DuraMAT
Durable Module Materials Consortium

Characterization of the impacts of module degradation and failure rates on PV project economics

DRAFT Analysis. Comments welcome.

Michael Woodhouse[(1)], Henry Hieslmair[(2)], Andrew Gabor[(3)], and Sang Han[(4)]

(1) NREL Strategic Energy Analysis Center (SEAC) (2) DNV GL (3) Brightspot Automation (4) Osazda Energy and the University of New Mexico

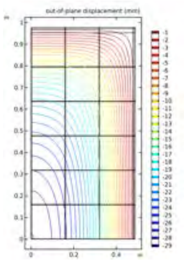
Presentation Outline

- **Introduction (Teresa Barnes, DuraMAT Director, 5 minutes)**
- Problem Statement by Henry Hieslmair, DNV GL (10 minutes)
- Impacts to a Portfolio of PV Projects (Mike, 15 minutes)
- Overview of the Osazda Energy Solution to Cell Cracking (Sang, 10 minutes)
- Quantified Value Proposition of Reducing Cell Cracking (Mike, 10 minutes)
- Conclusions, Next Steps, and Questions (Everyone, 10 minutes)

Effect of Cell Cracks on Module Power Loss and Degradation

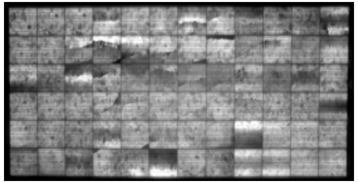
EPRI, NREL, LBL, Southern Company

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

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Conceptual Project Cash Flows Considering Varied Degradation and Failure Rates

