DuraMAT
Durable Module Materials Consortium

DuraMAT: Accelerating Improvements in Module Durability

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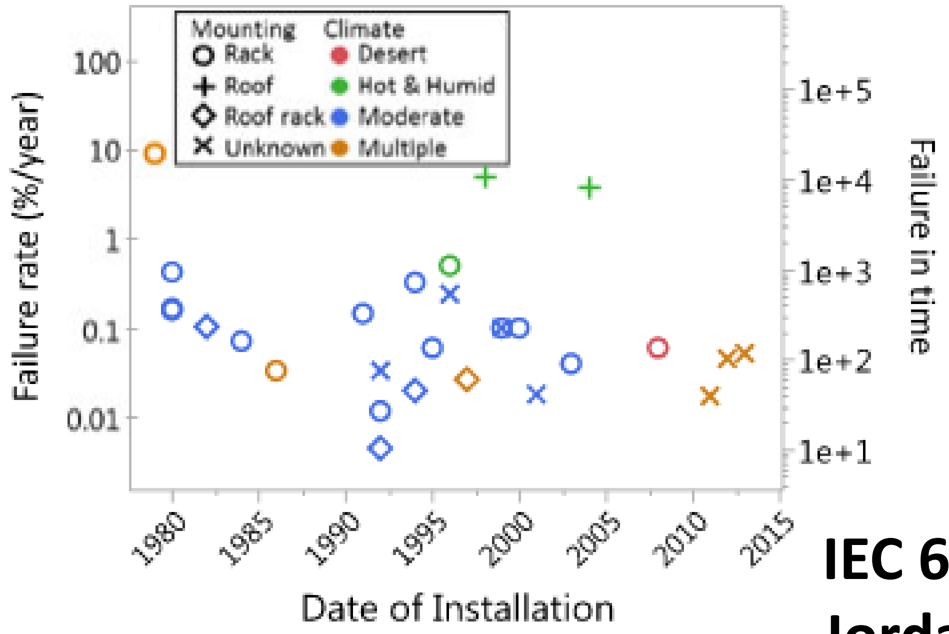
[1]NREL, [2]Sandia, [3]SLAC, [4]LBL

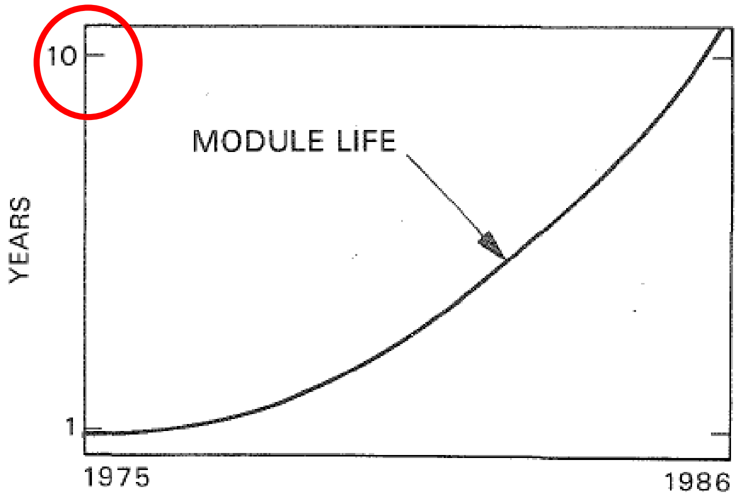
What Is DuraMAT?

- A national laboratory research consortium focused on precompetitive research needs in module packaging
- A Five Year Program
- Four Core National Laboratories
- University and industry researchers partnering with national labs
- 14-20 member Industrial Advisory Board co-manages DuraMAT
- An Energy Materials Network research consortium integrating national lab capabilities, industry led projects, and university research in module durability

