributor to plant under-performanceme
Of unknown lifetime
Large #s of failures are occurring at plants that are < 3 years old; in some cases, plants have been repowered and failed in < 1 year., despite installation training.
No one smoking gun.

Example of a Poor Installation Outcome

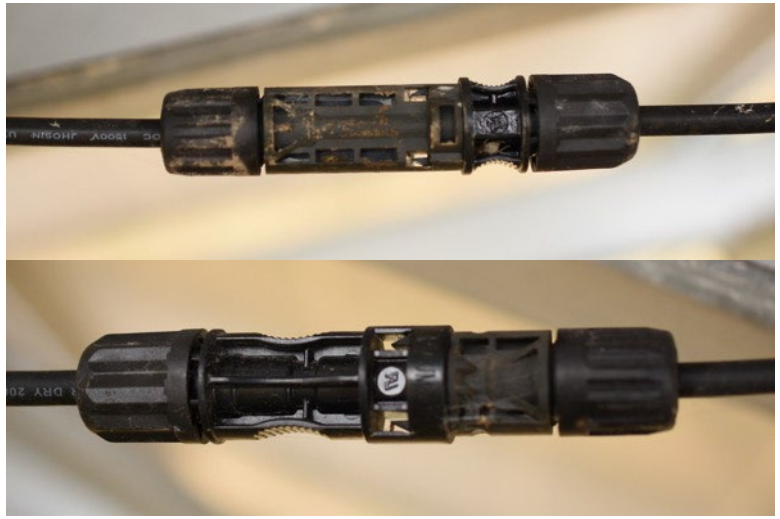
"Issues were found in all samples, pointing to incorrect assembly techniques, incorrect tooling and improper part handling. All products are severely compromised, not covered by warranty and unsafe for field use."

Liability assessment for connector failures at 75MW site

Connector Myths

- Mismatch is the number 1 failure mechanism for connectors
- Failures are 100% installation related
- Always the field assembled connectors
- Module reliability is what really matters

Module to Module Connectors



- Field-made jumper to accommodate a module replacement
- Cable routing left connectors laying in trays where they could be submerged
  - connectors are IP68, but….only if they're assembled correctly
- Electrical arc to racking

- Cross-mating between replacement modules
- Single module model, two j-box & connector assemblies
- In total, four different connectors observed on site
  - Original module
  - Replacement module
  - Home runs & harnesses
  - Field repair

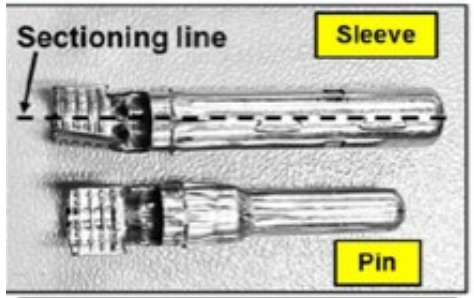
Manufacturing Quality: Micro-forensics Analysis

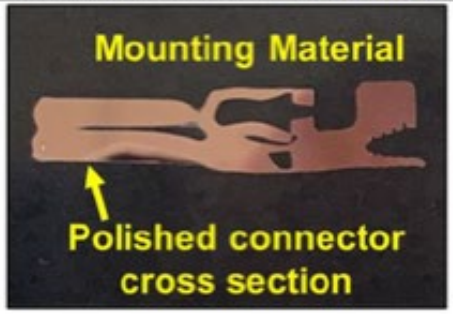
Micro-forensics study conducted by Tapasvi Lolla and Wayne Li of EPRI

EPRI ELECTRIC POWER RESEARCH INSTITUTE

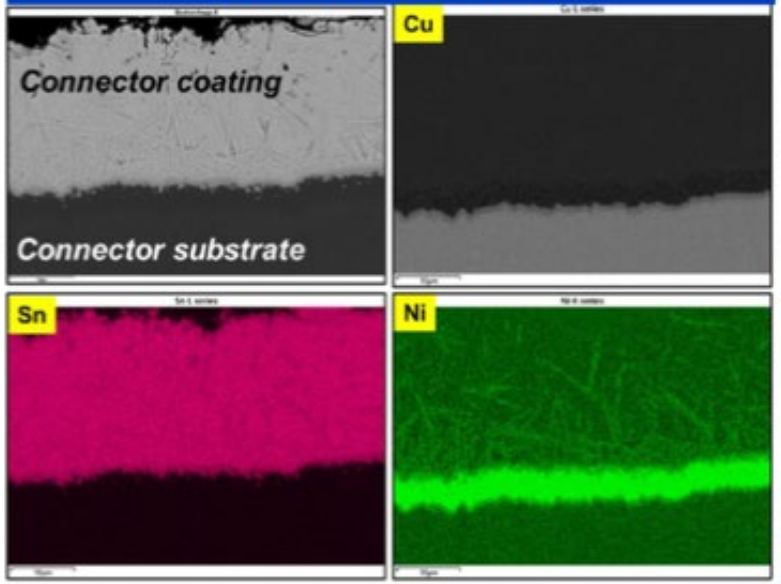
Part 1- Baseline: Analysis of as-manufactured connectors

Sample preparation

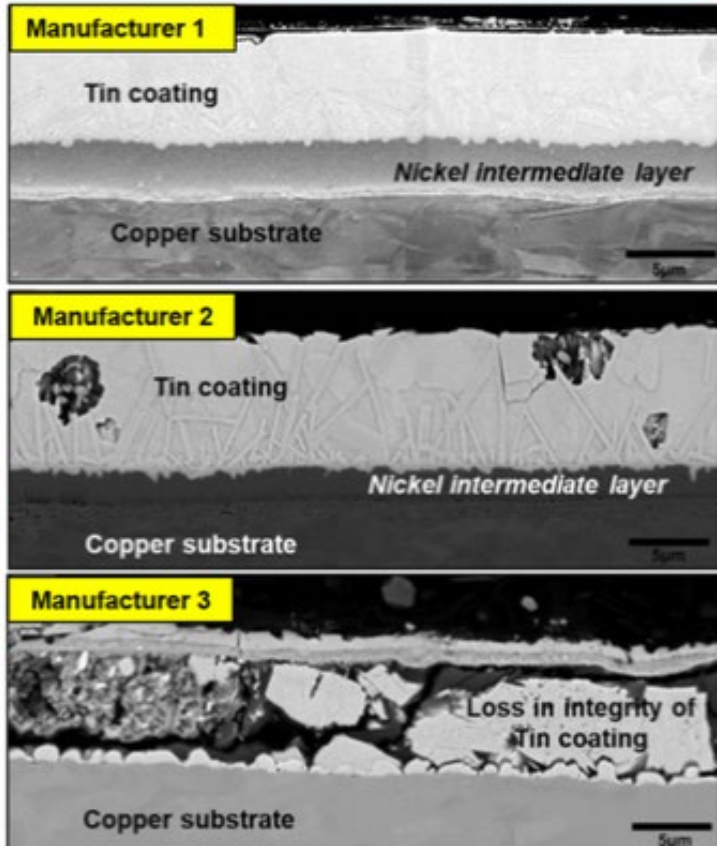




Typical coating structure shows a layered morphology with Tin (Sn) outer and Nickel (Ni) intermediate layer



Variability in coating structures of commercially available connectors

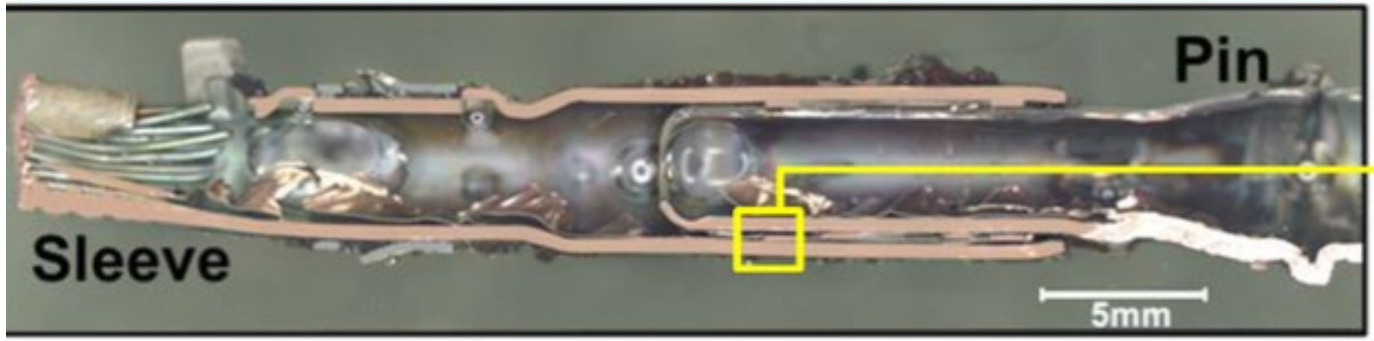


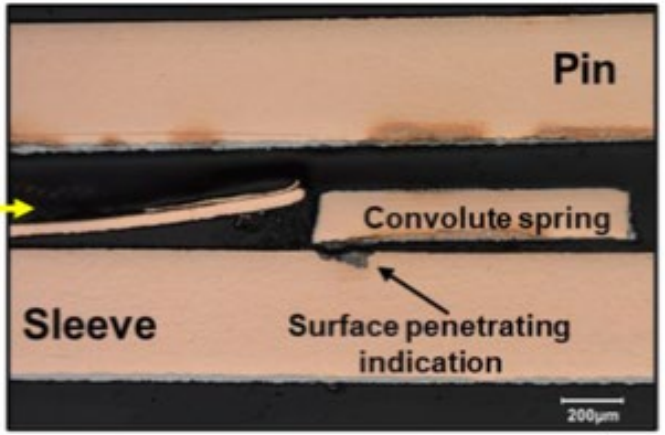
Findings from this study have shown evident variability in structure and integrity of coating layers in commercially available connectors

Micro-forensics: Failure Analysis

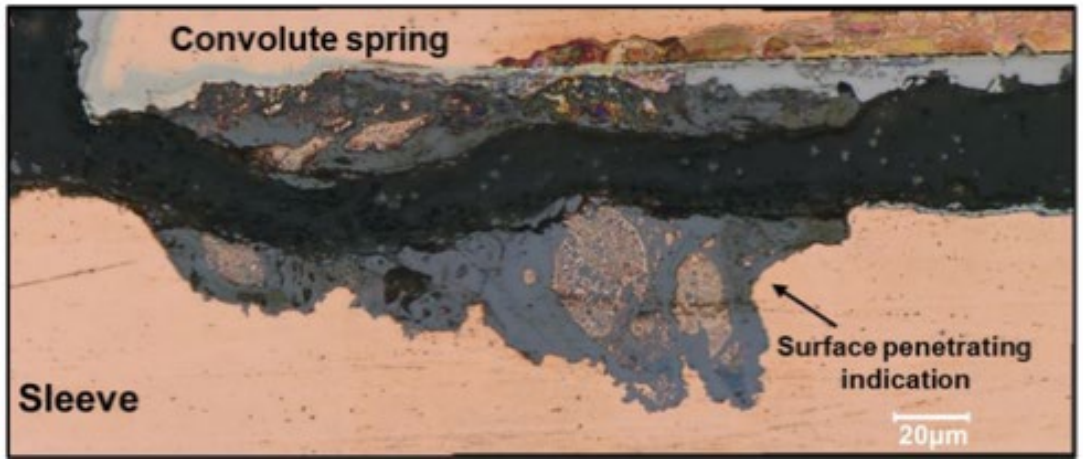
Part 2: Analysis of failing connectors

Mounted and polished cross section of connector from field





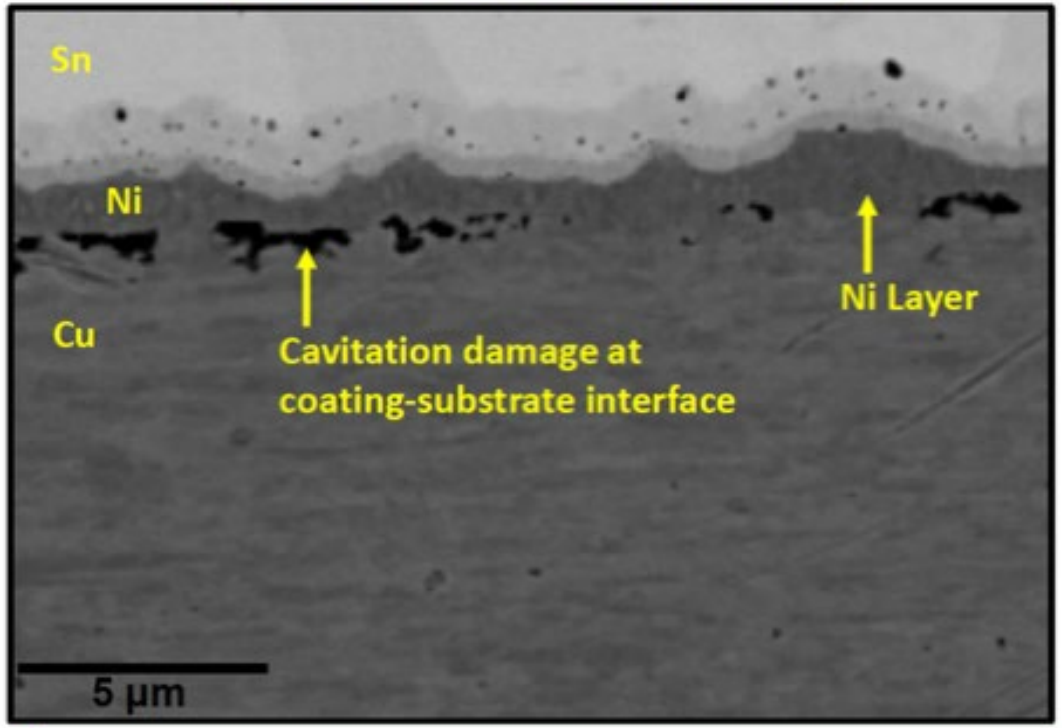
Contacting surfaces of failing connectors show signs of oxidation and local melting at contacting surfaces



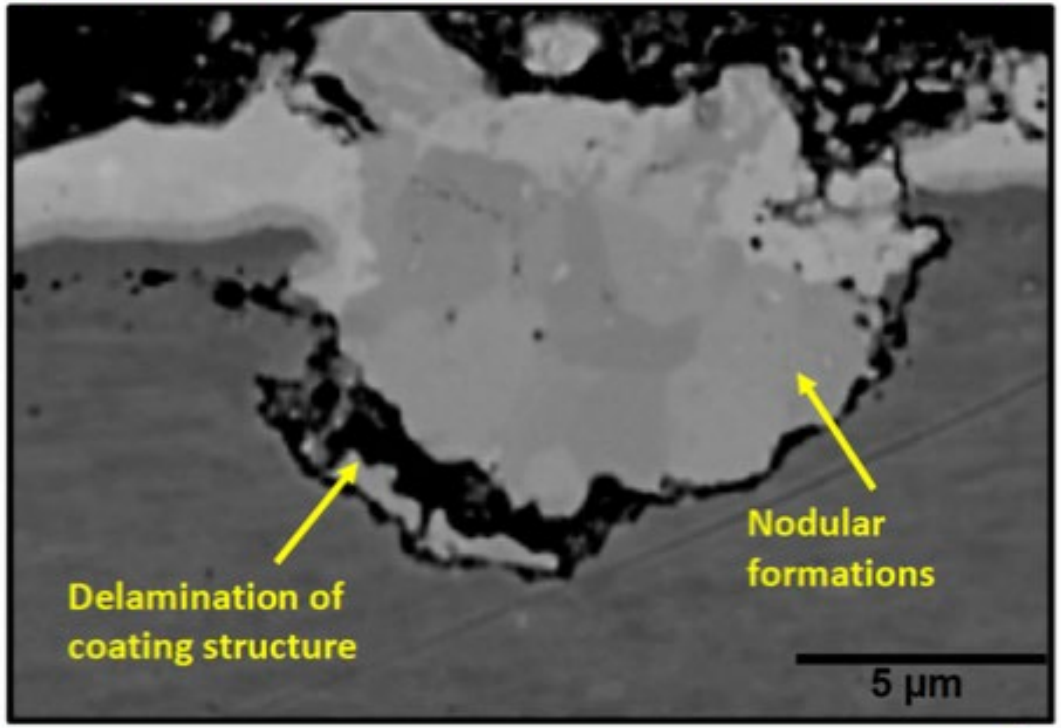
Additional Forensics Analysis

Part 2: Degradation of coating structure in field

Sub surface void formation



Thin Nickel layer and formation of nodules



Evidence of coating degradation during service observed at contacting surfaces. Such degradation mechanism may be a precursor to sub-surface oxidation and higher resistance at contacting surfaces, leading to eventual failure

Summary of Micro-Forensics Work

- But metallurgical analysis is needed to confirm degradation and identify the processes that lead to failure
- Structural coating on pin and socket needs closer investigation
- Next steps: EPRI is continuing to examine unfielded connectors from different manufacturers and harvested connectors that represent different stages of degradation.

Project Summary: Why This Work is Important

Take-aways:

- Quality is a concern on the manufacturing side but installation is likely the most critical and difficult-to-control variable
- Connectors are not the only problem; cables matter too
- Failure rates are likely to increase
- A lot at stake in the blame game
- Beware of assumptions; when in doubt contact the national labs

Moving forward, the Sandia project aims to:

- Link manufacturing defects to failure mechanisms;
- Expand our economic analysis and risk-assessment studies
- **identify the installation errors that are the most consequential;**
- Quantify degradation rates and failure occurrences at the power-plant level
- Create a National Lab Center for information sharing, including early failure warnings, best practices, etc.

Please support this effort:

- We need data
- We need connectors
- We need site access
- We need need your feedback and expertise

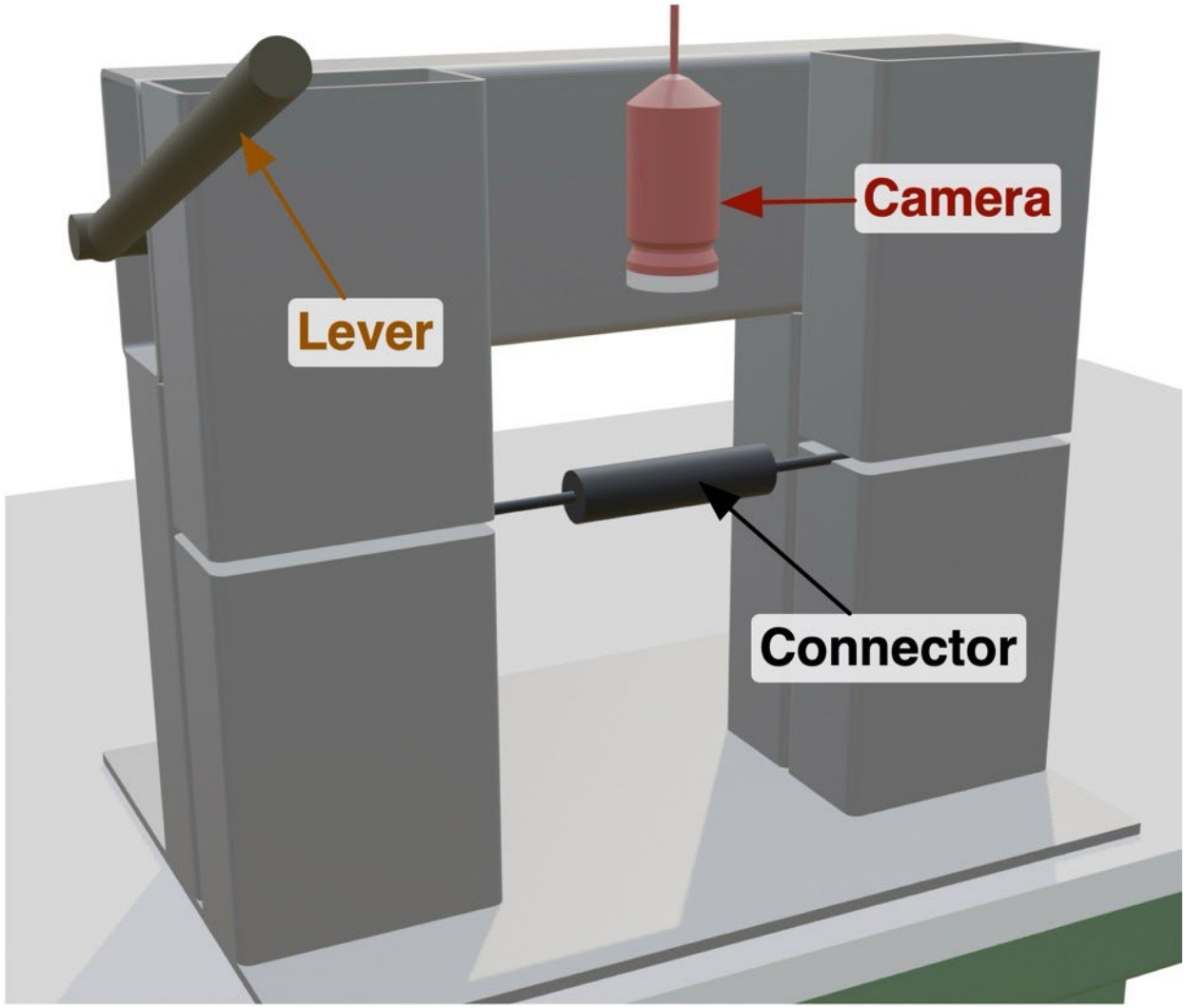
Upcoming Work: Automated tool to increase throughput

Current Challenge:

- Wire stripping and resistance testing are time consuming

Proposed solution:

- Develop tool to complete processes with a single lever pull



Uncapped Photovoltaic Connectors – A Combined Field and Chamber Study Verifies and Elucidates the Degradation

David C. Miller*, Rachael L. Arnold, Peter L. Hacke, Oscar Hathaway, Steven C. Hayden, Aubrey Jackson, Chun-Sheng Jiang, Jimmy M. Newkirk, Greg Perrin, and Kent Terwilliger

National Renewable Energy Laboratory (NREL), Golden, CO
*David.Miller@nrel.gov

2025 PV Reliability Workshop, Golden, CO
Wednesday, 2025/3/05, 16:20-16:40 MT

Photo from iStock-627281636

Motivation: Reliability of PV EBoS

- BoS components include: **cable connectors**, cables, branch connectors, rapid shutdown devices, & fuses.

- Quantifiable ($\leq$ x %·y^{-1}) replacement rate through 30y! *50y use TBD.*
  -SNL, NREL, EPRI effort (PY25-PY27): components, occurrence, cost.
  "National Lab Center for PV Electrical Balance-of-Systems Reliability"

Example of PV fires in Italy.
Fiorentini et. al., PVRW 2020.
https://www.nrel.gov/docs/fy21osti/80055.pdf

- Consequences of degradation and failure include:
  offline-modules, -strings, -inverters;
  system shutdown; <u>arc fault</u>; and <u>fire</u>!!!
- Concerns (robustness): *availability, safety, and technology adoption.*

What is the Degradation Mode of “Uncapped Connectors”?

From the PVQAT Survey: (https://doi.org/10.1109/JPHOTOV.2024.3414178)

- **Uncapped connectors** - no plastic end caps; half ends left open to the environment.
  -Commonly practiced in today’s PV installations.

Examples of plastic ends caps (top), and where they are used in PV connectors (bottom).
https://www.leader-solar.com/product/solar-connector-sealing-caps-for-female-and-male-pv-connector.html

Field examples
Wang et. al., PVQAT TG10 2022/6/28.

- In PV, separate mechanical and electrical installation steps common.
  -These may occur days, weeks, months apart.

- Contamination (micro-arcing) and corrosion suspected.

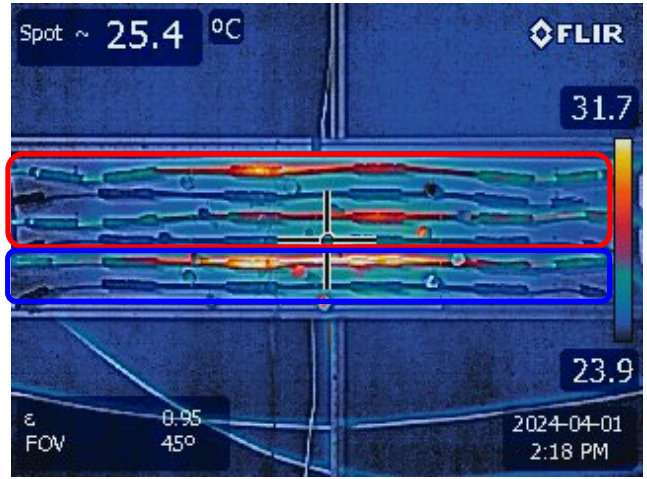
Uncapped Connectors: Degradation Was Distinguished in C-AST for Humid locations

Q: "If uncapped connectors are common, can they be distinguished in accelerated tests?"

A: Yes, C-AST distinguished between uncapped and plugged/unaged connectors.

A: Two humid locations more degraded than a hot location.
Limited distinction between hot-dry site and unaged controls.

A: Durability of successive generations of unaged connectors did not follow their order of market use.



Thermographic image of Barstow, PEI 1x3 samples @ 10 A after 2nd Tropical-a sequence.

Uncapped Connectors:
Design and Implementation of the Field + C-AST Experiment

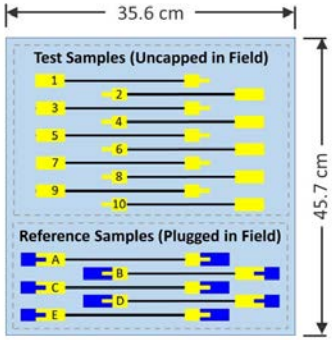
Initial field aging.

- Goal: demonstrate the validity (mode) and further distinguish (environments, stressors) uncapped connectors.
- Uncapped and plugged samples deployed in:

Barstow, CA; Gaithersburg, MD; PEI, CAN.

-Plugged – using opposite half ends assembled to PE dowel

-Field aged April through July, 2023.



Schematic of field fixture for uncapped & plugged connectors.

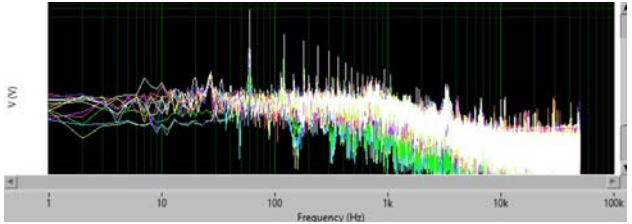
Field fixture, under module in Barstow.

Subsequent C-AST chamber aging.

- Returned connectors run as 1x3 assembly (greater # samples).
- Stepped DC + AC electrical waveform stress

(no 1000 V system bias; simulate PV + representative inverter noise).

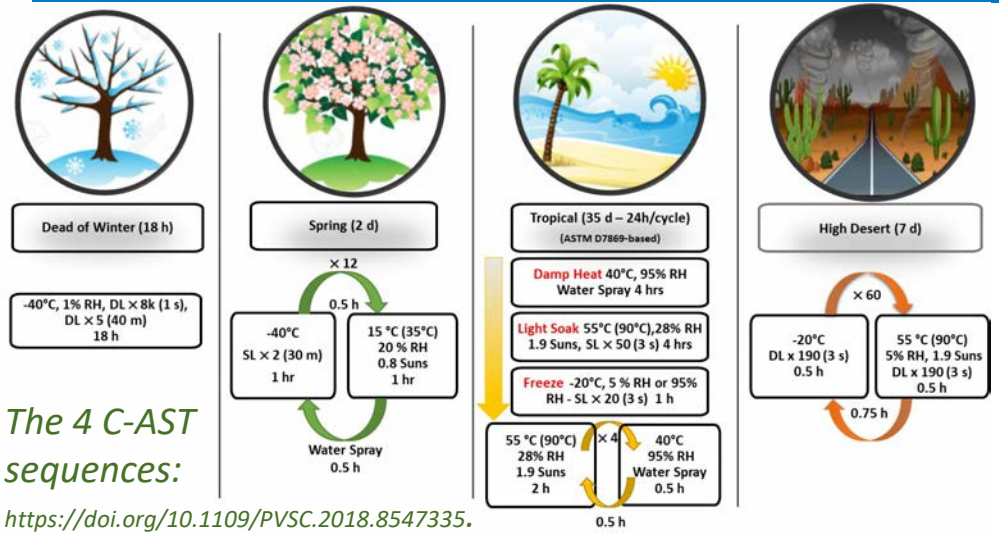
- Read point characterizations: R-I, visual-, and IR-imaging.



FFT of the DC + AC current stressor waveform.

The two uncapped connector C-AST fixtures.

NREL's Combined-Accelerated Stress Test (C-AST)



The 4 C-AST sequences:

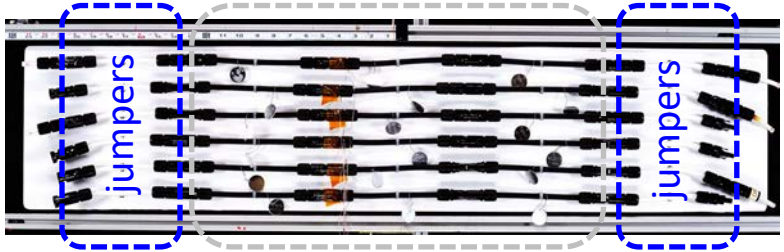
https://doi.org/10.1109/PVSC.2018.8547335.

- Philosophy: apply the many application stressors simultaneously, at greatest levels encountered in challenging PV field locations.
- Tropical sequence based on ASTM D7869 (automotive clear coat paint in Miami), then tailored to PV in Miami.
  - -hot-humid, water spray stresses applied.
- # cycles: AC >> DC, thermal (modest) > TC (max).
- ~3.5 runs of C-AST is ~4000h of IEC TS 62788-7-2 A-series UV dose.

SEQUENCE NAME	TOTAL DURATION {d}	# AC CURRENT CYCLES {dimensionless}	# DC CURRENT CYCLES {dimensionless}	# MODEST THERMAL CYCLES·RUN^{-1} {dimensionless}	# MAXIMUM THERMAL CYCLES·RUN^{-1} {dimensionless}	H, CUMULATIVE RADIANT EXPOSURE {MJ·m^{-2}}
Winter	0.7	0	0	0	1	0.0
Spring	1.8	0	12	9	30	0.1
Tropical	38	96,596,679	175	182	36	3.1
Desert	7.6	14,472,271	65	12	72	0.3

Estimates for # cycles in C-AST.

Results of the Uncapped Connector C-AST Experiment



fielded

- Failed 1x3's: 9/9 uncapped; 1/3 plugged.
- Failed jumpers: 17.
- Stressor current < 50 A DC (UL rated).

Image of C-AST uncapped connector fixture 1 after Tropical-2a.

Final results (after visual, HiPot, forensics).

LOCATION	NUMBER FAILURES:	C-AST RUN 1 SEQUENCE: Winter	Spring	Tropical-a	Tropical-b	Desert	C-AST RUN 2 SEQUENCE: Winter	Spring	Tropical-a	Tropical-b	Desert
Barstow, CA (BSk: steppe)	uncapped										3
	plugged										
	jumper								4	1	
PEI, CAN (Dfb: continental)	uncapped								2	1	
	plugged										
	jumper								1	1	1
Gaithersburg, MD (Cfa: subtropical)	uncapped					1			1		1
	plugged									1	
	jumper								4	4	1
DC±AC CURRENT at HIGH IRRADIANCE {A}		0		10±6	15±8	20±10	0		30±10	35±2	40±0
DC±AC CURRENT at LOW IRRADIANCE {A}		0	5±3	5±3	7.5±4	10±5	0	12.5±6.3	15±7.5	17.5±8.8	20±0

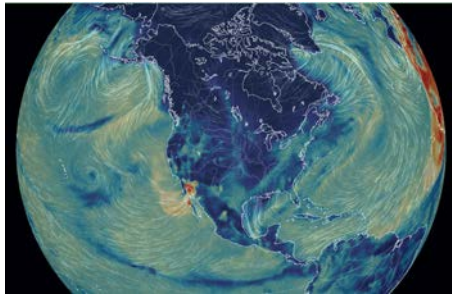
Results:

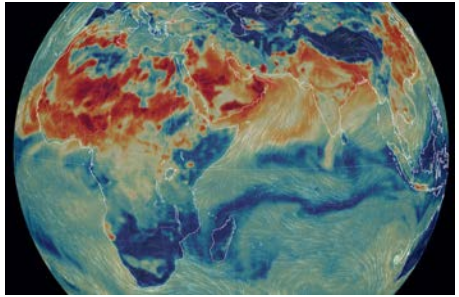
- Uncapped samples failed before the plugged sample ⇒ uncapped connectors are valid concern.
- Humid locations failed before hot-dry (corrosion > contamination).
- Improved mechanical constraint reduced jumper failure attrition.

Resistance Increased Through the Uncapped C-AST Experiment

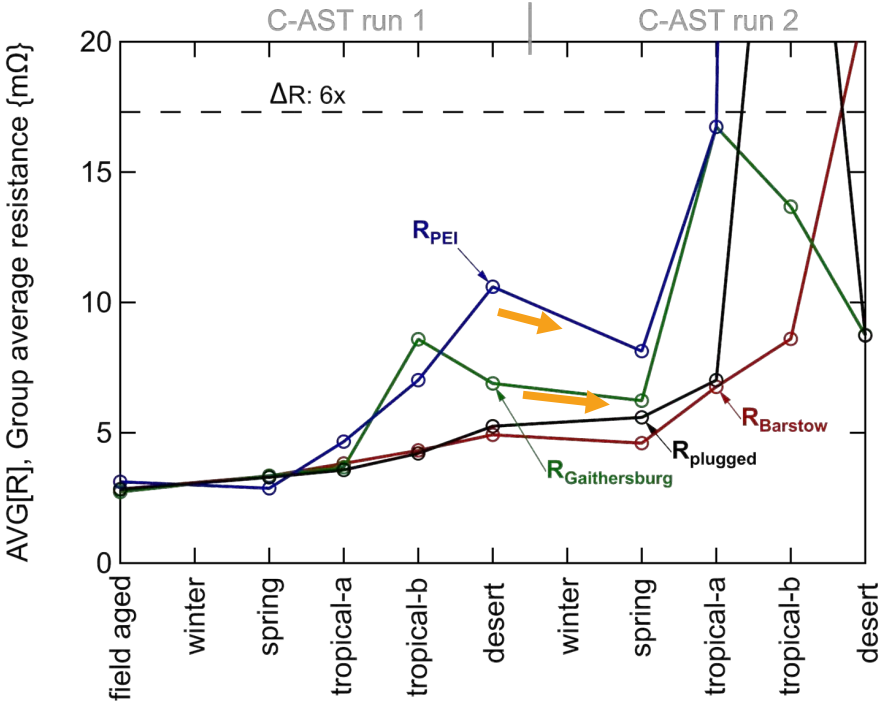
- Initial AVG[R] similar for the field aged connectors, increases with each C-AST sequence read point.
- Gaithersburg degrades quickest, fails quickest.
- Recovery observed (e.g., after Desert-1).
  - -Different than ΔR from failed specimens.

- **Plugged** references typically not greatly distinguished from Barstow.
  - -USA not as severe for PM10 as MENA, India, China.
  - -Different from dropped connector (dirt).



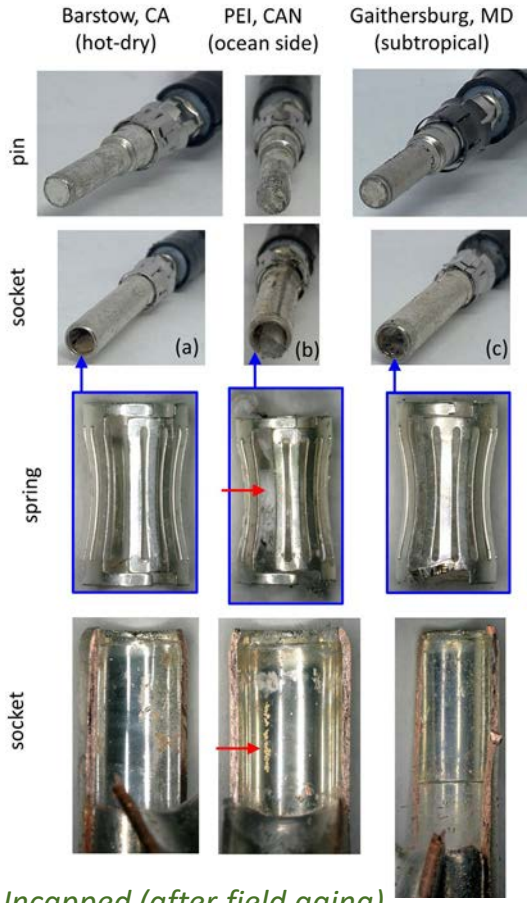


PM10 in western (e.g. Imperial valley) and eastern hemispheres on 2025/1/21.
https://earth.nullschool.net/#current/particulates/surface/level/overlay=pm10/



Average resistance of remaining connector assemblies, stabilized for 1 minute at 10 A.
6x ΔR limit (this study) is shown for comparison.

What Happened? Comparing the Uncapped and Plugged Connectors After Field Aging

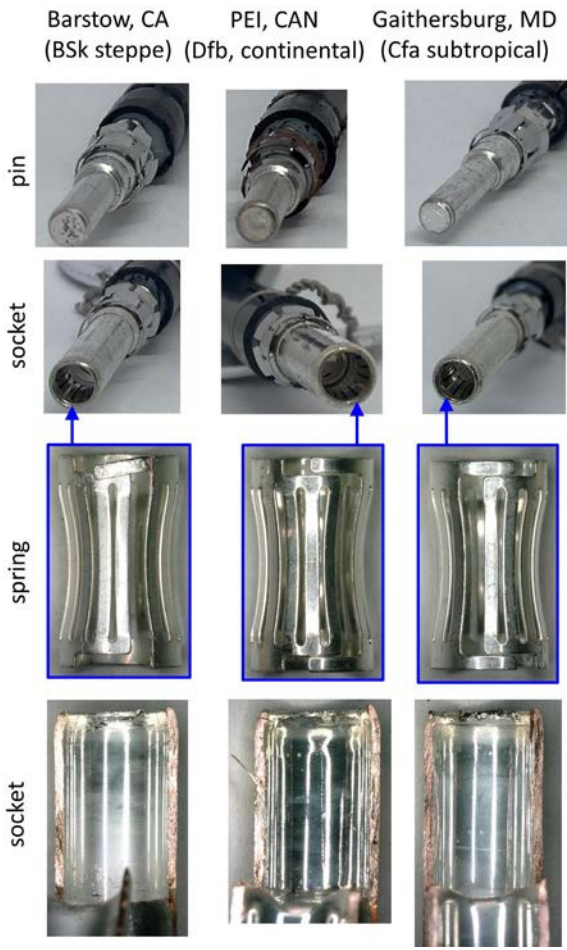


Uncapped (after field aging).

Images of individual connectors prior to 1x3 assembly.

<u>Features (uncapped-left vs. plugged-right)</u>:

- Darker or discolored (yellow) appearance.
  - -Including inside socket.
- Roughened or cracked surface.
- Organic contamination
  - -Insect bodies/appendages, spider web & eggs.
  - -Observed for PEI, Gaithersburg.



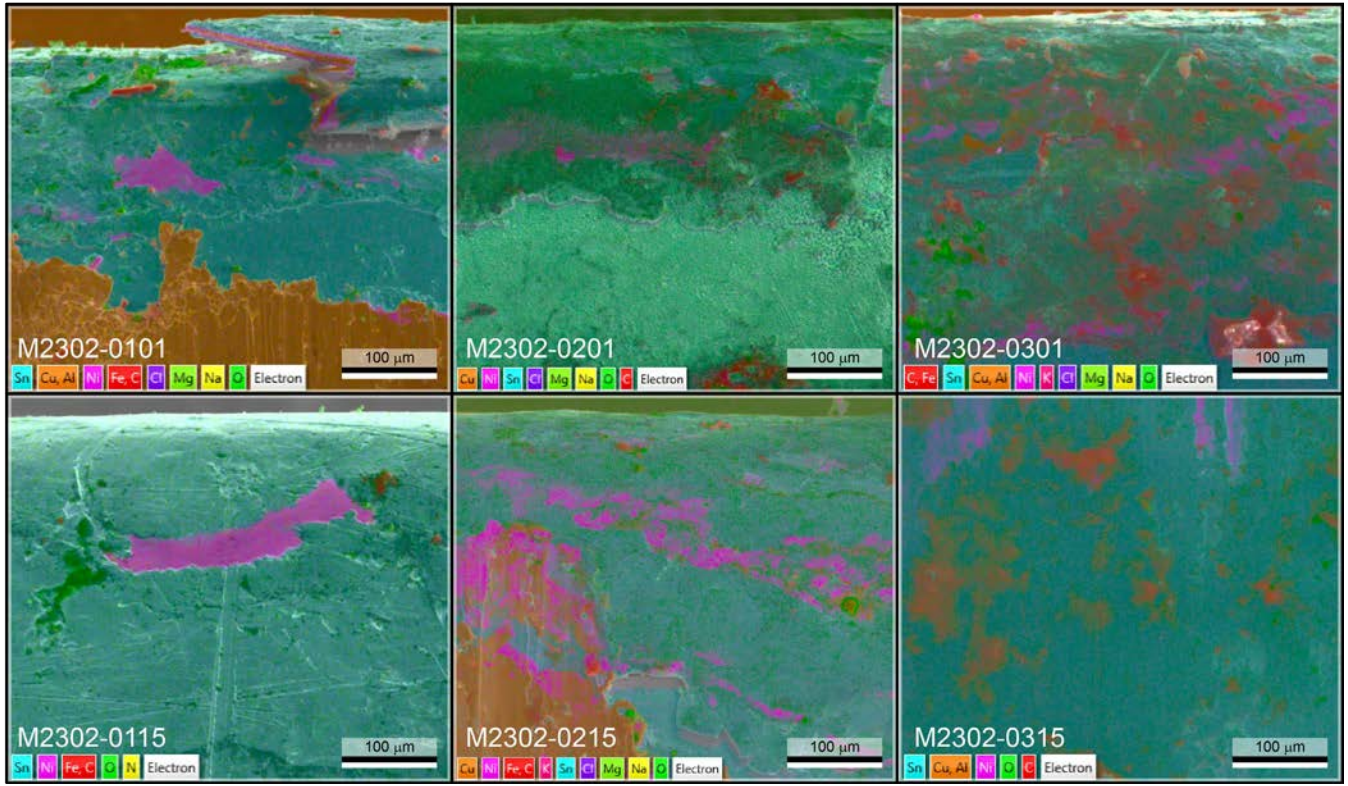
Plugged (after field aging).
(Plastic housing removed by machining).

What Happened? Comparing the Morphology and Composition of the Connector Pins After Field Aging

Barstow, CA (hot dry) | PEI, CAN (ocean side) | Gaithersburg, MD (humid)

uncapped

plugged



-metal pin on "– " half end-

- PEI: increase in oxygen. Intermediate Ni layer likely obscured.
- Gaithersburg: local compromises in Sn outer layer. Cu base observed.
- Humid locations: Cl in uncapped.

	Barstow		PEI		Gaithersburg	
	uncap	plug	uncap	plug	uncap	plug
	101	115	201	215	301	315
Sn	49.2	53.8	19.3	39.1	29.0	48.4
O	29.2	27.5	57.5	36.8	37.4	19.7
C	15.9	14.7	20.5	18.9	28.6	28.4
Ni	3.8	2.6	0.6	2.9	2.4	2.2
Al	1.0	0.6	0.4	1.1	0.5	0.9
Si	0.5	0.3	0.2	0.0	0.0	0.0
K	0.4	0.5	0.2	0.4	0.3	0.4
Na	0.0	0.0	0.6	0.2	0.8	0.0
Cl	0.0	0.0	0.4	0.0	0.2	0.0
Mg	0.0	0.0	0.2	0.2	0.2	0.0
Cu	0.0	0.0	0.0	0.0	0.5	0.0

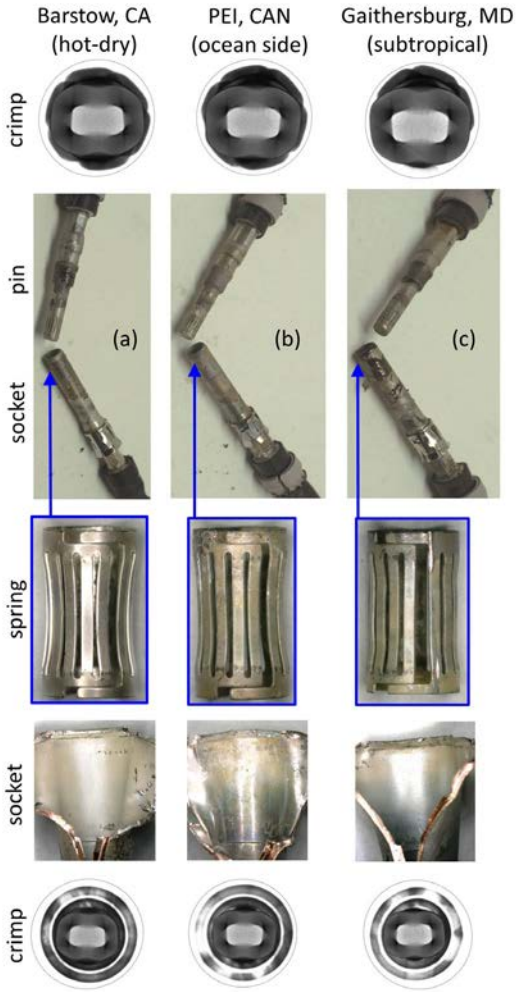
field aged $\rightarrow$ C-AST aged

What Happened? Comparing the Uncapped Connectors After C-AST Aging

- Moderately affected representative samples selected for forensics. (Deformed plastic only).
- Scorched at pin/socket connection.
- Melted/decomposed plastic housing observed on surface of pin and socket. (e.g., T_m PA >260 °C)
  - -Dark copper color for PEI.
- Likeness of contact spring observed on metal pin.

- 3 unfurled connectors observed (as in 2024 Connectors workshop), not selected for forensics.

Unfurled Gaithersburg connector.



F/A of representative connectors. (Plastic housing removed by machining).

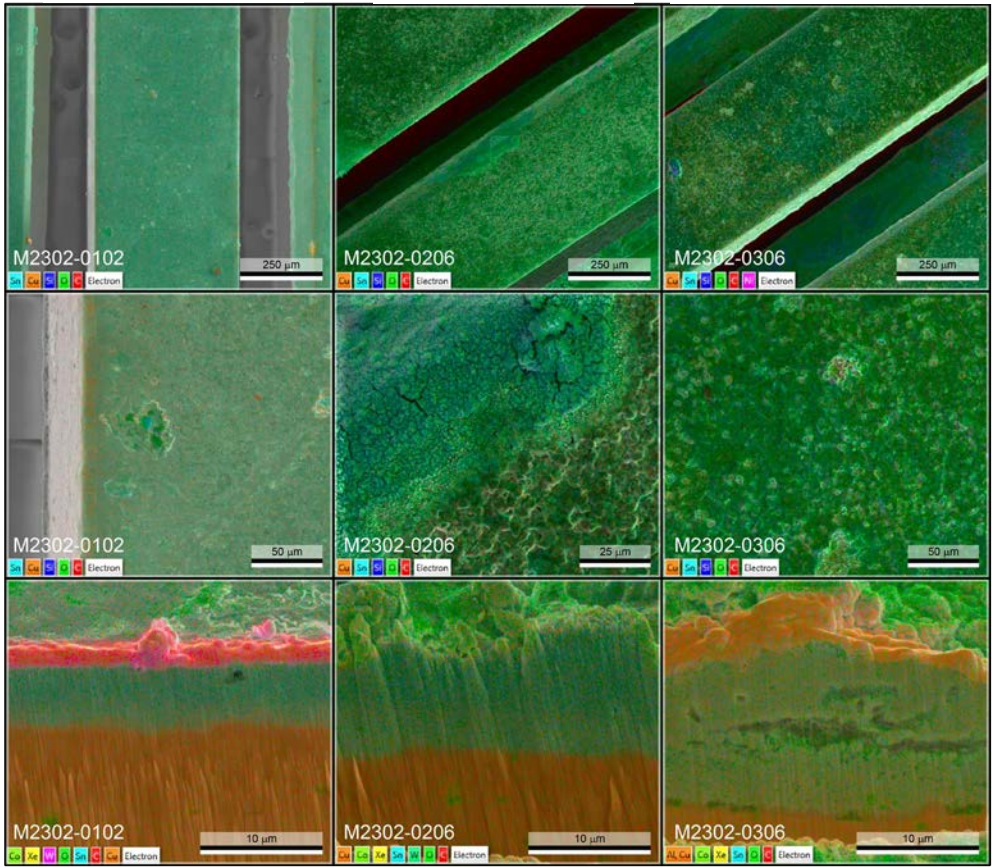
What Happened? Comparing the Morphology and Composition of the Contact Springs After C-AST

Barstow, CA | PEI, CAN | Gaithersburg, MD

surface

surface zoom

cross-section



-the contact spring ensures mechanical and electrical connection between the pin and socket-

- Barstow: minimal damage to metal layers. Some deposits of oxide species on surface. (No overt changes from field aged condition).
- PEI: surface corrosion, including localized spots … O and salts (Mg, Na, K, Cl) … transformed into thickened outer scale.
- Gaithersburg: surface corrosion (including localized thinning of Sn outer layer) transformed into thickened oxide.

Can ΔT, ΔR Criteria Be Applied to Degraded Uncapped Connectors?

Q (stakeholders): What ΔT or ΔR could be used to identify failed connectors?

Categories:

-Unaffected (visual inspection only).

-Physically deformed or bent (> ~2 mm).

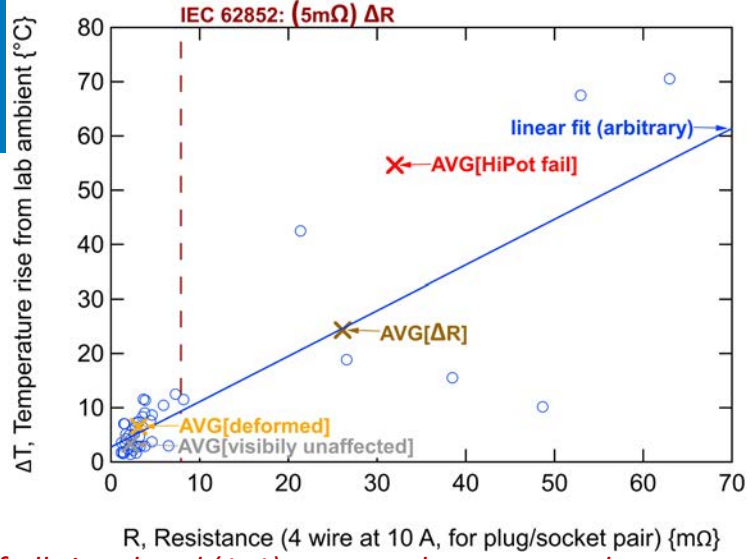
-ΔR[unaged] >50% or ≥5 mΩ (IEC 62852).

-Fails IEC 61215 MQT 15 wet leakage test.

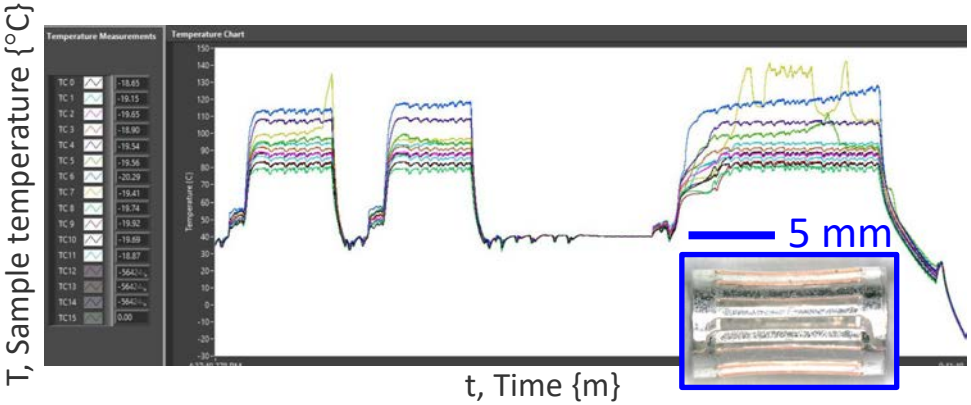
•Body deformed for ΔR ≤ 5mΩ. ΔR *too high*?

•Δ of 10's of °C or mΩ: metal accessible.

•ΔT or ΔR criteria: it's complicated! Multiple louvers in contact spring may allow revitalization of performance.



Analysis of all singulated (1x1) uncapped connectors, by category.



T-t history from Tropical-2 sequence for C-AST of uncapped connectors. Inset shown for representative contact spring.

Results of the Reference Connector C-AST Experiment

Image of C-AST unaged reference connector fixture 1 after Desert-2.

Motivations:

- Compare uncapped to unaged connectors (further validate).
- Compare 3 generations (future chamber study).

Results:

- Failed 1x3 assemblies:
  -0/4 gen a; 4/4 gen b; 4/4 gen c.
- Failed 1x1 gen b jumper: 14.

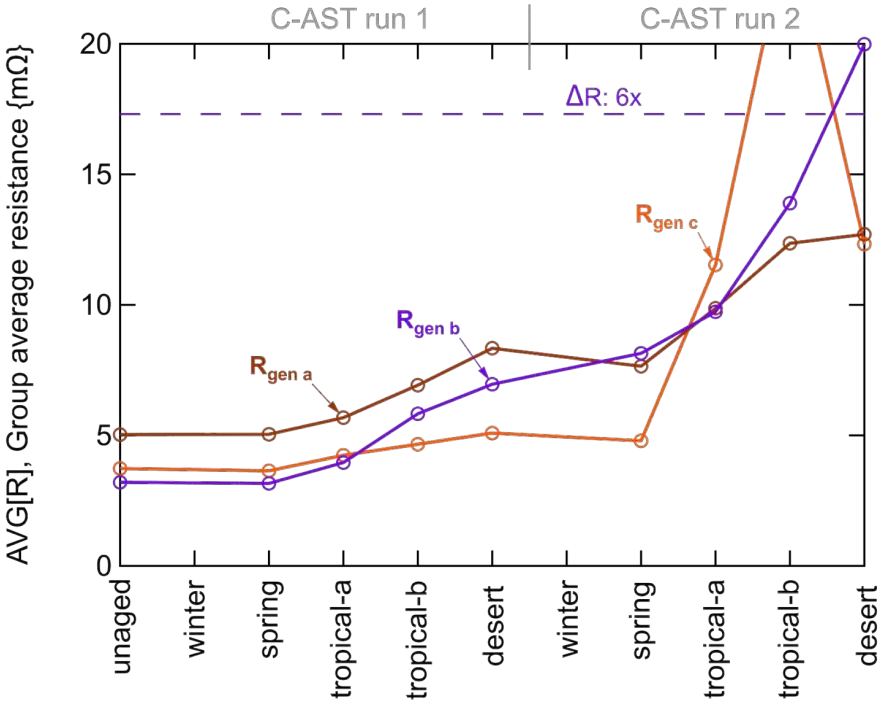
SPECIMENS	NUMBER FAILURES:	C-AST RUN 1 SEQUENCE: Winter	Spring	Tropical-a	Tropical-b	Desert	C-AST RUN 2 SEQUENCE: Winter	Spring	Tropical-a	Tropical-b	Desert
generation a (past) I_{rating}: 30 A (10 AWG)	reference										
	jumper (generation b)									2	1
generation b (present) I_{rating}: 50 A (8 AWG)	reference										4
	jumper (generation b)								2	4	1
generation c (future) I^{rating}: 69 A (8 AWG)	reference								1	2	1
	jumper (generation b)								1	3	
DC±AC CURRENT at HIGH IRRADIANCE {A}		0		10±0	15±0	20±10	0		30±10	35±2	40±0
DC±AC CURRENT at LOW IRRADIANCE {A}		0	5±0	5±0	7.5±0	10±5	0	12.5±6.3	15±7.5	17.5±8.8	20±0

Final results
(after visual, HiPot, forensics).

- Generation b (Cu/Ni/Sn and Cu/Sn) did not fail early in the experiment ⇒ consistent with Barstow connectors.
- Generation c (Cu/Ni/Sn) failed prematurely.
- Generation a (?Cu/Ni/Sn?) proved surprisingly robust (exceeding current rating).

Resistance Increased Through the Reference C-AST Experiment

- Greater initial AVG[R] for gen a (10 AWG) than gen b and gen c (8 AWG).
- Gen c degrades abruptly in C-AST run 2.
- Gen b degrades like Barstow (figures same scale).
  - -Same model as uncapped samples (field→C-AST).
- Gen a does not exceed study's ΔR threshold.
  - -Does not have locking latches. NEC: cannot use.



Average resistance of remaining connector assemblies, stabilized for 1 minute at 10 A.
6x ΔR limit (this study) is shown for comparison.

Uncapped Connectors: Degradation Was Distinguished in C-AST for Humid locations

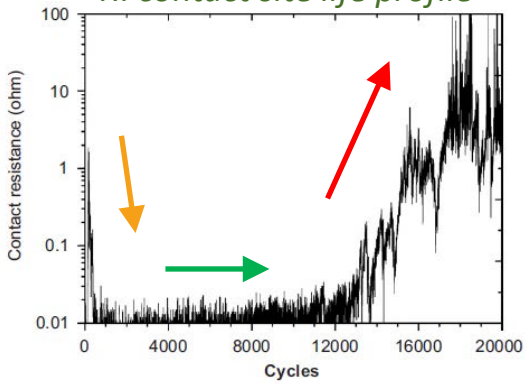
Q: "If uncapped connectors are common, can they be distinguished in accelerated tests?"

A: Yes, C-AST distinguished between uncapped and plugged/unaged connectors.

Q: What factors affect "fretting corrosion" of uncapped connectors?

A: Humid locations (corrosion) > hot-dry (contamination).
Limited distinction between hot-dry site and unaged controls.

R: contact site life profile



Loss of contact performance from fretting corrosion (degradation with abrasion, oxidation, diffusion, creep). Sankara et. al., doi:10.1016/j.triboint.2007.05.004.

A: Durability of successive generations of unaged connectors did not follow their order of market use.

Acknowledgements

☞Thanks to:

-Dr. Michael Kempe and Bill Sekulic of NREL.

-NREL MICRO (microscopy and forensics group)

-Collaborators for field aging (~confidential).

-PVQAT TG10 (~200 recent followers).

CPS / Agreements 38524, 52802:

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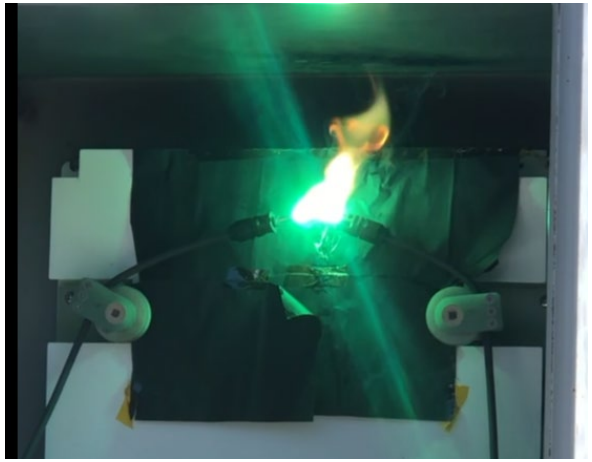


PV connectors: the live disconnect experiment at NREL

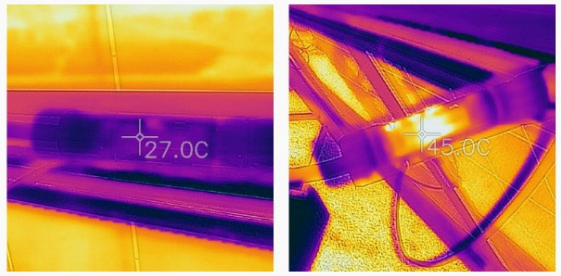
Additional comments & questions: David.Miller@nrel.gov

PVQAT TG10 and the National Lab Center for PV Electrical Balance-of-Systems Reliability

- Collaborating national labs effort Sandia, NREL, EPRI (PY25-PY27) on BoS components, including: connectors, cables, RSD's, cable ties, …

- Monthly PVQAT TG10 web group meetings covering the state of the industry as well as feedback on testing and results.

- Example topics: counterfeit PV connectors, automotive connectors, connectors in PV wire harnesses.



Infrared inspection of intact (left) and degraded (right) cable

Cracking of tracker cable at the controller box.

Informal dinner, Wednesday, 2025/3/05, after the PVRW
Venue: Table Mountain Inn, 1310 Washington Ave, Golden
Meet at the registration desk @ 17:45, after the PVRW.

- Presently 125 members, all stakeholders welcome!

Please inquire to: Laurie BURNHAM lburnha@sandia.gov; David MILLER David.Miller@nrel.gov

Also: https://energy.sandia.gov/programs/renewable-energy/photovoltaics/pv-systems-and-reliability/pv-connectors/

Nominal Operating IGBT Temperature (NOIT)

A metric for establishing reliable inverter operations

PV Reliability Workshop

Denver, CO

Nick de Vries and Clay Helms

March 3rd, 2025

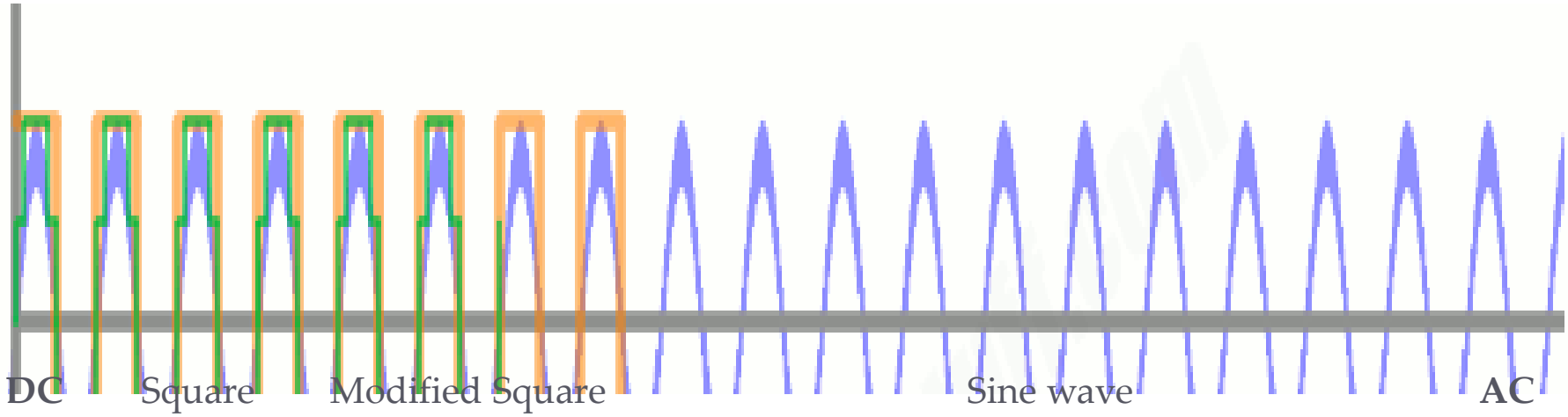
Introduction to Silicon Ranch

- Based in **Nashville, TN**, Silicon Ranch is one of the largest independent solar power producers in the country.
- We own and operate 180 solar power facilities, totaling **3 GWp.**
- Silicon Ranch is unique in the business of creating renewable energy, as we are, first and foremost, about **serving people and creating economic development opportunities.** Everything we do flows from there.
- We **develop-to-own** all our projects and have a **100% track record** of seeing them through from start to finish.
- Thanks to this develop-to-own strategy, we've created a seamless **feedback loop** of lessons learned from our operating projects to our new projects in design.
- We update our design and construction standards in real time as we identify areas of improvement remotely or in the field, continually driving for **higher quality and more reliable facilities**.

SILICON RANCH

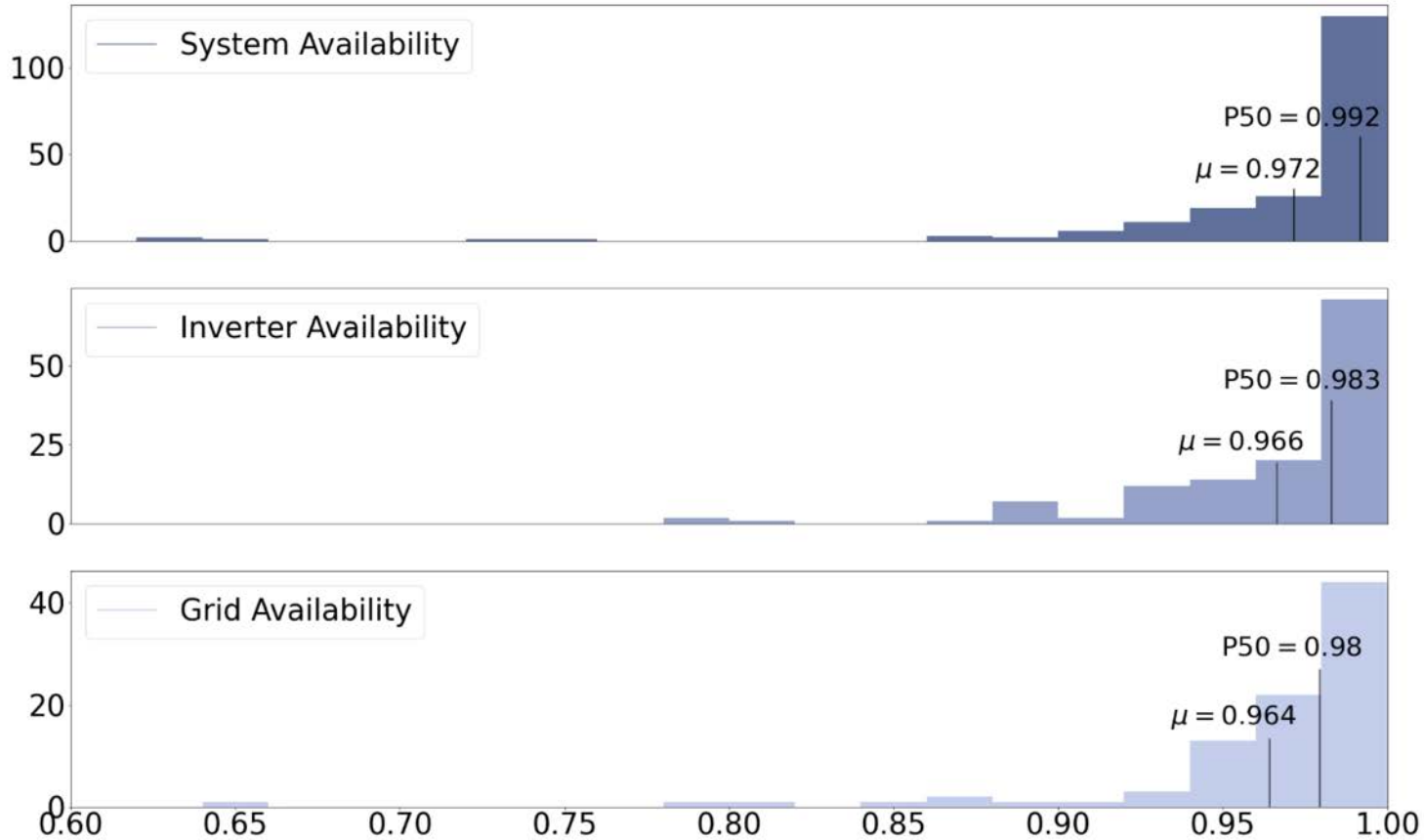
Discussion Goals

1. Importance of Inverter Availability
2. Role of temperature on Inverter Reliability
3. How temperature is used on cell & module performance and reliability work
4. Primary driver of IGBT temperature
5. Offer a definition of Nominal Operating IGBT Temperature
6. Examples of how to use it



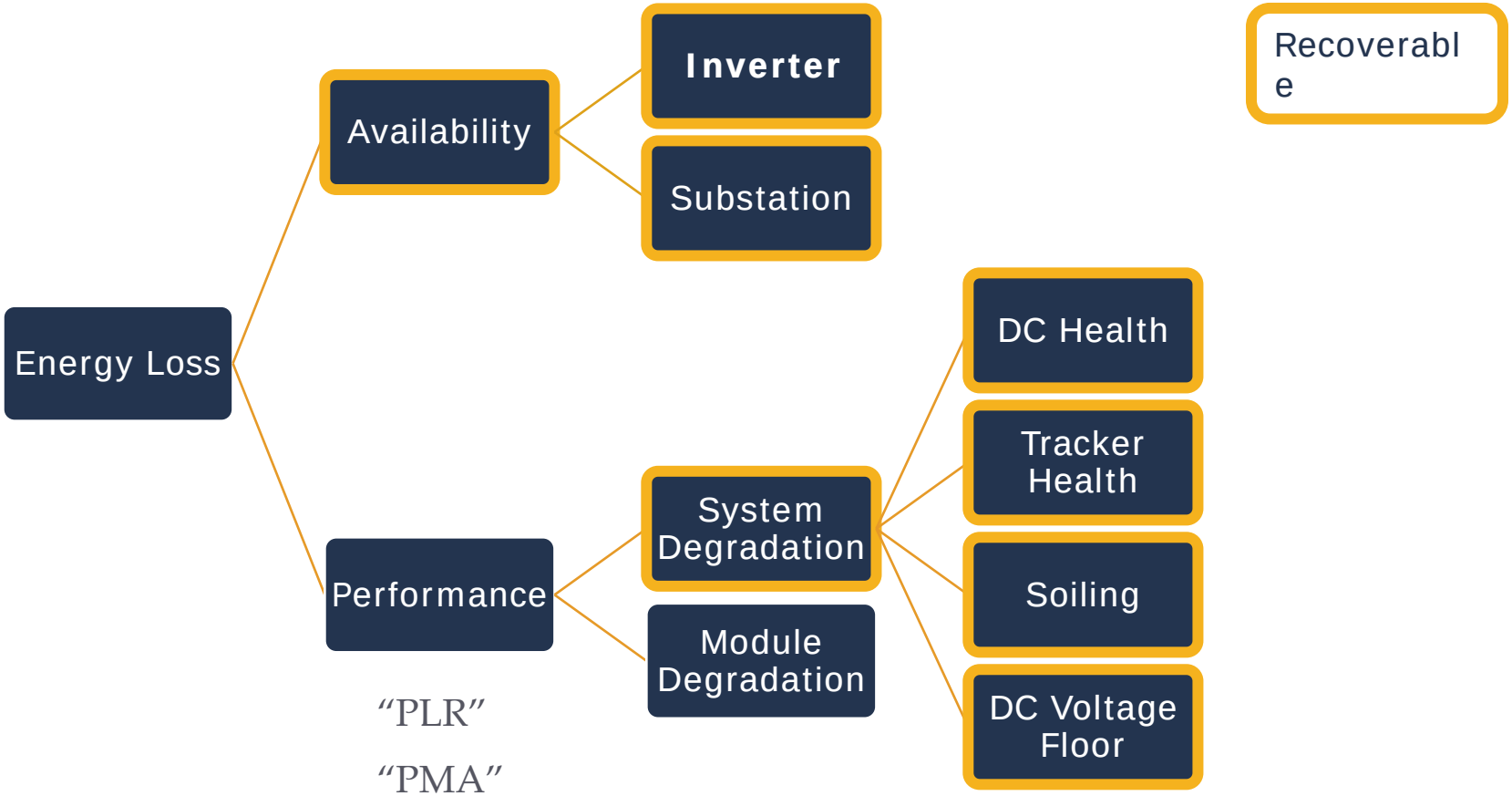
Inverter availability

kWh Analytics, 2024 Paper "Bringing solar availability assumptions back down to earth: the case for adjusting to 97%"



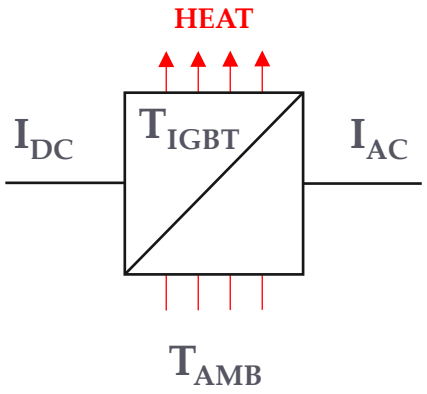
- **99% availability is possible**, but not given, nor easy to accomplish
- **Inverter availability** and long-term reliability is a big deal, and we have **few technical metrics with which to evaluate them.**

Where does Inverter Reliability fit into an energy loss map

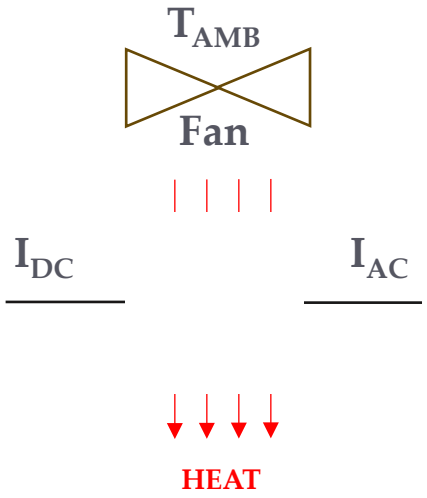


- At SRC we view inverter availability as having a primary influence on plant availability and that it is **recoverable**

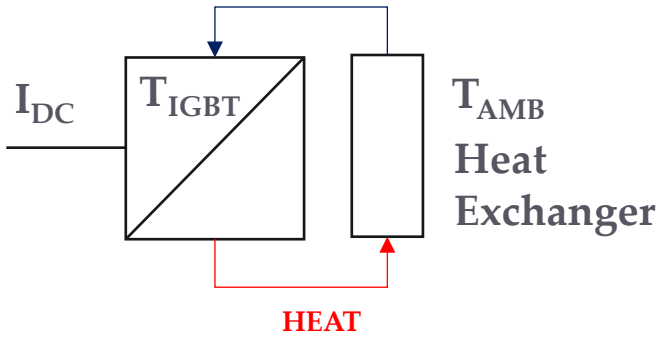
Inverter Product Variation



Passive Air Cooled



Active Air Cooled



Active Liquid Cooled

- SRC Fleet includes over 5000 Inverters, first built in 2011
- **All use IGBT Integrated Gate Bipolar Transistors (IGBTs)**
- String inverters are typically passive or active air cooled
- Central inverters are typically active air or liquid cooled
- **Compare temperature characteristics on all of them**

Why IGBT temperature is important?

Failure sites	Causes	Stresses	Modes	Mechanisms
Bond pad	High temperature	Thermal overstress	Open circuit	Metallization reconstruction[30]
Bonding wire: bond	CTE mismatch between die and wire by temperature excursion	Thermomechanical stress	Bond wire liftoff	Fatigue [31]
Bonding wire: heel	Expansion and contraction of bond wire due to temperature change	Thermomechanical stress	Bond wire heel cracking	Fatigue [32]
Bonding wire: body	High temperature	-Thermoelectrical stress -Thermomechanical stress under corrosive environment	-Open wire -Wire burnout	-Electromigration [33] -Stress corrosion - Joule heating
Solder joint	-CTE mismatch by temperature excursion -Transformation in solder microstructure at high temperature	Thermomechanical stress	Solder joint cracks	Fatigue or grain growth [34][35]
Ceramic substrate	Thermal shock	Thermomechanical stress	Delamination	Delamination of metallization [36]

The paper: *Thermal Management on IGBT Power Electronic Devices and Modules. 2018, Cheng Qian, et al.*

All IGBT failure mechanisms are caused by thermomechanical stresses and temperature!

Managing and maintaining particular **IGBT temperature** is therefore **imperative for long term reliability.**

Therefore a new metric which characterizes the IGBT and its associated cooling system **is needed**

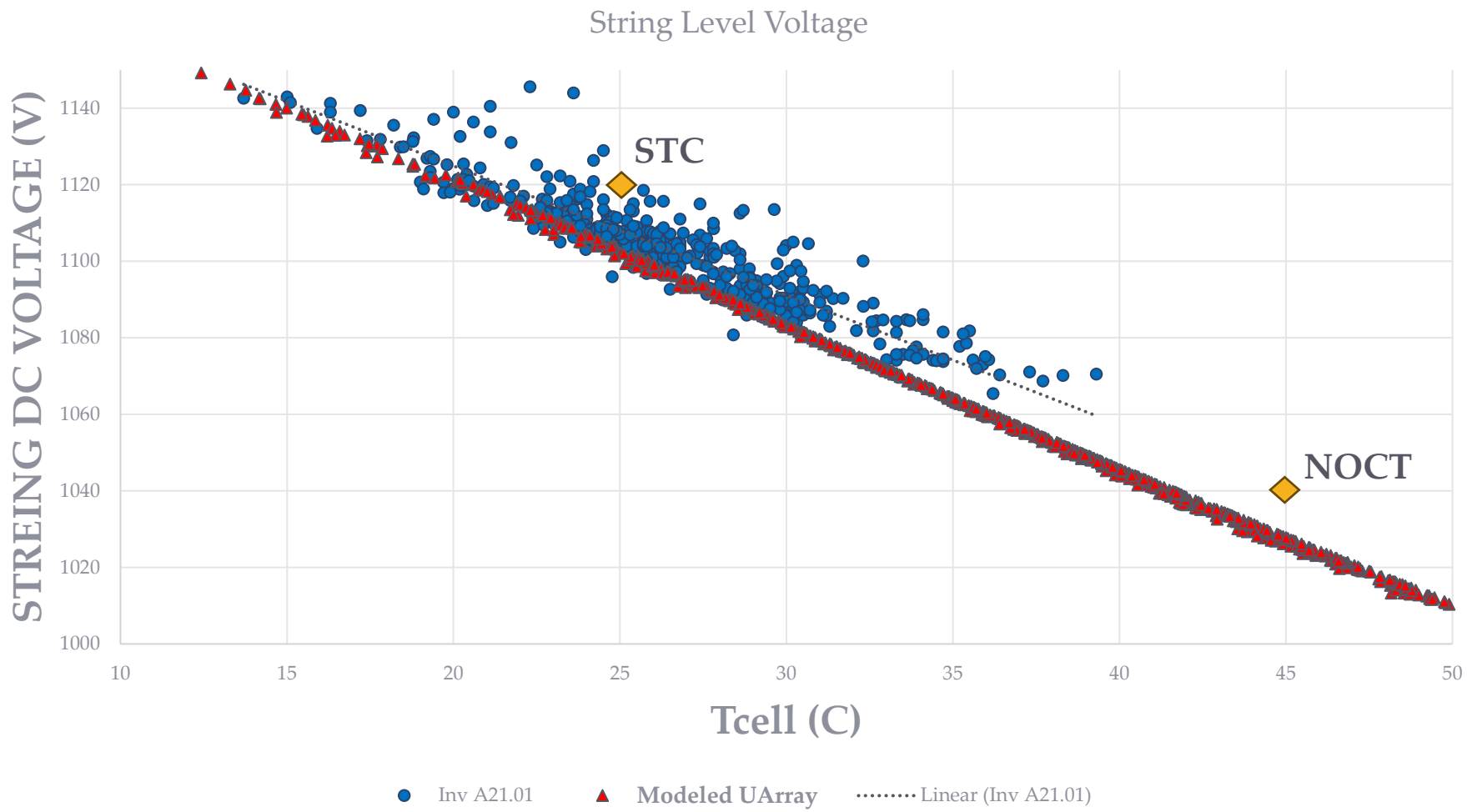
Drawing inspiration from other semiconductor devices ...

