DuraMAT
Durable Module Materials Consortium

Glass/Glass Focus Group:

Module Technology and Durability Roadmap

Dana Kern-Sulas (NREL)
Archana Sinha (SLAC)

With contributions from G/G focus group members

DuraMAT Glass/Glass Focus Group

The G/G Focus Group was created one year ago with a mission:
Identify critical research directions in G/G packaging and how research in DuraMAT 2.0 can drive this area forward.

SEMINAR TALKS

Talk 1: **Robust Module Packaging and Encapsulant Design** (by Charlie Gay, VioletPower)

Talk 2: **Characterization of Contact and Interconnect Issues in Silicon Photovoltaics** (by Kristopher Davis, UCF)

Talk 3: **A Walk through Bifacial G/G Performance & Reliability** (by Chris Deline & Silvana Ayala Peláez, NREL)

Talk 4: **Reliability Testing for Moisture Related Diagnostics in Photovoltaic Modules** (by Mihail Bora, LLNL)

Talk 5: **Observations of Transparent PV Materials in Field and Laboratory Weathering** (by Jared Tracy, DuPont)

GROUP MEMBERS

National labs

Sandia National Laboratories, SLAC, NREL, Lawrence Livermore National Laboratory

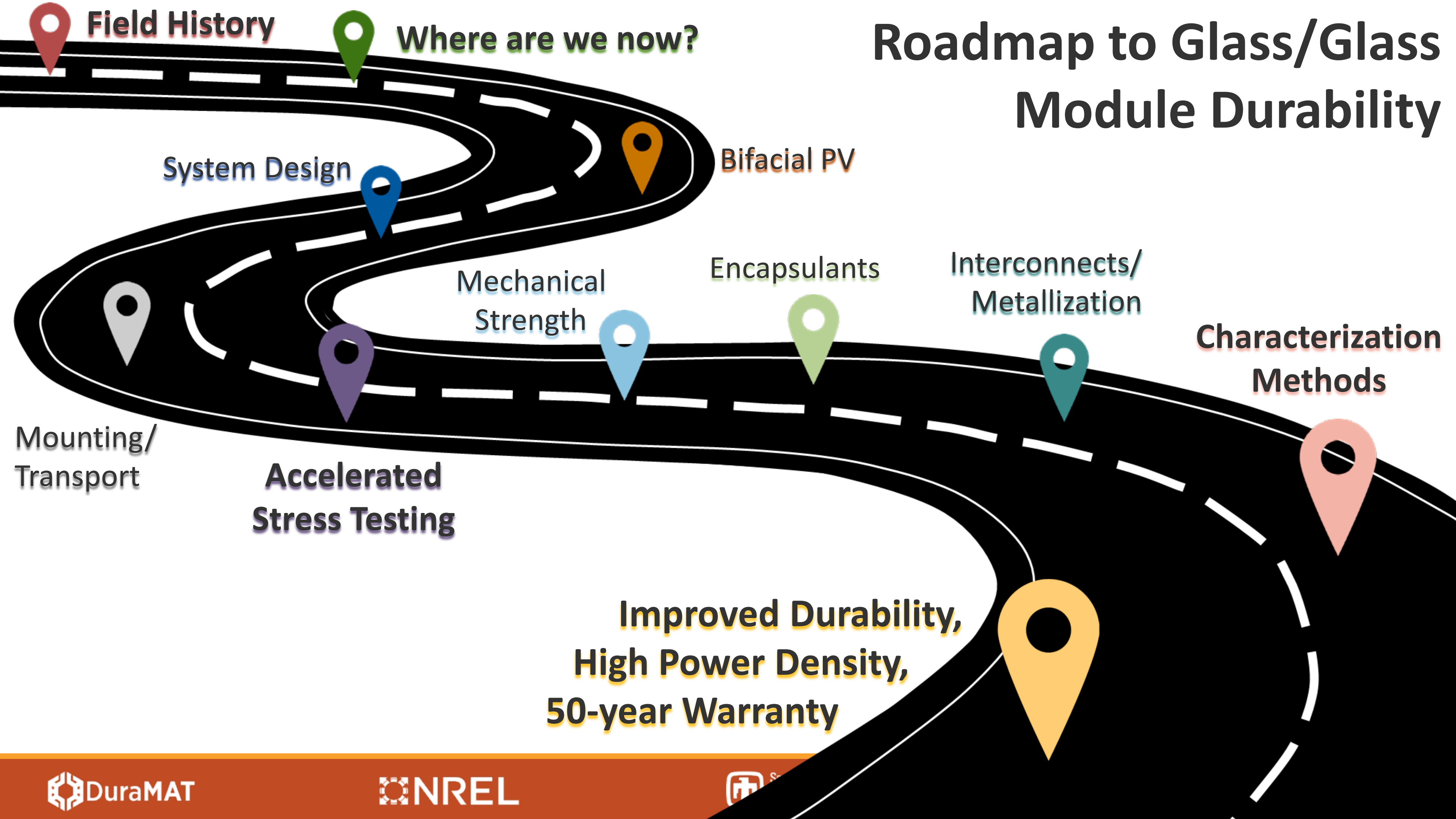
Industry

Violet Power, DuPont, SunPower, Constellation (An Exelon Company), SwiftSolar, Silicon Ranch

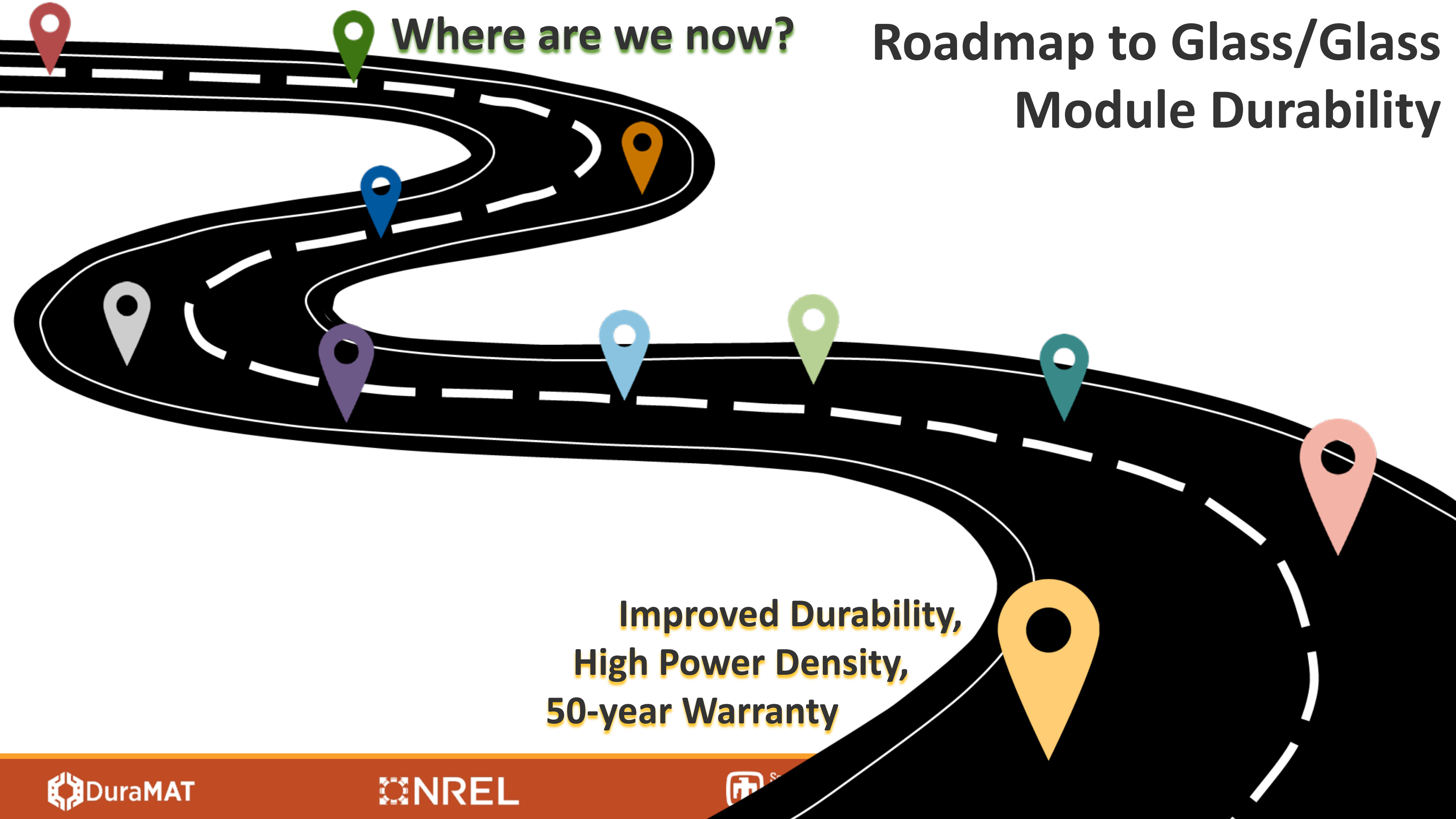
Universities

Arizona State University, UCF, Stanford University

Roadmap to Glass/Glass Module Durability

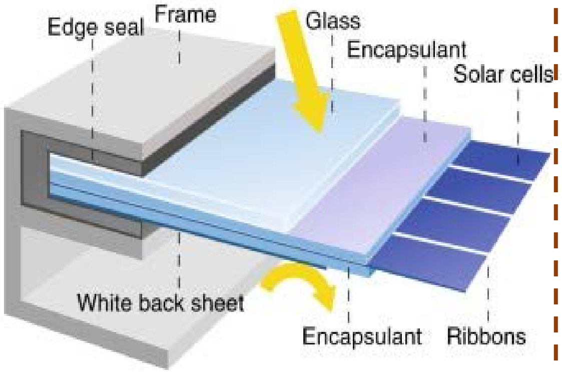


Roadmap to Glass/Glass Module Durability

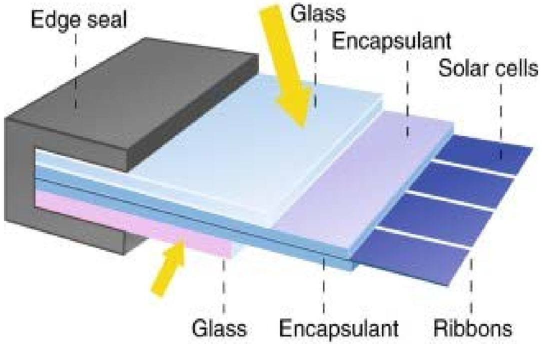


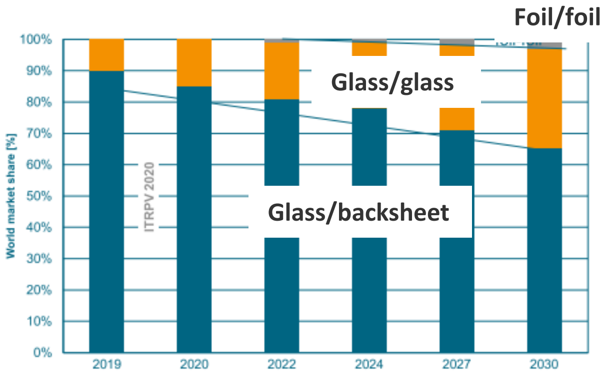
Where are we now? *Growing Market of G/G Modules*