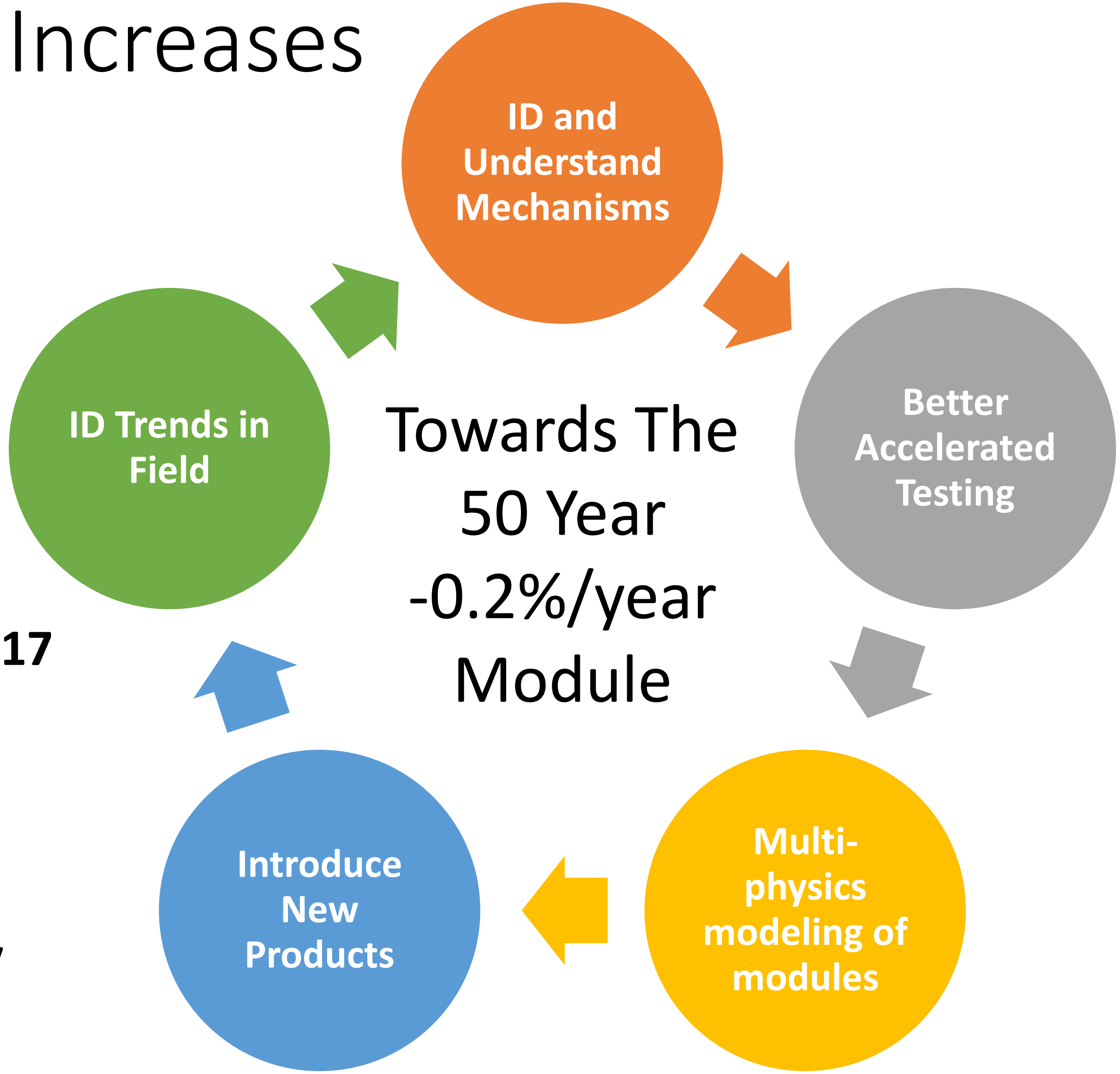
Data Driving Reliability Increases



IEC 61215
Jordan, 2017



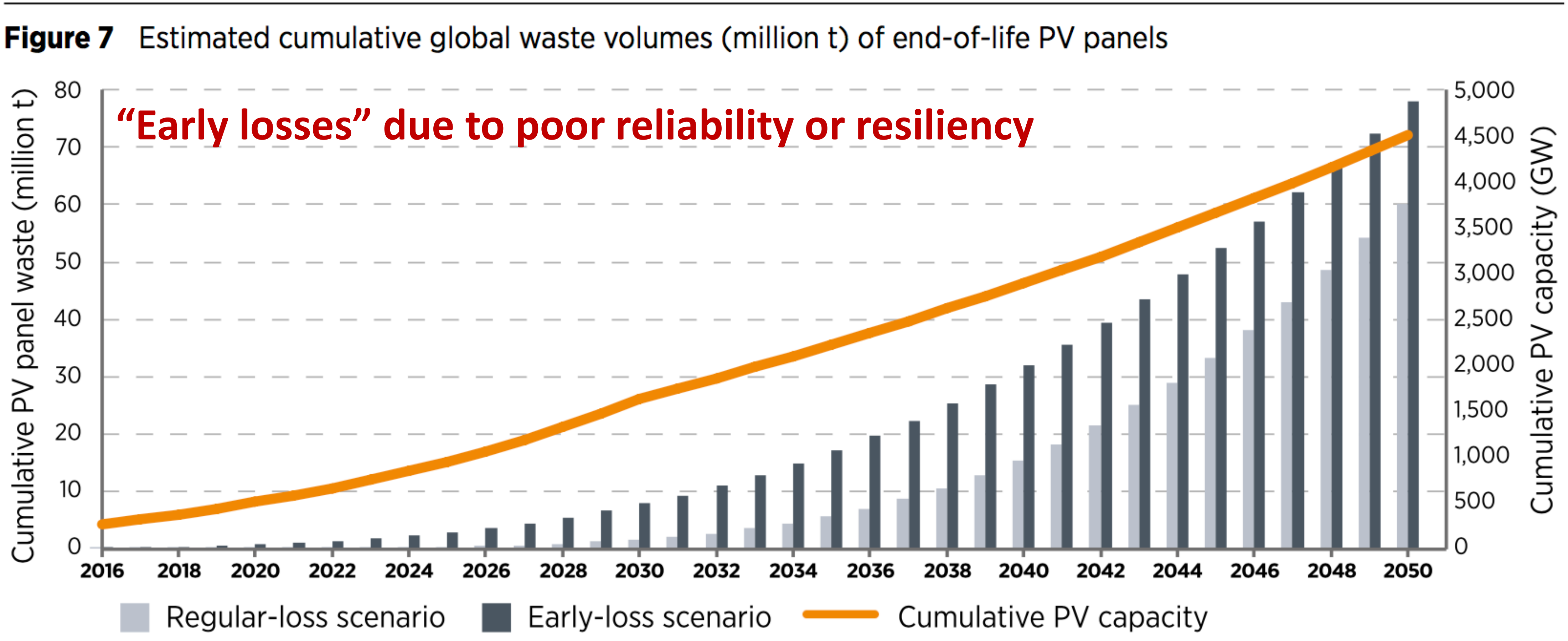
JPL Block Buy
1986



Challenges of 50 Year Modules…

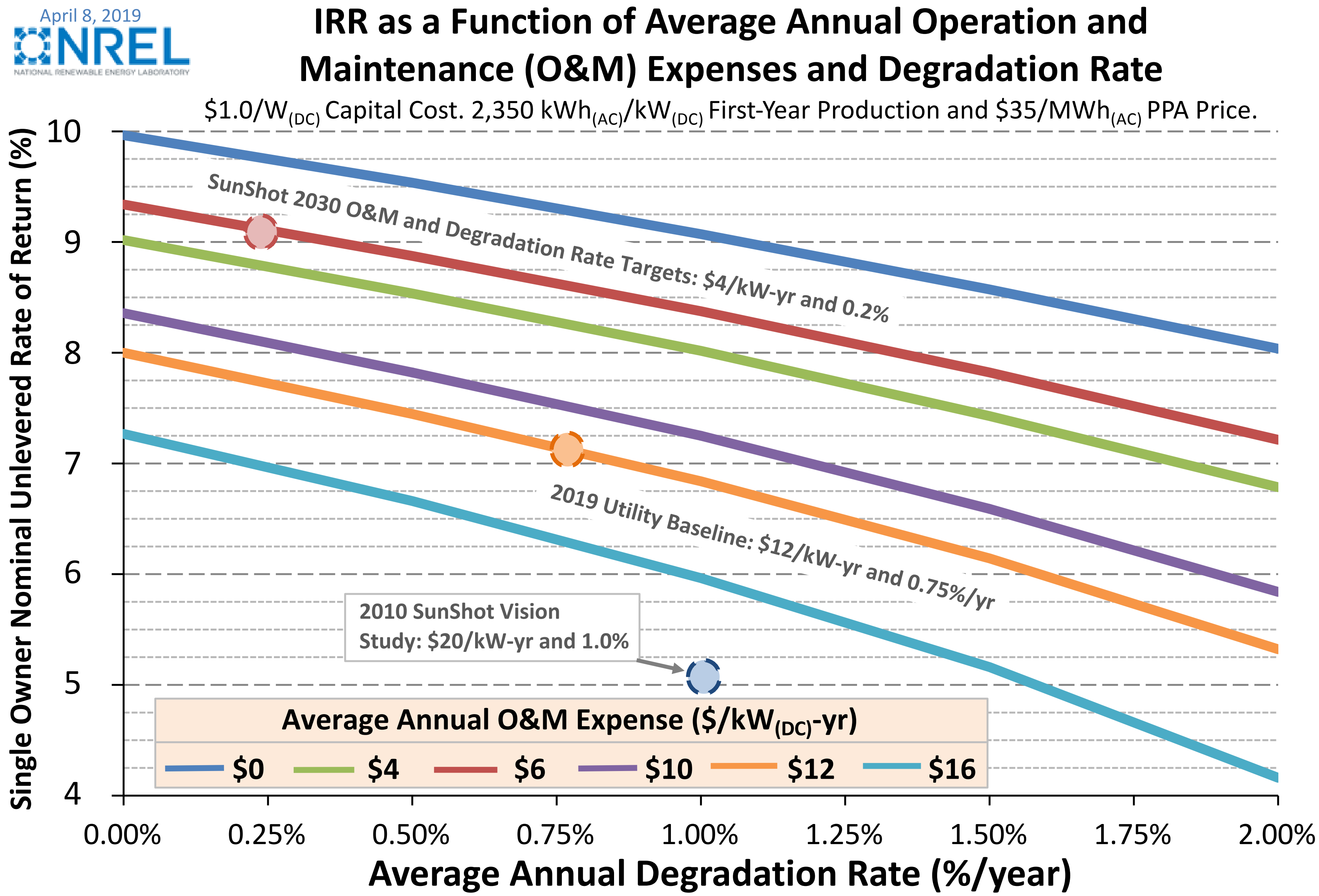
- Defining what we mean by ”50 year module”
  - -0.2% Degradation rate?
  - Economically useful life?
  - Warranty period?
- Developing predictive tests that would indicate the potential for 50 year service life
  - Need to get better at identifying ”infant” failures and early weaknesses
  - The industry is growing so fast that they can sell GW of new problems before we see those problems in the field
  - Old problems come back
- Believing you have a 50 year module
  - **Testing, modeling, data**
  - **Understanding chemistry and physics (kinetics and thermo)of degradation mechanisms**
  - Process control, quality control, certification
- Convincing buyers you have a 50 year module
  - Warranty, insurance**, testing, modeling, data**
  - Only interesting to buyers focused on IRR/NPV rather than $/W
  - Confidence for Longer PPAs + merchant tail
  - Sustainability and Circularity

Reliability and PV Waste Volume



Stolen from K. Wambach – IRENA 2016

Impact of Degradation Rate and O&M on Utility-Scale Project IRR



Module degradation rates are a subset of system degradation rates.

DuraMAT focuses on ***Module degradation.***

Reducing degradation rates enables longer system lifetime AND higher returns throughout the life of the project.

Lower degradation rates can mean lower O&M expenses

DuraMAT Objectives

Central Data Resource

- Heterogeneous data – system performance, materials, etc.
- Accessibility
- Centrality
- Security
- Adaptability

Multi-Scale, Multi-Physics Model

- Publicly Accessible
- Experimentally Validated
- Bulk, Interfaces, Interconnects, and stressors modeled

Disruptive Acceleration Science

- Data-Driven
- Predictive
- Validated by outdoor tests
- Materials, modules, and systems

Fielded Module Forensics

- Identify module failure modes affecting field performance
- Multi-scale
- Multi-modal
- Practical
- Validated

Materials Solutions: Leverage the capabilities to design, develop, and de-risk materials that address reliability problems. ECAs, backsheets , anti-soiling coatings, flexible packaging, cell cracking, moisture barriers, etc.

Field failures missed by current tests

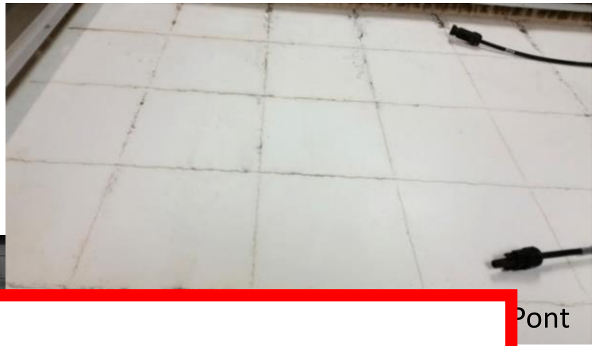
Backsheet cracking:
UV, cyclic oxidative/hydrolytic stress, CTE stress, EVA acidity

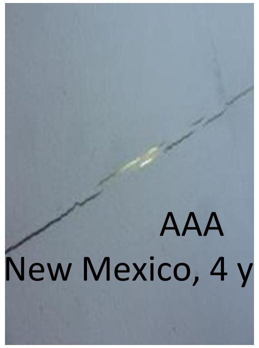
Potential-Induced Degradation (PID):
System voltage, humidity, tempe
light, soiling

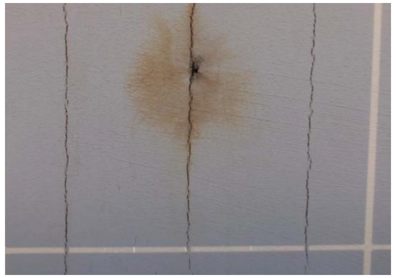
Grid finger corrosion & delamin
System voltage, humidity, tempe
light, soiling

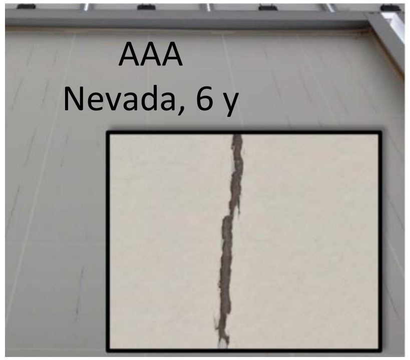
Light and elevated temperature induced degradation (LeTID):
Light, elevated temperature, current

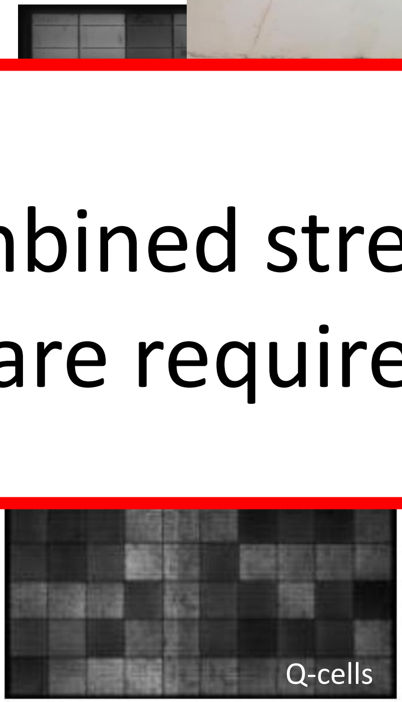
Snail trails -> delamination:
Mechanical loading, UV, electric field, moisture, impurities