PV Cells! (Silicon & Thin Film)

Nominal Operating Cell Temperature (NOCT) is a testing standard geared to the **operational conditions** of solar cells, defined as the temperature reached by open circuited cells in a module assuming **800W/ m² irradiance**, **20°C ambient temperature** and **wind speed of 1m/ s** with the PV module at a **tilt angle of 45°** and its back side open to the breeze (as opposed to conditions where panels are mounted on roofs and heat builds up under the panel)

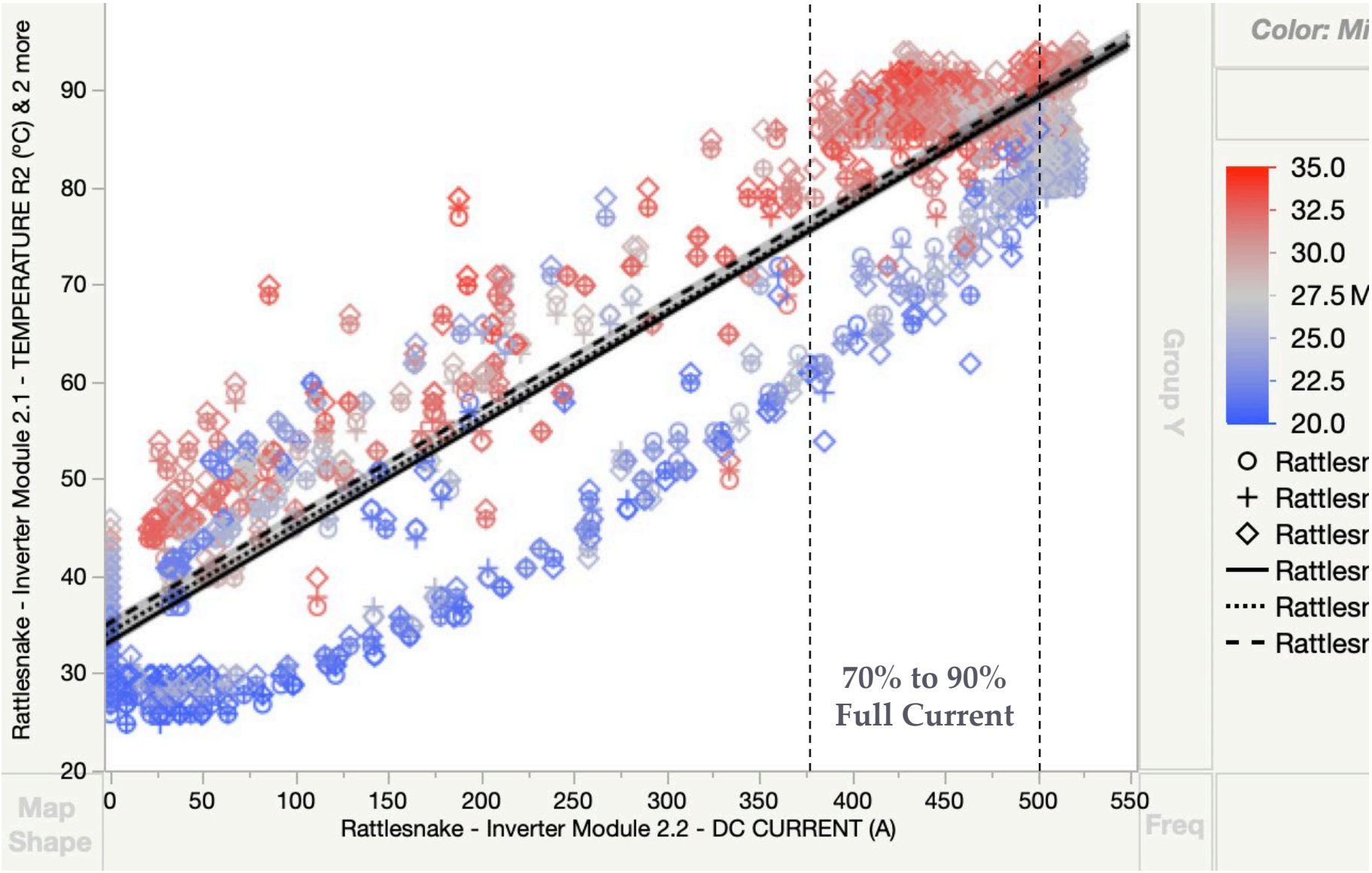
SILICON RANCH

STC and NOCT role in assessing module performance



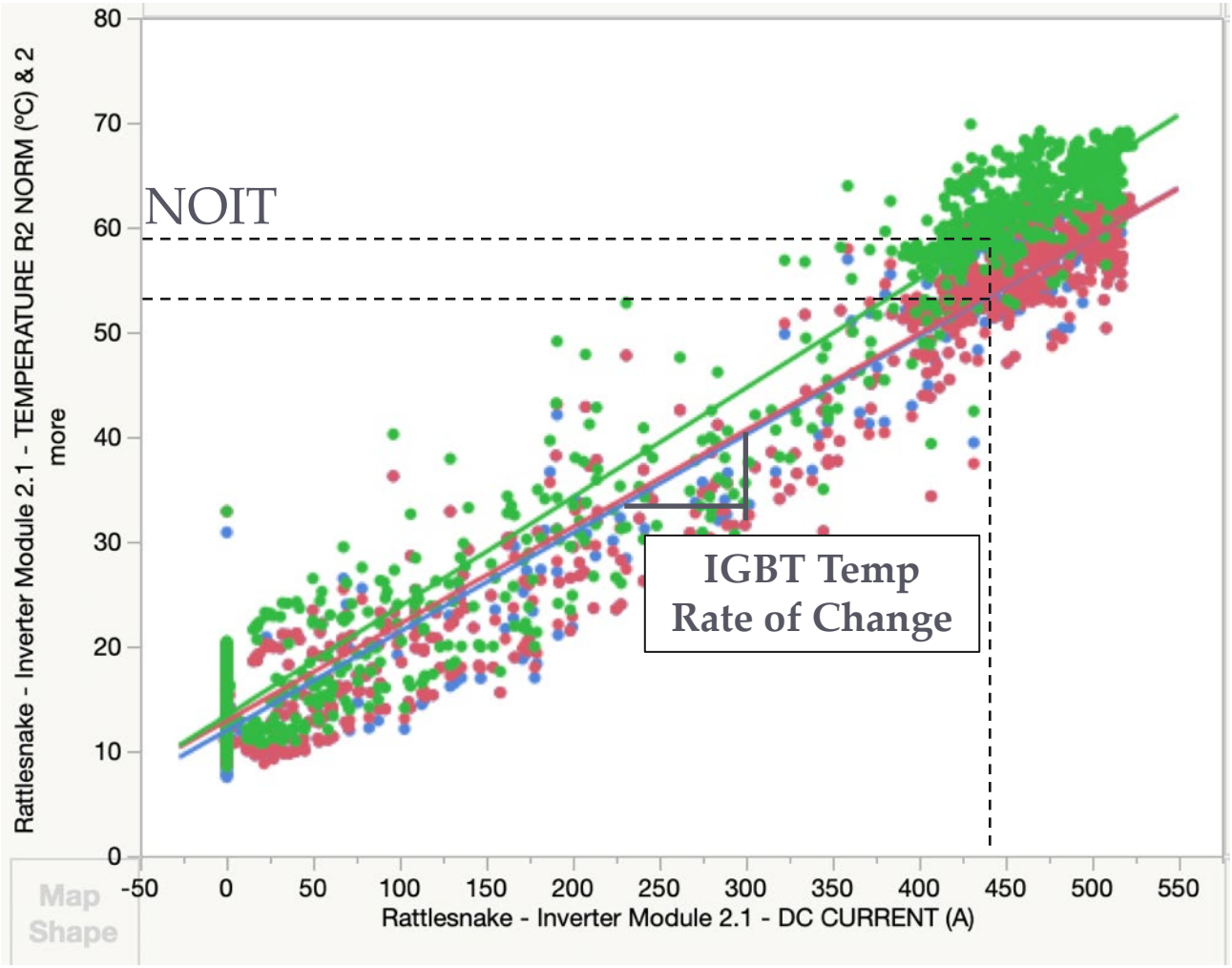
- STC and NOCT values are used to set expected module performance in lab and field conditions
- And field data can be evaluated against this values

IGBT Temp vs DC Current Relationship



- DC current is the primary influence on IGBT temp
- Distinct bifurcation of the trend comes from Ambient temp

Normalized IBGT Temp vs DC Current



Proposed NOIT Definition

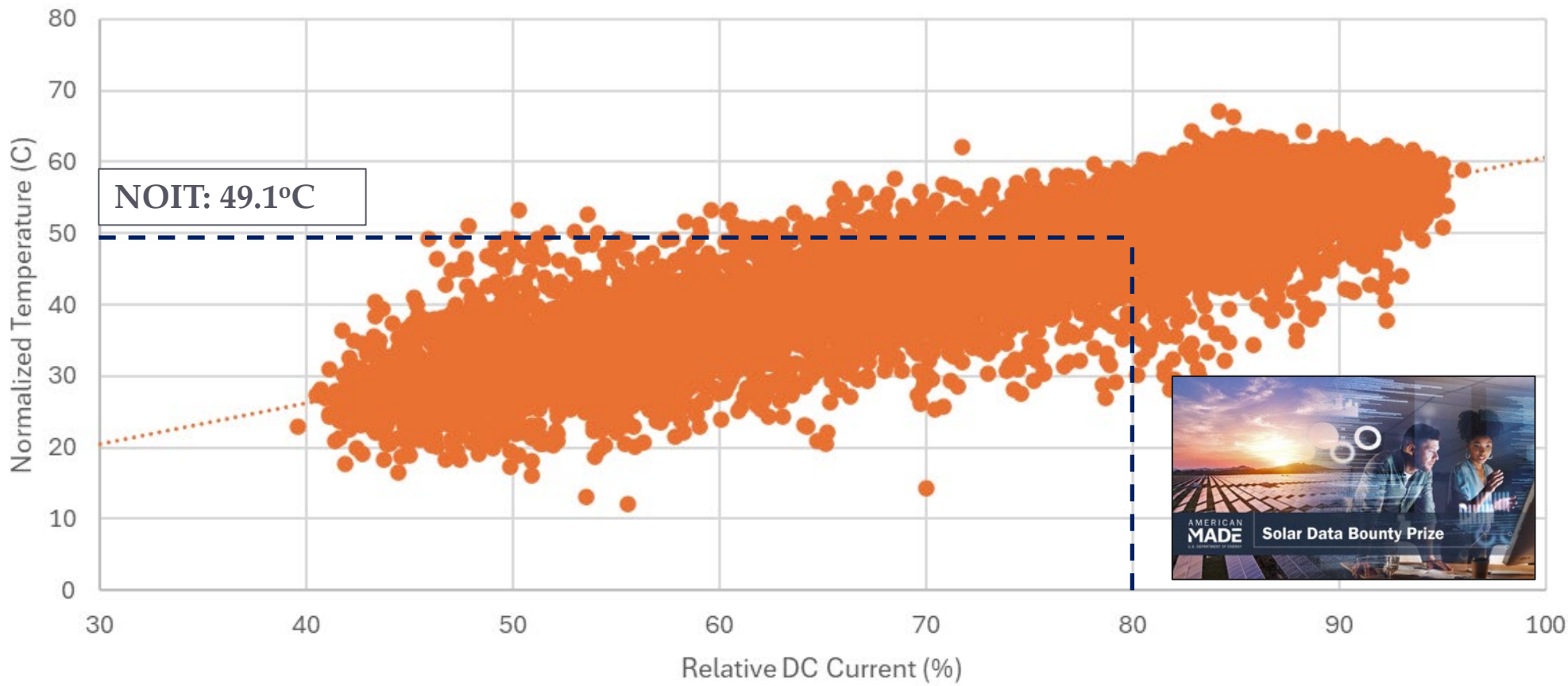
Normalized IGBT Temperature ($T_{IGBT} - T_{AMB}$)

At 80%. of inverter's full current

- Normalizing for ambient temp sharpens the data
- Three IGBTs within the same inverter are shown with distinctly different trendlines
- Different Nominal IGBT Operating Temps (NOIT) all in one inverter

SILICON RANCH

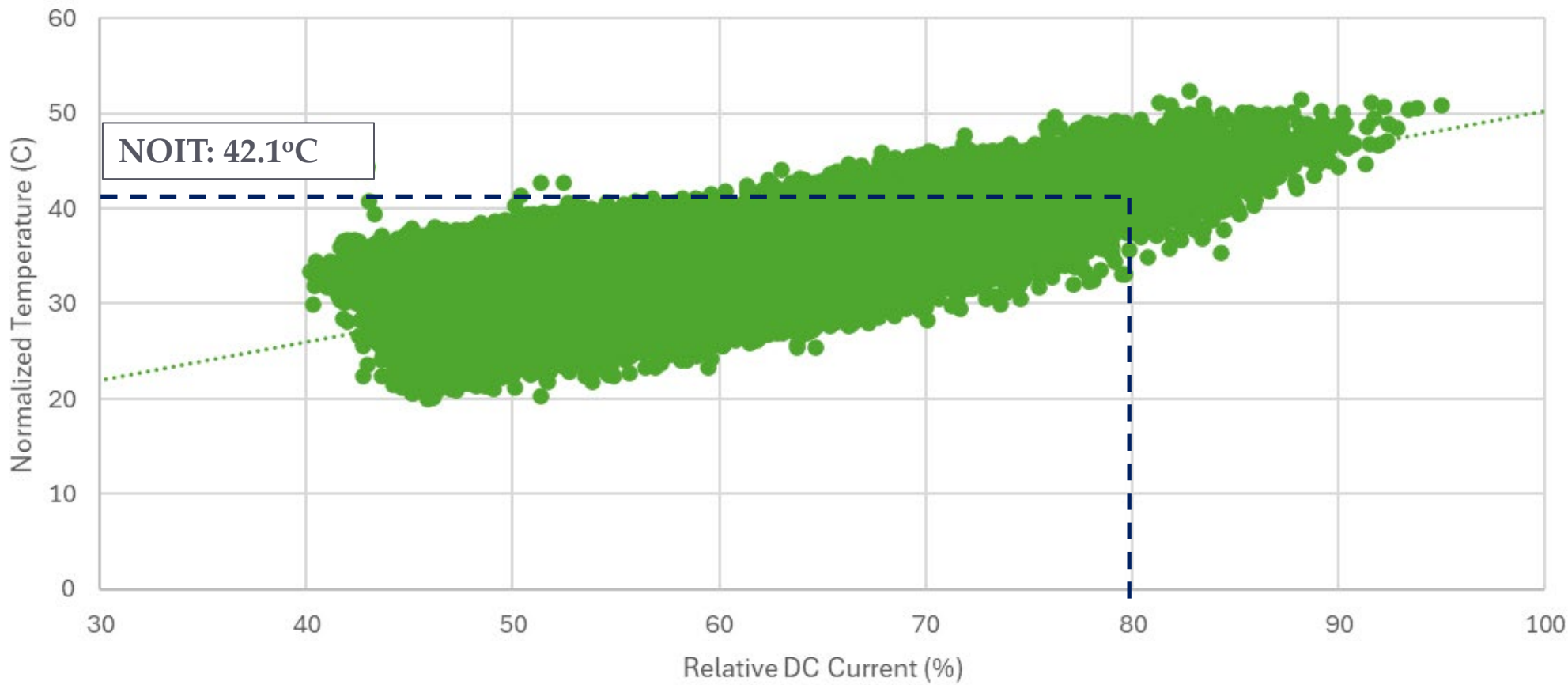
Central Inverter A, 7yrs old, Colorado
2024 at 5-min granularity



- Central Inverter A , 3000 kVA, Active Air Cooled
- NOIT is 49.1 ºC above ambient
- This data is available on PVDAQ! Winner of the Solar Data Bounty Prize

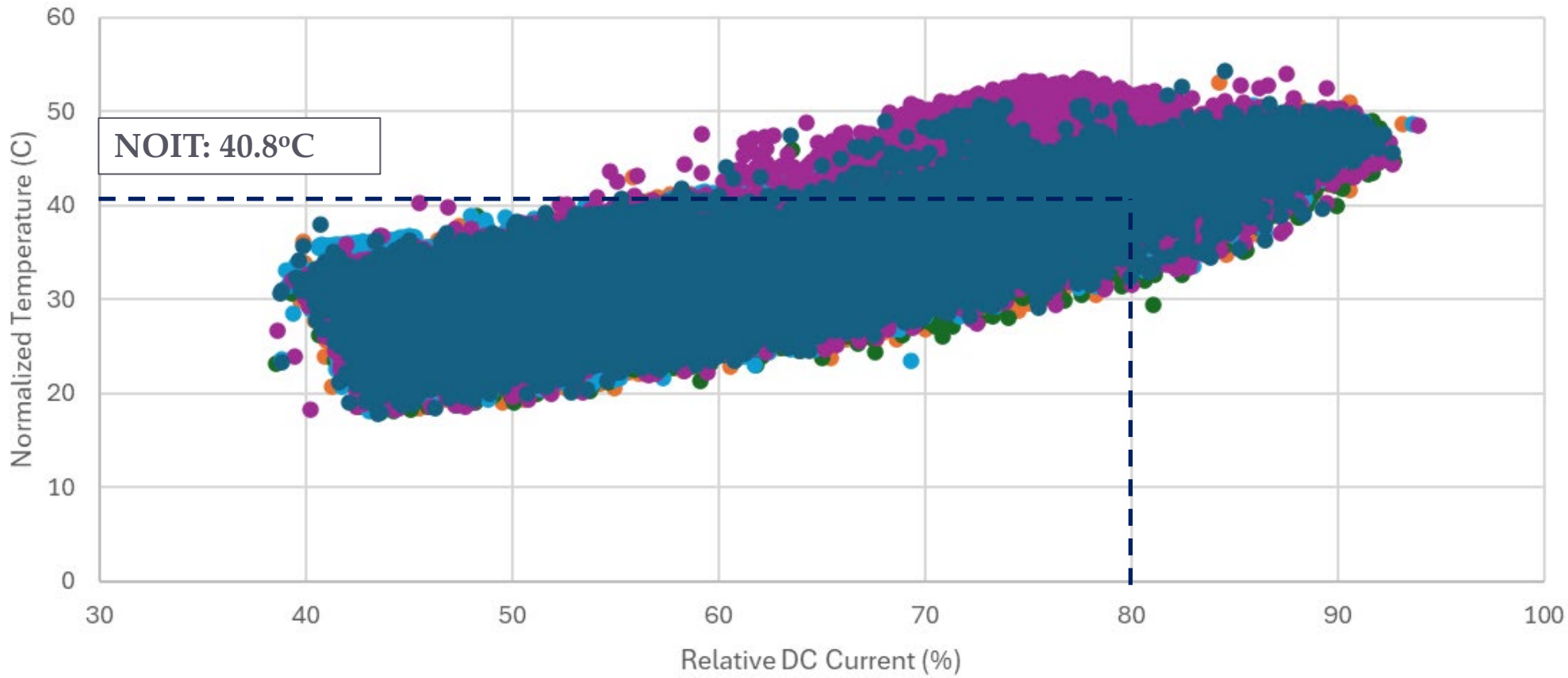
SILICON RANCH

Central Inverter B, 2 years old, Kentucky 2024 at 5-min granularity



- Different model inverter
- Central Inverter B , 3400 kVA, Active Air Cooled
- NOIT is 42.1 ºC above ambient, lower than model A

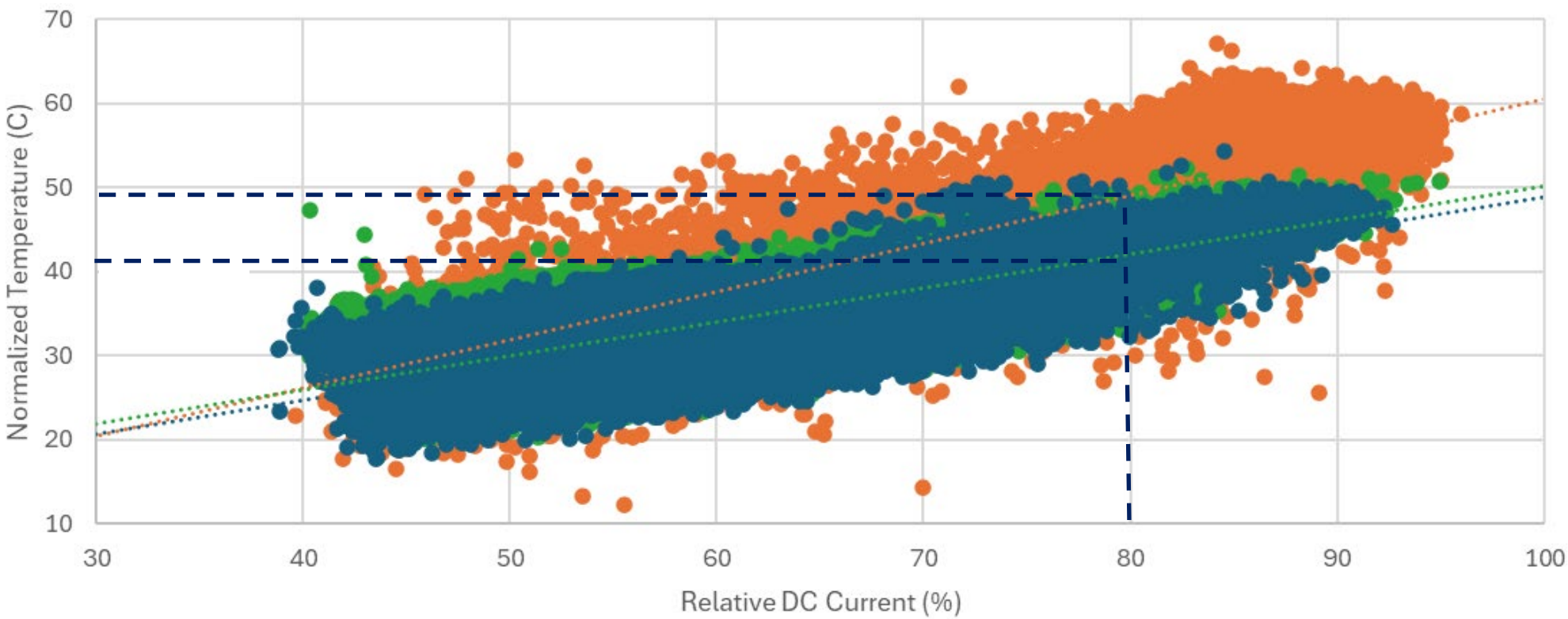
Central Inverter B, 1 year old, Georgia 2024 at 5-min granularity



- Same model, different MPPT voltage window
- NOIT is 40.8 ºC above ambient, lower than model A
- One of the 10 inverters plotted has a curious rise in temp between 50 and 85% full current

Central Inverter A & B Combined

2024 at 5-min granularity



- Comparing both models of inverter, across multiple sites, inverter model has a distinctly higher NOIT.
- INV efficiency is the same, cooling performance is different
- Choice of which INV to buy is clear

Conclusions

- PV power plant energy loss is heavily dependent on Inverter Availability, and it is recoverable.
- **Temperature is the most pertinent stressor** and typically already measured and reported by inverters
- Ambient temperature must be accounted for, yet DC current is what impacts inverter temperature the most.
- **NOIT can be measured for any inverter in either a lab or field environment**
- **NOIT and the rate of temperature change can identify some forms of maligned inverter operations**
- Similar to expected module temperate coefficient and NOCT values, an **inverter product should be evaluated by its NOIT, as it is a leading indicator of inverter reliability**

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Thank You!

Our work is funded by the sale of renewable energy to hundreds of customers, nationwide

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SILICON RANCH

Technology Innovation Institute

Qualification Test Standards for Floating PV

2025 PV Reliability Workshop | Session 9

Marriott Denver West – 6 Mar 2025, Golden, CO

Mauro Pravettoni, Paula Araujo and Min Hsian Saw
Senior Director - Solar Energy Systems

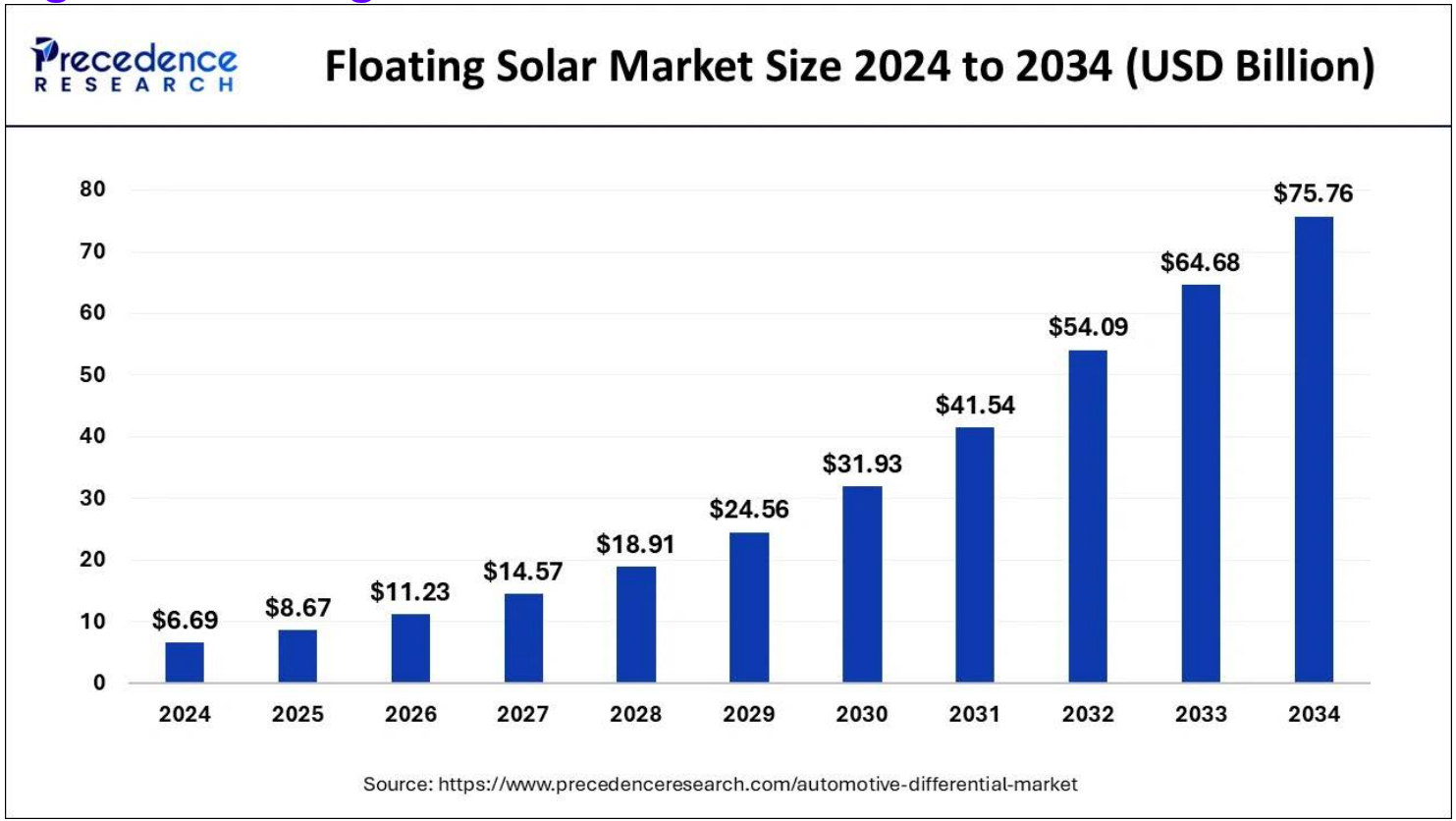
tii.ae

“Conventional” vs. “integrated” PV

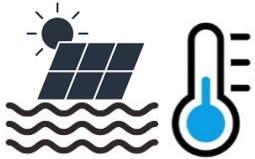
Conventional PV

Floating PV

Floating PV: market perspective
Annual global floating solar installations



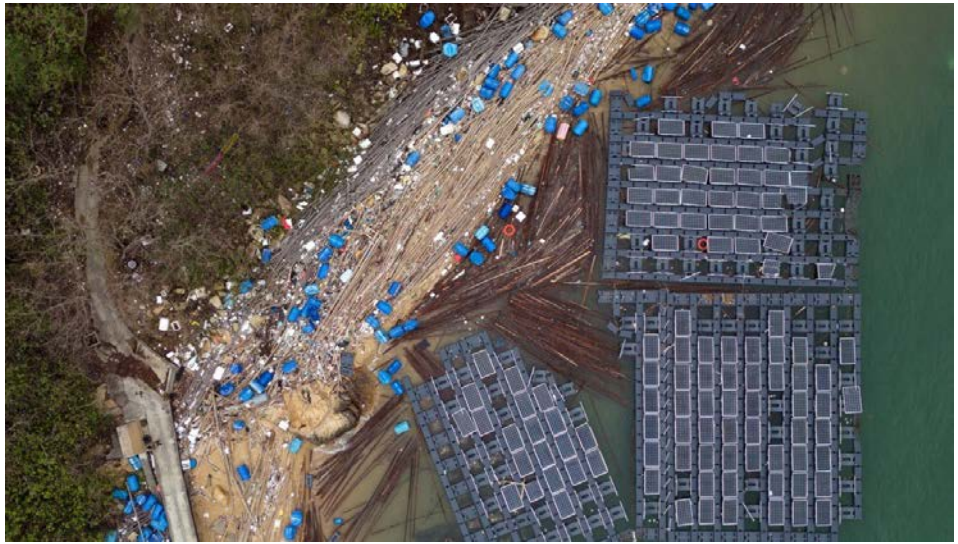
Floating PV: technology perspective
The main advantages of FPV for the MENA region

- Reduced evaporation
- Better performance of cooler modules 
- Dual-use (aquaculture)
- Synergy with energy-intensive desalination
- Decarbonization of offshore oil platforms

Floating PV: technology perspective
New reliability challenges

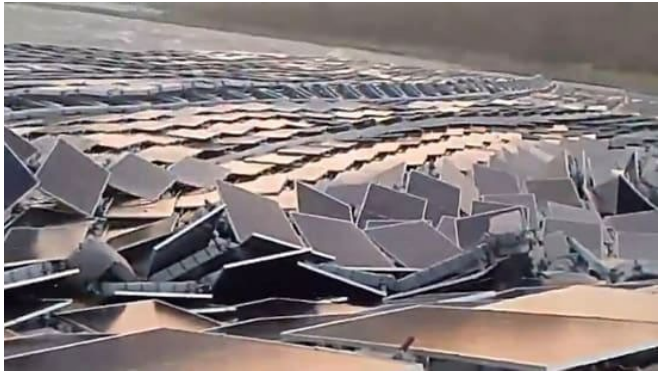
200 solar panels washed up on shores of Hong Kong marine park to be cleared in wake of concerns over possible water contamination

Mysterious mass was found by group of kayakers on March 19 at Sha Chau and Lung Kwu Chau Marine Park in city's northwestern waters



Two Largest Floating Solar Plants in India Suffered Severe Damages

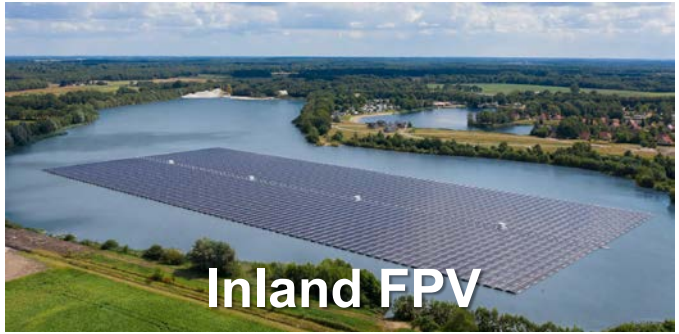
IndianWeb2 Monday, April 29, 2024 0 Comments



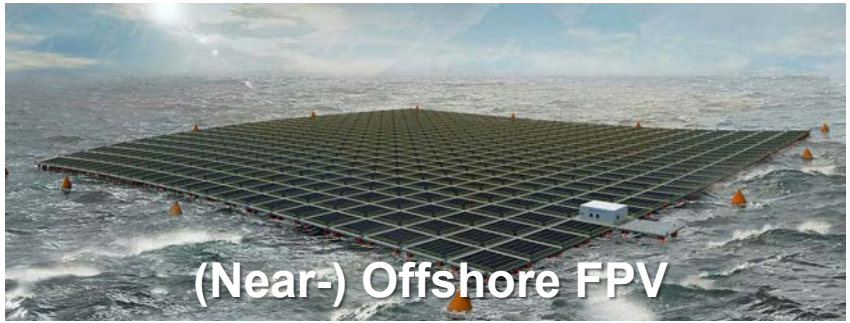
Saw et al., *Sayuri-PV* (2024)

Floating PV: technology perspective
New reliability challenges

Floating PV: technology perspective
New reliability challenges



- UV degradation
- Ammonia
- Humidity & condensation
- PID
- Biofouling
- Mechanical stresses
- Thermal shock



- UV degradation
- Ammonia
- Humidity & condensation
- Salt-mist + PID
- Biofouling
- Wave-induced mechanical stresses
- Thermal shock
- Wind-induced mechanical stresses

Saw et al., *Sayuri-PV* (2024)

Towards a qualification protocol for FPV
Proposed classification of floating systems and risk assessment

		Inland Waterways		*Nearshore*		*Offshore*	
Physically separated from water	*By physical distance*	PID: *	Impact: -	PID: **	Impact: -	PID: **	Impact: -
		Ammonia: ***	Vibration: *	Ammonia: **	Vibration: *	Ammonia: *	Vibration: *
		Salt-mist: -	Torsion: -	Salt-mist: *	Torsion: -	Salt-mist: *	Torsion: -
		Biofouling: -	Immersion: -	Biofouling: -	Immersion: -	Biofouling: -	Immersion: -
		Thermal shock: -		Thermal shock: -		Thermal shock: -	
	By physical medium (e.g., membrane)	PID: *	Impact: -	PID: **	Impact: -	PID: **	Impact: -
		Ammonia: ***	Vibration: *	Ammonia: **	Vibration: *	Ammonia: *	Vibration: *
		Salt-mist: -	Torsion: *	Salt-mist: *	Torsion: **	Salt-mist: *	Torsion: ***
		Biofouling: -	Immersion: -	Biofouling: -	Immersion: -	Biofouling: -	Immersion: -
		Thermal shock: -		Thermal shock: -		Thermal shock: -	
Not physically separated from water	*Rigidly joined buoys*	PID: *	Impact: *	PID: ***	Impact: **	PID: ***	Impact: ***
		Ammonia: ***	Vibration: *	Ammonia: **	Vibration: **	Ammonia: *	Vibration: ***
		Salt-mist: -	Torsion: -	Salt-mist: ***	Torsion: -	Salt-mist: ***	Torsion: -
		Biofouling: *	Immersion: -	Biofouling: **	Immersion: **	Biofouling: ***	Immersion: ***
		Thermal shock: *		Thermal shock: **		Thermal shock: ***	
	Non-rigidly joined buoys	PID: *	Impact: *	PID: ***	Impact: **	PID: ***	Impact: ***
		Ammonia: ***	Vibration: *	Ammonia: **	Vibration: **	Ammonia: *	Vibration: ***
		Salt-mist: -	Torsion: *	Salt-mist: ***	Torsion: **	Salt-mist: ***	Torsion: ***
		Biofouling: *	Immersion: -	Biofouling: **	Immersion: **	Biofouling: ***	Immersion: ***
		Thermal shock: *		Thermal shock: **		Thermal shock: ***	

Saw et al., *Sayuri-PV* (2024)

* Lowest severity ** Medium severity *** Highest severity

The ongoing IEC standardization activity
State of the art

IEC TS 63496

TECHNICAL SPECIFICATION

Floating photovoltaic power plants – Design guidelines and recommendations

ACD 2023-03

Target 2026-02

IEC TS 63618

TECHNICAL SPECIFICATION

~~High density polyethylene (HDPE)~~ floating body used in floating photovoltaic system

ACD 2024-12

Target 2026-12

IEC TS 63637

TECHNICAL SPECIFICATION

Guidelines for qualifying PV modules for operation in floating solar platforms

ACD 2025-02

Target 2027-04

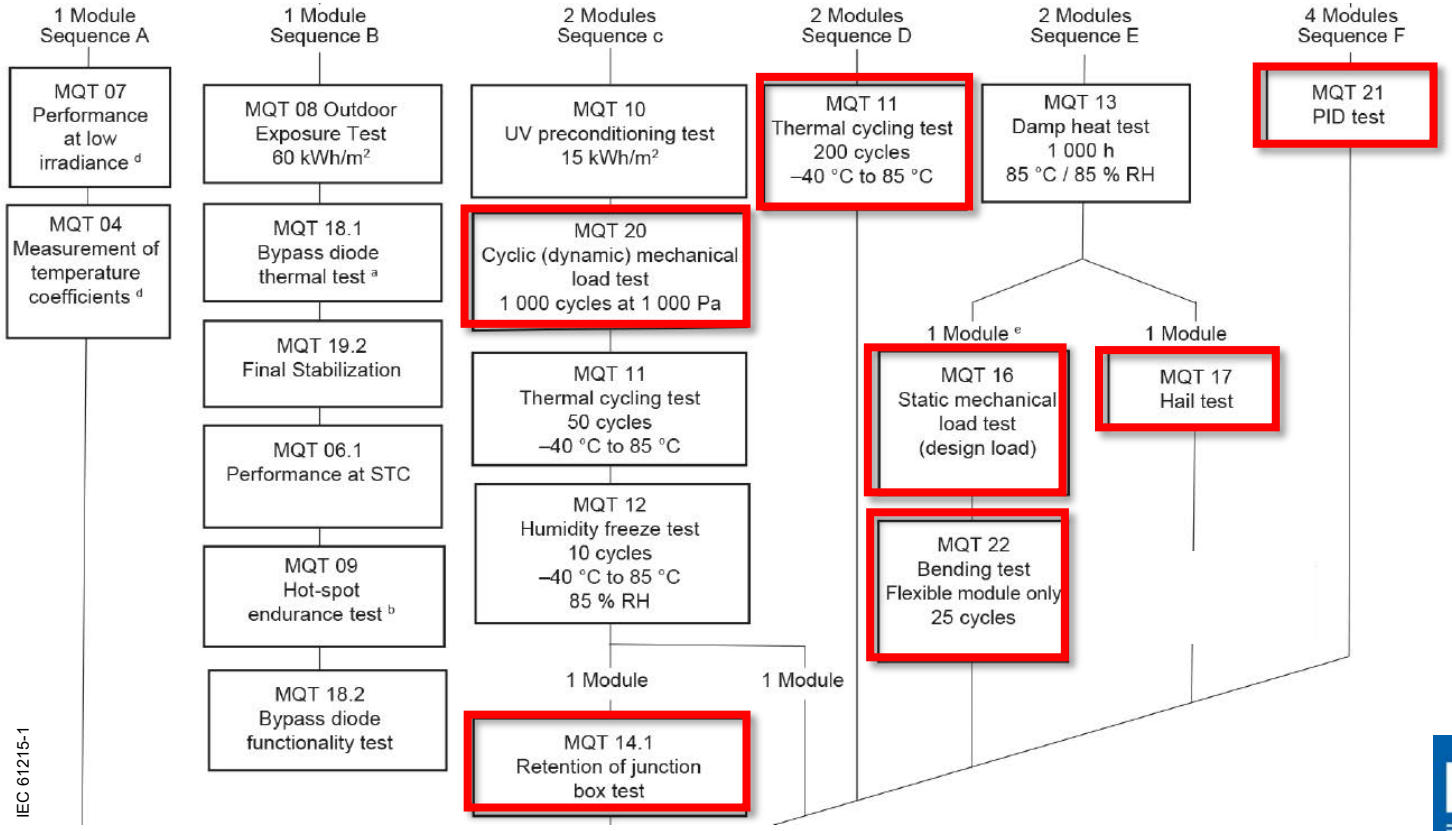
The ongoing IEC standardization activity
IEC TS 63637

- # P-members: 48

- # P-members voting: 31
  - in favour: 31 (100%)
  - against: 0

- # P-member participating: 7

Towards a qualification protocol for FPV
Possible gaps in IEC 61215



Towards the CD of IEC TS 63637

Draft flowchart of a technology specific qualification plan ("FQT")

IEC

82/2326/NP

NEW WORK ITEM PROPOSAL (NP)

Proposer:	Date of proposal:
Secretariat	2024-11-25
Date of circulation:	Closing date for voting:
2024-11-29	2025-02-21

IEC TC 82 : Solar photovoltaic energy systems

Secretariat:	Secretary:
United States of America	Mr George Kelly
Need for IEC coordination:	Horizontal function(s):

Aspects concerned:

Title of proposal:

Guidelines for qualifying PV modules for operation in floating solar platforms

☐ Standard ☒ Technical Specification ☐ Publicly Available Specification

Proposed project number:

Scope

(as defined in ISO/IEC Directives, Part 2, 14):

This document specifies requirements, testing methods, and performance criteria for photovoltaic (PV) modules intended for use on floating solar platforms. It aims to ensure the reliability and durability of PV modules when deployed in environments associated with bodies of water (e.g., lakes, reservoirs, near-shore, and offshore settings). The standard covers mechanical, electrical, and environmental factors that affect the operation of PV modules on floating systems.

This document does not intend to replace the qualification and type approval IEC 61215 series but aims at integrating it with more specific tests for the water environment. It is intended to apply to all terrestrial flat plate module materials such as crystalline silicon module types as well as thin-film modules. It does not apply to modules used with concentrated sunlight although it may be utilized for low concentrator modules (1 to 3 suns). For low concentration modules, all tests are performed using the irradiance, current, voltage and power levels expected at the design concentration.

The objective of this test sequence is to determine the electrical characteristics of the module and to show, as far as possible within reasonable constraints of cost and time, that the module is capable of withstanding prolonged exposure in the water environment.

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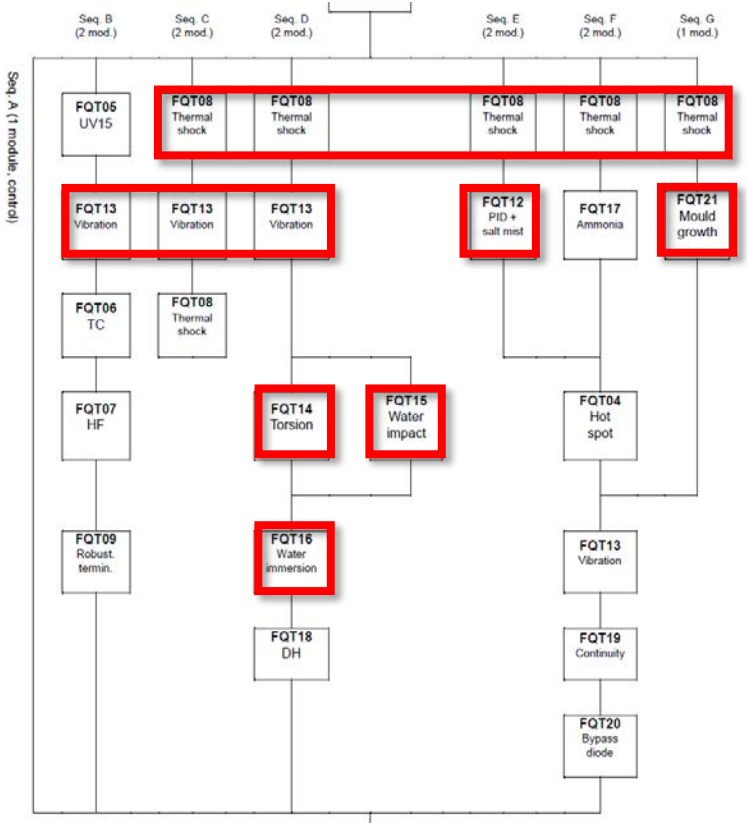


Towards the CD of IEC TS 63637
Classification of environmental conditions (IEC 60721-3-6)

Stress type	*n* = 1	*n* = 2	*n* = 3	*n* = 4	*n* = 5	*n* = 6	*n* = 7
6K*n* (climatic)	-	-	-				
6B*n* (biological)	-	mould, fauna					
6C*n* (chemical)	-	salt, pollution					
6S*n* (mech. active)		dust soot	sand				
6M*n* (mechanical)	no engine						

Towards the CD of IEC TS 63637
Classification of environmental conditions (IEC 60721)

Table A.2 – Climatic conditions

Environmental parameter	Unit	6K4 (temperate)	6K5 (cold)	6K6 (tropical damp)	6K7 (tropical dry)
Air temperature (min / max)	°C	–25 / +55	–40 / +55	+5 / +55	–20 / +70
Water temperature (min / max)	°C	0 / +35		+15 / +35	
Surface temperature (min / max)	°C	–25 / +70	–25 / +70	0 / +70	
Gradual change of temperature	°C/min	3			
Rapid change of temperature (air/water)	°C	+40/+5		+40/+15	
Rapid change of temperature (surface/water)	°C	+50/+5		+70/+5	
Humidity (high / low)	%	95 / 10			

Towards the CD of IEC TS 63637
Classification of environmental conditions (IEC 60721)

Wind	m/s	30	50	
Rain	mm/min	6	15	
Solar radiation (max)	W/m^2	1120		
Water, other than rain	m/s	3	10	
Hail (diameter and velocity)	mm m/s	25 23		NA

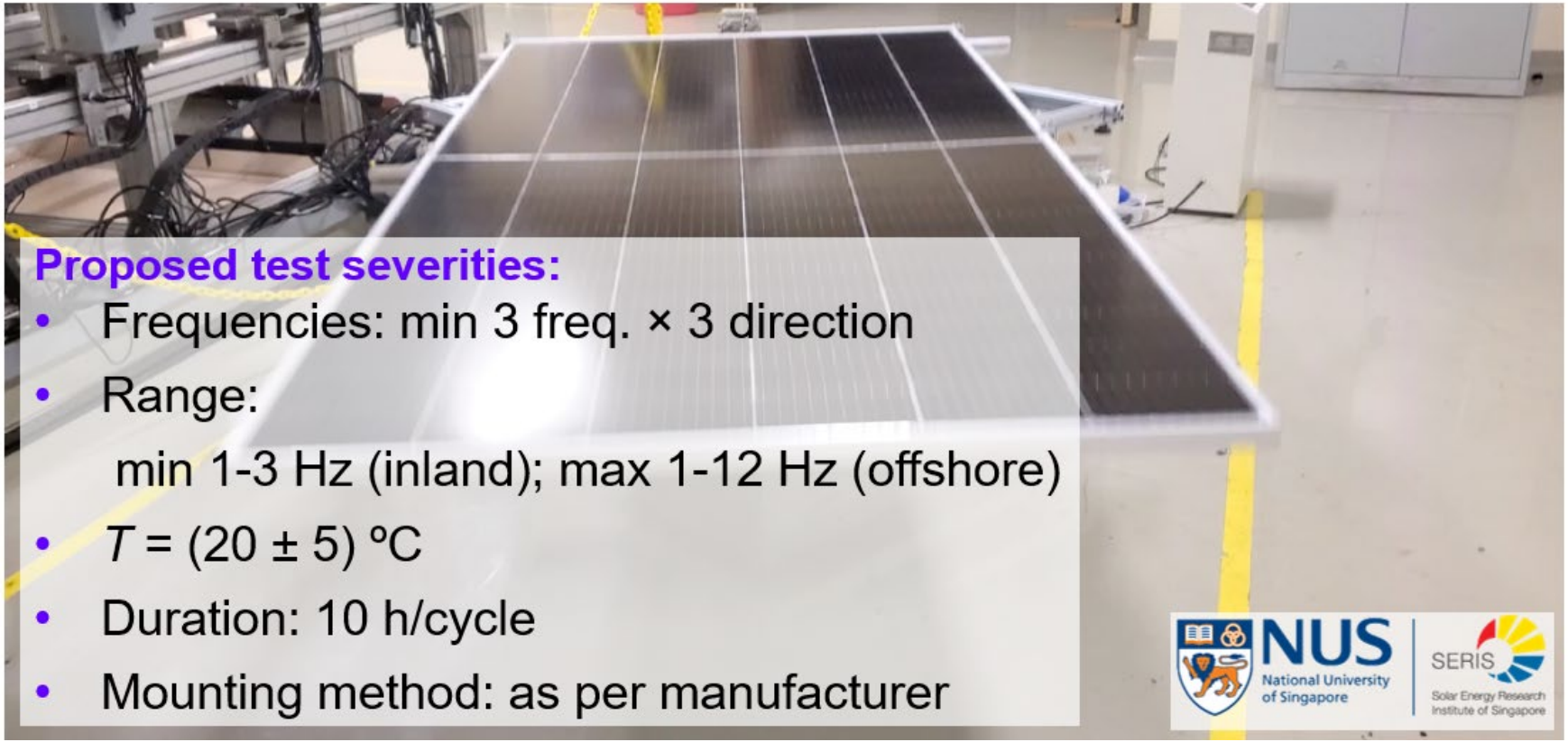
Towards the CD of IEC TS 63637
Classification of environmental conditions (IEC 60721)

Table A.5 – Mechanical conditions

Environmental parameter	Unit	6M1	6M2
Stationary vibration (sinusoidal): - displacement amplitude - acceleration amplitude - frequency	 mm m/s^2 Hz	NA	 1.5 10 2-13
Angular motion (angle/frequency): - around X-axis (roll) - around Y-axis (pitch) - around Z-axis (yaw)	deg / Hz	22.5 / 0.14 10 / 0.2 4 / 0.05	NA

New stress tests for FPV

FQT 13: Vibration test (ref: IEC 60068-2-6. Test Fc)

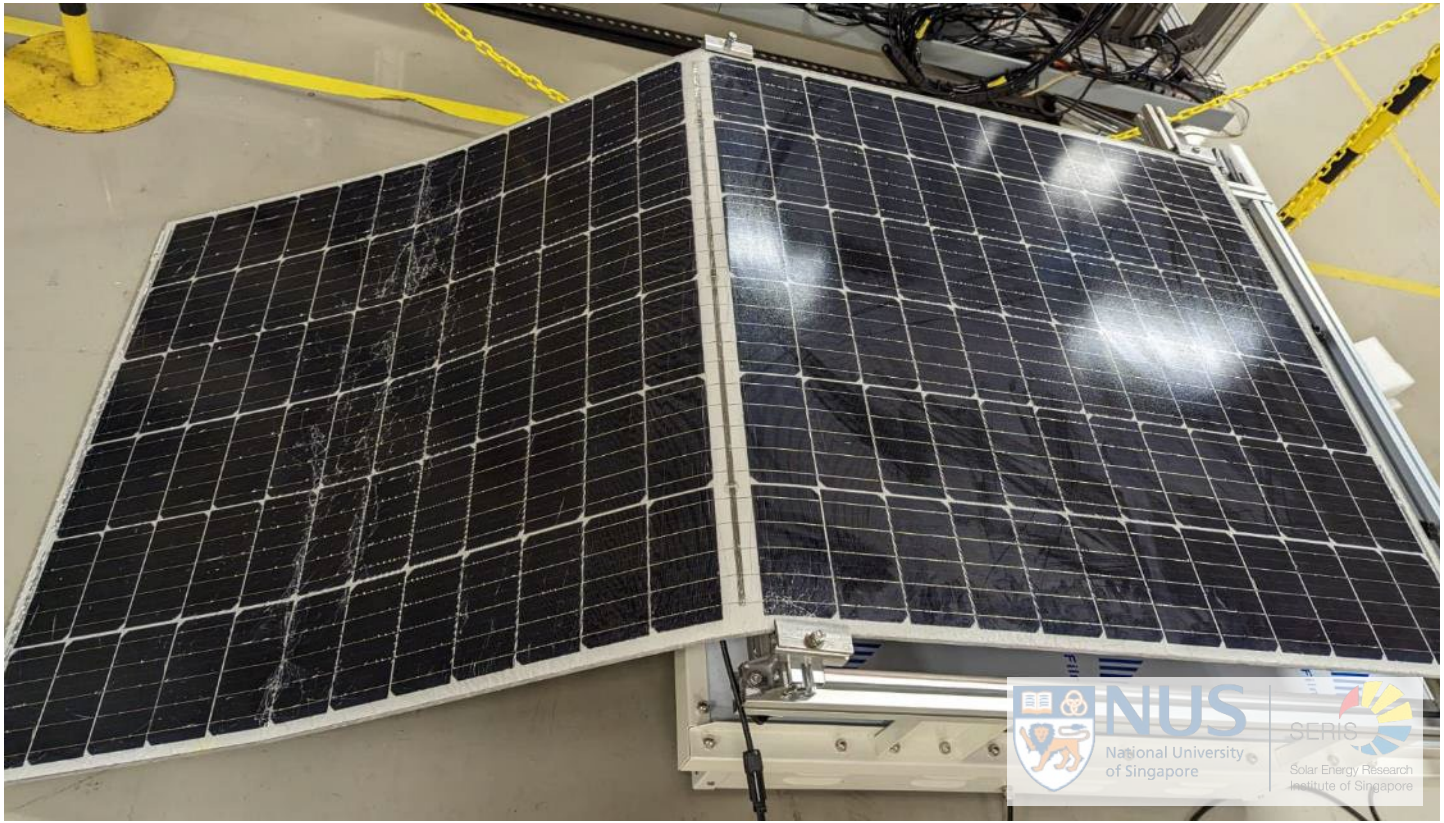


Proposed test severities:

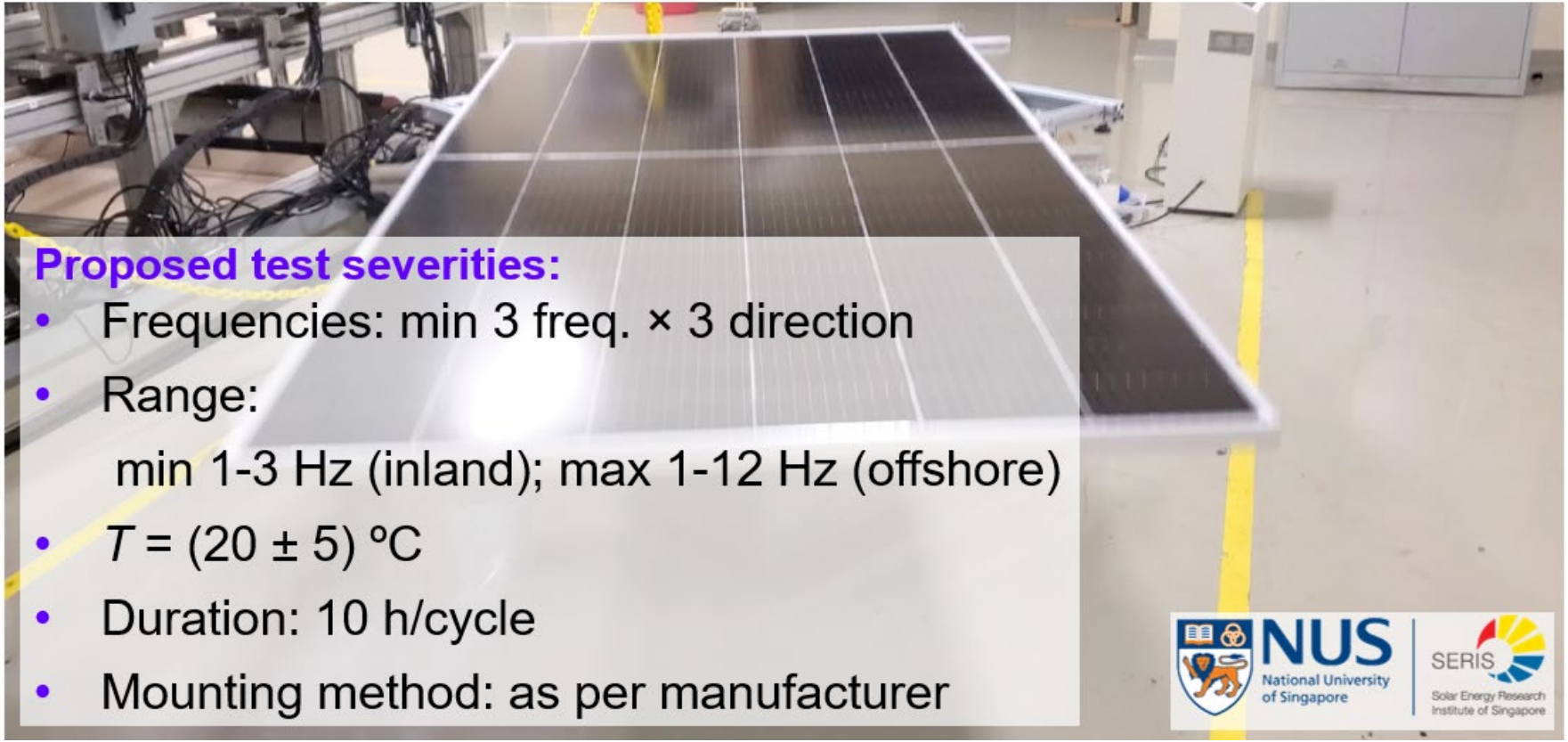
- Frequencies: min 3 freq. × 3 direction
- Range:

  min 1-3 Hz (inland); max 1-12 Hz (offshore)
- T = (20 ± 5) ºC
- Duration: 10 h/cycle
- Mounting method: as per manufacturer

New stress tests for FPV
FQT 13: Vibration test, example of failure



New stress tests for FPV
FQT 14: Torsion test



Proposed test severities:

- Frequencies: min 3 freq. × 3 direction
- Range:

  min 1-3 Hz (inland); max 1-12 Hz (offshore)
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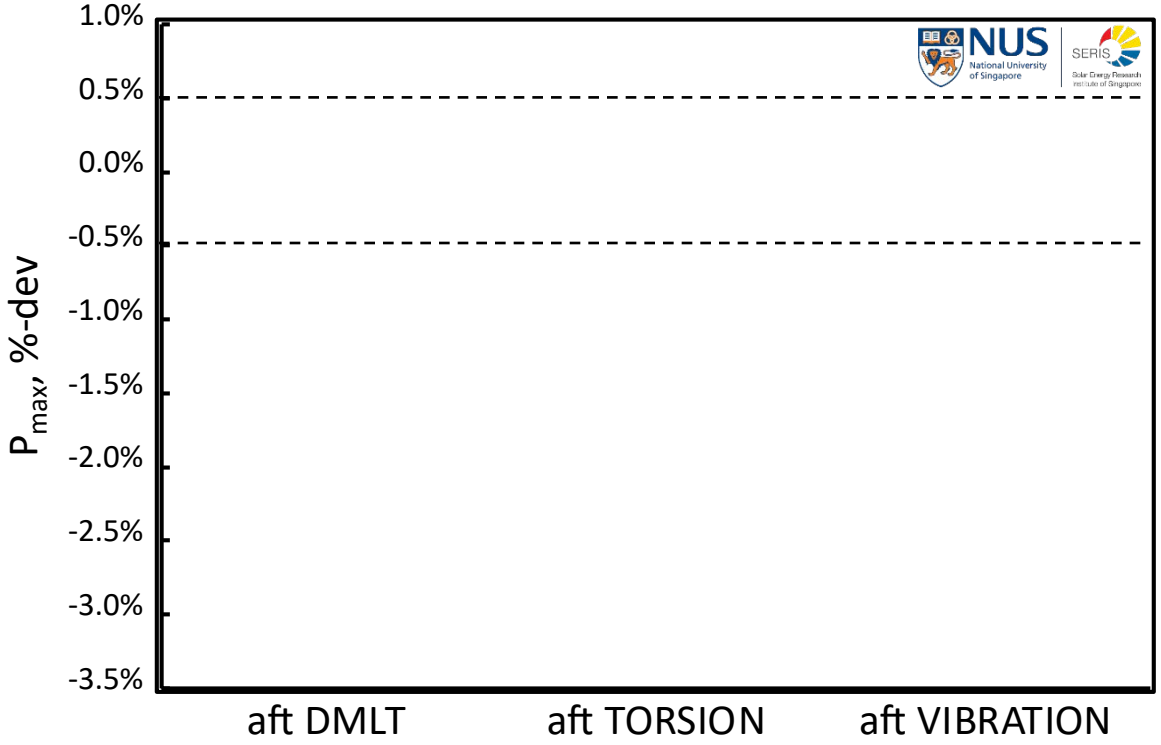
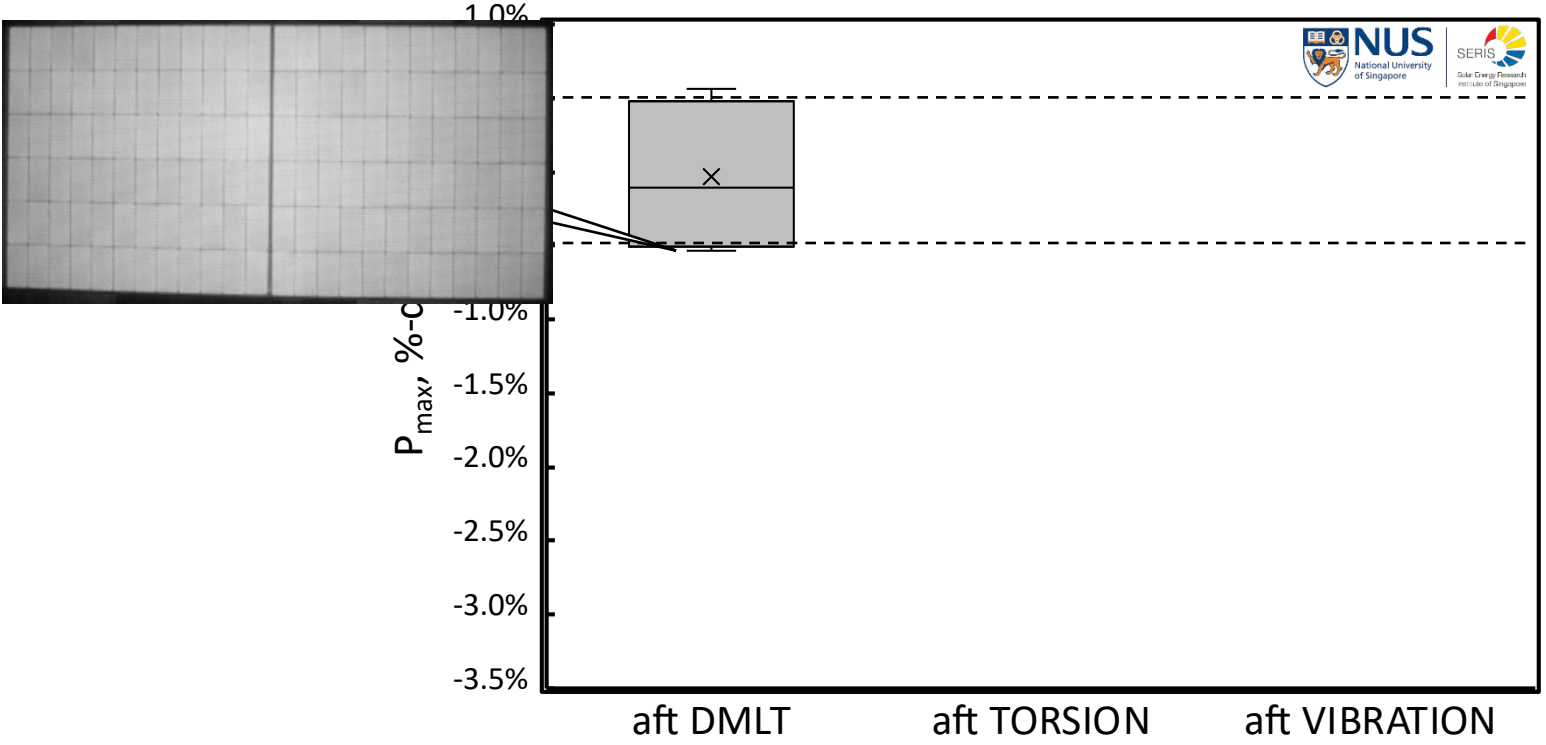
- Duration: 10 h/cycle
- Mounting method: as per manufacturer

NUS National University of Singapore | SERIS Solar Energy Research Institute of Singapore

Mechanical stress tests at SERIS for FPV
Preliminary results



Mechanical stress tests at SERIS for FPV
Preliminary results



Mechanical stress tests at SERIS for FPV
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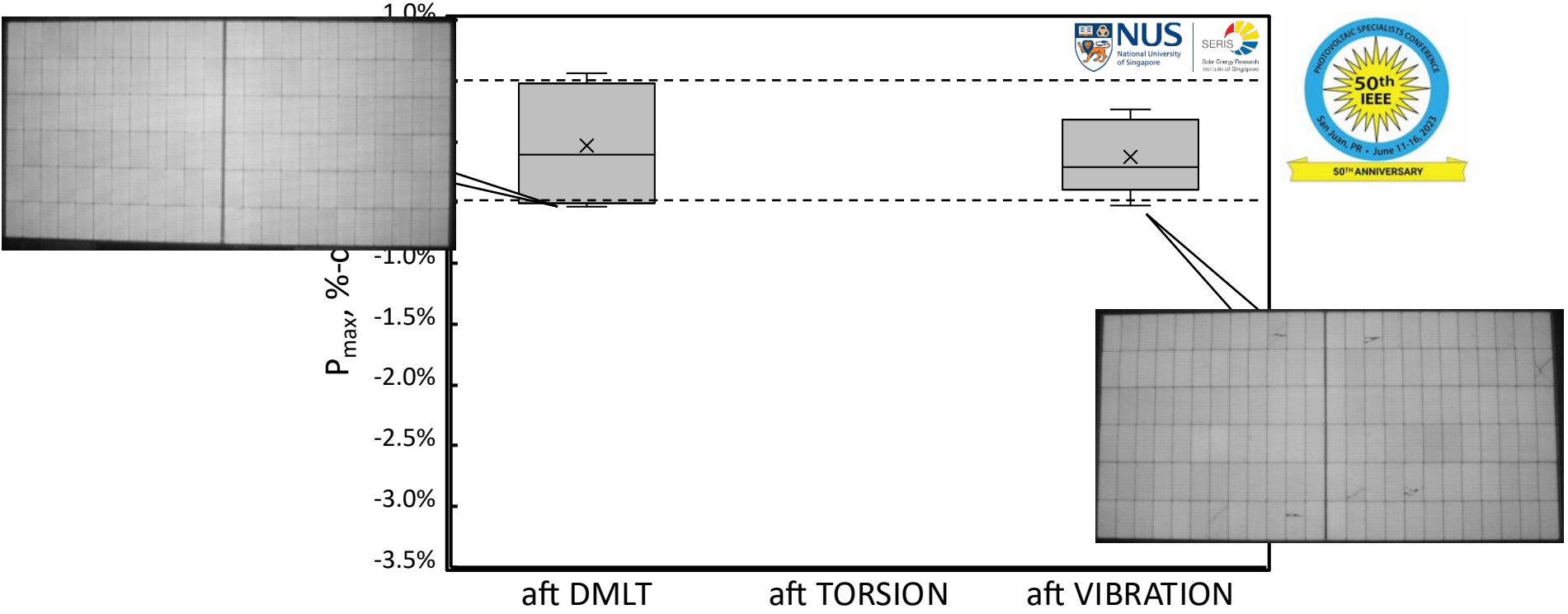
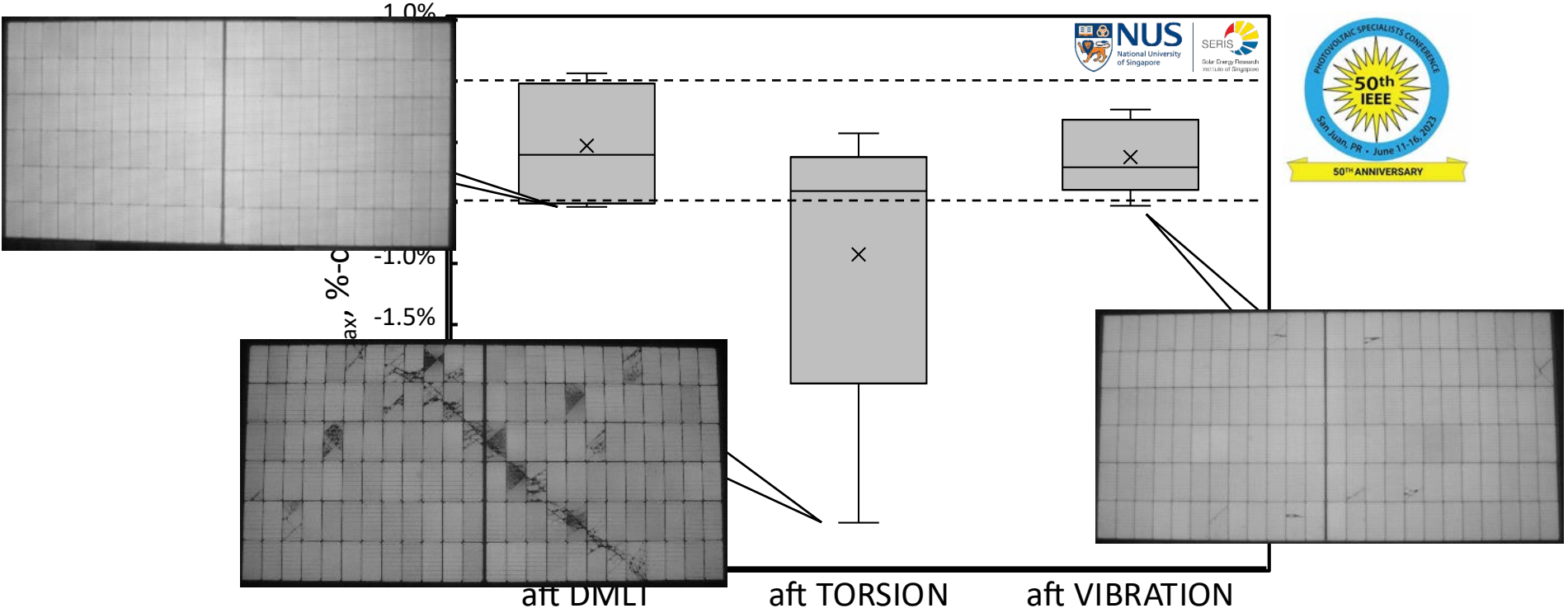


Mechanical stress tests at SERIS for FPV
Preliminary results



Biological stress tests for FPV
Soiling & biofouling (ref: IEC 60721-2-7)

Attacking agent		Growth and survival factor		Possible effects on module components
		Temperature	Humidity	
Bacteria		– 3°C to +75°C	Presence of water	• Corrosion on metallic components
Marine borer		saltwater + freshwater		• Penetration of the insulation of electrical cables
Algae		saltwater + freshwater		• Variations in size could induce shading

Saw et al., *Sayuri-PV* (2024)

Biological stress tests for FPV
Soiling & biofouling (ref: IEC 60721-2-7)

Figure 4 Image of the underwater part of the floatovoltaics completely colonised by fouling fauna, and especially mussels of the species *Mytilus edulis* (source: Oscar Bos/Wageningen Marine Research).

Conclusions

- FPV is receiving growing interest, with projected >4 GW new installations in 2026, and >10 b$ market size by 2030
- Concerns on module reliability are being addressed, particularly for offshore FPV
- Among the most critical aspects – confirmed by field data – are mechanical stresses and bio-chemical stresses
- A draft flow-chart with new stress tests dedicated to FPV was submitted to IEC as NWIP
- **The NWIP was voted positively: Project Team to be formed and start this month**
- First Committee Draft (CD) planned by Dec 2025

Technology Innovation Institute

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PVRW 2025

Reliability of TOPCon solar Cells: Understanding Degradation and Recovery of *poly*-Si/SiO_x Passivating Contacts

Aditya Ratnapagol, Sumit Agarwal

Colorado School of Mines

William Nemeth, Paul Stradins, David L. Young

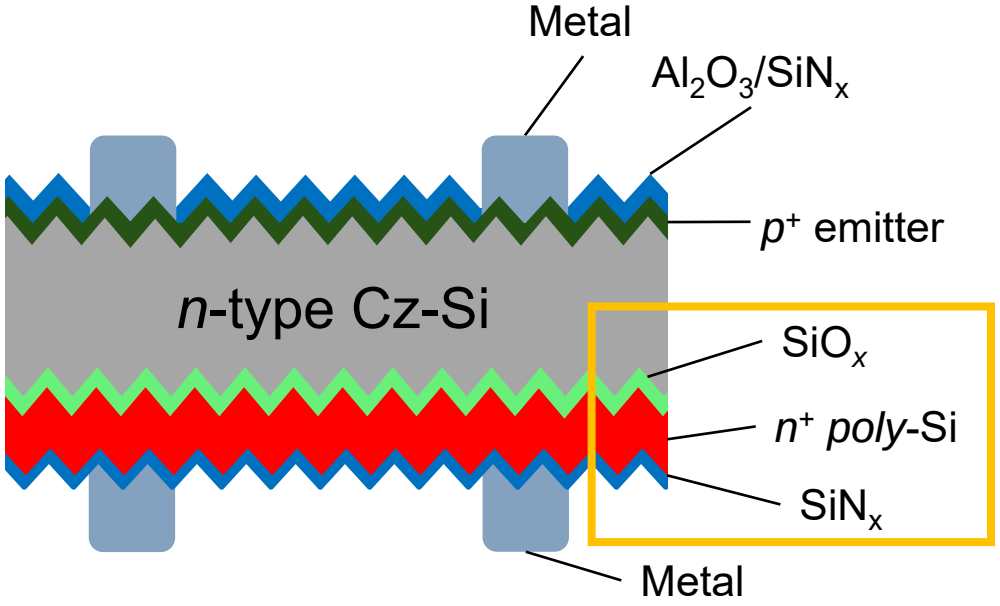
National Renewable Energy Laboratory

6th March 2025

What is a TOPCon Solar cell?

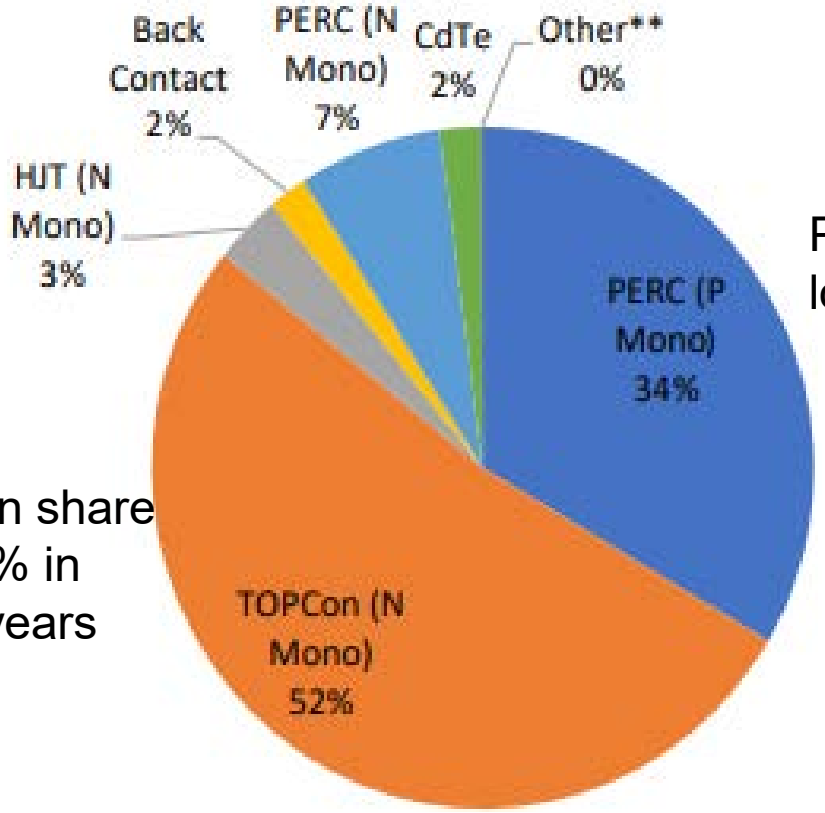
TOPCon cell

Tunnel oxide passivating contact



- *n*-Cz silicon wafer
- P-doped *poly*-Si on thin oxide (~1.5 nm)
- Cell efficiency ~24%

PV shipments by technology in 2023



PERC will lose share

TOPCon share ~70-80% in next 5 years

- *p*-type solar cells approaching their efficiency limits of 24.5%
- Efficiency limit for TOPCon is 28.7%
- TOPCon technology compatible with existing PERC production

Feldman, Solar industry update (May 2024).
pv-magazine, Why TOPCon will Keep Domination in Future Five Years? (Sept 2024).

TOPCon Module and Cell Reliability

Reliability issues in TOPCon		
Type of failure	**Degradation**	**Test Temperature**
LID/LeTID (noncritical)	0.2% P_{mpp}	25/75 °C
Thermal Cycling (noncritical)	0.7% P_{mpp}	-40/85 °C
Damp Heat	1.6% P_{mpp}	85 °C
PID	1.6 - 2.0% P_{mpp}	85 °C
UVID: Module level	5% P_{mpp}	60 °C
UVID: Cell level	7% relative efficiency loss	60 °C
Surface Passivation Degradation (SPD)	**~ 2 - 3 % P_{mpp}**	**> 200 °C**

None of these tests can detect the surface passivation degradation

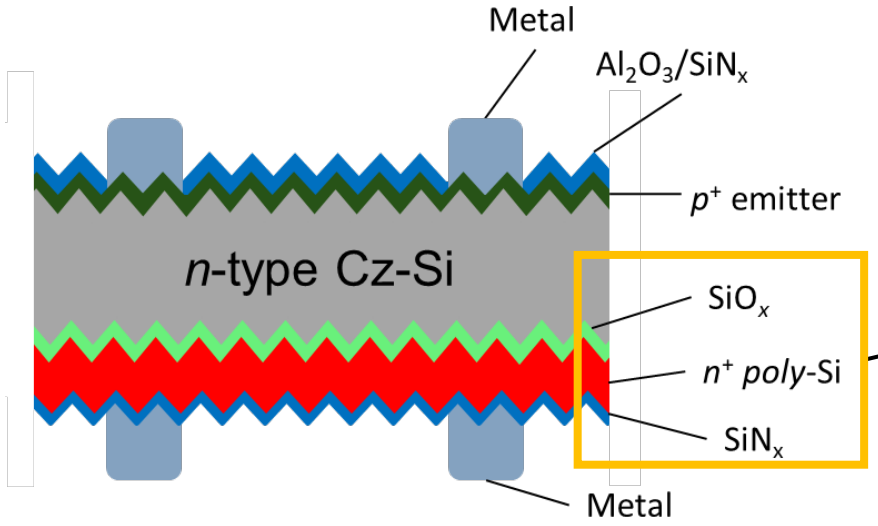
- Slow kinetics
- Extremely long annealing time required
- For a fielded module installed in Kansas operating at ~60 °C
  - > 10 years to degrade
  - > 60 years to recover

Surface degradation tests should be performed on cells or symmetric structures

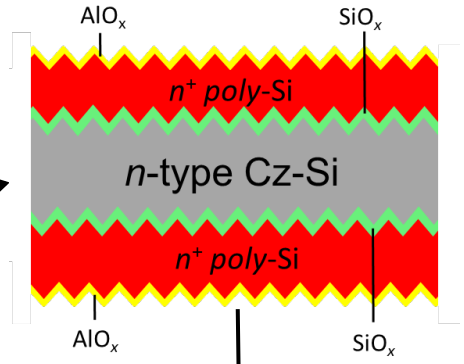
PVEL, PV Module Reliability Scorecard, 2024

Thome, F. et al., Solar RRL **8**, 2400628, 2024

In this talk- Surface passivation degradation (SPD) of TOPCon contacts



Symmetric TOPCon contact



Metallization Firing

↓

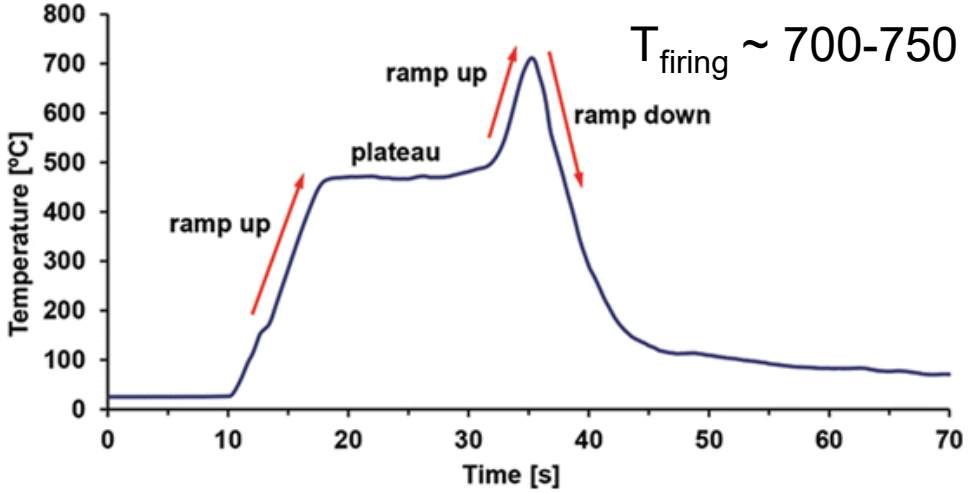
Accelerated tests

↓

Carrier lifetime measurements

Firing profile

T_{firing} ~ 700-750 °C

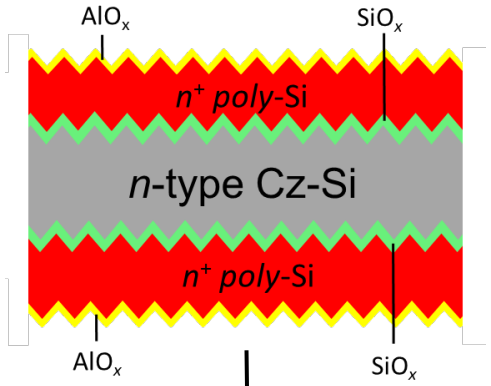


iV_{oc}: Overall passivation quality **(High iV_{oc} is beneficial)**

J_0: Surface passivation quality at interface **(High J_0 is detrimental)**

Yuguo *et.al.*, Screen-Printed Front Junction n-Type Silicon Solar Cells.(2016).