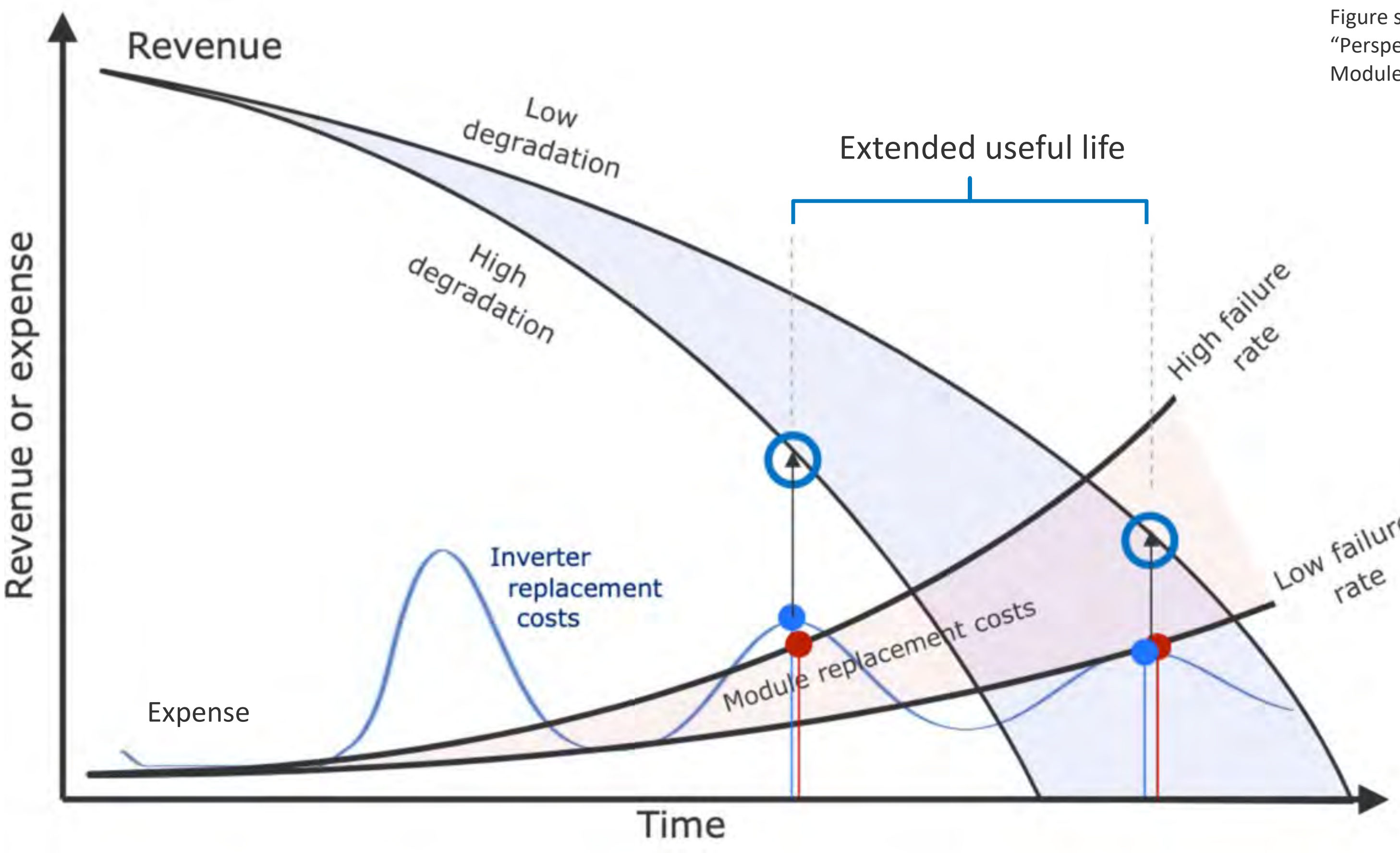
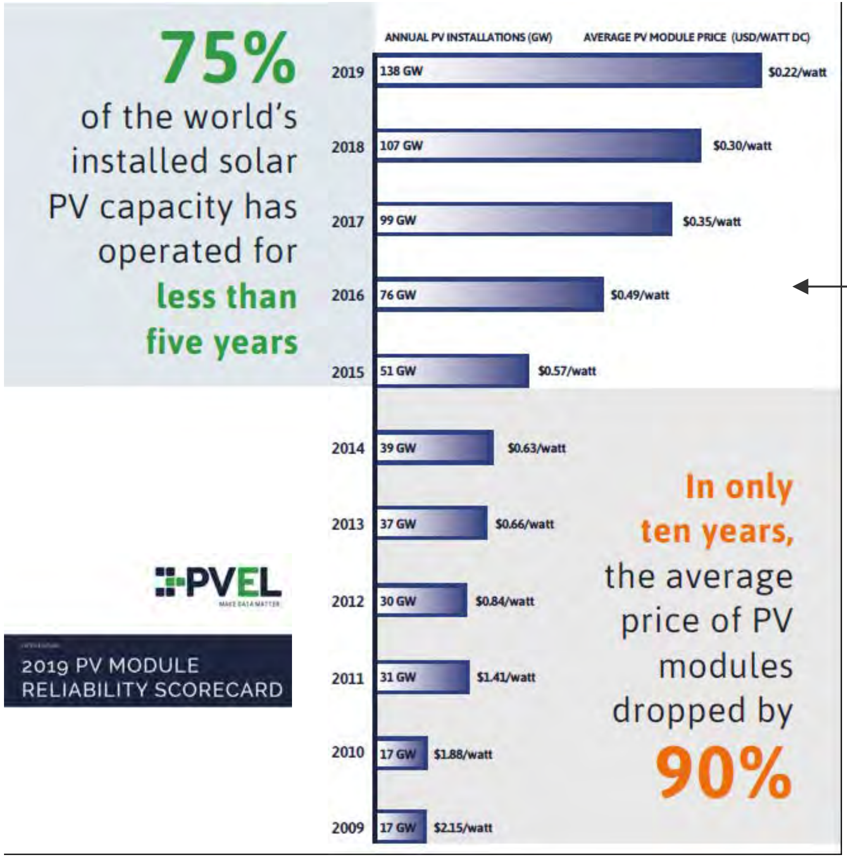


Figure source: Henry Hieslmair "Perspectives on the Useful Life of Modules", Presentation at the 2020 PVRW

What reliability data exists?