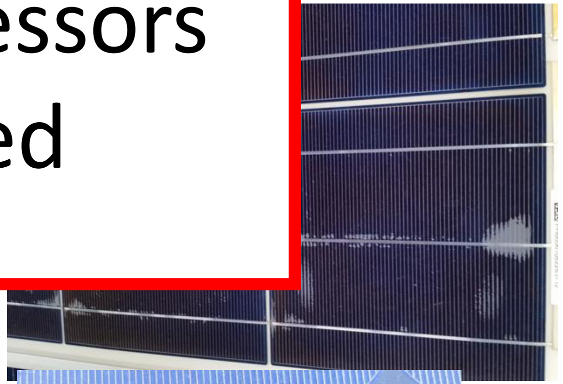








203 kWh -7.46 %

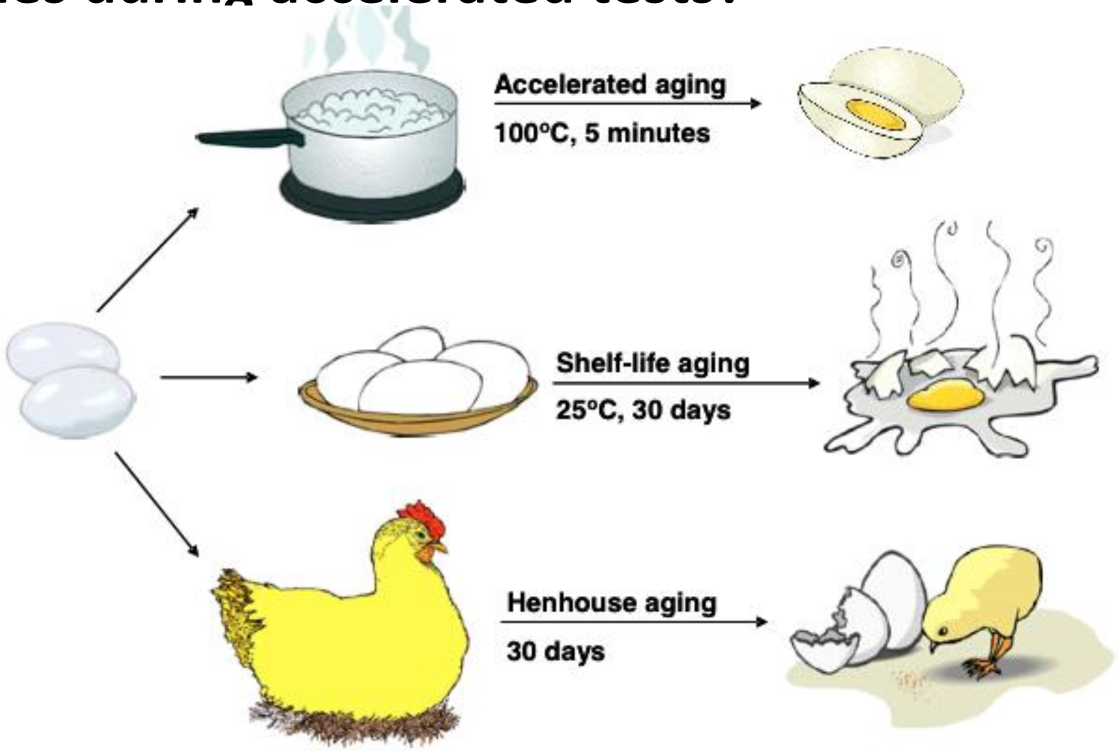


Combined stressors are required

Should We Turn It Up To Eleven?

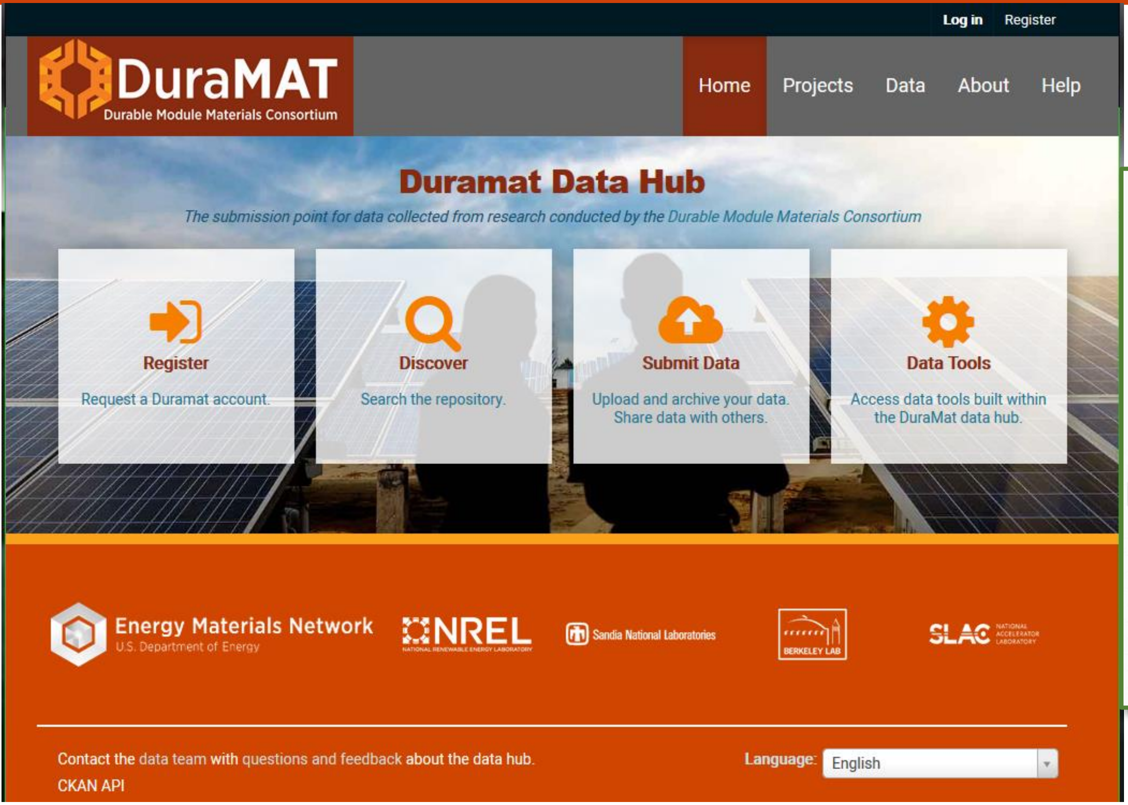
Can I just increase stress levels or times during accelerated tests?

Maybe. Possible issues:

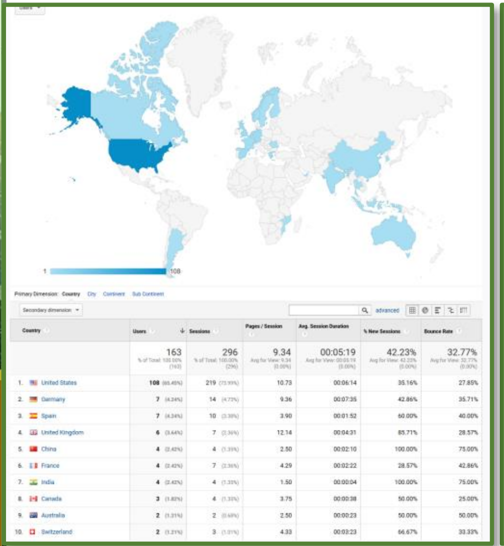


- **You might apply the right stress, but accelerate an irrelevant process**
- **Your new material may have a failure mechanism that requires a new stress or combination of stresses**
- **The results are still not quantitatively related to product lifetime**

The DuraMAT DataHub https://datahub.duramat.org



- Google analytics now integrated and reporting US and global usage of site.

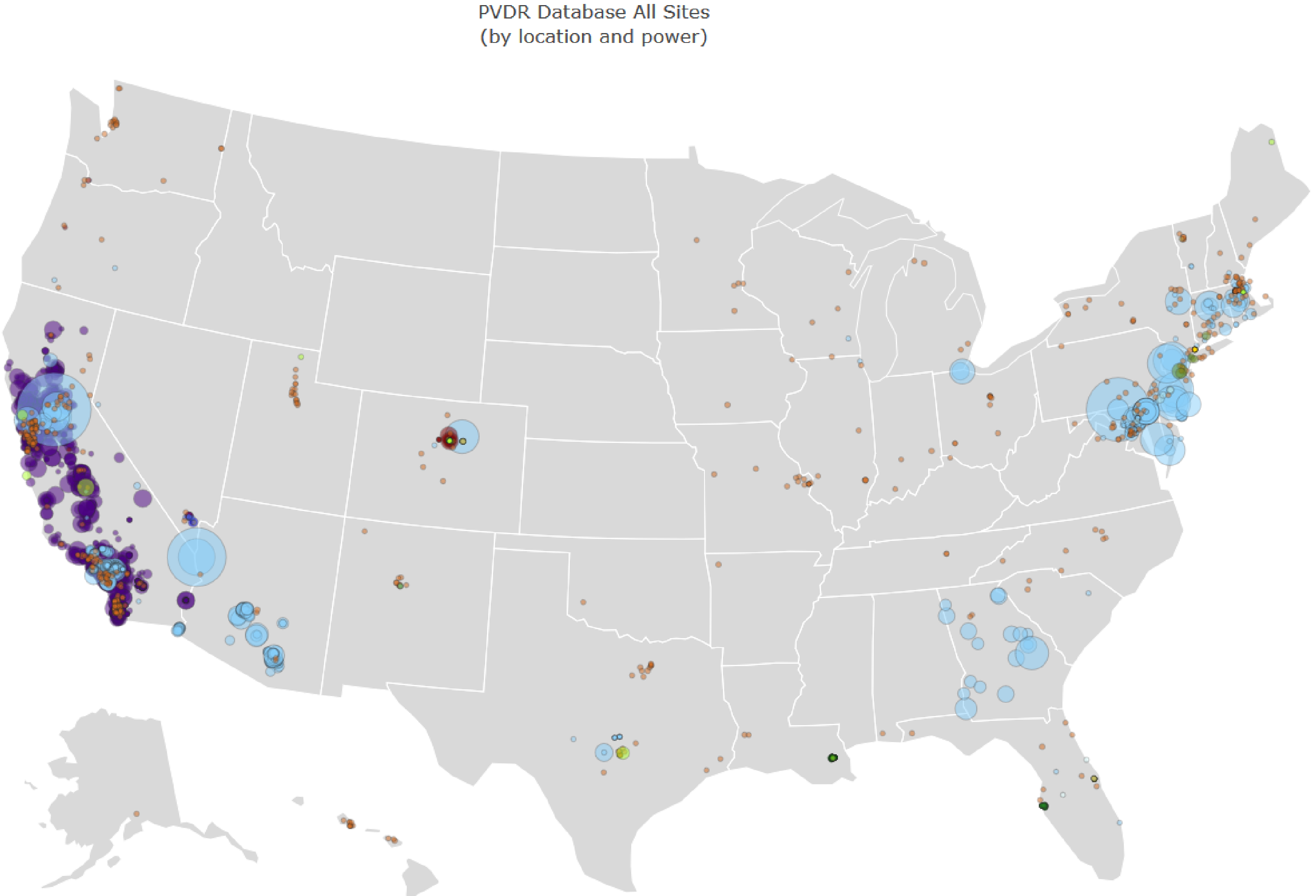


- Active Time-Series database with research access via Jupyter Notebook Tools

Data Hub Metric	Current count	Since 7/1/2019 (Q3)	Since begin FY19
Registered Users	91	10.98%	193.55%
Projects	45	4.65%	73.08%
Datasets	92	64.2%	441.18%
Data Resources/Files	547/1358	60.43%	1016.33%

Time-Series Database –PV Fleets (PV-DRDB)