Degradation and recovery of TOPCon contacts



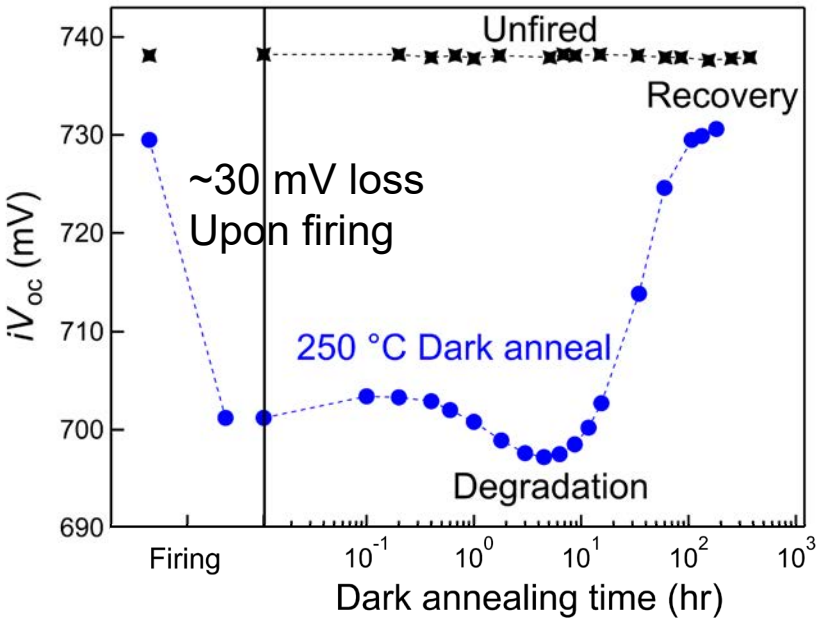
Unfired & Fired at 670 °C peak

↓

Dark annealing 250 °C

↓

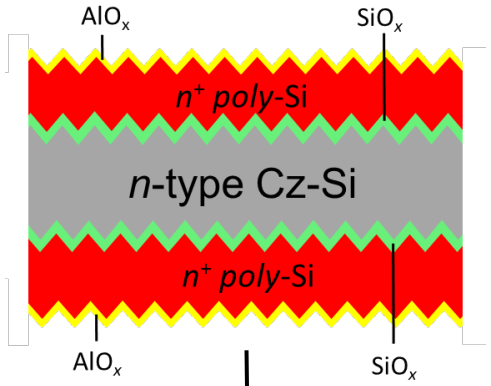
Carrier lifetime measurements



- Unfired samples: Stable iV_{oc} and J_0
- Fired sample:
  - Instability in surface passivation
  - At 250 °C in the dark
    - Degradation: ~10 hr
    - Recovery: ~200 hr
- Stable bulk lifetime → **Not LeTID**
- **Purely a surface phenomenon**

Winter, M. *et al*., IEEE J-PV **10**,423 (2020)
Kang *et al.*, Sol. Energy Mater. Sol. Cells **215** (2020)
Chen *et al*., *Sol. Energy Mater. Sol. Cells* **236**,111491 (2022)

Degradation and recovery of TOPCon contacts



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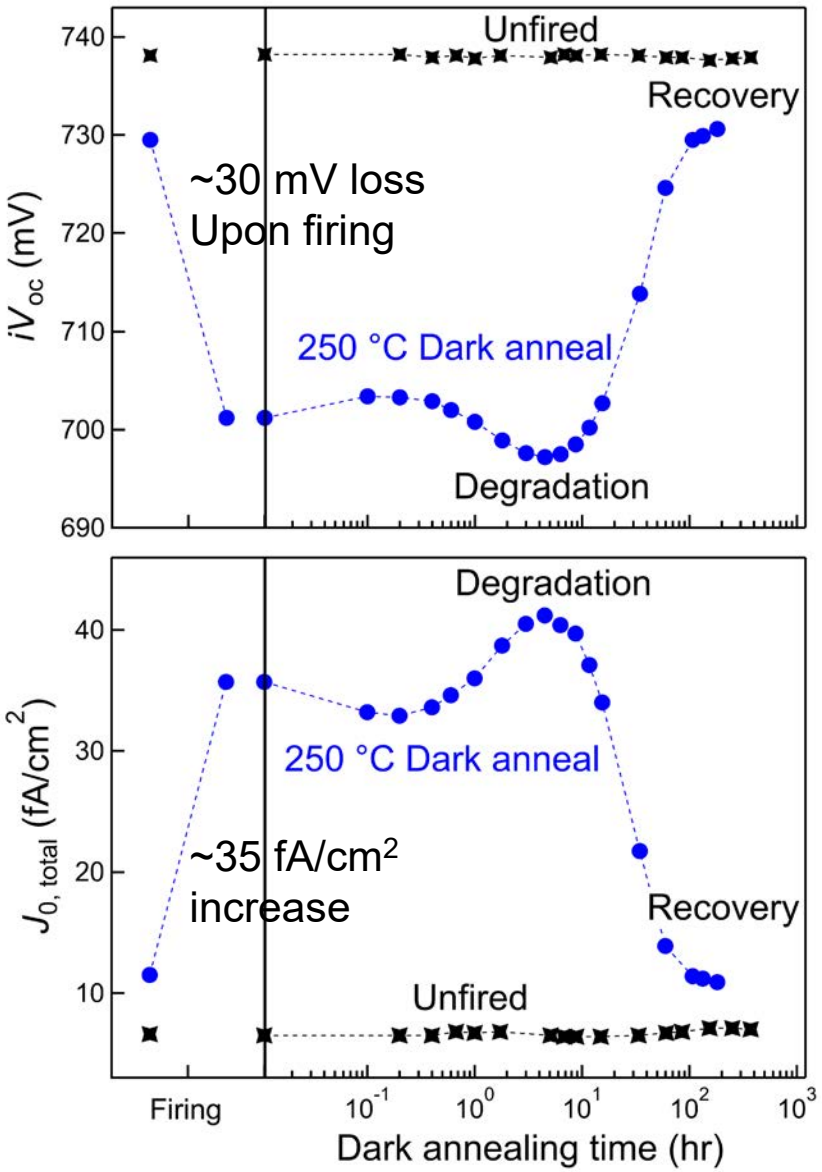

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Winter, M. *et al.*, IEEE J-PV **10**,423 (2020)
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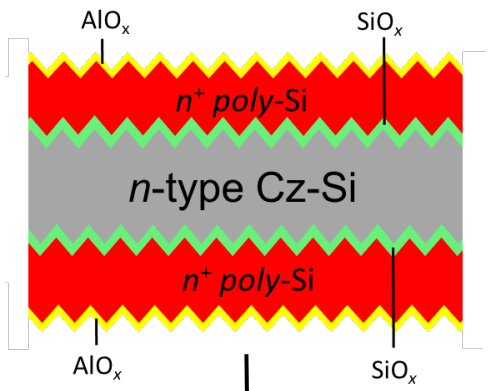
Effect of annealing temperature on stability of TOPCon contact



Firing at 670 °C peak

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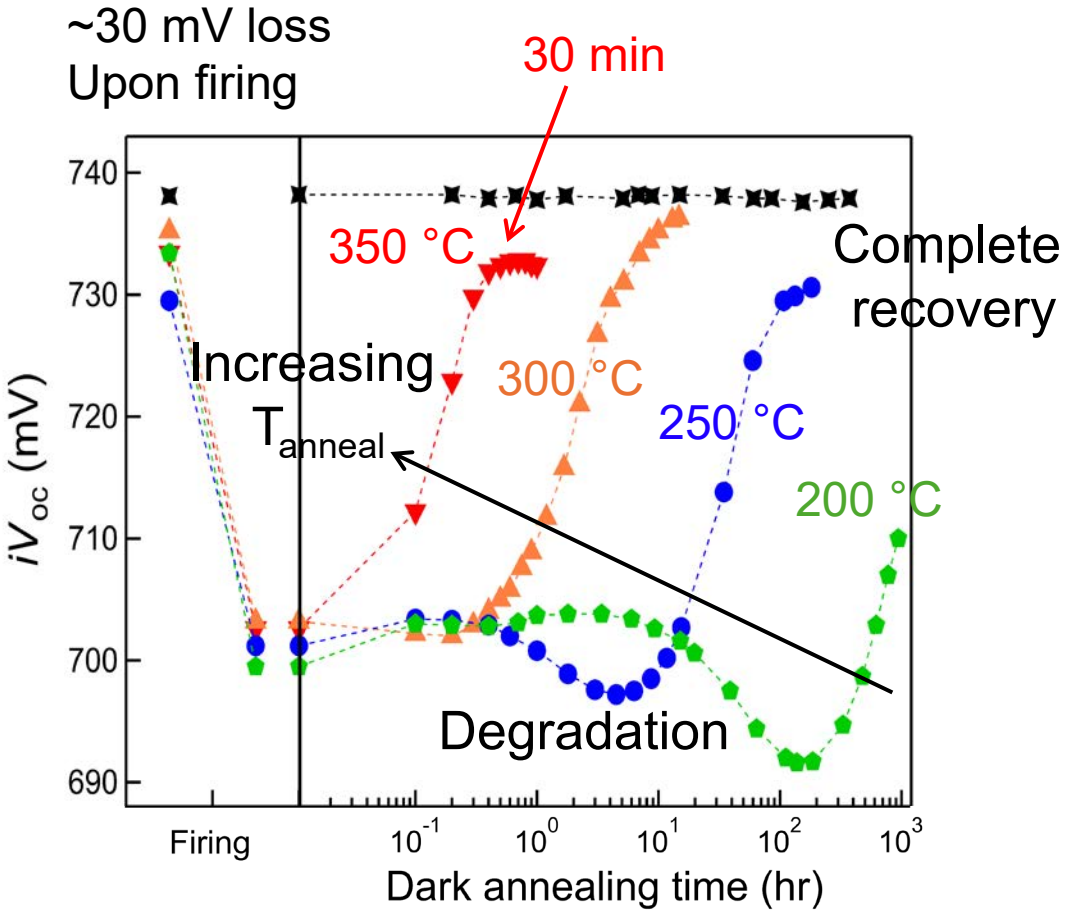
Dark annealing 200-350 °C

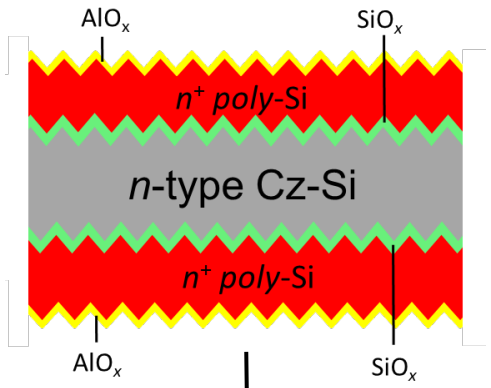
↓

Carrier lifetime measurements



- For T_{anneal} < 300 °C → degradation and recovery
- Degradation and recovery processes are thermally activated
- For T_{anneal} > 300 °C → direct recovery
- Long recovery time > 1000 hr at 200 °C
- Module reliability tests cannot capture surface degradation

Accelerated recovery of TOPCon contacts under intense illumination

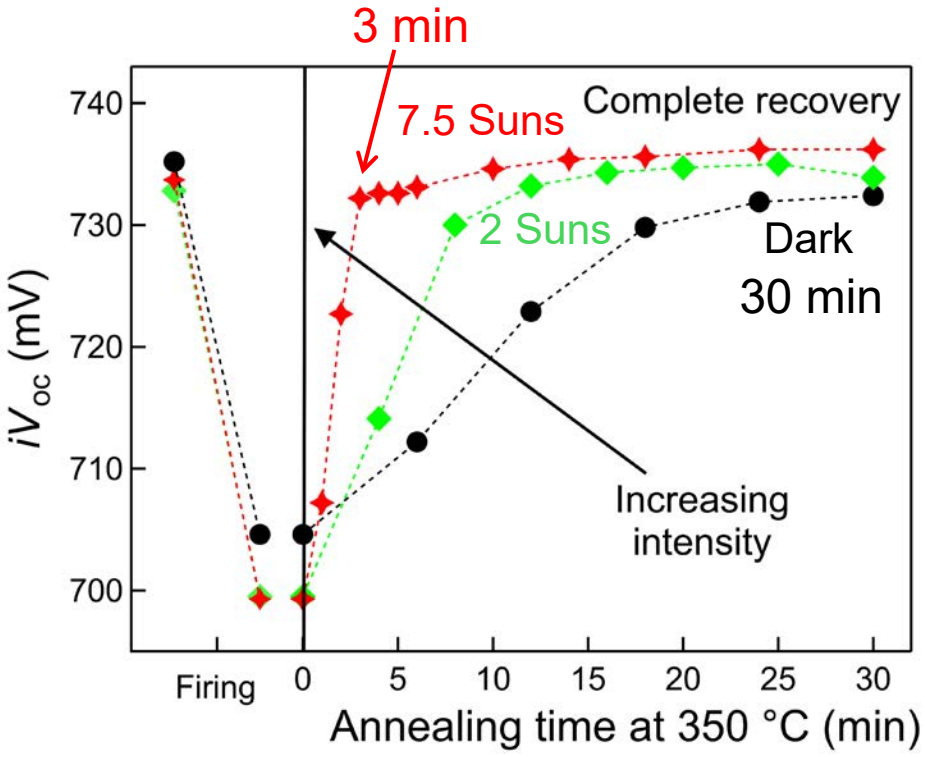


Firing at 670 °C peak

Illumination annealing
0-7.5 Suns and 250-350 °C
(AM 1.5 G spectrum)

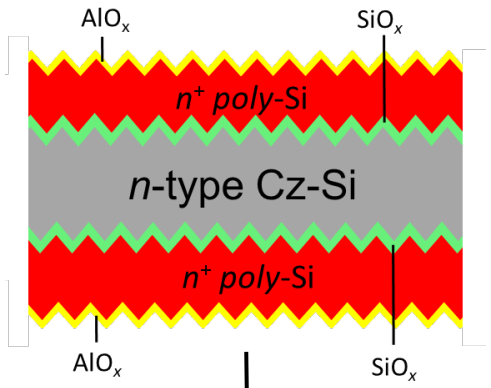
PCD
measurements

350 °C, vary illumination



- Illumination significantly accelerates degradation and recovery processes
- Annealing at elevated temperature and intense illumination for quick recovery

Accelerated recovery of TOPCon contacts under intense illumination



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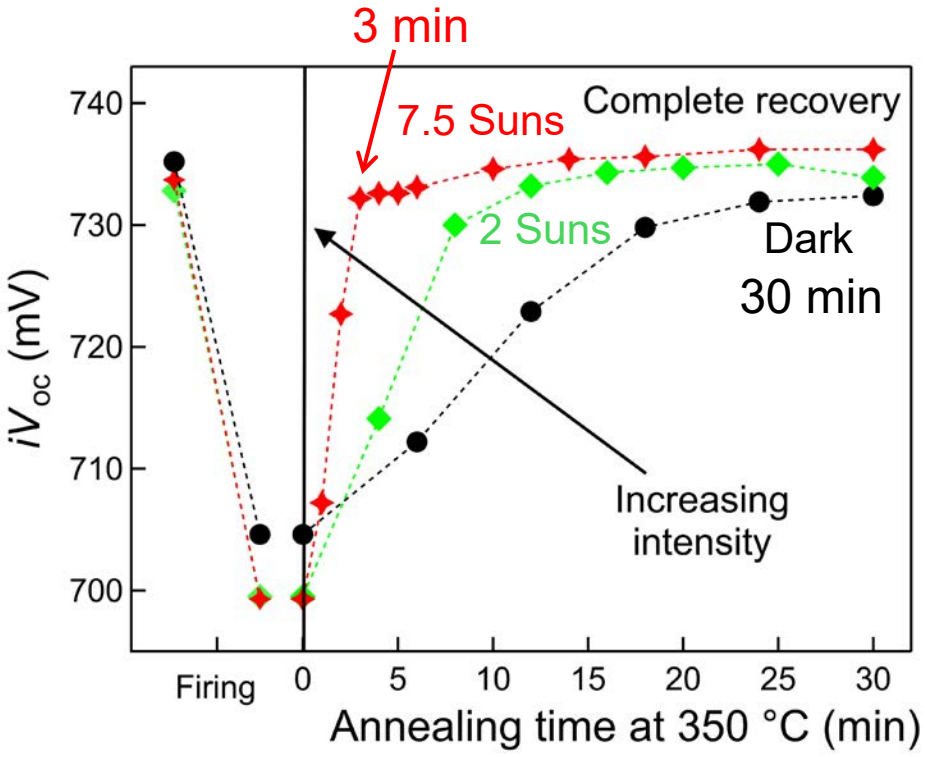
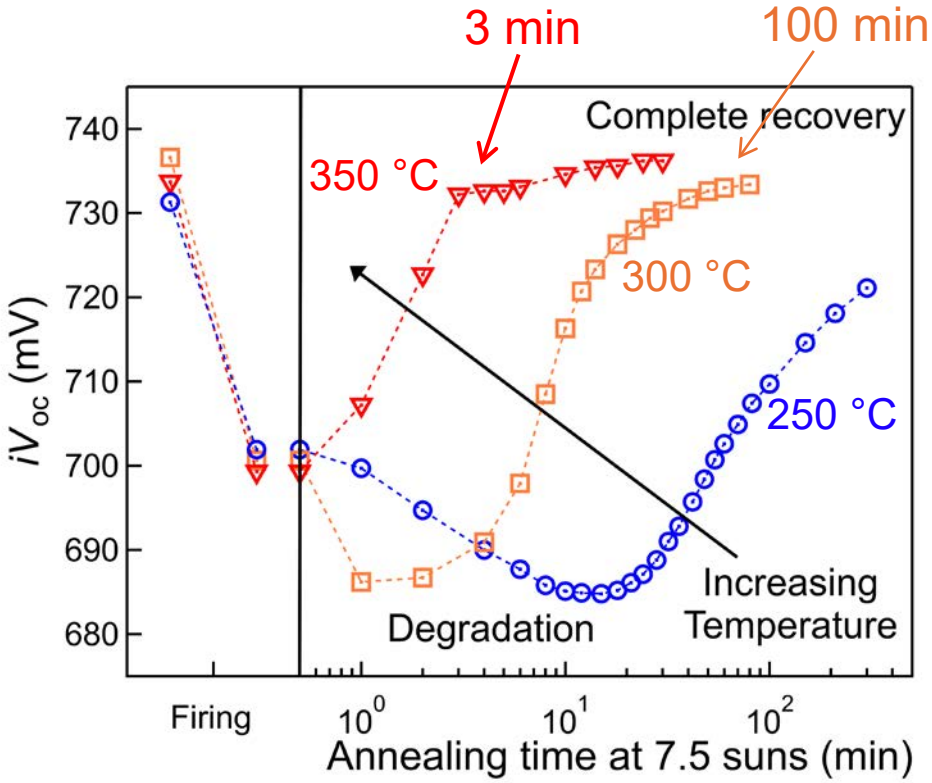
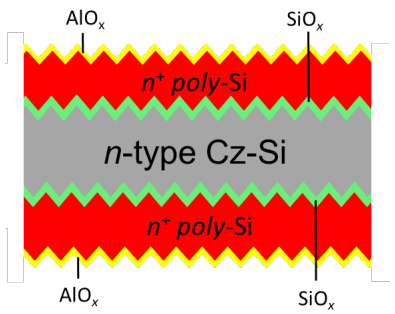


7.5 Suns, vary temperature



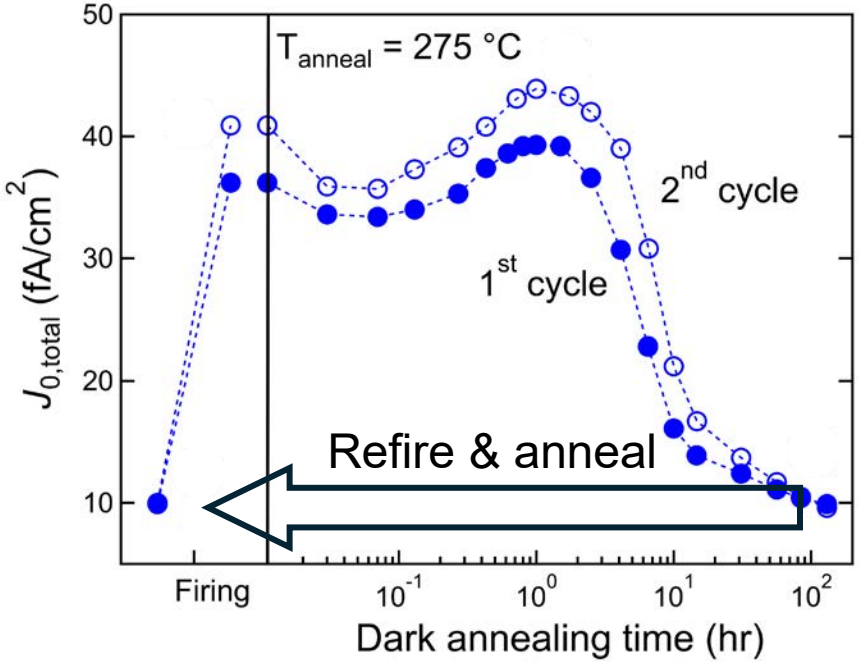
- Illumination significantly accelerates degradation and recovery processes
- Annealing at elevated temperature and intense illumination for quick recovery

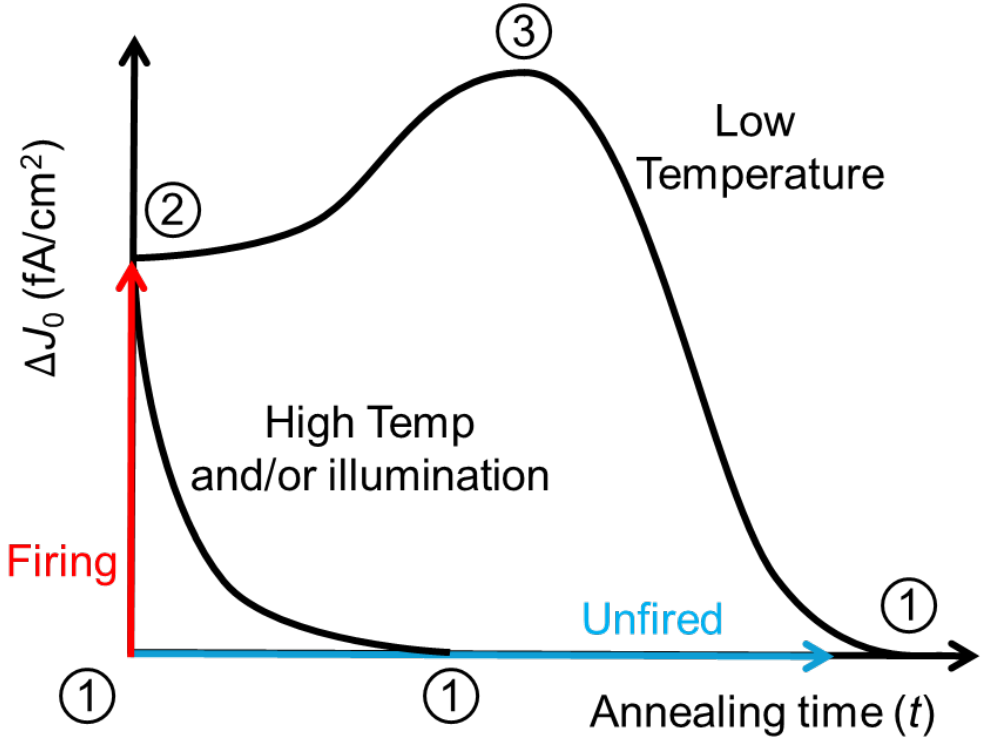
Cyclability of degradation and recovery processes



Symmetric TOPCon contact

Repeated firing and annealing





- Identical J_0 evolution for 2 consecutive cycles
- Cyclic nature of degradation and recovery

States:
1. Unfired or completely recovered
2. Fired
3. Completely degraded

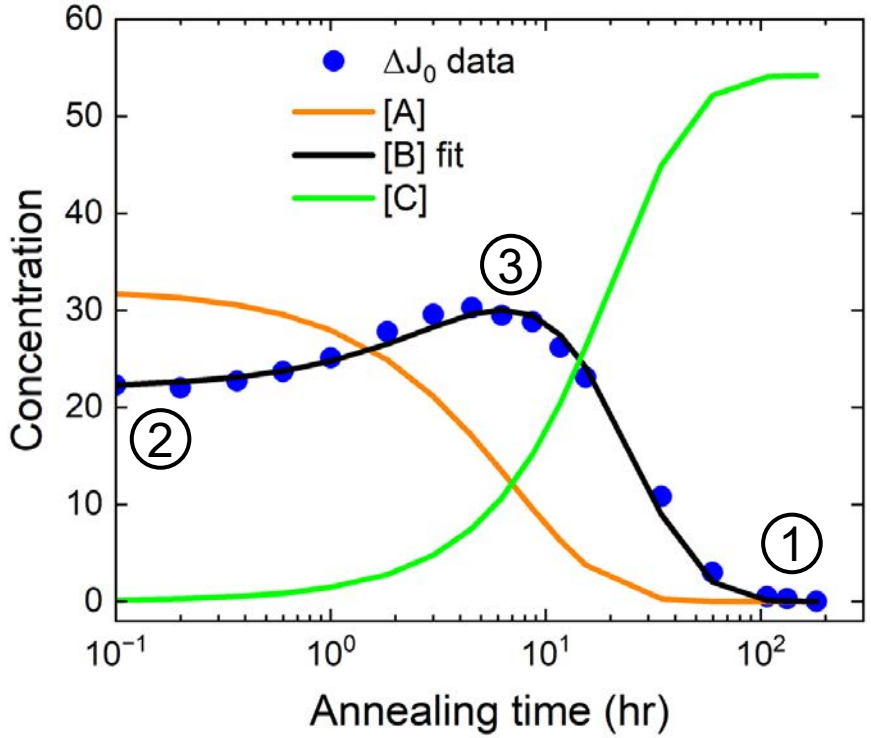
Activation energy for degradation and recovery processes

$$A \xrightarrow{k_{deg}} B \xrightarrow{k_{rec}} C$$

Defect precursor — Defect — Stable state

$$\Delta J_0 \propto [B]$$

	n^+ *poly*-Si/SiO_x contact	
Activation energy (eV)	Dark	Illuminated 7.5 Suns
Degradation	1.24	0.76
Recovery	1.51	1.15



The model allows to estimate the time required for degradation and recovery

For a fielded module installed in		
City (Average temperature)	Years to degrade	Years to recover
Kansas (~ 60 °C)	>10	>60
Phoenix (~ 75 °C)	>4	>20

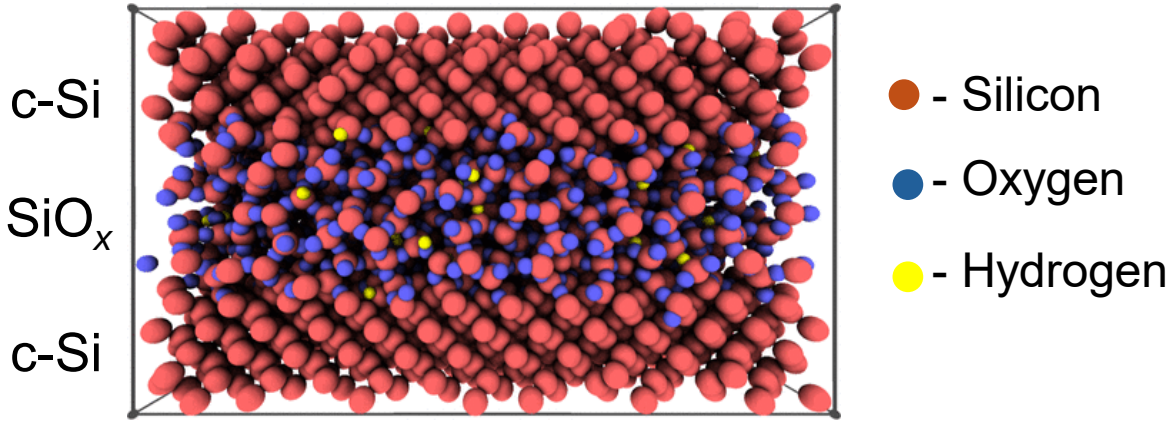
Hypothesis for defect formation and passivation

$$A \xrightarrow{k_{deg}} B \xrightarrow{k_{rec}} C$$

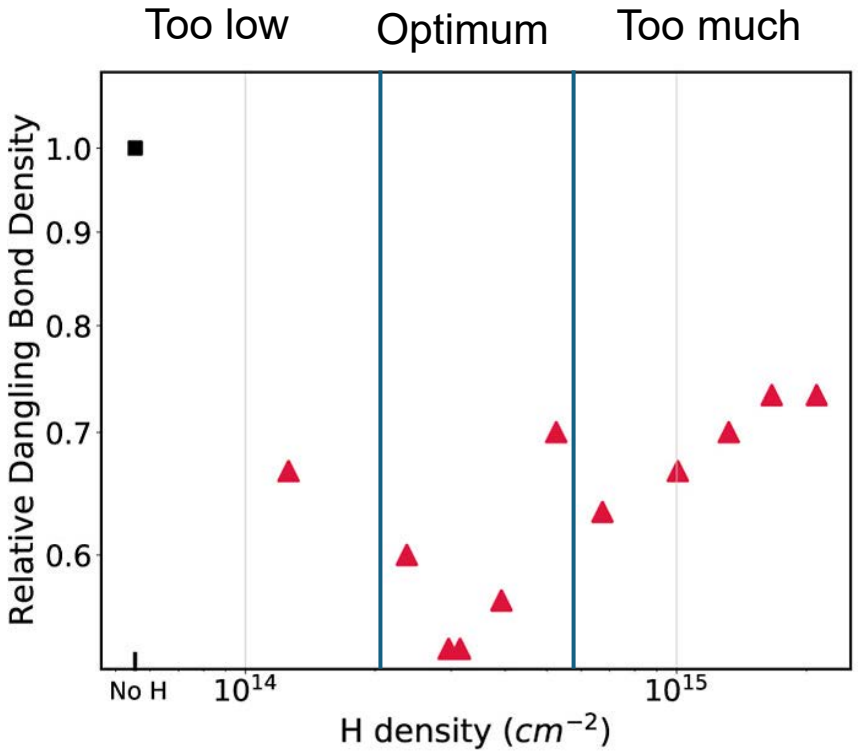
Defect precursor — Defect — Stable state

$$\Delta J_0 \propto [B]$$

- Firing increases the [H] near SiO_x/*c*-Si interface
- Optimum [H] → minimum J_0
- Defect state B may correspond to dangling bonds
- Linked to hydrogen movement near interface



Simulated c-Si/SiO_x stack containing ~5800 atoms at the hydrogen concentration of [H] = 3.0 × 10^{14} cm^{-2}.

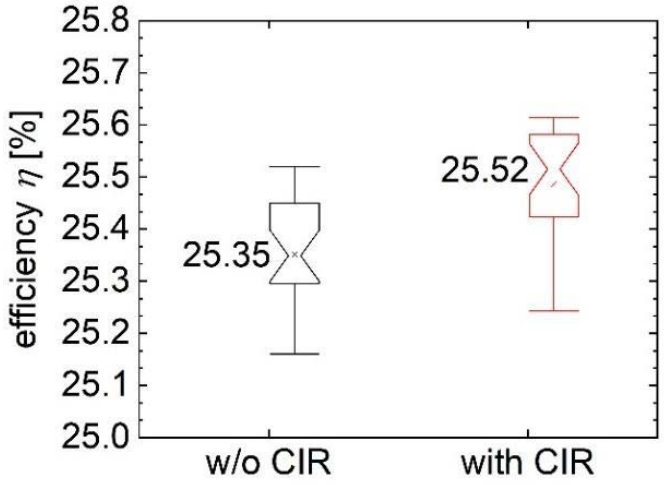


Diggs et al., ACS Appl. Mater 2024, 7, 8, 3414.

Liu et al. Sol. Ener. Mats & Solar Cells 2025, 282, 113340
Kang et al., ACS Appl. Mater. Interfaces 2021, 13, 46, 55164.

Industrially relevant surface passivation recovery (SPR) process

Trina solar: Carrier induced regeneration (CIR) tool using light and heat



Daming Chen, Silicon workshop, July 2024, Breckenridge.

Jinko/UNSW Hydrogenation tool

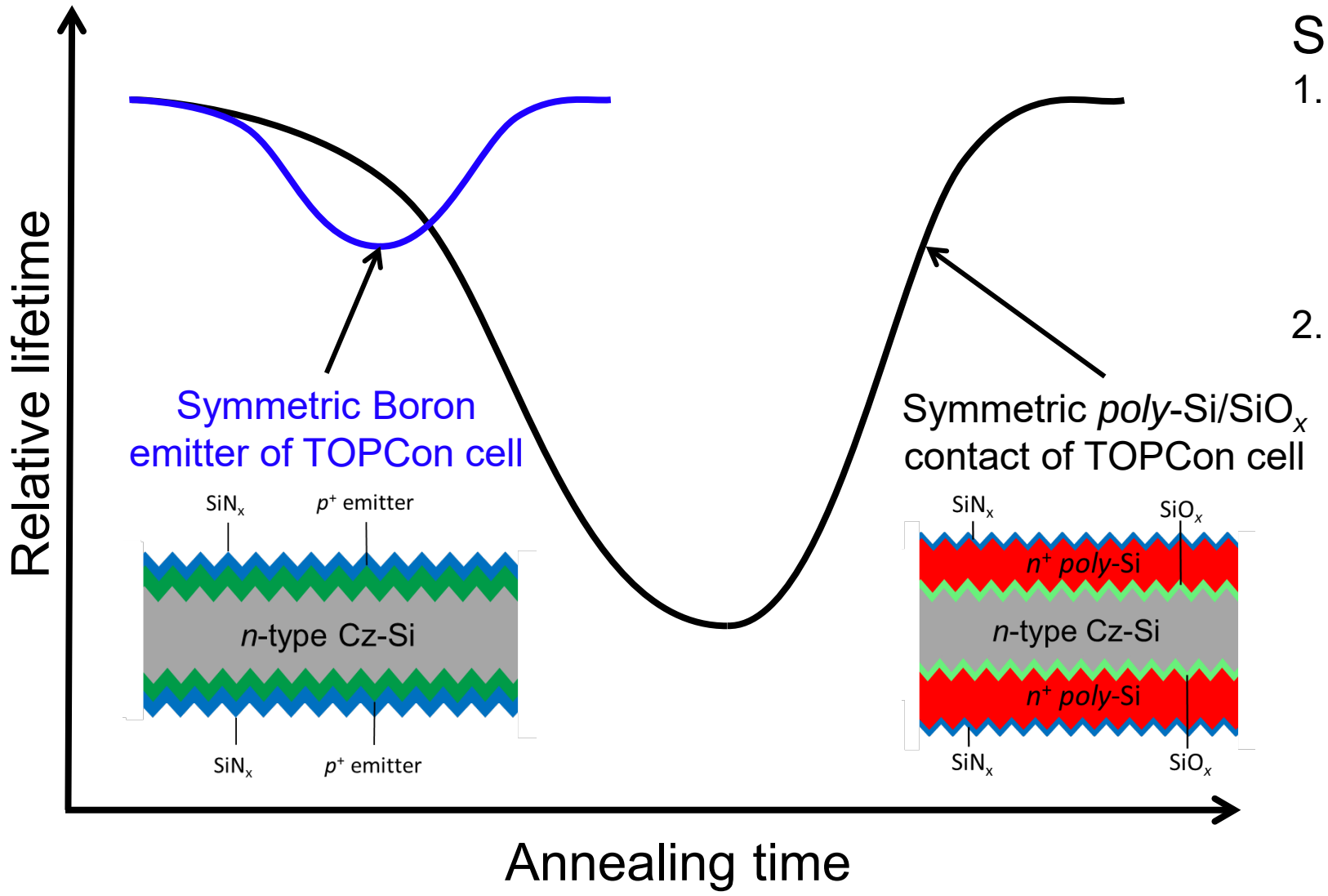
Illumination of cells using LED source at temperatures over the range of 400-600 °C.

	V_{OC} (mV)	J_{SC} (mA/cm^2)	FF (%)	Efficiency (%)
Before	696.3	41.15	82.03	23.51
After	703.2	41.35	83.07	24.15
Difference	6.9	0.20	1.04	0.64

Chen et al., Prog. Photo Volt. 2021;29:1213.

Ask the manufacturer whether they have implemented the surface passivation recovery process. If they haven't cells will degrade.

Comparing front and rear surface degradation in TOPCon cells



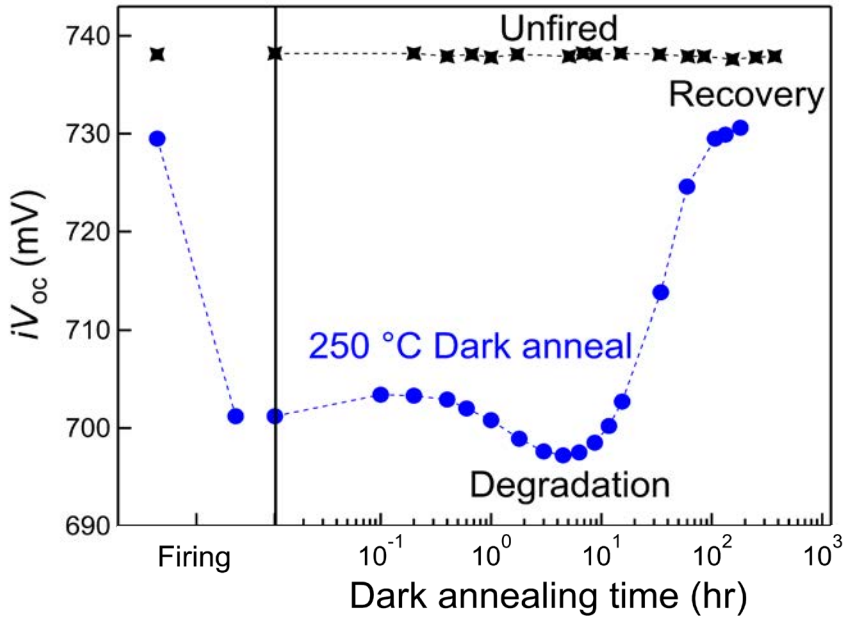
Surface passivation degradation:

1. Front Boron emitter:
   a) Less magnitude of degradation
   b) Fast
2. Rear *poly*-Si/SiO_x contact:
   a) Higher magnitude of degradation
   b) Slow
   c) Cannot be captured by module reliability tests
   d) Important to treat cells before deployment

Chen et al., Sol. Ener. Mats & Solar Cells, 207 (2020) 110353.

Summary

- TOPCon solar cells are the industrial mainstream and expected to dominate in future.
- Unresolved reliability issues remain like moisture penetration, PID and UVID
- We presented, surface passivation degradation (SPD) of TOPCon contacts
- None of the standard reliability test can capture surface degradation
- Surface passivation degradation:
  - Significant loss after firing
  - Degradation and recovery upon annealing
  - Cyclic processes
  - Accelerated by adding illumination
- Industrial Surface Passivation Recovery (SPR) process:
  - Annealing at elevated temperatures and intense illumination



- **Ask the manufacturer whether the cells are treated with Surface Passivation Recovery (SPR).**

Acknowledgements

NREL Silicon Photovoltaic Team

- Dr. David L. Young (Co-PI)
- Dr. Paul Stradins
- William Nemeth
- San Theingi
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- Markus Kaupa
- Dr. Harvey Guthrey
- Dr. Steven Harvey
- Dr. Thien Truong

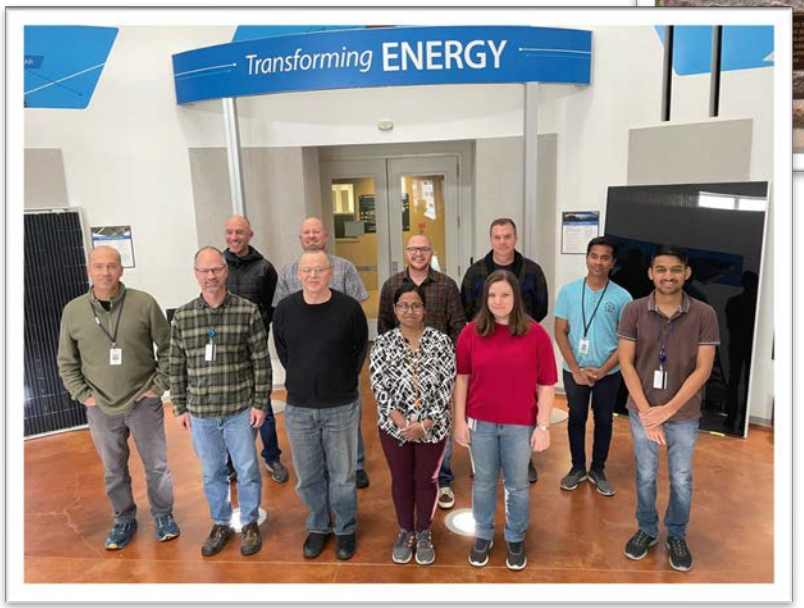
Prof. Sumit Agarwal's Research Group:

- Dirk Steyn
- Chirag Mule
- Xue Wang
- Andrew Kaye
- Wallis Scholl
- Tanzid Hossain

Alumni:

- Dr. Caroline Anderson
- Dr. Kejun Chen

Colorado School of Mines



NREL

Thank you for your attention!
Questions?

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Aditya.Ratnapagol@nrel.gov

U.S. Department of Energy

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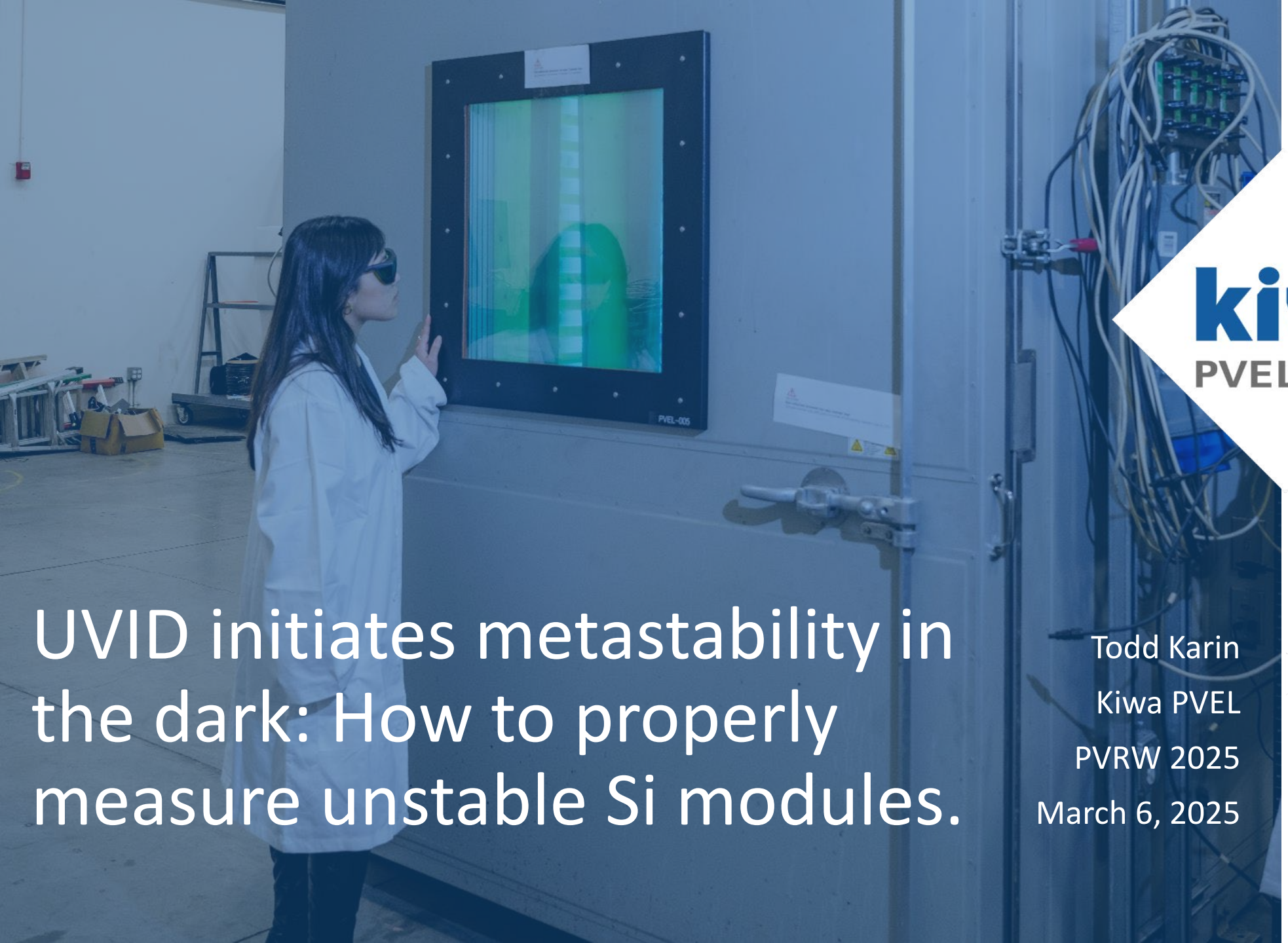


UVID initiates metastability in the dark: How to properly measure unstable Si modules.

Todd Karin

Kiwa PVEL

PVRW 2025

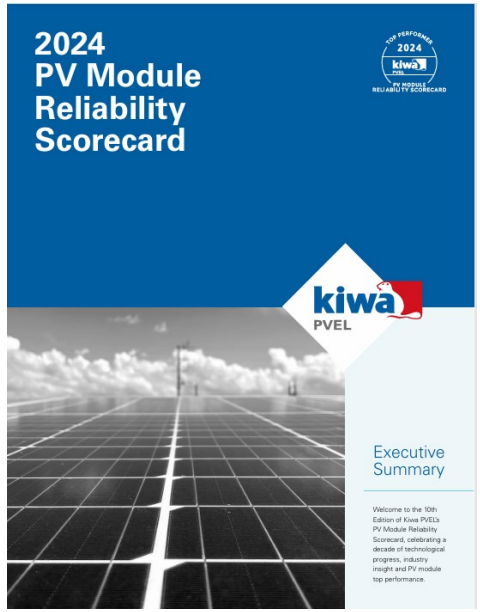
March 6, 2025

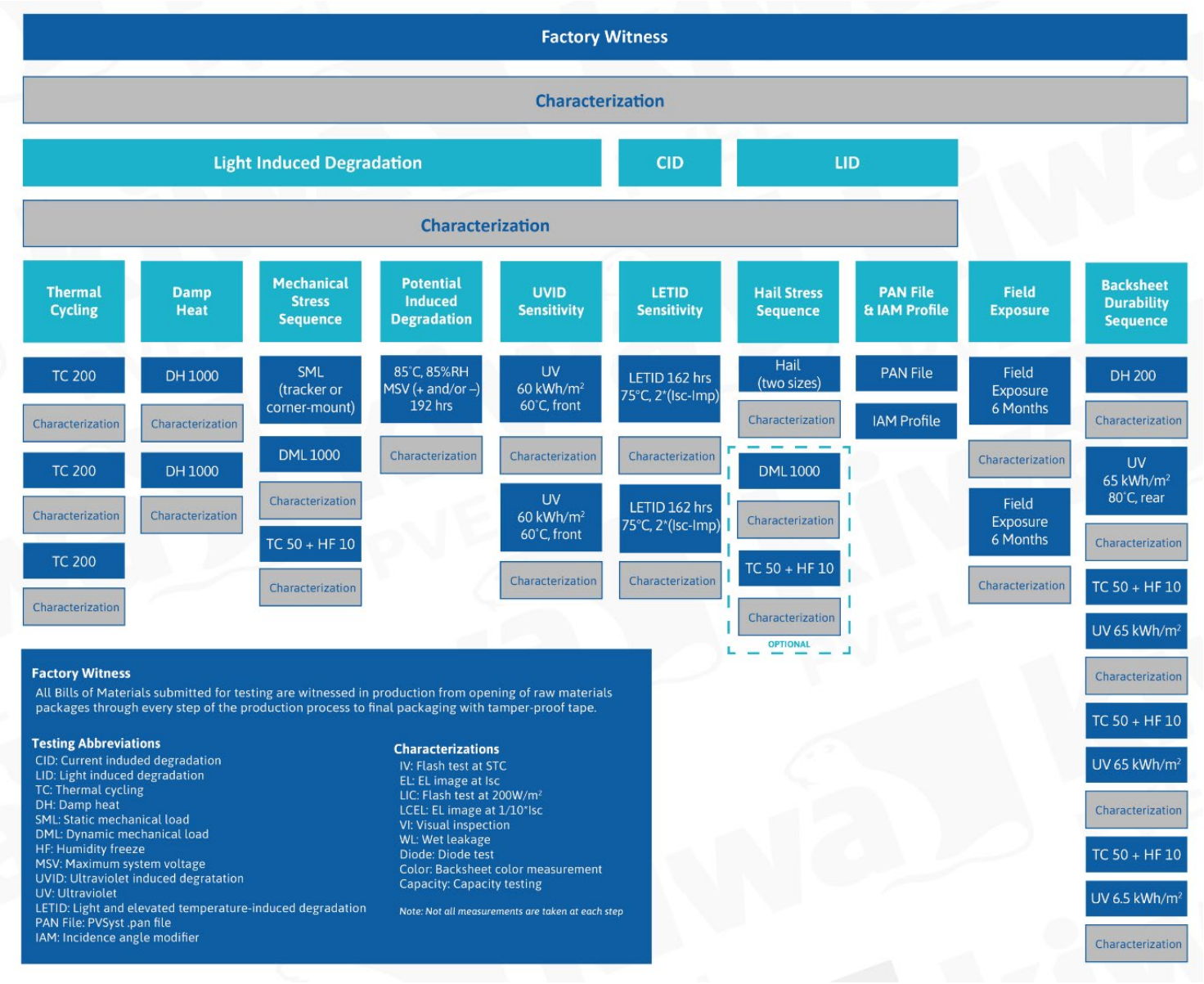
kiwa PVEL

We Create Trust

Kiwa PVEL

- Independent lab for PV Module **Performance and Reliability Testing**
- Product Qualification Program (PQP)
- Regularly updated
- Often ahead of the IEC standards group
  - Added UVID before standard is finished.
  - Implementing UVID stabilization procedure





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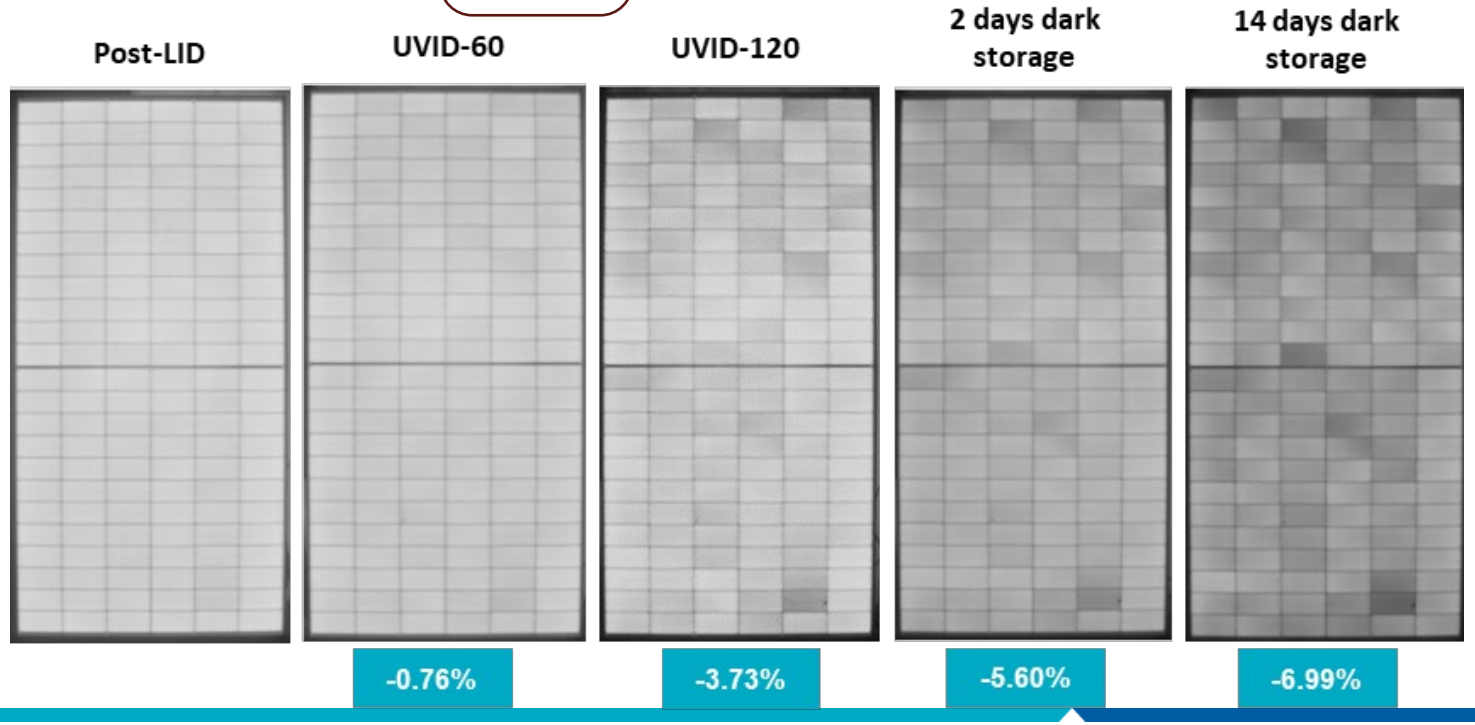
UVID Induces Metastability

- We are all used to treating silicon modules as stable in storage…
  - **Not anymore!**

This talk: what's going on and how to properly measure unstable modules

Industrial Topcon module.

Step#	Pmp%	Voc%	Vmp%	Isc%	Imp%	FF%
Post-LID						
UVID-60	-0.76	-0.84	-1.02	0.60	0.31	-0.52
UVID-120	-3.73	-2.31	-3.24	-0.17	-0.45	-1.29
After 2 days dark storage	-5.60	-3.39	-4.98	-0.47	-0.60	-1.83
After 14 days dark storage	-6.99	-4.18	-5.66	-1.28	-1.42	-1.68



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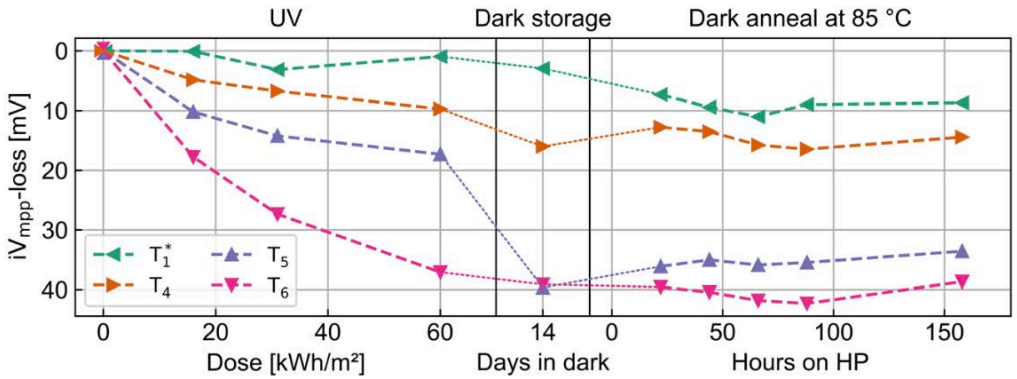
Prior work

Prior work has recognized the dark storage issue.

Cells:
0.5%-3.0% degradation in dark



[1]

Hydrogen diffuses away from the passivation layer in the dark

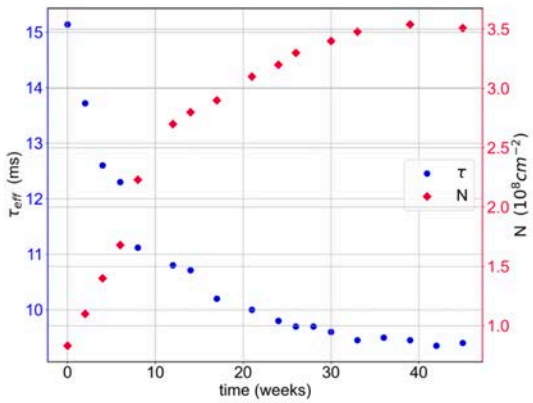
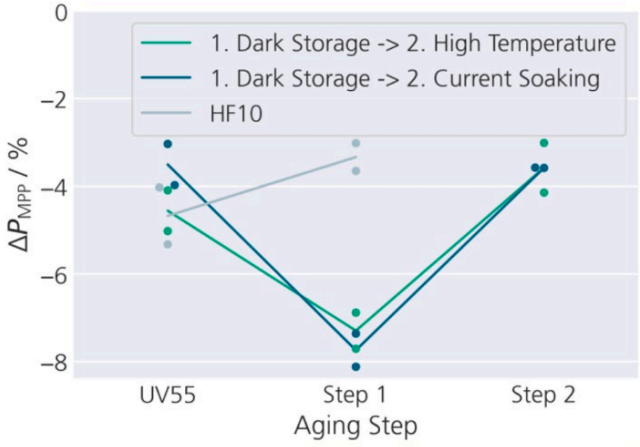


Fig. 1 Degradation of the surface passivation of silicon heterojunction solar cells. The quality of the surface passivation of four silicon heterojunction cells with varying thickness was tracked over the course of a year by monitoring the effective minority carrier lifetime τ_{eff} (blue circles). From analyzing these measurements at different temperatures and different injection levels, we determined the time-dependent defect density at the c-Si/a-Si:H interface N(*t*) (red diamonds).

[2]

Dark storage reversed by high T or current injection.



[3]

[1] Thome et. al. Solar RRL 2024, 8, 2400628
[2] Diggs, A., Zhao, Z., Meidanshahi, R.V. *et al.* Hydrogen-induced degradation dynamics in silicon heterojunction solar cells via machine learning. *Commun Mater* **4**, 24 (2023).
[3] Gebhardt, P., Kräling, U., Fokuhl, E., Hädrich, I. and Philipp, D. (2024), Reliability of Commercial TOPCon PV Modules—An Extensive Comparative Study. Prog Photovolt Res Appl.

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Meta-stability during dark storage after UVID-120

- What happens during repeated flashing of a TOPCon module?
  - Recovers just from the light of the flash tester.

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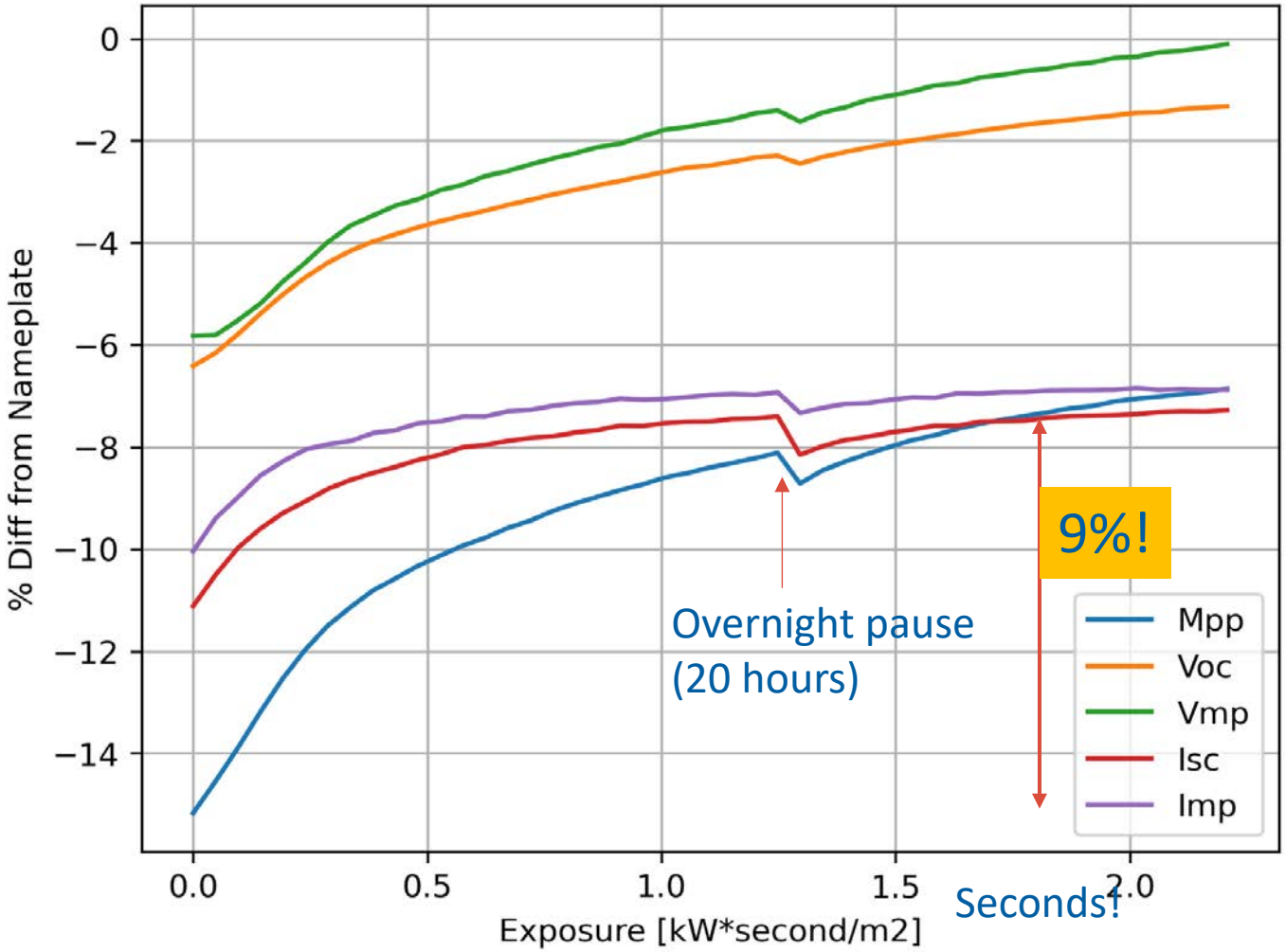
Meta-stability during dark storage after UVID-120

- What happens during repeated flashing of a TOPCon module?
  - Recovers just from the light of the flash tester.

- Module is TOPCon, Post UVID-120 i.e. “1 year equivalent” and left in dark storage for 3 months.
- **Module Pmp recovered by 7% after around 1 second of accumulated exposure.**
- After leaving in dark for 20 hours, MPP dipped again by 0.6%!
- Dark storage degradation is large enough to be relevant and adds a very large uncertainty.



Dark storage degradation for TOPCon happens on the timescale of days and is reversed within **seconds** of full-spectrum 1 sun light.

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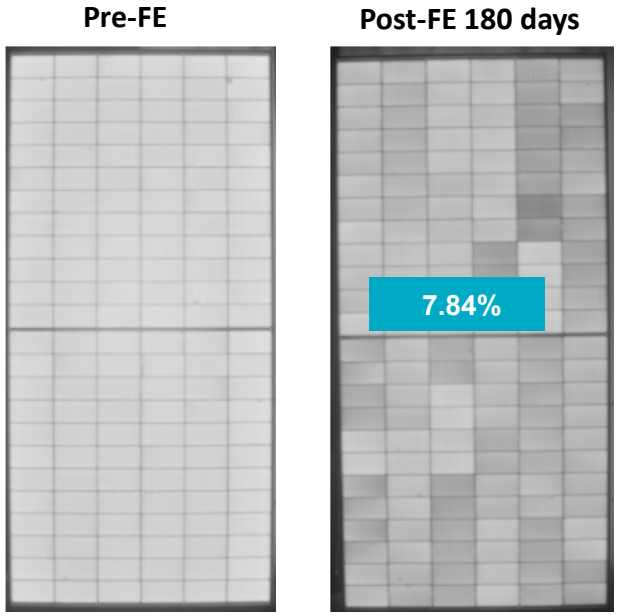
Does the metastability exist for fielded modules?

- **Metastability not just created in a UVID test chamber, it's also created in outdoor-aged modules.**
- Fielded modules have all the signatures of UVID:
  - Checkerboard EL
  - Mostly Voc loss
  - UVID metastability.
- Two TOPCon modules deployed in Davis, CA for 6 months
  - Modules showed an average of -6.3% power loss.
  - Power loss increased up to -7.8% after 11 days of storage in dark.
  - Module recovered power loss after 2 hours of light soaking.

Fielded modules also show the metastability.



	Pmp(%)	Voc(%)	Isc(%)	FF(%)
Pre-FE				
Post FE 180 days (+7 days dark storage)	-6.26	-3.46	-1.12	-1.83
After 11 days of dark storage	-7.84	-4.72	-1.12	-2.18
After 2 hrs of LS indoor	-2.08	-1.28	-0.45	-0.37

*All measurements are with respect to pre-FE

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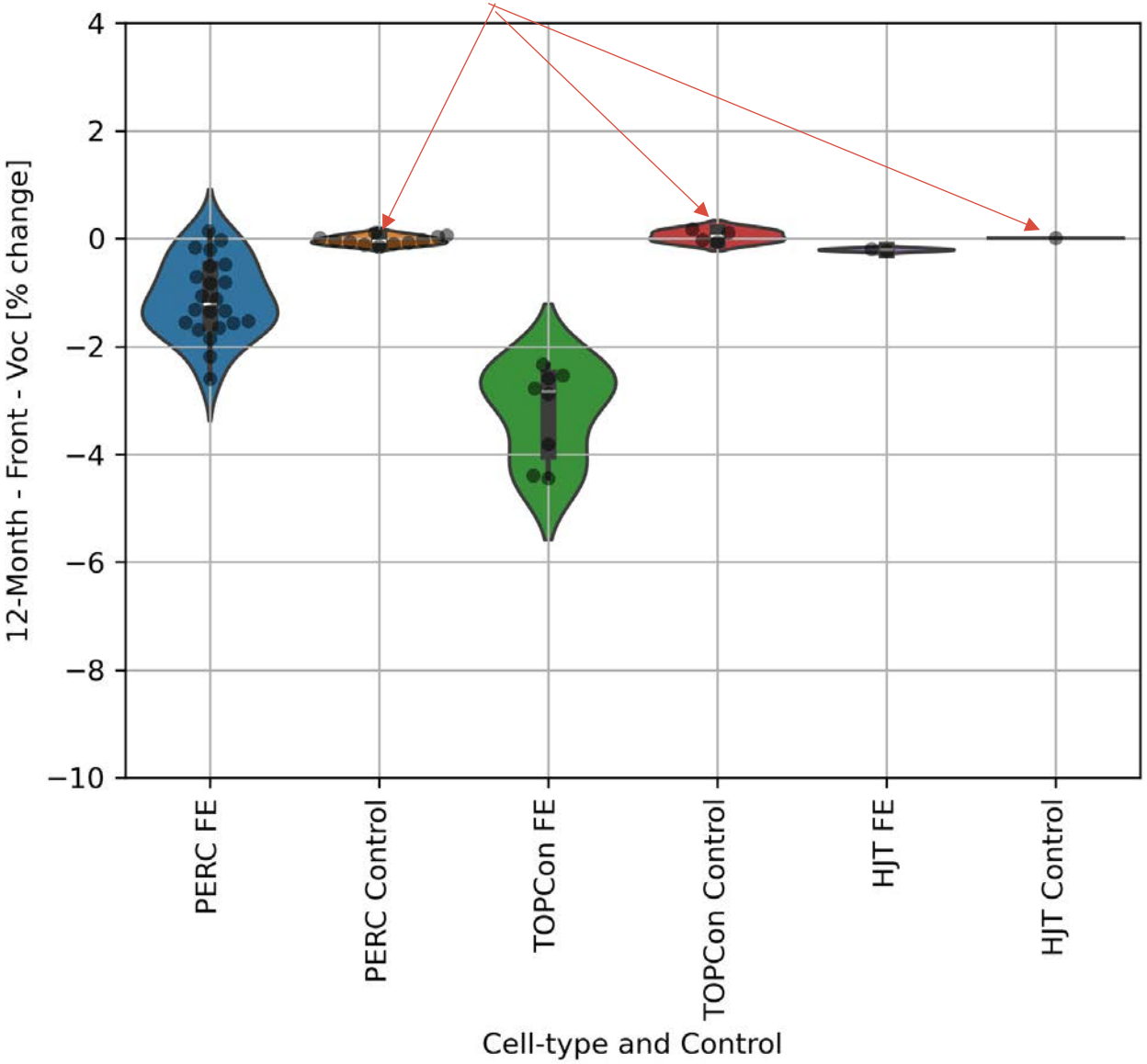
Are unexposed modules stable?

- **Field Exposure (FE)**: Modules fielded for 12 months.
- Control modules (left inside for 1 year) do not degrade in voltage.
- Also, Voltage loss in TOPCon is worse than PERC/HJT (attributed to UVID).

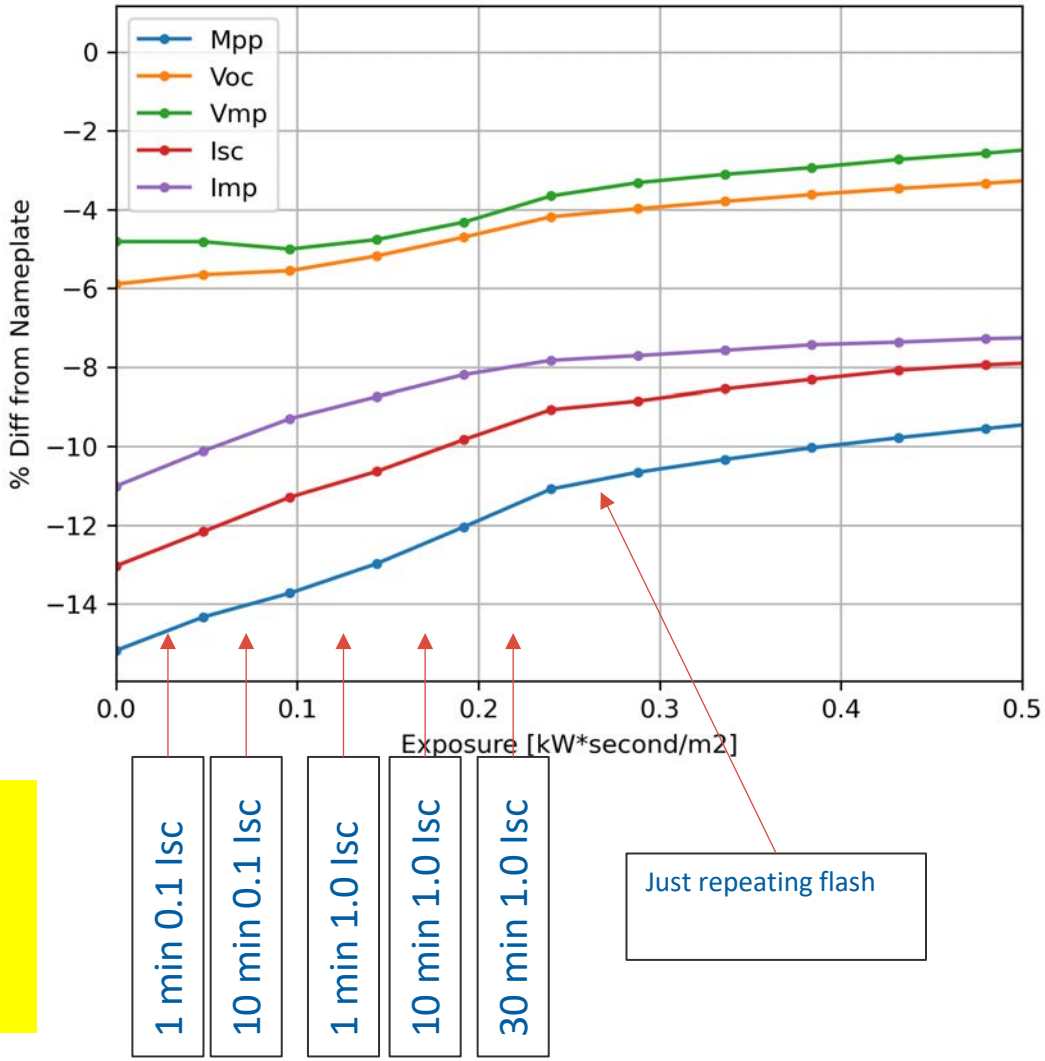
Control modules are stable



Modules have good stability (<1%) before exposure to UV light.

Methods for recovery

- **Current injection is not a good candidate for dark-storage recovery.**
- Even 30 minutes of charge injection at 1.0 Isc is approximately equal to the recovery achieved in just 0.05 seconds of light.



Light is necessary for recovery process: voltage alone does not cause recovery at the same rate.

TOPCon

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Full spectrum light causes recovery, but what wavelengths are most important?

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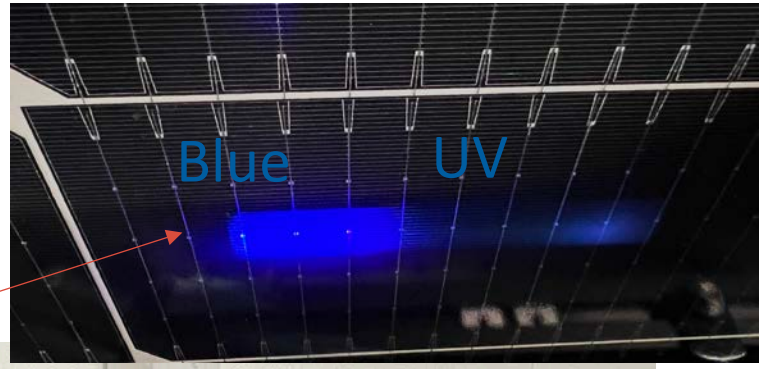
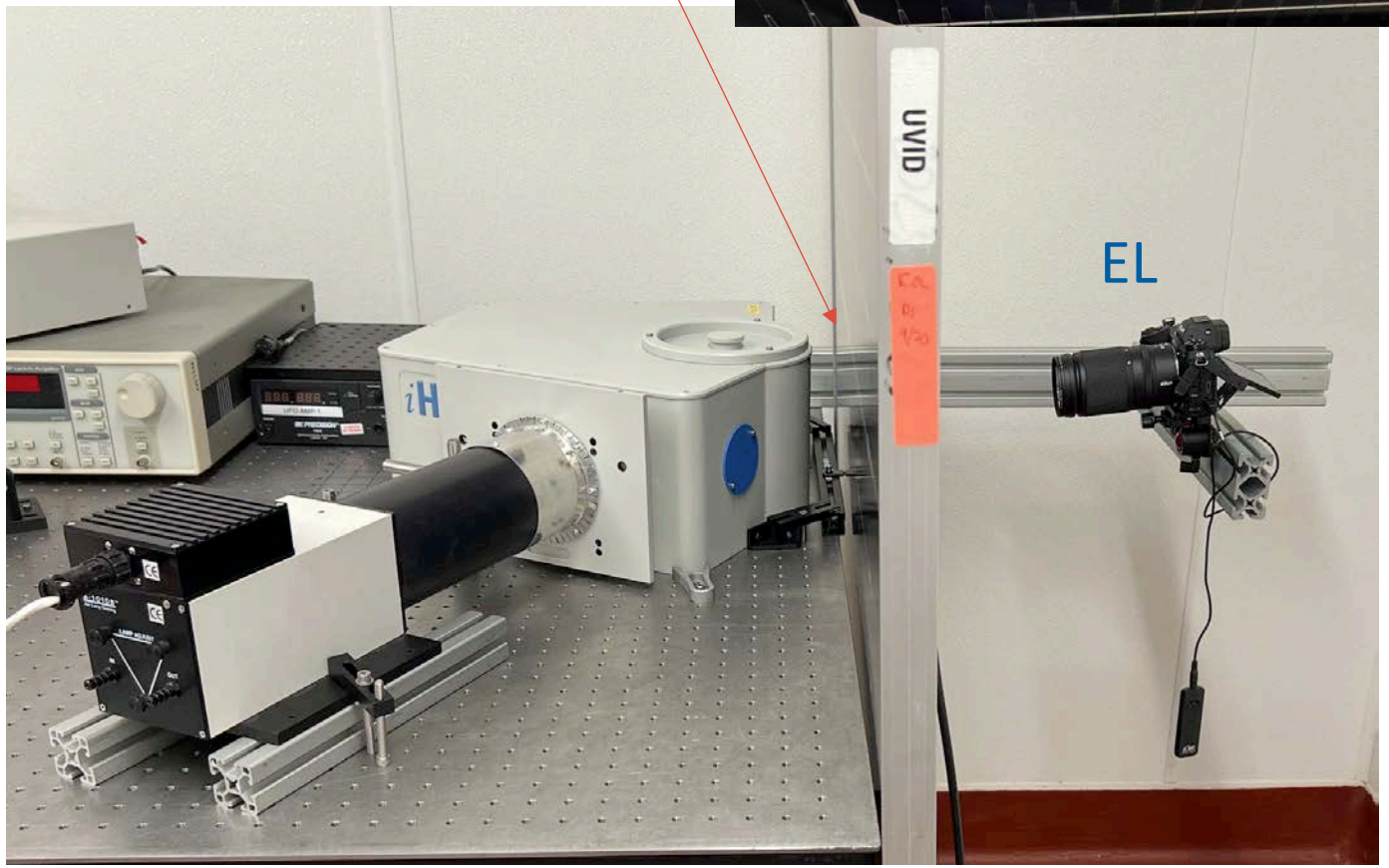
UVID Recovery wavelength dependence



Blu-V (?)
Rain-blue (?)

Front of mod

- Used a xenon arc lamp and a spectrometer to send a UV-Blue rainbow to the module.
- Took EL images from the back.
- Input light is blocked when taking the EL image.



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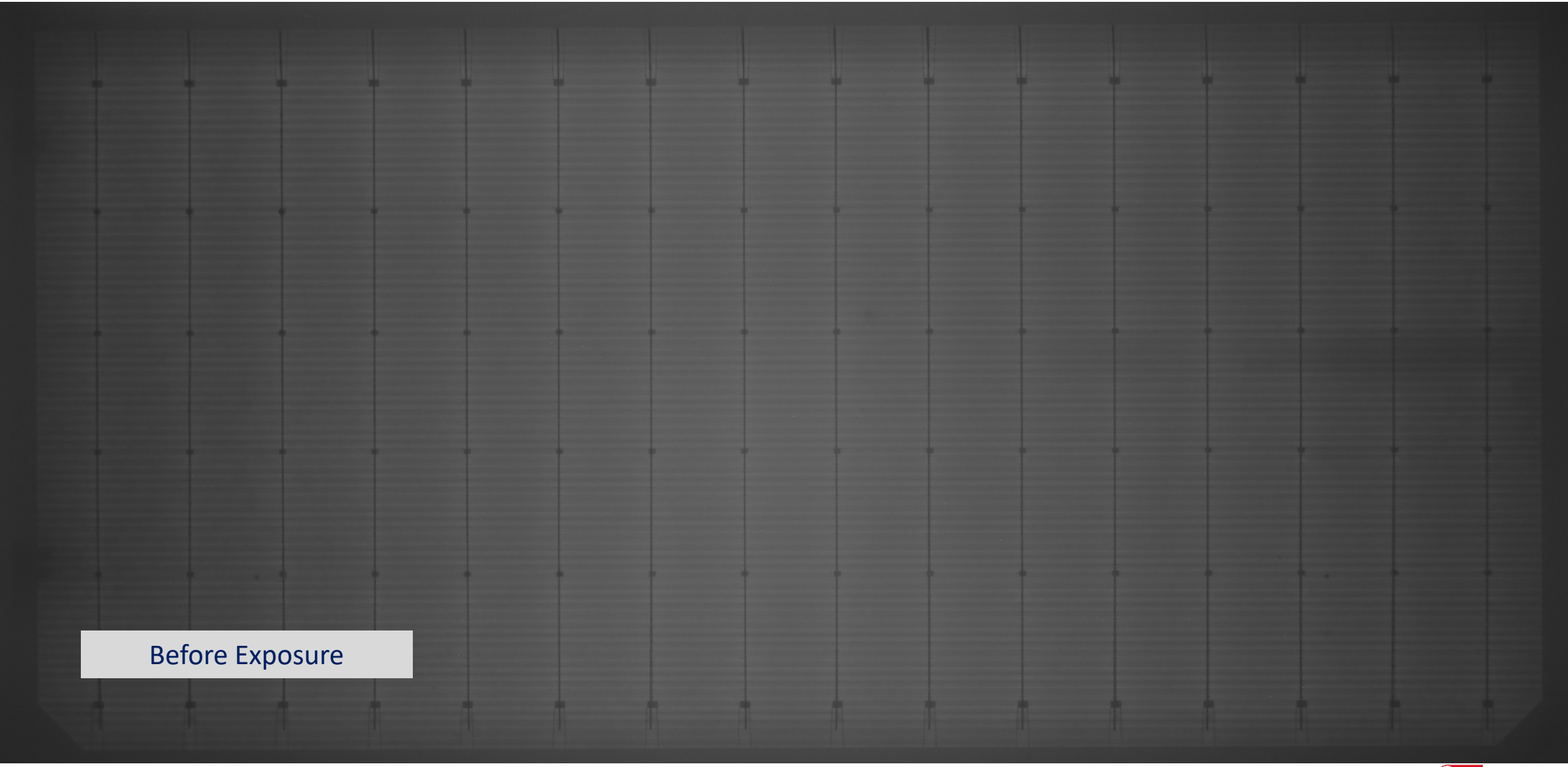

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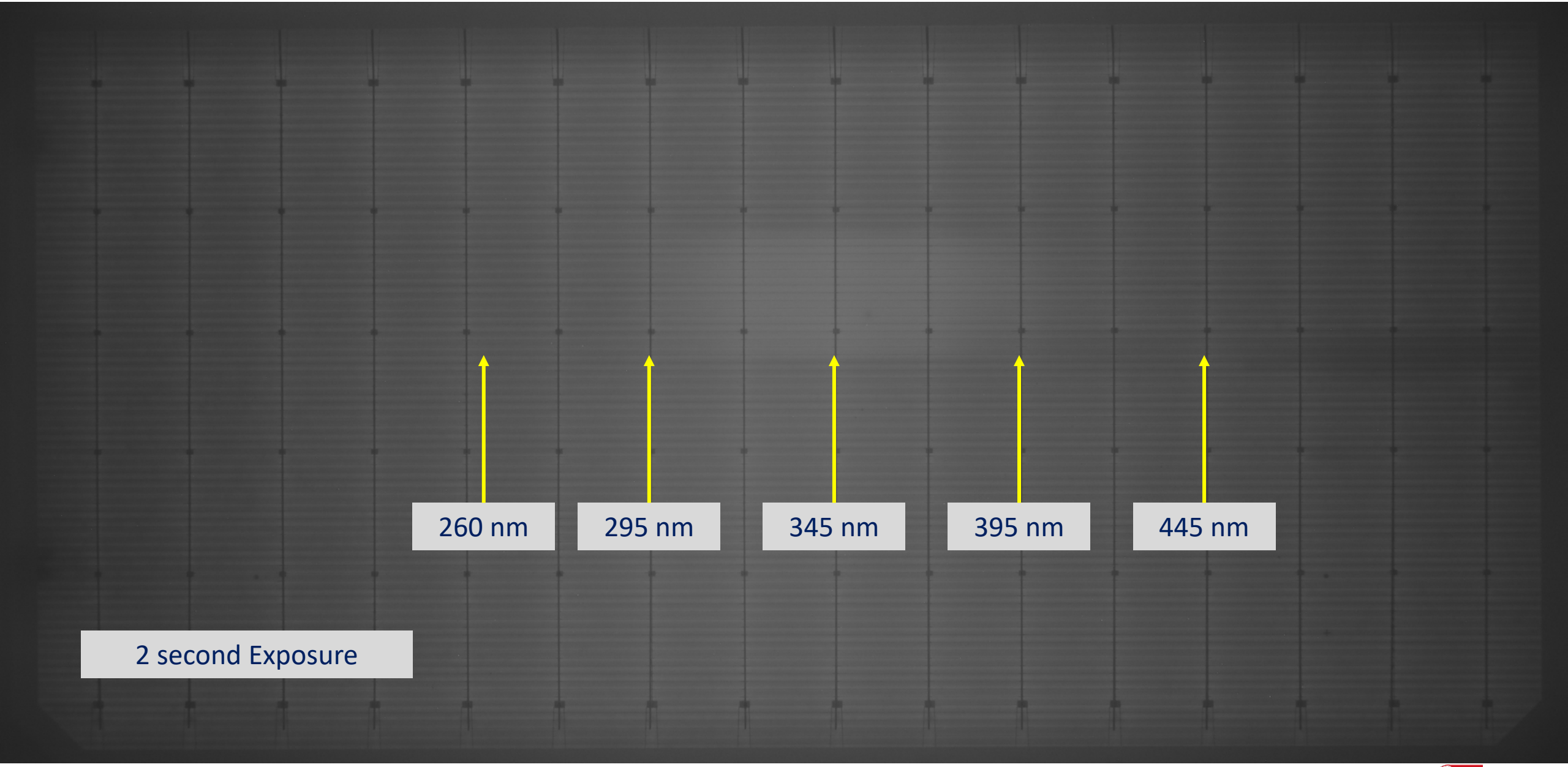

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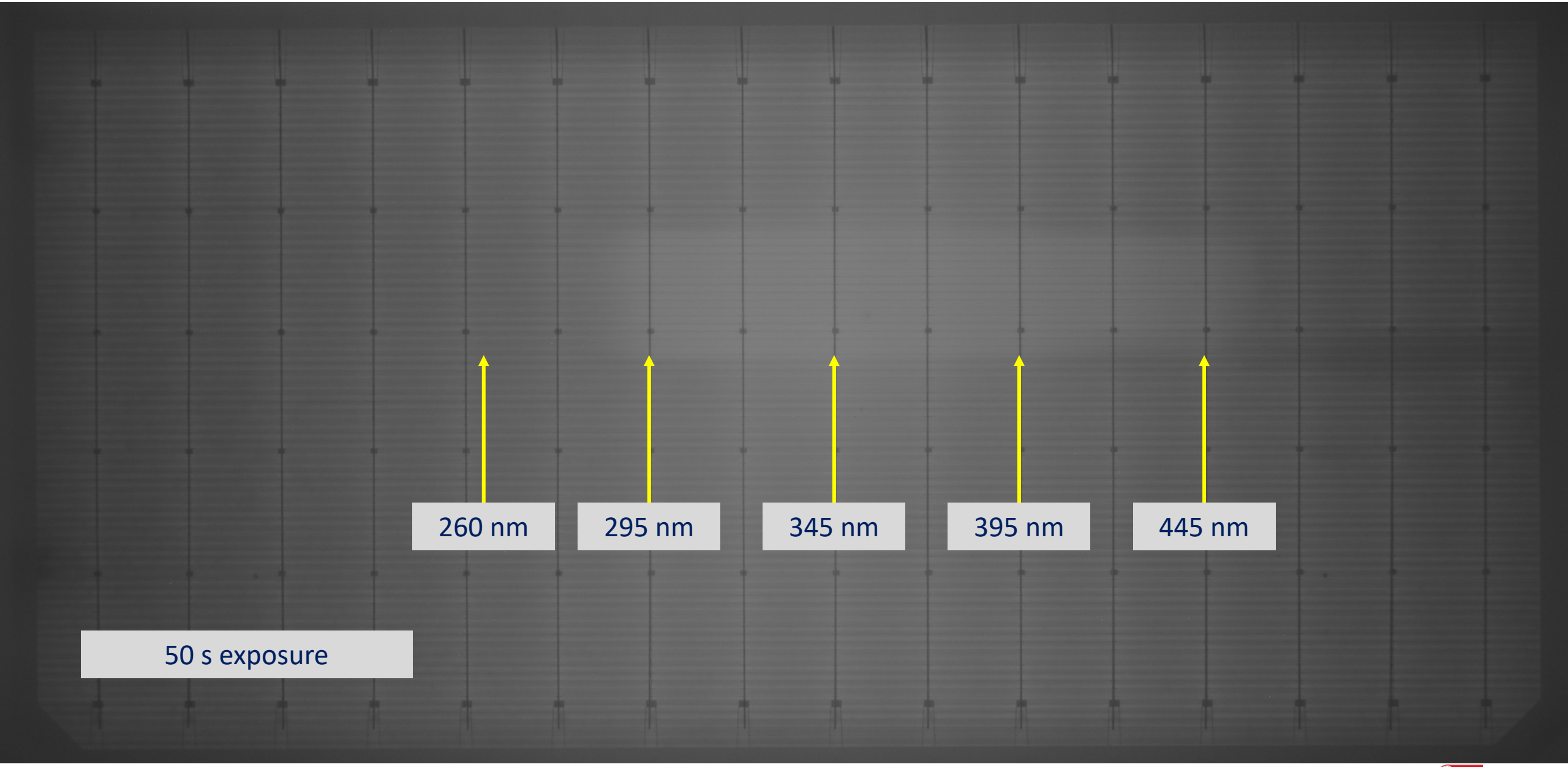

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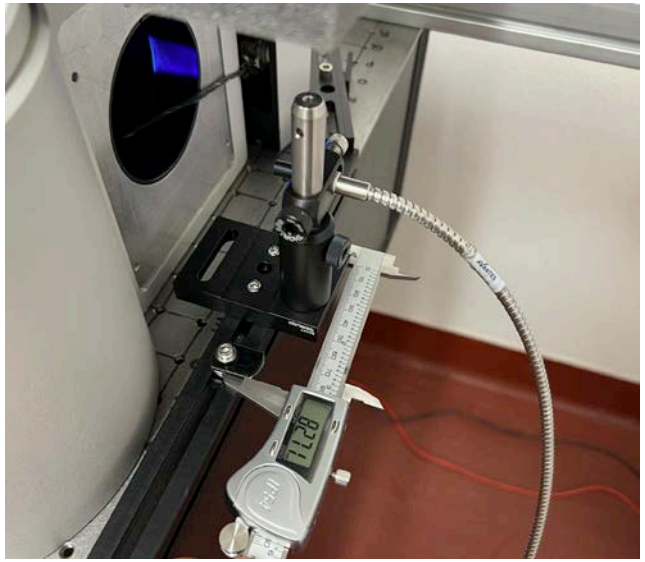
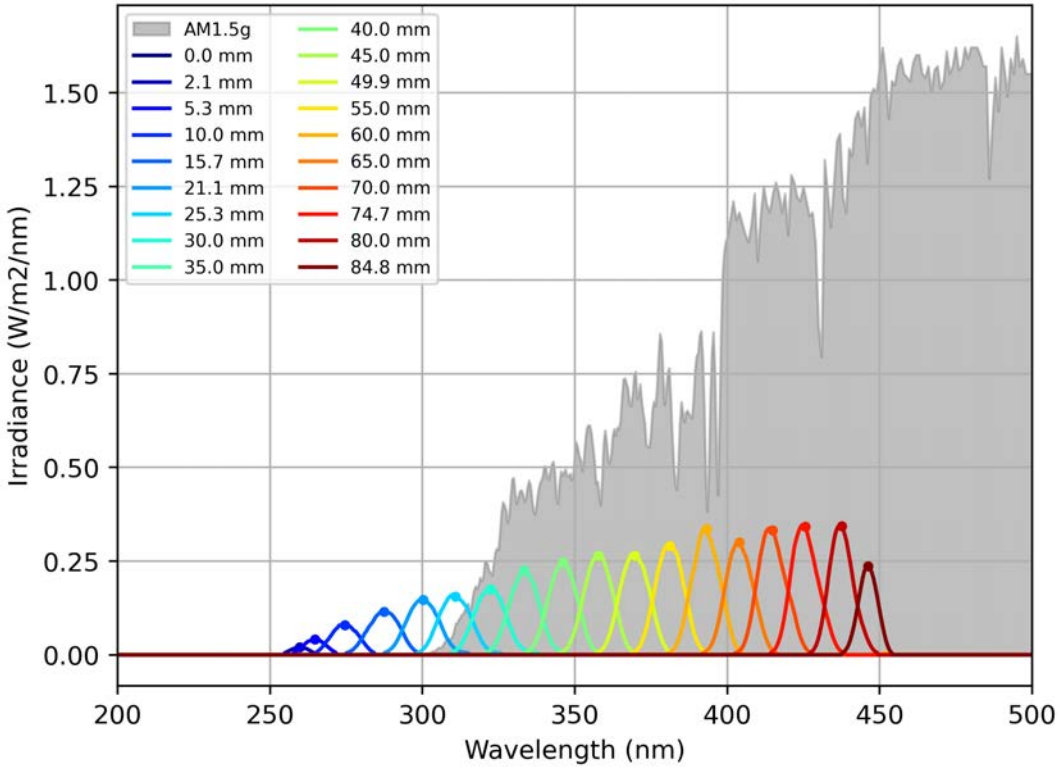
Spectrum vs. position

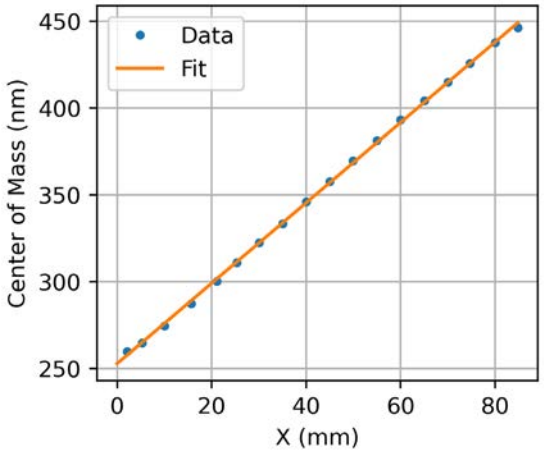
Found the dependence of spectrum on position using a spectrometer.