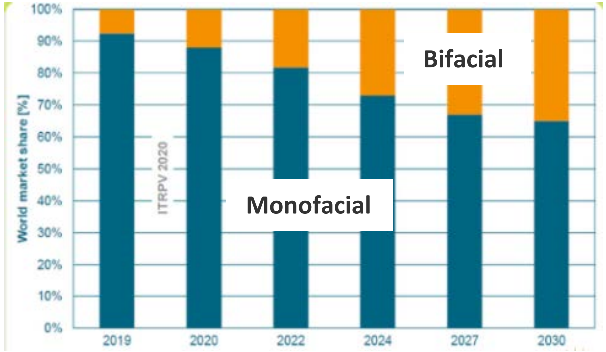
G/B Modules



G/G Modules





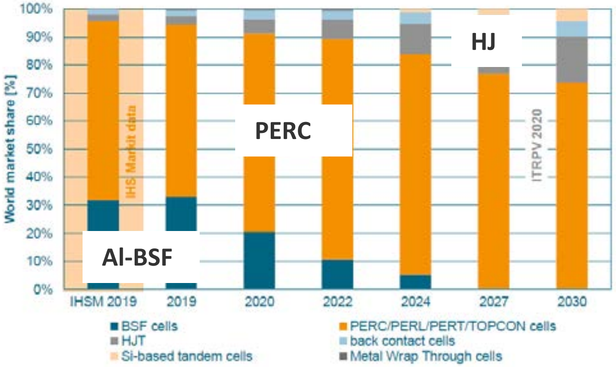


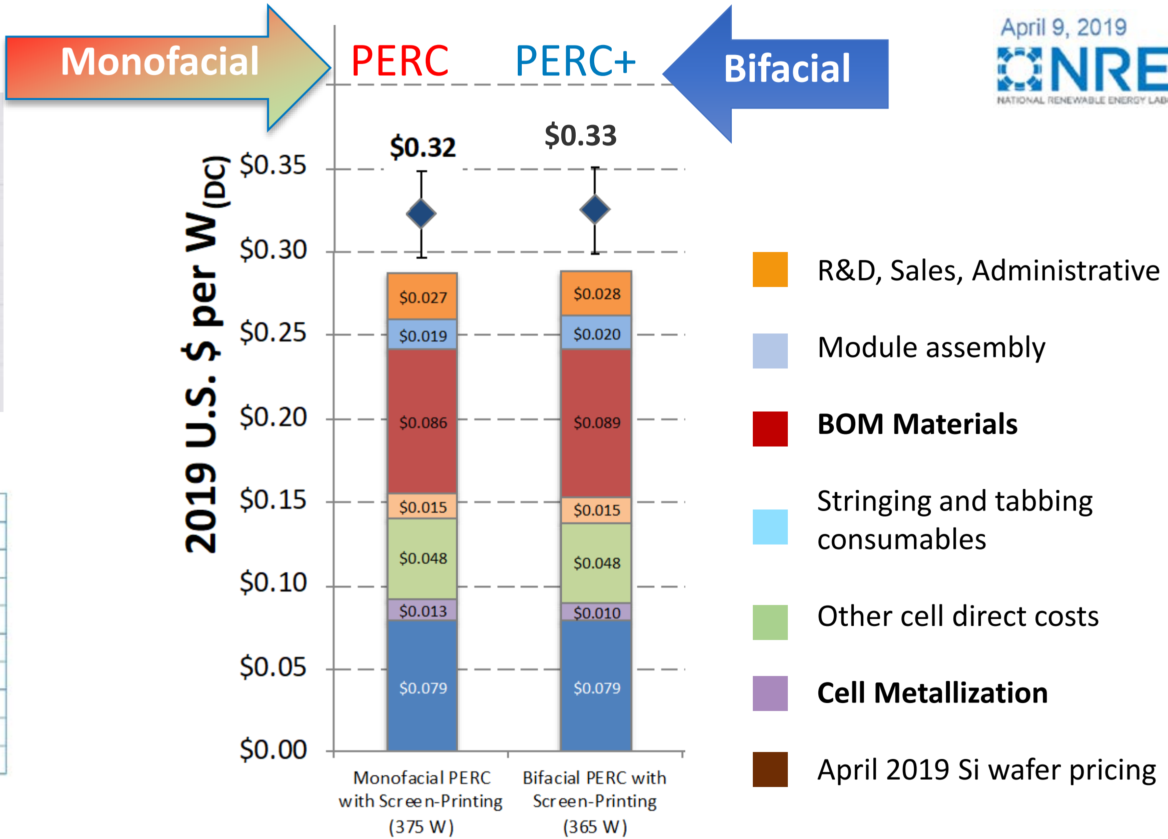
Where are we now? *Bifacial Module Cost Comparison*

Chris Deline (NREL)

April 9, 2019 NREL NATIONAL RENEWABLE ENERGY LABORATORY

Different cell technology



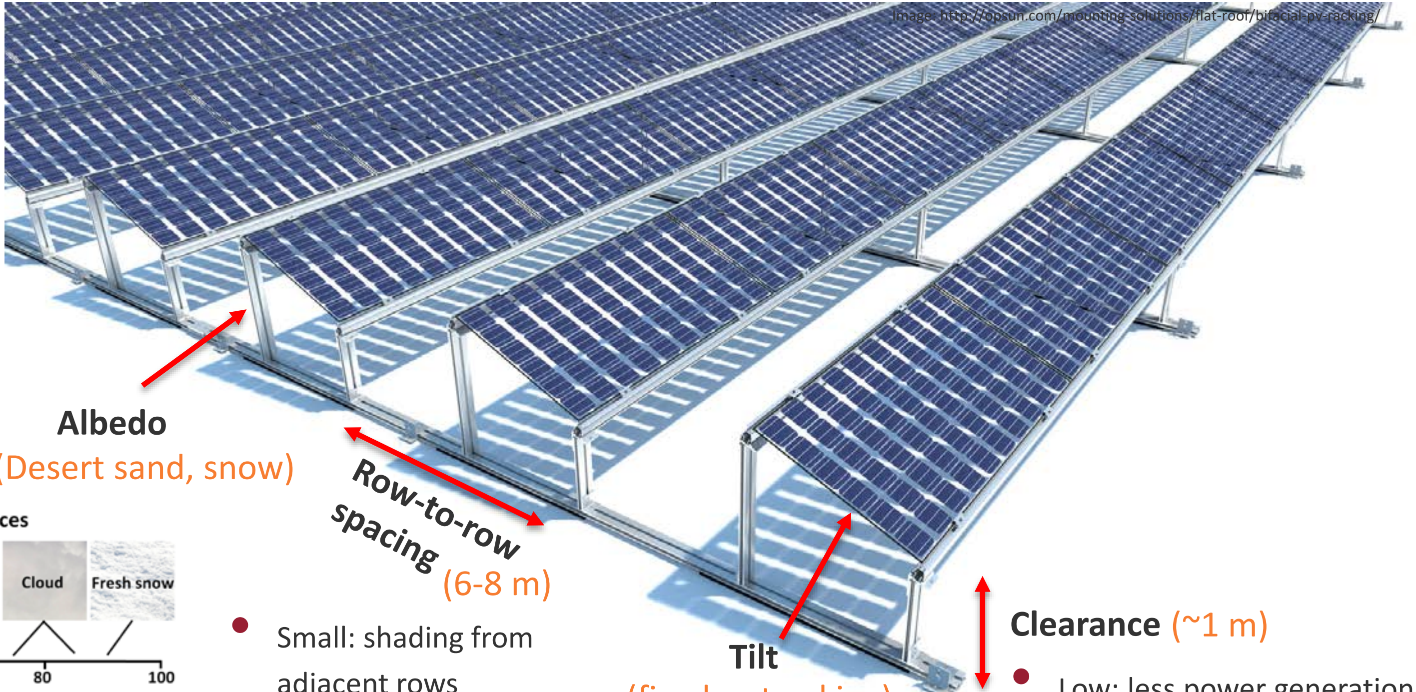


Where are we now? *Designing Bifacial PV Systems*

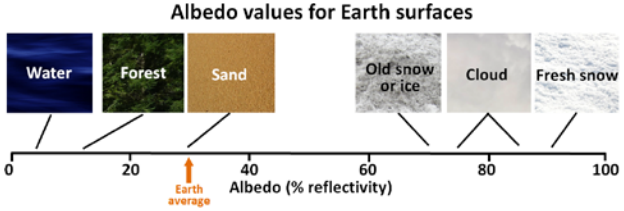
C. Deline, et al. (NREL)

Irradiance Model
Location
Weather
Sky Diffuse Model

Others:
Spacing between cells
#rows, #panels
Mounting Structure
Other scene elements



Albedo
(Desert sand, snow)



Row-to-row spacing (6-8 m)