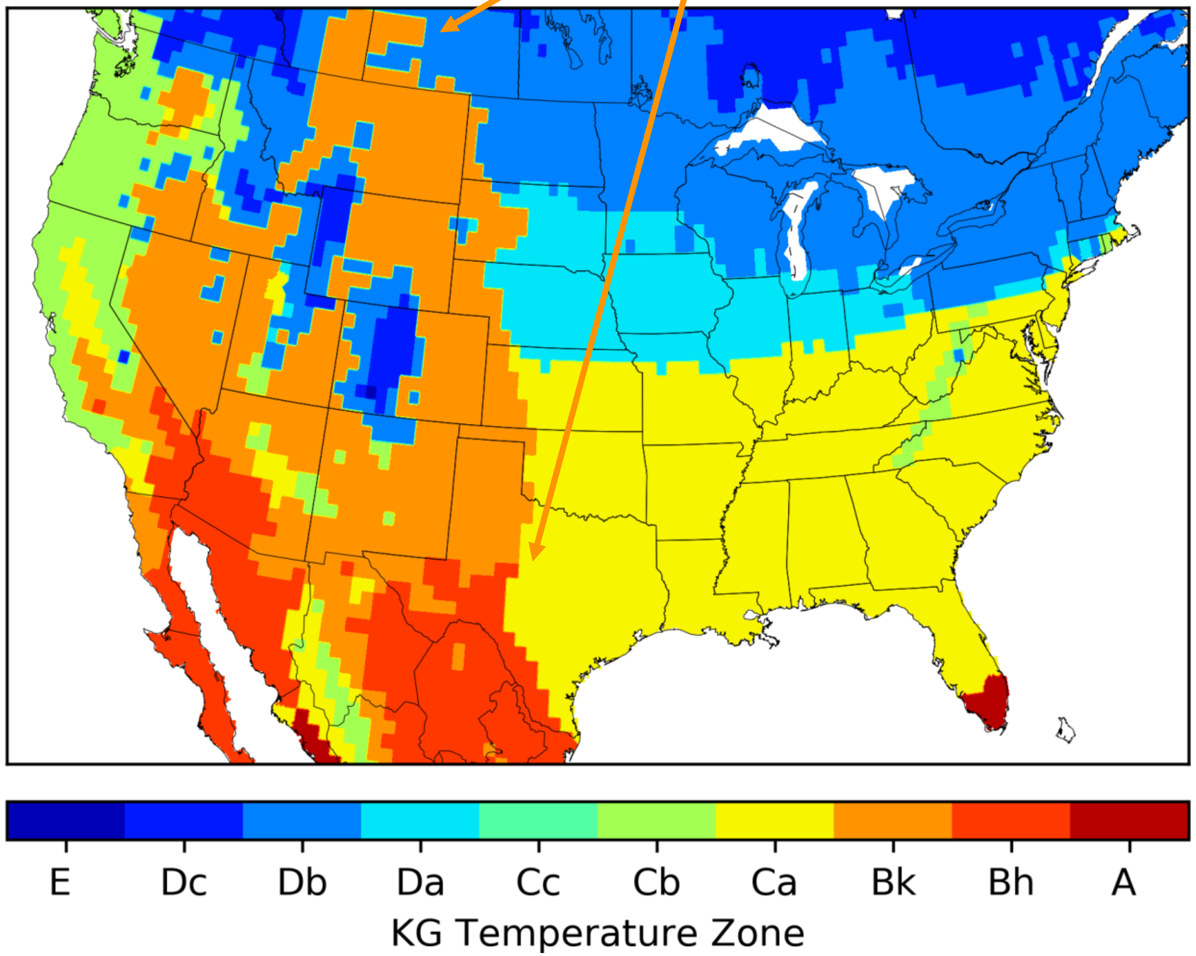
- Confidentially and securely pools performance data from medium and large PV plants to establish a benchmark of cumulative performance and degradation rates for the US solar fleet.
- Launched early in 2019 and has more than 1,062 MW of systems from four asset owners already signed up.

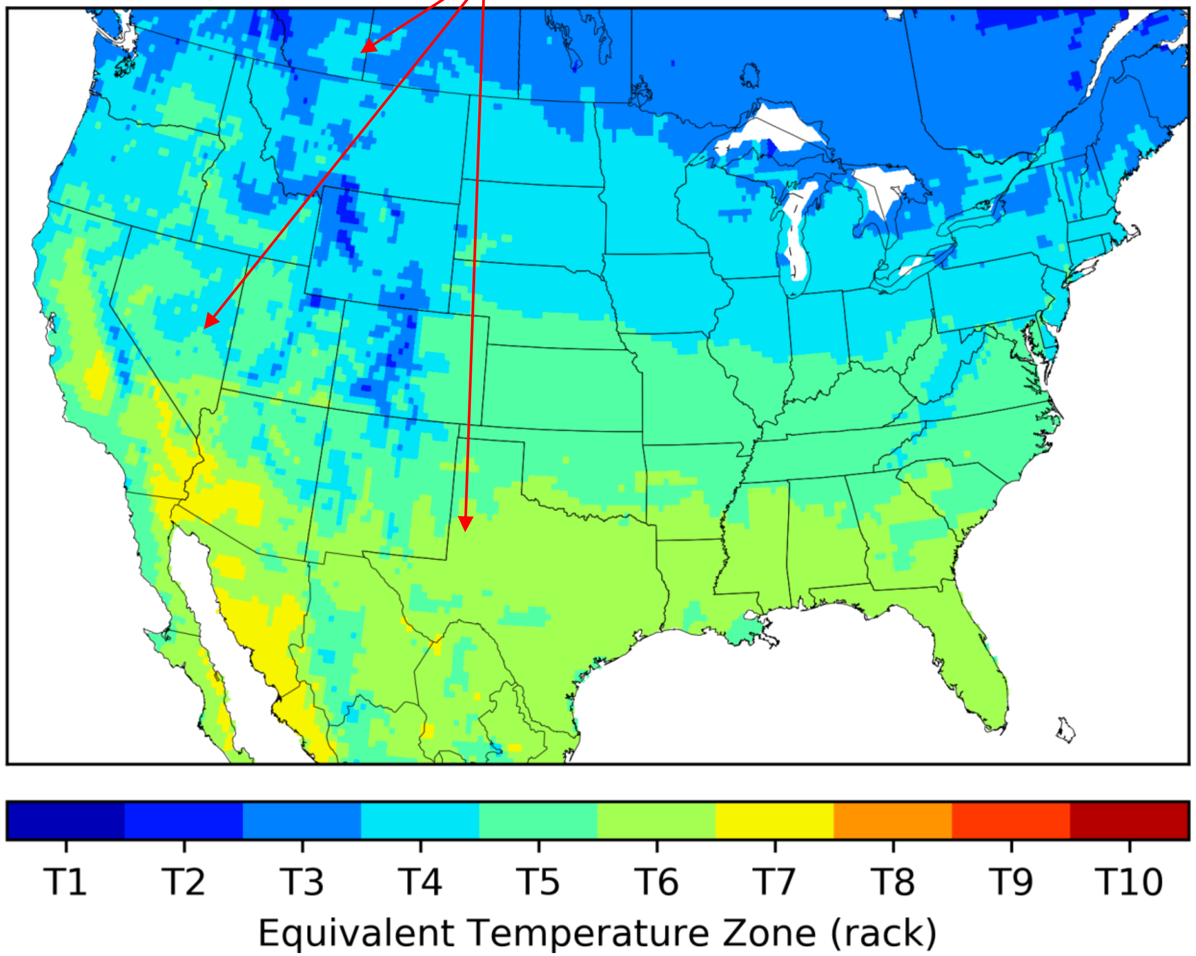


PV Climate Zones vs. Koppen Geiger

KG zone places regions from Mexico to Canada into a single zone (Bk).

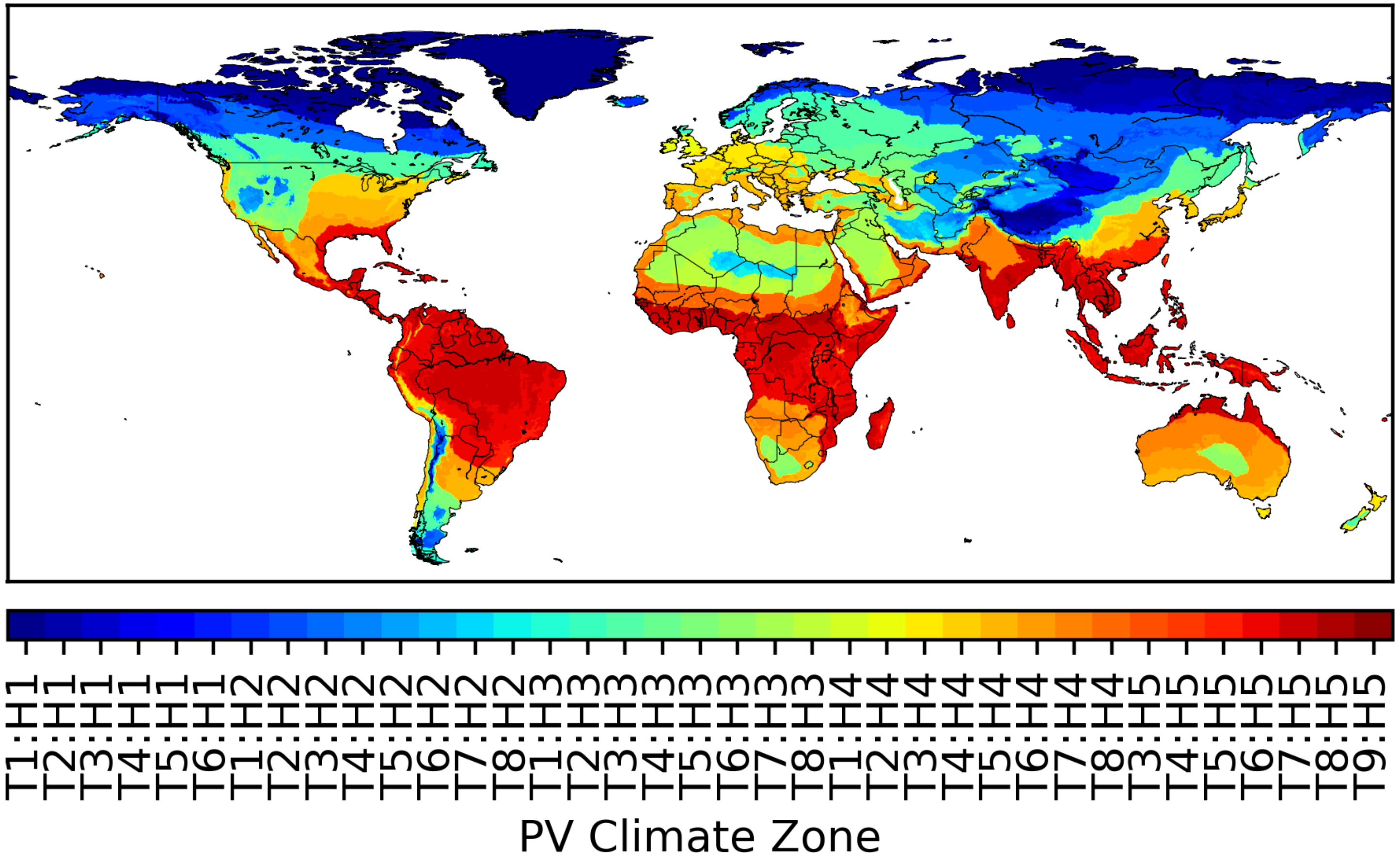
PVCZ puts these areas into 3 different zones.