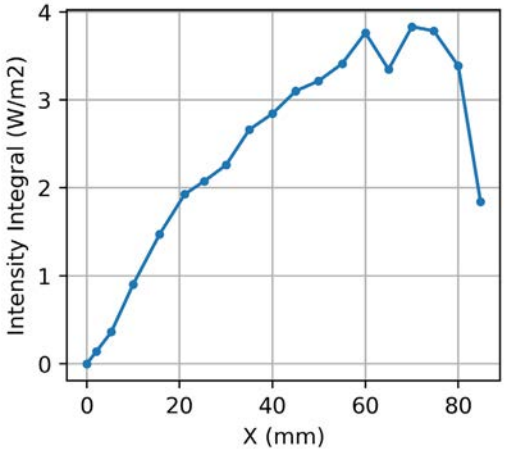


Note: intensity in UV to blue region is comparable to AM1.5G



Find center and integral





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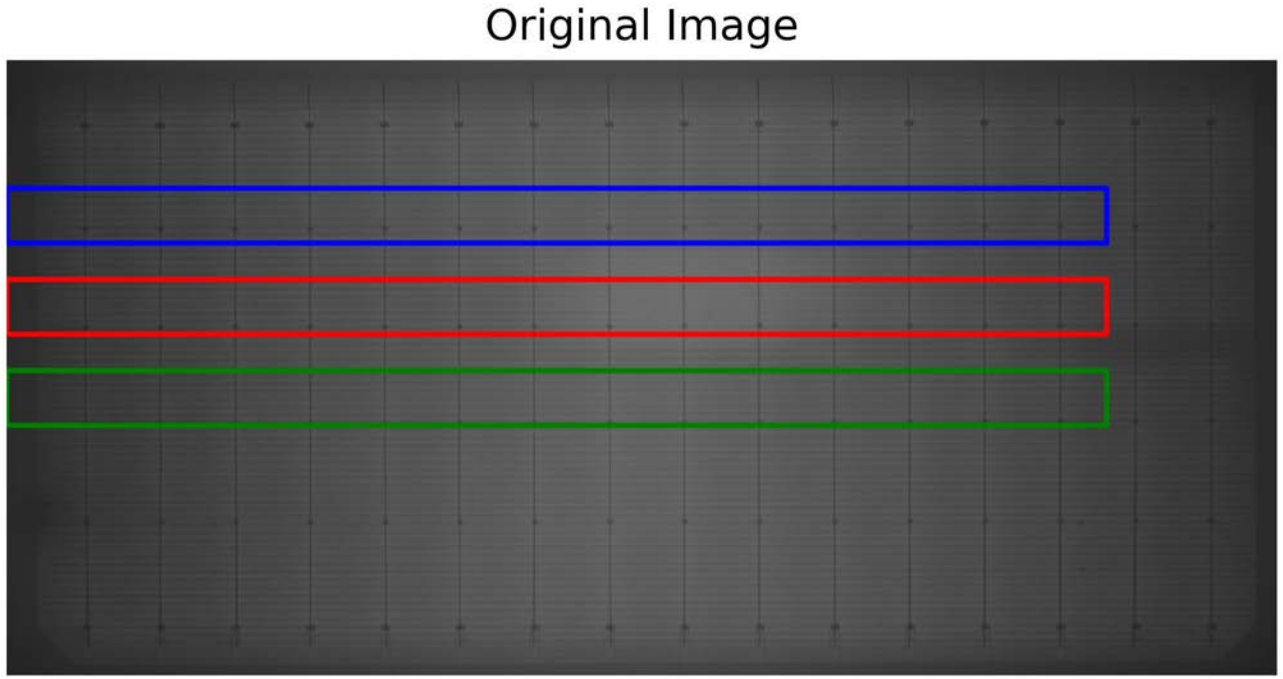
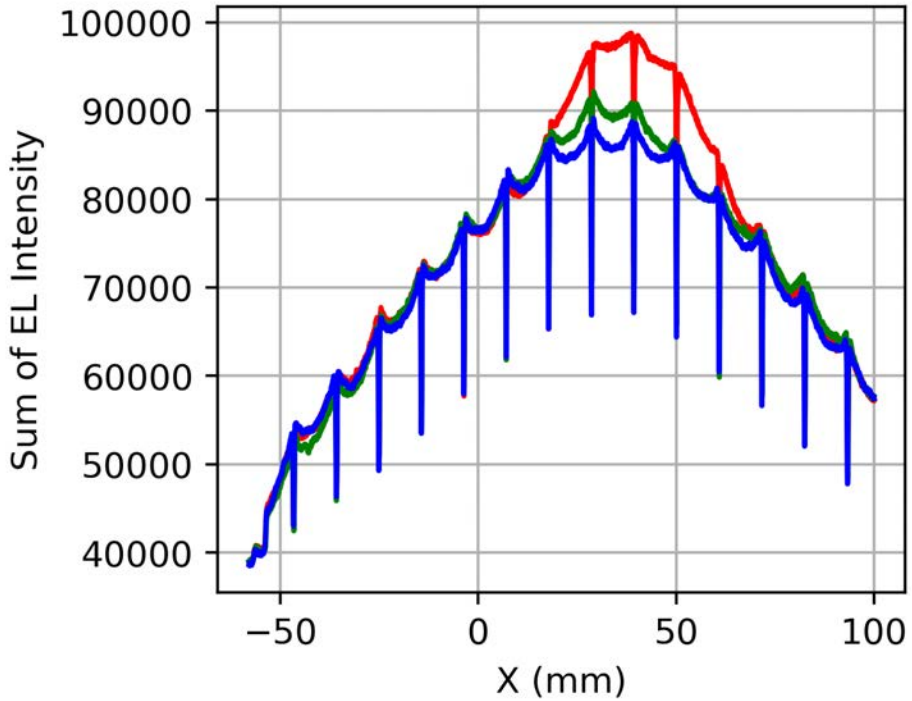
EL Image analysis





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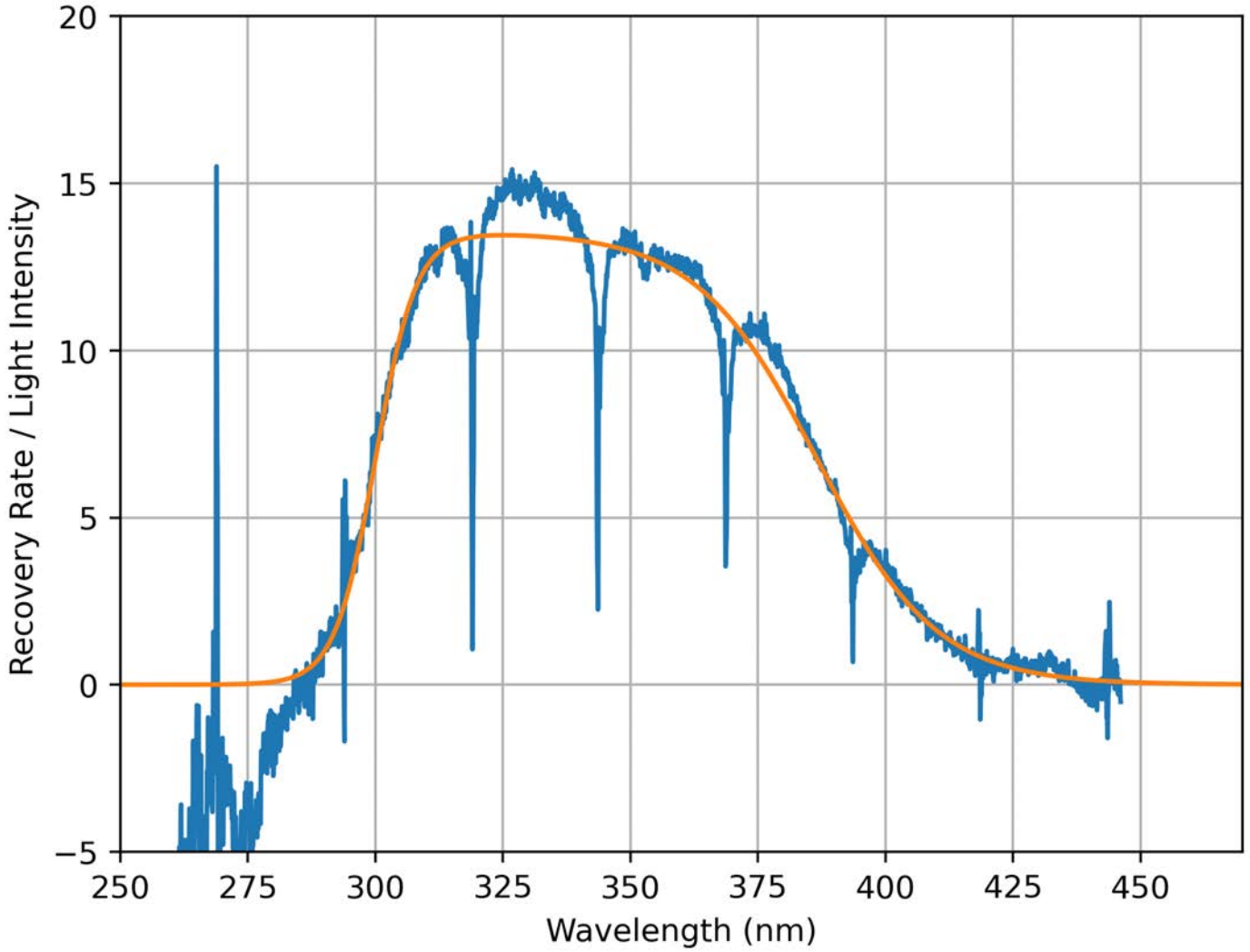
Put it together

- Combine the wavelength + power at each location with the amount of EL brightening to get the recovery rate normalized by light intensity.
- Note: glass cuts off around 300 nm.

UV light causes recovery of UV-induced dark metastability.



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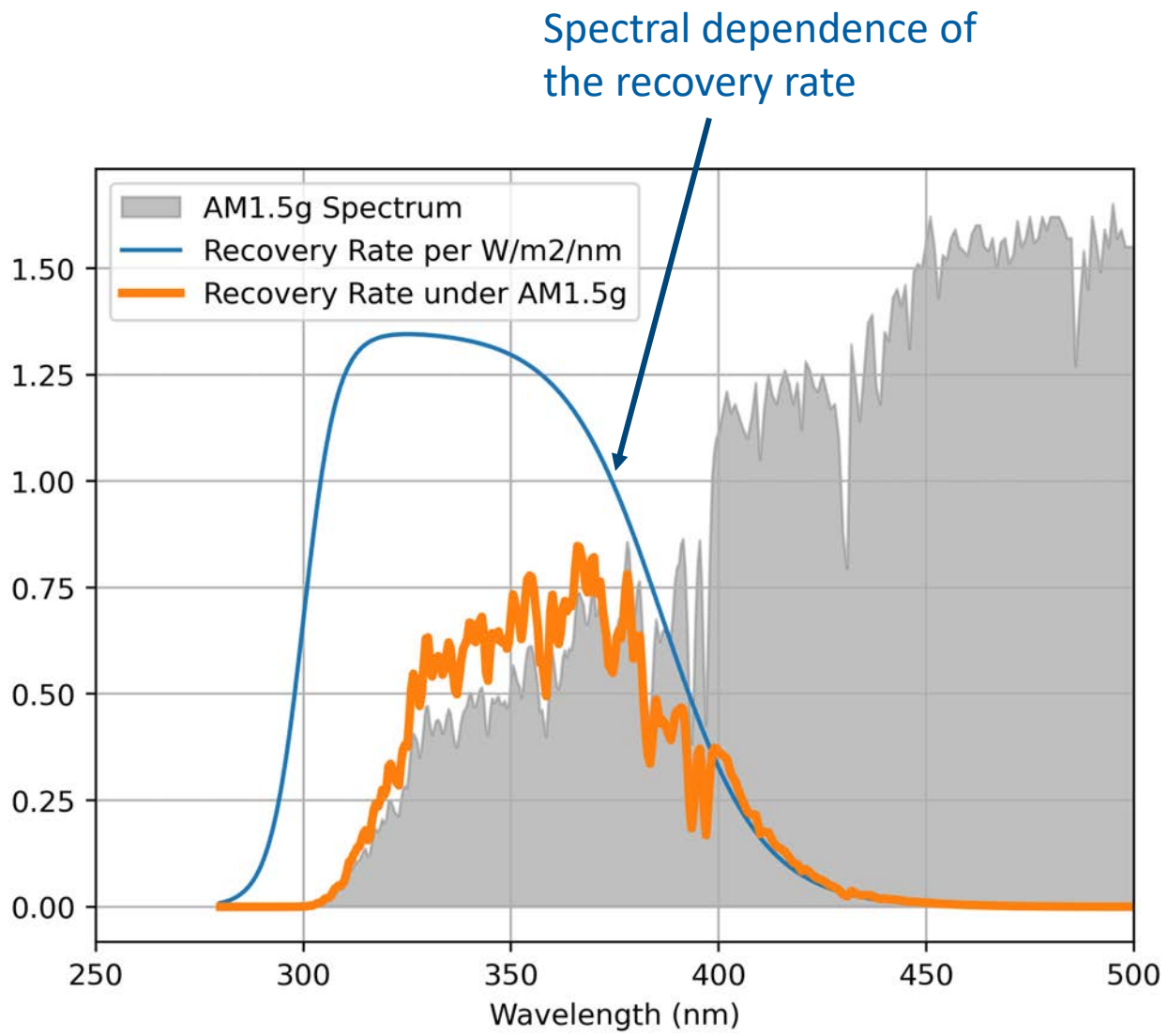
Spectral dependence of recovery

Recovery under full spectrum light almost completely due to UVA exposure in range of 320 – 400 nm (for TOPCon).

- Note glass cuts off below 300 nm.
- (Note: this is a tricky measurement – exact shape should be verified with further measurements.)



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What is happening in the cell during dark degradation and recovery?

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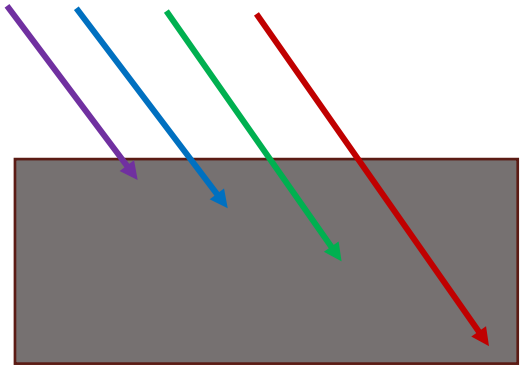
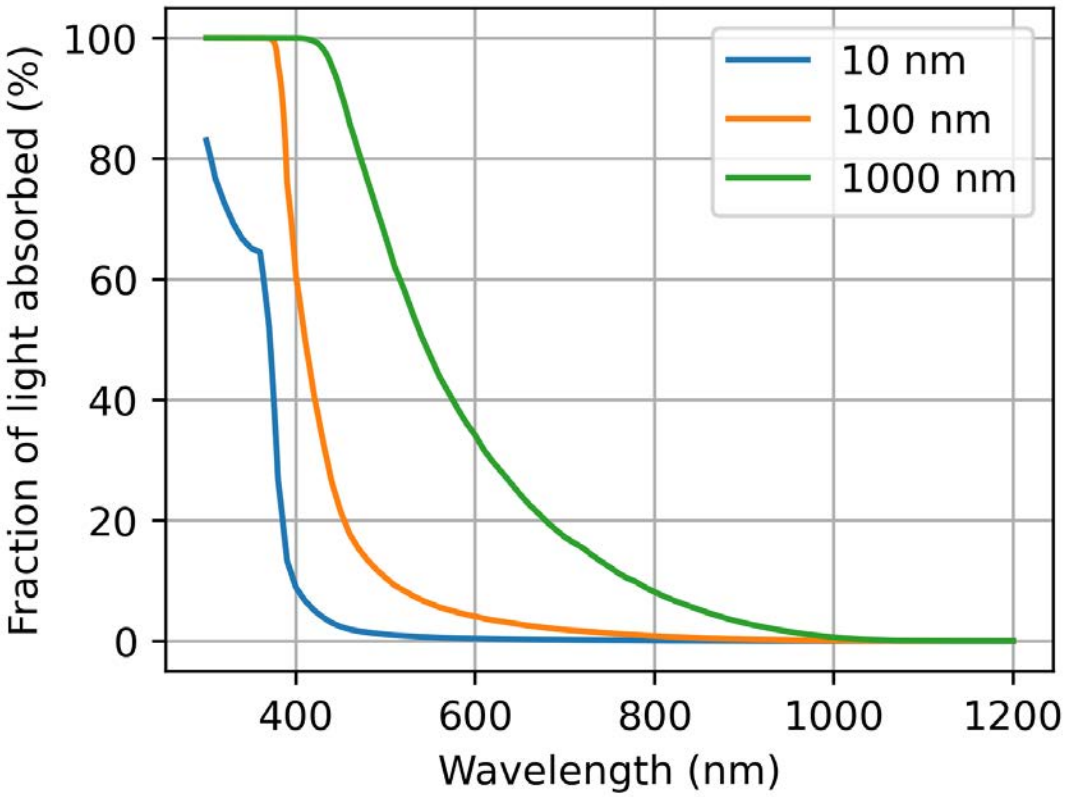
External Quantum Efficiency (EQE) primer



- Nearly 100% of UV light is absorbed in the top 100 nm of the cell, longer wavelength light is absorbed deeper into the cell.
- **The quantum efficiency in the UV region probes the quality (passivation) of the front surface**.



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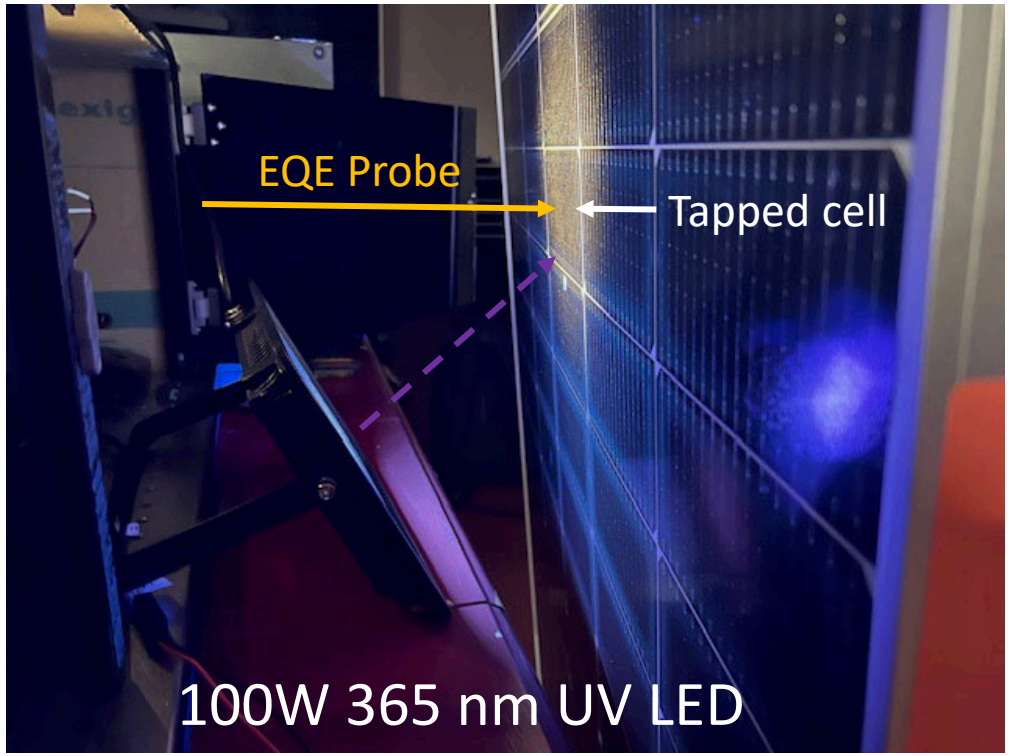
EQE change during recovery

- TOPCon module experienced UVID followed by several months of dark storage.
- Acquired EQE before and after a 2 minutes dose from UV LED at 365 nm.



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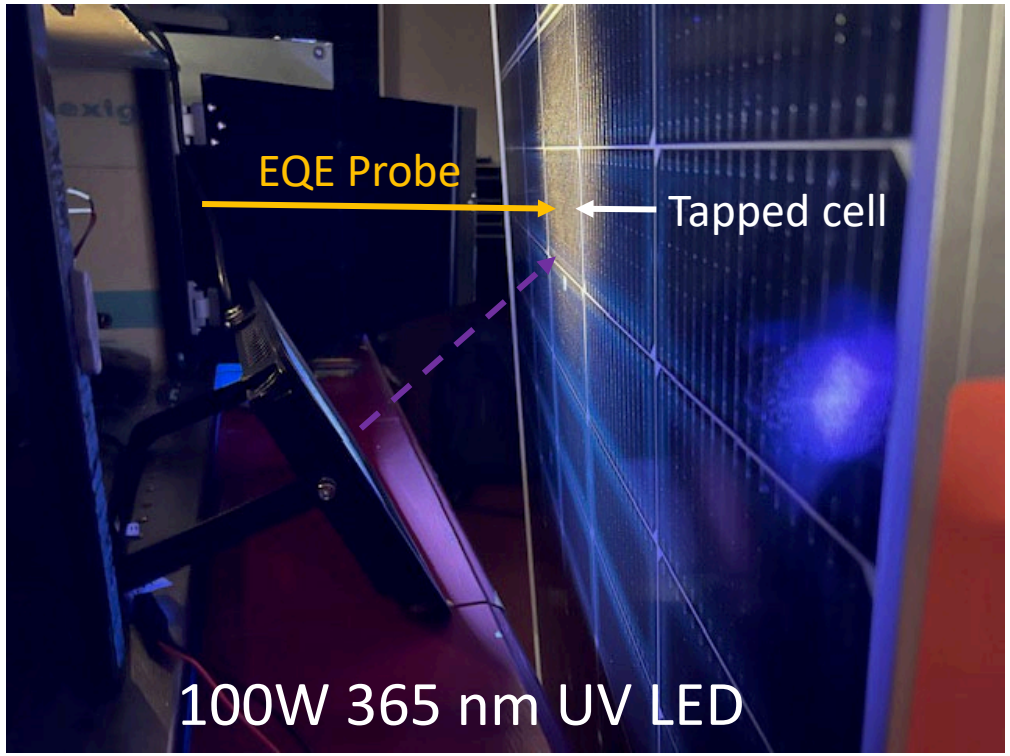
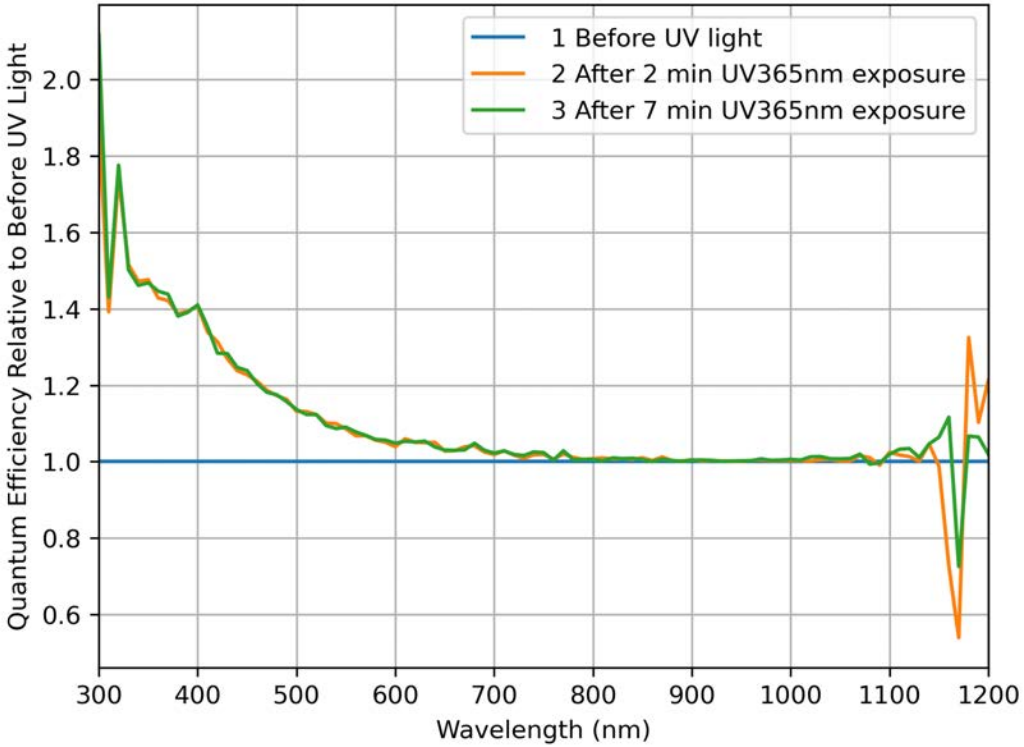


- Change in EQE during recovery shows power gain is greatest in the blue/UV region.

Clear evidence that:

Dark-storage reduces the front-side passivation



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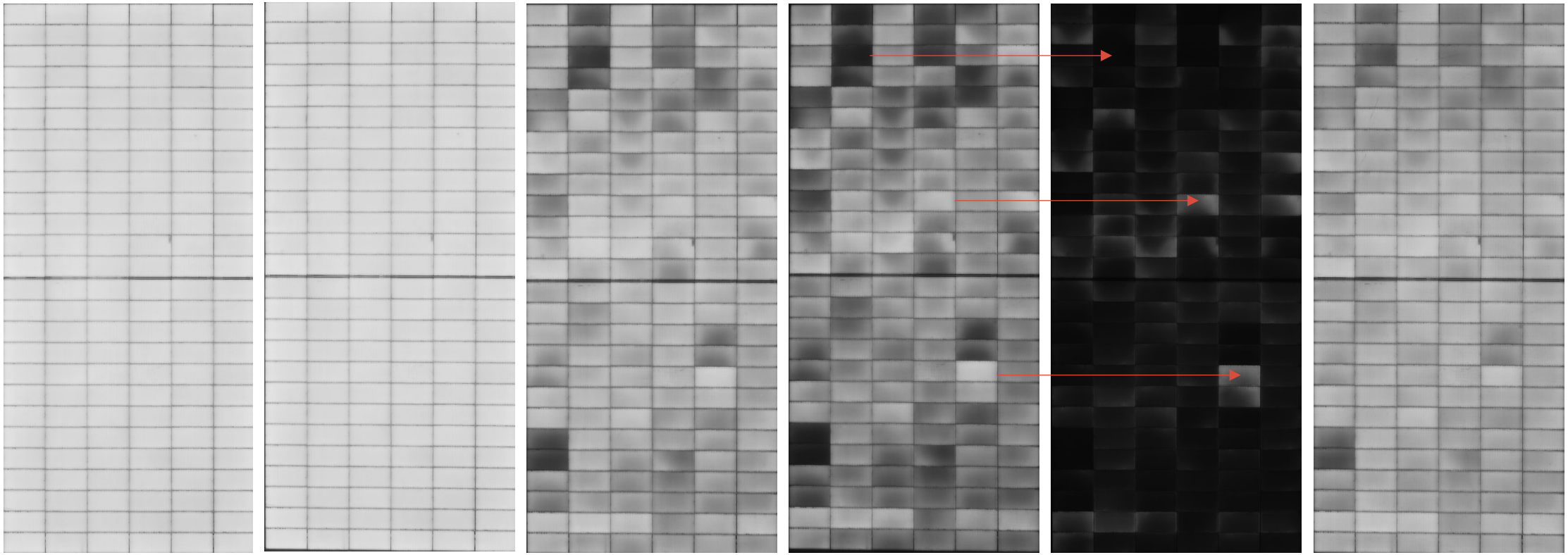
All images taken on same settings.

Correlation between UVID-120 and dark storage EL

- Cells that darken more in UVID also darken more in dark storage.
- Full recovery is not achieved.

Pre-LID	LID 40 kWh/m2 Pmp: +0.3%	UVID-60 Pmp: -3.7%	UVID-120 Pmp: -6.2%	Dark storage 13D	Light Soak 2 kWh/m2



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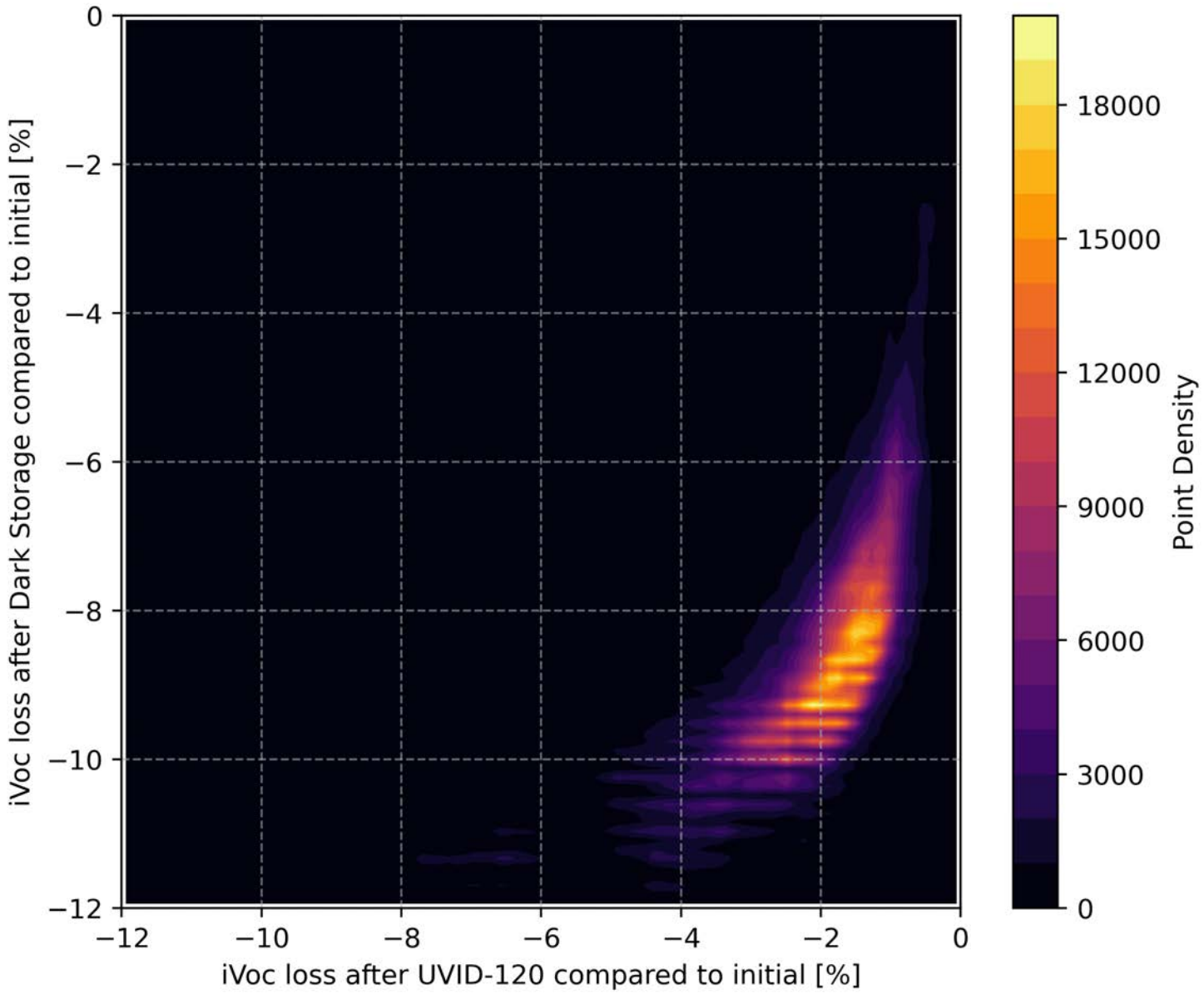
Susceptibility to UVID correlated to dark degradation

- **The areas of cells that degrade more in UV also degrade more in dark storage.**
- Starting to see saturation of dark storage loss.



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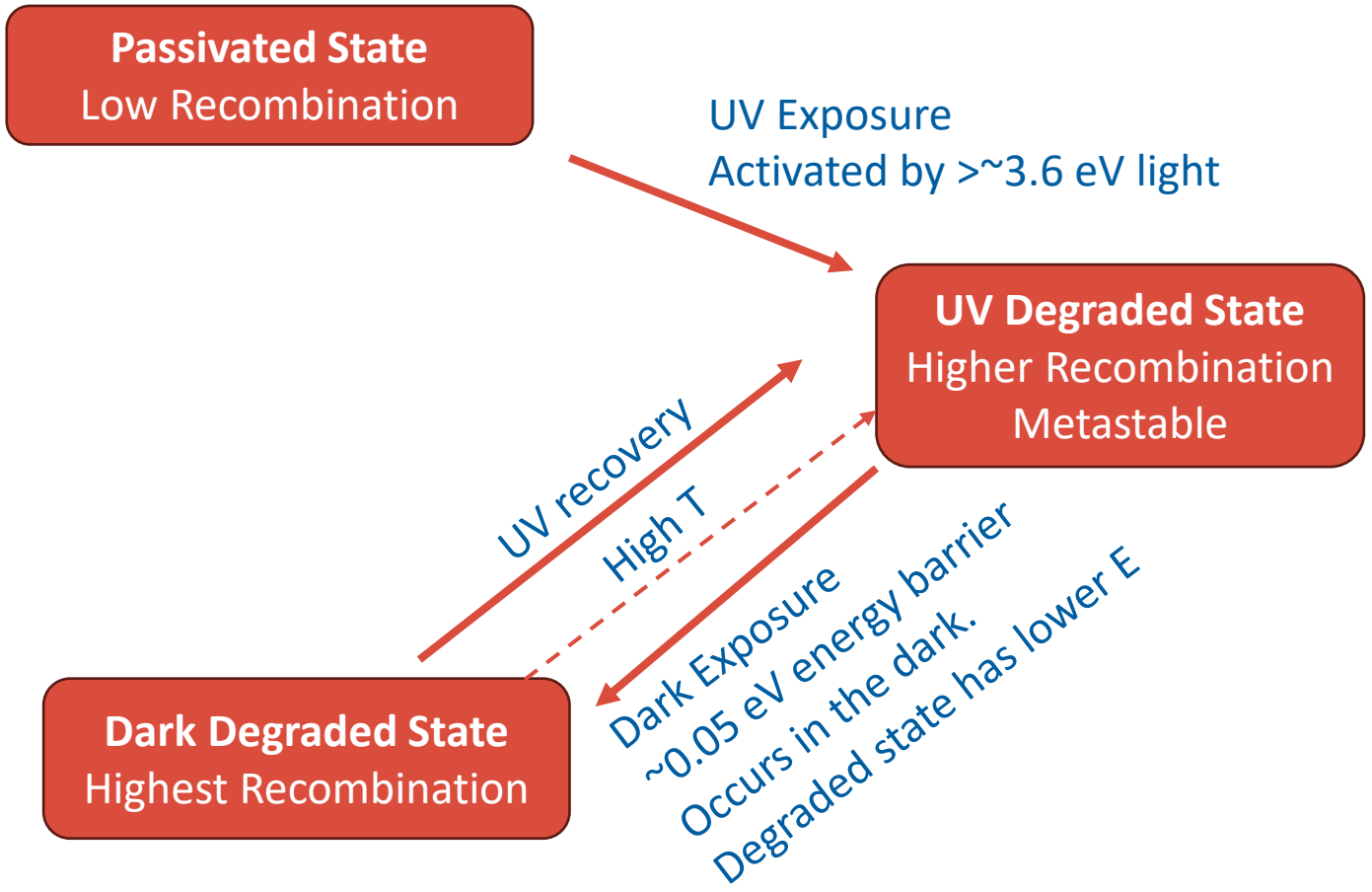
Hypothesis for UVID + Metastability three state model on TOPCon cells

Observations

1. Dark degradation rate low before UVID.
2. UVID damages front-side passivation.
3. Dark degradation occurs quickly (~days) once UV degraded.
4. Rate of dark degradation is correlated to extent of UVID.
5. UV lig`ht can reverse dark storage degradation
6. Full recovery to initial state is not achieved.
7. High temperatures can partially recover (prior work)



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UVID Recovery on HJT Module

Conclusion: HJT cells are different, they degrade in Isc and FF during dark storage

(*low sample size)

- Voc is perfectly stable, degradation driven by Isc loss.
- Suspect a different mechanism from TOPCon: contact resistance?

Step#	PMP	VOC	VMP	ISC	IMP	PMP%	VOC%	VMP%	ISC%	IMP%
Post-LID	555.32	53.66	45.73	12.83	12.14					
UVID60#1	550.43	53.66	45.62	12.76	12.07	-0.88	0.00	-0.24	-0.55	-0.58
UVID60#2	549.26	53.67	45.64	12.73	12.04	-1.09	0.02	-0.19	-0.75	-0.83
2-day	546.91	53.67	45.51	12.68	12.02	-1.51	0.02	-0.47	-1.14	-0.99
2-week	546.98	53.64	45.67	12.67	11.98	-1.50	-0.04	-0.13	-1.25	-1.32
Post-LID	554.28	53.68	45.92	12.8	12.07					
UVID60#1	550.66	53.69	45.8	12.76	12.02	-0.65	0.02	-0.26	-0.31	-0.41
UVID60#2	549.03	53.71	45.77	12.71	12.00	-0.95	0.06	-0.32	-0.67	-0.59
2-day	548.60	53.72	45.77	12.71	11.99	-1.02	0.08	-0.32	-0.67	-0.67
2-week	548.06	53.7	45.83	12.68	11.96	-1.12	0.04	-0.20	-0.94	-0.91

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UVID Recovery by technology

Pmax	Bad PERC	Good PERC	HJT	Bad TOPCon	Good TOPCon	Tiers1 TOPCon	Bad TOPCon (outdoor)
Initial	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LID	0.0%	0.0%	0.1%	0.4%	-0.1%	-0.1%	-0.7%
UVID60	-1.9%	-1.3%	-2.7%	-3.7%	-1.0%	-3.1%	-3.5%
UVID120	-3.0%	-1.9%	-4.5%	-5.6%	-1.4%	-4.4%	-11.1%
Dark Storage	-3.8%	-2.3%	-6.3%	-12.3%	-2.6%	-12.1%	-10.1%
LS 50Wh/m^2	-3.8%	-2.4%	-6.0%	-5.7%	-2.4%	-5.0%	-3.4%
LS 1000Wh/m^2	-3.7%	-2.3%	-5.5%	-5.6%	-2.3%	-4.9%	-3.4%

TOPCon/PERC: Short light soak is sufficient

HJT: Short light soak not sufficient, need 0.5 to 1.0 kWh/m2

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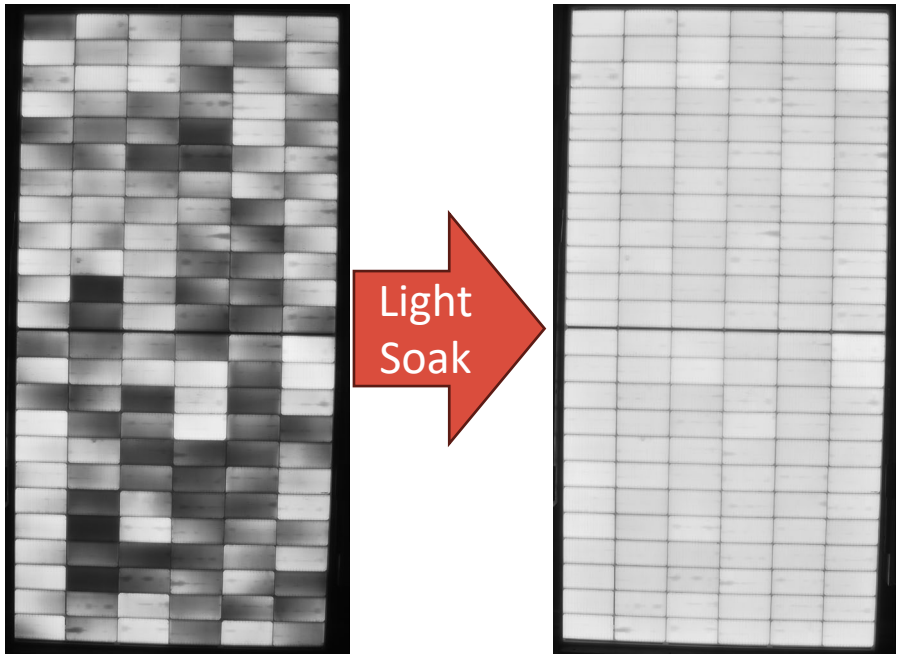
Kiwa PVEL's new stabilization procedure.

- Kiwa PVEL's new stabilization procedure uses a **full spectrum light soak**
  - Light source requirement:
    - Intensity over 500 W/m2, indoors or outdoors.
    - Class CCC light source.
  - TOPCon or PERC: At least 100 Wh/m^2 of light with at least 4 Wh/m^2 of UVA. (320-400 nm)
  - HJT: At least 500 Wh/m^2 of light with at least 20 Wh/m^2 of UVA.
  - CdTe: no light soak requirement (different stabilization procedure)
  - Soak performed at open-circuit.
  - Total dose not to exceed 2000 Wh/m^2
- Module to be flashed within 4 hours of coming off light soaking.



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El Cheapo module stabilization

- Kiwa PVEL uses a full spectrum light soak.
- But what if you don't have access?
- **Indoors**: 365 nm LEDs work great for stabilization. They are cheap, easy to use, and don't heat the module (wear safety glasses!)
- **Outdoors:** TOPCon stabilizes completely in 2 minutes of >500 W/m2 sun conditions (probably shorter).

Everbeam 365nm 100W UV LED Black Light - High Performance LED Bulbs, IP66 Waterproof - Ultraviolet Flood Lighting for...

★★★★☆ 3,215

$79.98

✓prime Two-Day
FREE delivery Thu, Mar 6

Add to cart

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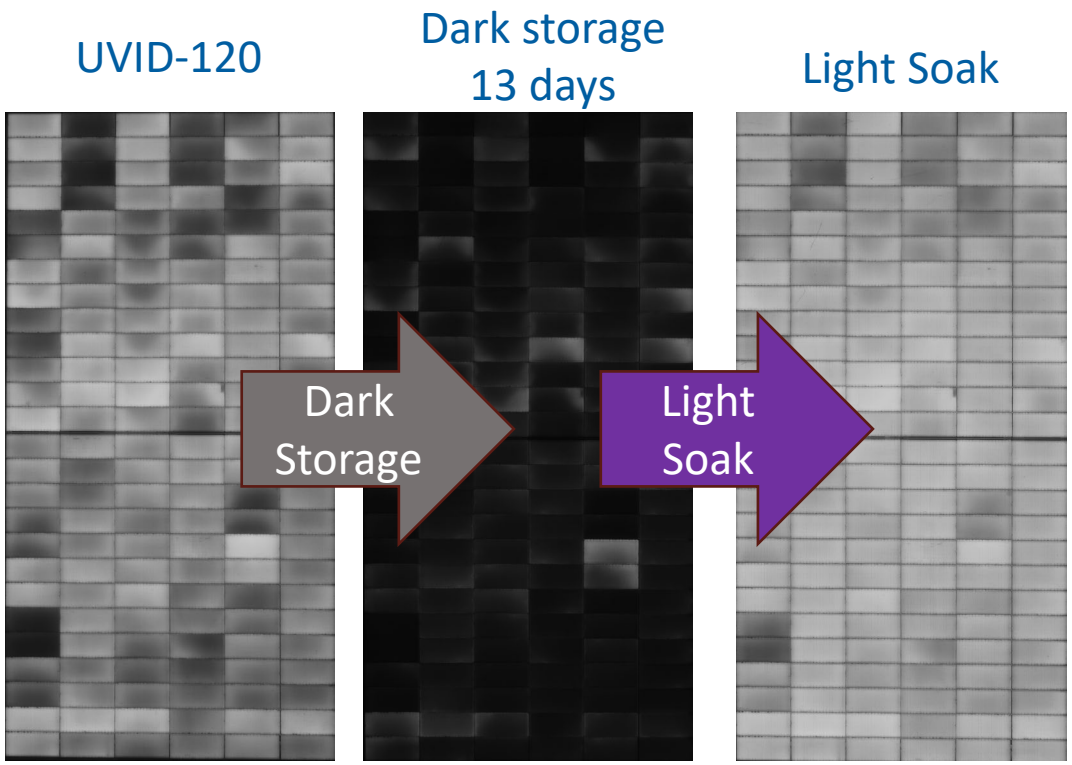
Summary

- **Dark Storage** metastability is a significant problem for test labs:
  - TOPCon (and HJT) modules exposed to UV or outdoors can develop this metastability.
  - Independent test labs and researchers should all **apply light soak** before measurements on UV-exposed modules.
  - A UV-sensitive TOPCon module can degrade in the dark at a rate of 1% power loss per day.
- Dark Storage degradation is <u>not a problem for field performance</u> – it disappears once the sun comes out.

- Mechanism: dark storage degradation on TOPCon is caused by front-side passivation loss and recovery.



Thanks to Duramat Funding

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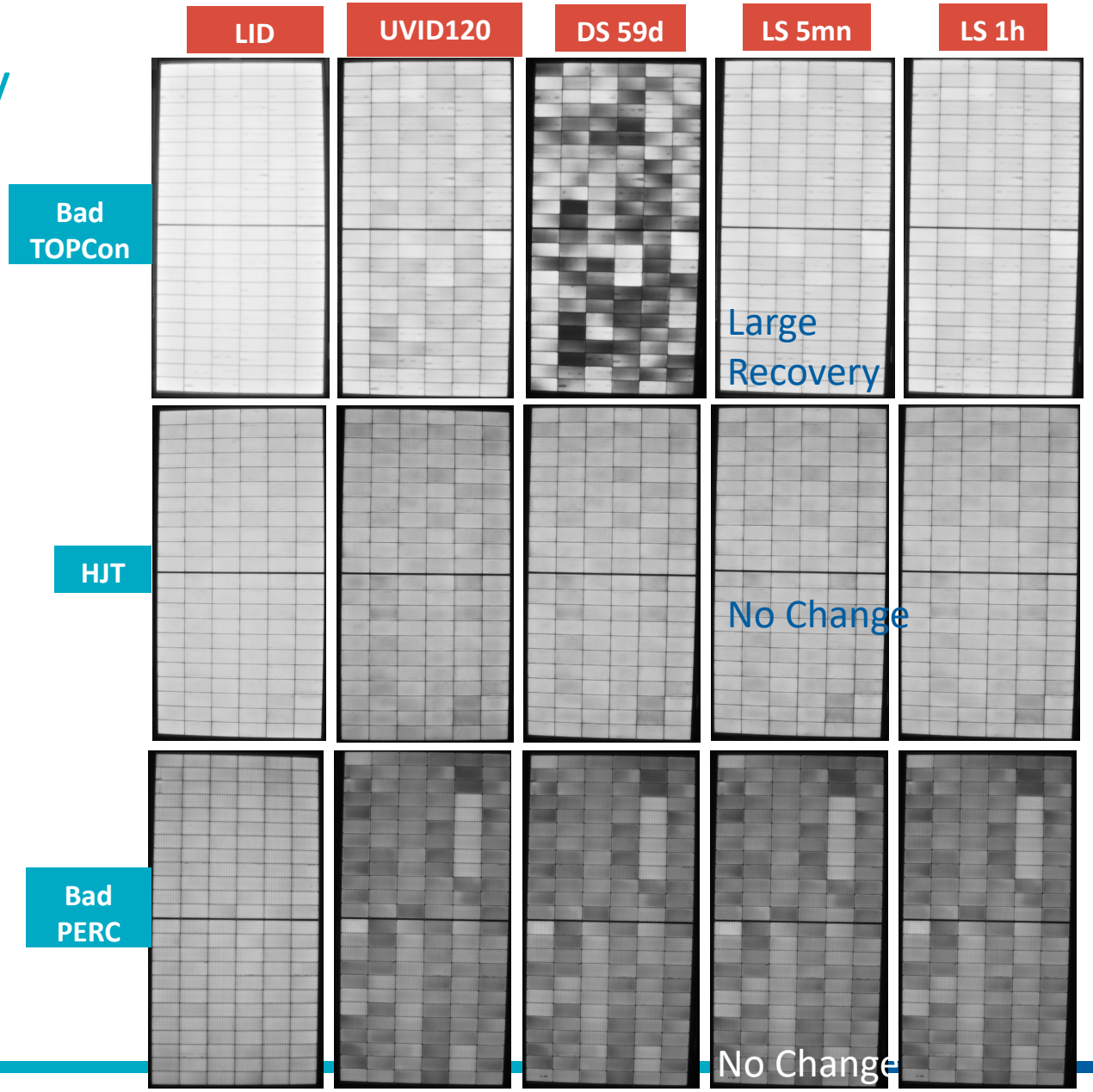
Technology differences in recovery

- Different technologies are different in impact of light soaking on dark storage
- TOPCon BOM with bad UVID performance quickly recovers clean EL signal after 5 minute light soak (~1000 W/m2)
- HJT BOM shows negligible Voc change after light soaking, but slight improvement in Pmp driven by FF.

Conclusions

- **TOPCon**: A 5 minute (1000 W/m2) light soak is effective for recovering dark storage degradation on TOPCon. No additional recovery at 1 hour.
- **PERC:** 1 hour light soak has little effect on PERC Voc
- **HJT:** 5 minute light soak is not sufficient to stabilize HJT, 1 hour is sufficient for FF recovery. Suspect different mechanism. Recovery is not necessarily related to UVID.



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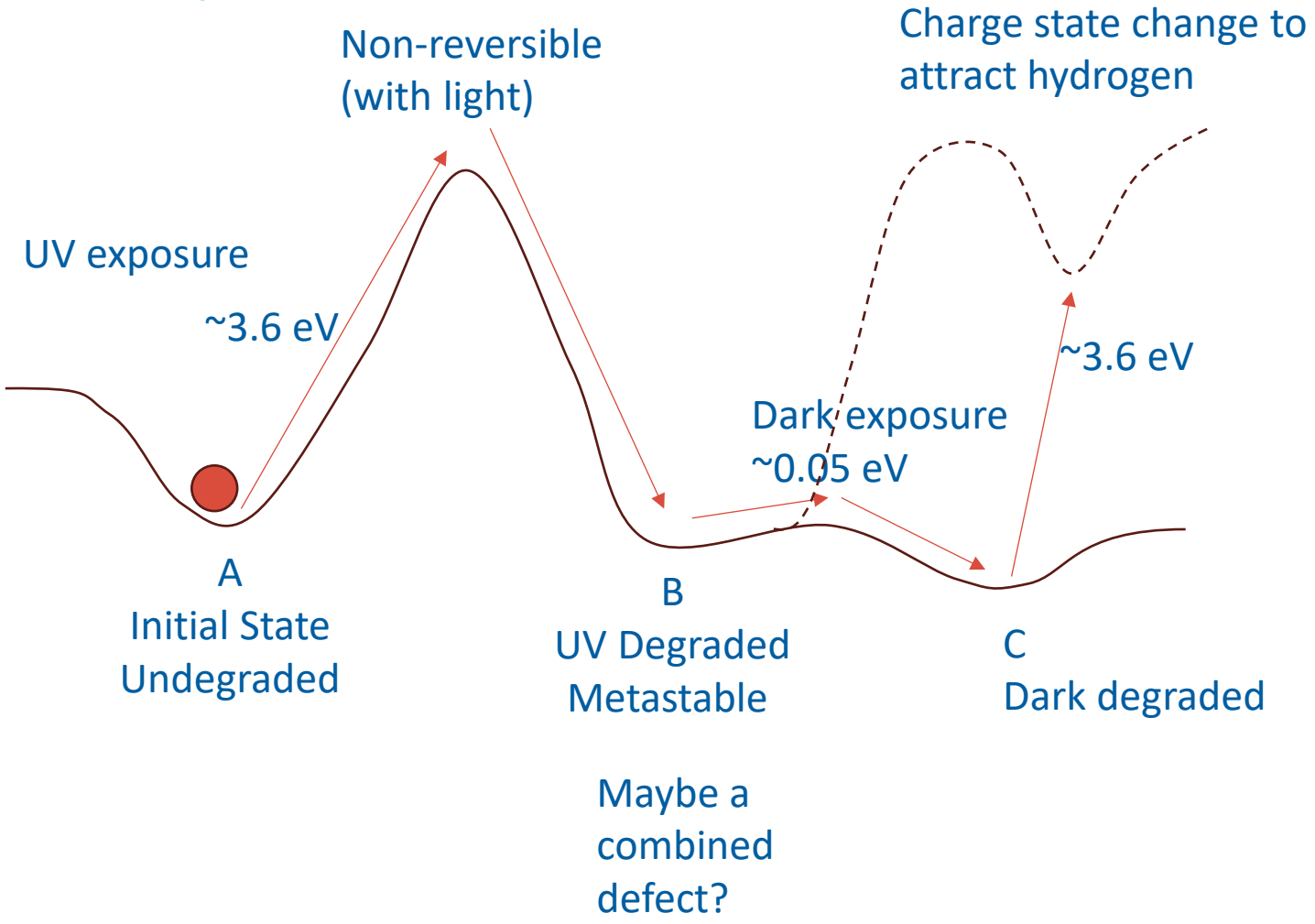
Hypothesis for UVID + Metastability three state model

Observations

1. Dark degradation rate low before UVID.
2. Dark degradation occurs quickly once UVID degraded.
3. Rate of dark degradation is correlated to extent of UVID.
4. Full recovery to initial state is not achieved. UV exposure both causes A -> B and B -> A.



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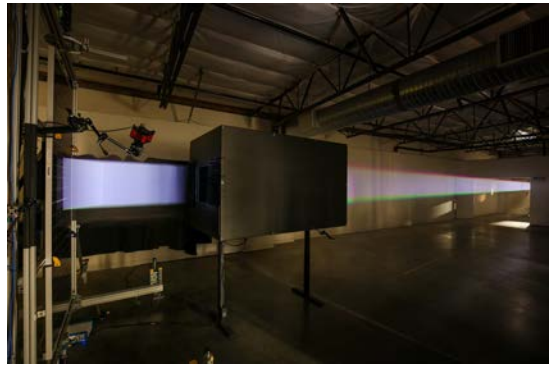
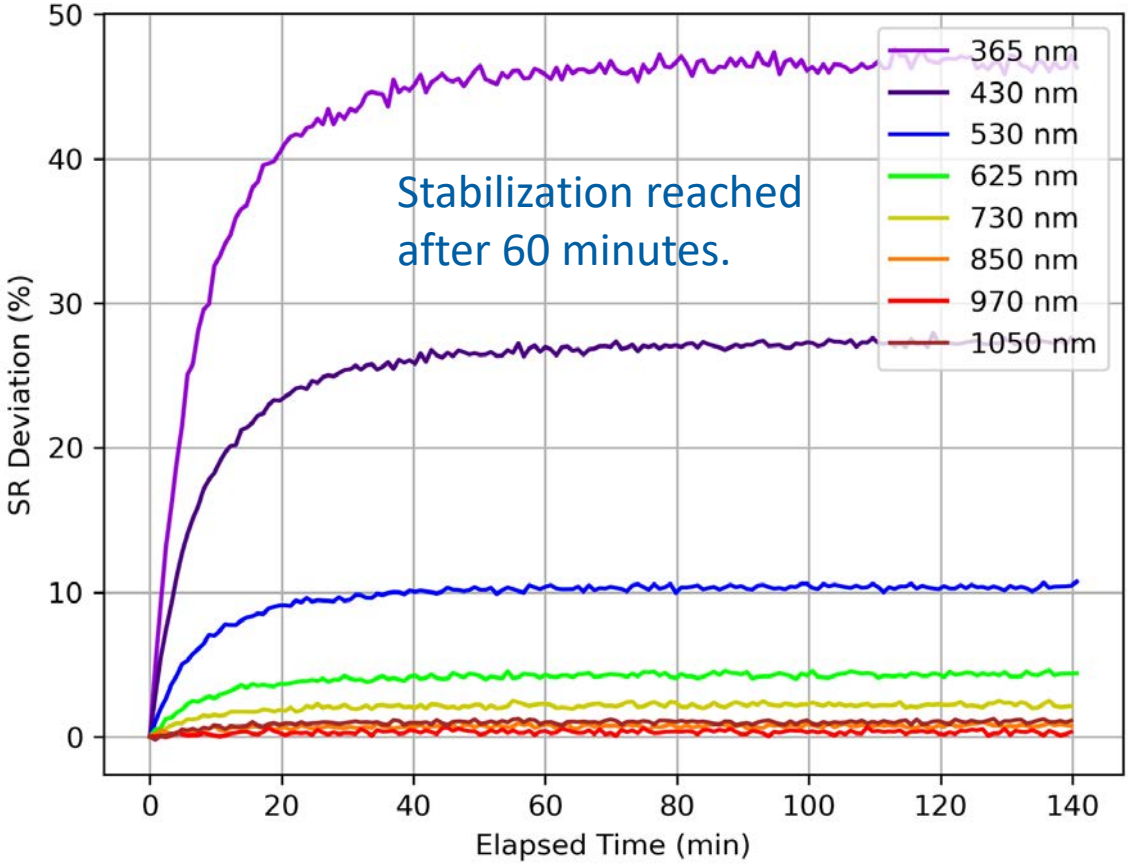
Metastability measured with EQE vs. time

- Module: Commercial TOPCon module. UVID-120 + 3 months of dark storage. Tapped out single cell.
- Plotting change in SR vs. time using an LED EQE setup. Plot is relative to SR measured at t=0. Bias light turned on at t=0.
- Bias irradiance ~100 W/m2 of 630nm light.
- Overall, getting huge 0% to 45% increase in responsivity depending on wavelength.
- DUT temperature only changes by 3 C during test, and cannot explain the huge increase in blue response.
- How much light needed?
  - This experiment used ~0.01 W/m2 of UV 365 nm.
  - Causes recovery with time constant of 15 minutes.
  - Recovery complete after only a dose of 0.01 Wh/m^2 of UV 365 nm LED.

Recovery is very fast: Even in early morning outdoor conditions of 10 W/m2 (0.4 W/m2 of UV). Expect recovery within 2 minutes





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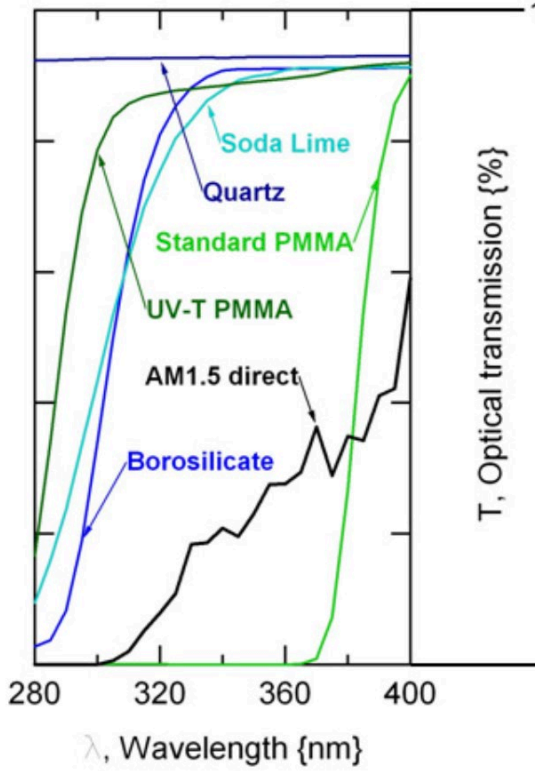

[1] David C. Miller, Michael D. Kempe, Cheryl E. Kennedy, and Sarah R. Kurtz "Analysis of transmitted optical spectrum enabling accelerated testing of CPV designs", Proc. SPIE 7407, High and Low Concentrator Systems for Solar Electric Applications IV, 74070G (20 August 2009); https://doi.org/10.1117/12.826251

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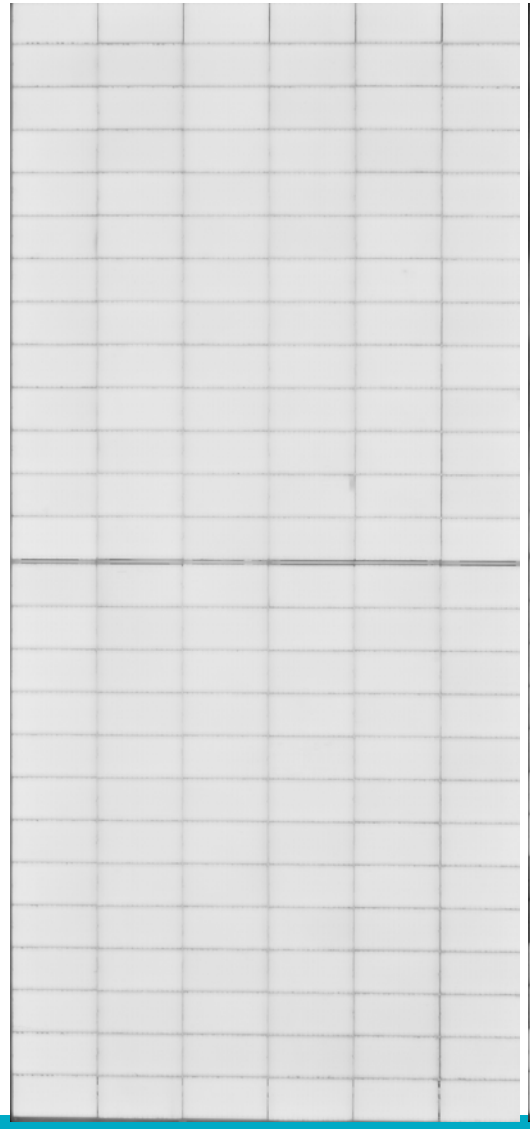
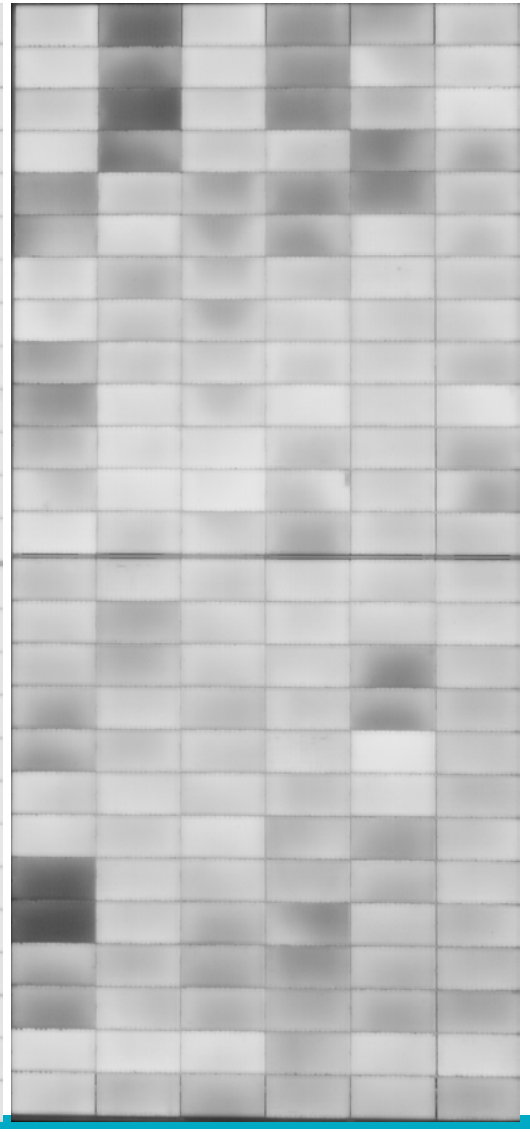
Low current EL

- Pattern is almost the same at 0.1 and 1.0 Isc cell to cell.

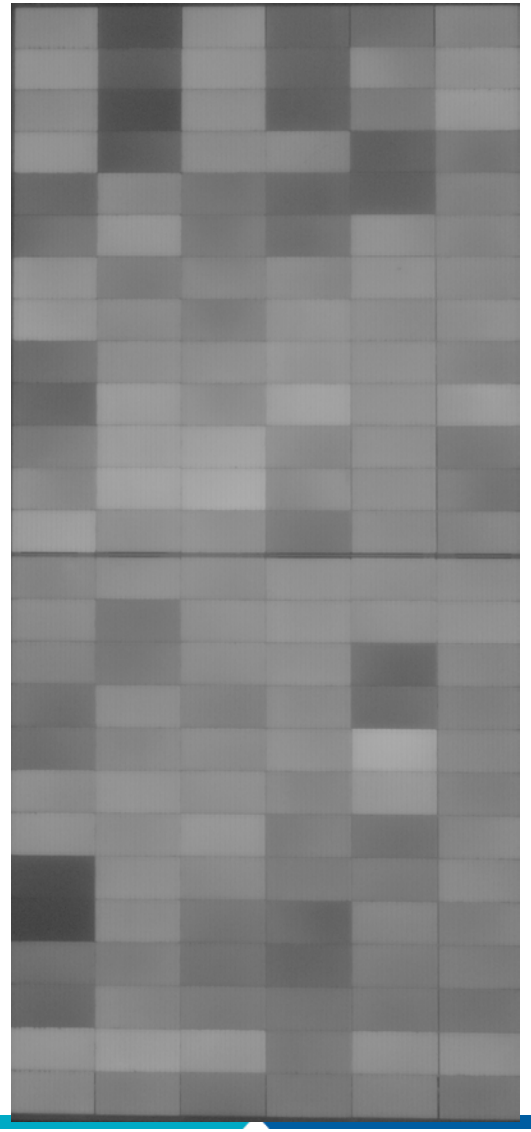
Post-LID



UVID-120
1.0 Isc



UVID-120
1.0 Isc



Log scale images.

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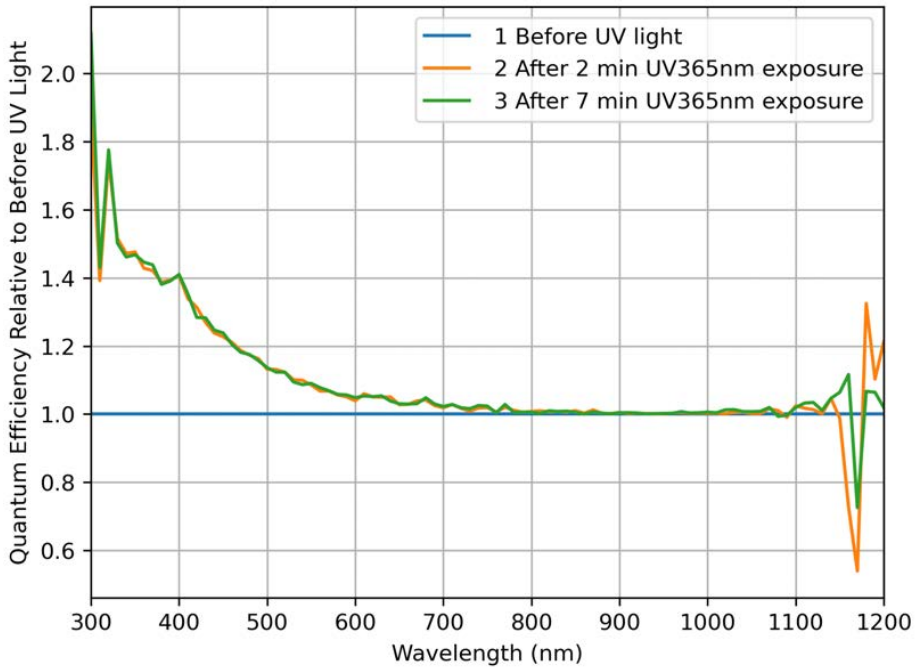
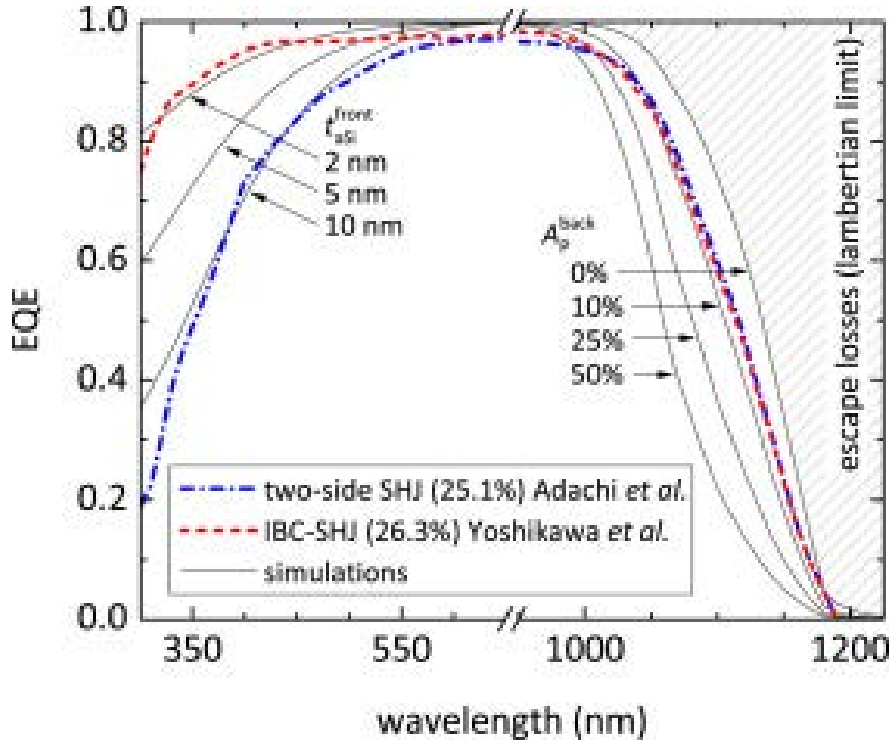


Improving front surface passivation causes enhancement of EQE in blue and UV region.



Haschke, J., Dupré, O., Boccard, M., & Ballif, C. (2018). Silicon heterojunction solar cells: Recent technological development and practical aspects - from lab to industry. *Solar Energy Materials and Solar Cells, 187*, 140-153. https://doi.org/10.1016/j.solmat.2018.07.018

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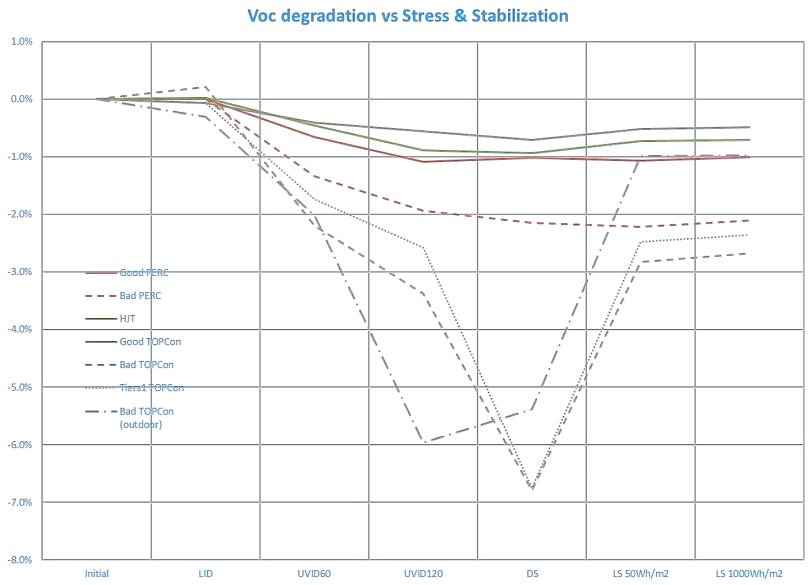
Post-UVID stabilization – Results

- Stabilization results varying with technology:
  - No obvious recovery for PERC (within measurement noise).
  - Negligible Voc recovery for HJT, obvious but very slow FF recovery (consistent with manufacturers data).
  - Fast and effective recovery for TOPCon (all parameters).



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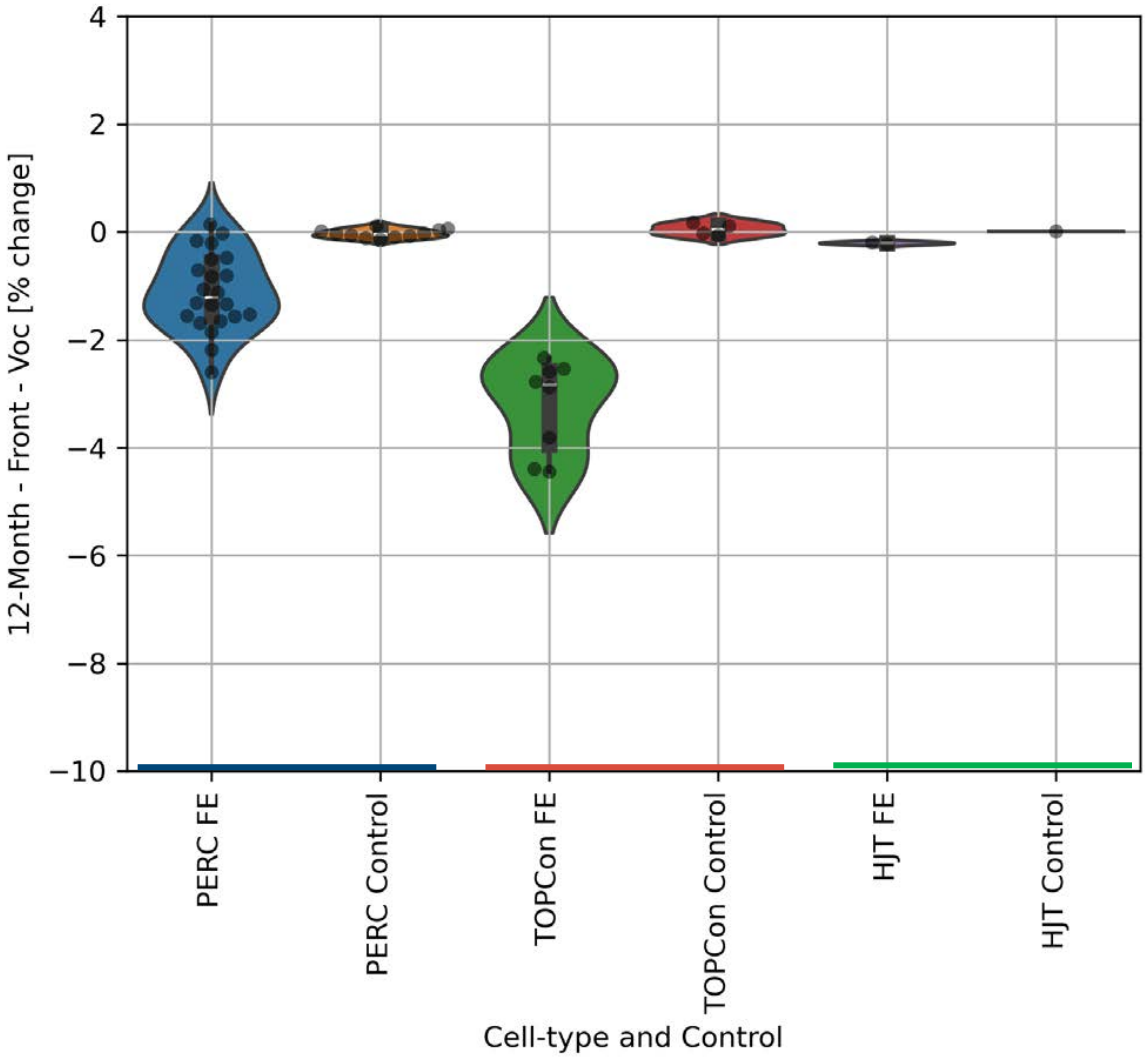
Voltage loss on Fielded Modules

- Each dot is a 1 year outdoor exposure.
- Note: Voc of control modules highly stable for all cell technologies.
- **Significant Voc loss for TOPCon, with less Voc loss for PERC and HJT.**
- Suggests that Voc loss is a significant problem in outdoor exposure as well.
- What's causing this? Is it UVID?



Note: time from unmounting to flash not strictly controlled

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Outline

- First talk: **Accelerated UVID Testing and Comparison to Outdoor Testing**
  - UVID Extent in Kiwa PVEL testing
  - UVID data overview
  - UVID inhomogeneity – need to test many cells.
  - FE data – shows UVID is real outdoors.
  - Voc vs. MPP vs. Isc.
  - Effect of spectrum – different bulbs.
  - Damage model (?)
- Second Talk: **UVID initiates metastability in the dark: How to properly measure unstable Si modules. Todd Karin**
  - Not your grandma's silicon – dark metastabilities
    - Examples from field and lab testing.
    - Unstressed modules.
    - HJT vs. TOPCon.
  - Metastability.
    - Three state model.
  - UVID recovery
    - Different methods tried.
      - CID
      - Full spectrum
      - UV light
  - PVEL's chosen stabilization method.

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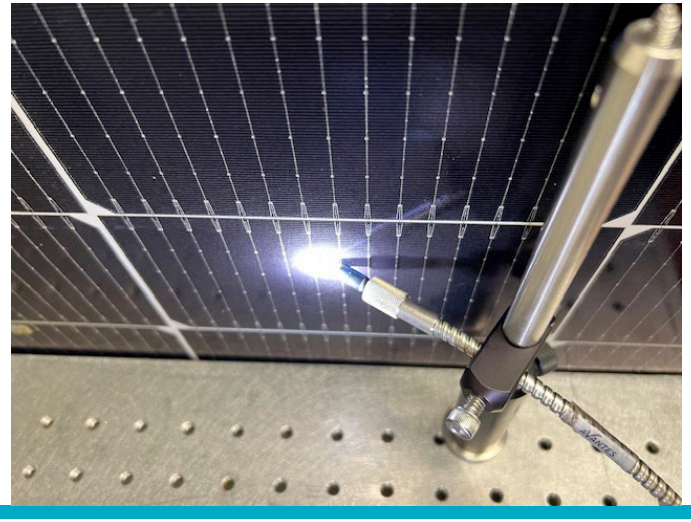
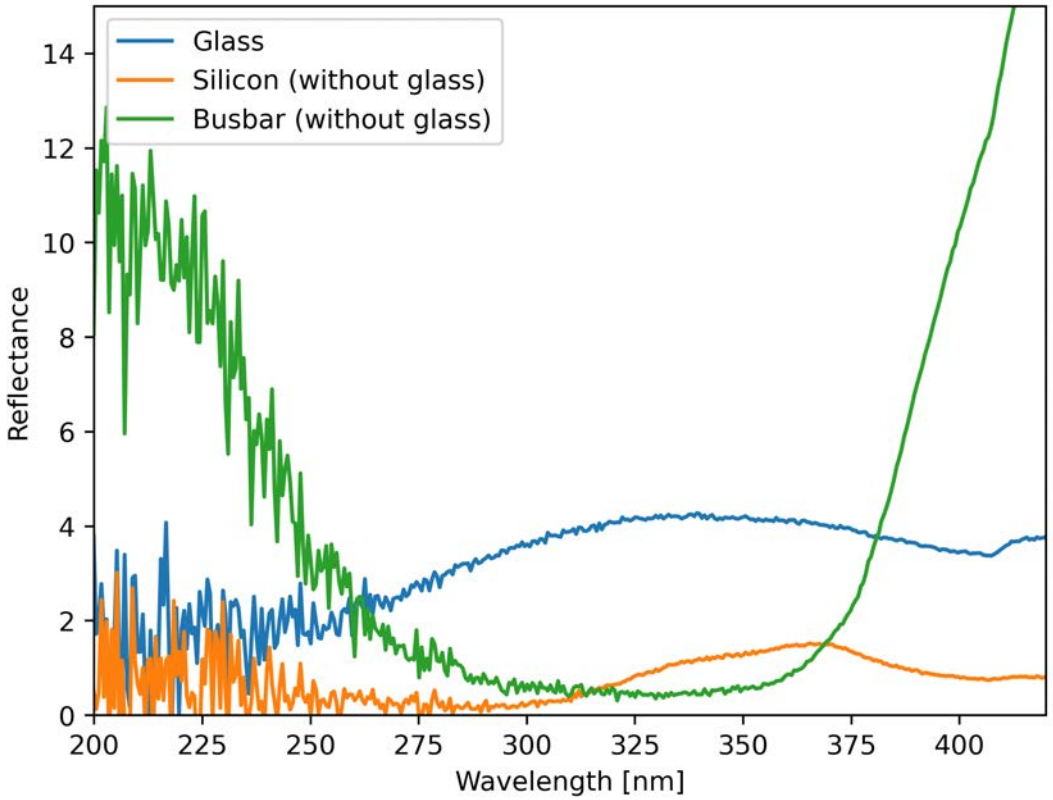
UV cut is around 320 nm for encapsulant.