- Small: shading from adjacent rows
- Large: more land use

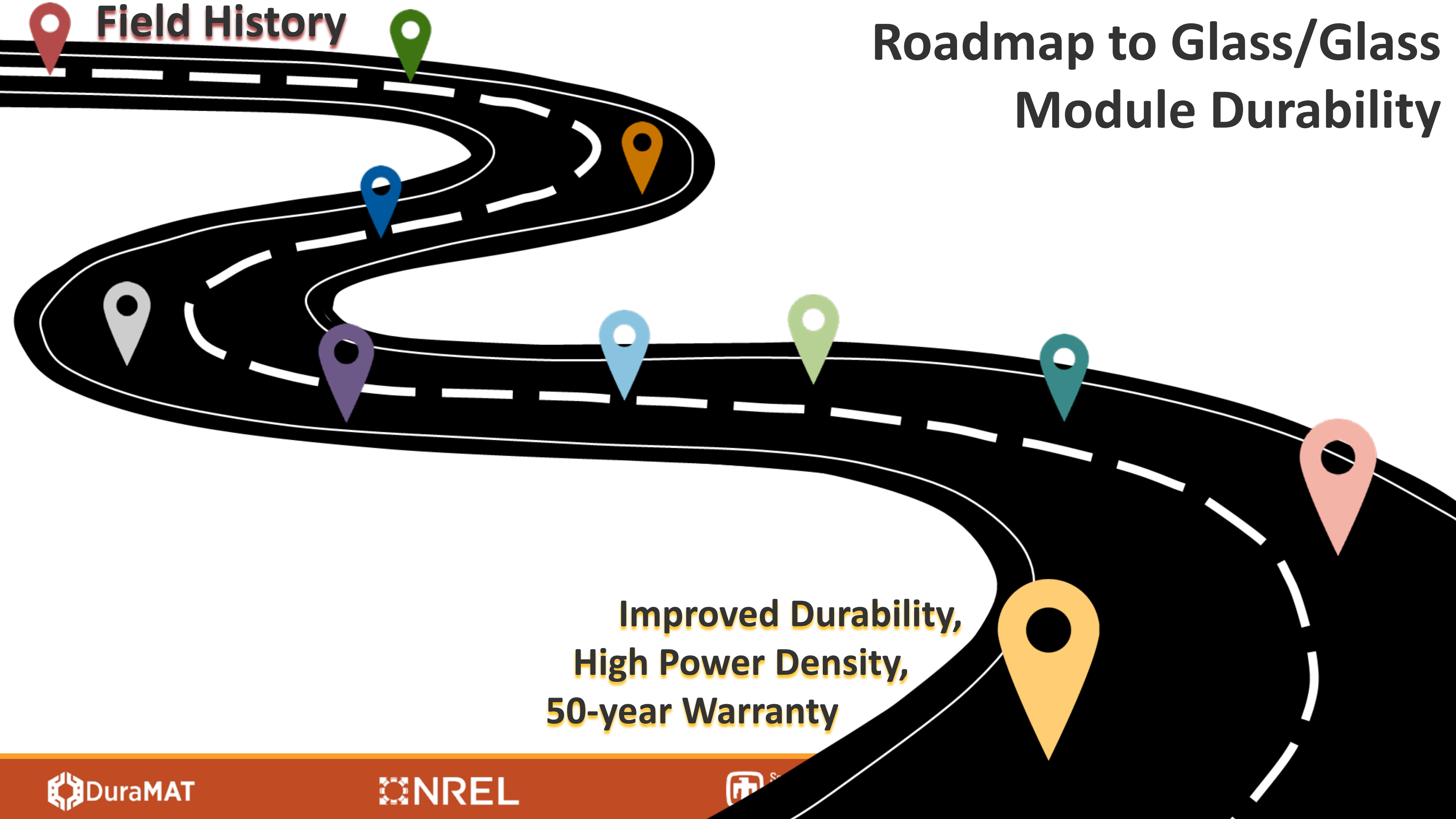
Tilt
(fixed or tracking)

- Fixed: 10-12% higher
- Tracking: 25-30% higher

Clearance (~1 m)

- Low: less power generation
- High: higher cost of mounting structures

Roadmap to Glass/Glass Module Durability

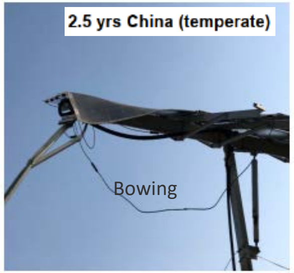


Field History *Learning from Old-Generation G/G Modules*

Old G/G modules exhibited a greater degradation than G/B construction

Jared Tracy, et al. (DuPont)

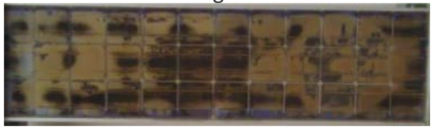
Mounting structures



Packaging materials

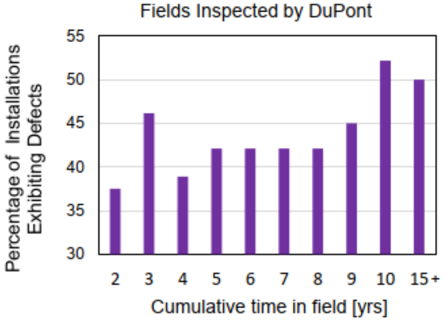
9 yrs Arizona (hot/dry)

Severe EVA browning and delamination



8 yrs India (hot/dry)

14 yrs SW China (subtropical)



G/G comprises ~8% of all sites

Historical field failure modes:

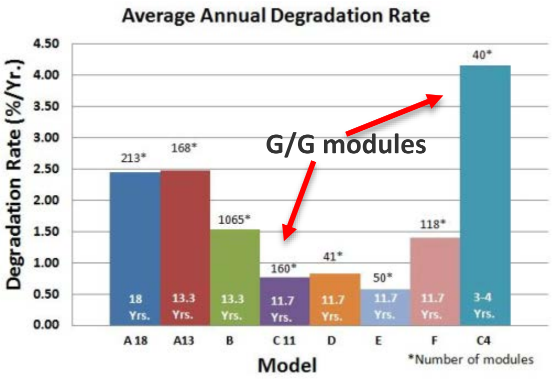
- Delamination/bubbles
- Glass cracking
- Encapsulant discoloration
- Busbar corrosion
- Junction box corrosion

New-generation G/G bifacial modules are emerging with better packaging and robust mounting hardware

Field History *Learning from Old-Generation G/G Modules*

Different bill of materials

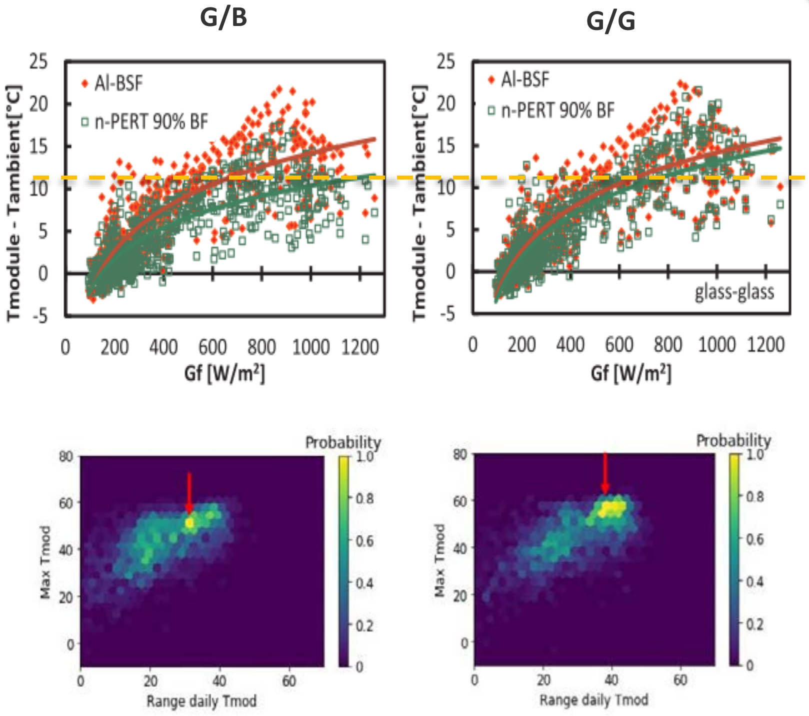
1900 modules
Arizona climate
4-18 years old



Laminate	M#	Pmax deg (%/y)	Parameters affected	Dominant degradation modes
G/B	A13	-2.29	FF>>Isc>Voc	Solder bond deg, Browning
	B	-1.53	FF>>Isc>Voc	Solder bond deg, Browning
	D12	-0.83	FF>>Isc>Voc	Solder bond deg
	E12	-0.57	Isc>>FF=Voc	Substrate warping
	F12	-1.40	FF>>Isc=Voc	Solder bond deg
G/G	C12	-0.77	Voc>Isc=FF	Delamination
	C4	-4.14	FF>Voc>>Isc	Delamination, hotspot

Ref: Singh, et al., PVSC, 2013

Different operating temperatures

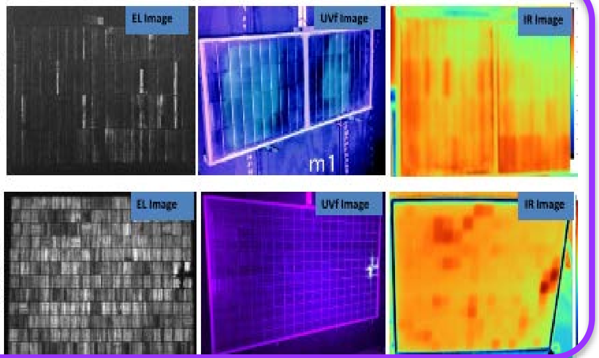


Ref: Lamers, et al., SOLMAT, 2018; Jordan, et al., PVSC, 2018

Field History *Learning from Old-Generation G/G Modules*

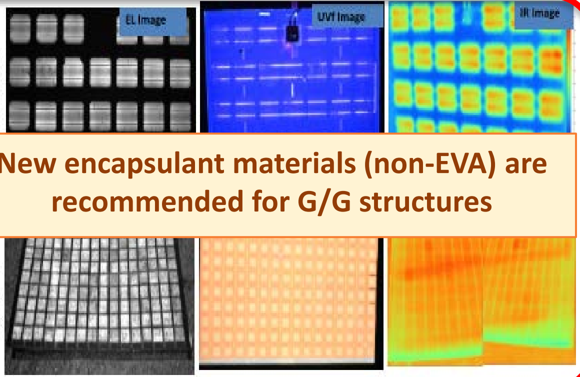
G. Tamizhmani, et al. (ASU-PRL)

Inspected 75 G/G modules from Arizona



Ionomer
10-35 y old

Local delamination
Local hotspots



New encapsulant materials (non-EVA) are recommended for G/G structures

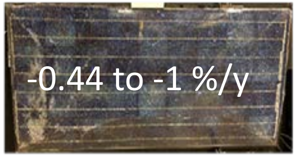
EVA
10 y old

Browning
Delamination
Interconnect corrosion
Local hot spots

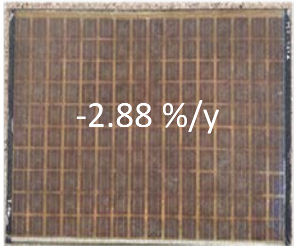
Ref: Thorat, et al., PVSC, 2020

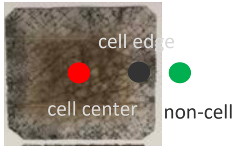
Different degradation pathways

G/B



G/G



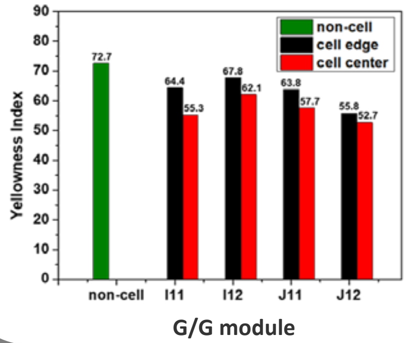


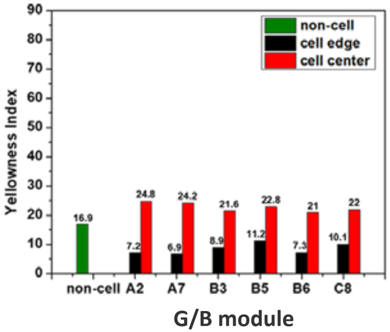
Yellowness index

- **G/B:** cell center > cell edge > non-cell
- **G/G:** non-cell > cell edge > cell center