Global PV Climate Zones

- **We have developed a climate zone scheme specific to PV degradation**.
- Use it!
- Data freely available on datahub, open-source python package and web tool.
- Future work will analyze how degradation modes and rates depend on climate zones.



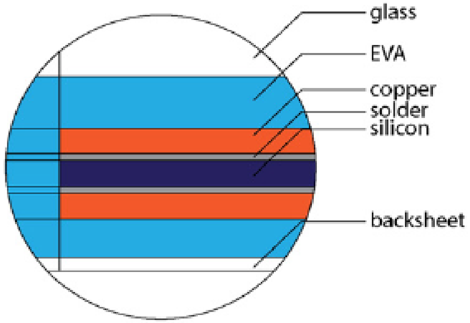
pip install pvcz

https://pvtools.lbl.gov/pv-climate-stressors

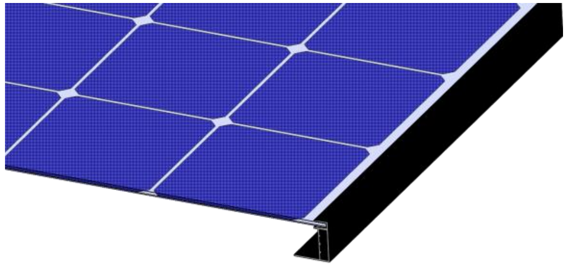
This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency (DOE) and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement Number DE-EE0007137

Multi-scale, Multi-physics Modeling for PV Reliability

- **Goal:** A modeling capability to accurately inform module lifetime
  - Applicable to multiple PV **scales**: From interconnects to full modules
  - Incorporating multiple degradation **physics**: Mechanical stress, thermal stress, materials effects, and more

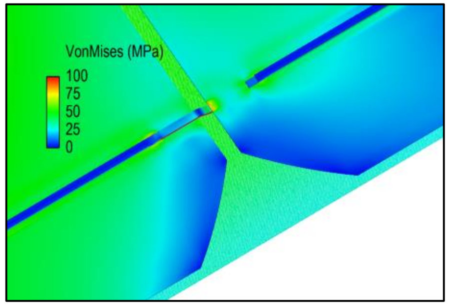


Interconnect damage [Bosco, NREL]

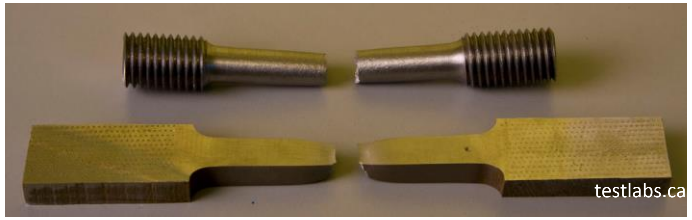


Full Modules [Hartley, SNL]

Mini-Modules [Hacke, Owen-Bellini; NREL]



Thermal stress
[Hartley, SNL; Bertoni, ASU]



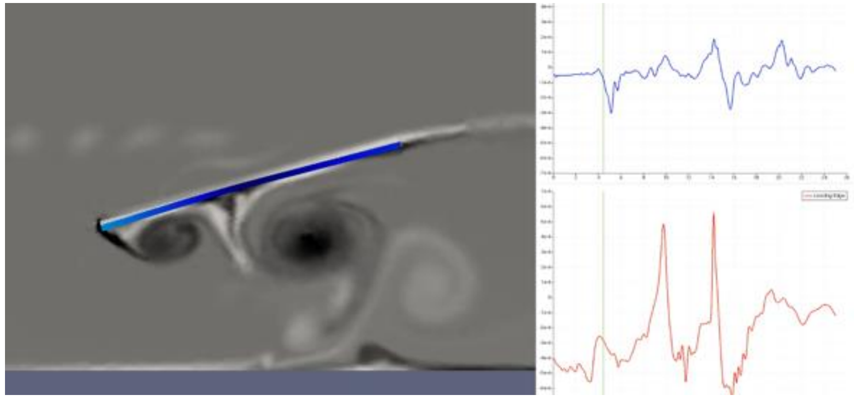
Material responses:
- Encapsulant viscoelasticity [Maes, SNL]
- Electrically Conductive Adhesive damage mechanisms [Bosco, NREL]
- Backsheet aging [Owen-Bellini, NREL; Moffit, SLAC]

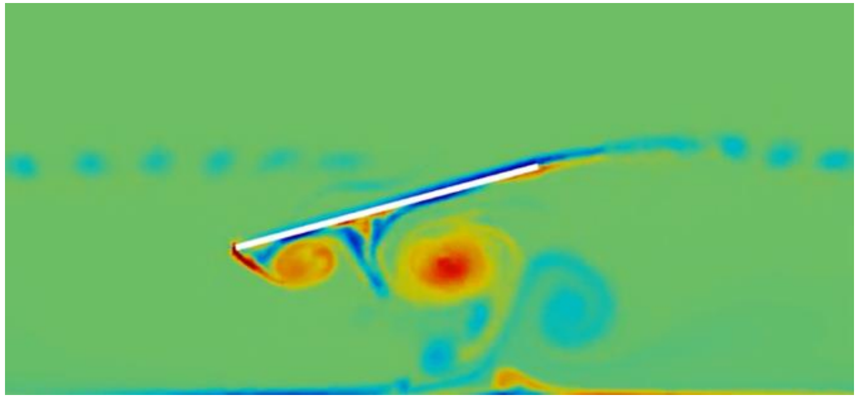
Mechanical stress
[Hartley, SNL]

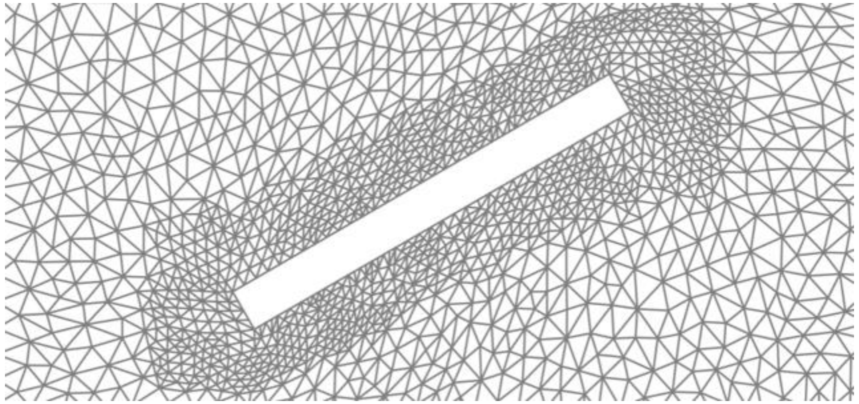
External Loads - Wind

- Modules are getting bigger and often mounted 1 or 2 up on trackers
- Torsional galloping at moderate windspeeds can be catastrophic
- Industry standard moving to high stow angles (60^{o}) rather than flat

- Significant module deflection (+/- 1m) due to mechanical loading is possible





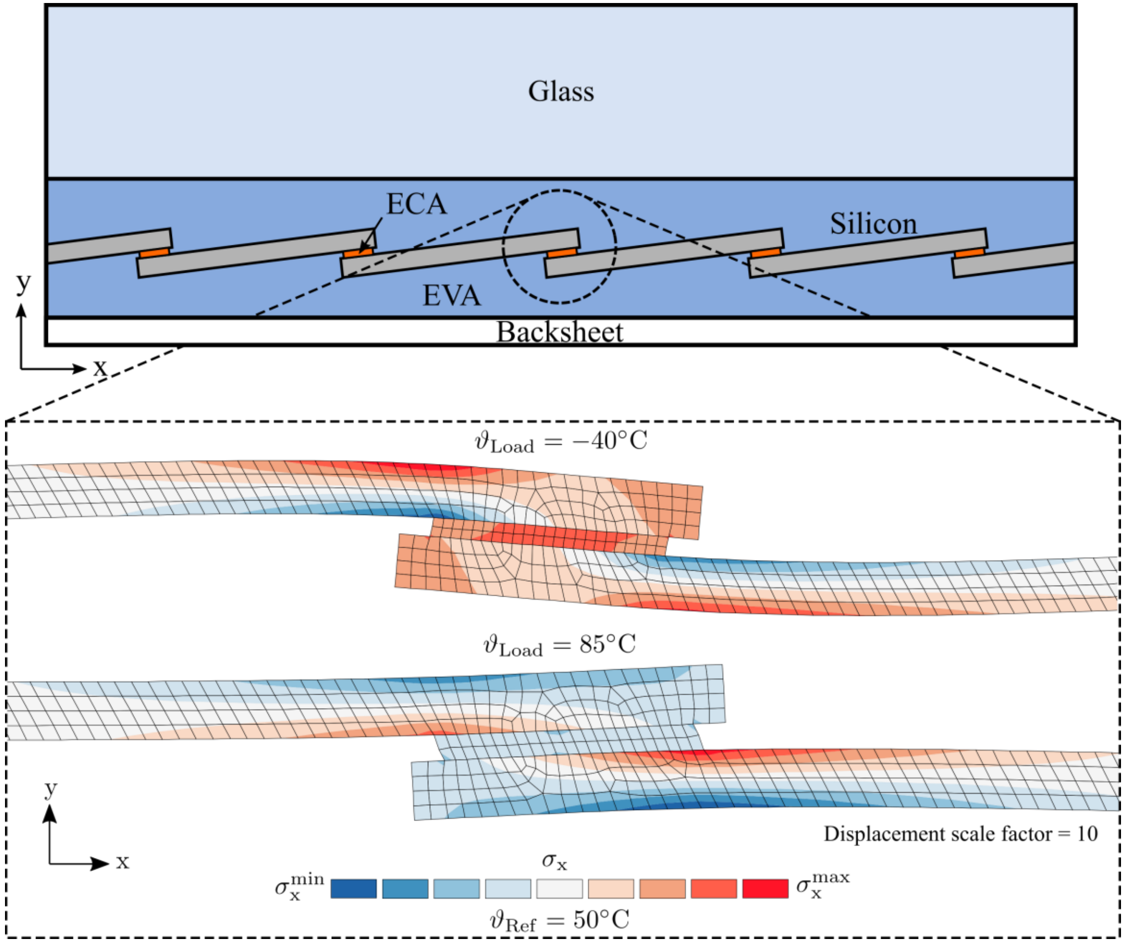


Sub-models: ECA Linear Viscoelastic Constitutive Model

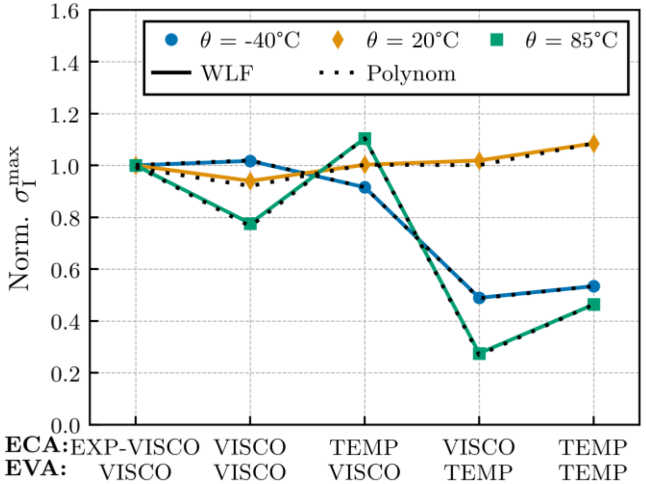
FEM simulation of a shingled cell module

Finite Element Simulations of a submodel of a generic shingled cell module have been performed. Differences in the results between high and low fidelity material models are highlighted. The results indicate a need for high-fidelity material models which are currently not available for most of the materials employed in PV applications. Low-fidelity material models as provided by ECA or EVA manufacturers seem to be insufficient for accurate predictions of the stress and strain states inside a PV module.