Silicon reflectance





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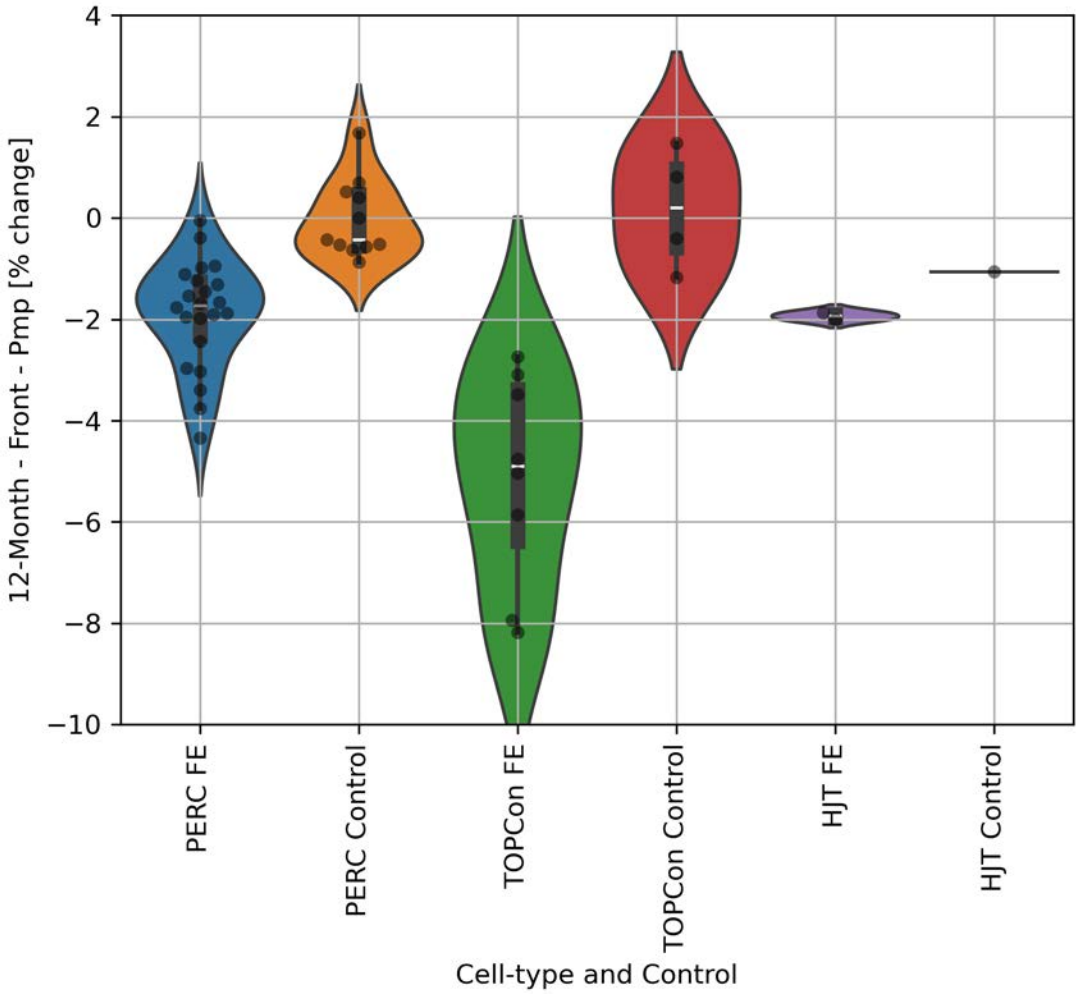

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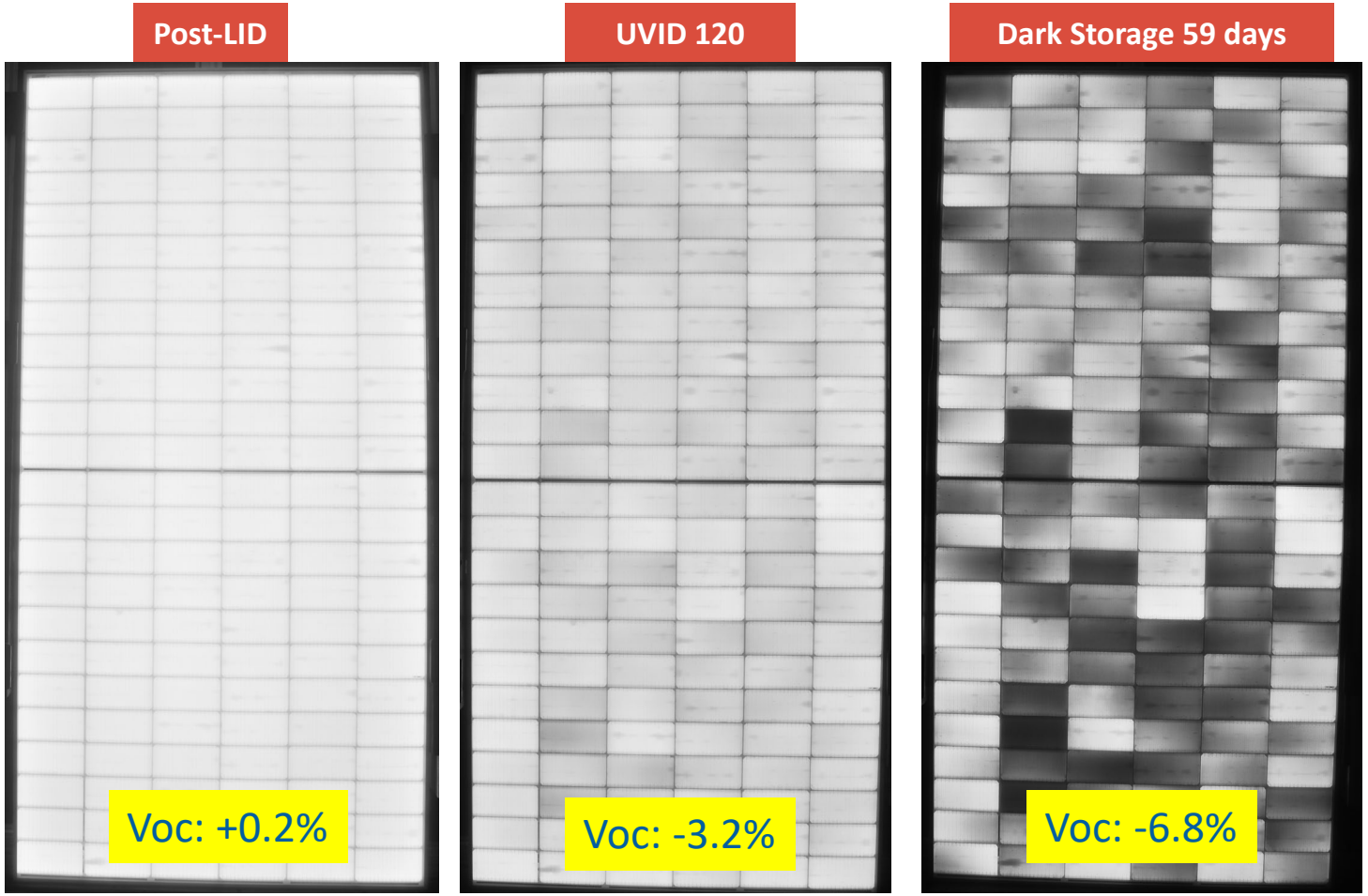
UVID Induces Metastability

- We are all used to treating silicon modules as stable in storage…
- **Not anymore!**

- Outline:
  - TOPCon cells degrade under UV into a metastable state.
  - Under dark storage at room temperature, the modules will continue to degrade on a timescale of days to weeks.
  - Dark storage degradation can be reversed with light soaking.
  - Pay attention to this if you want to make any conclusions from TOPCon flashes.



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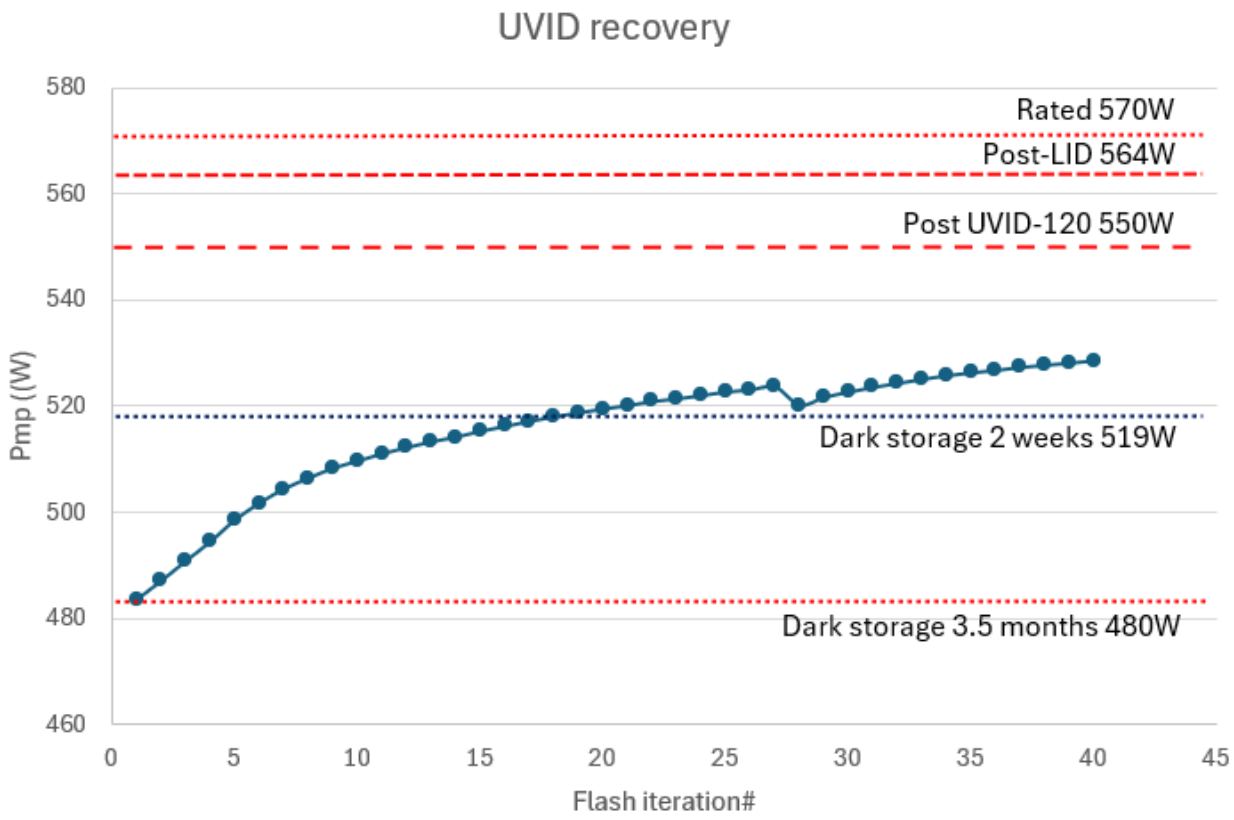

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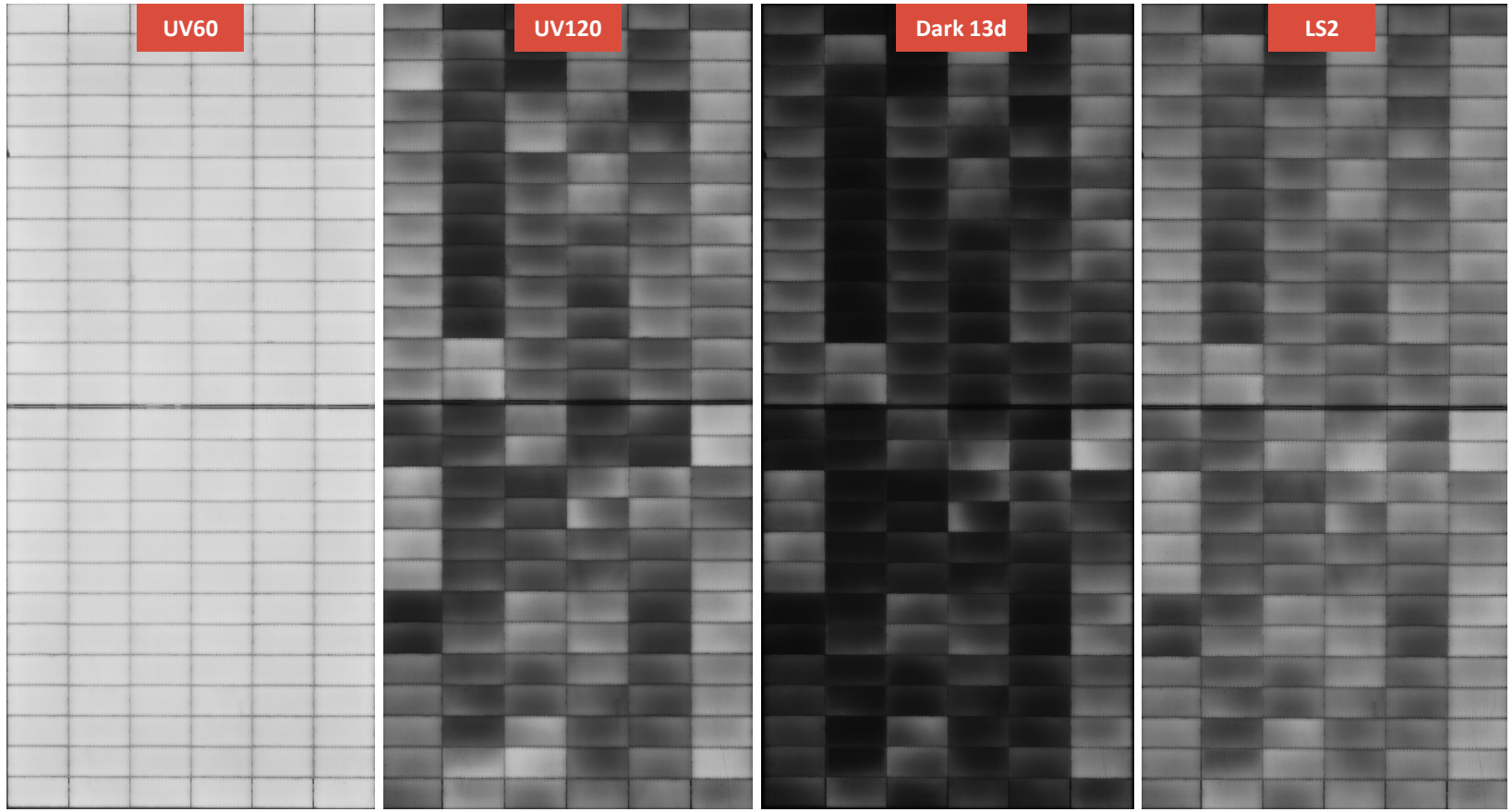
Correlation of UVID and Dark Metastability



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  - Pay attention to this if you want to make any conclusions from TOPCon flashes.

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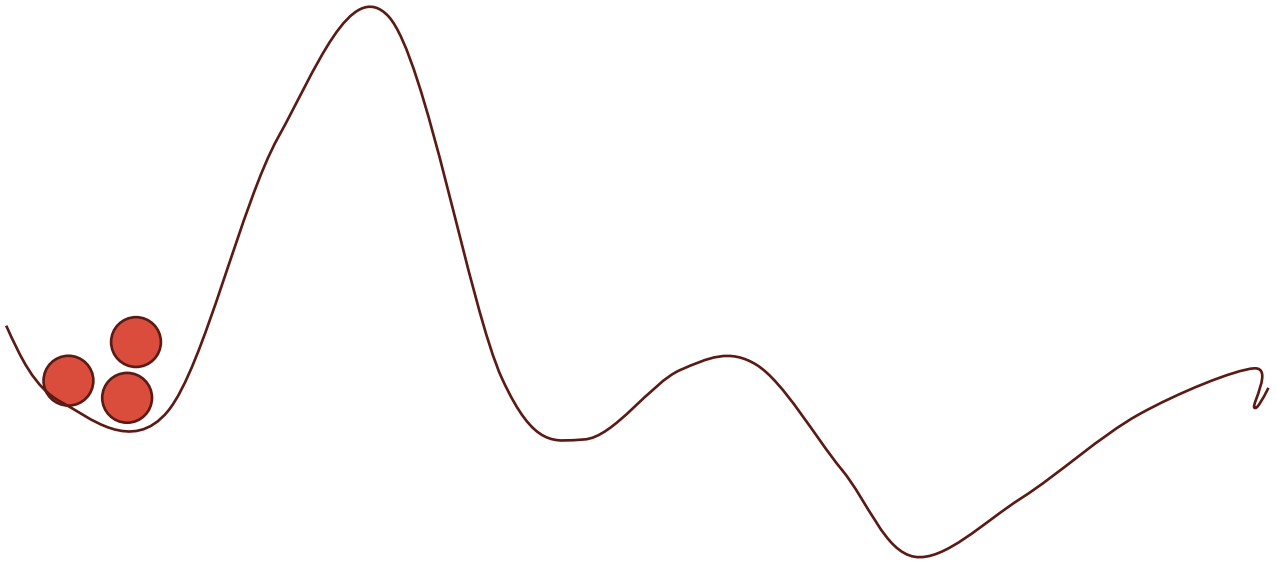
Other theories

Possible that UV light causes defects, and prolonged exposure with lots of defects turns some of them permanent.



***Journal of Solar Energy Research Updates*, 2023, 10, 36-45**

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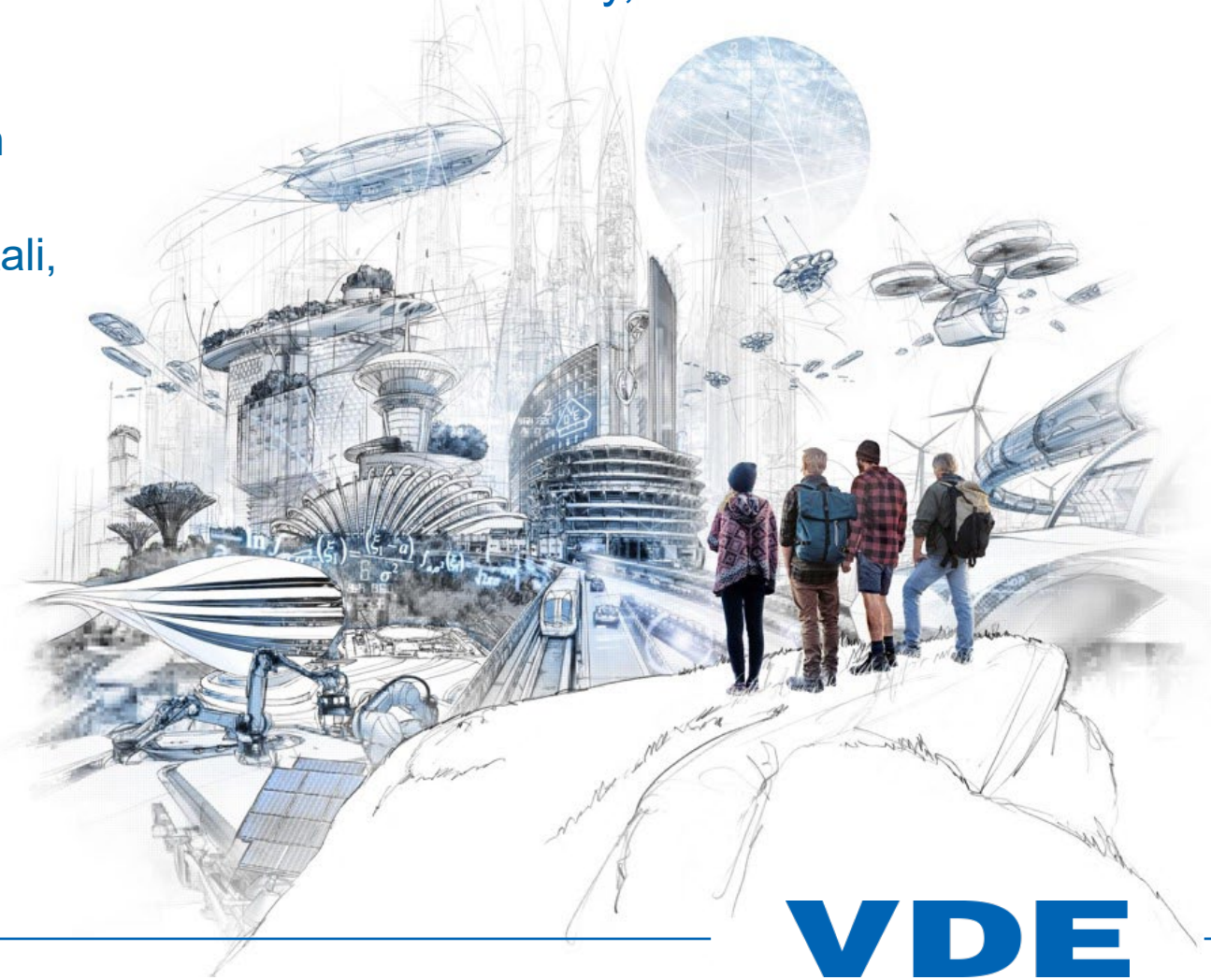
Effectiveness of Hail Stow in PV Systems

Forensic investigation into March 2024 hail events Fort Bend County, TX

Co-Authors

Array Technologies: Kathy Hanson, Sumanth Lokanath, Aaron Gabelnick

VDE Americas: Dr. Peter Bostock, Jon Previtali, Dr. Jonathan Allen, Dennis Weaver



Jon Previtali

Vice President | VDE Americas

2025 PV Reliability Workshop

VDE

About VDE Americas technical advisory services

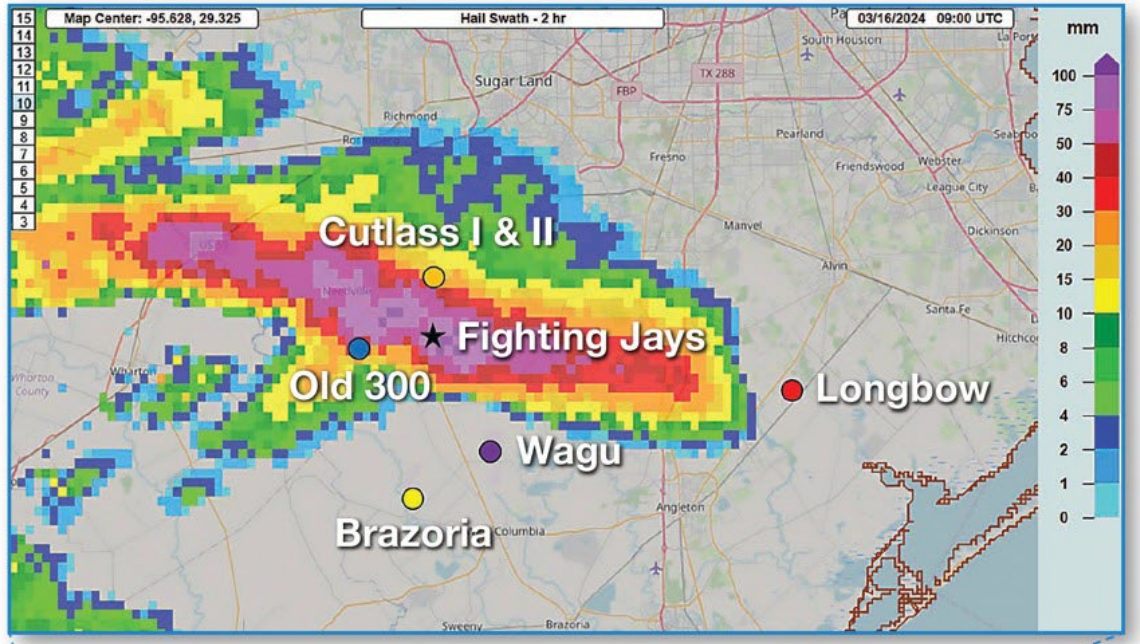
VDE Americas provides **technical advisory and risk mitigation services** to equipment manufacturers and those who develop, finance, construct, own, operate, and insure large-scale solar power generation and energy storage facilities. Our products and services have facilitated the financing of **over $15 billion in operating renewable energy assets**. Our parent company is one of the largest technology organizations in Europe.

We are the world's leading expert in solar project hail risk intelligence and loss prevention.

Severe weather event analysis in Fort Bend County area

Three utility PV projects located within 15 km (9.3 mi) of Fighting Jays solar farm:

- **Cutlass 1** [108 MWp]
- **Cutlass 2** [272 MWp]
- **Old 300** [270 MWp]



NOAA National Severe Storms Laboratory (NOAA NSSL), 2024

Area of interest is roughly 30 miles south-by-southwest of Houston

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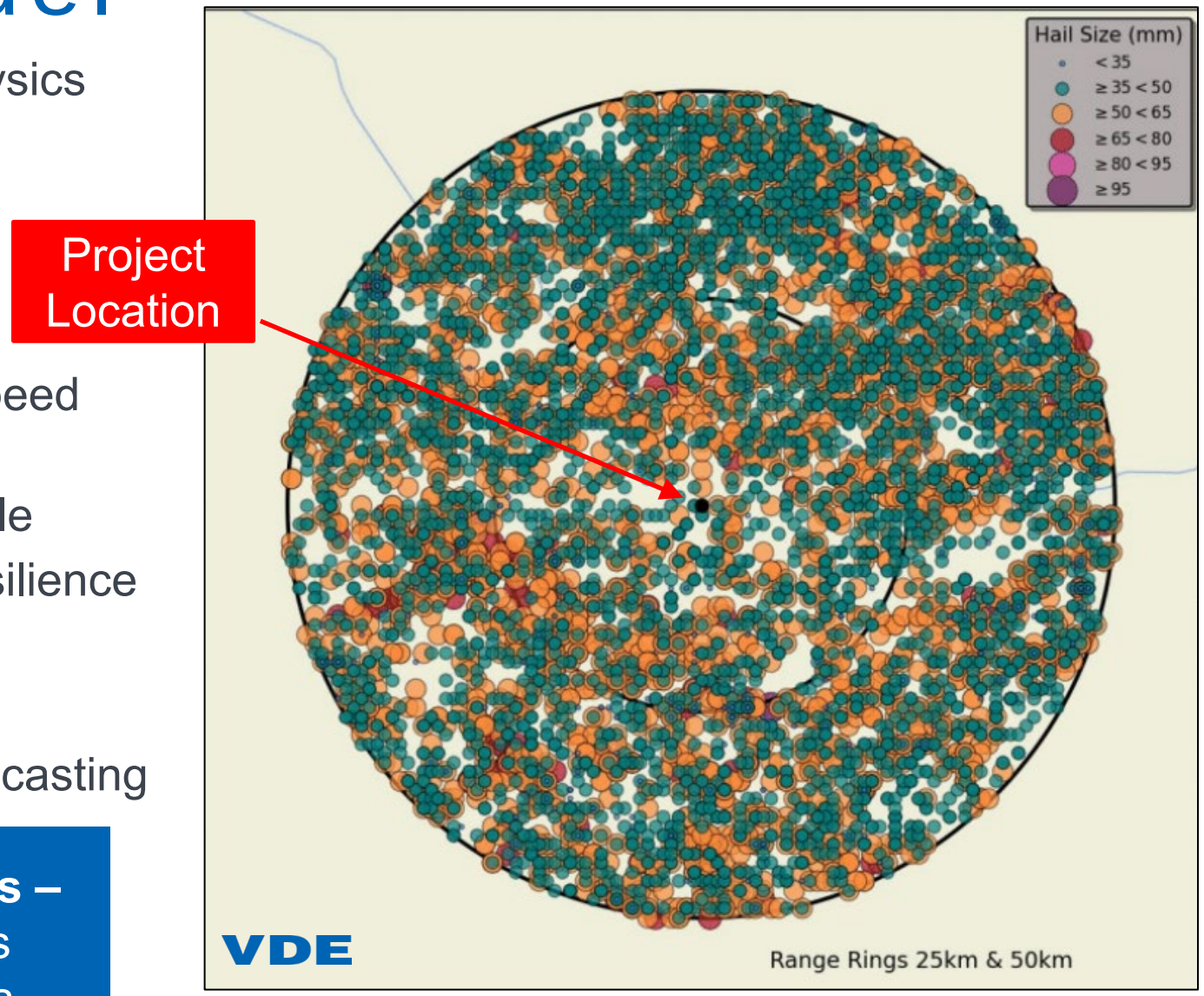
VDE Hail Risk Model

- Coupled Hail Meteorology – Impact Physics Model
  - Hail D_{max} observations
  - Hail size distribution
  - Hailstone density distribution
  - Wind speed modification of hail speed and direction
  - Impact energy of hail on PV module
  - Empirically derived PV module resilience
  - Hailstorm swath width factor
- Compared with forensic analyses
- Spatial scaling of hail data used for forecasting

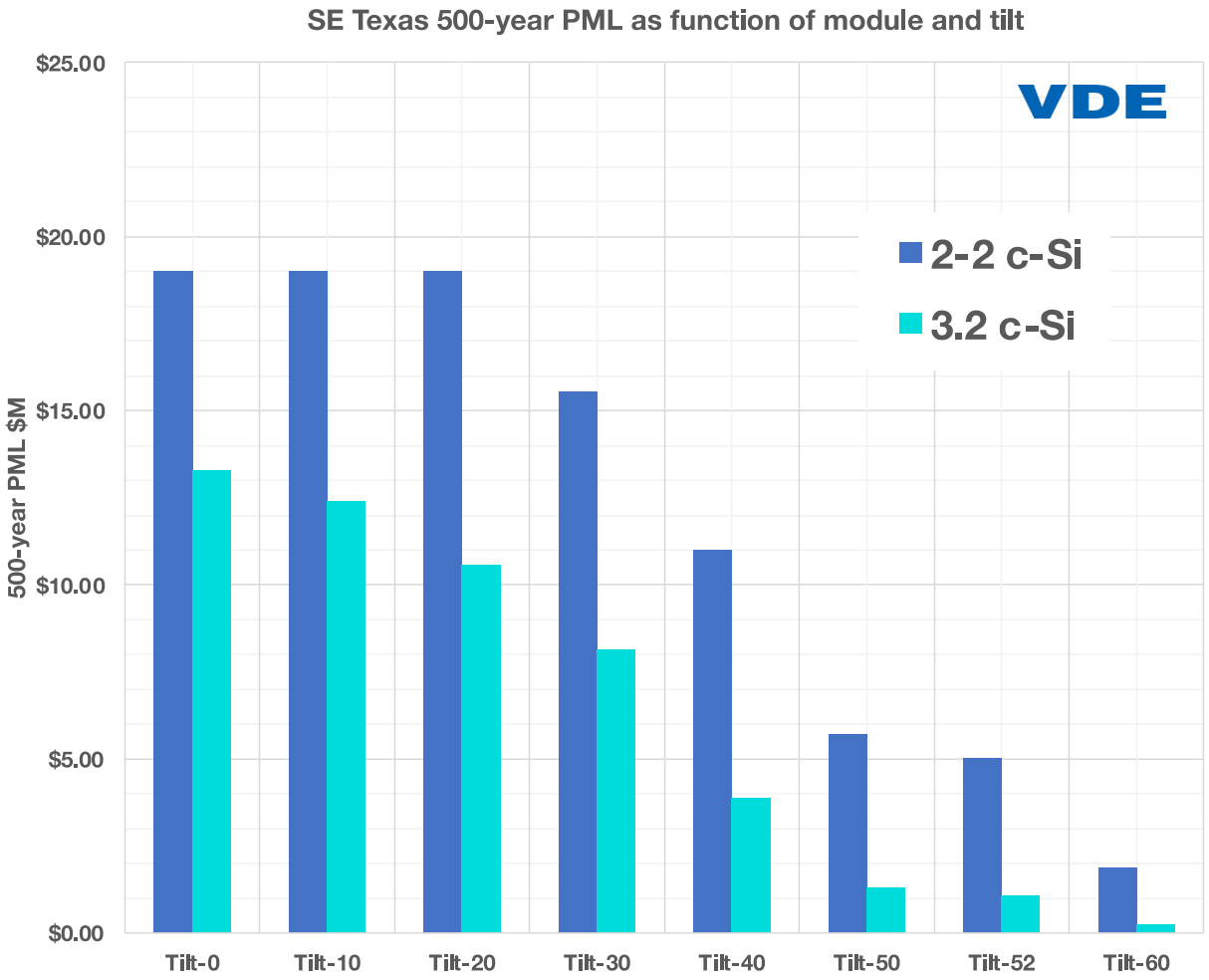
Predictive for specific PV power plants – location, plant size, module type, glass type, module angle, hail stow strategies, $/W replacement cost, etc.



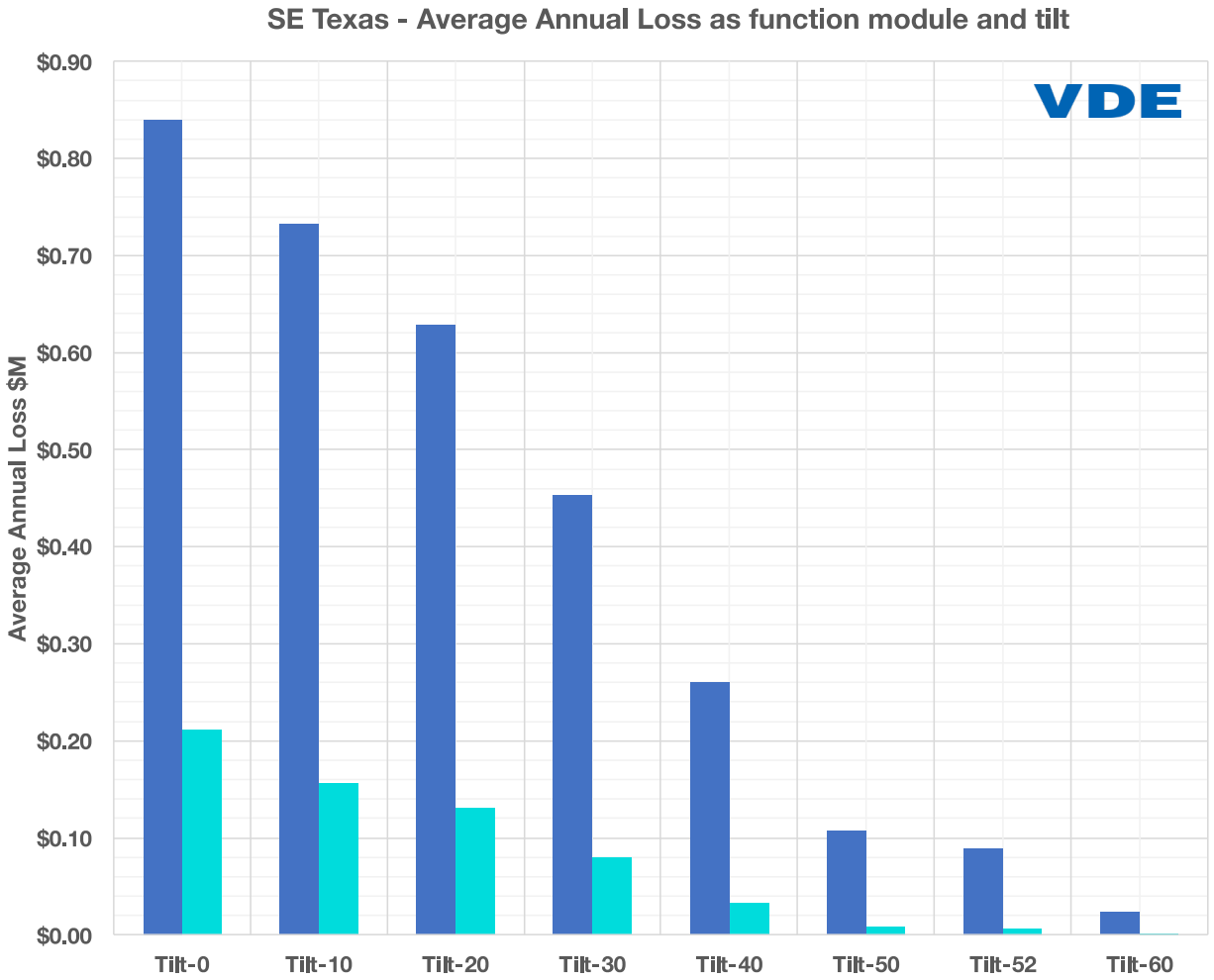
Hail Observations with Size in Region (VDE)

VDE Hail Risk Model

Risk comparison for 2-2 mm dual glass v 3.2 mm glass-poly modules, Southeast TX project



500-yr Probable Maximum Loss, PML (VDE)



Average Annual Loss, AAL (VDE)

Severe hail events on March 15, 2024

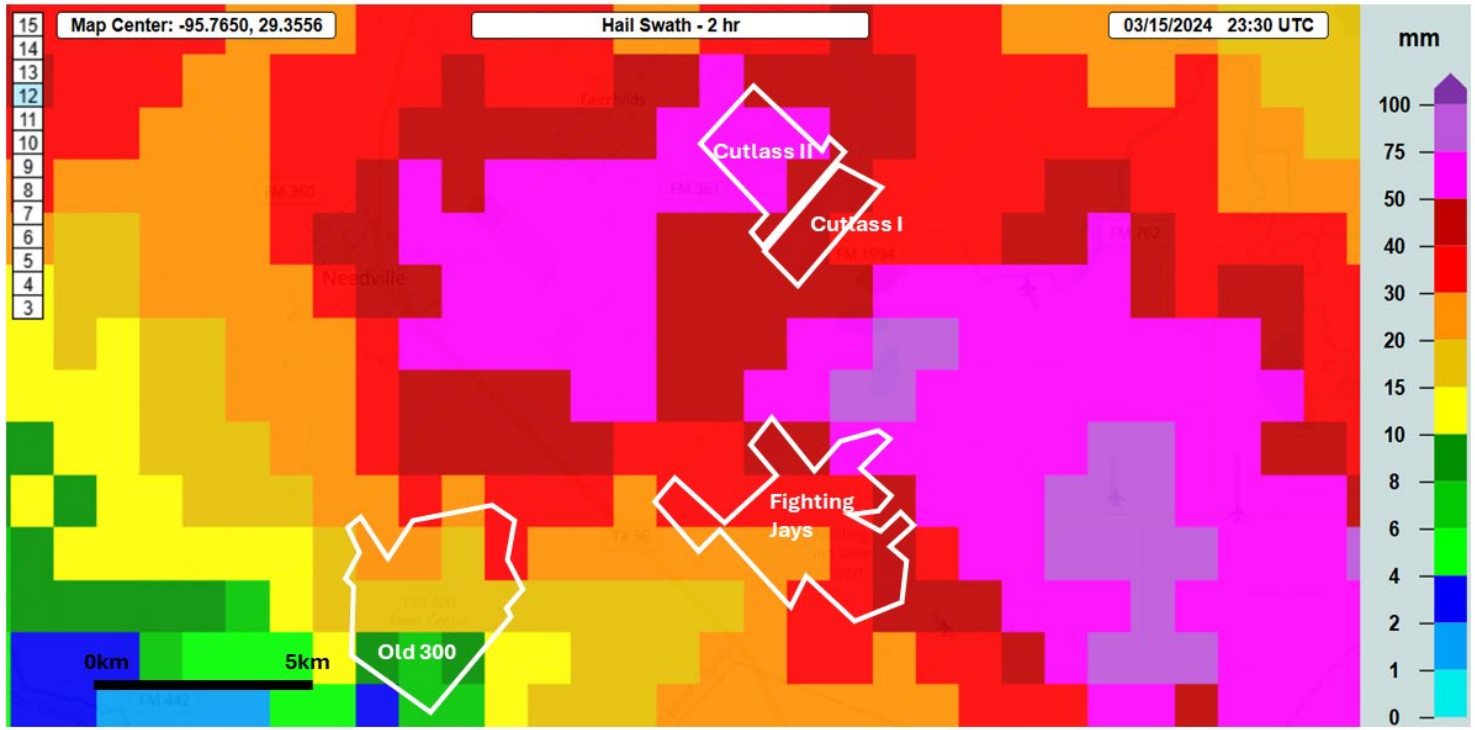
Storm 1

- No MESH* project overlap

Storm 2

- More intense that Storm 1 with MESH project overlap
- Around 5:00–6:30 p.m. CDT
- Up to 51 mph windspeed at site
- Storm moving at about 23 mph
- Westerly prevailing wind, wind direction at sites during hail unknown

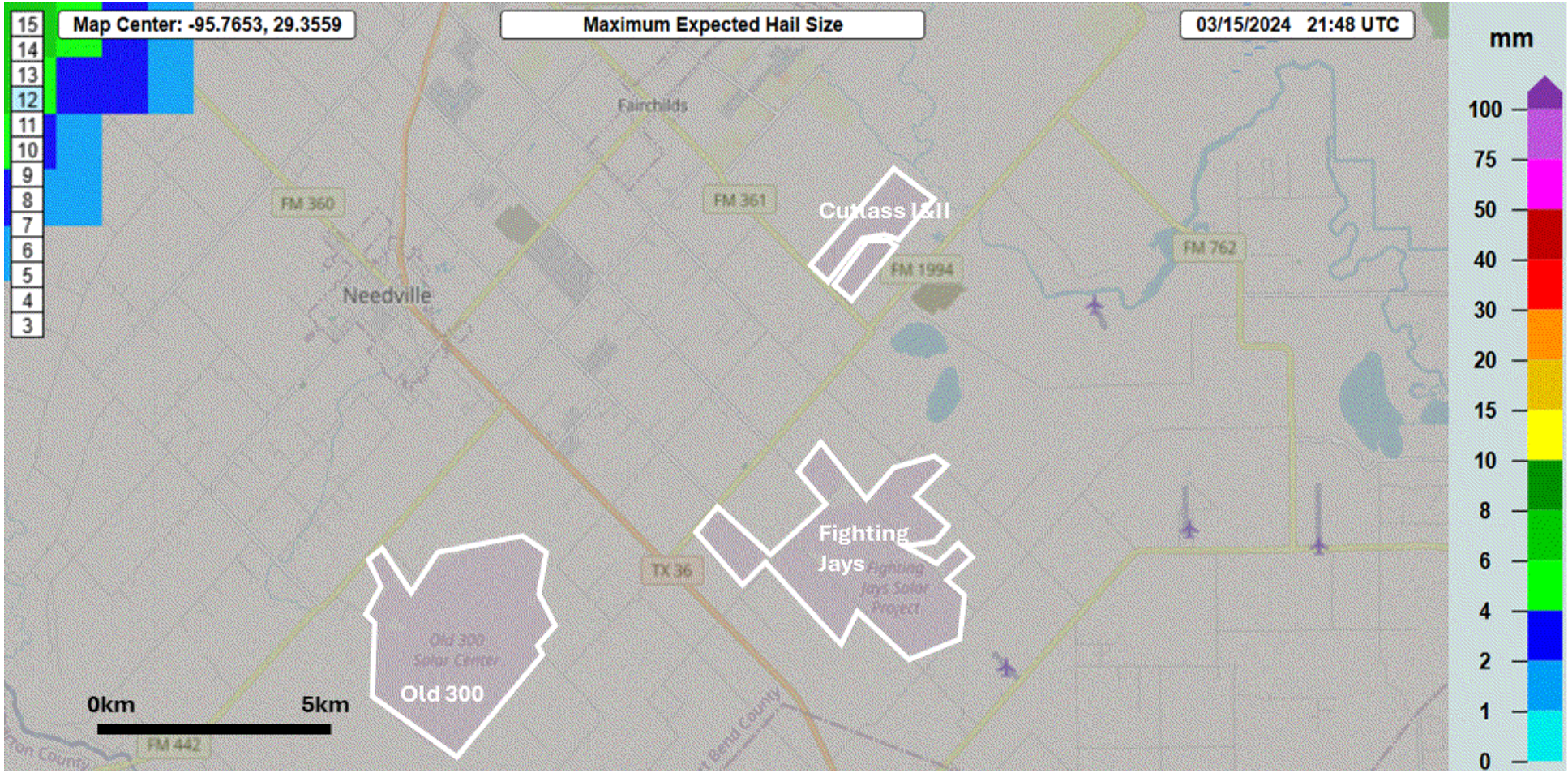
Note: *Some spatial uncertainty exists*



NOAA National Severe Storms Laboratory (NOAA NSSL), 2024

****MESH** = maximum estimated size of hail*

76-minute hail event time lapse for Storm 2 on March 15, 2024



NOAA NSSL, 2024

MESH data for Storm 2 hail event **on March 15, 2024**

Fighting Jays

- Potential maximum hail size of 50–75 mm

Old 300

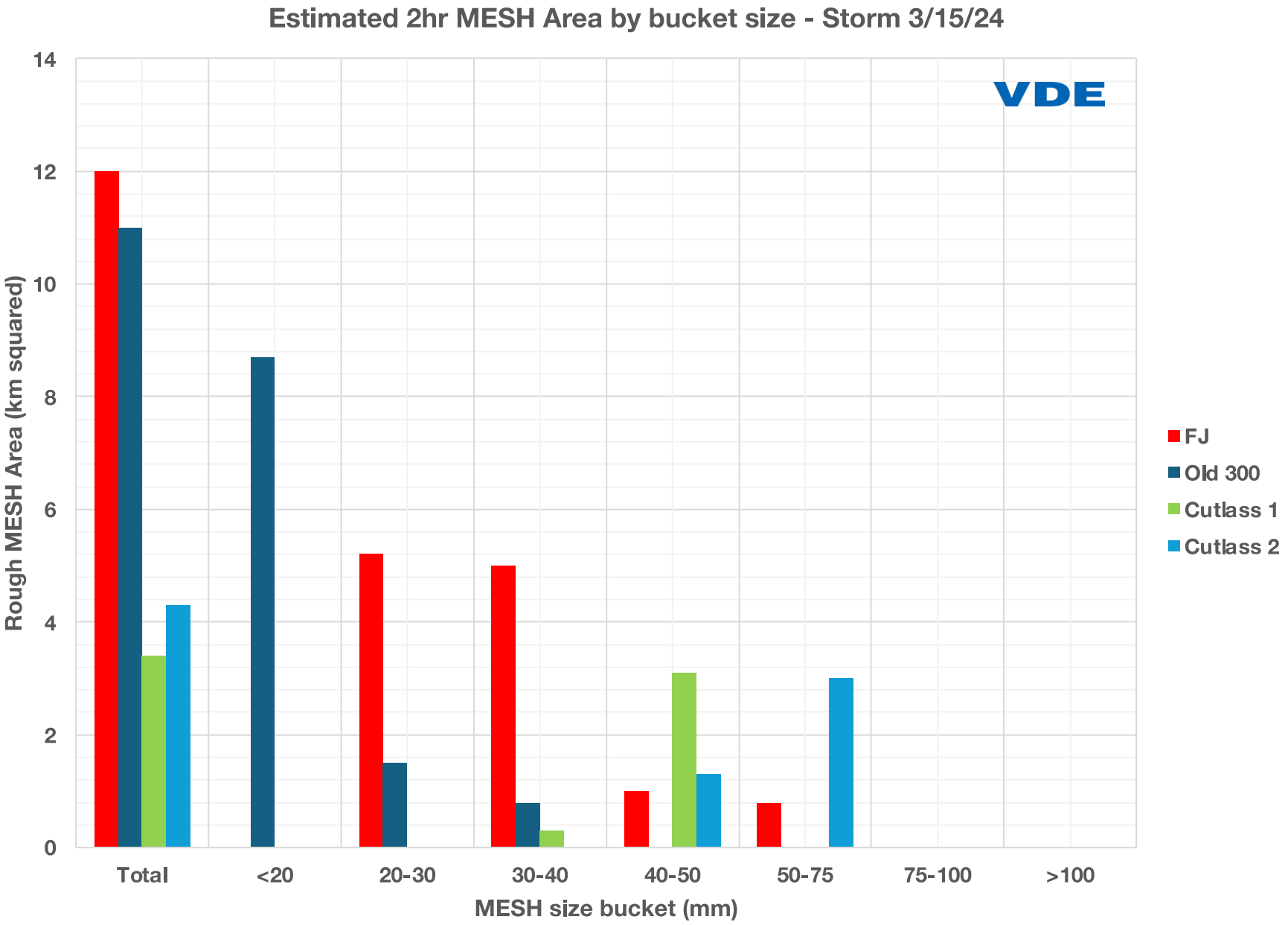
- Maximum hail size of 30–40 mm

Cutlass I

- Mostly 40–50 mm hail across project area

Cutlass II

- Mostly 50–75 mm hail across project area

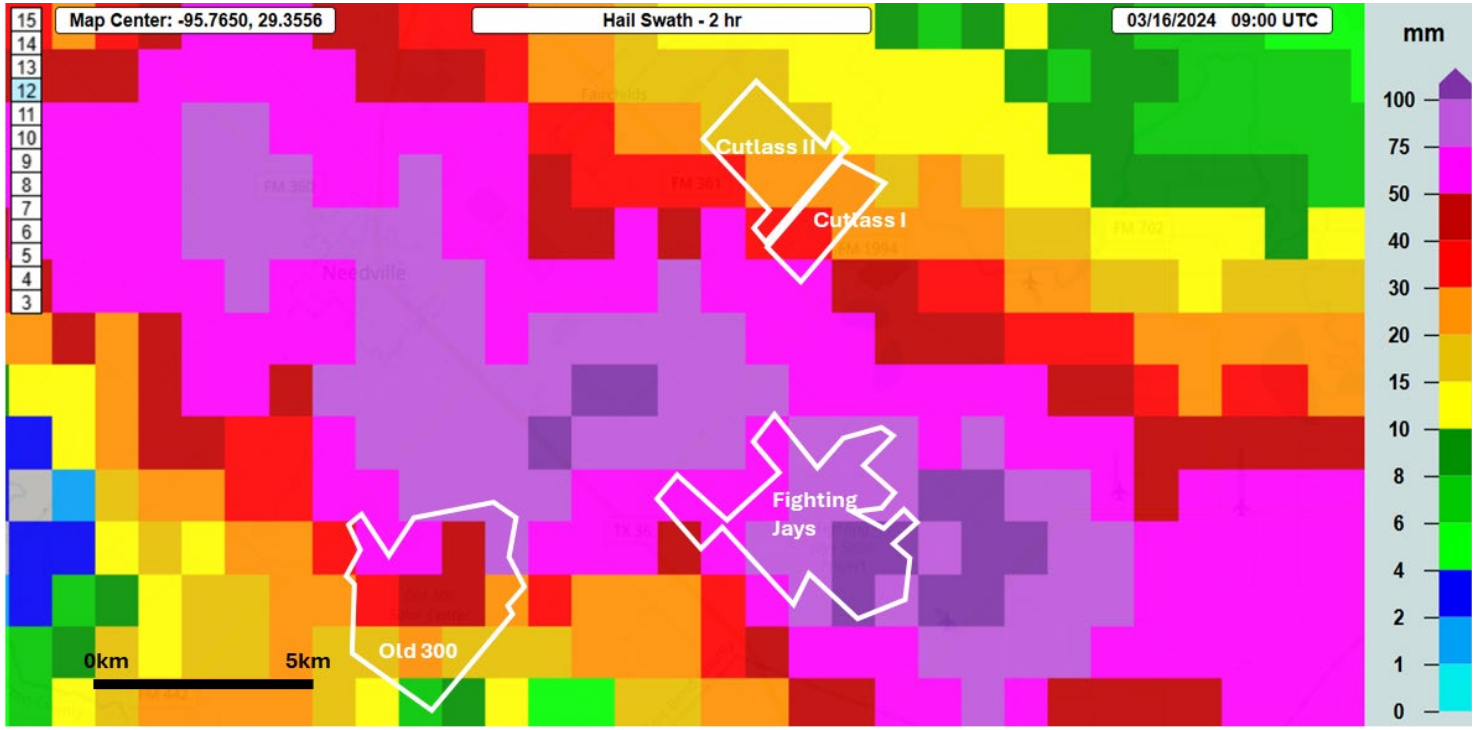


Severe hail event on March 16, 2024

Major overnight hailstorm:

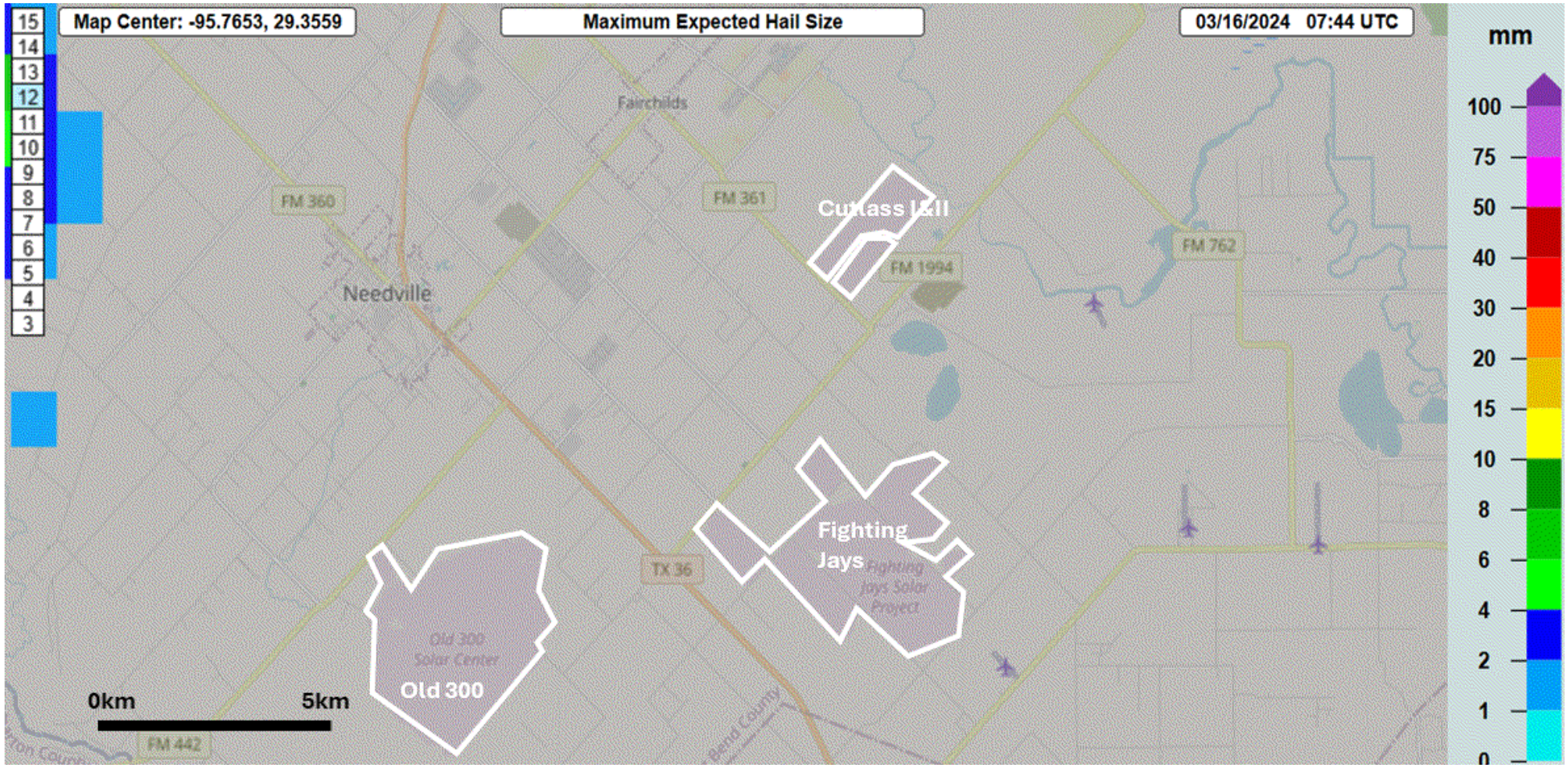
- More severe than Storm 2 hail event on March 15
- Around 2:30-3:30 a.m. CDT
- MESH project overlap
- Up to 31 mph wind speed at site
- Storm moving about 30 mph
- Westerly prevailing wind, wind direction at sites during hail unknown

Note: *Some spatial uncertainty exists*



NOAA NSSL, 2024

56-minute hail event time lapse for on March 16, 2024



NOAA NSSL, 2024

MESH data for overnight hail event **on March 16, 2024**

Fighting Jays

- Max hail size >100 mm on southeastern flank
- 50% of project area exposed to hail size of 75–100 mm

Old 300

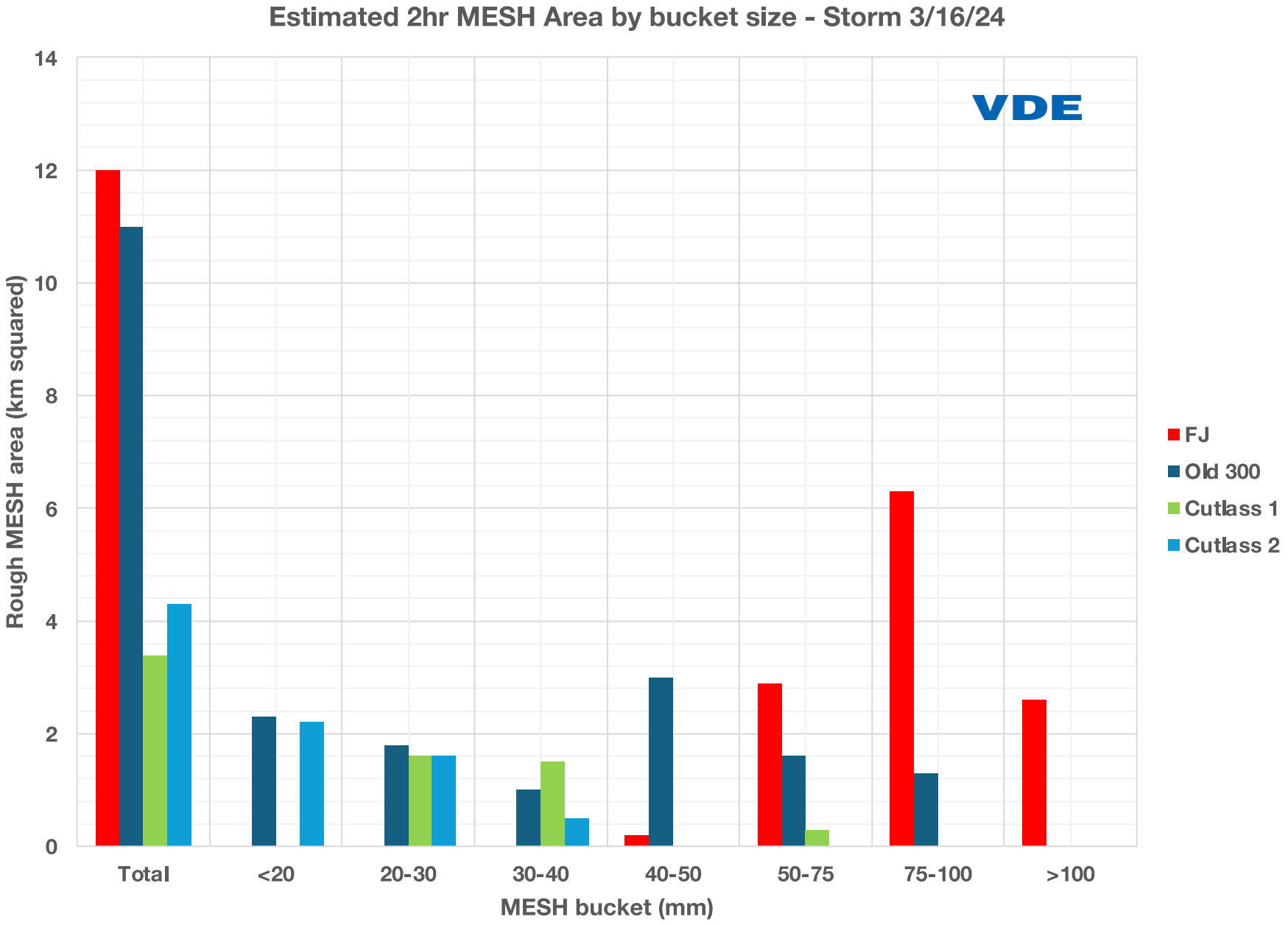
- Max hail size of 75–100 mm on northeastern flank
- Confirmed by operations

Cutlass I

- Max hail size 50–75 mm at southern tip with gradient across project area
- Ambiguity in operations reports (unclear if staff on site, some said no, some yes hail)

Cutlass II

- Max hail of 30–40 mm



Synopsis of hail event impacts

Fighting Jays

- **Hail damage** (no public details available)

Old 300

- **Hail damage limited to ~40 modules** on a non-stowed tracker (motor fault predated storm)
- <10 modules damaged due to wind-blown objects
- Oil gauge damaged on one MVT [medium-voltage transformer], causing inverter skid shutdown
- Tracker stow direction relative to wind direction unknown

Cutlass I

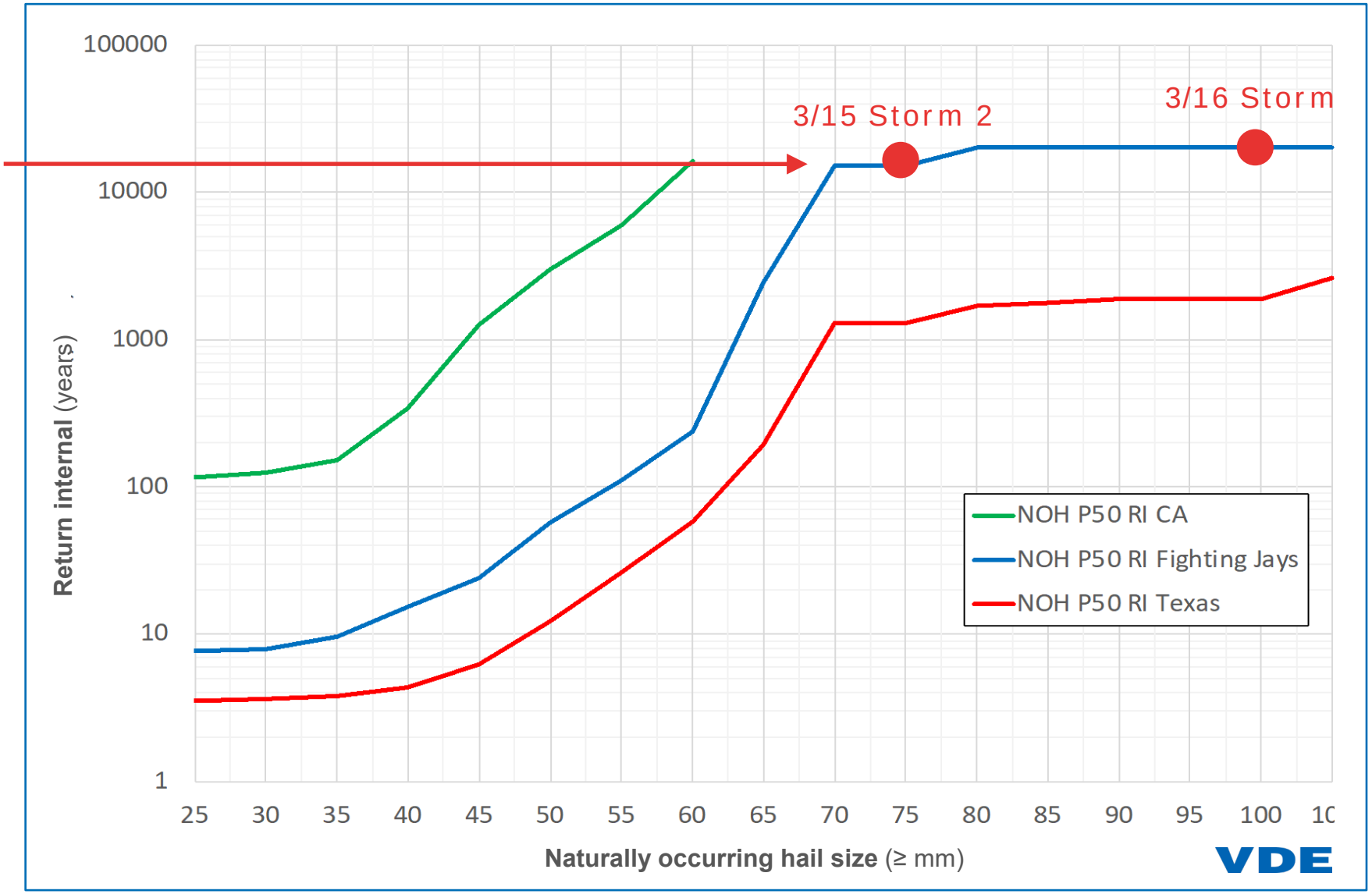
- **No hail damage reported**
- Stowed per protocol to nearest extreme angle
- Tracker stow direction relative to wind direction unknown

Cutlass II

- **No hail damage reported**
- Project under construction
- Unknown portion of plant in hail stow per protocol.
- Tracker stow direction relative to wind direction unknown

Hail return interval **for Fort Bend County area**

Storm system generated atypically large hail for area



Note:
Size estimates are uncalibrated with spotter data, so could be slightly smaller in reality but still exceptionally large.

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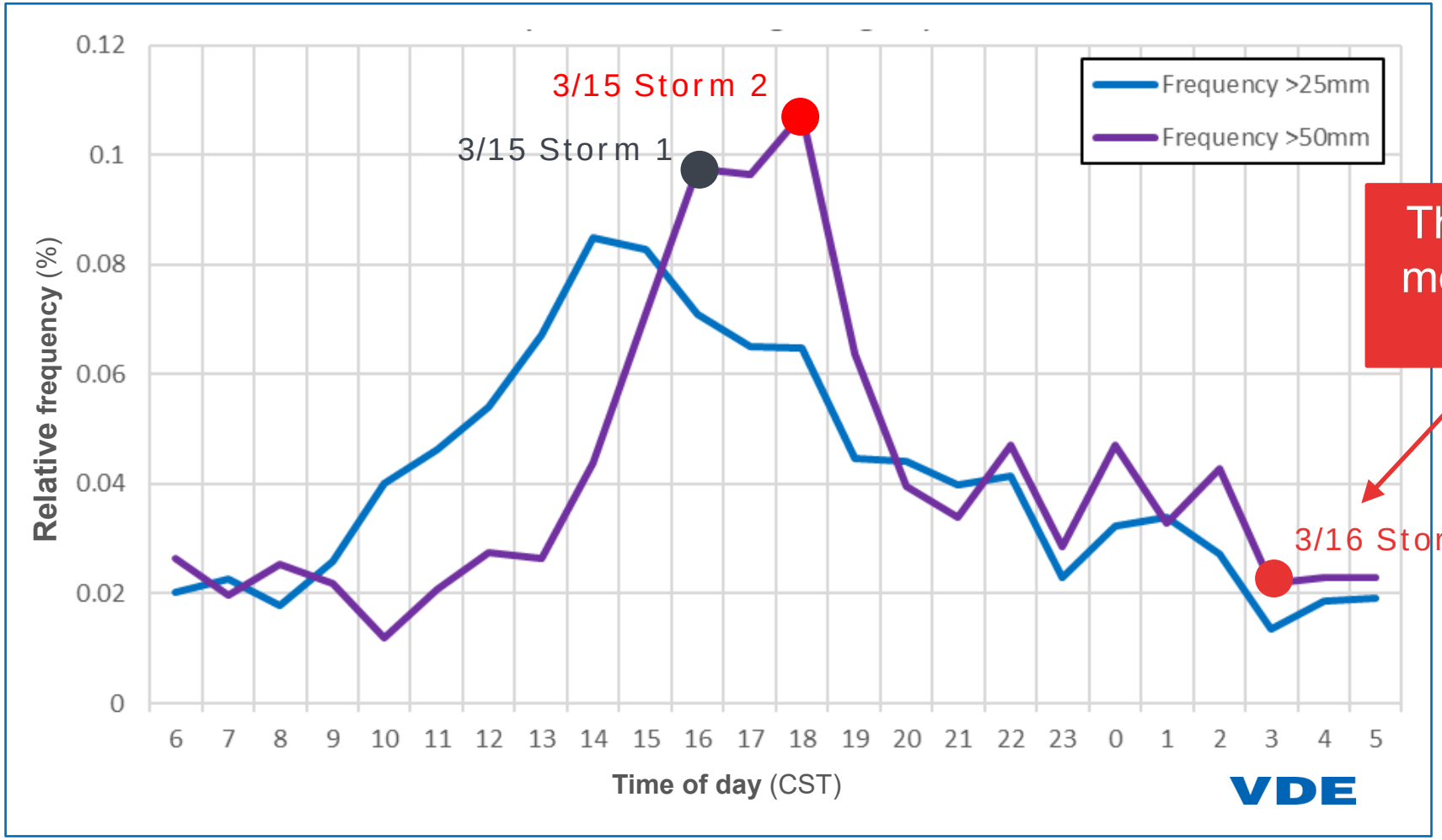
Diurnal hail risk **for Fort Bend County area**



The overnight timing of the most intense hailstorm was very unusual

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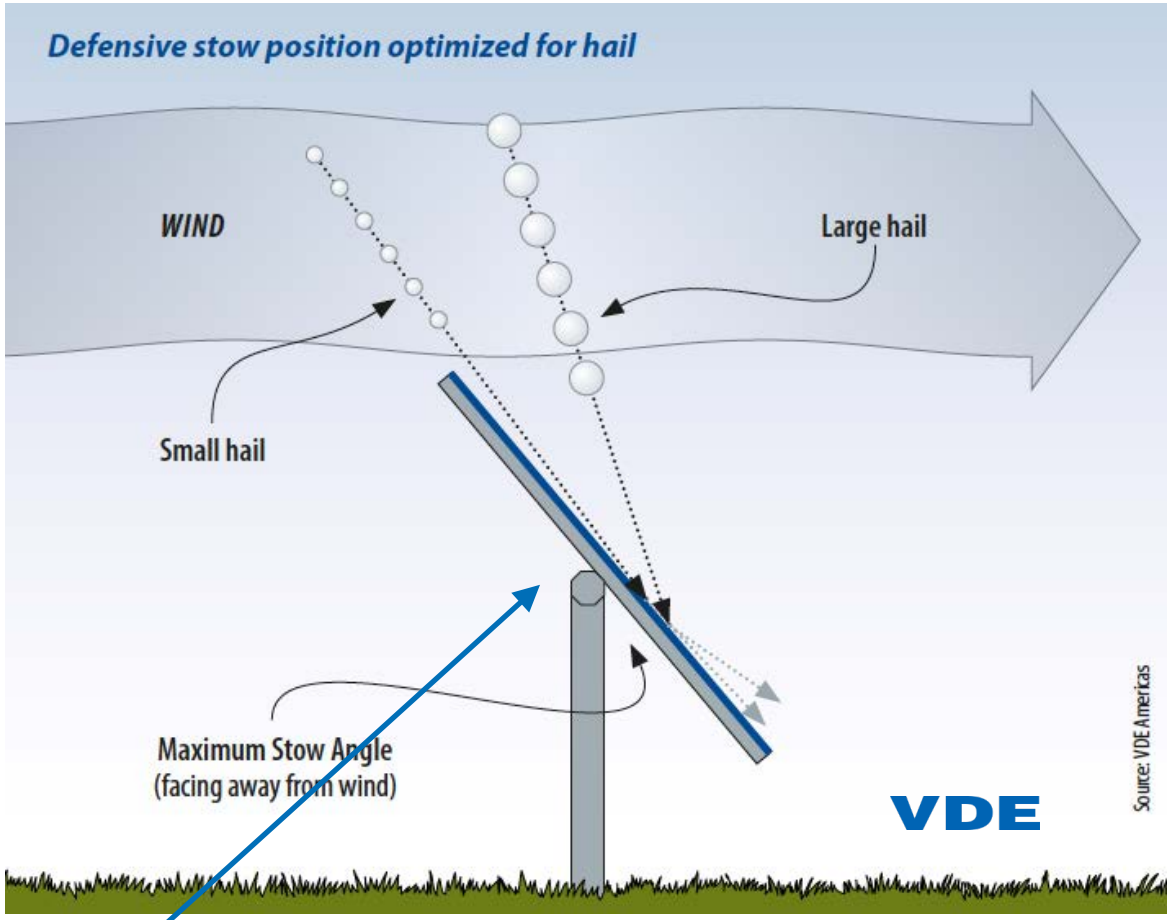
Key findings **from Fort Bend County forensic investigation**

- **Hail stow prevented module damage** at multiple projects exposed to >1-in-500-year hail.
- At Old 300 or Cutlass I & II, there was **no hail damage to modules in a defensive stow position**.
- **Hail damage was limited to modules not in a defensive hail stow position.**
- Reliable **weather forecasting and quick response times are critical** to success.
- It is **important to have a nighttime hail stow protocol** as hailstorms can occur overnight.



Defensive hail stow protocols are effective for the prevention of physical damage to PV modules

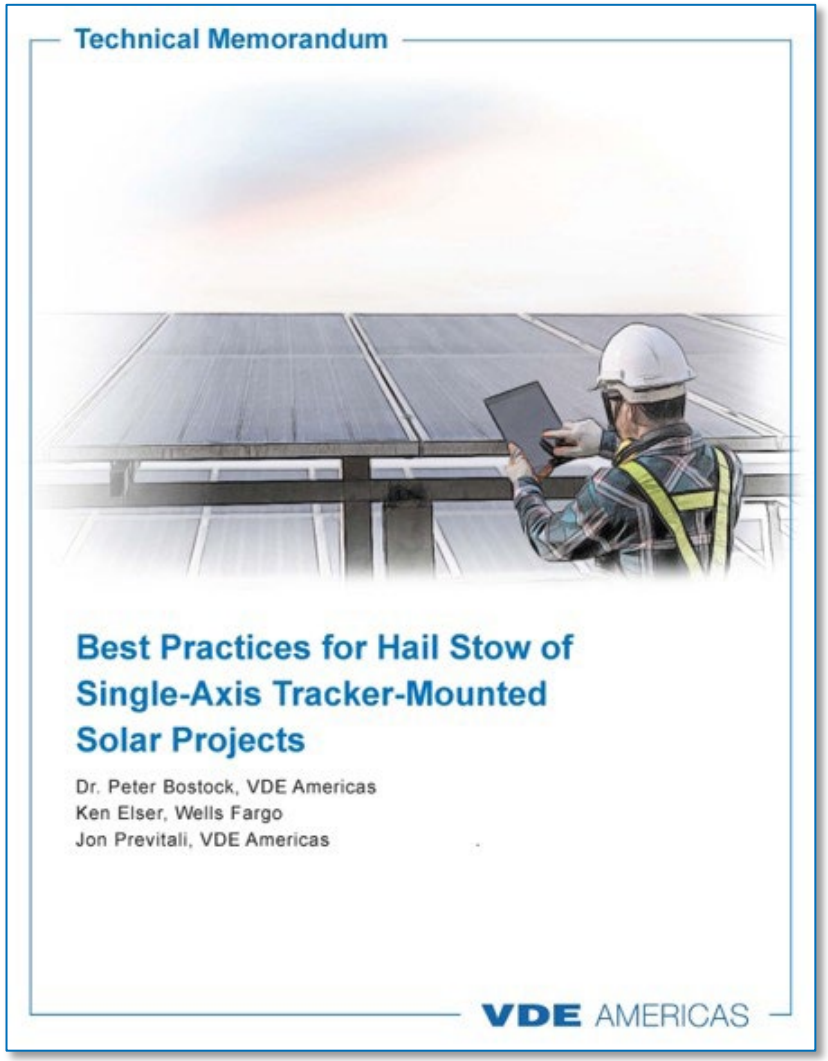
VDE

Download VDE's best practices for operational hail defenses

Co-authored with Wells Fargo, VDE's free tech memo provides specific and actionable insights proven to safeguard solar projects against hail damage.

Best practices include:

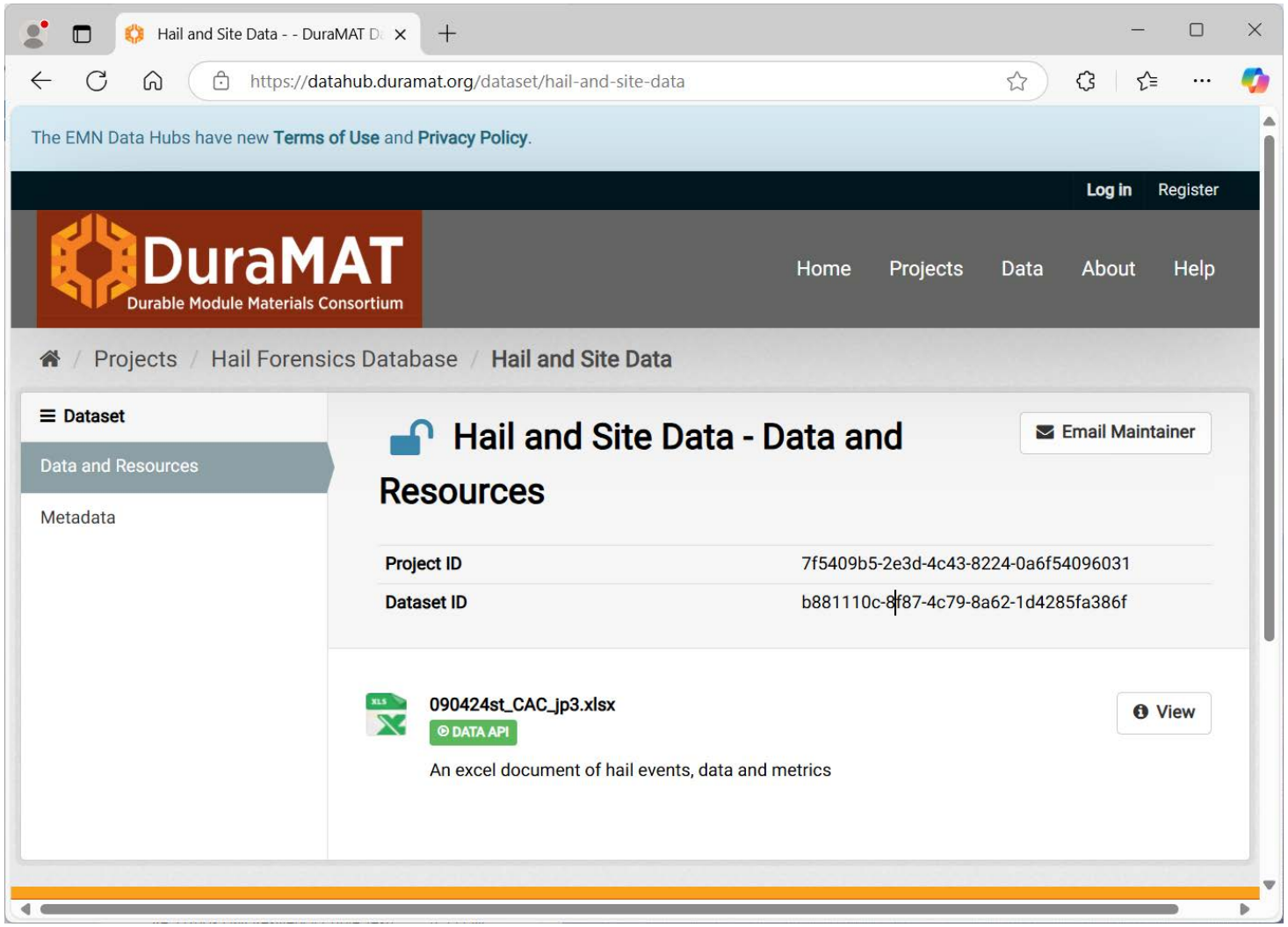
- Recommendations for **before** a severe hailstorm
- Recommendations for **during** a severe hailstorm
- Recommendations for **after** a severe hailstorm



Scan QR code or visit VDE Americas' newsroom at **vdeamericas.com**

VDE

Donate or Access Data on the DuraMAT Hail Forensics Database



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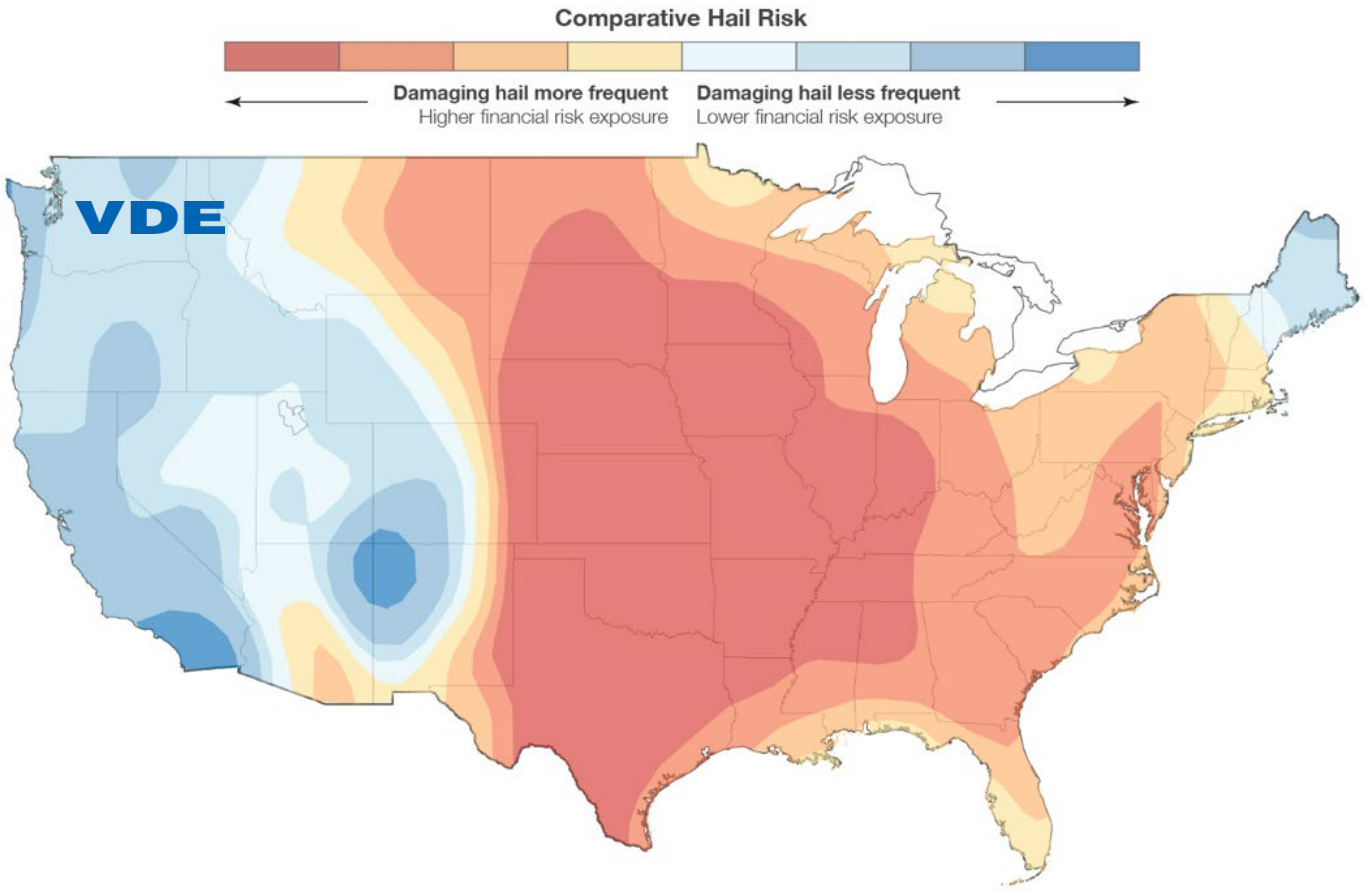
We are protecting critical energy assets to ensure a worthwhile future.