HJT, Tiling ribbon, 500W

Half-cell, MBB

PERC bifacial, shingled, 6 busbar

Mono ~ Multi by volume

PERC adoption

B-O LID mitigation, 5 busbar

"Compendium" published July 2016

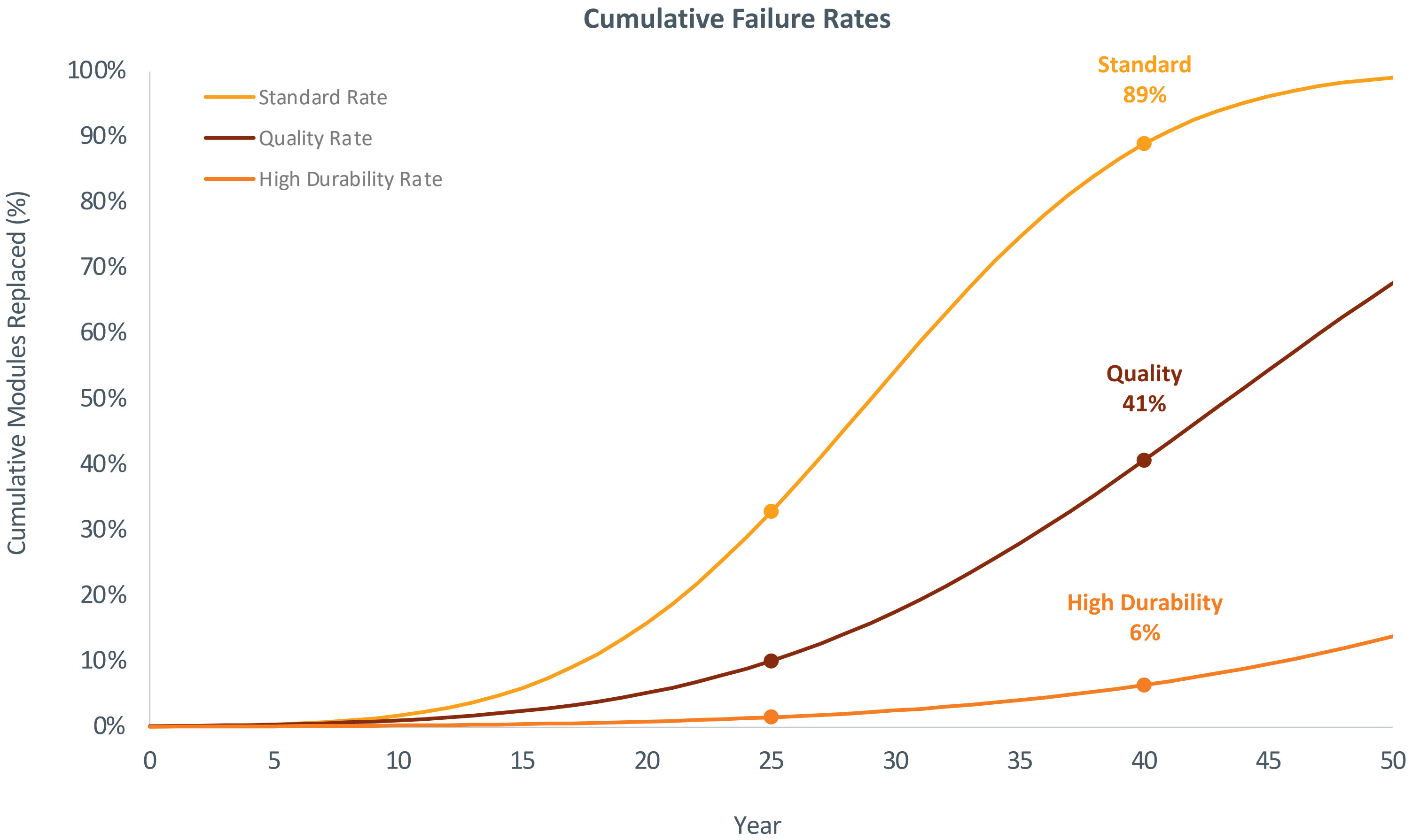
4 busbar

3 busbar

Manufacture date of modules

2 busbar

Failure Profiles for Standard, Quality, and High Durability



Concept derived from: Henry Hieslmair "Perspectives on the Useful Life of Modules", Presentation at the 2020 PVRW.