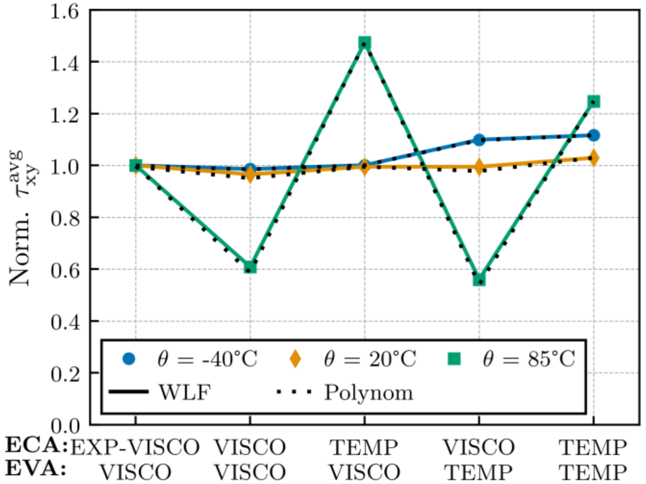
A generic shingled cell model as application of the ECA constitutive model



First principal stress in the silicon cell



Shear stress in the ECA interconnect



Numerical simulations utilizing low and high-fidelity material models deliver significantly different results, highlighting the need for high-fidelity material models for simulations of PV applications.

High-fidelity material models combined with accurate loading conditions allow for predictive simulations of the PV modules thermal and mechanical response.

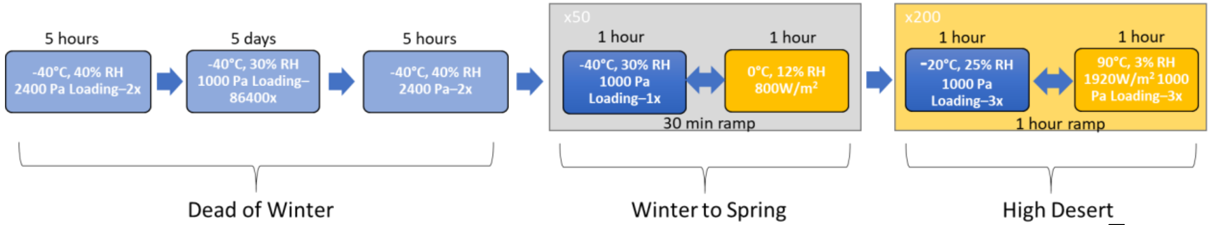
Disruptive Accelerated Testing: C-AST of AAA and PVDF

Challenge: Current accelerated stress tests do not cause backsheet cracking seen in the field.

Solution: Develop accelerated test that combines stresses (C-AST) as seen in the natural environment

Similar cracking in C-AST and fielded AAA samples

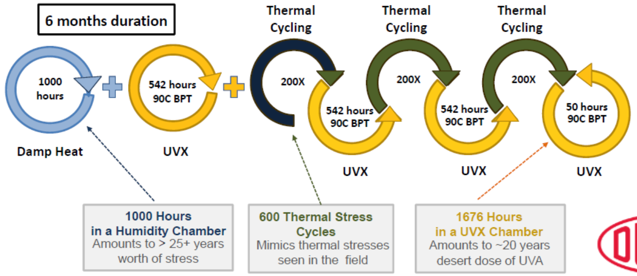
Typical C-AST Cycle (~40 days)



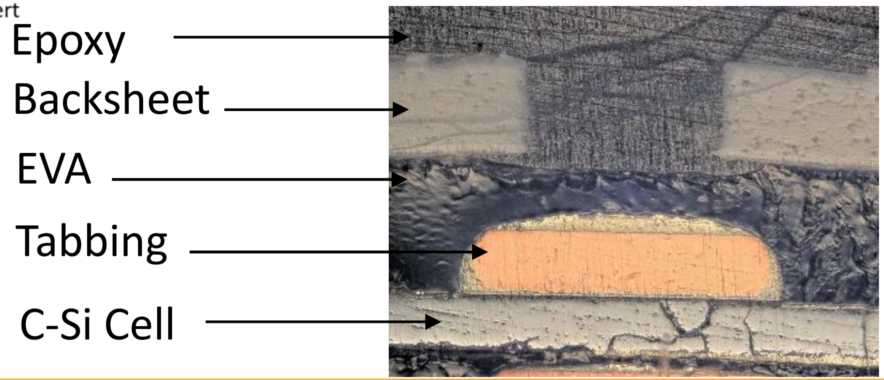
Identify cracking mechanism with a combination of cross sectional imaging and finite element analysis.

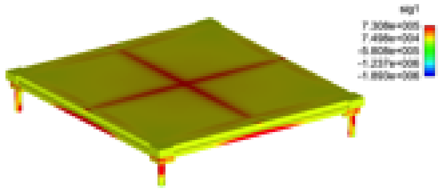
vs

Module Accelerated Sequential Test (FAST MAST)



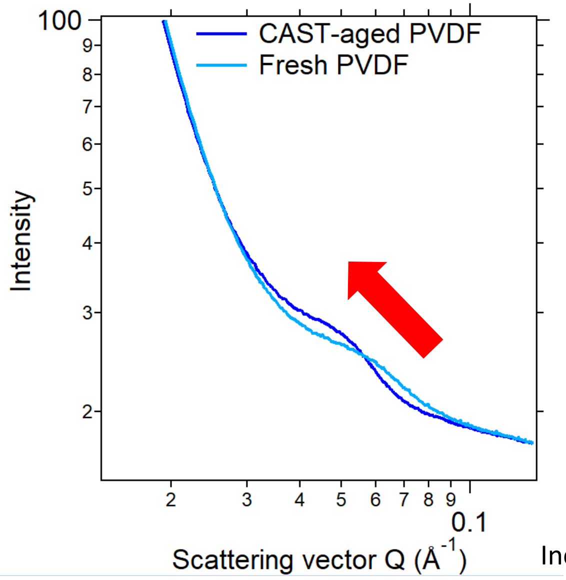
DU PONT

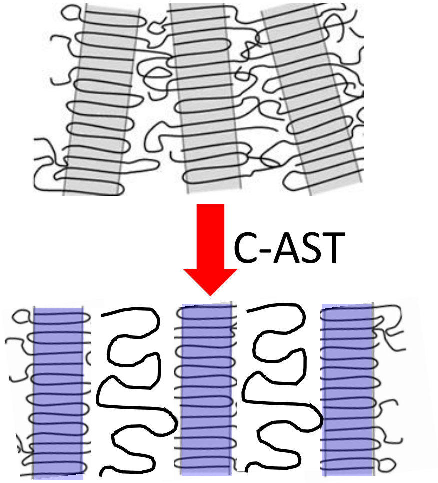




Detailed Analysis of C-AST and field-aged Backsheets

SAXS of PVDF

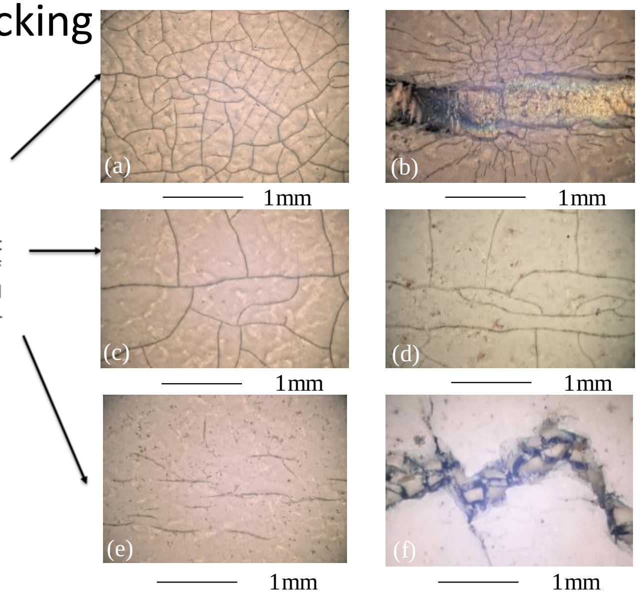




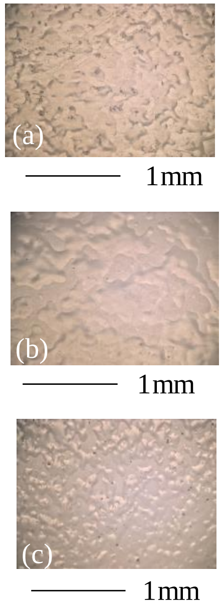
Increased long period spacing after weathering
Is this the same for field-aged PVDF?