Please join us.



Jon Previtali
Vice President | VDE Americas
jon.previtali@vde.com

VDE

Full-scale, High-speed Wind Testing of Trackers

Measured Accelerations on PV glass

Tushar Guha, PhD, Nextracker, Fremont CA
Majid Nili, PhD, Nextracker, Fremont CA
Kent Whitfield, Nextracker, Fremont CA
David Kresse P.E. Nextracker, Fremont CA
Jeroen van Dam, NREL, Boulder CO

March 2025

nextracker

Outline

- Full scale testing program overview
- Comparison of measured accelerations
  - Tracker tilt angles measured
  - End of row .vs. mid-bay locations
  - Exterior .vs. exterior rows
  - PV glass .vs. torque tube (TT) locations
  - TT accel: row 1, 2, and 5 comparison
- Frequency content
- Exploratory PV shaker test
- Summary

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Full Scale Testing – NREL Flatirons campus

600+ channels of data since 2020

Data includes:

- wind
- force
- strain
- torque
- acceleration
- displacement
- control status
- video

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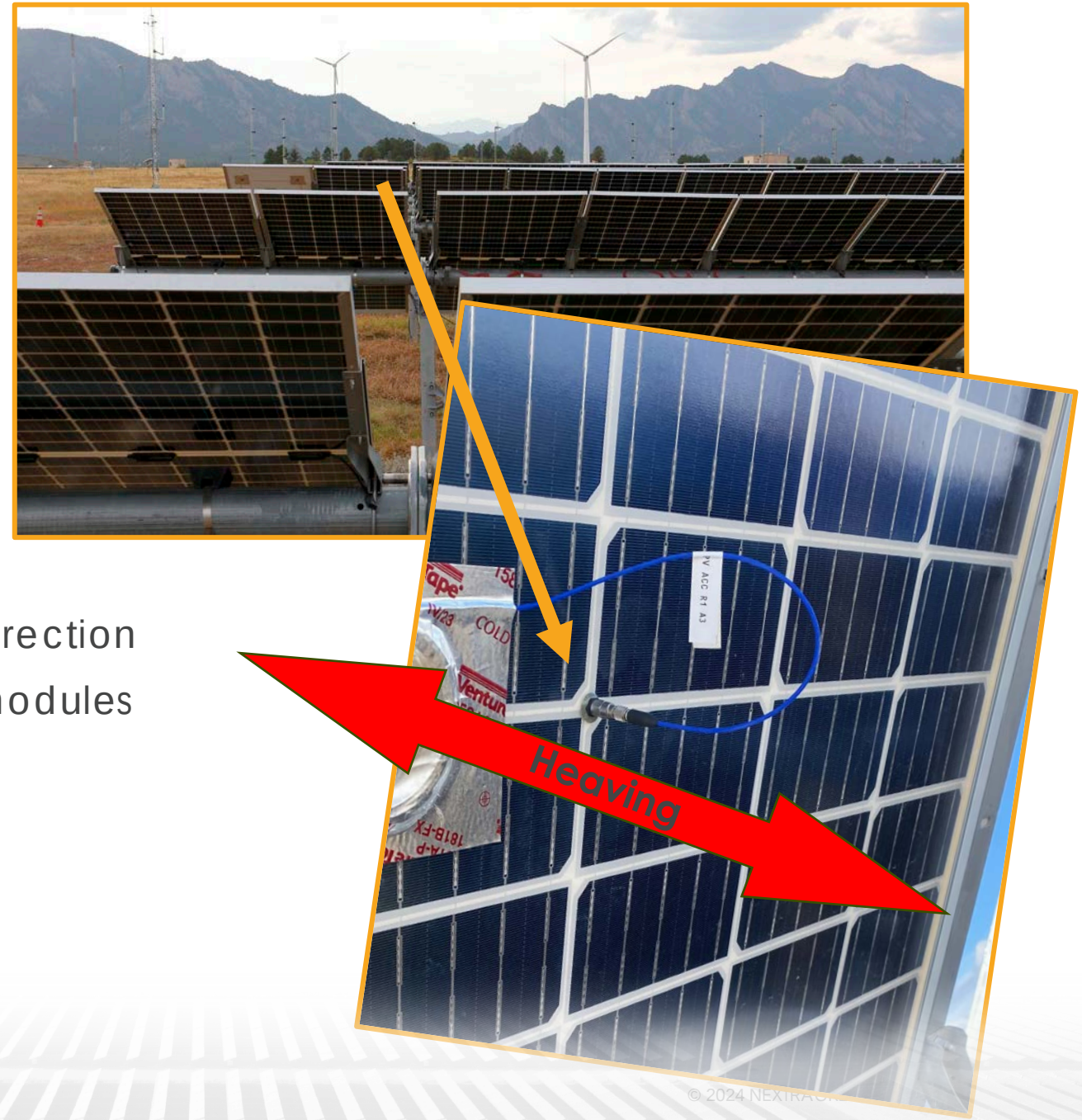
Instrumentation

Tracker configuration:

- 87 module rows w/ 2-module cantilever
- PV modules, 2m x 1m size (old size)
- Dual glass, 2mm thickness



Instrumentation:

- Focused on the out-of-plane, **(heaving)** direction
- PV accelerometers: backside of four PV modules
  - 2x Row 1: end and mid-bay, bay 4
  - 2x Row 5: end and mid bay, bay 4
- TT accelerometers: Up/Down, E/W, twist
  - 7x Row 1, Row 2, Row 5 mid-bay

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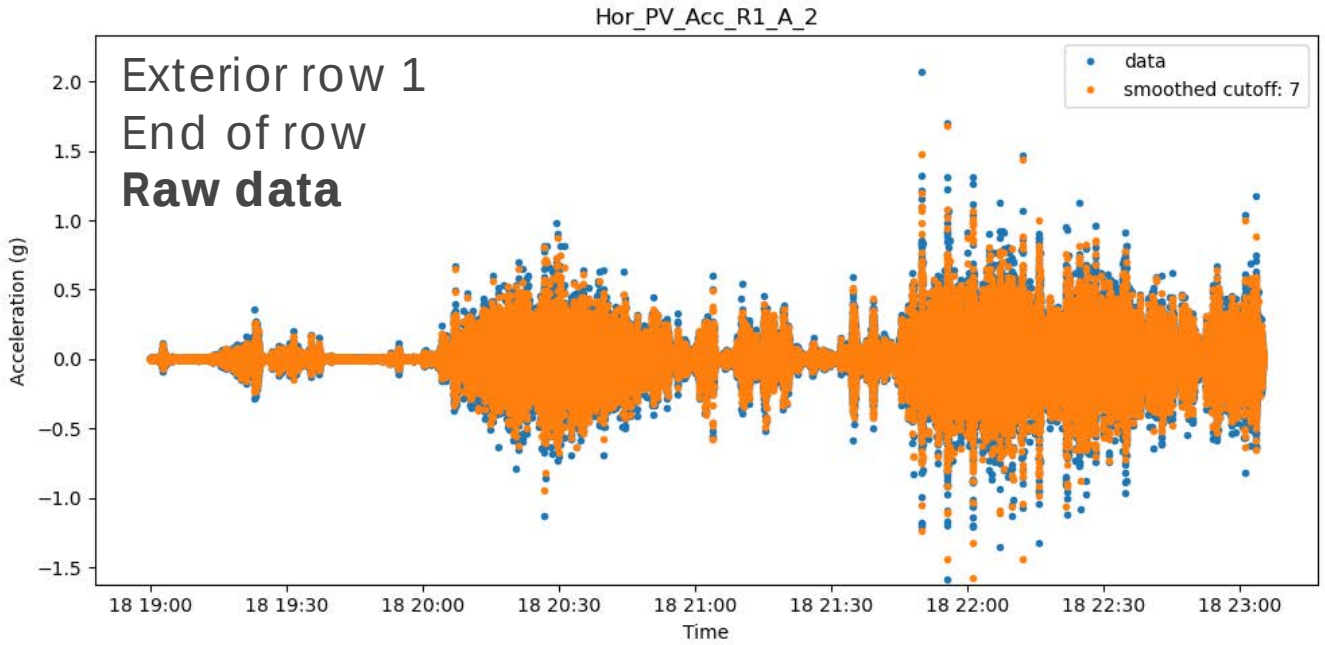
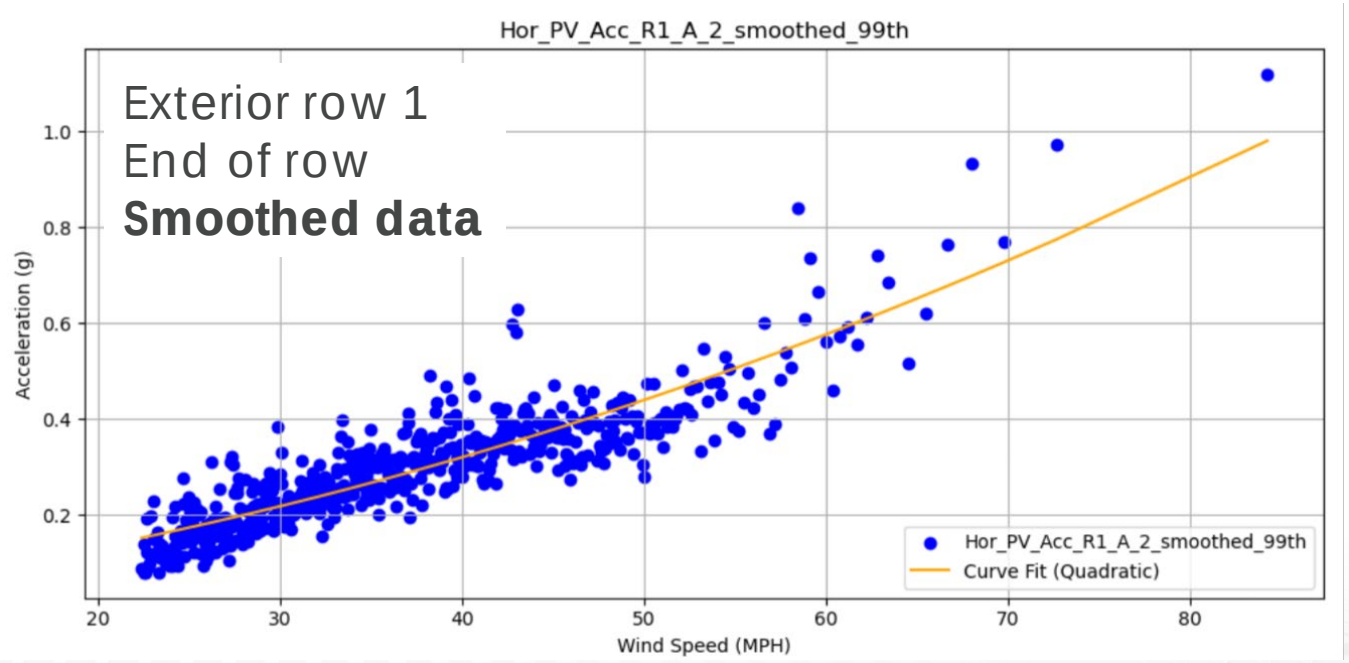
Data Handling

- 20 hz raw data
- 7 Hz cutoff frequency
- 99th percentile
- Quadratic fit presented for clarity
- **Disclaimers**:

1. Variability of accelerations observed under different wind conditions.
2. Extrapolation to 110 mph is the expected trend, not based on measured data (shown below as **)





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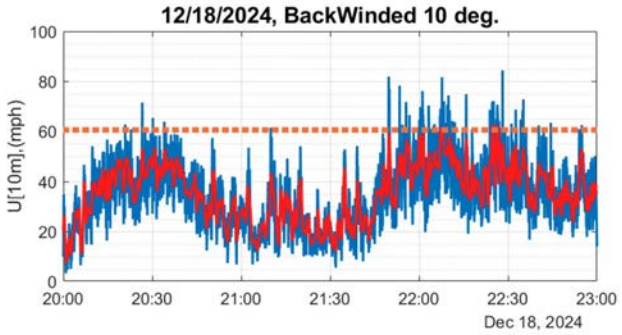
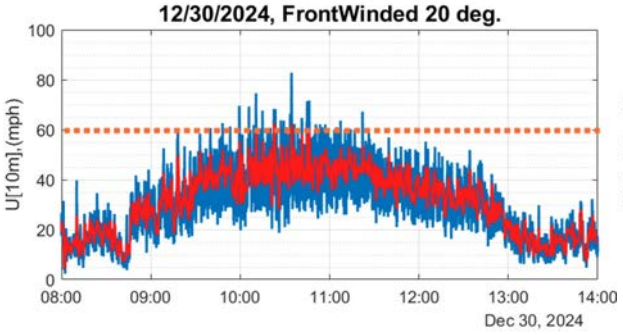
Tilt Angles Compared, (-10°, +20°, +60°, -60°)

- Four recent wind events during December and January
- Trackers maintained at fixed tilt angles throughout wind event
- Wind direction (mostly) orthogonal to the trackers. Cornering winds may differ
- More, higher wind speed data is needed to build statistical validity

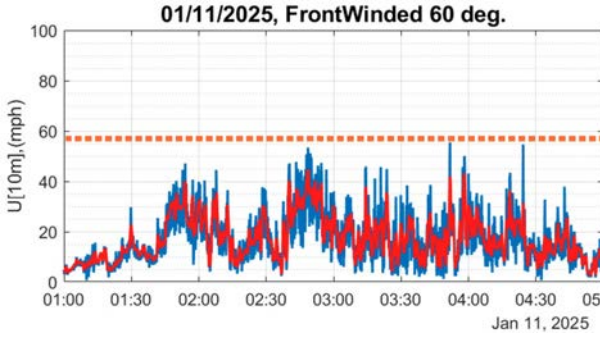
12/18/24
Back winded 10°



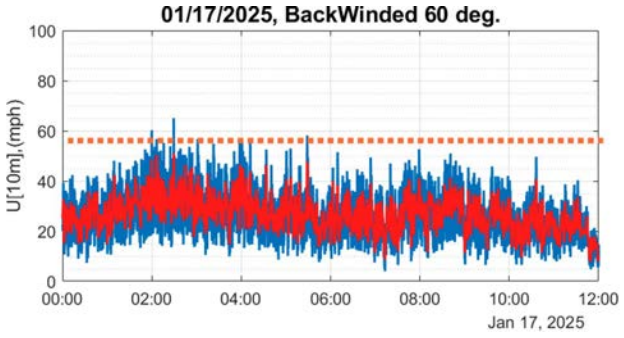
12/30/24
Front winded 20°



01/11/25
Front winded 60°



01/17/25
Back winded 60°



3s gust — 60s mean

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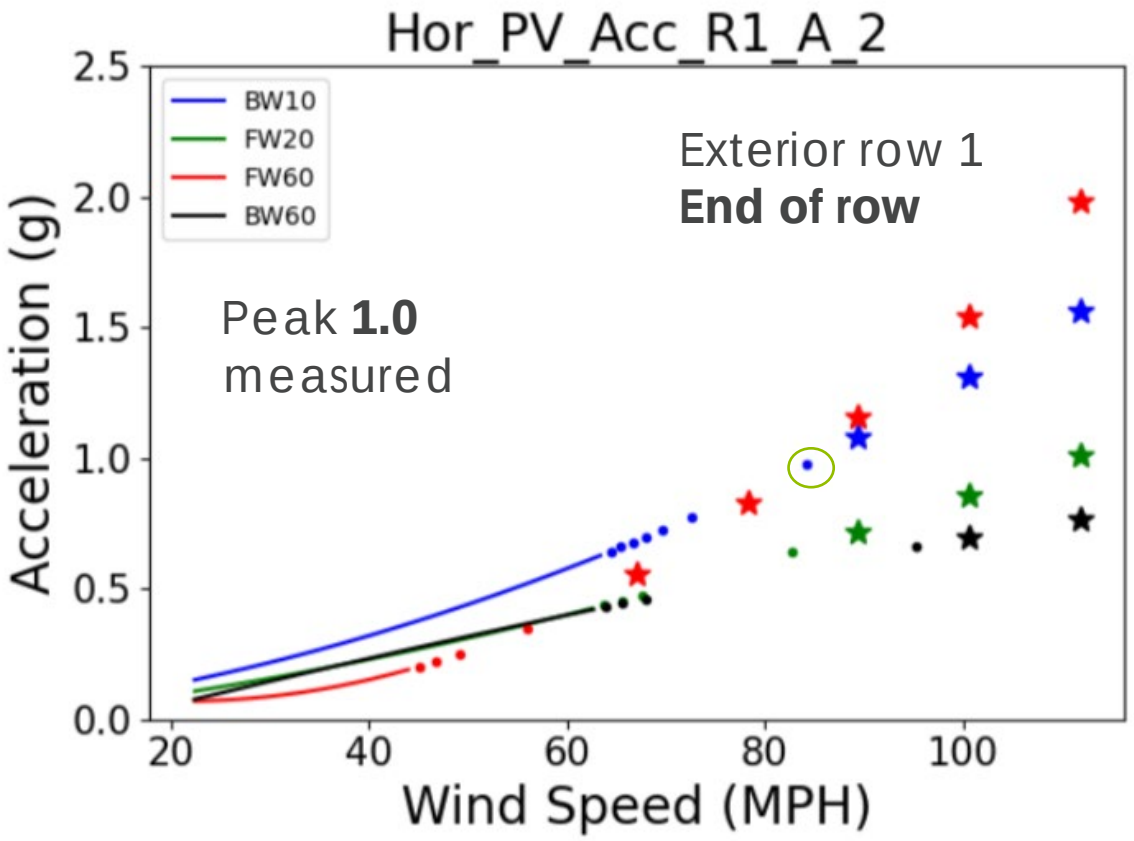
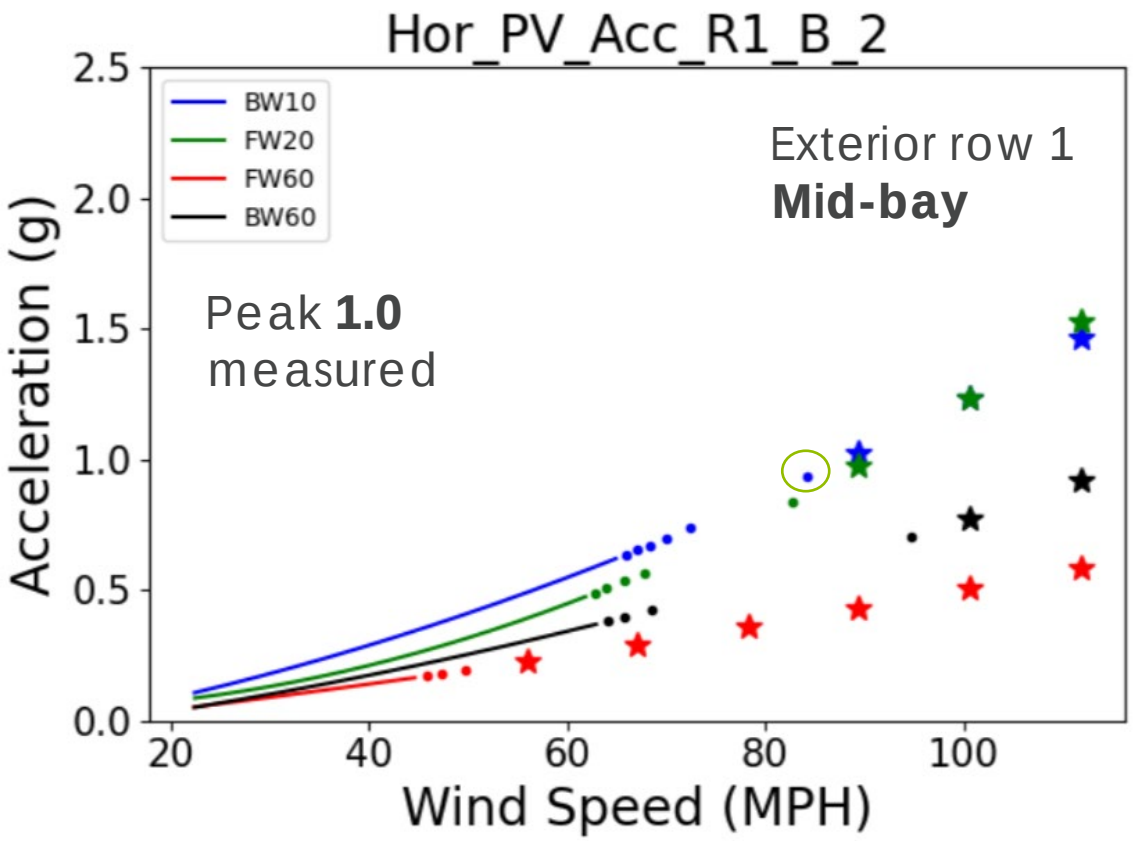
PV Acceleration: Row End .vs. Mid-bay

- Row 1 accelerations are equivalent between end and mid-bay
- End positions are near foundation piles, “stiff”, while mid-bay positions are “flexible”
- Actual low tilt positions are higher than commanded, due to row twist and higher normal force





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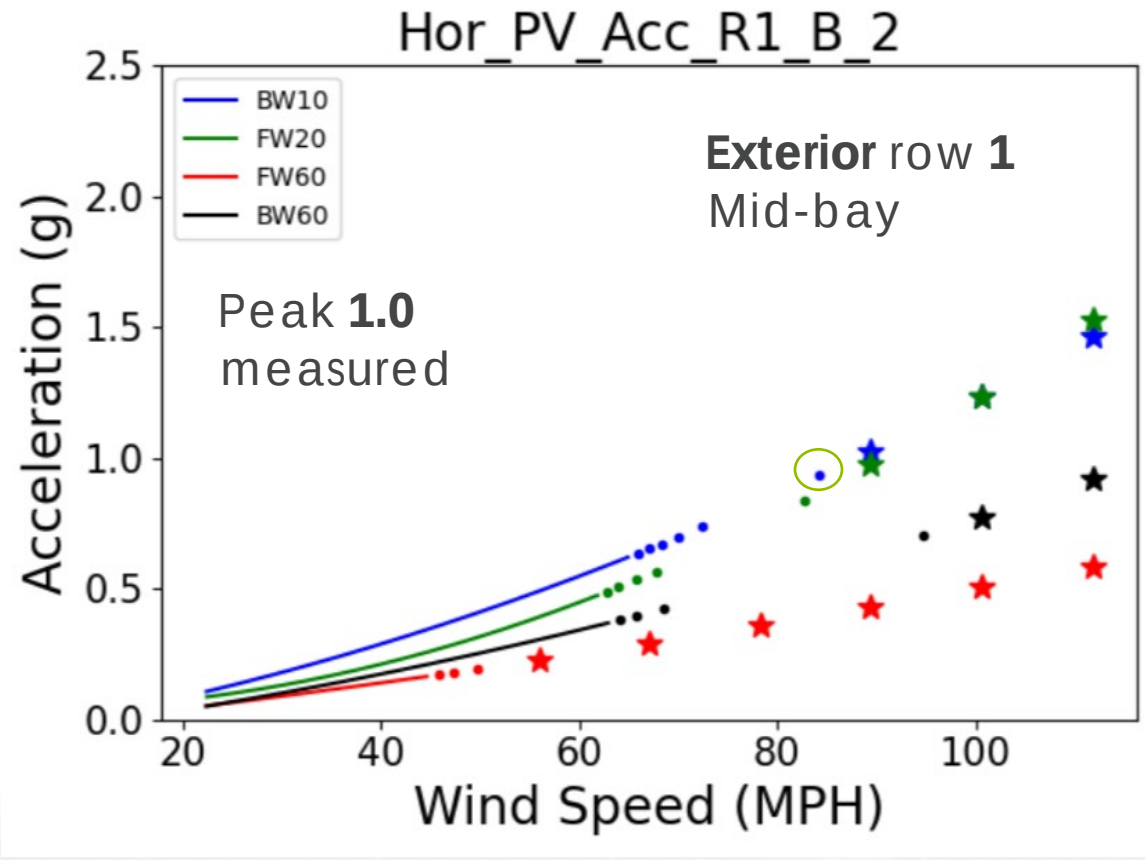
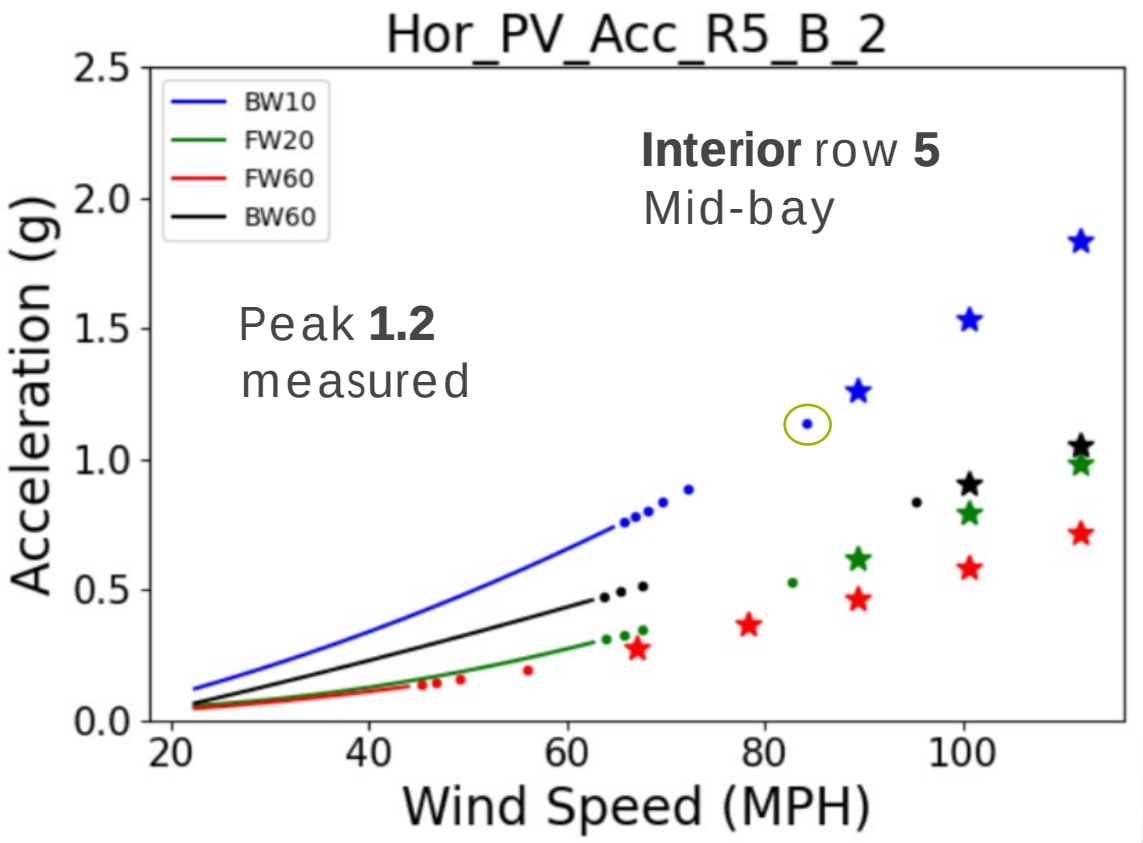
PV Acceleration: Row 1 .vs. Row 5

- Interior rows have lower normal force / wind pressure
- But generally, have increased accelerations compared to row 1





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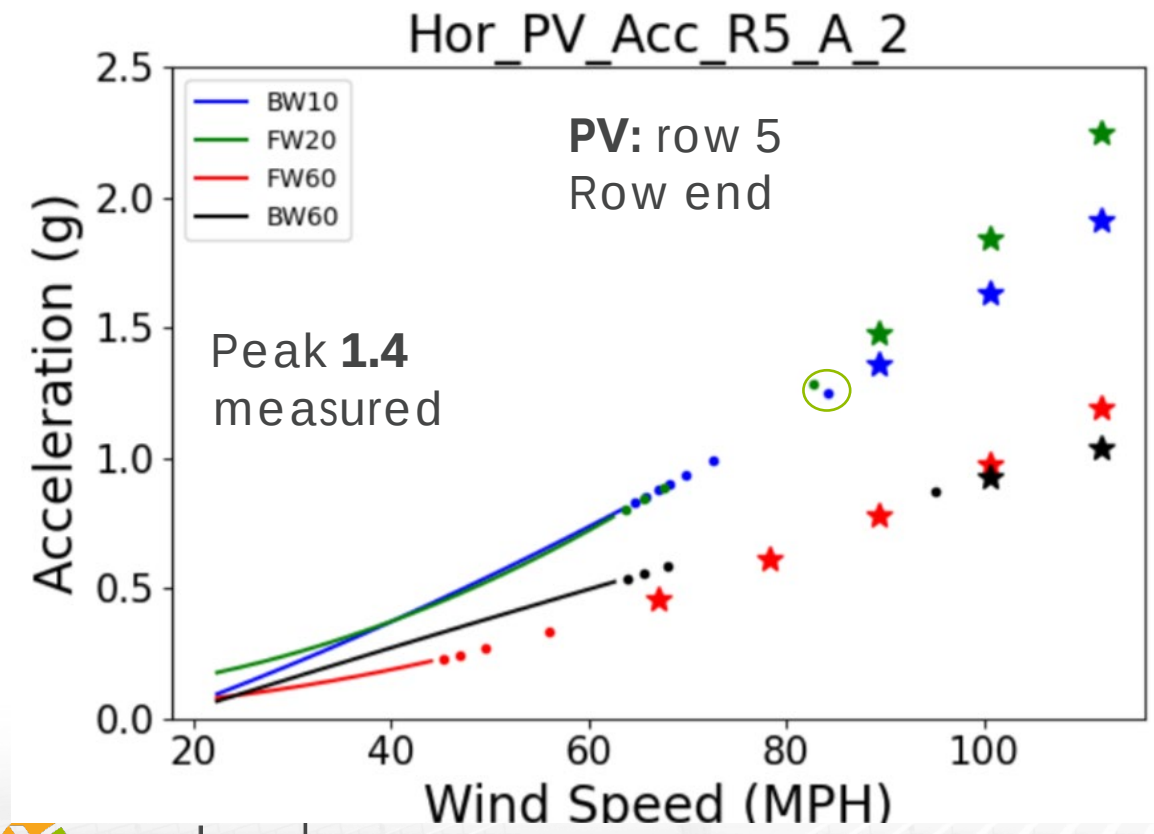
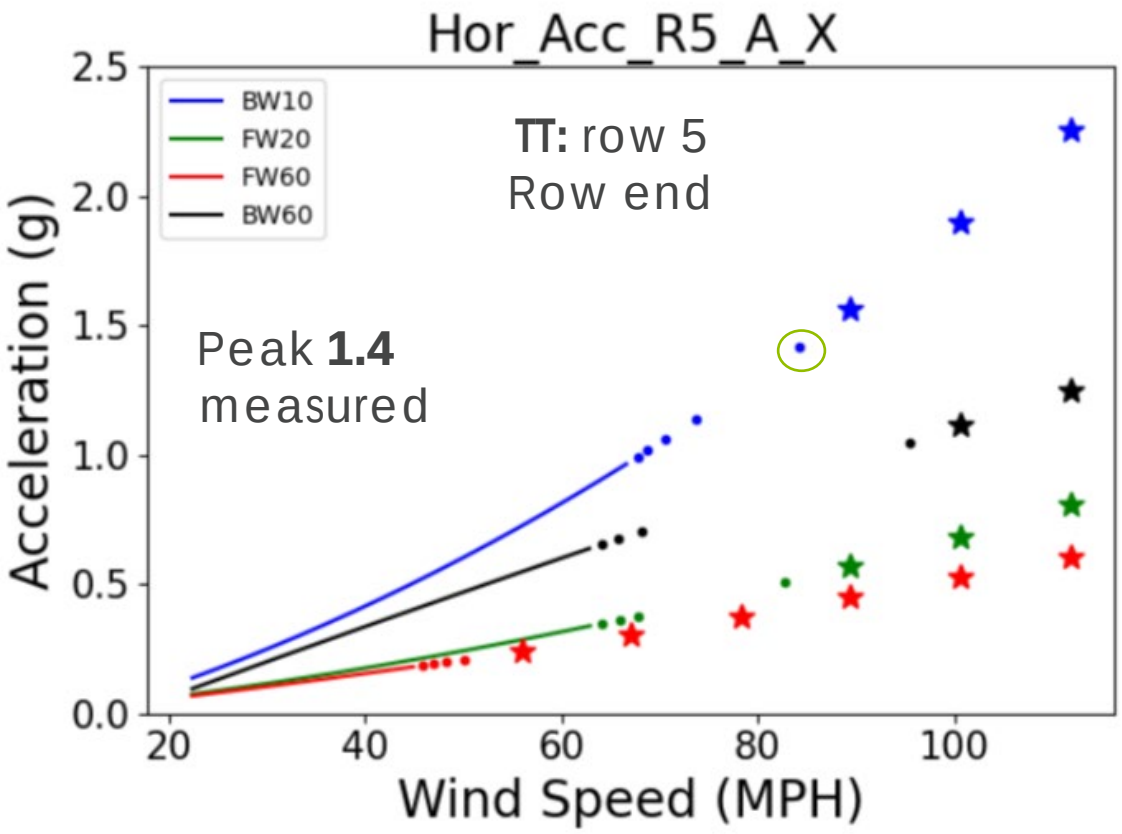
Acceleration: PV glass .vs. Torque Tube (TT)

- PV modules are mounted to a common structural member, or torque tube
- Equivalent accelerations (sometimes lower)observed on torque tube compared to PV glass





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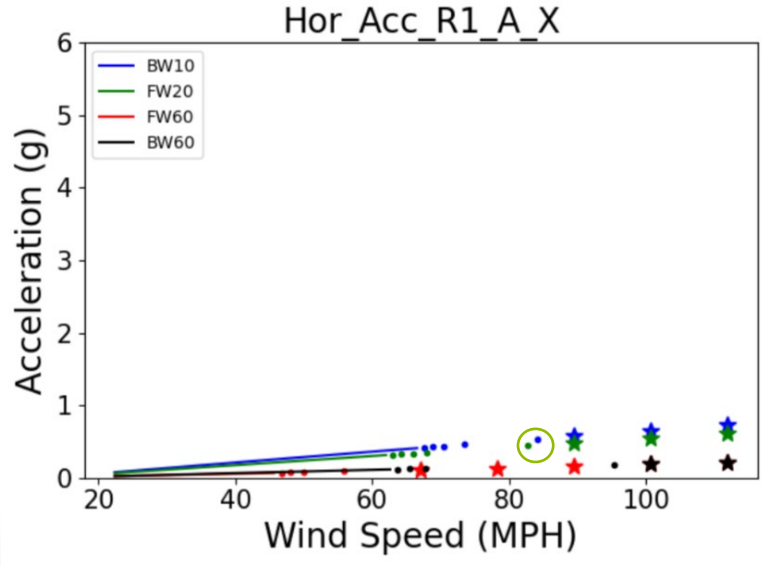
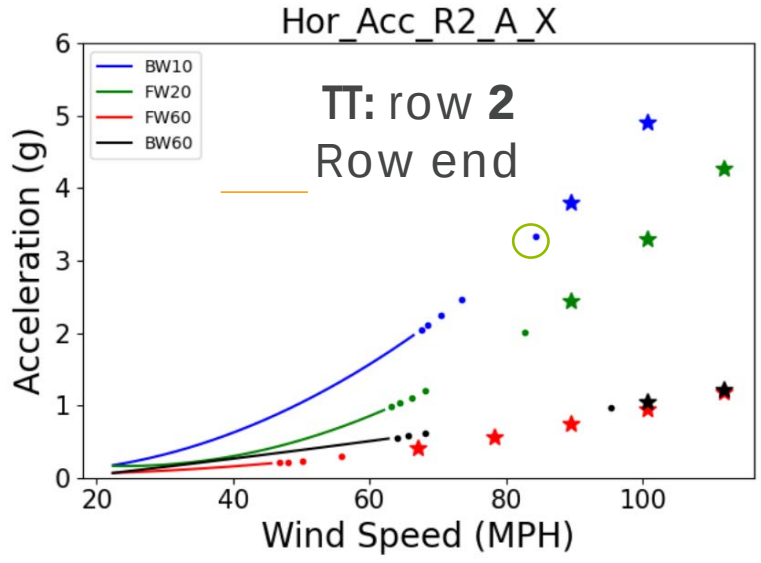
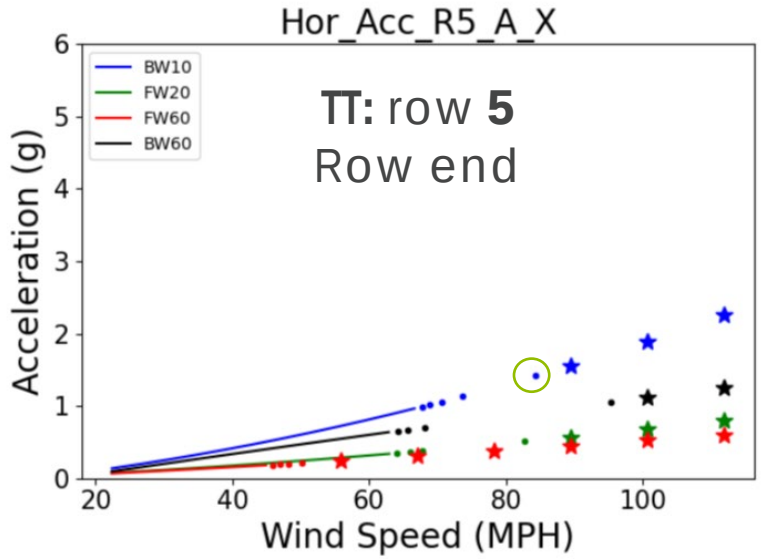
TT Acceleration, Row 1, 2, and 5

- Highest accelerations observed are on row 2 TT (do not have accels on PV here)
- At low tilt angles, row 2 TT accelerations are substantially higher than row 1 or row 5
- Vortex shedding from row 1 impinging onto row 2 causes higher accelerations (at low tilt angles)
- Other tilt angles and wind directions may produce other results







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Video, Row 1 and 2 (backwinded 10°)

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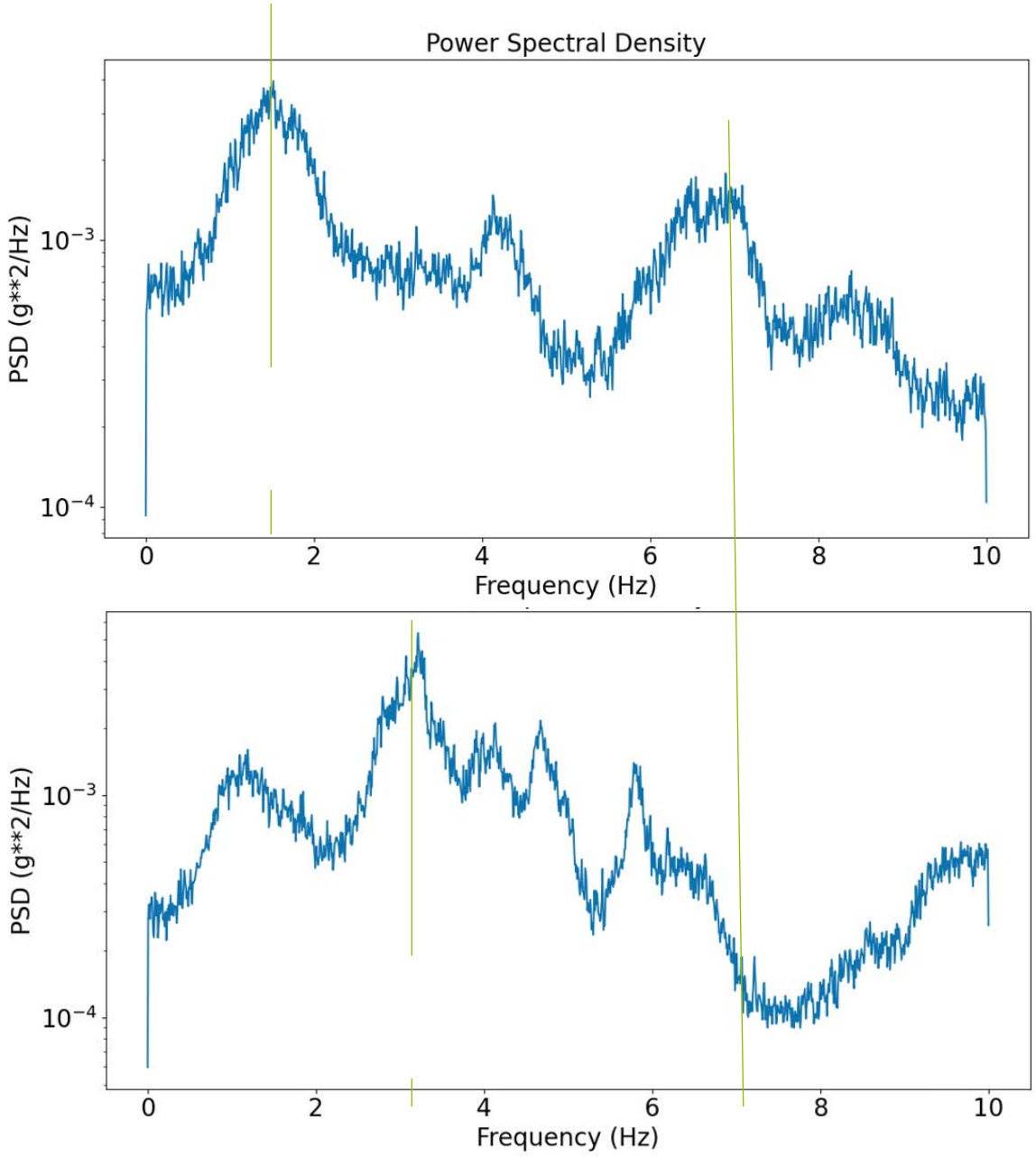
Accel Frequencies: PV glass

PSD frequency distribution:
Row end .vs. mid-bay position

- PSD Data from -10° tilt
- End of row position: peaks at 1.5 and 7 hz
- Mid-bay position: peak at ~3 hz (not at 7 hz)
- Frequency distributions influenced by position on tracker more than tilt angle
- Frequency distributions vary by wind conditions



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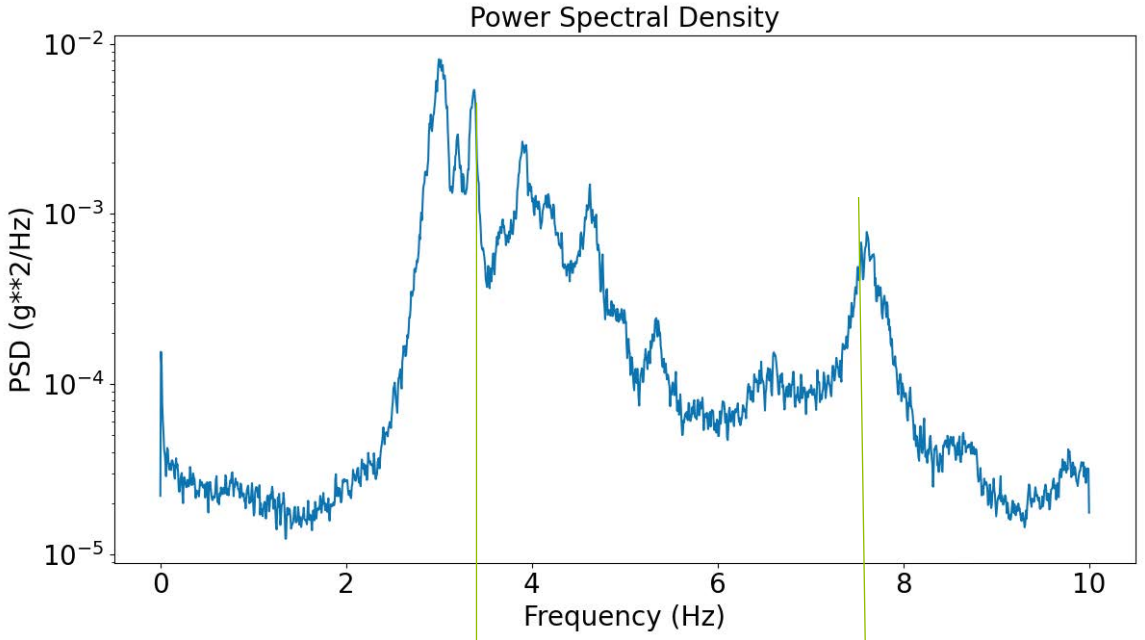
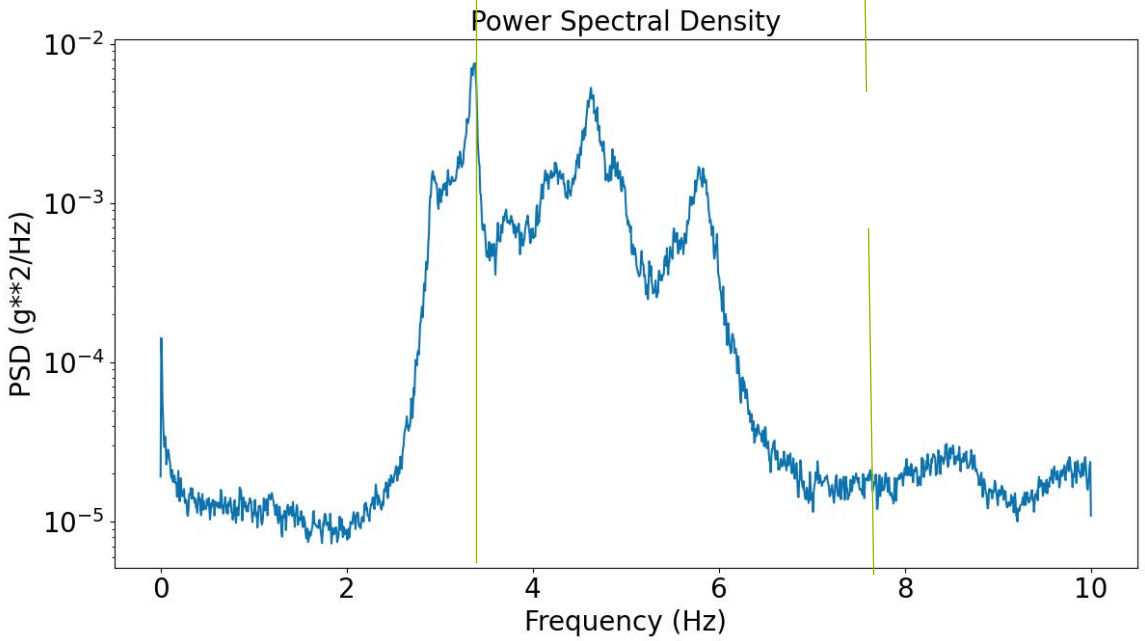
Accel Frequencies: Torque Tube

PSD frequency distribution:
Row end .vs. mid-bay position

- PSD Data from -10° tilt
- End of row position: peaks at 1.5 and 7 hz
- Mid-bay position: peak at ~3 hz (not at 7 hz)
- Frequency distributions influenced by position on tracker more than tilt angle
- Similar pattern as measured on PV (slide 12)
- Frequencies vary by wind conditions





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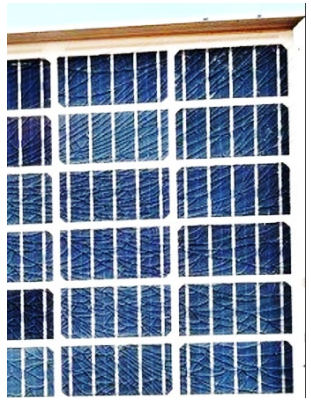
Exploratory Testing

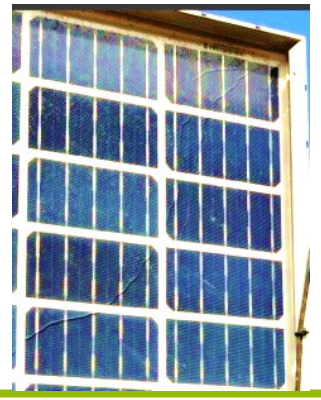
"Tough Break: Many Factors Make Glass Breakage More Likely"
Silverman et al., 2024

- Key Questions:
  - At what level of vibration acceleration do we start to see module mechanical failures?
  - Is the failure influenced by
    - BOM,
    - quality control,
    - field application/conditions?

Trapped sand

High and Low-Energy Fractures





- Approach:
  - Seismic shaker vibration at 5 Hz.
  - Step stress approach. 1g to 5g's in approximate 1-hour intervals.

- Variables:
  - Mounting rail length
  - Module types
  - New vs. field aged

- New module, high quality ~3.5 g's
- Similarity to breaks seen in field.
- Much, much more work required.

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Summary and next steps

- PV glass accelerations (heaving) may vary due to many factors: (wind, stiffness, position, Freq)
- Predicted PV accelerations for high-wind (110 mph) and high tilt positions is < 2.0 g
- Predicted PV accelerations for high-wind (110 mph) and low tilt positions is < 6.0 g
- At low tilt angles, row 2 has substantially higher accelerations (measured 3.5 g at 80 mph)
- Position along row (end .vs. mid-bay) does ***not*** seem to have influence on ***accelerations***
- Position along row (end .vs. mid-bay) ***does*** seem to have an influence on ***frequencies***
- Sensitivity of PV glass to vibration amplitude and frequencies needs more investigation

- Future investigations to include:
  - Large format PV modules
  - Different rail configurations
  - More instrumentation
  - More wind testing

- Suggest investigations:
  - Instrumentation of more field sites
  - Correlation of acceleration to PV stress
  - Characterization of PV resistance to vibration environment

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GAMECHANGE SOLAR
REPOWERING THE PLANET

Fatigue Loading of Single Axis Solar Trackers

March 6, 2025

Scott Van Pelt – Chief Engineer

Speaker Introduction

Get to know your speaker for this presentation

Scott Van Pelt, P.E.

As the Chief Engineer, oversees the customer-facing engineering team at GameChange Solar. In this role, he is responsible for the execution, accuracy, and timeliness of all technical deliverables.

He is a Professional Engineer licensed in two dozen states, and functions as the Structural Engineer of Record for many GameChange projects.

With over a decade of experience in the renewable energy space, Scott has served as a voting member of multiple national and international standards committees.

Agenda

1
Fatigue Loading Basics

2
Understanding Fatigue Loading in a Hurricane

- CPP Study

3
Existing Design Approaches

- Mechanical Testing
- Design Standards
- Finite Element

4
Proposed Test Plan

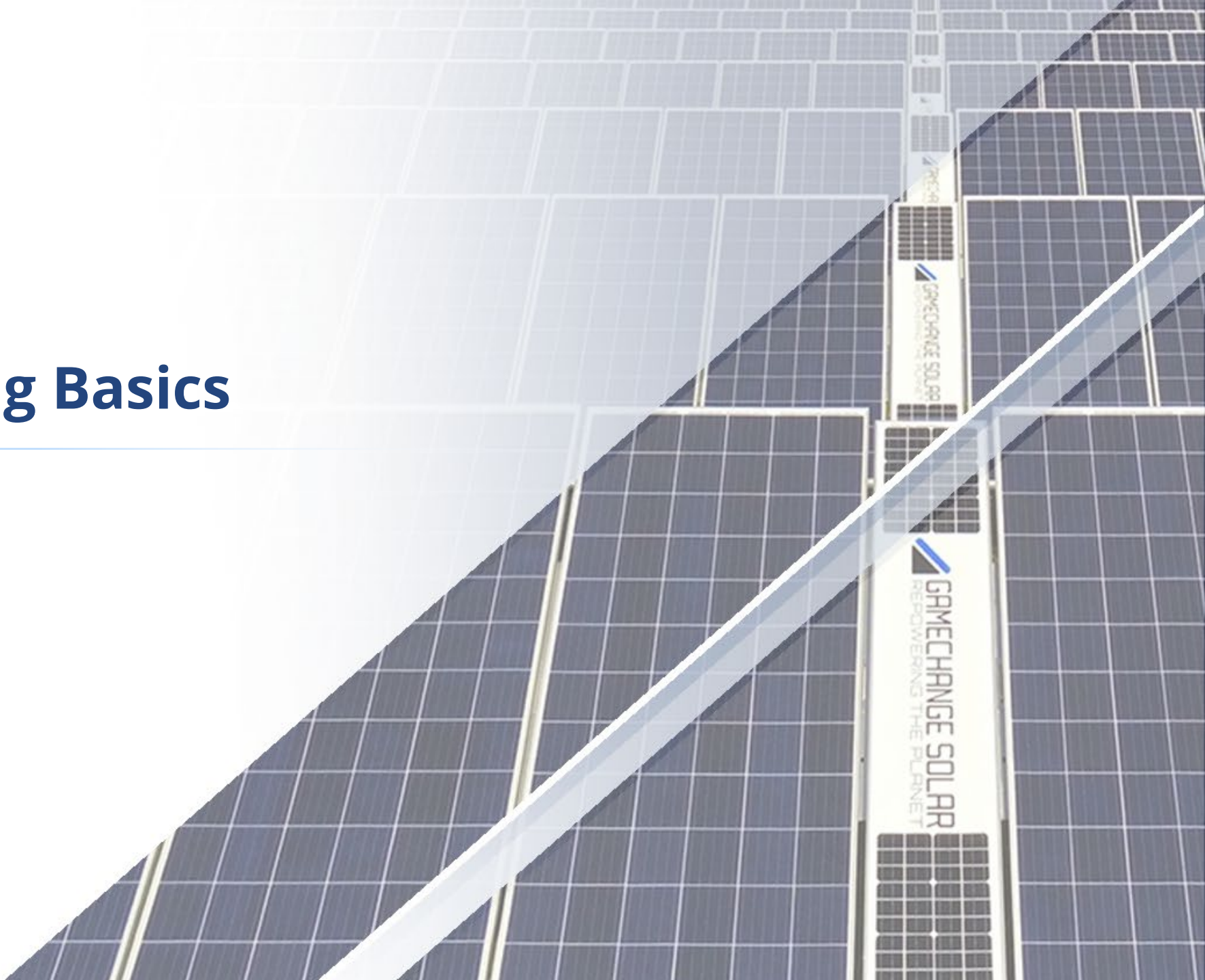
- Case Study

5
Other Considerations

- Regular shaped structural members
- Module to Rack connection

6
Conclusion

1. Fatigue Loading Basics



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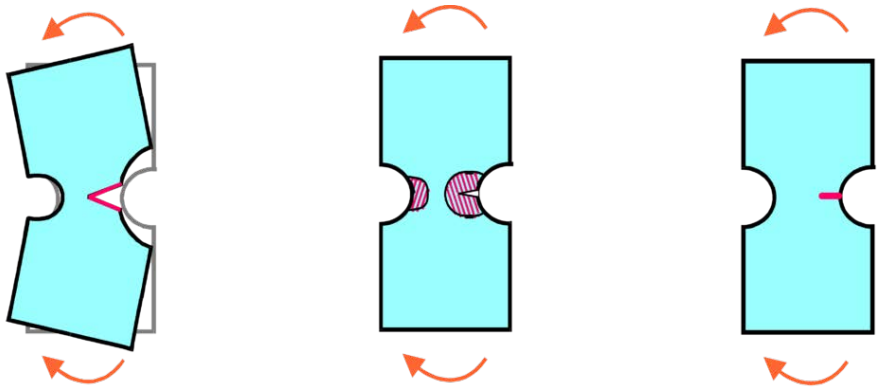
What is Fatigue Loading?

Failure due to repeated small loads

- Material is repeatedly stressed over time
- Stress builds up in microscopic material and manufacturing defects
- Damage accumulates over time, leading to cracking and fracturing typically originating from those defects
- Thinner gauge material particularly susceptible to fatigue-style failure
- Purlins on single-axis solar trackers are thin gauge and experience repeated loading during wind events



Static failure (large global deformation and large plastic strain)

Low cycle fatigue (small local plastic strains)

High cycle fatigue (small local elastic strains)

Source: Yasin ÇAPAR Mechanical Fatigue

Fatigue Loading due to Weather Events

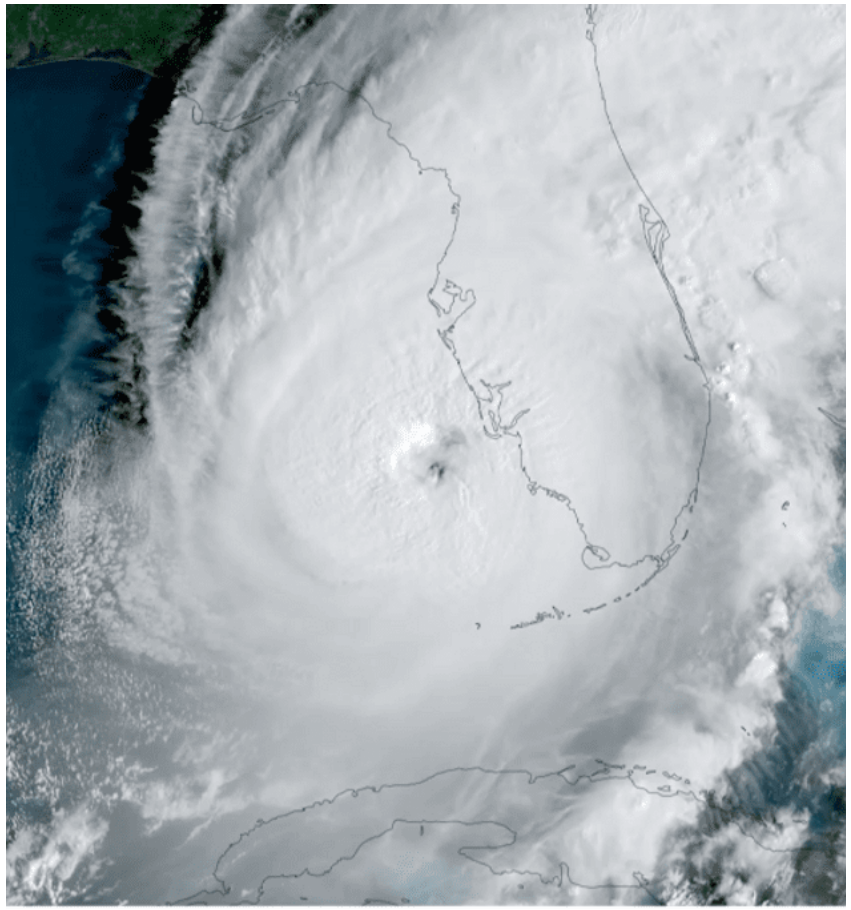
Current codes and standards geared to 3 second gust

- Existing codes are geared to maximum wind gust (one 3-second-long event) with certain return interval
  - 300 years
  - 700 years
  - 1700 years

  But existing codes are silent on the duration of the peak load or the cyclical nature of the loading in general

- Hurricanes impart many wind gusts, but exact count and amplitude is not well understood

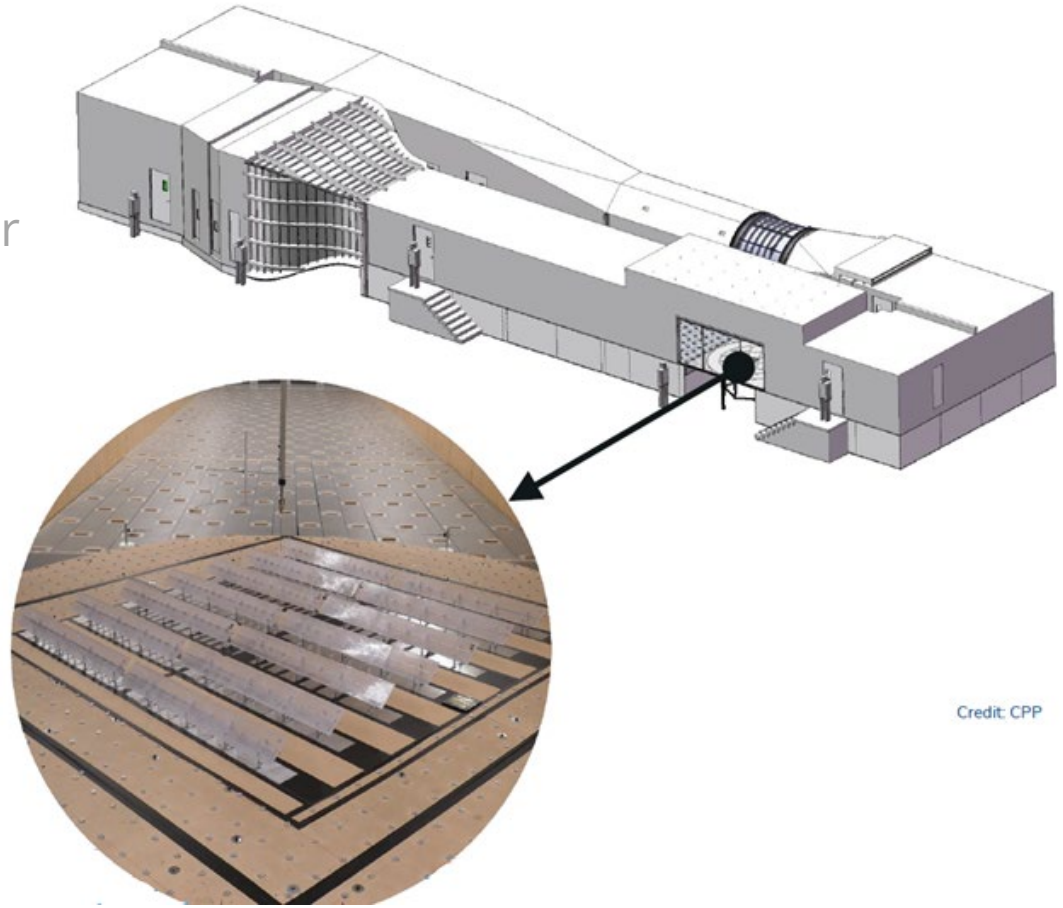
- Non-Hurricane prone regions may also have consistent, possibly gale force, wind gusts [future work]



Pressures from Wind Tunnel Testing

Common form of analysis for Tier 1 Tracker and Fixed Tilt vendors

- Scale model trackers inside a wind chamber using integrated sensors to measure wind loading
- Range of tilt angles and compass angles accounted for
- Accounts for roughness of the ground
- Static Gust Coefficients (GCs) determined through sensor data to quantify wind loading based on rigid tracker geometry
- Gust Coefficients are produced for each component
- Dynamic testing quantifies load amplification due to movement in the tracker system under wind loading



Credit: CPP

2. Fatigue Load in a Hurricane

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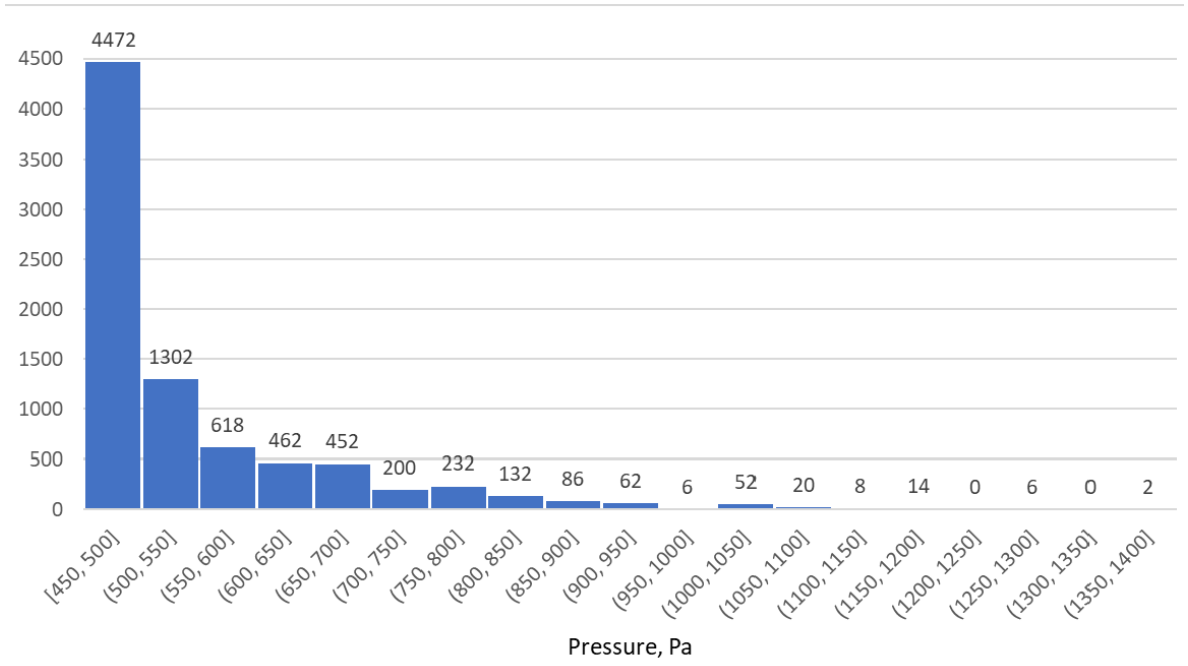
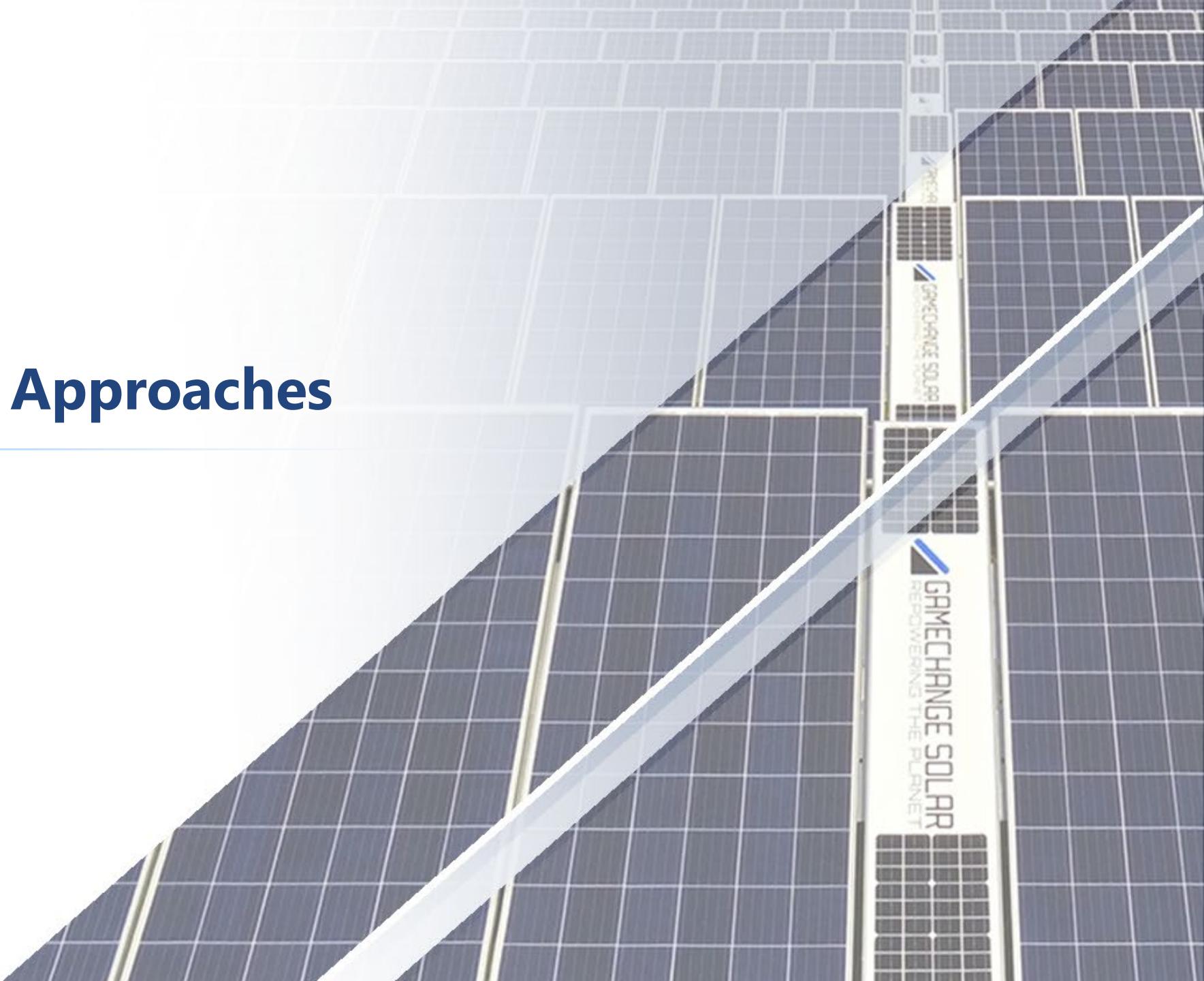
Cyclical Load amplitude and cycle count

1st known study of cyclical loading due to a hurricane event performed by CPP

- Data from Sarasota Bradenton International Airport during Hurricane Ian (Category 2, 2022)
- Max wind gust speed of 110 mph per ARA
- Discrete cycles determined using rain-flow analysis then binned by amplitude



3. Existing Design Approaches



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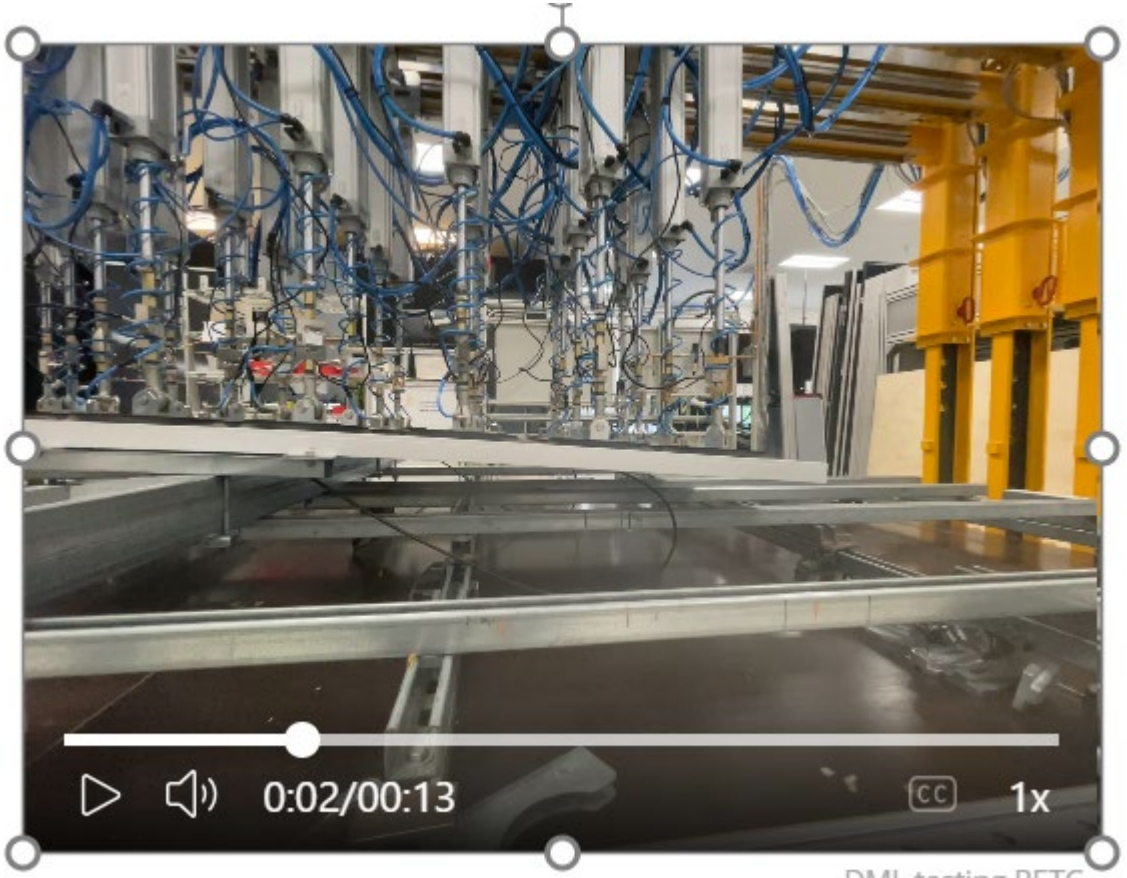
Existing Test Standards

Testing with DML Machine

- IEC 62782 “Photovoltaic (PV) modules - Cyclic (dynamic) mechanical load testing”
- Single module
- Load applied and removed (one cycle)
  - 3 to 7 times per minute
- 1000 cycles
- 1000 Pa



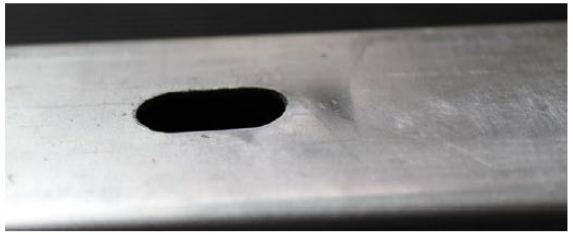
DML testing RETC

Existing Test Standards

Purlin design passes IEC 62782 but fails testing per CPP analysis

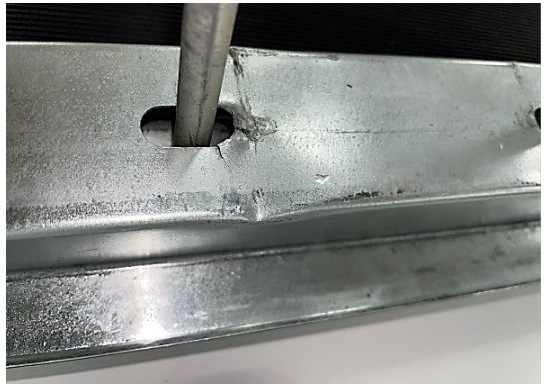
Purlin Design A **Passes** IEC 62782 Testing

- 1000 Cycles
- 1000 Pa



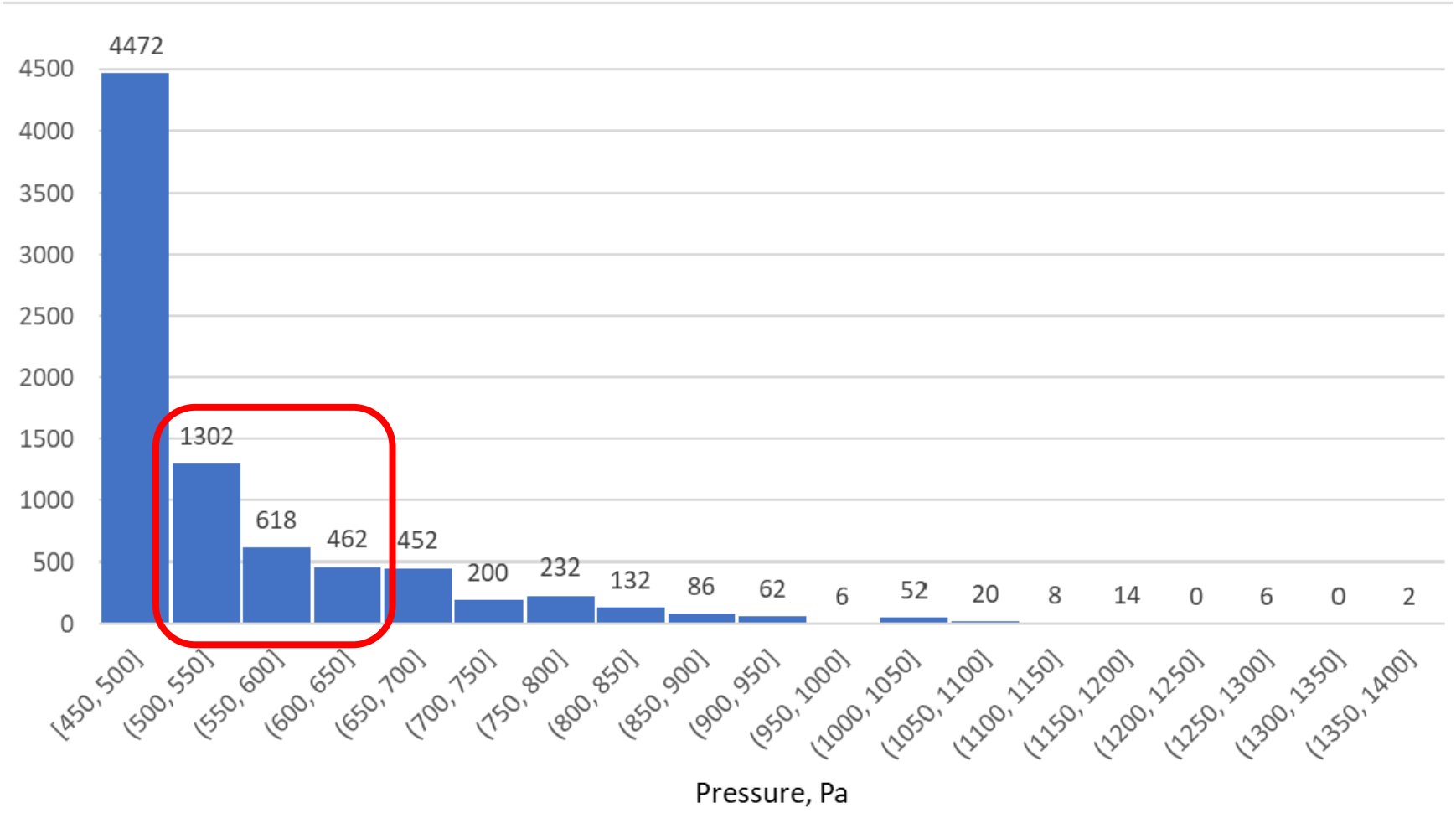
Purlin Design A **Fails** Testing per CPP Analysis

- 2000 Cycles
- 625 Pa



Testing per Subset of CPP Analysis

2000 cycles at 625 Pa, just a subset of the full storm, caused failure in a test setting



Existing Design Standards

American Iron and Steel Institute (AISI) S100

- Section M of AISI S100 covers fatigue loading of cold formed steel parts
- Tracker purlins qualify under Stress Category 1
- Using CPP analysis on the order of 4,000 cycle counts results in a maximum stress amplitude of 198 ksi [1,365 Mpa]
- Per static analysis, stress in purlins at design level (3 second gust) event is less than material yield stress of 80 ksi
- AISI S100 is clearly under conservative for tracker purlin design

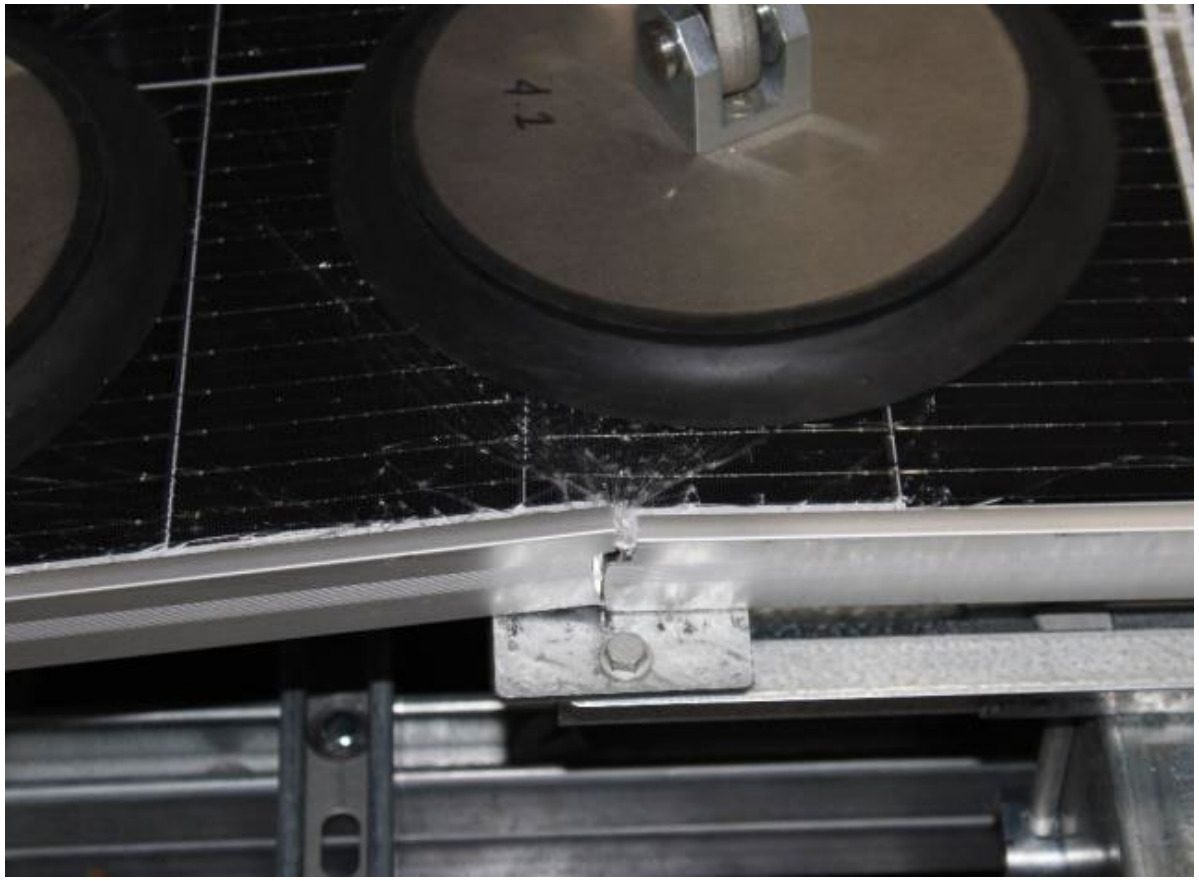
Table M1-1
Fatigue Design Parameters for Cold-Formed Steel Structures

Description	Stress Category	Constant C_f	Threshold F_{TH}, ksi (MPa) [kg/cm^2]	Reference Figure
As-received base metal and components with as-rolled surfaces, including sheared edges and cold-formed corners	I	3.2×10^{10}	25 (172) [1760]	M1-1
As-received base metal and weld metal in members connected by continuous longitudinal welds	II	1.0×10^{10}	15 (103) [1050]	M1-2
Welded attachments to a plate or a beam, transverse fillet welds, and continuous longitudinal fillet welds less than or equal to 2 in. (50.8 mm), bolt and screw *connections*, and spot welds	III	3.2×10^{9}	16 (110) [1120]	M1-3, M1-4
Longitudinal fillet-welded attachments greater than 2 in. (50.8 mm) parallel to the direction of the applied stress, and intermittent welds parallel to the direction of the applied force	IV	1.0×10^{9}	9 (62) [633]	M1-4

Existing Design Standards

Failure can occur in either Racking or PV Module

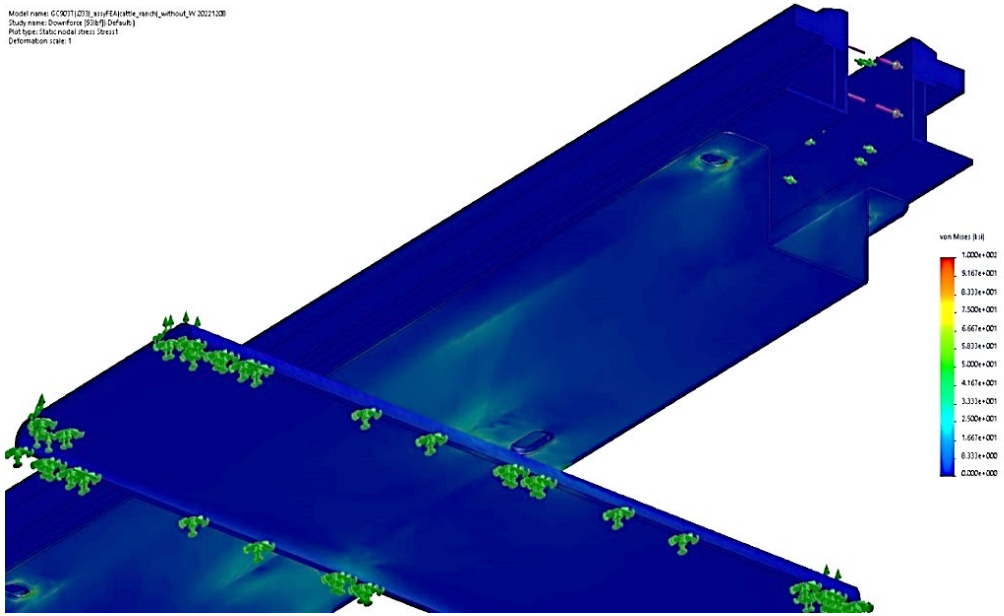
- PV Module is **NOT** a uniform shape or material covered by existing standards
- Aluminum, which is commonly used for PV module frames is particularly susceptible to fatigue failure.