Impermeable glass traps the acetic acid and prevents oxygen ingress for photobleaching

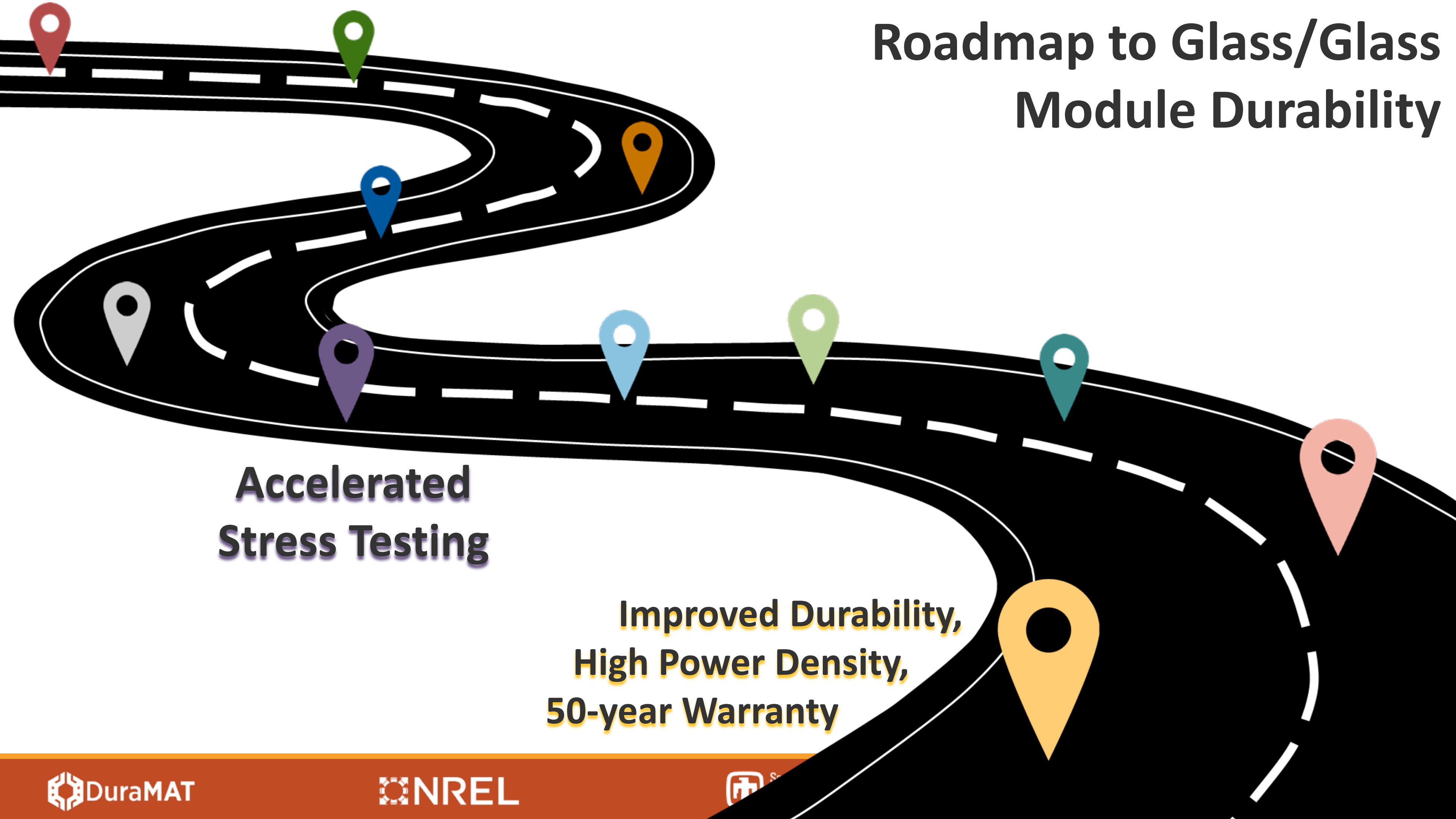
Higher rates of browning, delamination & cell interconnect corrosion



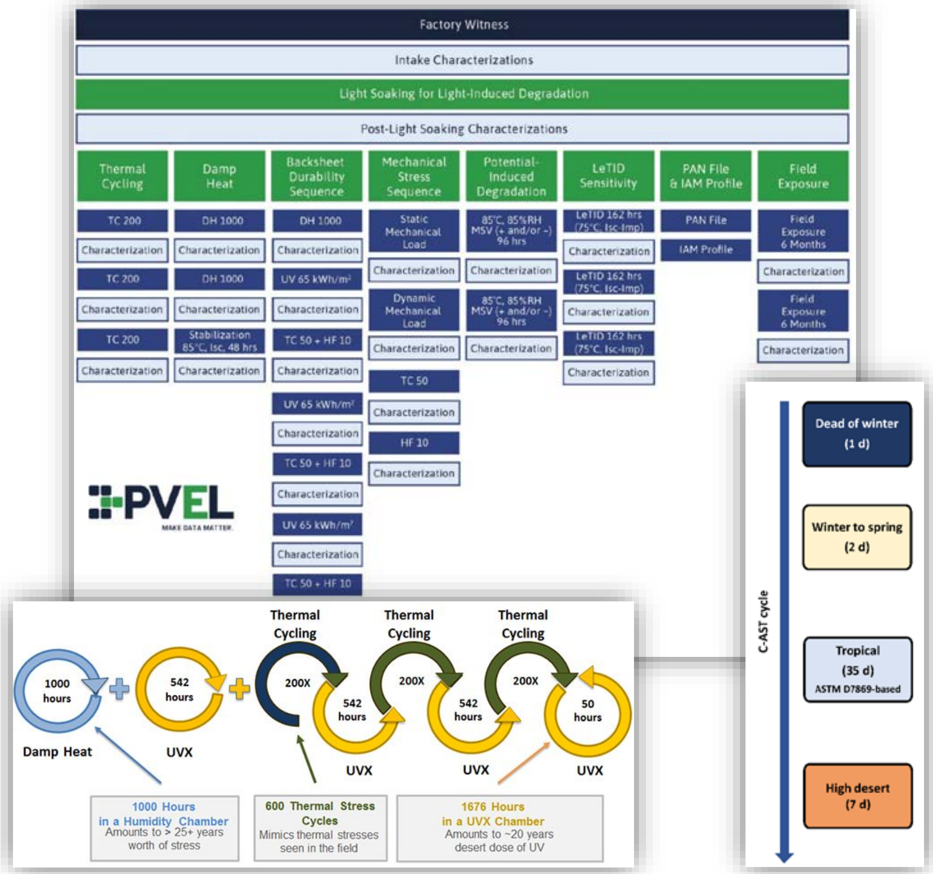


Ref: A. Patel, et al., *IEEE JPV*, 2020

Roadmap to Glass/Glass Module Durability



Accelerated Stress Testing *Adapting for New Designs and Bifacial PV*



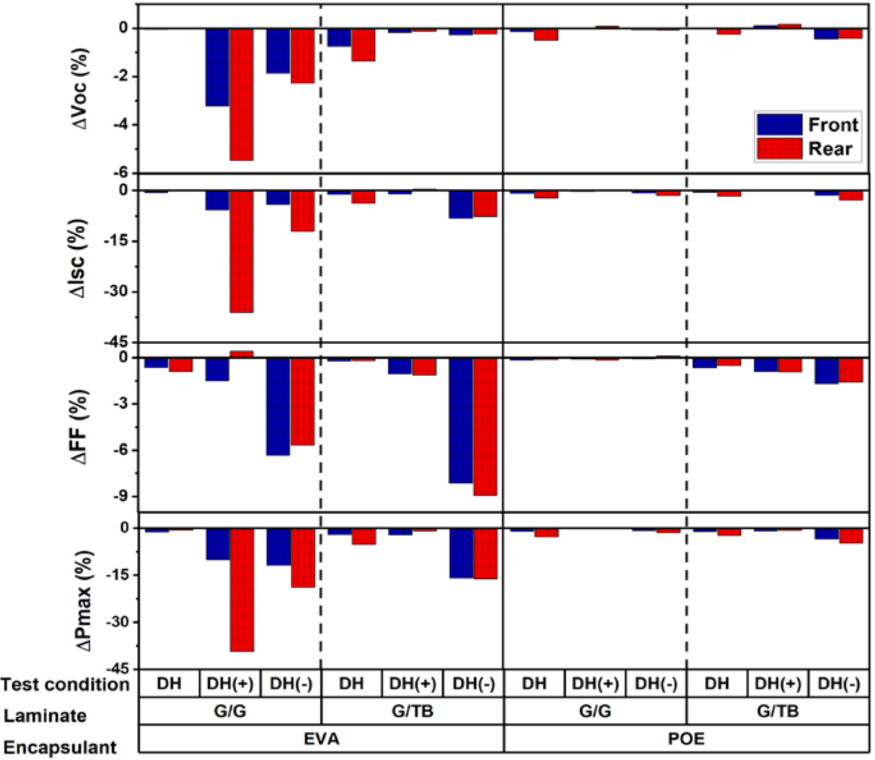
Earlier tests designed for monofacial; Bifacial and G/G, initially qualified without regarding rear-side power.

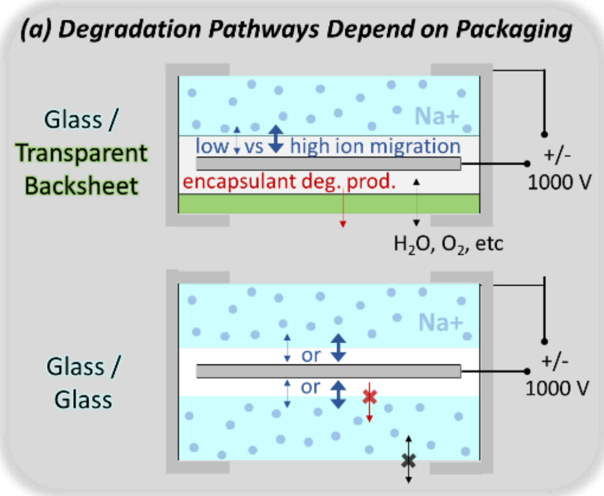
- **IEC 61215:2020 updated** with amendments to the thermal cycling, bypass diode, hot spot endurance, and UV pre-conditioning tests to consider rear side.
- **Extended and combined accelerated stress** testing is becoming more common, though results comparing G/G and G/B are still few.
  - PVEL Product Qualification Program (PQP)
  - Combined-Accelerated Stress Test (C-AST)
  - Module Accelerated Sequential Test (MAST)
  - IEC 63209
- Most common tests to compare G/G and G/B in literature include **DH and PID**.