PA cracking

Micro-cracking covers entire backsheet surface of field-aged and CAST-aged

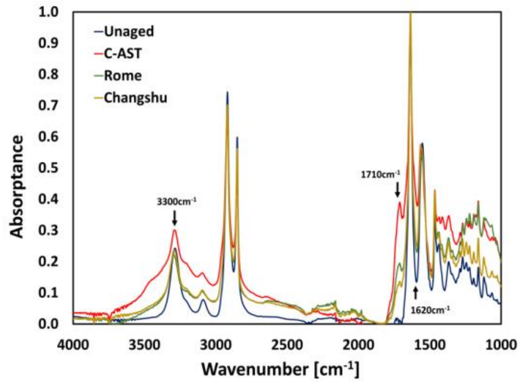


Optical microscope images for the air surface of the backsheets: (a) over a cell and (b) macrocrack above cell tabbing for C-AST sample; (c) over a cell and (d) above cell tabbing for Changshu sample; (e) above cell tabbing and (f) macrocrack between cells for Rome sample

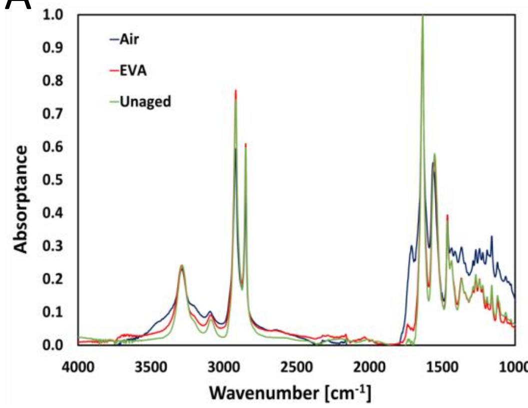


No micro-cracking on aged backsheet layers behind cell (UV shaded)

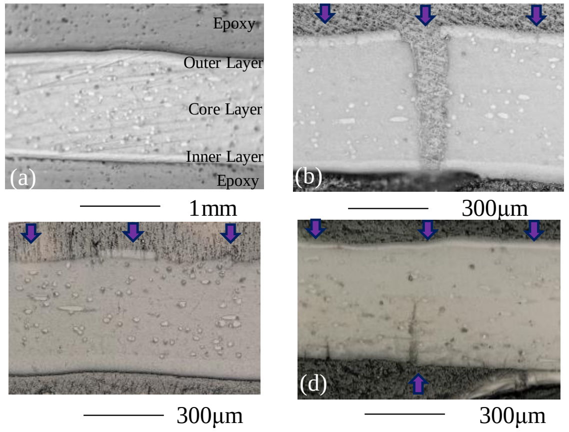
FTIR of PA



FTIR of pristine, C-AST and field-aged AAA



Comparison of shaded and unshaded layers in C-AST



Cross-sectional microscope images for: (a) unaged AAA backsheet, (b) C-AST parallel to the macrocrack observed above cell tabbing (c) Changshu sample above cell tabbing and (d) Rome sample above cell spacing. Purple arrows indicate possible UV exposure paths.

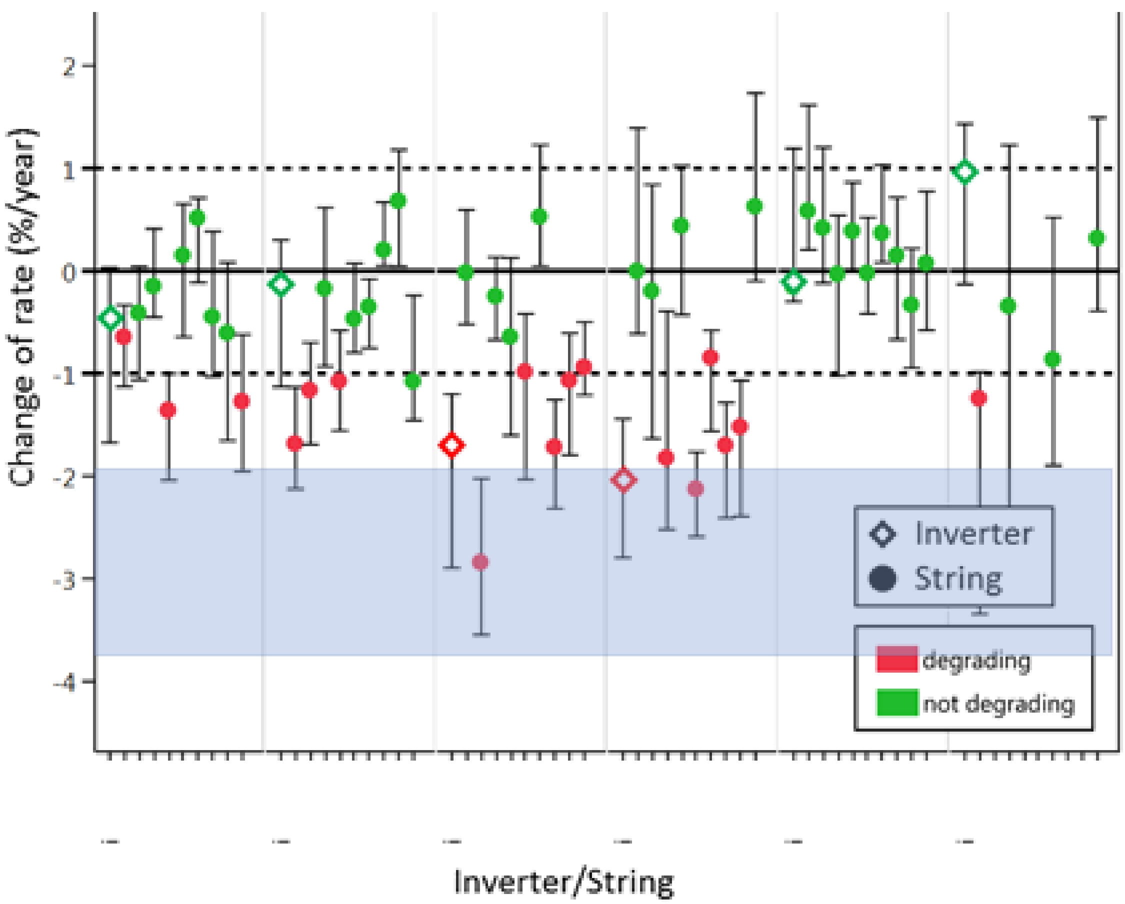
Correlation between FTIR signatures, UV exposure and cracking. Supports idea that UV is primary driver for degradation.

DSC and DMA could indicate changes in crystallinity and increased brittleness which leads to cracking and supports UV-induced chain breaking of amorphous regions and recrystallization

Two mysteries of underperforming plants…

- PV plants are contractually obligated to deliver set amounts of power
- What do you do when your plant is not generating enough power?
  - Check the inverter and string level data – find the ”bad guys”
  - Fly an IR camera – confirm bad strings or modules
  - EL imaging – what went wrong?
  - Warranty Claim?
  - Repair, Replace, Revamp, Repower

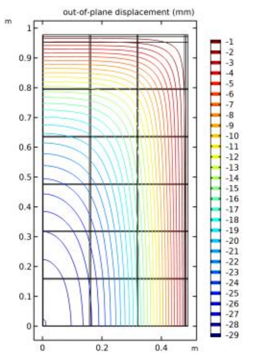
Inverter Production Data



Effect of Cell Cracks on Module Power Loss and Degradation

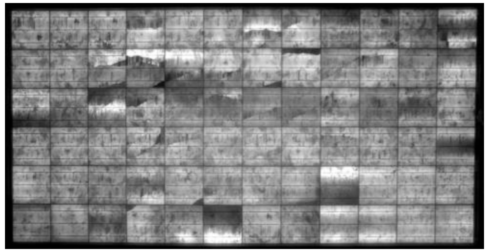
EPRI. NREL, LBL, Southern Co

Leveraging Lab Capabilities for Industry-led Research



Predictive simulation using finite element modeling (full modules)

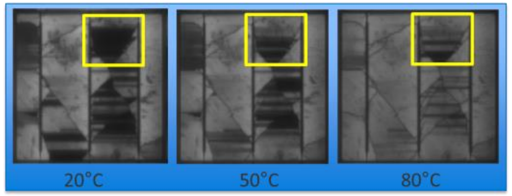
Field testing at NREL's small-scale outdoor test array



Data management and analytics for crack detection and analysis

Accelerated aging (full modules)

Field testing at two large-scale PV plants



Temperature-dependent electroluminescence imaging

Technology Summary & Impact

Understanding crack impacts reduces lifetime PV plant performance risk

- Set crack thresholds for large-scale PV plant commissioning, base O&M on knowledge of crack progression and effects on performance and safety
- Reduce uncertainty in LCOE predictions through improved warranty and insurance contracts and better plant performance
- Inform module designs that are less susceptible to cracking
- Enable improved qualification test procedures
- Improve simulation capabilities around module reliability and durability as it relates to cracks and metal fatigue

Cells can be cracked during installation

Degradation Characterization in Fielded Modules using Luminescence and Thermal Imaging.

NREL, PVEL, Purdue

Leveraging Lab Capabilities for Industry-Driven Research

Industry Question: Can we develop a technique to identify an interconnect manufacturing "excursion" in fielded modules?

Module Forensics

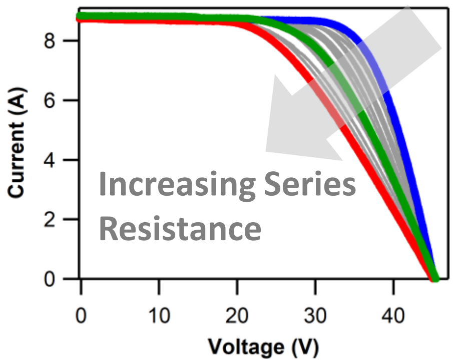
- Developing spatially-resolved methodology for module forensics, using a case study of 23 modules that degraded in the field.

Advanced Characterization and Method Development

- Correlate module images with current-voltage characteristics to determine the image combinations that can be used to identify failure mechanisms.

Set of 23 Fielded Modules with Varying Degrees of Degradation

Modules Show Fill Factor Loss Due to Increased Series Resistance



8-36% Power Loss over Two Years

Loss Correlates with Fill Factor

R_{series} Problems Located by Imaging

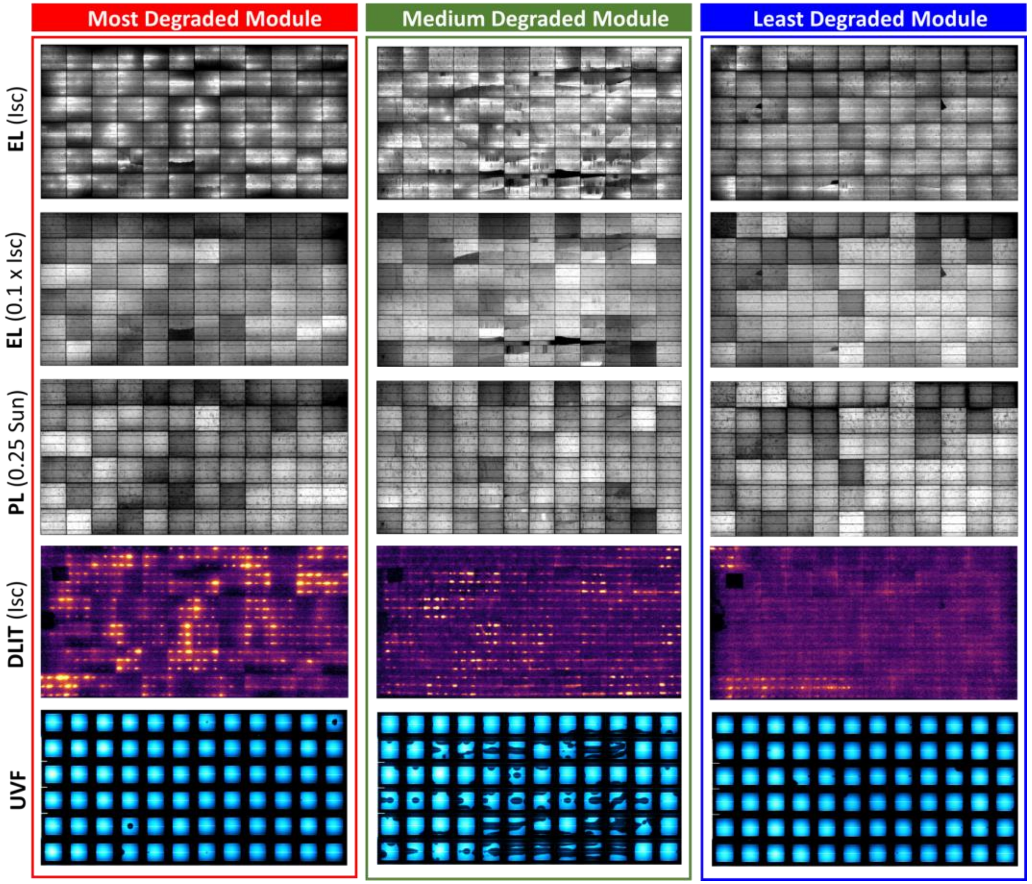
Flash test data from the 23 field-degraded modules are being further analyzed by quantitative fitting to a physical model.