Finite Element Modeling

Simulations of stress on computer-modeled parts

- Designed to identify yielding of structural steel components under static or fatigue loading
- Sensitive to input assumptions such as residual stresses from manufacturing, steel galvanization, and bolted connection preload
- Purlin Design A modeled using FEA did not highlight a risk of failure under CPP loading conditions



FEA Model showing no failure for Purlin Design A

4. Proposed Test Plan

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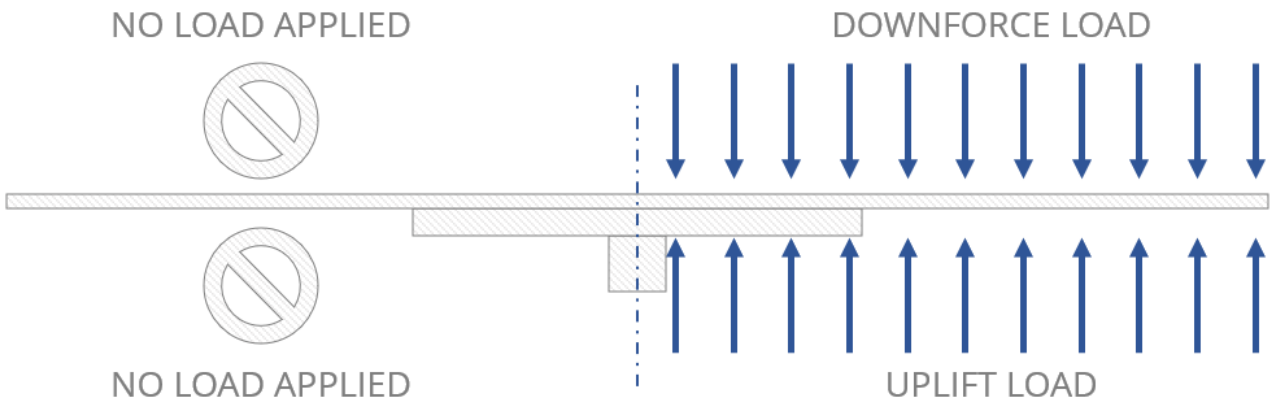
Proposed Test Plan

Testing with DML Machine

- Perform Cyclical loading at 3 levels
- Cycle counts align with CPP analysis
- Assembly consists of 2 modules, 3 purlins
- Pressures scaled from CPP study
  - Max wind speed for 50-year MRI
  - Proportional to square of wind speeds
  - Ladder-style loading
- Load 1 half of module to better model unbalanced loading
- Perform in tandem with static mechanical load testing per IEC 61215 / UL 61730 and with same pass / fail criteria

Pressure (Pa)		
Interior	Perimeter	Cycle Count
600	1200	4000
1000	2000	1000
1400	2800	100
1000	2000	1000
600	1200	4000

Ladder fatigue loading for 110mph wind event



Half of module loaded to simulate unbalanced wind loading

Case Study

Hurricane-prone purlins evaluate per proposed test plan

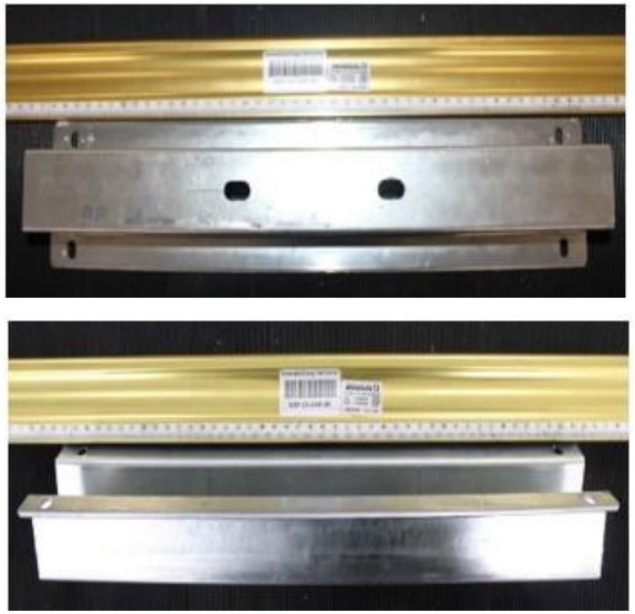
- Example Site: Near Jacksonville (hurricane prone)
  - Strength level wind speed: 107 mph
  - Expected wind speed during design life: 90 mph
- Loads scaled from CPP report

$$800\text{Pa} = \underbrace{1400\text{Pa}}_{\text{Report Pressure}} * \underbrace{[90\text{mph}}_{\text{Site Wind Speed}}/\underbrace{110\text{mph}]^2}_{\text{Report Wind Speed}}$$

- Purlin Design B, GCS default design
- Cyclical loading performed on DML machine at RETC
- No crack propagation or other damage observed

Pressure (Pa)		
Interior	Perimeter	Cycle Count
400	690	4000
670	1160	1000
800	1380	100
670	1160	1000
400	690	4000

Ladder fatigue loading for 90mph wind event



Purlin Design B passes DML testing

5. Other Considerations

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Design Standards for Regular Shaped Components

AISI S100 can more accurately be used for components like the torque tube

- Equations in AISI may be appropriate for "regular" shaped members such as row tube
- Clear equations for longitudinally welded parts such as row tubes
- Comparable to stress the larger of the highest cycle count from ladder testing described above and gust wind speed (for non-hurricane prone sites)

$$F_{SR} = (\alpha C_f / N)^{0.333} \geq F_{TH} \qquad (Eq.\ M3\text{-}1)$$

where

F_{SR} = Design *stress* range

α = Coefficient for conversion of units
= 1 for U.S. customary units
= 327 for SI units
= 352,000 for MKS units

C_f = Constant from Table M1-1

N = Number of *stress* range fluctuations in design life
= Number of *stress* range fluctuations per day × 365 × years of design life

F_{TH} = Threshold *fatigue stress* range, maximum *stress* range for indefinite design life from Table M1-1

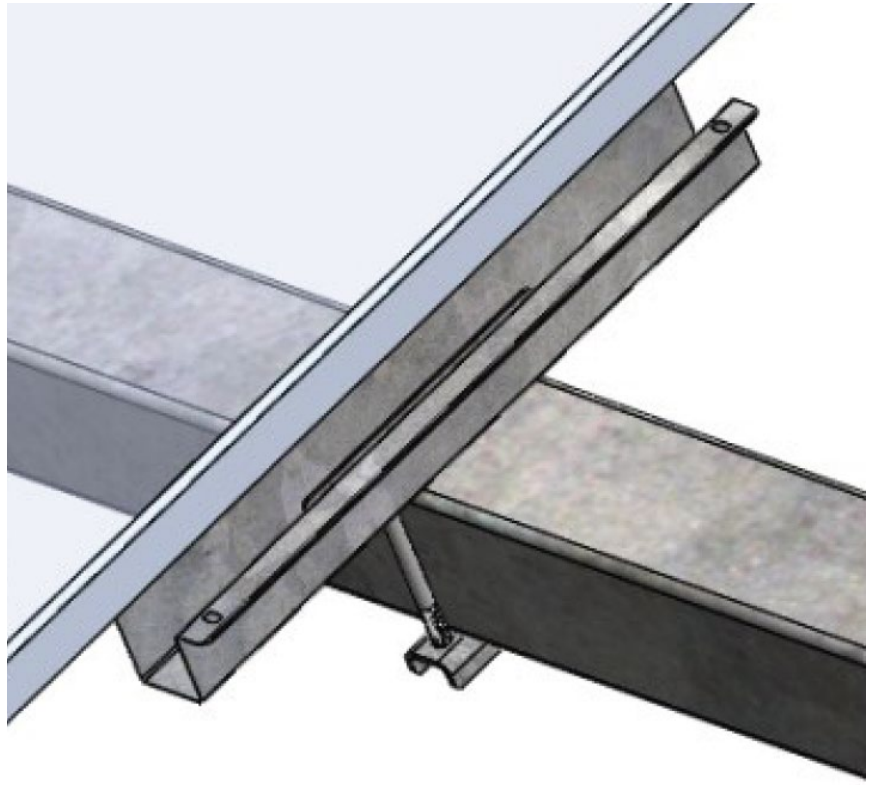
Table M1-1
Fatigue Design Parameters for Cold-Formed Steel Structures

Description	Stress Category	Constant C_f	Threshold F_{TH}, ksi (MPa) [kg/cm^2]	Reference Figure
As-received base metal and components with as-rolled surfaces, including sheared edges and cold-formed corners	I	3.2×10^{10}	25 (172) [1760]	M1-1
As-received base metal and weld metal in members connected by continuous longitudinal welds	II	1.0×10^{10}	15 (103) [1050]	M1-2
Welded attachments to a plate or a beam, transverse fillet welds, and continuous longitudinal fillet welds less than or equal to 2 in. (50.8 mm), bolt and screw *connections*, and spot welds	III	3.2×10^{9}	16 (110) [1120]	M1-3, M1-4
Longitudinal fillet-welded attachments greater than 2 in. (50.8 mm) parallel to the direction of the applied stress, and intermittent welds parallel to the direction of the applied force	IV	1.0×10^{9}	9 (62) [633]	M1-4

Nuts Not Backing Out

Fatigue loading can also result in loosening of bolted connections from purlin to tube

- Purlin to torque tube interface typically involves a torqued connection
- Prone to loosening under cyclical loading
- Must ensure doesn’t exceed critical threshold for loss of preload
- Non-visual failure, so harder to identify in the field compared to fractured or bent parts

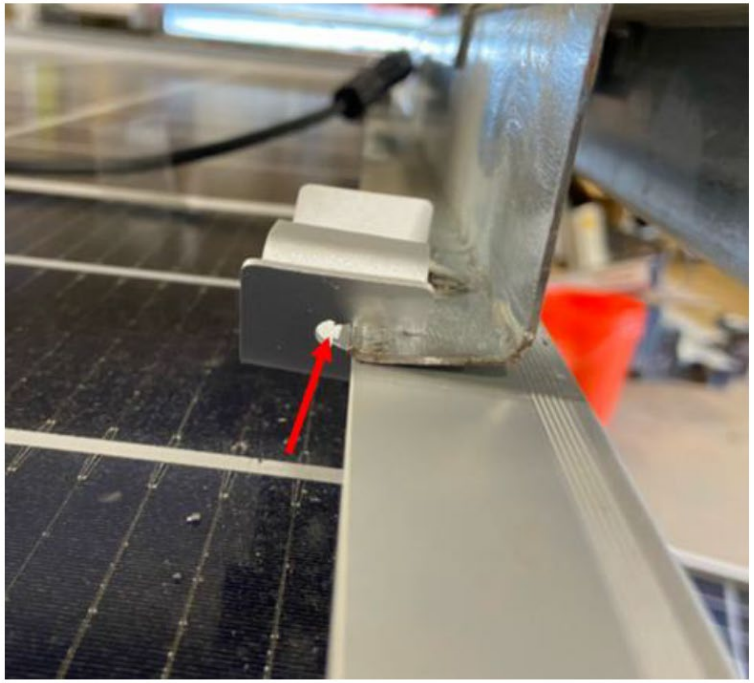


Bolted connection from purlin to tube

Unconventional Fastening Means

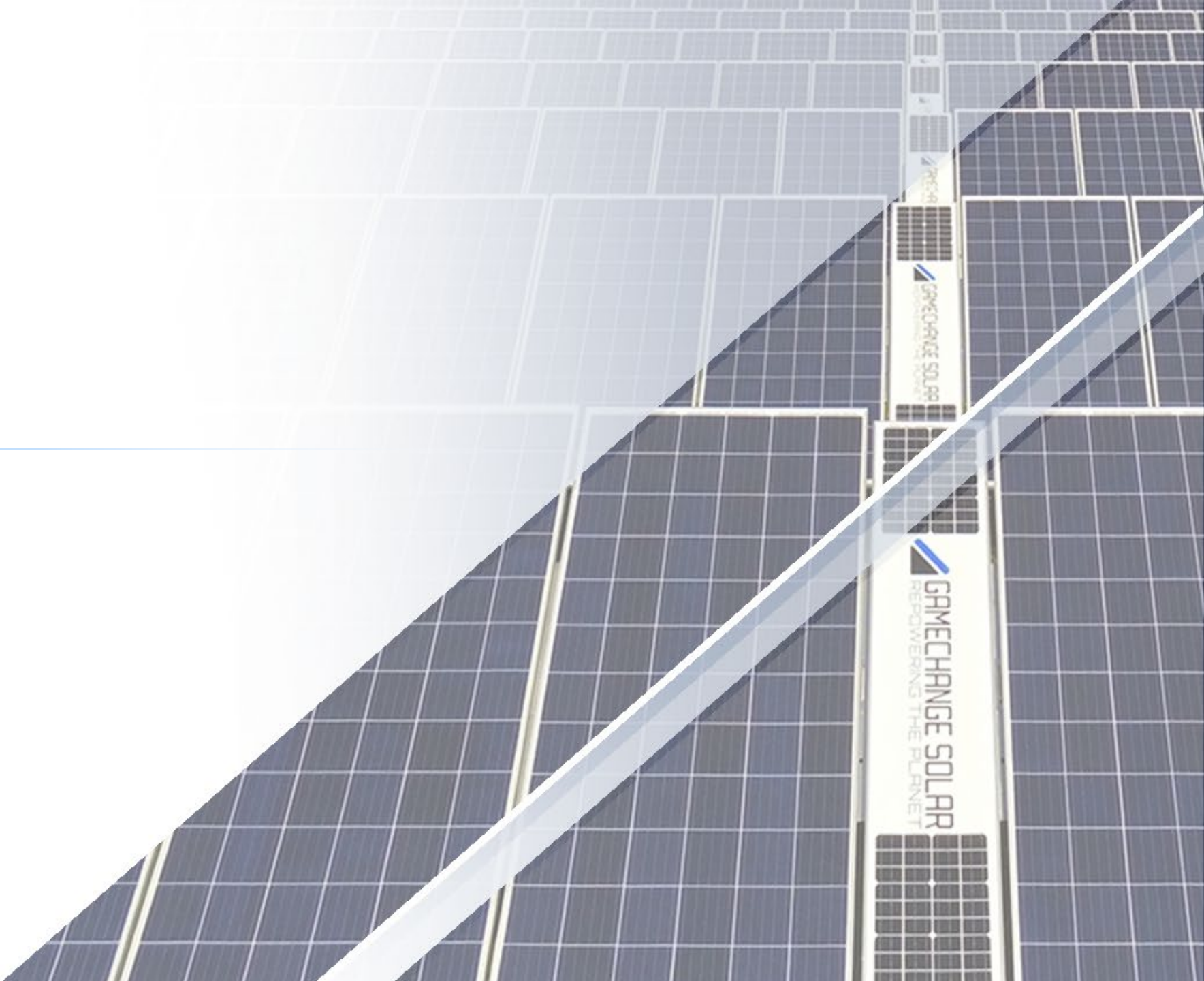
Fatigue issues may be latent failure mode

- Cyclical loading should be checked for compression clips, wedge systems, etc.
- Internal GCS testing has shown these parts may back off / fail under repetitive loading.



Clip shifted away from module edge under loading

6. Conclusions



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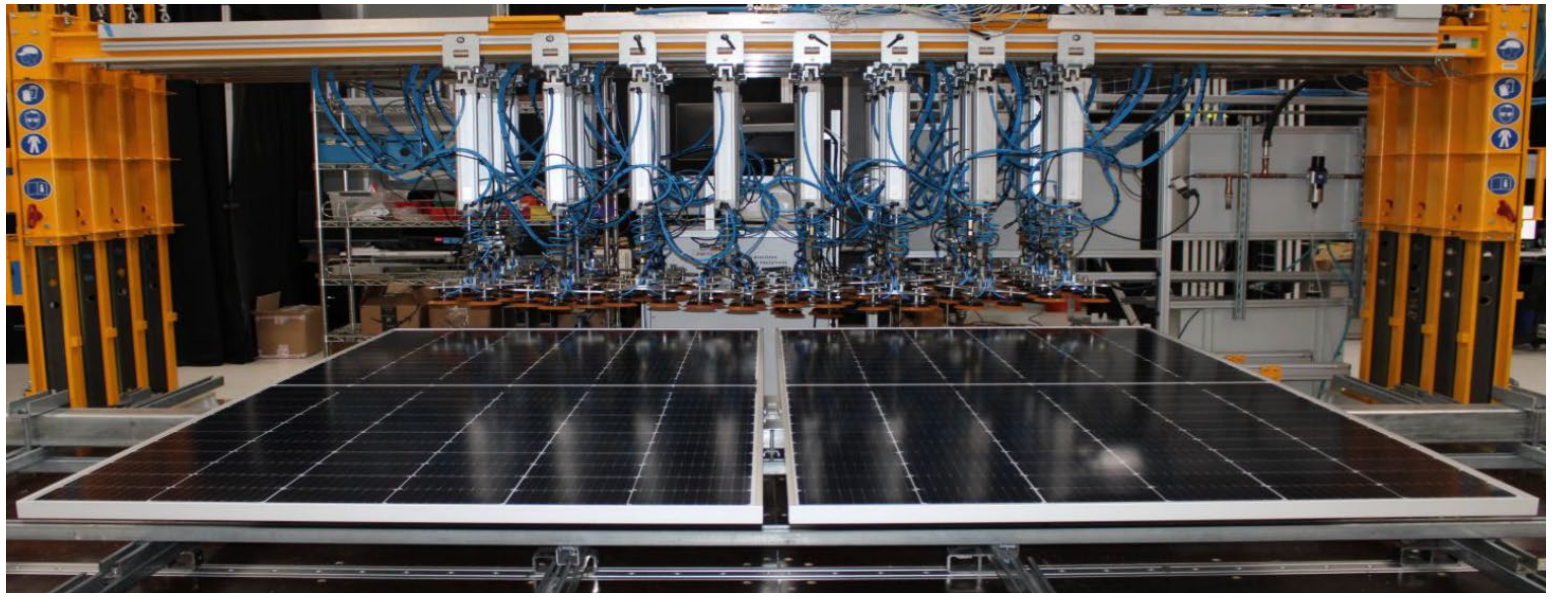
Fatigue Must be Considered for Long Term Viability of Solar Assets

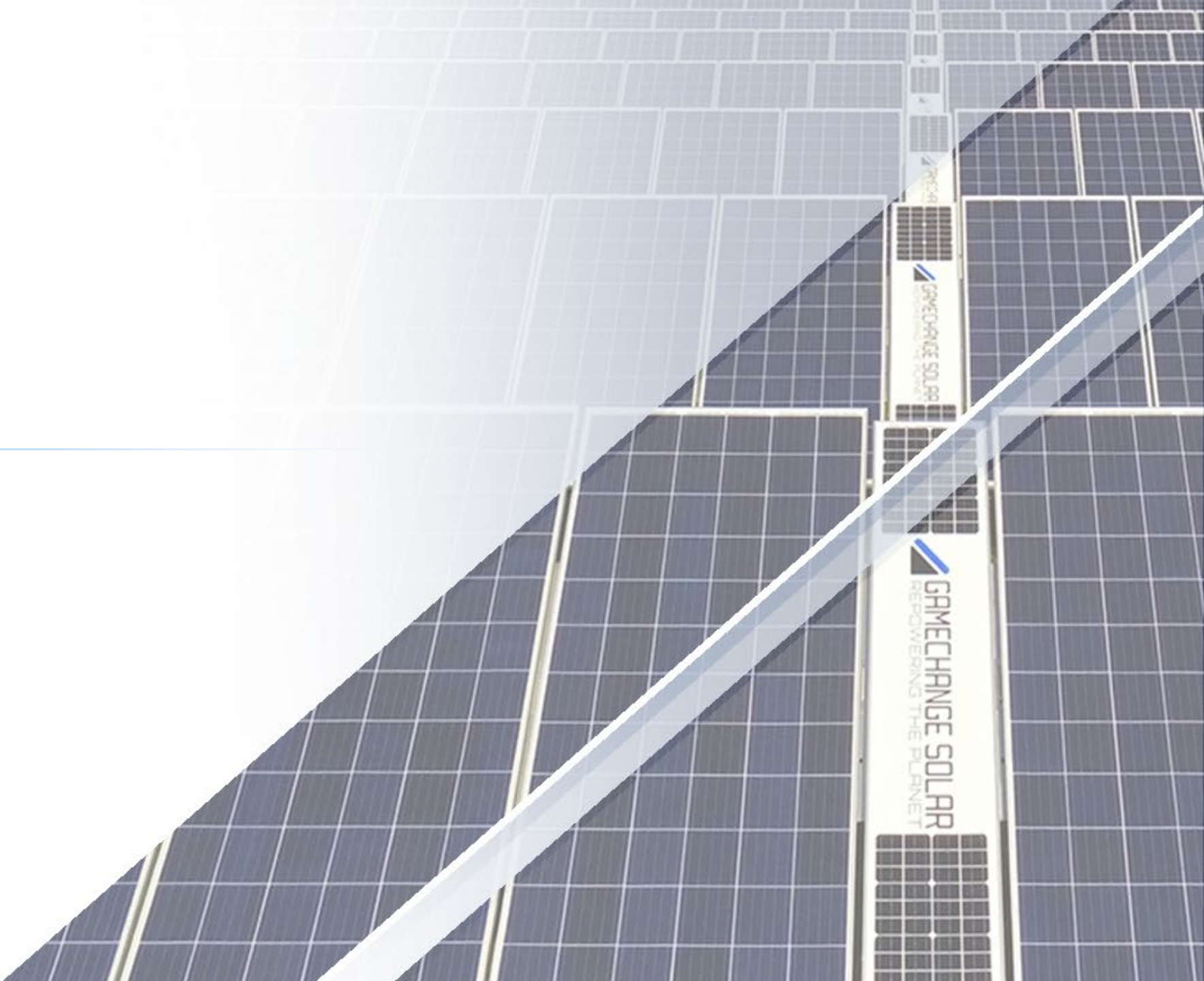
New testing procedure can help with this effort

- Existing IEC standards are not sufficient
- Test equipment exists for high cycle counts
- Using the proposed test procedure can more accurately predict performance of modules and racking structure during design wind event

- Future Work
  - Analyze cycle and amplitude counts for non-hurricane prone sites
  - Work with IEC committee to revamp standard 62782
  - DML testing with true unbalanced loading



THANK YOU



GAMECHANGE SOLAR
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Working to create a world powered by renewable energy

Is Your Project Underperformance Caused by Unreliable Trackers?

Dan Chawla

PV Reliability Workshop 2025

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- Technological focus on **Solar, Storage, Hydrogen, Onshore and Offshore Wind**.
- **Independent Engineer reviews** to support project financing and construction.
- **M&A due diligence** to support project, portfolio and platform investments or divestments.
- Analytics:
  - **Finance-grade energy yield assessments** for development projects.
  - **Repowering energy yield assessments.**
  - **Operational energy assessments** and **performance analysis.**
- **Developer Support** across all development stages for projects and portfolios.

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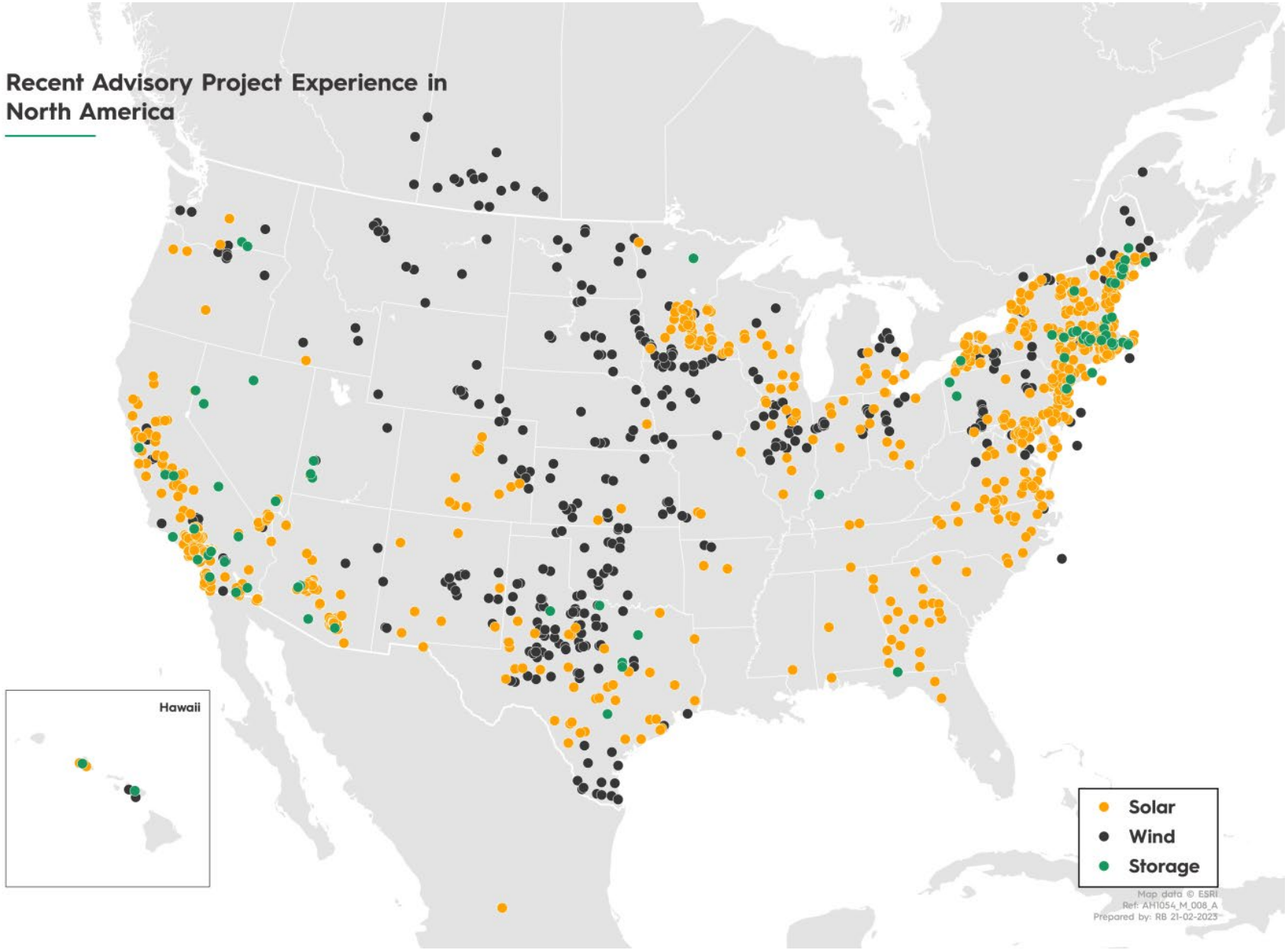
Recent North America Project Experience



2024 by the numbers

- Technical due diligence reviews of 38 GW of wind, solar and storage projects
- 20 finance-grade energy assessments (4.5 GW)
- Advisory services on over 120 unique PV projects and more than 45 unique battery energy storage system projects
- Supported $72 BN USD in renewable energy investment.

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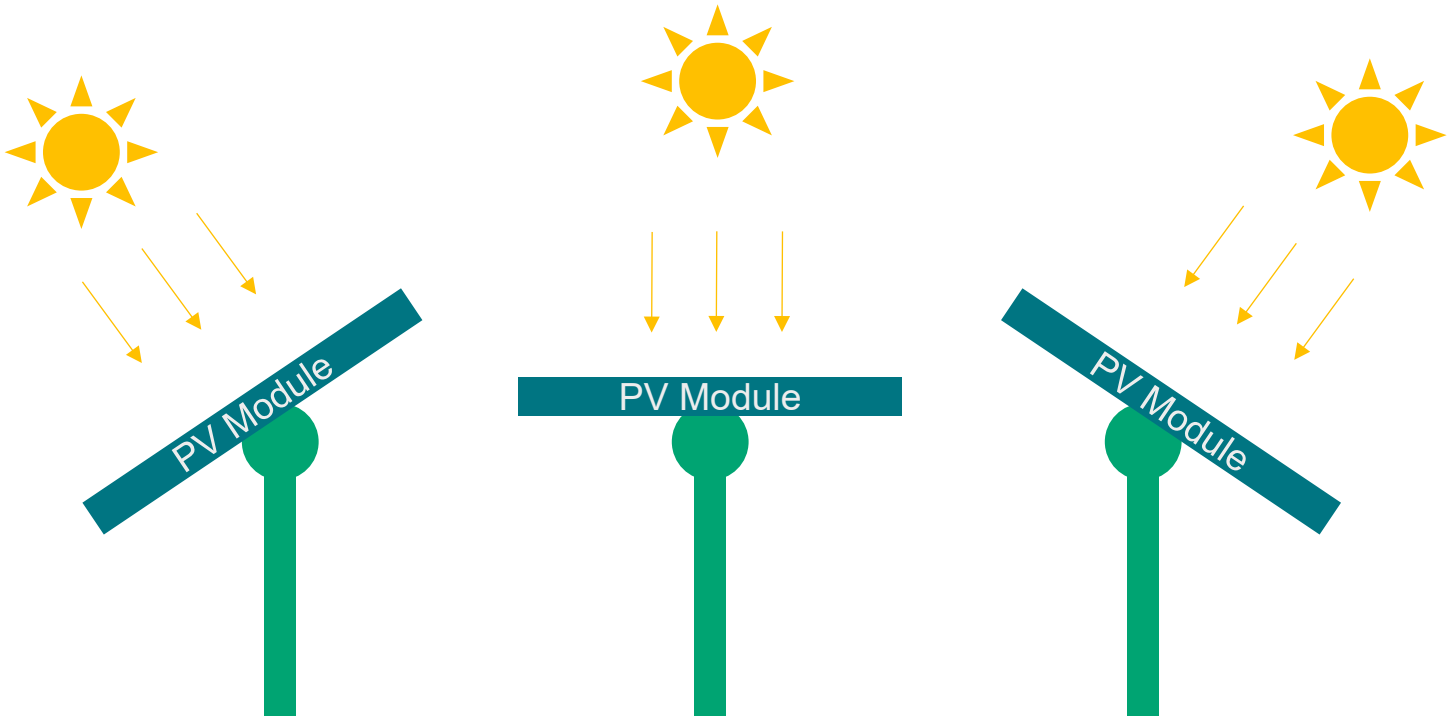
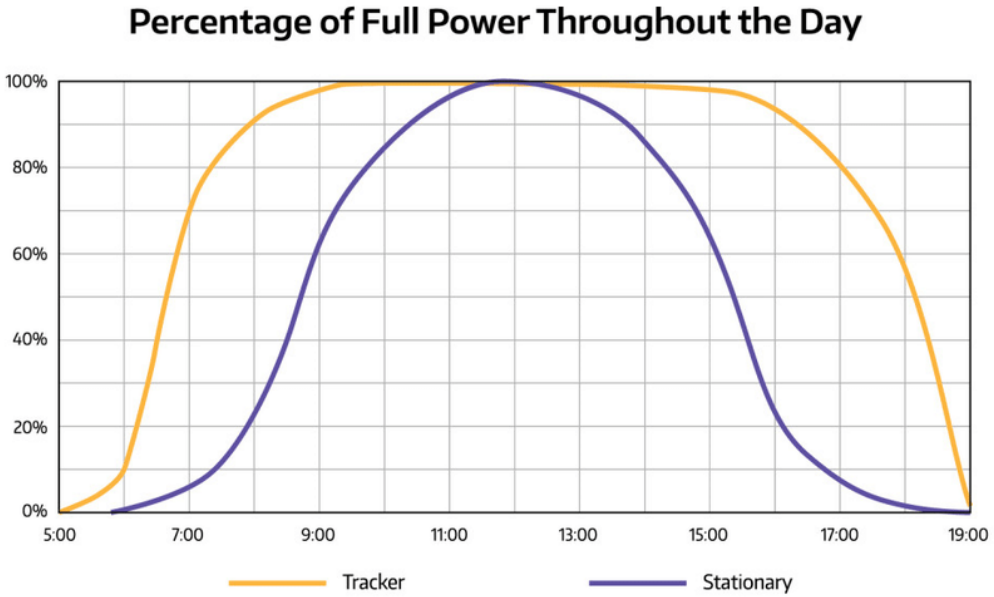
Background – What is a tracker?



Morning Noon Evening



Increased Energy Generation

Shintemirov et al. (2016). A sensorless MPPT-based solar tracking control approach for mobile autonomous systems.

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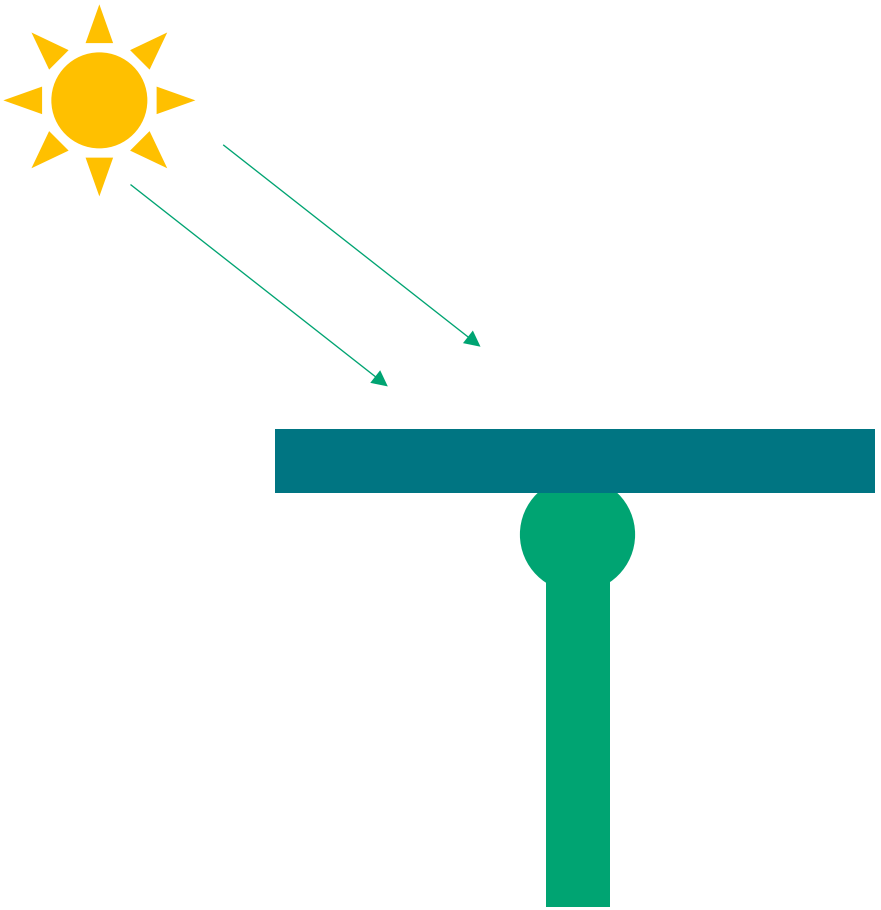
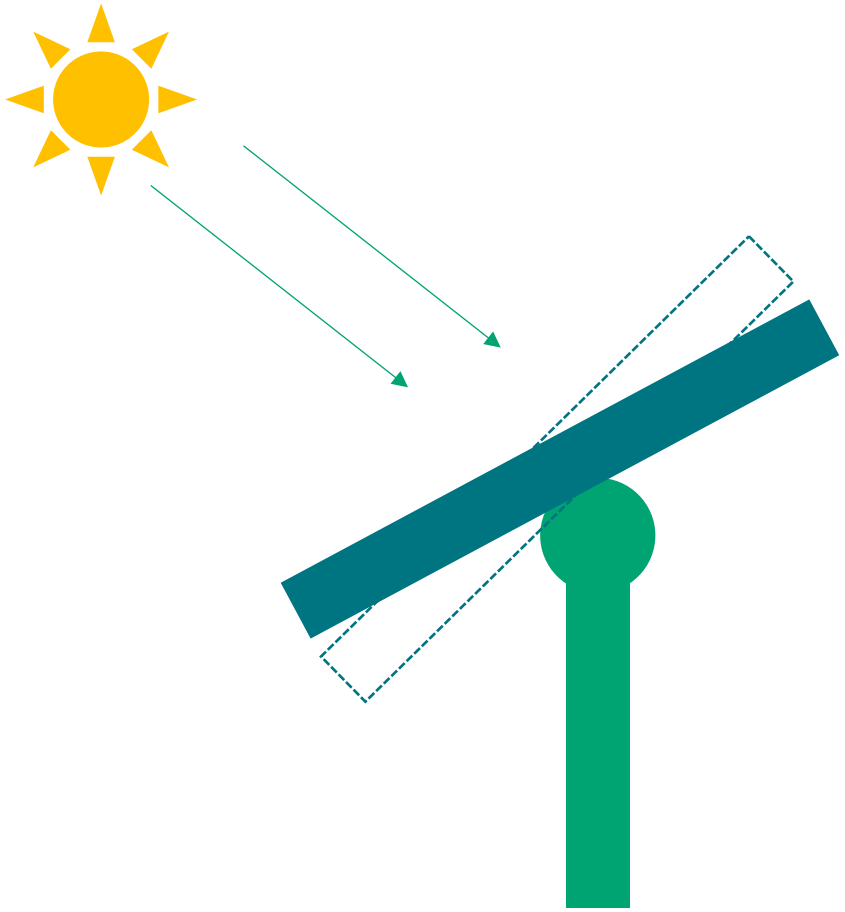
Background – How can a tracker underperform?



Tracker Offline or Stalled



Tracker Off Angle / Mistracking

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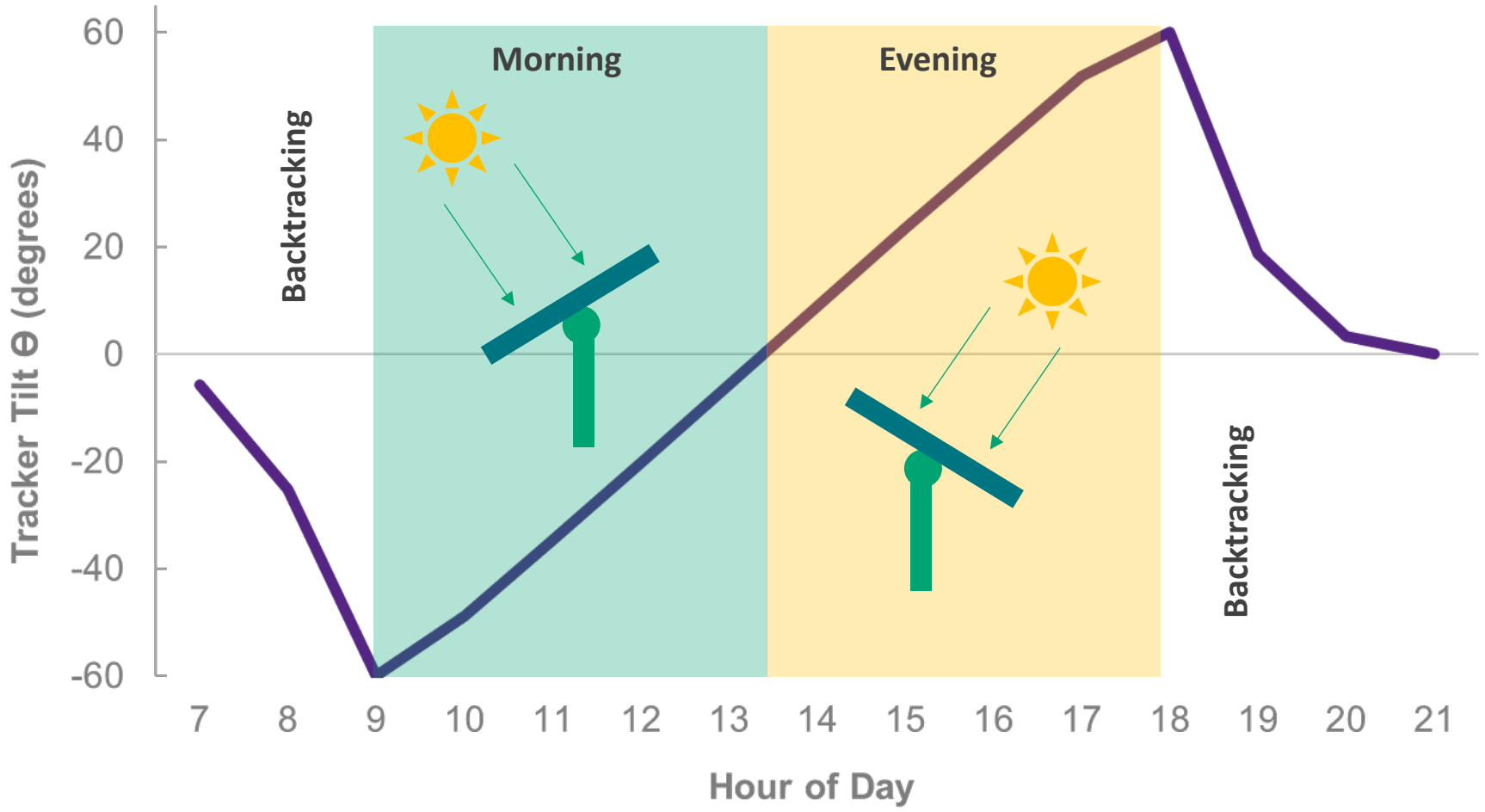
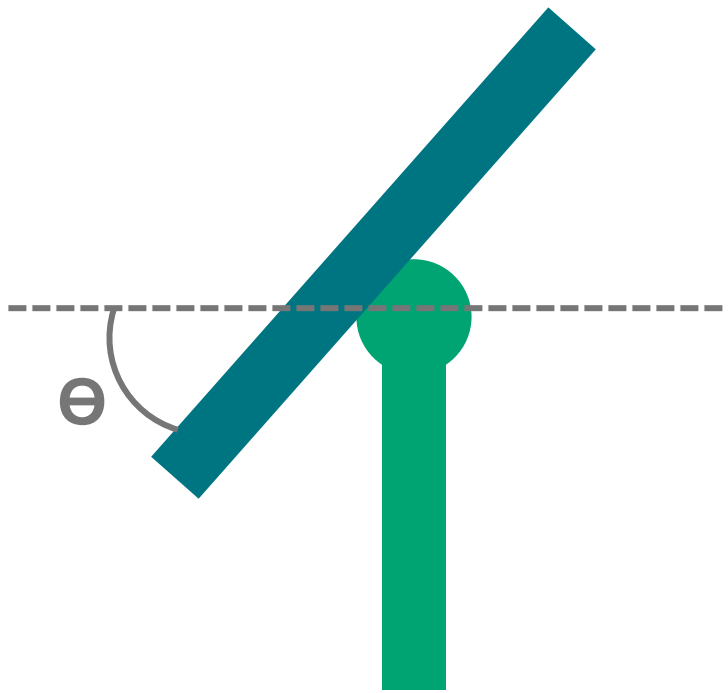
Background – Tracker DAS data





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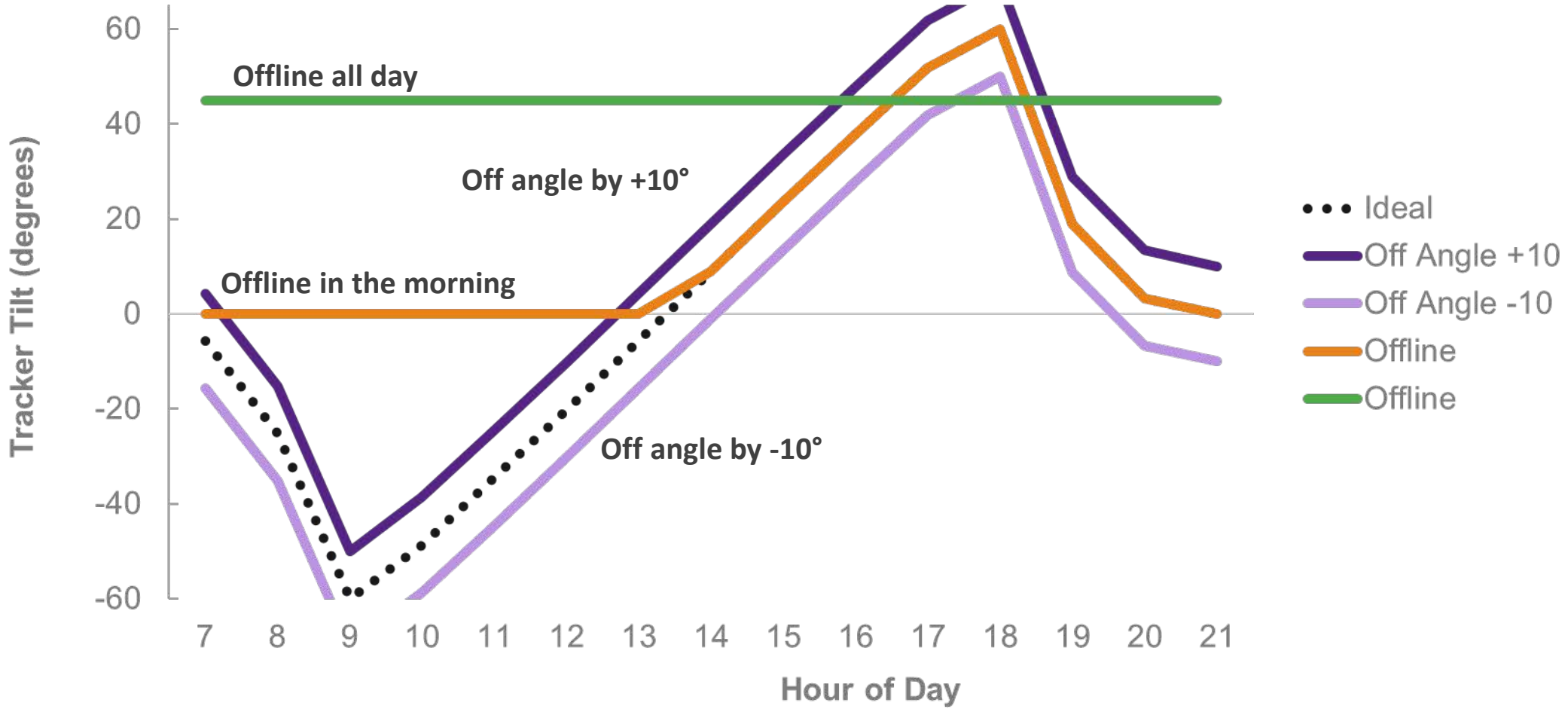
Background - Underperformance in the SCADA data



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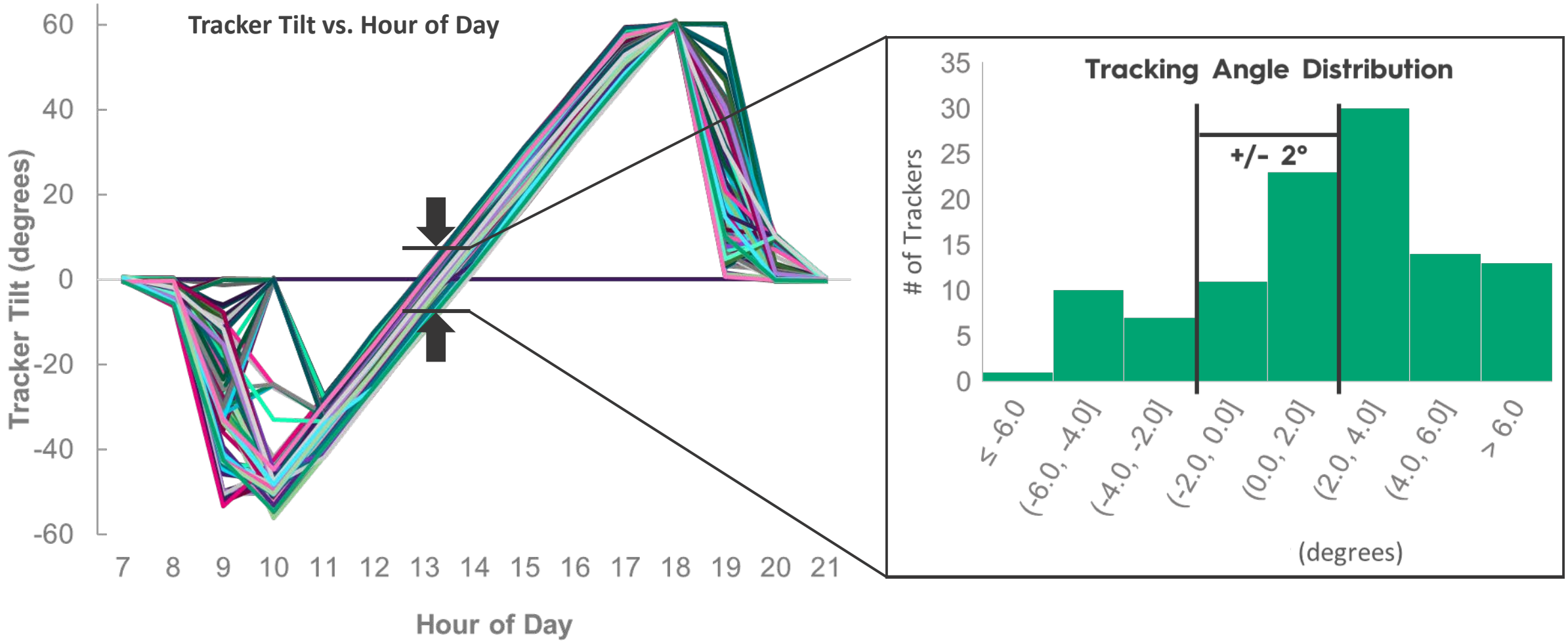
Methodology – Tracking Error



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Methodology – Tracking Error → Performance Index

Tracker Tilt DAS Data
+
Ideal Tracker Tilt Data

→

PV Modeling Tool
+
Global Horizontal Irradiance (GHI)

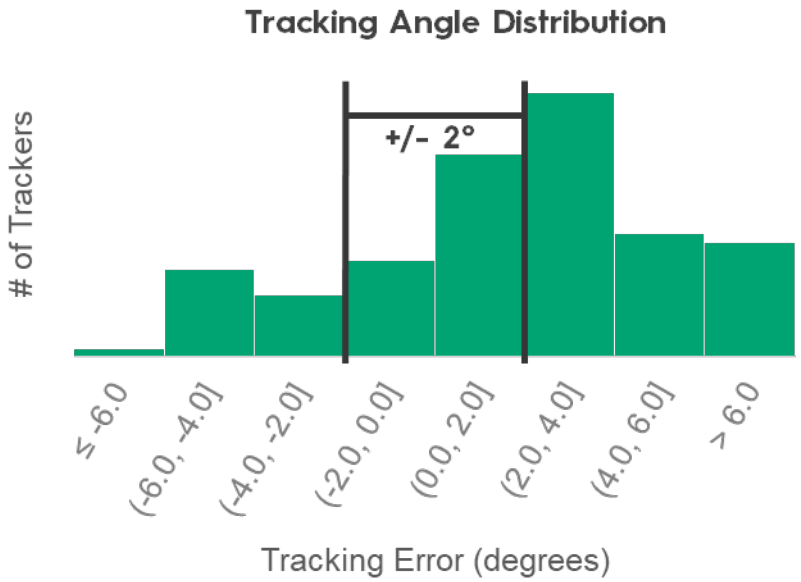
→

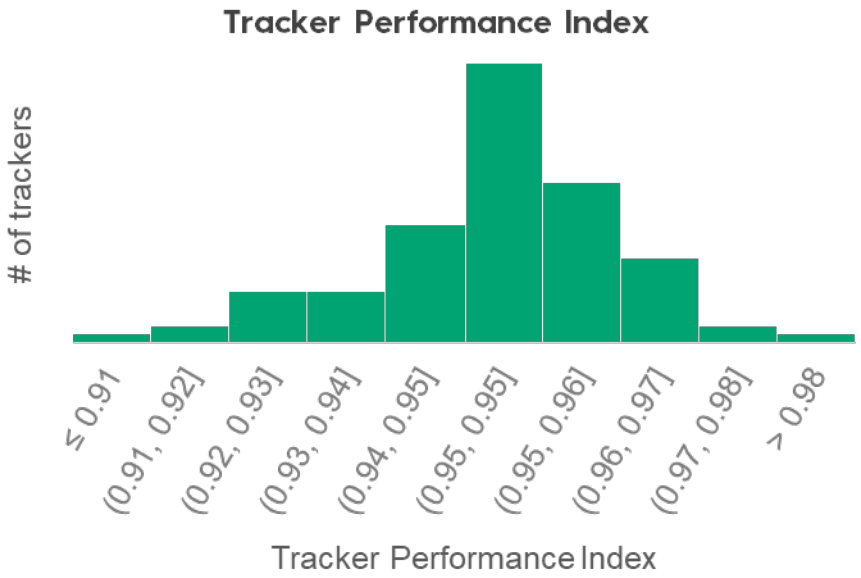
Plane of Array Irradiance (POA)

→

Performance Index

$$= \frac{\sum \mathrm{POA}_{\mathrm{tracker}}}{\sum \mathrm{POA}_{\mathrm{ideal}}}$$





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Methodology - Assumptions

- Tracker tilt sensors are accurate
- Tracker clocks are accurate
- Missing data are assumed to be tracker outages, tilt = last reported tilt
- PVLIB's tracking algorithm is close to "ideal"
- POA irradiance is linearly related to project energy production
- Hourly timestep

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Portfolio Summary

- 11 Ground Mount Projects
- 11 Tracker Suppliers
- ~2200 individual tracker rows
- DC Capacities: 3 to 70 MWdc, median 7.3 MW
- Commercial Operations Dates: 2016 to 2022
- Six months to two years of operational data per project
- Multiple Mounting Configurations: 1P, 2P, 3L

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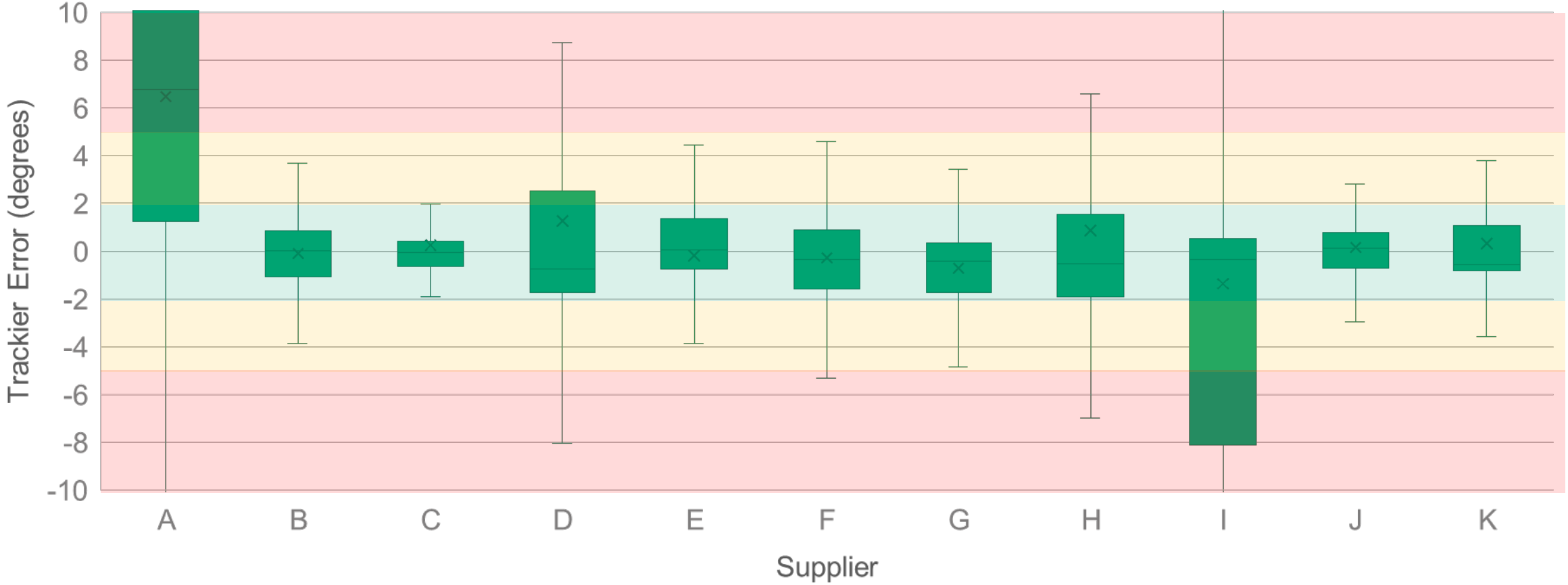
Tracking Errors – vs Ideal Tracker

$$Tracker\ Error = Tilt_{ideal} - Tilt_{actual}$$



Typically quoted tracker accuracy = +/- 2 degrees

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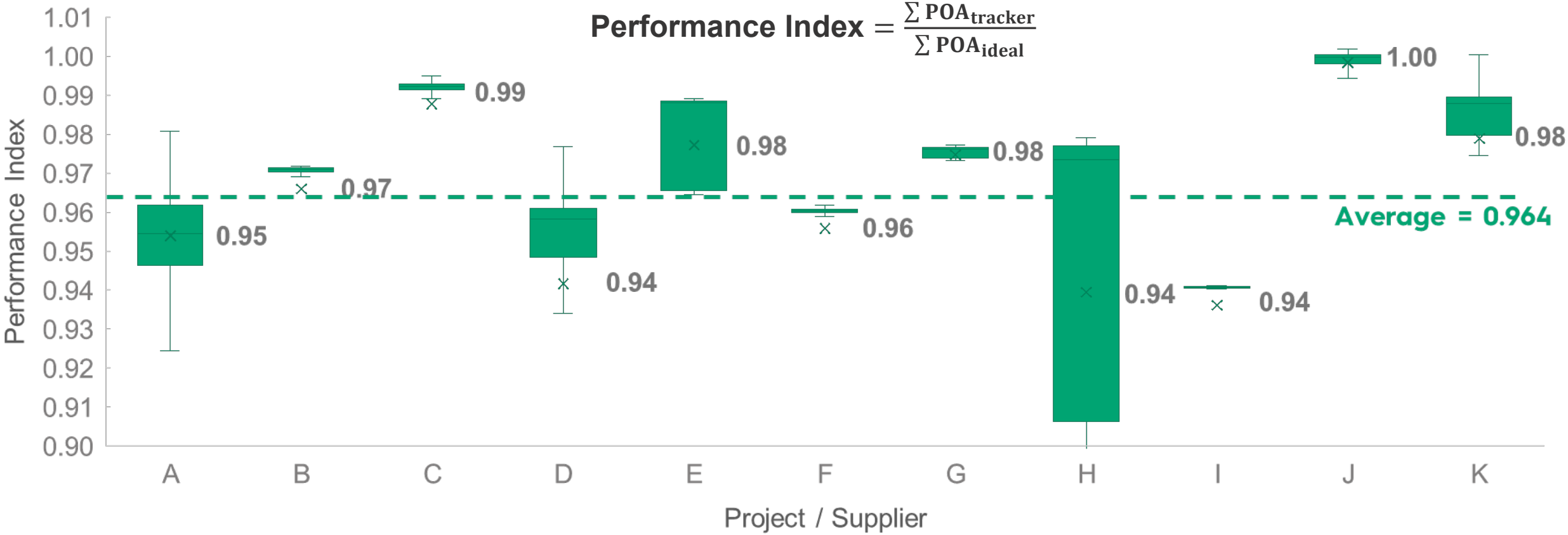
Performance Index by Supplier



Range of PIs exhibited by suppliers; average PI is 0.964

In some cases, range of PIs exhibited by trackers at the same project

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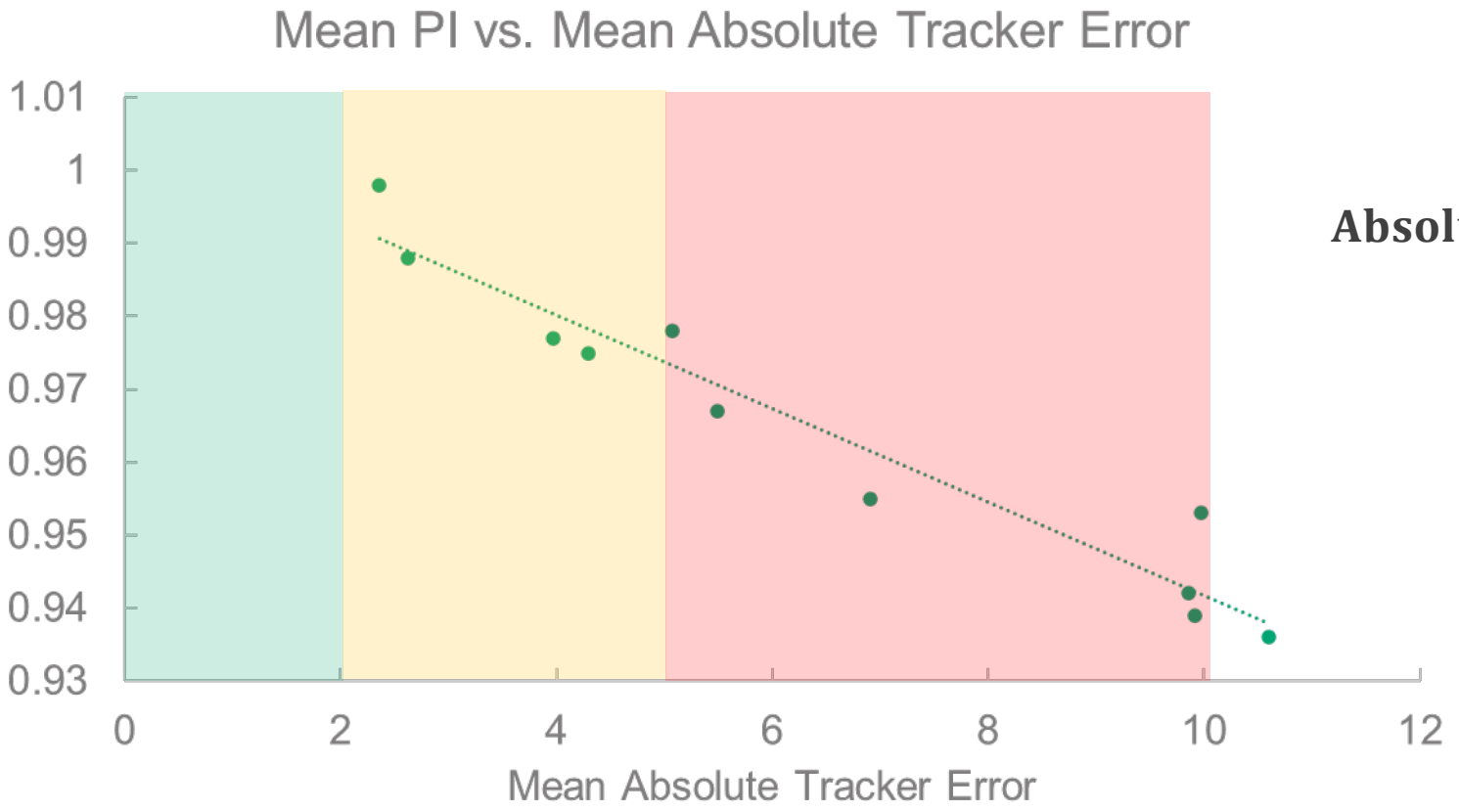
Performance Index vs. Tracking Error Relationship



$$\text{Absolute Tracker Error} = |\text{Tilt}_{\text{ideal}} - \text{Tilt}_{\text{actual}}|$$

$$\text{Performance Index} = \frac{\sum \text{POA}_{\text{tracker}}}{\sum \text{POA}_{\text{ideal}}}$$

Linear correlation between tracker error and performance index

Tracker performance index is quite good for errors in the +/- 2 degree range

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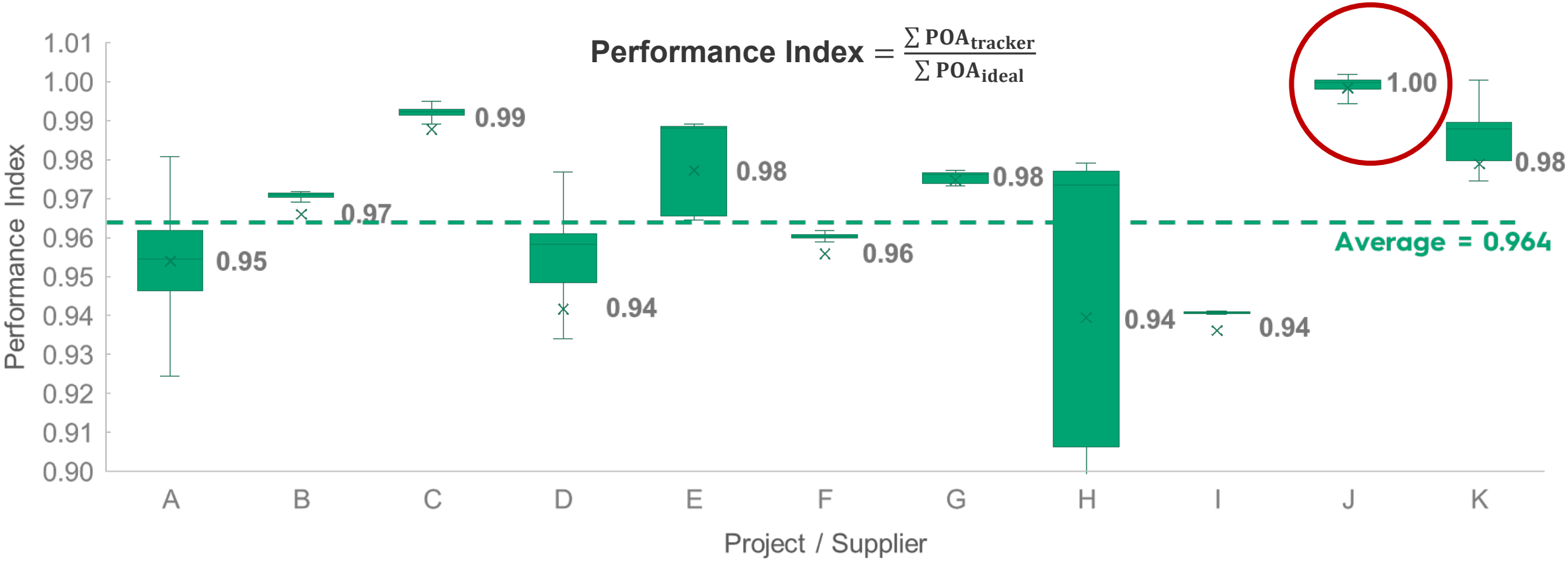
Ground Slope Case Study (Supplier J)



Range of PIs exhibited by suppliers; average PI is 0.964

In some cases, range of PIs exhibited by trackers at the same project

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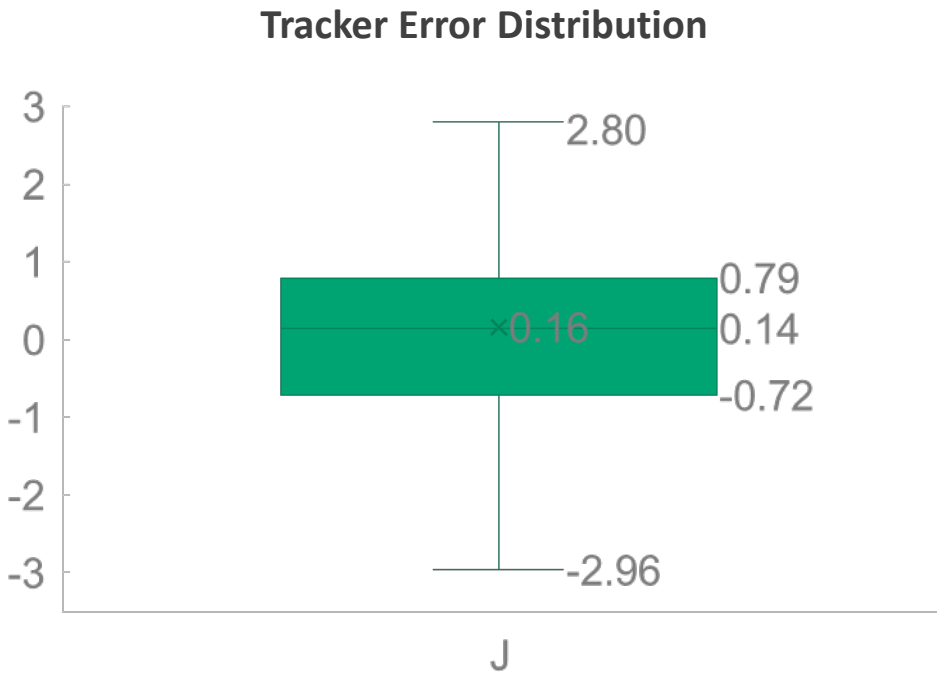
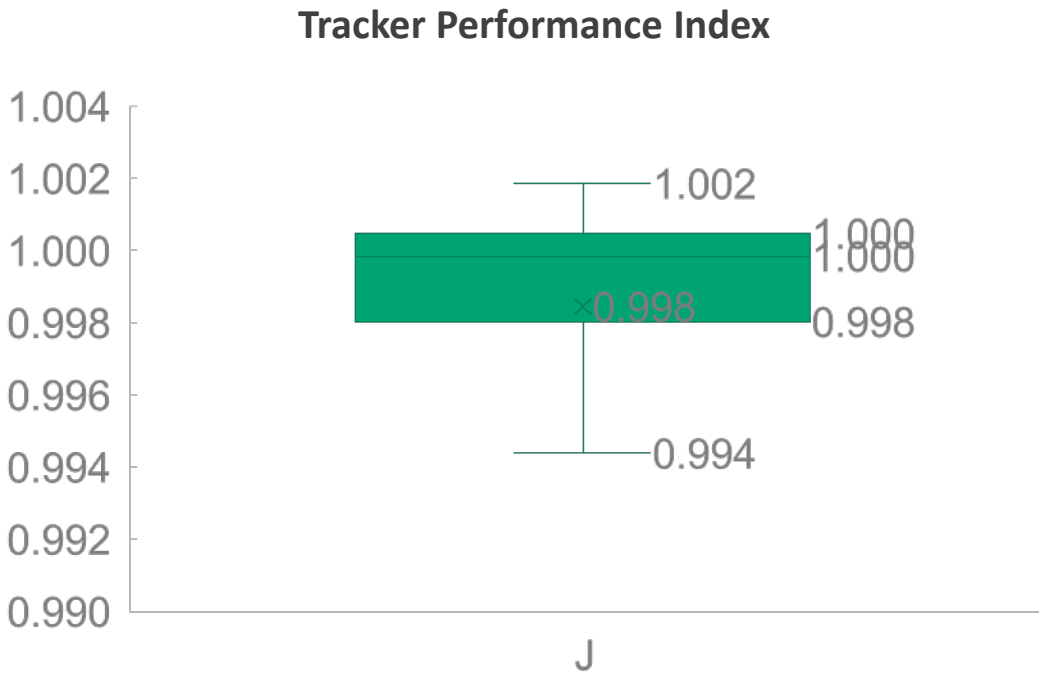
Ground Slope Case Study (Supplier J)

- Project: New construction, freshly commissioned trackers, underperforming energy estimate
- **Significant ground slope – 7% east to west grade**





The tracking system *appears* to be performing as expected.

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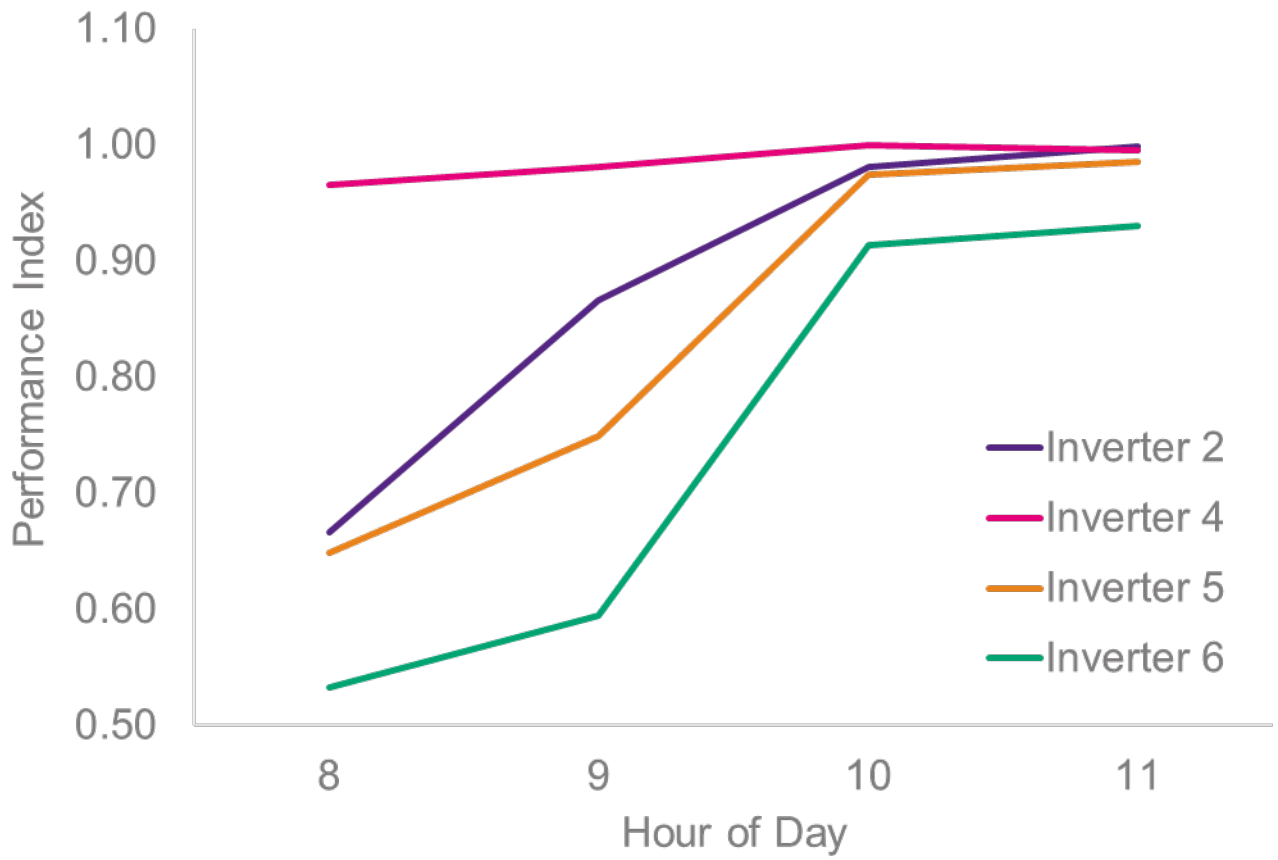
Ground Slope Case Study



Significant inter-row shading at 10 am

The ideal tracker and the actual trackers are set up for a "flat" site.

7% E-W grade at the site results in significant inter-row shading.

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Conclusions

- A methodology for evaluating the impact of tracker outages and mistracking on project performance has been presented.

- Portfolio
  - 11 tracker suppliers evaluated across 11 projects
  - Smaller ground mount projects, median capacity 7.3 MW
  - Six months to two years of operational data per project

- Results
  - Almost no suppliers are able to achieve the quoted +/- 2° accuracy while in operation
  - PIs range from 0.94-1.0.
  - Average PI is 0.964

- Limits of the methodology
  - Ground slope example shows that this methodology is not perfect

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Thank you.

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Glass and Silicon Recovery from Solar Modules Using Laser Processing

Pawan K. Kanaujia, and Mool C. Gupta
University of Virginia
&
Michael Owen-Bellini, Heather Mirletz, and David Young
National Renewable Energy Laboratory

PVRW- 3rd March 2025

This work was developed based upon funding from the Alliance for Sustainable Energy LLC. managing and operating contractor for the National Renewable Energy Laboratory for the U.S. Department of Energy.