Accelerated Stress Testing *Electrochemical Degradation in G/G*

Sulas-Kern, Owen-Bellini, Ndione, Spinella, Sinha, Ulicna, Johnston, Schelhas. *Submitted 2021.*

Current-Voltage Parameters

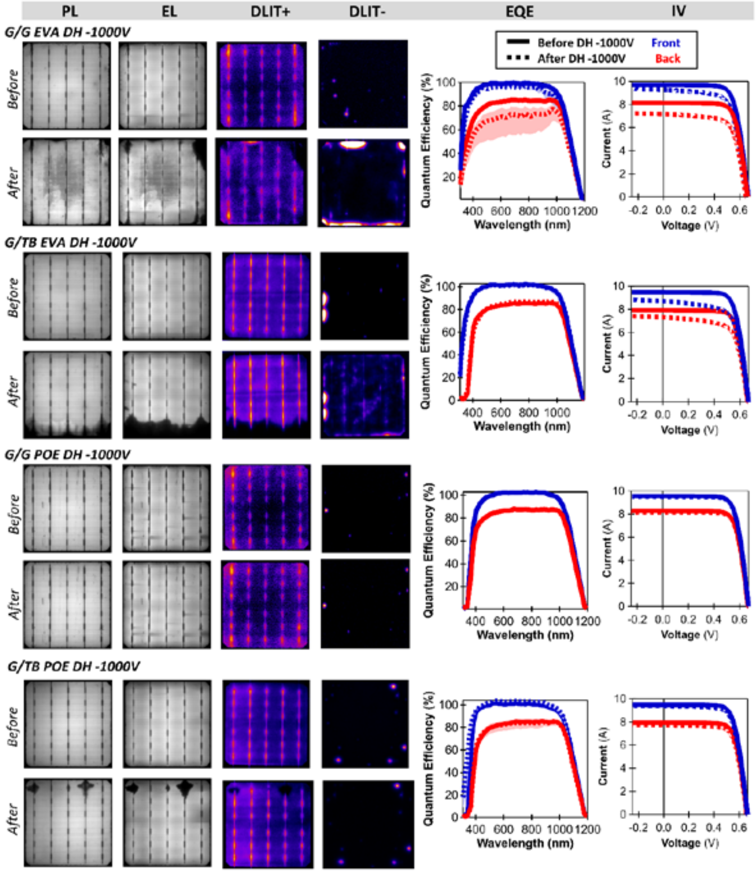




Proposed Degradation Modes Depend on Packaging

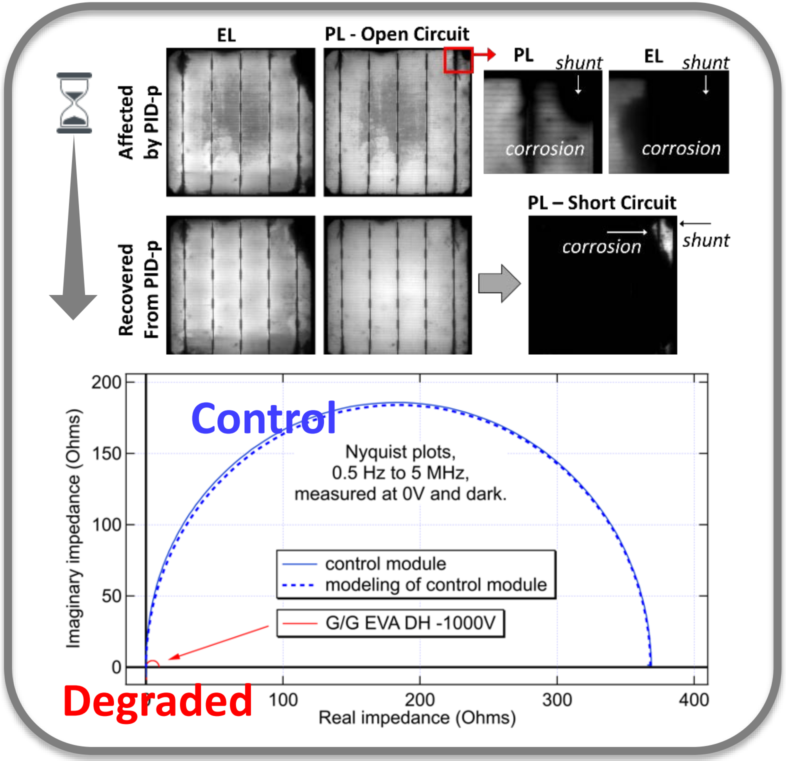
Modes under DH(-)	G/EVA/G	G/EVA/TB	G/POE/G	G/POE/TB
Shunting	X	X	--	--
Corrosion	X	X	--	X
Polarization	X	--	--	--

Accelerated Stress Testing *Electrochemical Degradation in G/G*

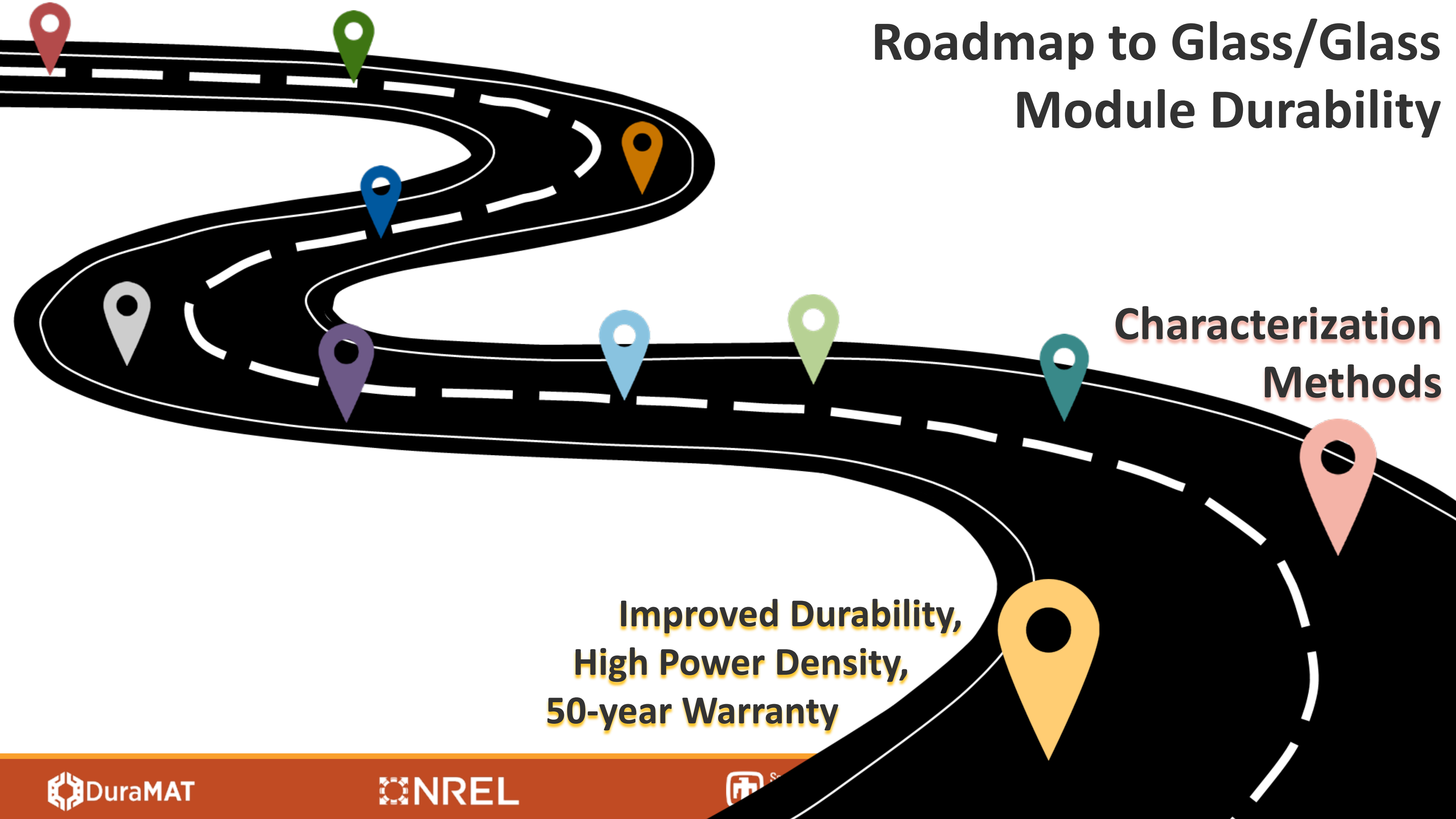


Sulas-Kern, Owen-Bellini, Ndione, Spinella, Sinha, Ulicna, Johnston, Schelhas. *Submitted 2021.*

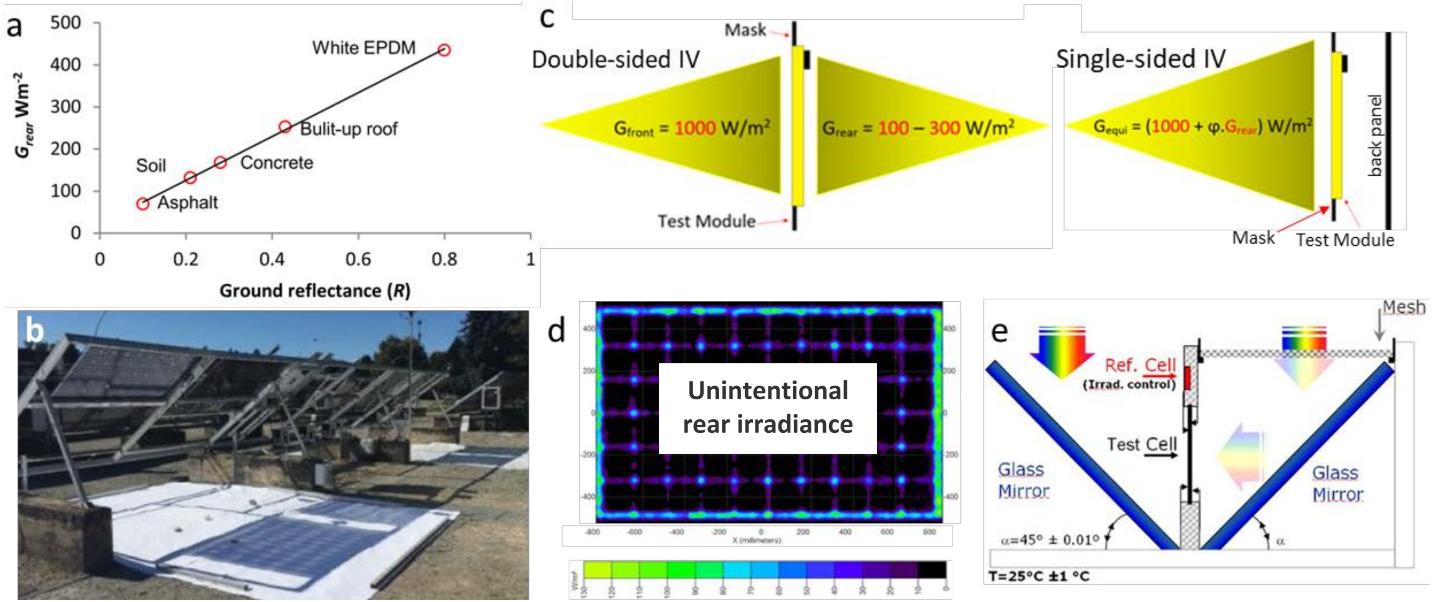
Identifying local corrosion, shunting and polarization



Roadmap to Glass/Glass Module Durability



Characterization Methods *Current-Voltage Curves*



Refs:

[a] C. Deline, et al. *IEEE J. Photovoltaics* 2017, doi: 10.1109/JPHOTOV.2017.2650565.