Collaboration with Purdue University Device Modeling Group

- Alam Group at Purdue is fitting quantitative models to the current-voltage results, which will be correlated with the PL, EL, DLIT, and UVF imaging.

Technology Summary & Impact

*Correlating **five different types** of module images with power loss from series resistance.*



1. Modules ranked by degradation severity using current-voltage curves.
2. Images recorded:
   a) EL (I_{SC})
   b) EL (0.1 I_{SC})
   c) PL
   d) Dark Lock-in Thermography
   e) UV-Fluorescence
3. Images are qualitatively and quantitatively investigated to determine patterns that correlate with module power loss.

DuraMAT Objectives and Key Results FY19

Central Data Resource	Multi-Scale, Multi-Physics Model	Disruptive Acceleration Science	Fielded Module Forensics
• Heterogeneous data resource established for performance, materials, albedo… • FedRamp cloud, Secure SSO, analytics • PV Fleet spun out • Multi-file upload • Two public analysis tools – PV climate and string sizer	• Experimentally validated models of trackers, modules, and submodules • FEM for mechanics of GG and G/BS modules • Model for torsional galloping • Model for thermo-mechanics of ECAs in shingled modules	• Field validation of CAST for AAA and PVDF backsheet failures. • In-situ I-V and EL in CAST • Outdoor accelerated test prototype • Chemistry of EVA discoloration due to UV ionization	• Detailed backsheet cracking mechanism • Field module library deployed • SVM for backsheet identification by FTIR • EL/PL screening of fielded modules and failure ID • XRT Measured cell stress in GG and G/BS

Materials Solutions: flexible packaging development and characterization (3), antisoiling coating, ECA development and characterization (2), crack tolerant metalization, roof attachment for flexible modules

Acknowledgements

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Sandia National Laboratories

BROOKHAVEN NATIONAL LABORATORY

Lawrence Livermore National Laboratory

SLAC NATIONAL ACCELERATOR LABORATORY

BERKELEY LAB

ASU Arizona State University

Stanford University

The University of Akron

Georgia Tech

CUNY THE CITY UNIVERSITY OF NEW YORK

Colorado State University

EPRI ELECTRIC POWER RESEARCH INSTITUTE

DSM
BRIGHT SCIENCE. BRIGHTER LIVING.

osazda ENERGY

SUNPOWER

WattGlass

DuraMAT's Industry Advisory Board

PVEL
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First Solar.
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EPRI ELECTRIC POWER RESEARCH INSTITUTE
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SILICON RANCH
SUNPOWER
WELLS FARGO
DUPONT
Southern Company
Constellation
An Exelon Company

PVRW

- DuraMAT program review with talks Tues and Weds and posters from all funded projects
- Lunch meeting to discuss DuraMAT projects
- Kickoff DuraMAT 2 planning and proposal process

PV Reliability Workshop

NREL hosts an annual Photovoltaic Reliability Workshop (PVRW) so solar technology experts can engage on current and forward-thinking subject matter in PV reliability.

This workshop provides a unique opportunity for group discussions that can yield answers and bring participants to a common understanding for current questions in module and system reliability. Improvements in PV reliability reduce the cost of solar electricity and promote investor confidence in the technology—both critical goals for moving PV technologies deeper into the electricity marketplace.

DuraMAT
Durable Module Materials Consortium

This workshop is planned in partnership with the Durable Module Materials Consortium.

2020 Workshop

The 2020 PVRW will be held Tuesday, Feb. 25, to Thursday, Feb. 27. The venue will be the Sheraton Denver West Hotel, including a room block for accommodations. Register now for PVRW 2020.

Durable Module Materials Consortium

www.duramat.org

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Transforming ENERGY

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  - Dana Sulas (NREL)

Capability Network

DuraMAT Projects	Data Management & Analysis	Predictive Simulation	Materials Forensics	Module Prototyping & Test	Outdoor Testing	Techno-economic Analysis
	DataHub	Multi-scale Module Simulation	Material Properties and Aging	Accelerated Testing	Non-Destructive Testing	Quantify LCOE
	Software Development and Machine Learning	Materials Modeling	Correlating Accelerated Testing and Field Data	UV Ionization Damage	Field Aged Module Library	Decision Support
	PVDAQ Upgrade	Flexible Modules	Barrier and Encapsulants	ECA and Contacts	Wind Loading and Structural Materials	Financial Modeling
	Data Visualization	Materials Selection	Cell Cracking	Module Design and Fabrication		Circular Economy
			Front Coating			

PV in the Circular Economy

- **Reliability to maximize economic useful life**
- **Resiliency to minimize "early" waste generation**
- **Refuse** low quality product
- **Resist** cutting corners on installation, quality control, acceptance testing

- **Reduce** material and energy intensity (higher yield systems?)
- **Repair** develop safe materials, procedures, and tests to avoid waste
- **Reuse** your components wisely in 2^{nd} life applications or as spares
- **Revamp** and **Repower** systems to extend EUL when needed
- **Recycle** when environmentally and economically beneficial
  - How do we make sure this is always true?

Degradation Mechanisms Missed By Qualification Tests

Backsheet cracking → **temperature, UV, cyclic oxidative/hydrolytic stress, CTE stress, EVA acidity**

PID → **System voltage, rain/humidity/condensation, temperature, light, soiling (light required to get an accurate picture of sensitivity)**

Grid finger corrosion – delamination → **System voltage, humidity, temperature, light, soiling**

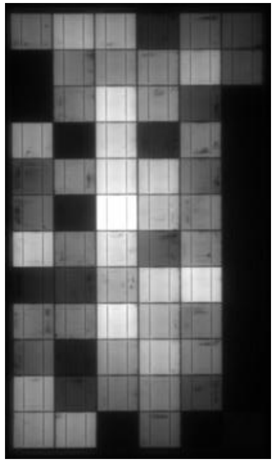
Edge seal failure → **Mech. load, CTE stress, UV, moisture, impurities**

Light and elevated temperature induced degradation → **Light, elevated temperature, current**

Snail trails→ delamination → **Mech. load, UV, electric field, moisture, impurities**

Delamination→ **CTE stress, UV, moisture, impurities, system voltage**

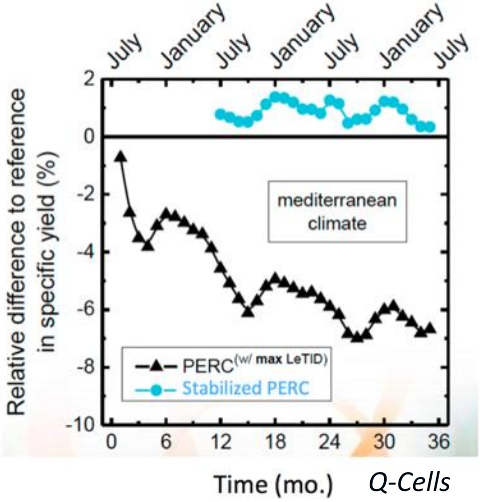
Polyamide backsheet



PID

Corrosion

Edge seal failure



LeTID

Snail trails

Delam.

Multiple factors working in combination leading to the degradation

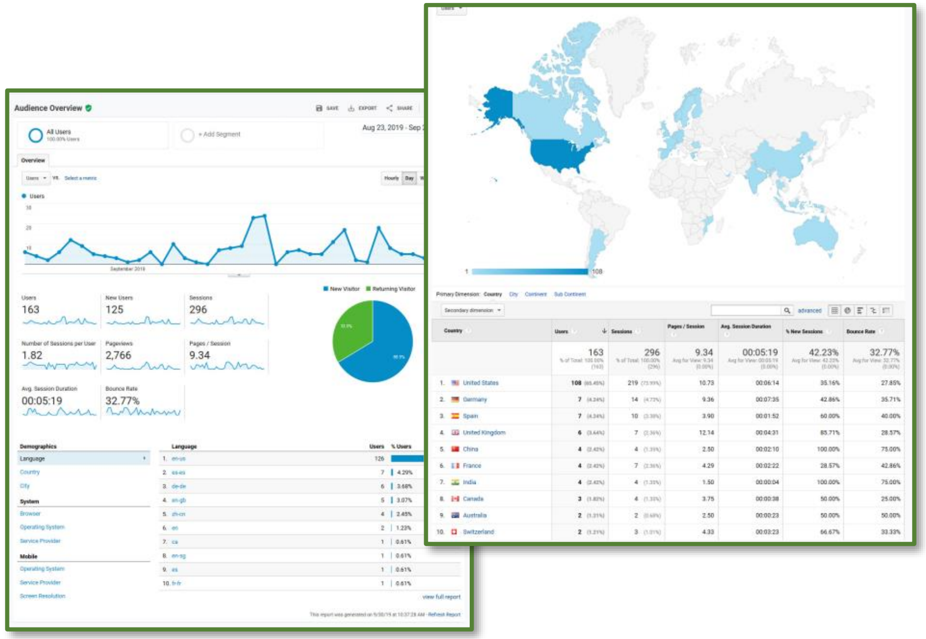
DuraMAT Datahub

Infrastructure

- DuraMat Data Hub continues increasing user activity and archive volume

Data Hub Metric	Current count	Since 7/1/2019 (Q3)	Since begin FY19
Registered Users	91	10.98%	193.55%
Projects	45	4.65%	73.08%
Datasets	92	64.2%	441.18%
Data Resources/Files	547/1358	60.43%	1016.33%

- Google analytics now integrated and reporting US and global usage of site.



- Time-Series database now active. Research access via Jupyter Notebook Tools available