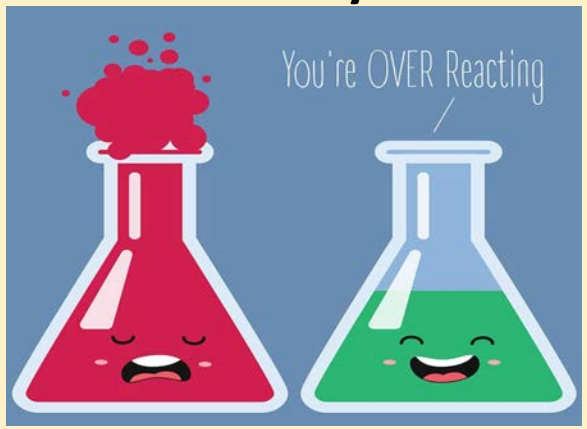
Problem Statement

- ✓ PV cumulative waste is expected to reach 78 million tons by 2050
- ✓ PV waste could create $15B in raw materials, generate new industries, new employment
- ✓ No economical component recycling technique available; End up in landfill

Current Solutions

Chemical Methods

- Too slow and takes days,
- Environmentally hazardous

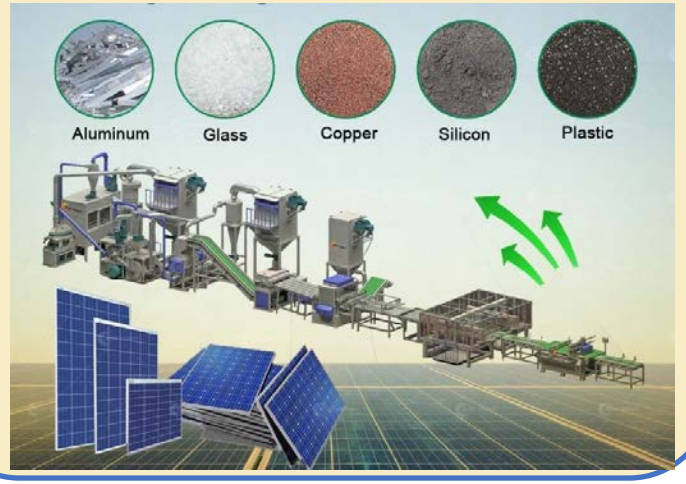


Thermal Methods

- High Temp. 500 ^{0}C, High Energy consumption
- Slow process, Harmful gasses

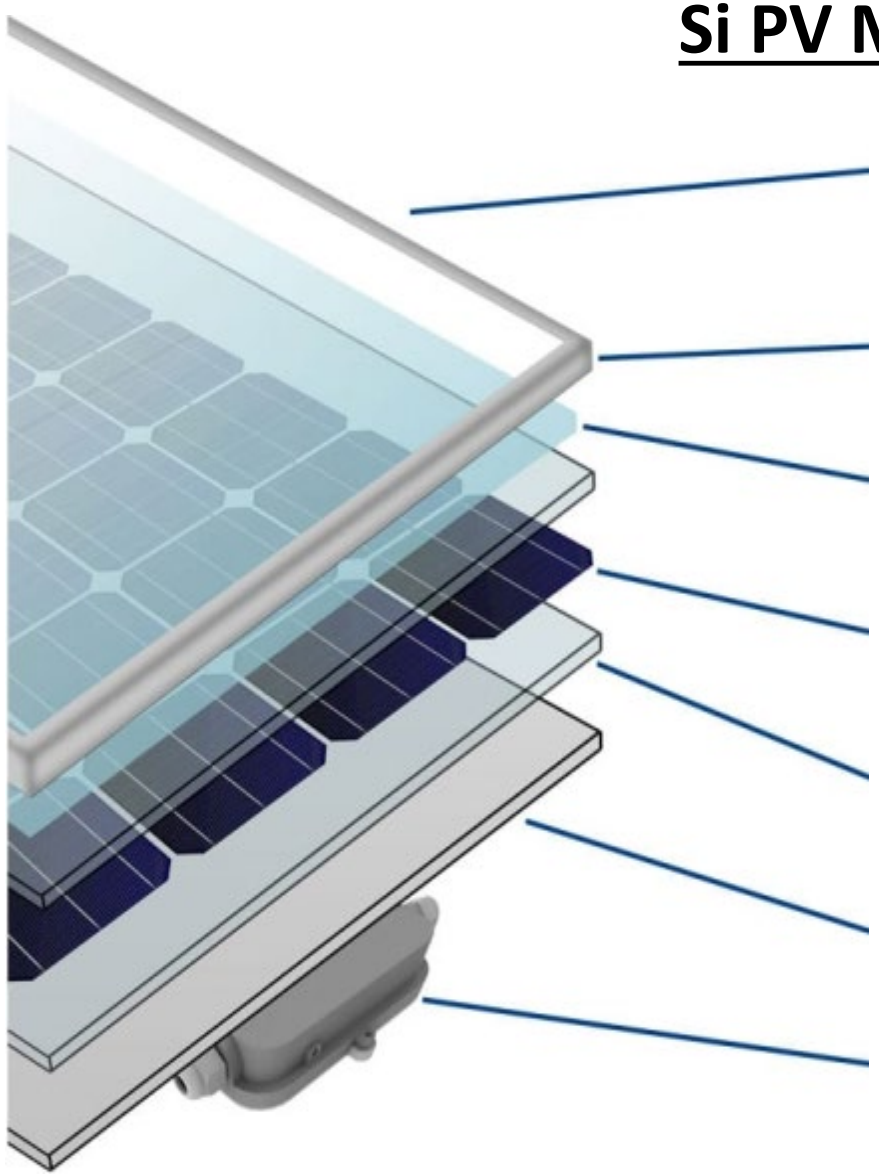
Mechanical Methods

Unavoidable Impurities, High energy consumption, Limited materials recovery



https://doi.org/10.3390/en16114327

Si PV Module



Aluminum frame

Tempered Glass

Encapsulant Material

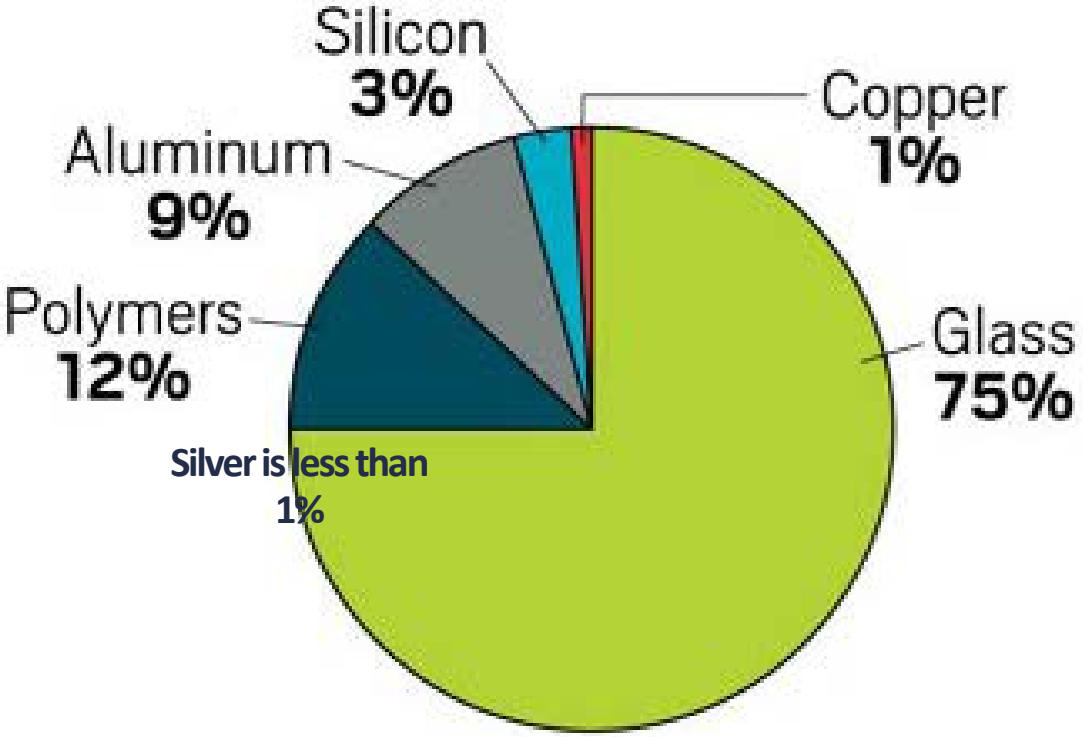
Silicon Solar Cell

Encapsulant Material

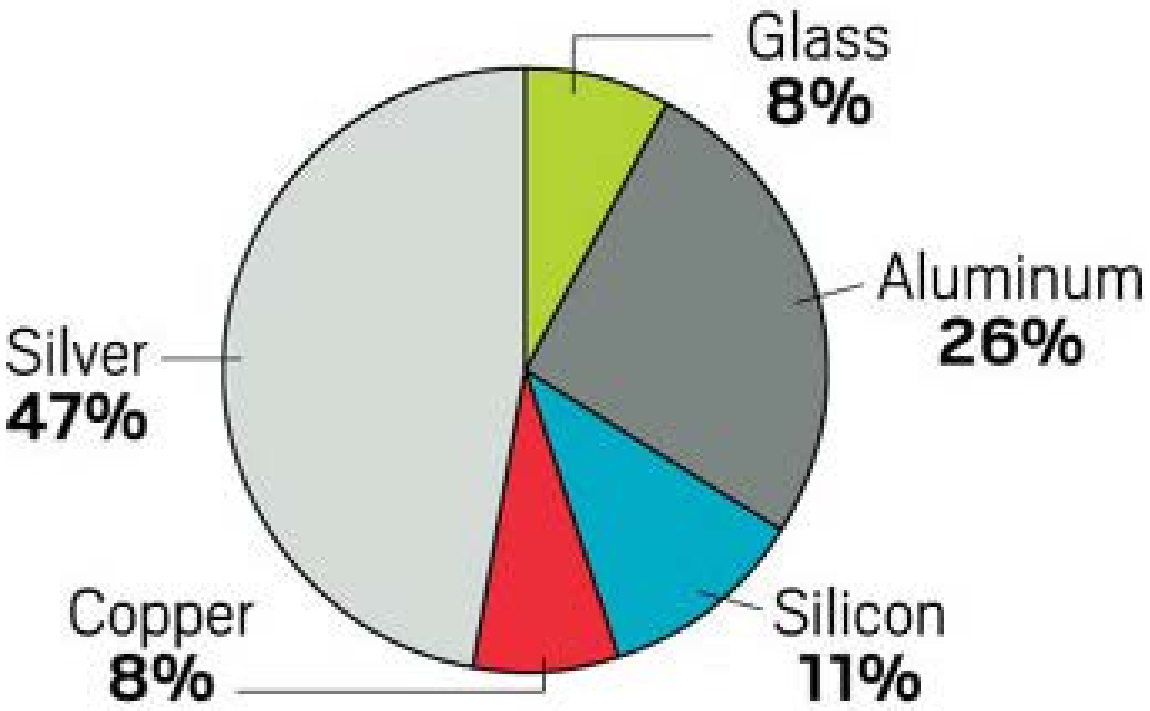
Backsheet

Junction Box

Recyclable material distribution within solar panels



Distribution of materials by mass

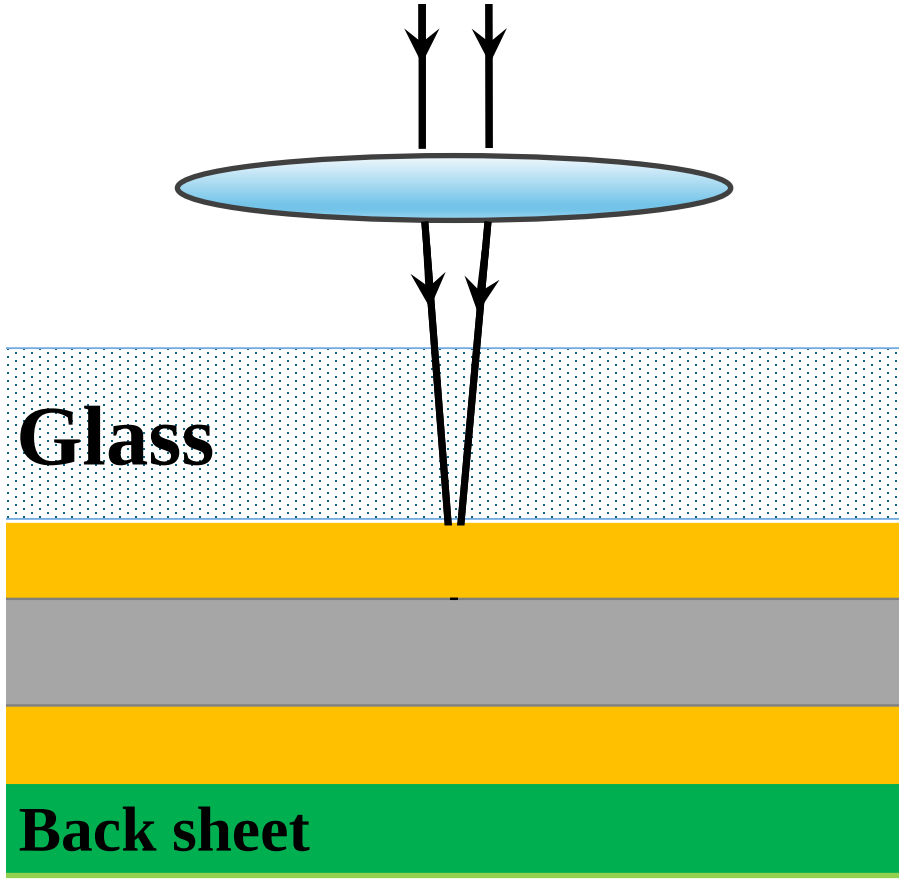


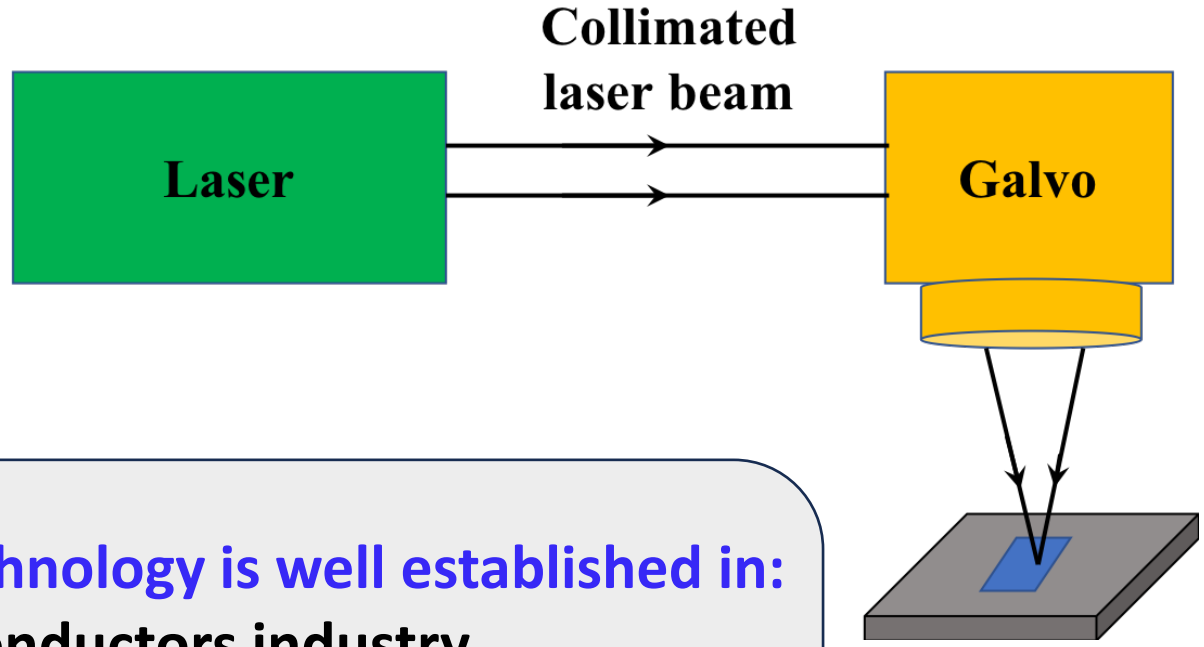
Distribution of materials by value

Source: Martin Bellman/Icarus

https://cen.acs.org/environment/recycling/Solar-panels-face-recycling-challenge-photovoltaic-waste/100/i18

Our PV Recycling Approach: Component Recovery Using High Power Lasers- Localized Heat, melting and ablation



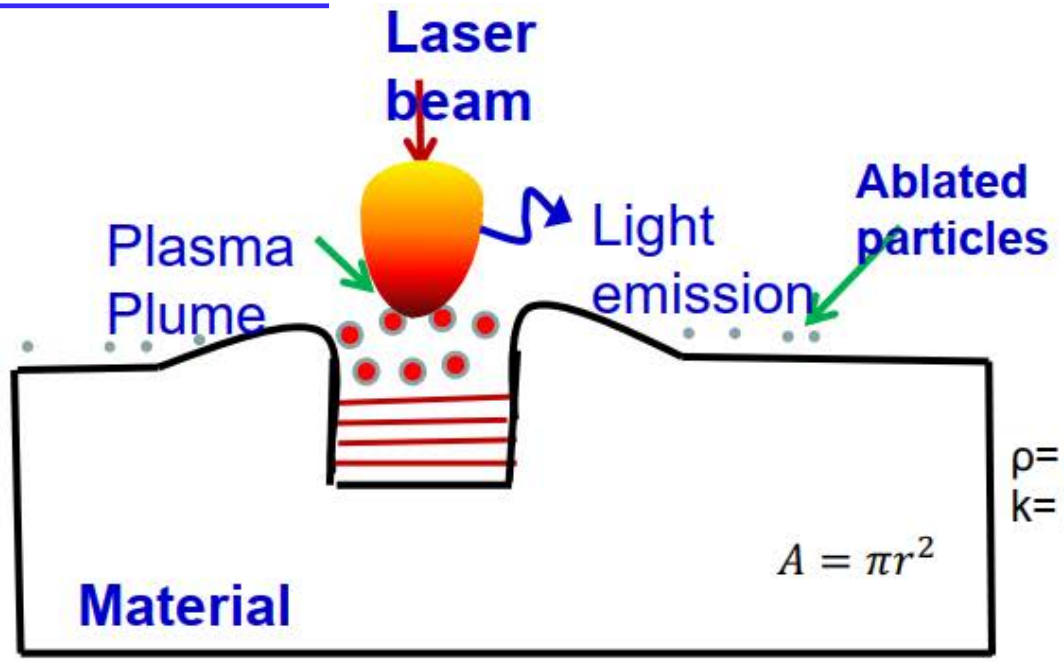


Laser technology is well established in:

- semiconductors industry
- Automotive manufacturing
- Aerospace
- biomedical etc.

Low-cost manufacturing

Laser matter interaction



- **Light Absorption, Temperature Rise, Melting, Vapor. Cooling & Solidification**

ρ= mass density, C_p= specific heat
k= thermal conductivity

$$I(r) = I_0 = const$$

$$D = \frac{K}{\rho c_p}$$

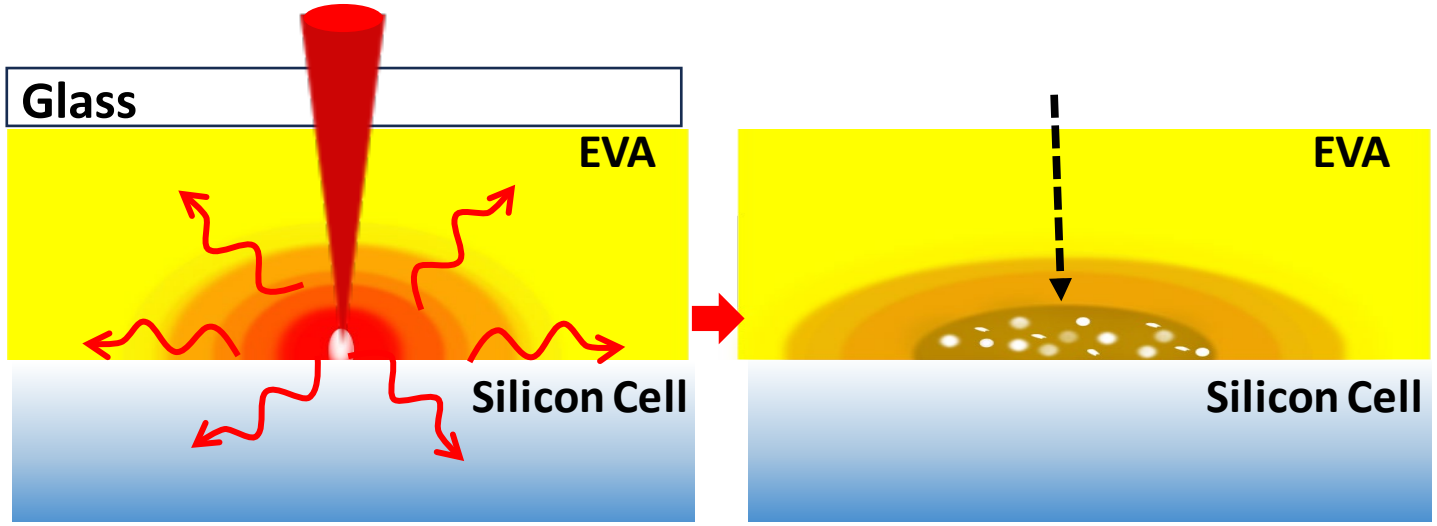
$$\rho c_p \frac{\partial T}{\partial t} - K \frac{\partial^2 T}{\partial z^2} = I_0 (1\text{-R}) \alpha e^{-\alpha z}$$

$$T(t,z) = \frac{I_0 (1\text{-R}) \alpha 2 \sqrt{Dt}}{K} icrfc\left(\frac{z}{2\sqrt{Dt}}\right)$$

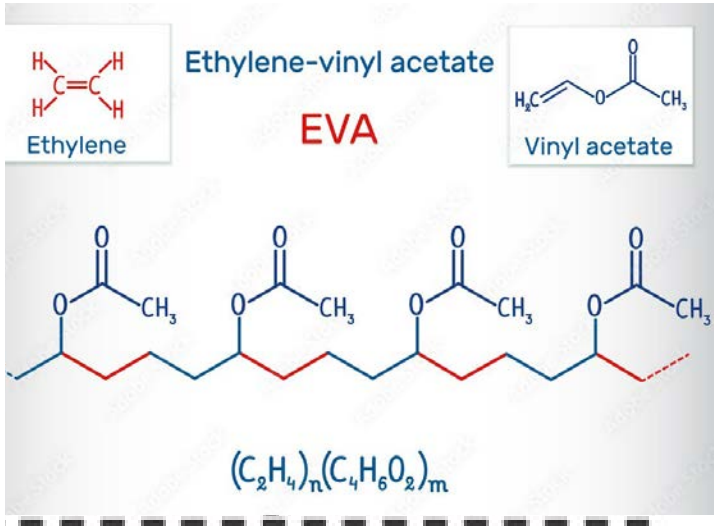
- **Localized energy deposition**
- **Short laser pulse width in nanoseconds**
- **temperatures over vaporization**

Source: David Sands, "Pulsed laser heating and melting" https://www.intechopen.com/chapters/25478

Heat- induced EVA debonding mechanism: Chemical modification



Laser induced EVA decomposition

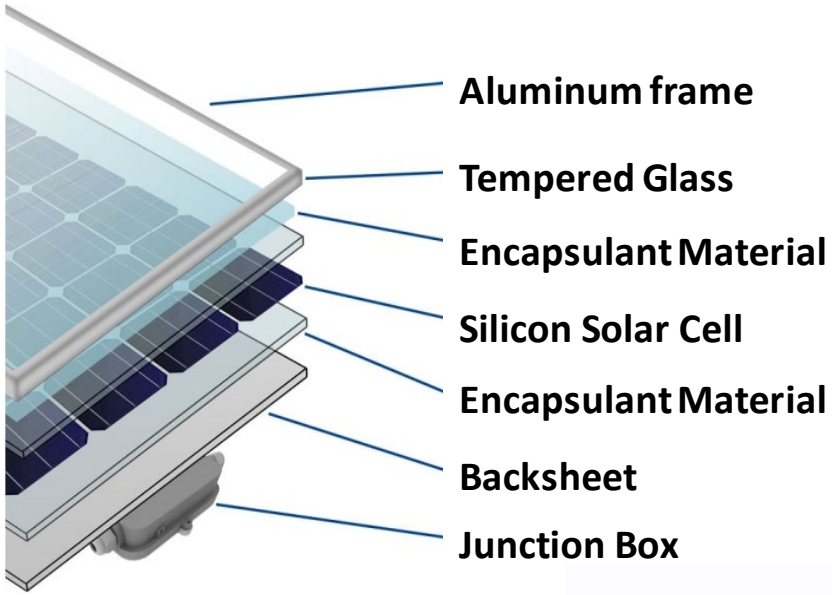


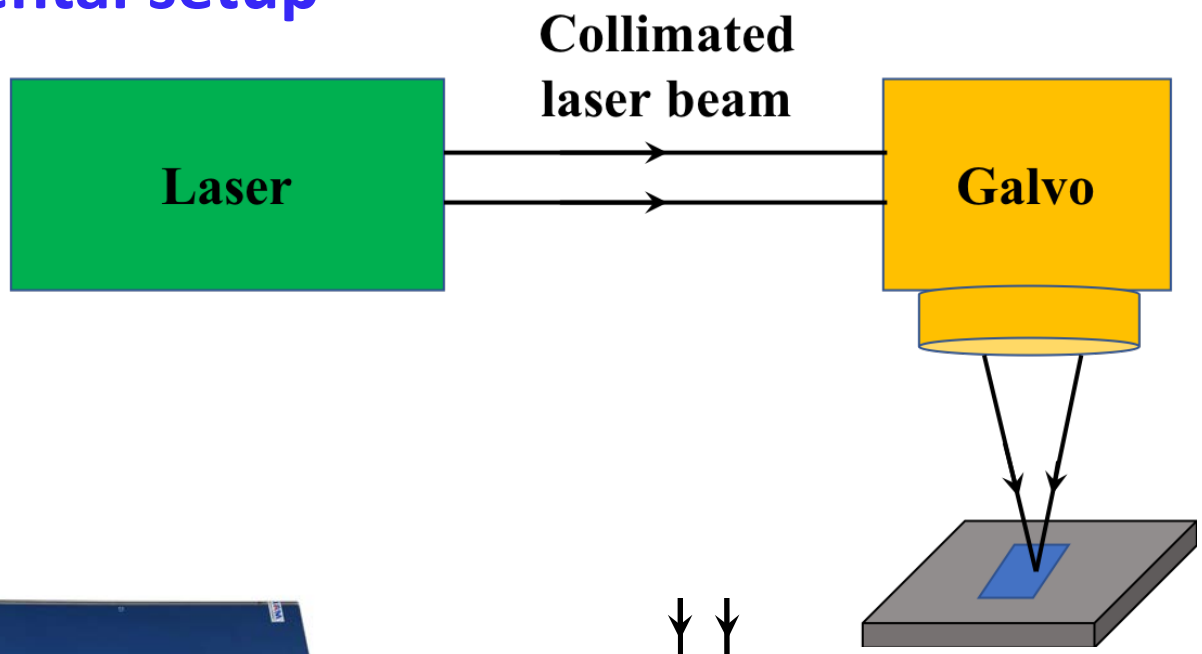
EVA Breakdown & Laser Effect:

- ❑ 300-350°C: Deacetylation removes acetate side groups.
- ❑ Above 400-450°C: Polyene structure undergoes allylic chain scission.
- ❑ Laser Impact: High localized temperature fully decomposes EVA at interfaces, causing debonding from silicon.

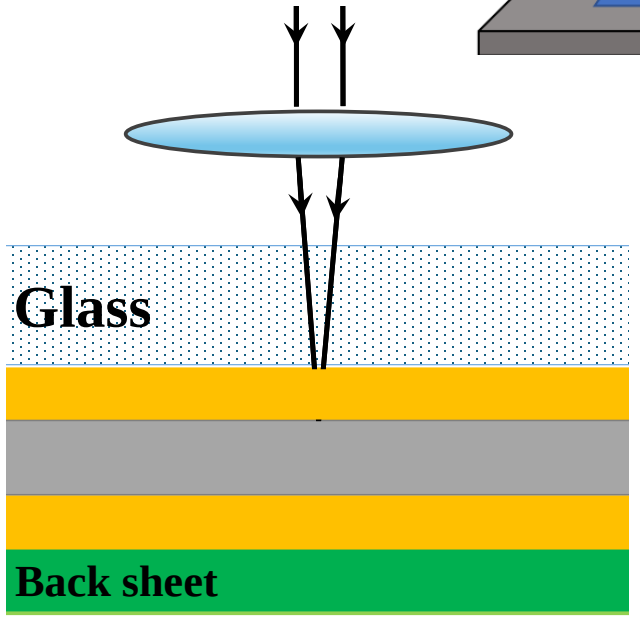
https://doi.org/10.1021/acs.iecr.1c01989

Si-PV Module Structure and Laser Experimental setup

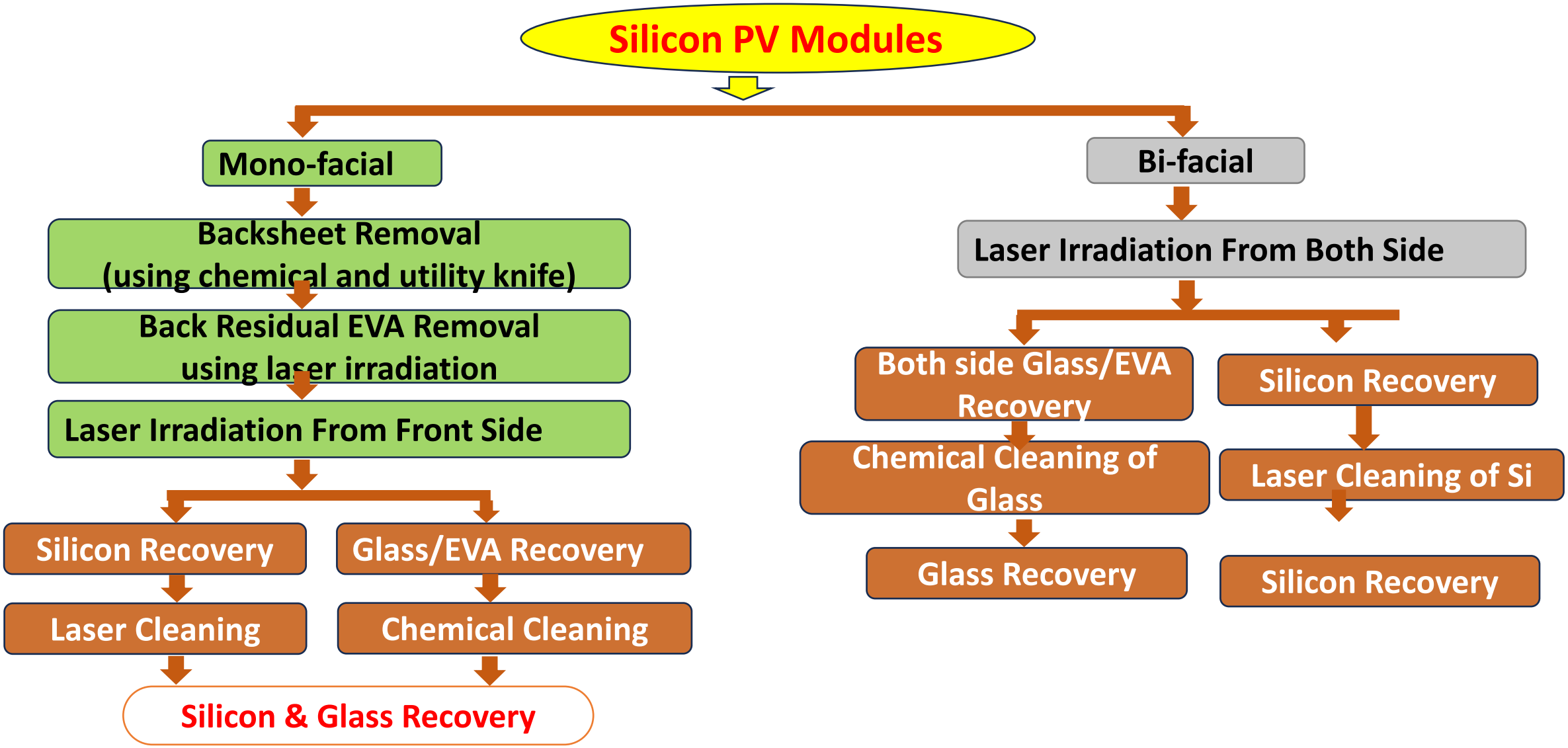




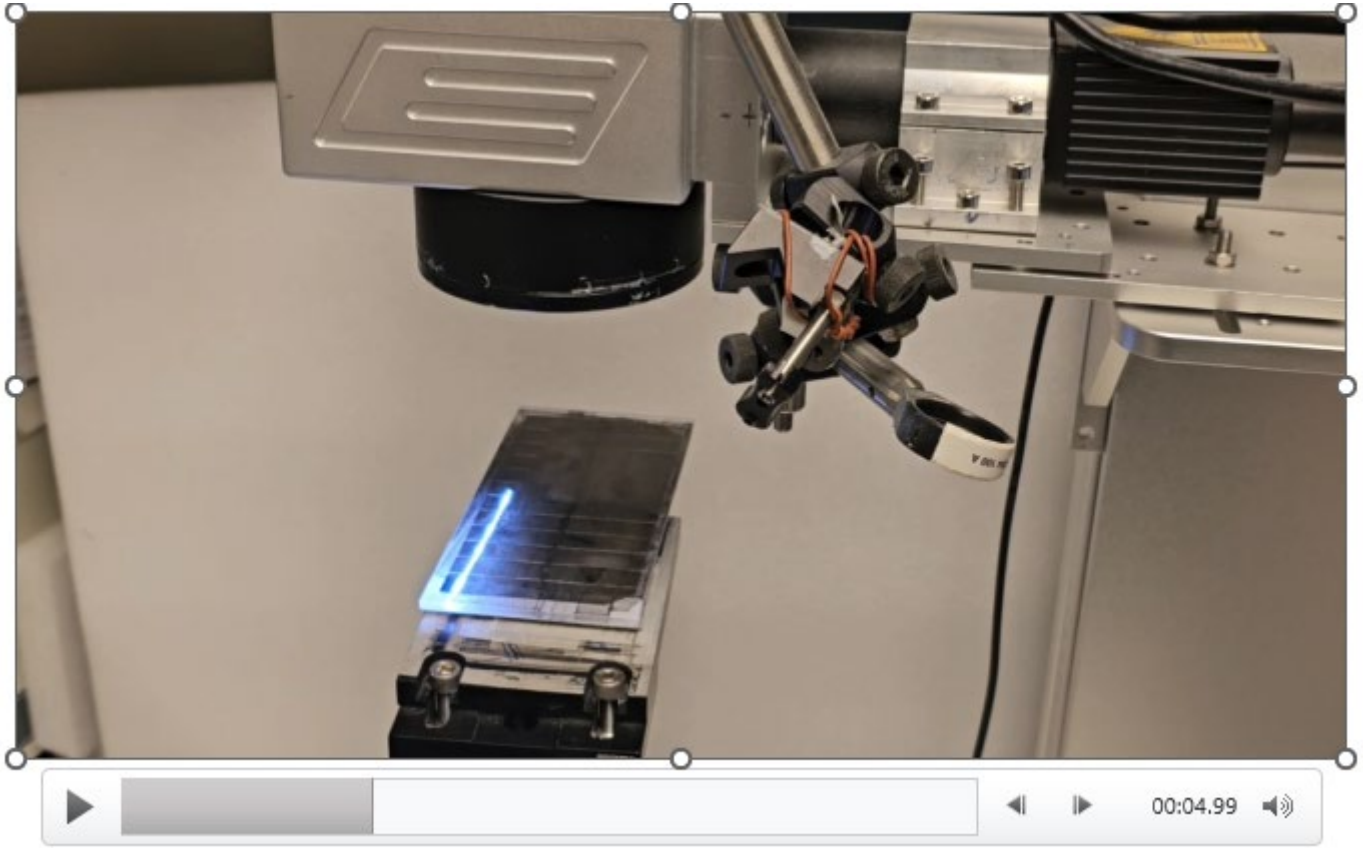
Fiber laser source (50 watt)



Process Flow Chart of PV Module Recycling Research

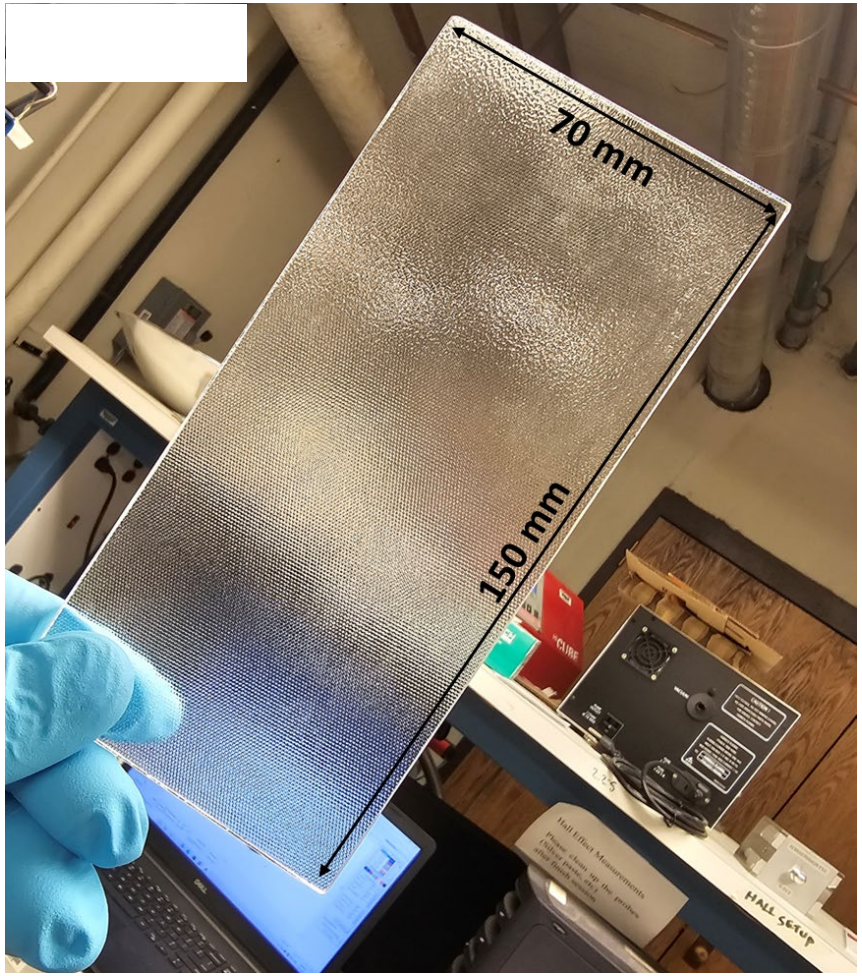


Glass/Silicon Recovery from Mono-facial Module

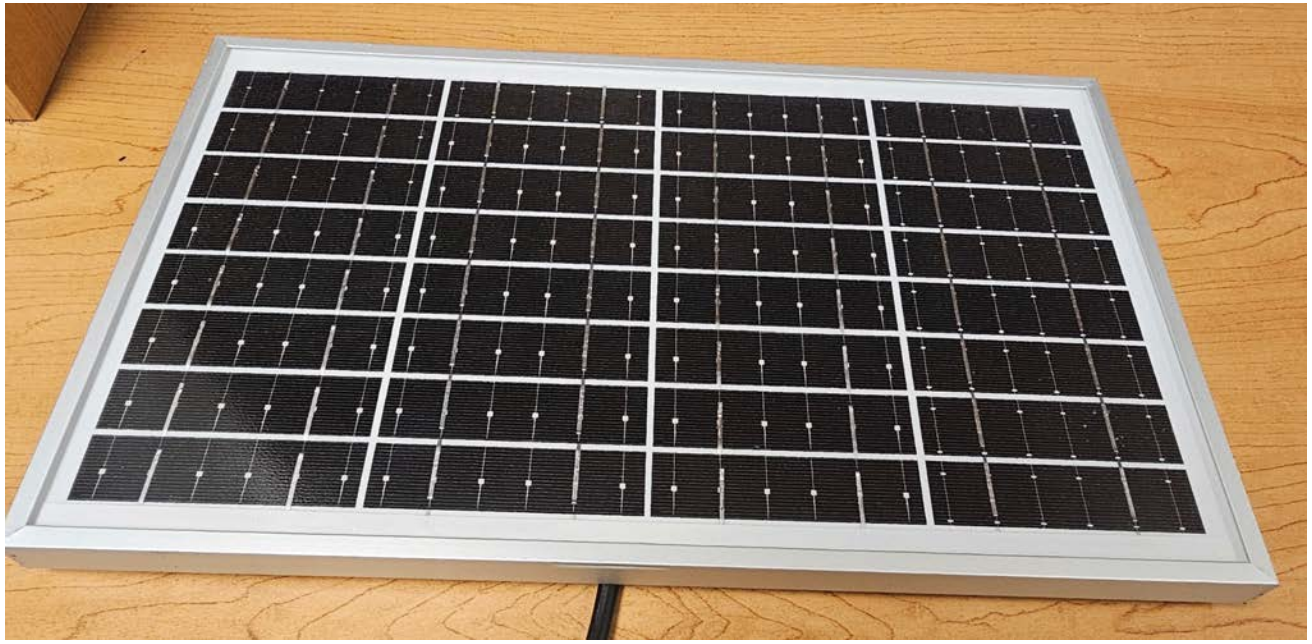


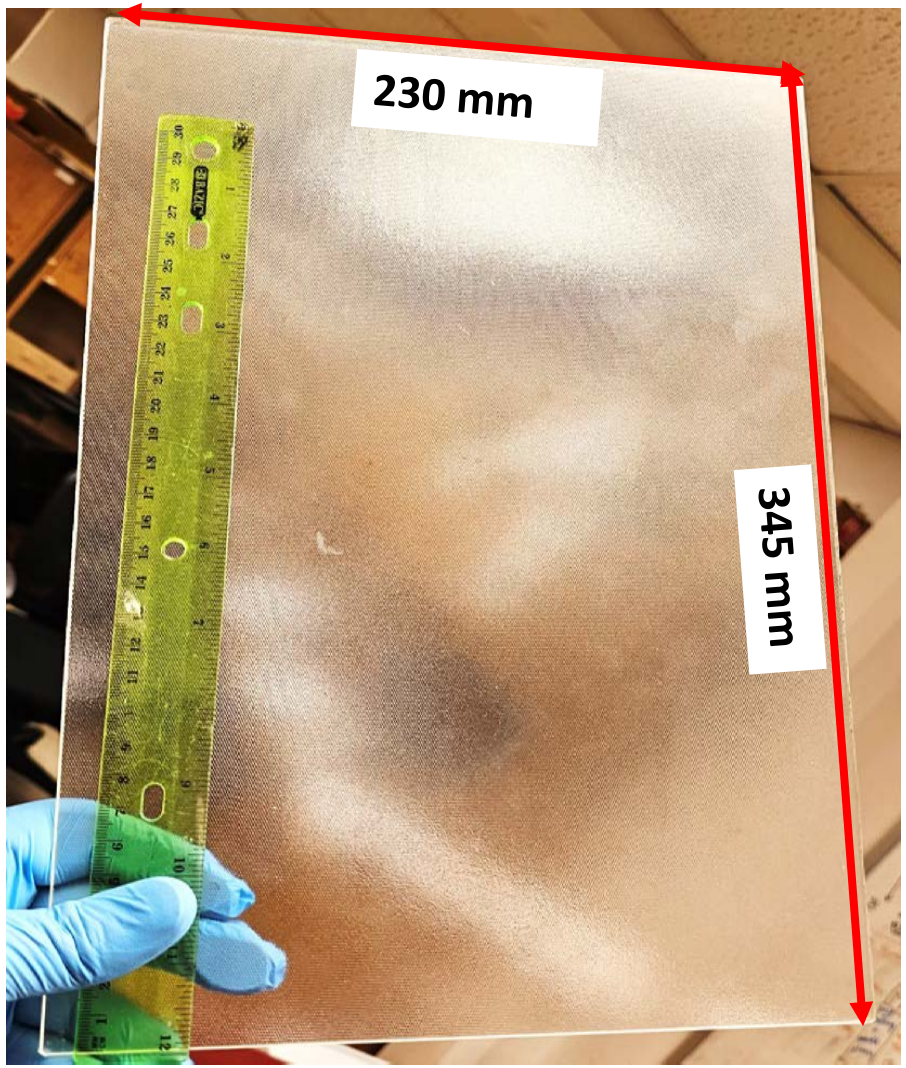
Commercial mini module of 7 cm x 15 cm

Recovered Glass



Larger size glass recovery from commercial mini modules

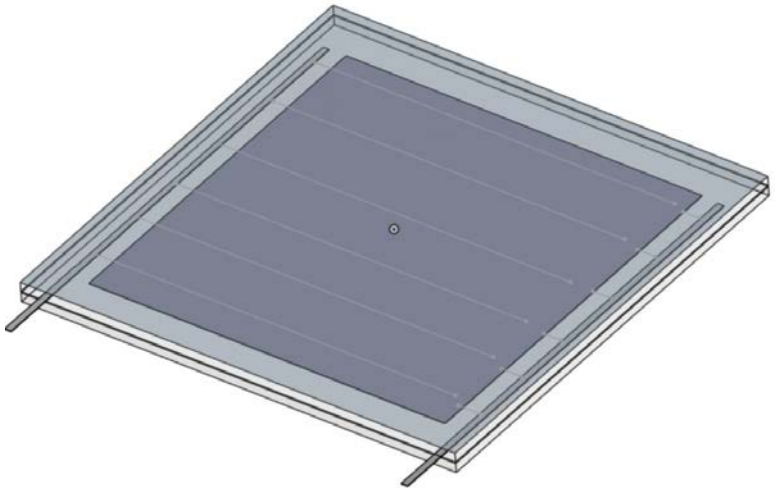




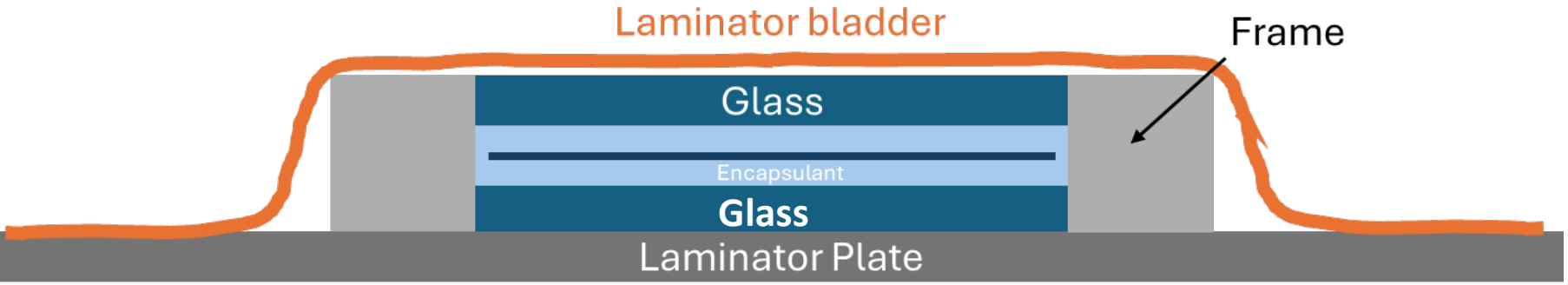
Glass recovery was performed by removing the backsheet with knife cuts followed by immersion in toluene and then laser recovery.

Bi-facial PV module sample preparation

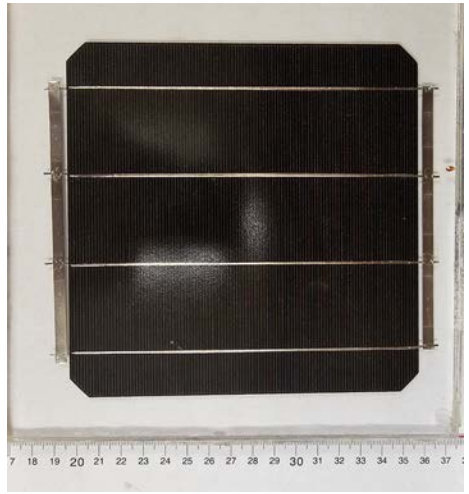
- 3.2 mm Solite Glass
- Bifacial PERC Solar cells
- Poly(ethylene-co-vinyl acetate) and Polyolefin Crosslinking Thermosets (EVA)
- TPE (Polyvinyl Fluoride-based) backsheets, if used.
- Solder-coated copper tabbing ribbons



Schematic Bi-facial Silicon PV modules



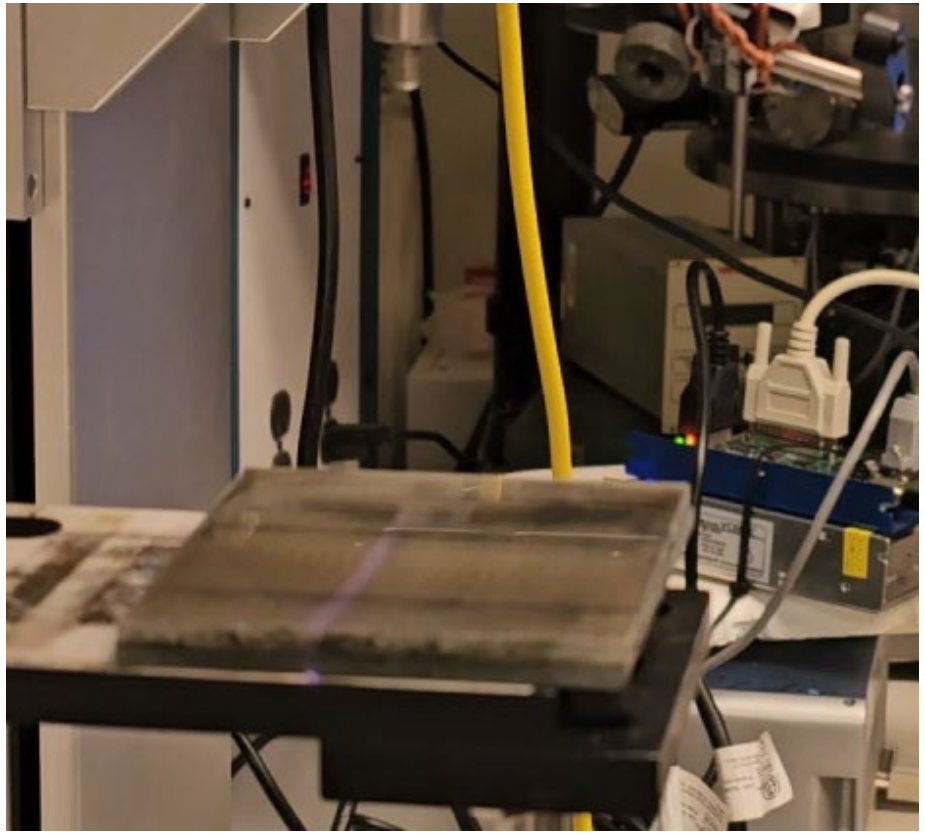
Schematic of cross section showing laminator layup

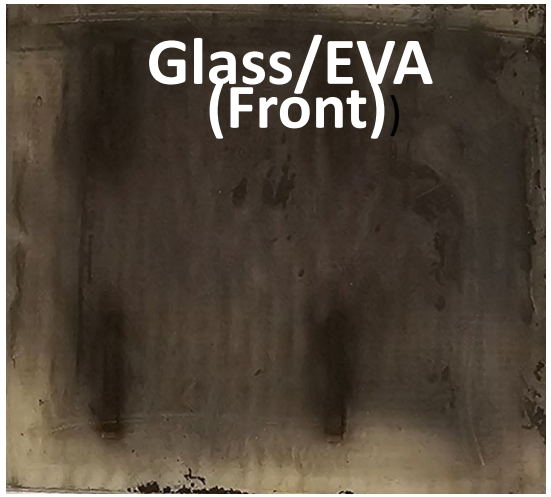


Bi-facial Silicon PV modules

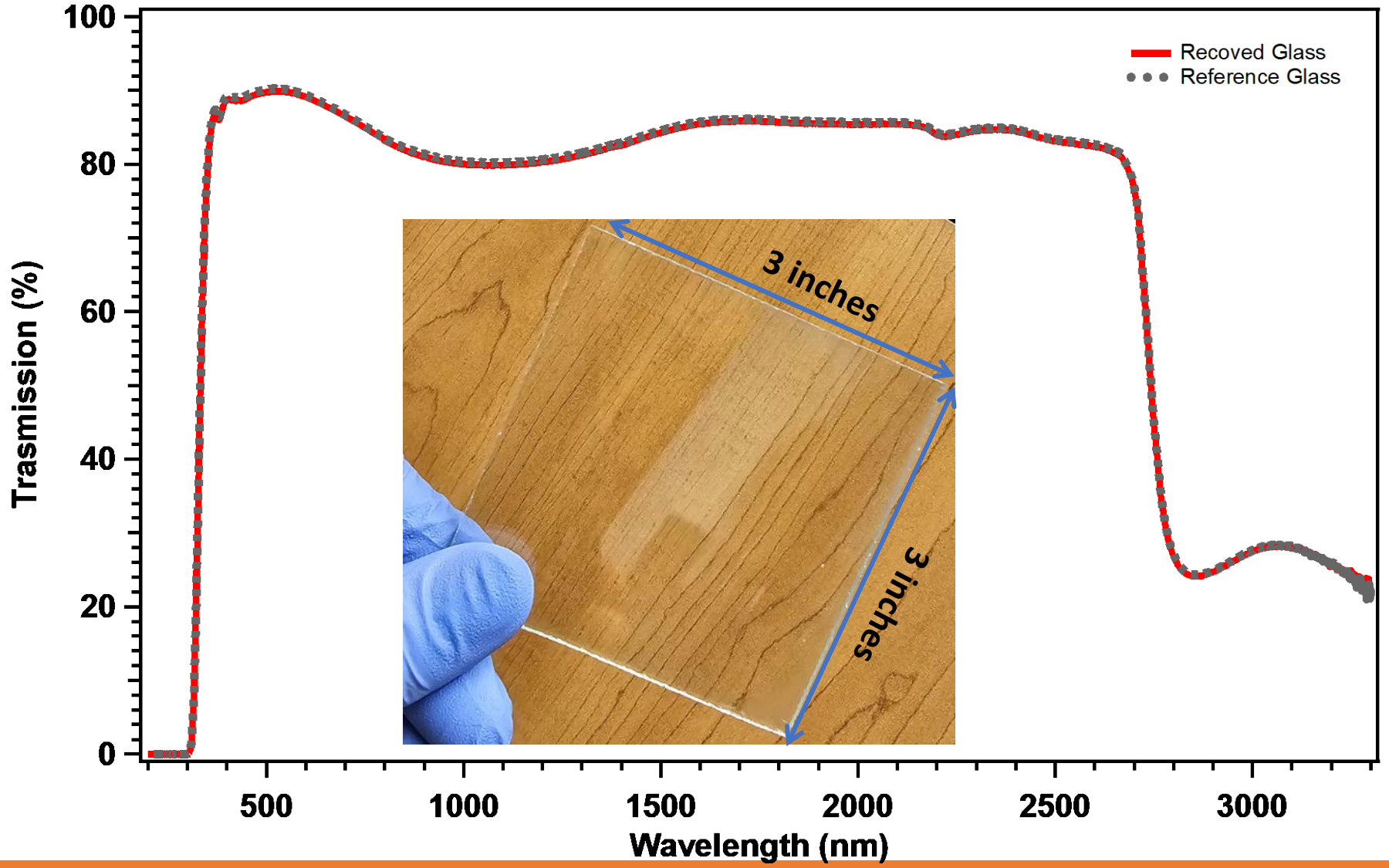
Dr. Michael Owen-Bellini (NREL)

Silicon Recovery from bi-facial solar modules

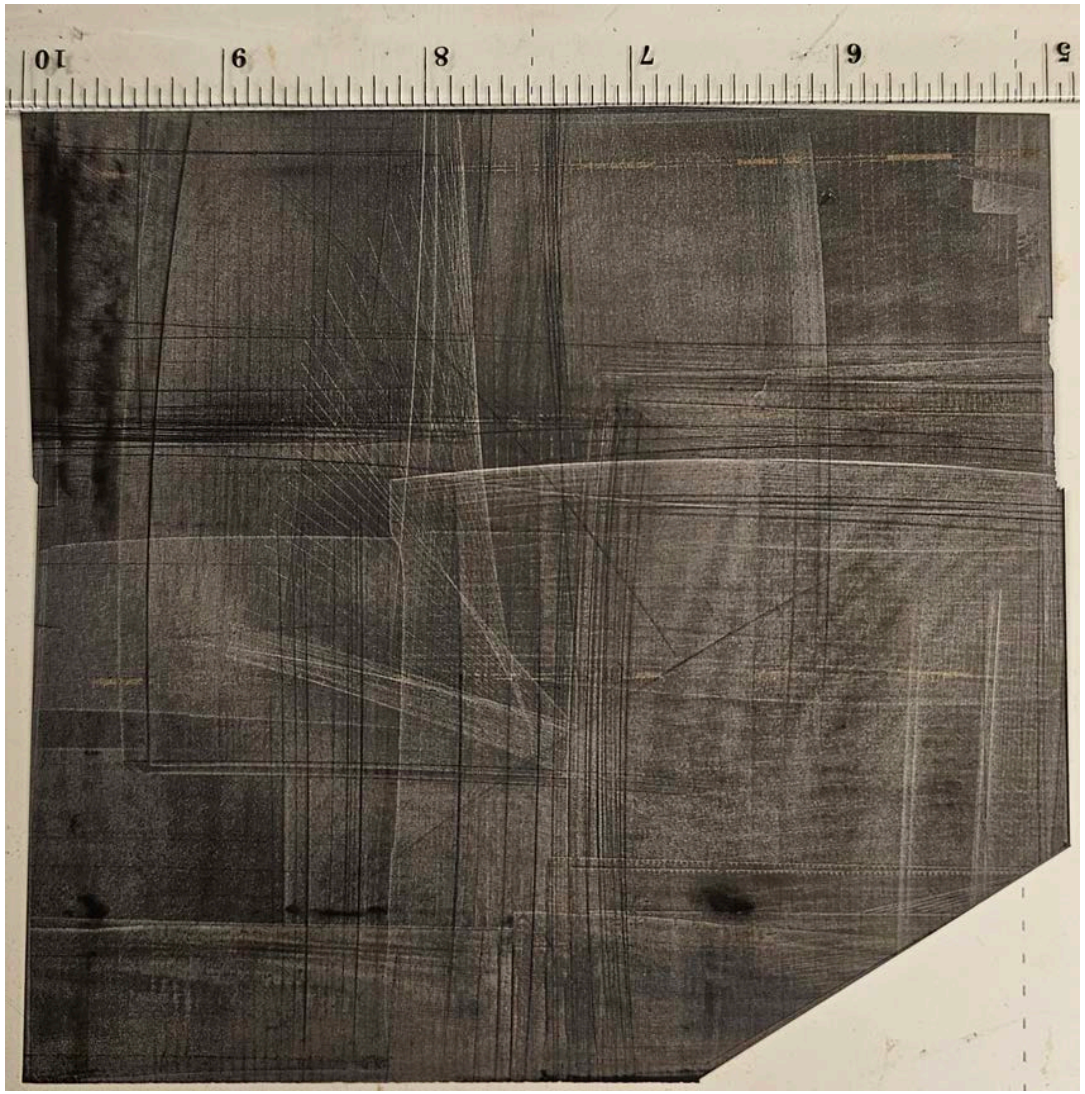




Transmission spectra of recovered Glass from Bi-facial module



Recovered Silicon Cells from Bi-facial NREL samples



Proposed Pilot Line Process Cost Analysis

J-box and Al frame separator $0.58 /module

Aluminum Frame, Junction box

Mono-facial

Bi-facial

Back sheet scoring/cutting $0.81/module

Toluene Bath $5.14/module

Back sheet removal $0.44/module

Laser Delamination $1.51/module

Remove Cu Wire $0.46/module

Cu Wires

Silicon Wafer Degumming $1.02

Silicon Wafer

Glass Washer, $1.76/module

Clean glass

Recycling cost analysis of Si-PV module

Mono-facial =$11.71/ module

Bi-facial =$5.33/module

Recovered material value =$9.5–13.4/module

: *Dr. Mirletz Heather (NREL)*

Laser Recycling Cost Analysis

- **Preliminary cost analysis indicates that laser recycling is likely cost-effective.**

In line with literature cost estimates

- ❑ **Dias et al 2022 = ~$250/ton; Deng et al 2019 = ~$400-$500/ton**
- ❑ **Our analysis = $240-$520/ton**

Recycling Cost	**$5.33 – $11.71/module** **$240 – $520/ton** **(Further reduction is possible)**
Pilot line minimum capex	**$1.3 – $2 million**
Sales of recovered materials (Al, glass, Cu, Si)	**$9.54 – 13.40/module** **$424 – 595/ton**

: ***Dr. Mirletz Heather (NREL)***

Conclusions

- Successfully demonstrated PV glass recovery and Optical transmission analysis confirms that recycled glass retains properties comparable to reference glass

- Intact silicon wafers have been successfully recovered

- Economic feasibility analysis indicates a cost-effective recovery process, with estimated costs of
  - ~$5.33/module for bi-facial
  - ~$11.71/module for mono-facial (further reduction is possible)
  - The recovered material holds a value of $9.54–$13.40 per module.

Future Work

I. Process Optimization

II. Different Encapsulant Material Evaluations

III. Detailed Cost Analysis and Economic Feasibility

IV. Further Evaluation of Recovered Materials

V. Scaling Up of the Laser Process

VI. Technology Transition: Develop Pathways for Industrial-scale Implementation and Commercialization.

Patents, Publications and Conference Presentations

Patents

[1]. Laser Process and System and Resultant Article of Manufacture, Mool C. Gupta, P. K. Kanaujia U.S. Patent Application No. 63/415,202, Oct 10, 2022.

[2]. Laser Process and System and Resultant Article of Manufacture (II), Mool C. Gupta, P. K. Kanaujia U.S. Patent Application No. 63/538, 209, Sep 13,'23.

Conference Presentations

[1]. P. K. Kanaujia, M. Owen-Bellini, M. Woodhouse, D. Young and M. C. Gupta, "Silicon Module Recycling by High Power Laser", PVRW, Denver, Colorado, Feb 27, 2024

[2]. P. K. Kanaujia, M. Owen-Bellini, M. Woodhouse, D. Young and M. C. Gupta, Water Jet Assisted Green Recycling of Si-Solar Cell Modules Waste at SPIE-24 (Defense +Commercial sensing), Maryland, April 21-25, 2024. *(Invited)*

[3]. P. K. Kanaujia, M. Owen-Bellini, M. Woodhouse, D. Young and M. C. Gupta, Recovery of Glass and Silicon Solar Cells from Si-Modules Through Laser Processing, IEEE Photovoltaics Specialist conferences (PVSC-52) Seattle WA, June 9-14, 2024 *(Oral Presentation)*

[4]. P. K. Kanaujia, M. Owen-Bellini, H. Mirletz, D. Young and M. C. Gupta, Silicon Recovery from End-Of-Life Solar Module Using High Power Laser Processing", Submitted to PVSC-53, June, 25, Montreal, Canada.

THANK YOU !

Module warranty backstop by Munich Re

Dr. Ronald Sastrawan
Director, Green Tech Solutions
Munich Re, Hong Kong

Munich RE

Image: tl6781 / stock.adobe.com

Munich Re

The world's largest reinsurer

Munich Re (Group)

- founded in 1880
- net result 2024: €5.7bn
- total assets 2024: €286.5bn
- approx. 43,000 employees

Rating

A.M Best	A+ (Superior)	stable
Fitch	AA (Very Strong)	stable
S&P	AA (Very Strong)	stable

PV warranty risk

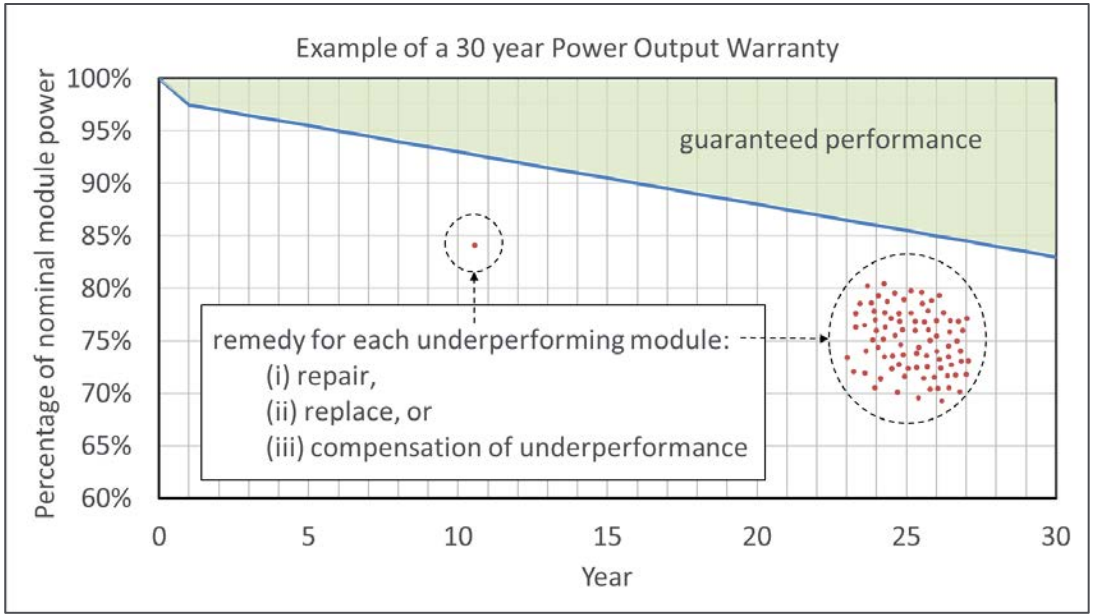
Image: tl6781 / stock.adobe.com

PV warranty risk

25 - 30 years power output warranty: a unique risk to the PV industry

Munich RE

- such a strong warranty is a great chance for the solar industry, but also a great risk
- low LCOE relies on long project lifetime
- **PV warranty insurance** protects
  - i. suppliers, **and**
  - ii. buyers (under supplier's default)
- **suppliers** require warranty insurance for
  - i. risk management, and
  - ii. sales & marketing support
- **buyers** require warranty-insured PV modules for
  - i. risk management, and
  - ii. fulfilling requirements of regulators, lenders, and tenders



PV warranty insurance has become a standard in the industry, but **must be requested in the procurement process**

The Munich Re due diligence process

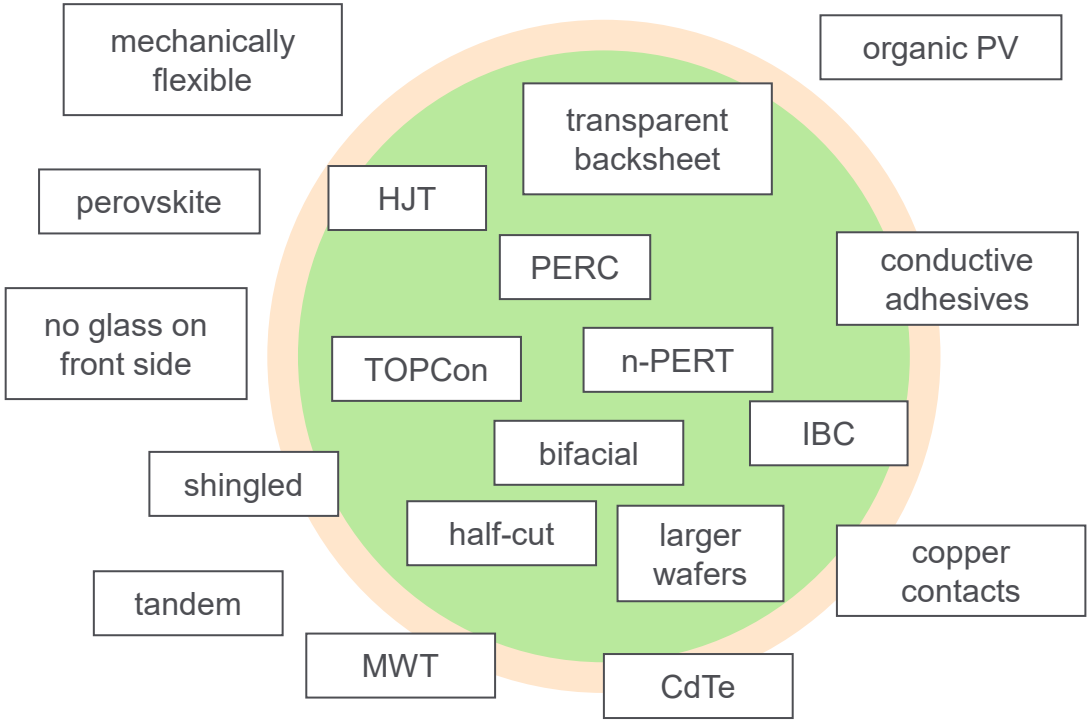
Image: tl6781 / stock.adobe.com

The Munich Re due diligence process

General assessment of technology

Munich RE

- a large zoo of commercial PV technologies exist today
- we focus on proven, mainstream technologies, while keeping our risk appetite as broad as possible
- our risk appetite is constantly evolving in line with the PV industry
- insuring technologies outside the circle might be possible, but risk assessment will take longer

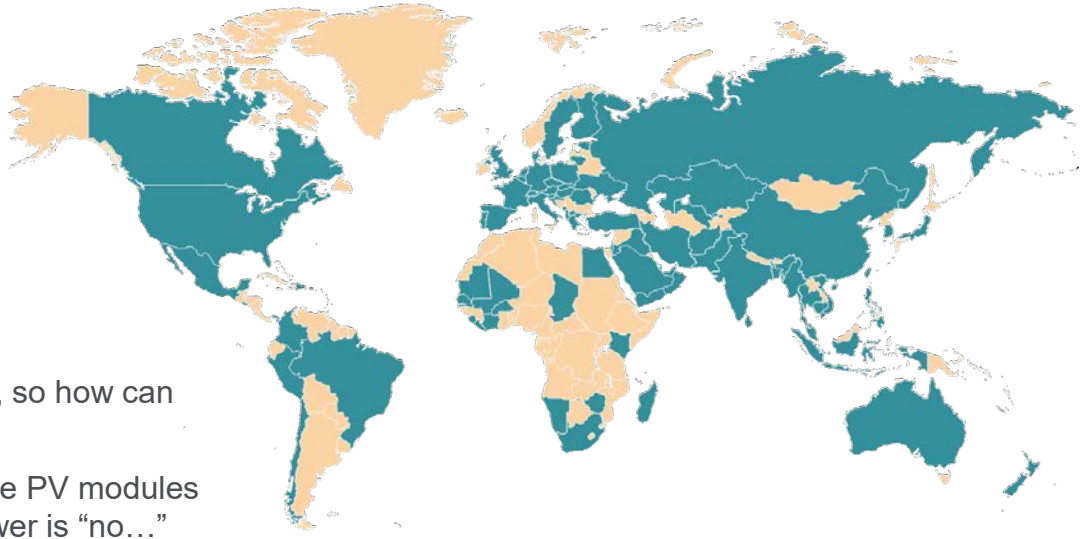


The Munich Re due diligence process

Munich RE

De-risking a vast, global portfolio consisting of countless different product types

Single PV project	Global insurance portfolio
10-100 MWp	50+ GWp
one supplier	30+ suppliers
one product type	countless product types
one location, climate	truly global
one project operator	many project operators



→ we cannot inspect each individual batch or project, so how can we de-risk our portfolio?

→ should we just insure all standard PV modules? Are PV modules now a standardised commodity product? Our answer is “no…”

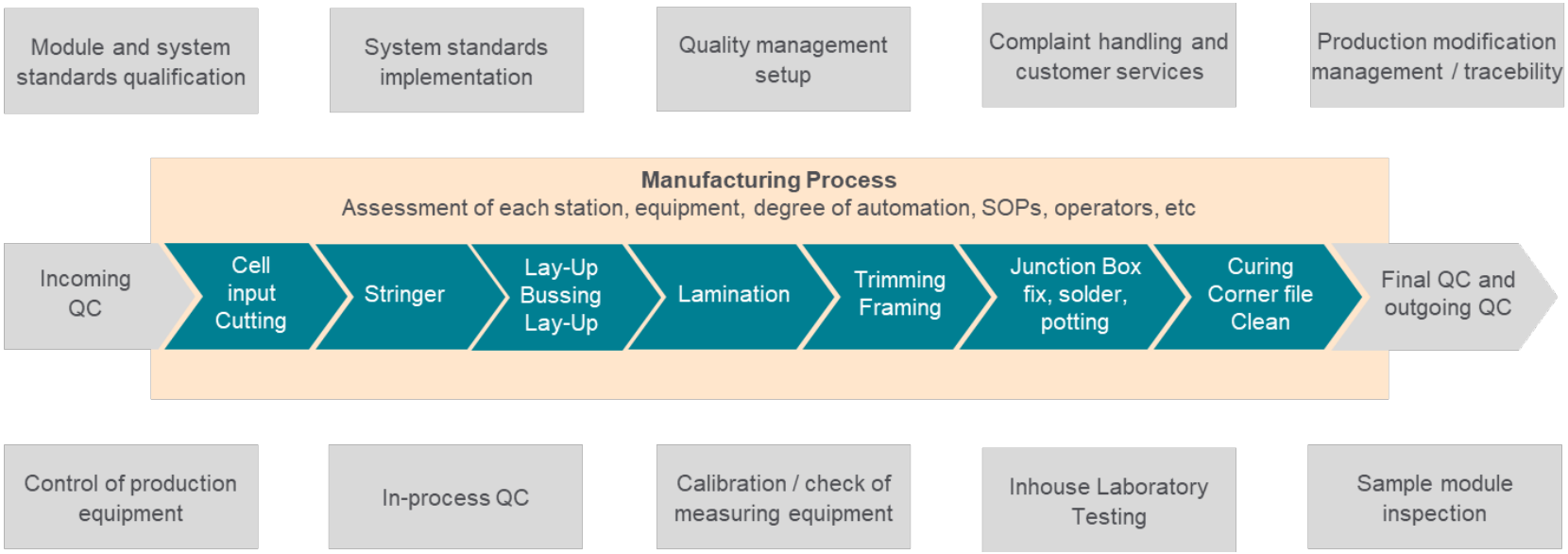
Goal of Munich Re’s factory inspections

- **addition to reliability tests** such IEC 61215 and 3x IEC
- assess ability of a PV module maker to **consistently** produce high-quality with low deviation
- vast majority of cell-to-module factories use similar process: **reveal differences between very similar factories**
- identify and **sort out sub-standard factories**

The Munich Re due diligence process

Factory inspection scoring system

Munich RE



- detailed scoring system developed and implemented in cooperation with Sinovoltaics
- overall score is based on 13 weighted categories, with numerous sub-scores
- detailed criteria is published in a paper downloadable from the web

SINO VOLTAICS

The Munich Re factory inspection charts

Image: tl6781 / stock.adobe.com

The Munich Re factory inspection charts

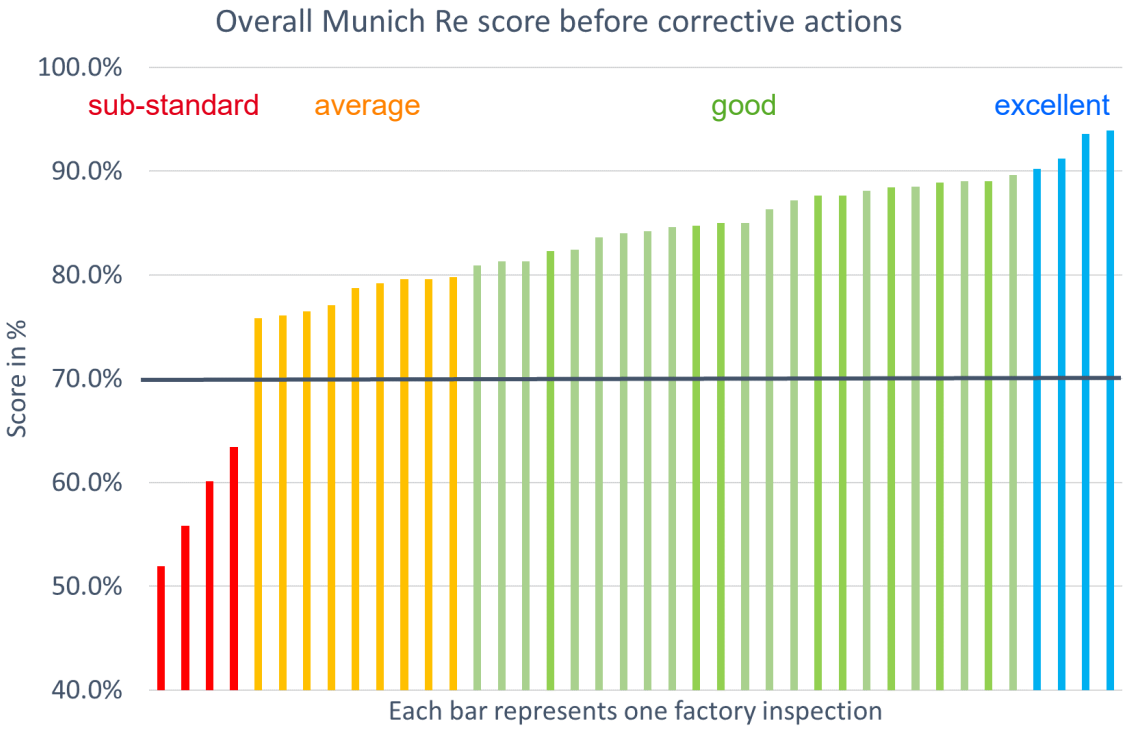
Overall score of 40 anonymous factories

Munich RE

- high ability to differentiate between very similar factories
  → no two factories received the same score

- reassuringly large field of average, good, excellent factories with surprisingly high variation

- **striking:** large gap to the sub-standard factories
  → good methodology to identify and sort out sub-standard risks



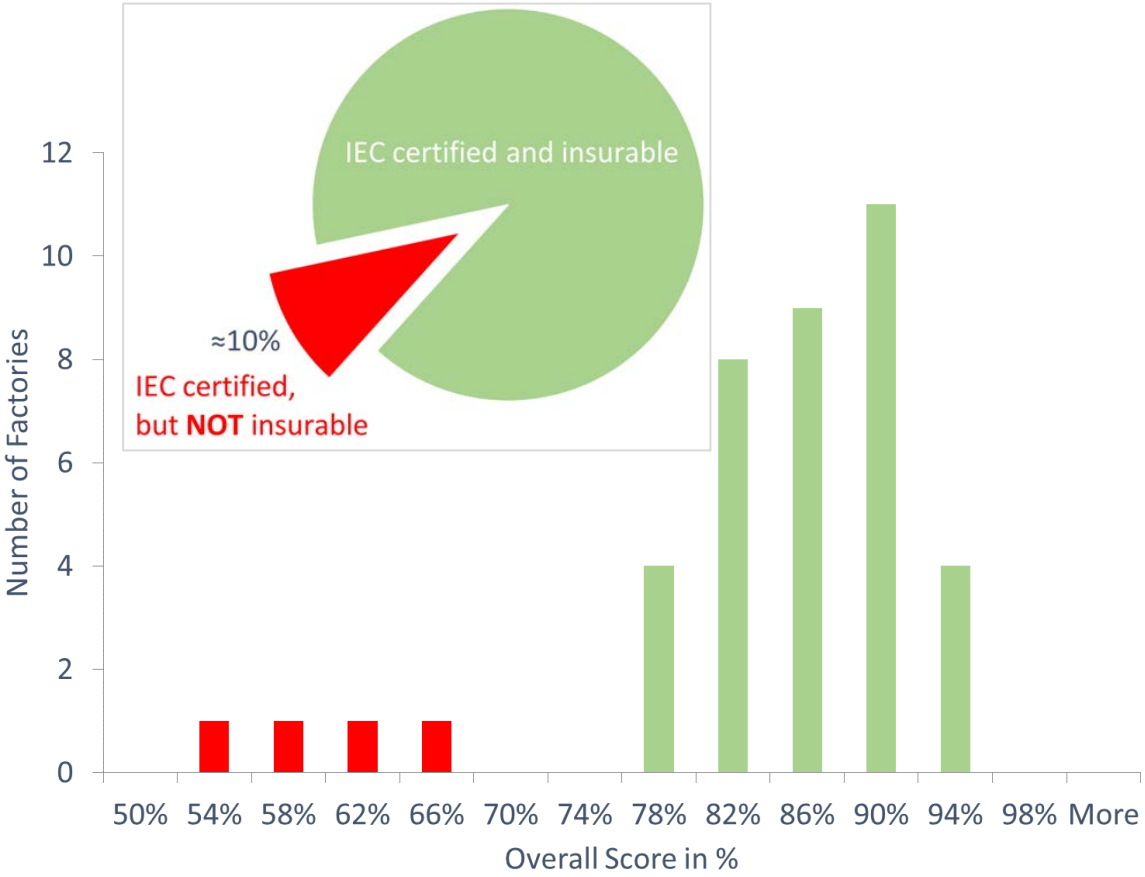
The Munich Re factory inspection charts

De-risking insurance portfolio

Munich RE

- 10% were NOT insurable, although all relevant IEC certifications were in place

- as insurers are de-risking their portfolios, buyers of warranty-insured modules benefit twofold:
  - i. insurance: loss mitigation in a PV warranty risk event, and
  - ii. confidence not to source sub-standard quality modules

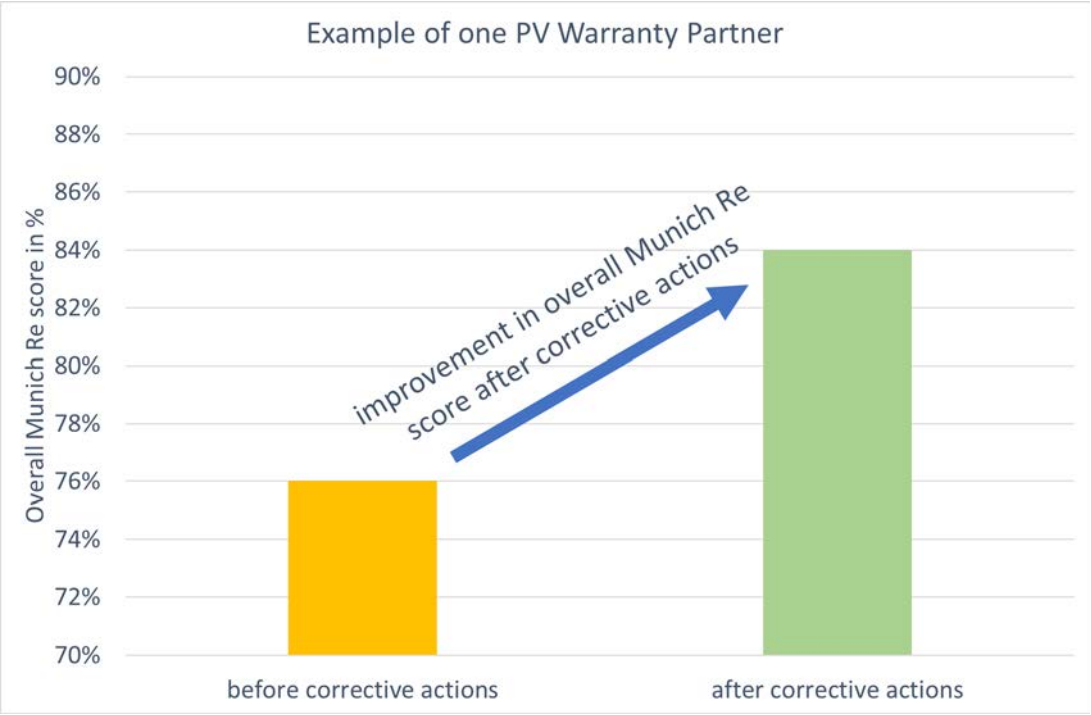


The Munich Re factory inspection charts

Improvements after corrective actions

Munich RE

- list of non-conformities is presented to each factory
- corrective actions must be implemented, documented and approved before insurance cover is granted
- support for continuous improvement is well received by factories, and even excellent factories receive many non-conformities
- clear improvement in score can be seen after re-audit



By rigorous due diligence, insurers are **contributing to enhancing the quality standard of PV module manufacturing**

Modelled distribution of degradation rates

Image: tl6781 / stock.adobe.com

Comparison of modeled degradation vs the actual degradation observed in the field

Munich RE

In order to price the risk, Munich Re is interested in **distribution curves** of degradation rates.

- **Modeled** annual degradation rates

  The Munich Re pricing model is based on a Monte-Carlo simulation of a large number of PV modules degrading over the years.

- **Actual** degradation observed in the field
  *Jordan et al, Progress in Photovoltaics 2016, Compendium of photovoltaic degradation rates***.**

  11,000 degradation rates from almost 200 studies from 40 different countries from all climate zones. After cleaning of the data, more than 1,500 annual degradation rates from real outdoor degradation in all relevant climate zones are still part of the analysis. The age of the modules varies from 1 to 30 years, with an average age of 15 years.

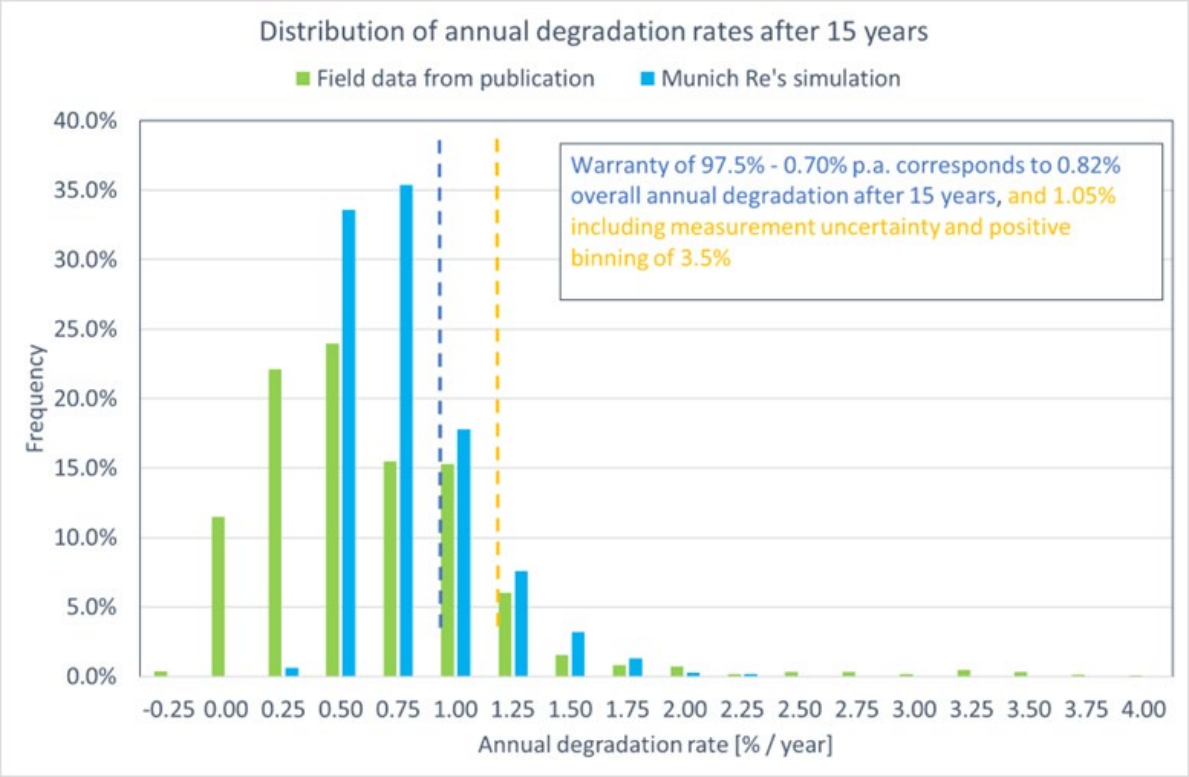
Comparison of our expected / modeled degradation vs the actual degradation observed in the field

Munich RE

Relation to performance warranty:

- Blue dashed line: warranty of 97.5% - 0.70% p.a.
  Taking into account the first-year initial degradation of 2.5%, the overall guaranteed annual degradation under this warranty is 0.82% in year 15.
- Orange dashed line:
  Taking into account the measurement uncertainty and the positive binning of in total 3.5%
- Bad and good modules:

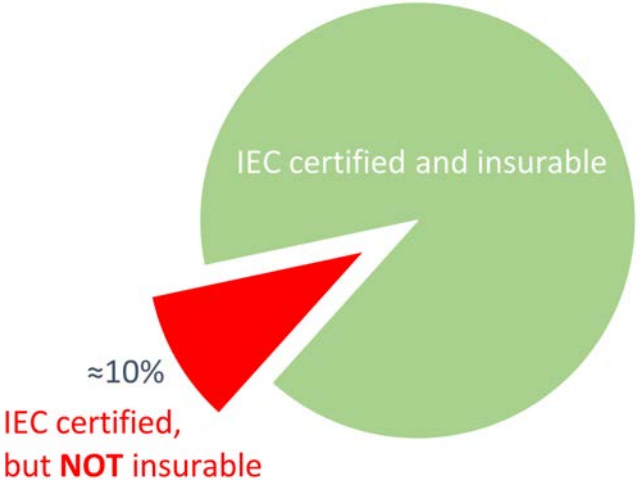
			with 3.5%	
Annual degradation rate	≤ 0.75	> 0.75	≤ 1.0	> 1.0
	Cumulative		*Cumulative*	
Field data from publication	74%	26%	89%	11%
Munich Re's simulation	70%	30%	87%	13%



Summary

Munich RE

- Munich Re conducts rigorous factory inspections at PV module makers seeking insurance and seeking to become Munich Re listed
- about 10% of factories have been NOT insurable although all relevant IEC standards were in place
- as insurers are de-risking their portfolios, PV projects using warranty-insured modules benefit from insurance and additional quality seal
- factories see a significant improvement after corrective actions. Thus, insurers are contributing to enhancing the quality standard of PV module manufacturing
- Munich Re models distribution curves of degradation rates to price the risk
- Acknowledgement:
  Sinovoltaics: for cooperation in development of scoring system and conducting repeatable and comparable inspections



SINO VOLTAICS

www.munichre.com/PVWarrantyPartner

Thank you very much for your attention!

Contact

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