[b] O.P. Kenny, et al. *PVSC* 2018, doi: 10.1109/PVSC.2018.8547853.

[c-d] T.S. Liang et al. *Eng. Res. Express* 2020, doi: 10.1088/2631-8695/ab7ee5.

[e] M. Ezquer et al. EU-PVSEC 2013, doi: 10.4229/23rdEUPVSEC2008-2CV.4.67

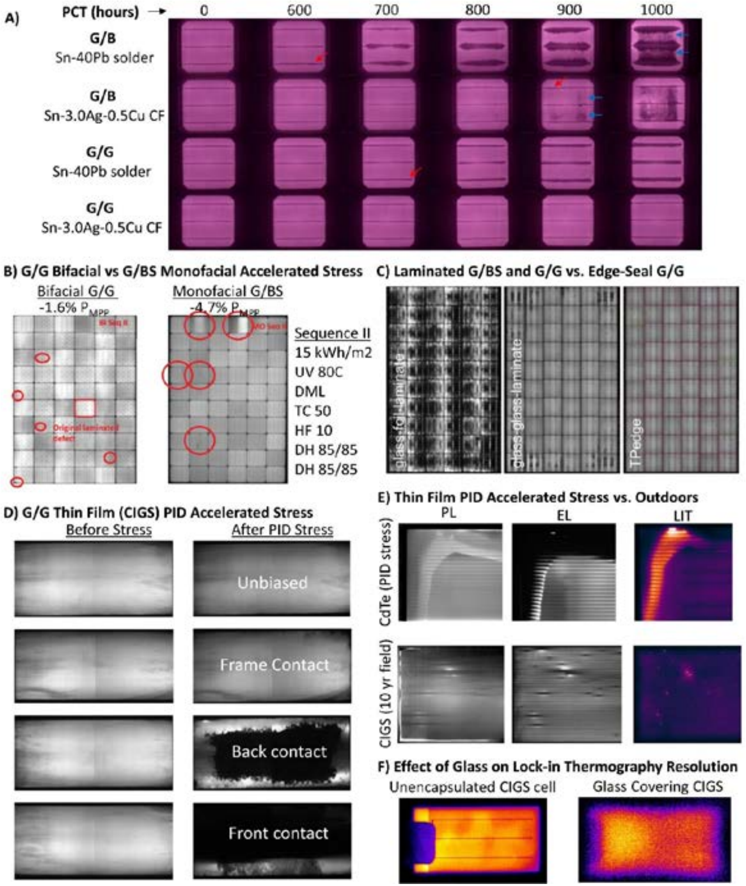
- Indoor and outdoor IV for monofacial modules described in IEC 60904
- IV procedures for bifacial modules recently released in 2019 (IEC TS60904-1-2)
- Rear spectrum/intensity depends on orientation, height, tilt, shading, transparent area of module, ground albedo, etc.
- Single-sided or double-sided IV possible depending on available equipment, but may not produce the same result.

Characterization Methods *Non-Destructive Imaging*

Soldering

Interconnects

Thin films



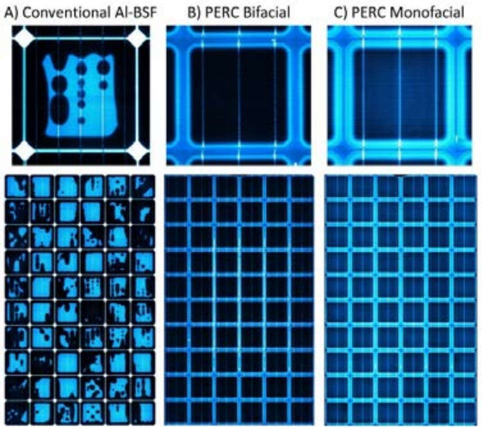
"Glass/Glass Photovoltaic Module Reliability and Degradation: A Review"
J Phys D. **2021** DOI: 10.1088/1361-6463/ac1462

Spatially-resolved characterization shows impacts of packaging schemes. (PL, EL, UVF, thermography)

Edge Seals

Some Key Results:

- Less cell cracking in G/G, but possibly more stress on interconnects.
- G/G showed less moisture ingress.
- G/G with EVA – more PID and corrosion.



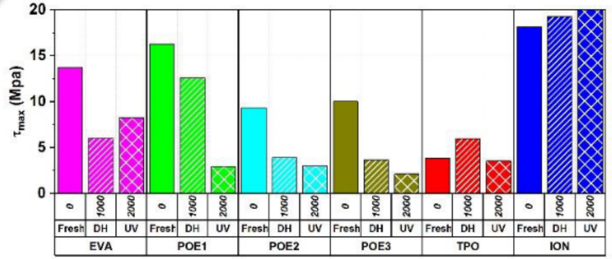
***Note:** Several conflicting results – More comparisons of experiments vs modeling are needed.*

Cell Cracks

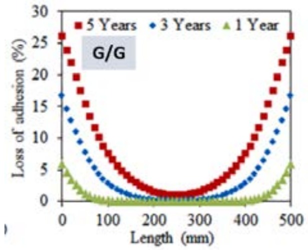
Characterization Methods *Materials Testing and Microscopy*

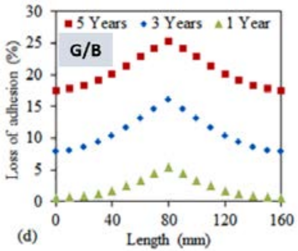
Invited Topical Review: "Glass/Glass Photovoltaic Module Reliability and Degradation: A Review" *J Phys D.* **2021** DOI: 10.1088/1361-6463/ac1462

Mechanical/Physical

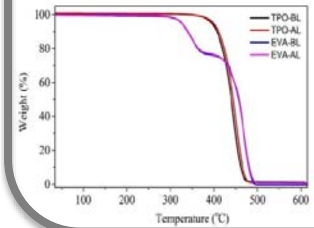


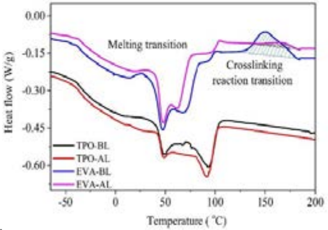
Shear Stress





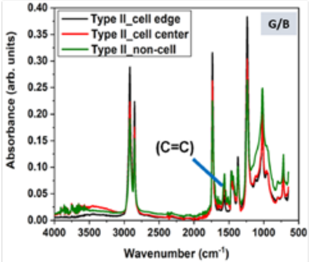
Adhesion Strength

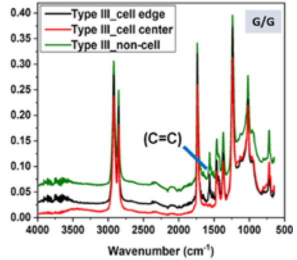




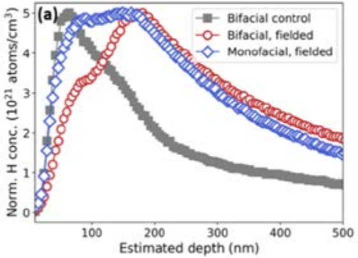
Thermo-mechanical Properties (DSC, TGA)

Chemical/Microstructure

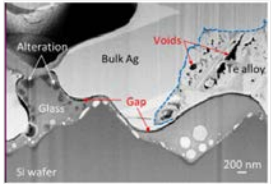


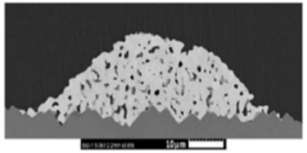


Bonding Environment (Raman, FTIR)



Chemical Profiles (D/TOF-SIMS, XPS, EDS, EELS)





Microstructure (SEM, TEM)

DuraMAT NREL Sandia National Laboratories BERKELEY LAB SLAC NATIONAL ACCELERATOR LABORATORY

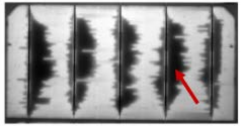
Characterization Methods *Multiscale Characterization*

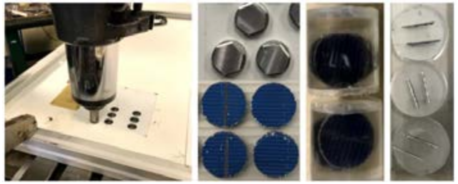
Kristopher Davis, et al. (UCF)

Microscopy

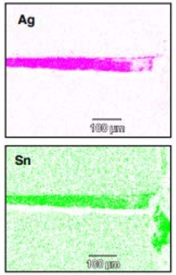
Iqbal, et al. 2021 submitted

EL

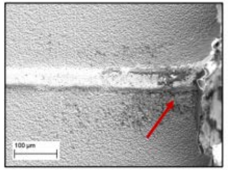




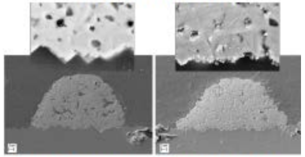
Coring



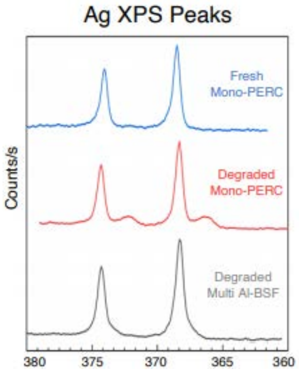
SEM / EDS



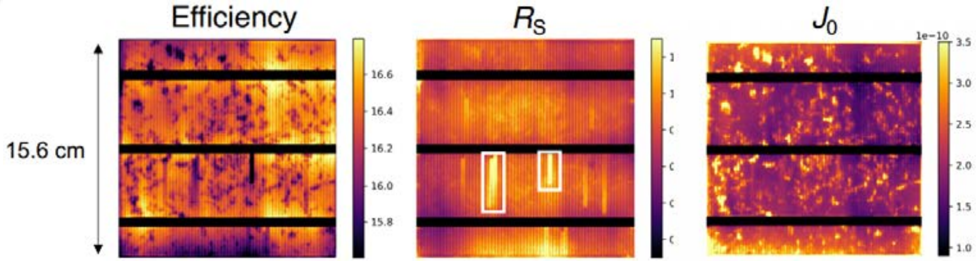
Cross-Sections



Good Contact Degraded Contact



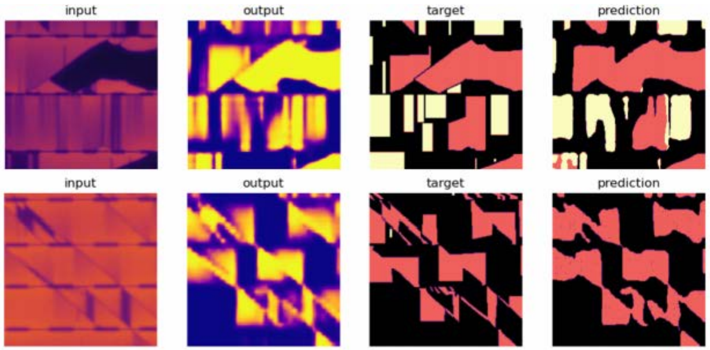
Quantitative Image Analysis

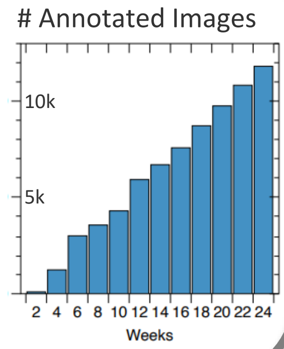


M.J. Hossain *et al.*, *Solar Energy Materials & Solar Cells*, 2019.

Machine Learning

PVSC 2021: Li, et al. Fioresi, et al.





Characterization Methods *Multiscale Characterization*

Kristopher Davis, et al. (UCF)

Microscopy

Iqbal, et al. 2021 submitted

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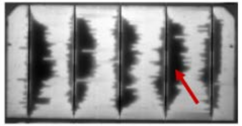
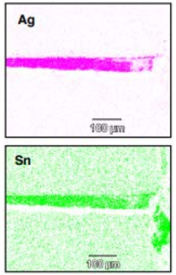
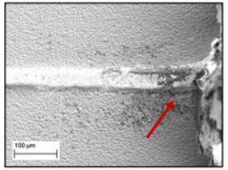


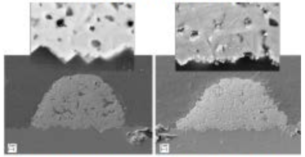
Coring



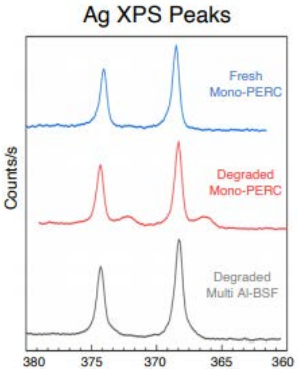
SEM / EDS



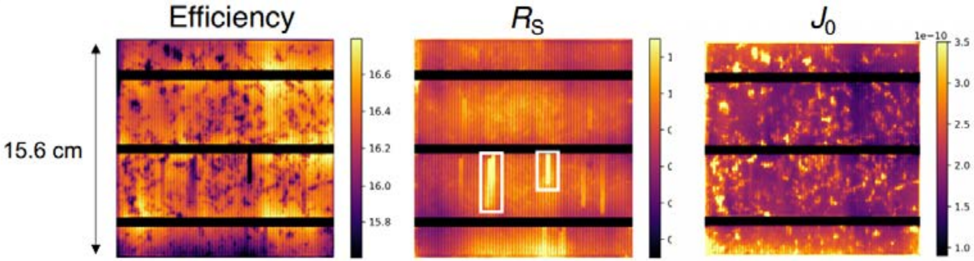
Cross-Sections



Good Contact Degraded Contact



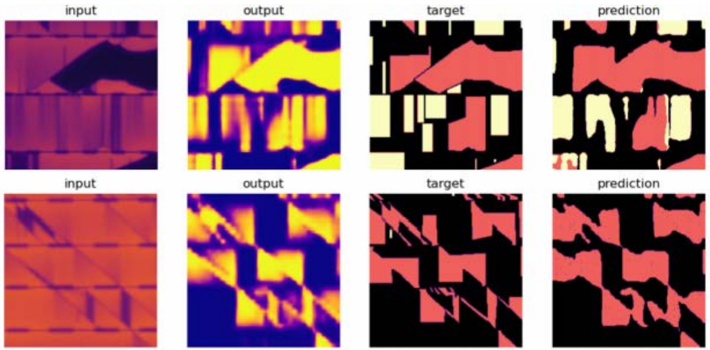
Quantitative Image Analysis

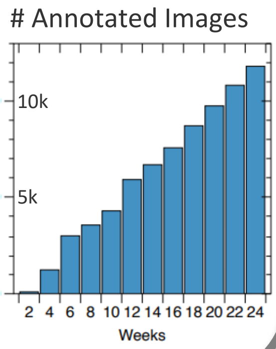


M.J. Hossain *et al.*, *Solar Energy Materials & Solar Cells*, 2019.

Machine Learning

PVSC 2021: Li, et al. Fioresi, et al.



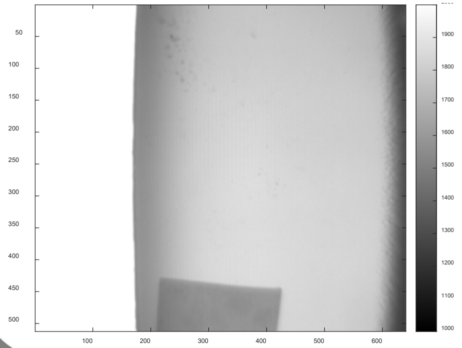


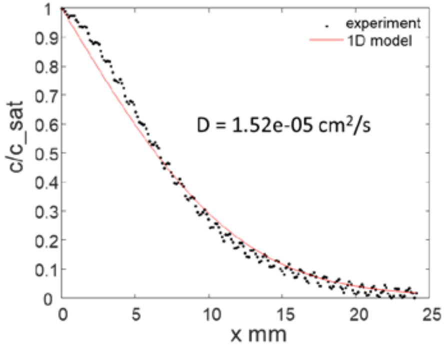
Characterization Methods *Water Ingress*

Mihail Bora (LLNL)

Hydroscanner

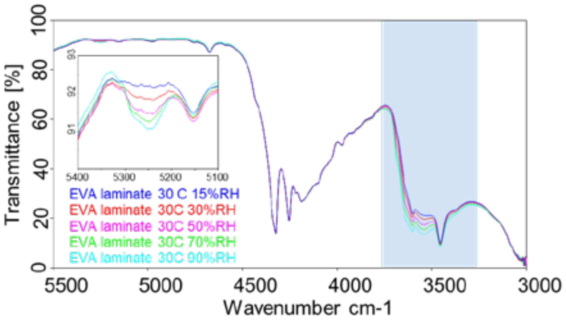
Water Diffusion

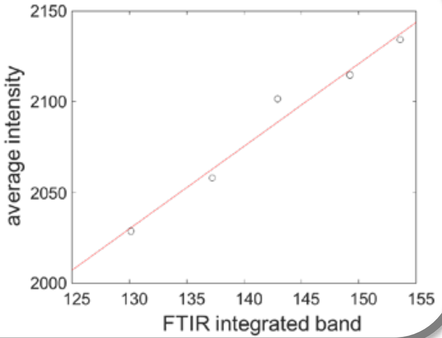




- Tested diffusion of water from the edge in glass-glass EVA laminates
- Derived diffusion coefficient
- Tested multiple encapsulant materials: EVA, polyolefin

Method Validation



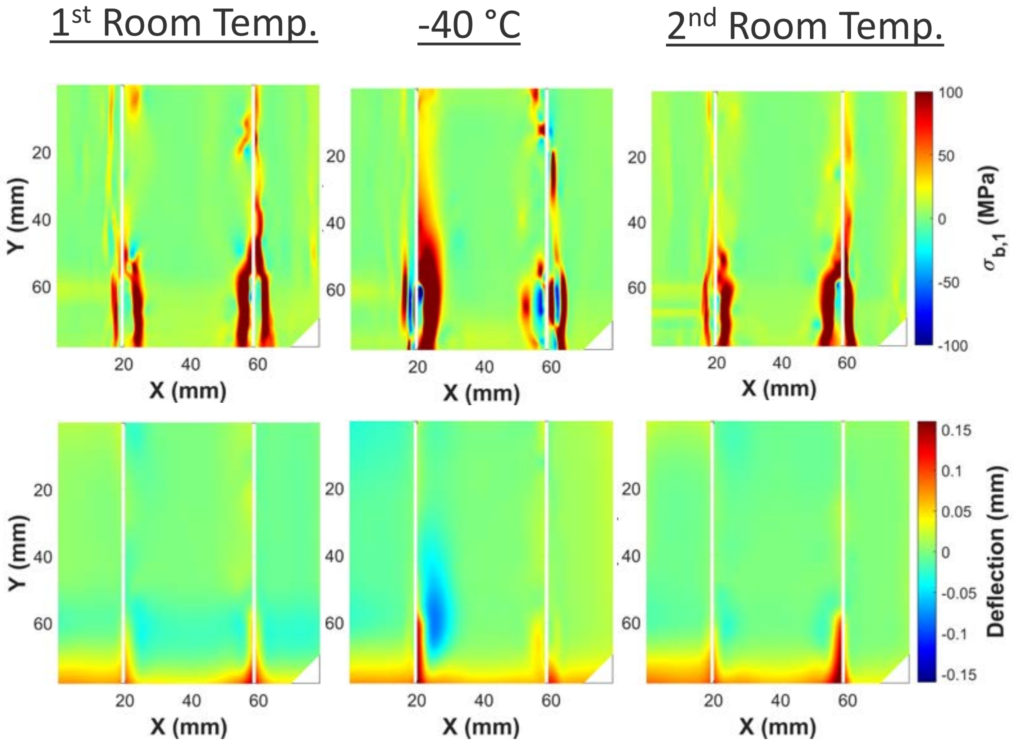


Good correlation between FTIR water band and Hydroscanner imaging (R^2=0.972)

Characterization Methods *X-Ray Topography*

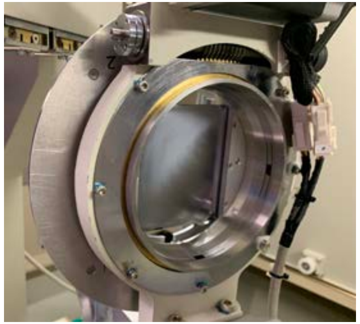
Low Temperature In-Situ Deflection and Stress Mapping in G/G Modules

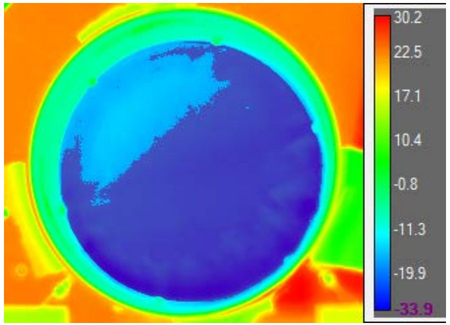
Mariana Bertoni, Ian Slauch (ASU)



Objective: Map deflection below the glass transition of the encapsulation materials.

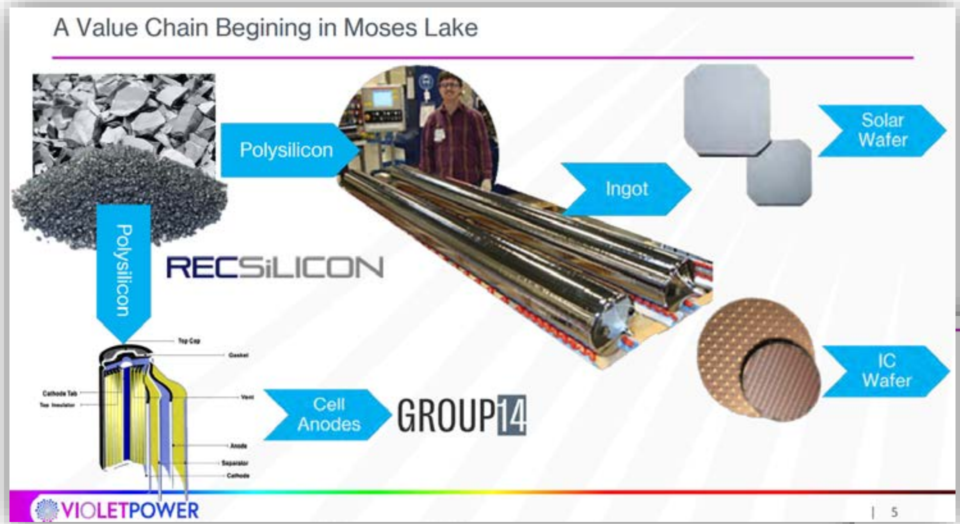
- Expect thermomechanical stress from soldering and lamination → heightened below glass transition.
- Currently investigating effects of water in EVA on cell stress over a range of temps.



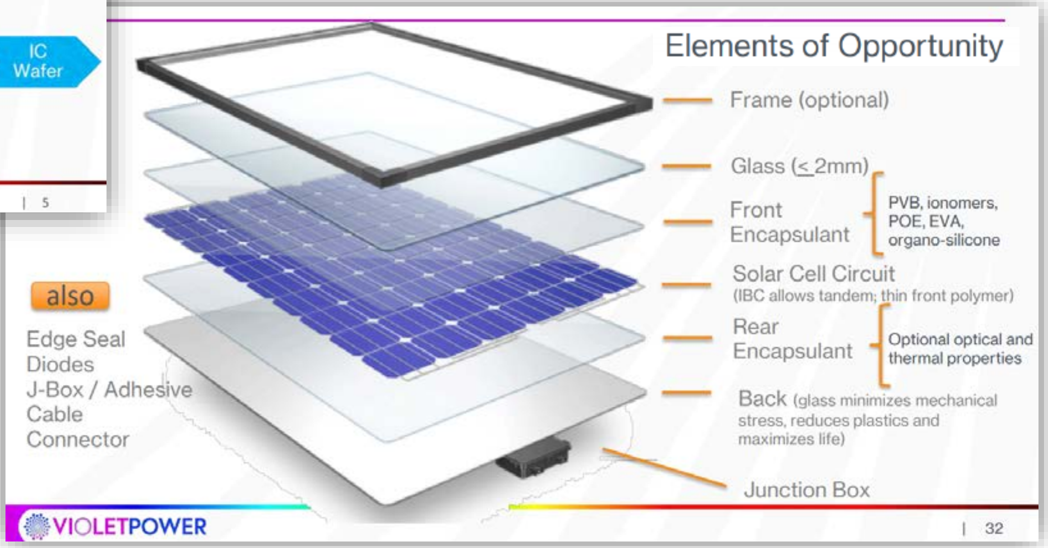


Looking Toward Sustainability and 50-year Modules

Charlie Gay (Violet Power)



U.S. Based Manufacturing



Focus on Durable Products

Module Packaging

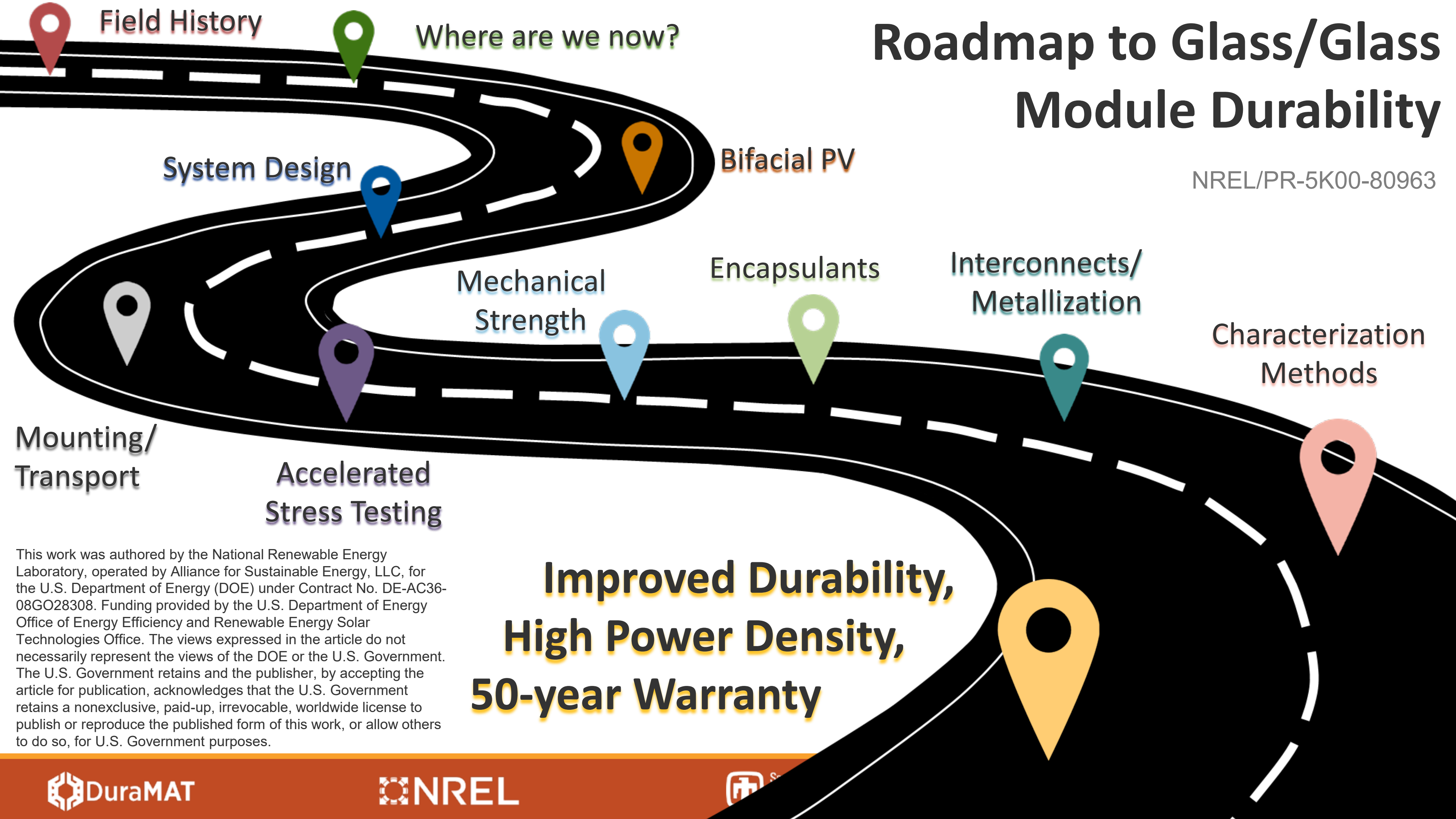
Things we know	Things we don’t know
Historically many G/G modules used **EVA**, which generates **acetic acid** causing corrosive degradation.	How will **field degradation modes** differ for newer deployed encapsulant chemistries and impermeable packages?
G/G packaging is **impermeable** (traps degradation products, but blocks moisture/atmosphere ingress)	
Higher conductivity encapsulants result in more PID, especially relevant with **rear-side Na+** from glass**.**	Are **rear PID effects** in G/G from Na+ or other species? What encapsulant/packaging combos are PID resistant?
Cost may influence encapsulant choices (e.g. use of EVA in mixed systems).	How durable are **mixed encapsulants**?
Higher G/G **operating temp** may influence degradation modes.	Is the increase in **operating temp** significant enough to have long-term impacts?
More difficult to lift **heavier** G/G modules	Tradeoff **of install/transport** versus **mechanical strength** when using thin glass, transparent backsheets, and frameless modules?
Transparent backsheets allow bifacial with less weight.	
Bifacial modules generate **more power per area** due to rear side light absorption.	Degradation rates for **system components** / wiring / etc when handling higher power density module designs?

Testing and Characterization

Things we know	Things we don't know
IV (TS60904-1-2) and **stress tests** (e.g. IEC 61215, 61730) updated to account for **rear power generation.**	How to simulate **rear light absorption** without making procedures time/resource intensive?
Coring G/G is more challenging than G/B.	How to core **heat treated and tempered** glass?
Once cored, traditional **microscopy and chemical** characterization methods will still be useful.	Will we find new degradation mechanisms that will require **modified procedures**?
New temp-dependent degradation mechanisms in bifacial cell designs (LeTID, LID, H diffusion, etc)	What **advanced characterization** is more sensitive to subtle chemical/structural changes?
Mechanical/structural measurements are important to distinguish between G/G and G/B (e.g. adhesion, XRT)	How to modify **G/G adhesion** testing to be comparable with pliable backsheets? Can measured **stress distribution** validate models and field observations?
Some **imaging methods** affected by G/G packaging (e.g. **UVF** for encapsulant yellowing and cell cracking; **thermal** image resolution is poor through glass)	Is UVF useful in G/G? How can thermal resolution be improved? Additional **info from rear-side** PL/EL/EQE?
Conflicting results between experiments vs modeling (e.g. mechanical strength)	What studies are needed **to become more predictive** of G/G degradation processes?

Roadmap to Glass/Glass Module Durability

NREL/PR-5K00-80963



Improved Durability, High Power Density, 50-year Warranty

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