Note that the cumulative modules replaced curves in these scenarios do not include the replacements of replacements.

Standard, Quality, and High Durability Module Characteristics

	Standard	Quality	High Durability
Experience & financials **(Use PV Tech Bankability)**	Recently founded	<10 years experience, B or A status	>10 years A status
Manufacturing quality	No information	Audit report A or B rating	Recent audit report with A rating
Module testing	Minimal	Extended-duration testing (similar PQP) <5% degradation	Very extended-duration testing <2% degradation + sequential tests
BOM	No information	BOM disclosed BOM controlled	BOM disclosed BOM controlled **Special construction**

Figure source: Henry Hieslmair “Perspectives on the Useful Life of Modules”, Presentation at the 2020 PVRW

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NREL's Solar + Storage Technoeconomic Analysis Portfolio

Component Manufacturing Costs ($)

Modules		Storage	
Crystalline Silicon	Thin-Film	Batteries	Solar Fuels

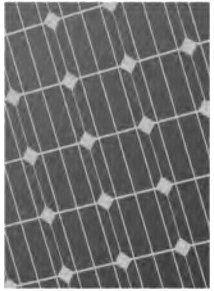


Illustration by Al Hicks, NREL


Photo from iStock, 1033236964


Photo by Dennis Schroeder, NREL 56318


Photo from iStock, 932140864

System Capital Costs ($)

PV Systems	PV Plus Storage

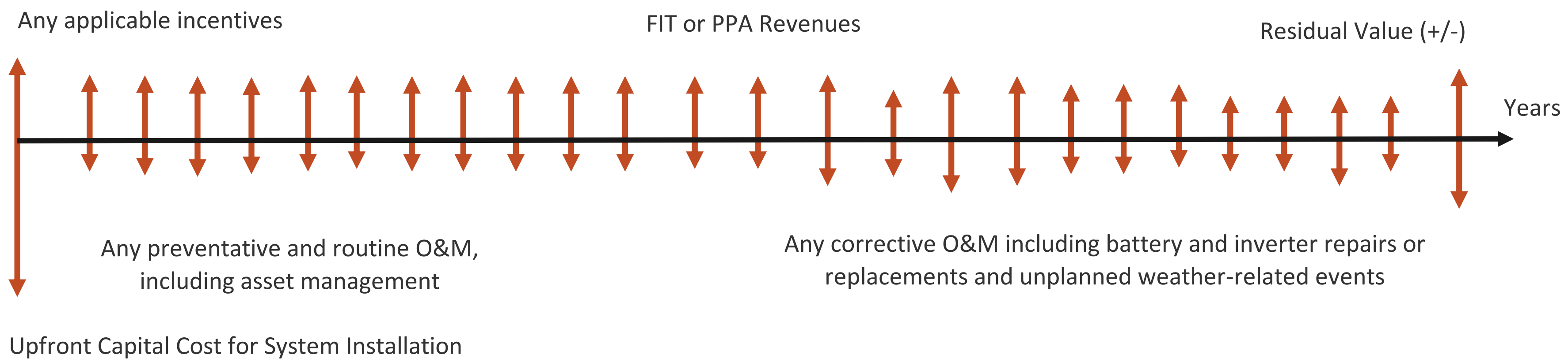

Photo from iStock, 938053682


Photo from iStock, 1128871378

NREL's Solar + Storage Technoeconomic Analysis Portfolio

Project *Pro Forma* Cash Flow Analysis

- **Levelized Cost of Electricity (LCOE)**
- **Internal Rate of Return (IRR)**
- **Levelized Cost of Solar + Storage (LCOSS)**



Problem Statement: Conceptual Project Cash Flows Considering Varied Degradation and Failure Rates

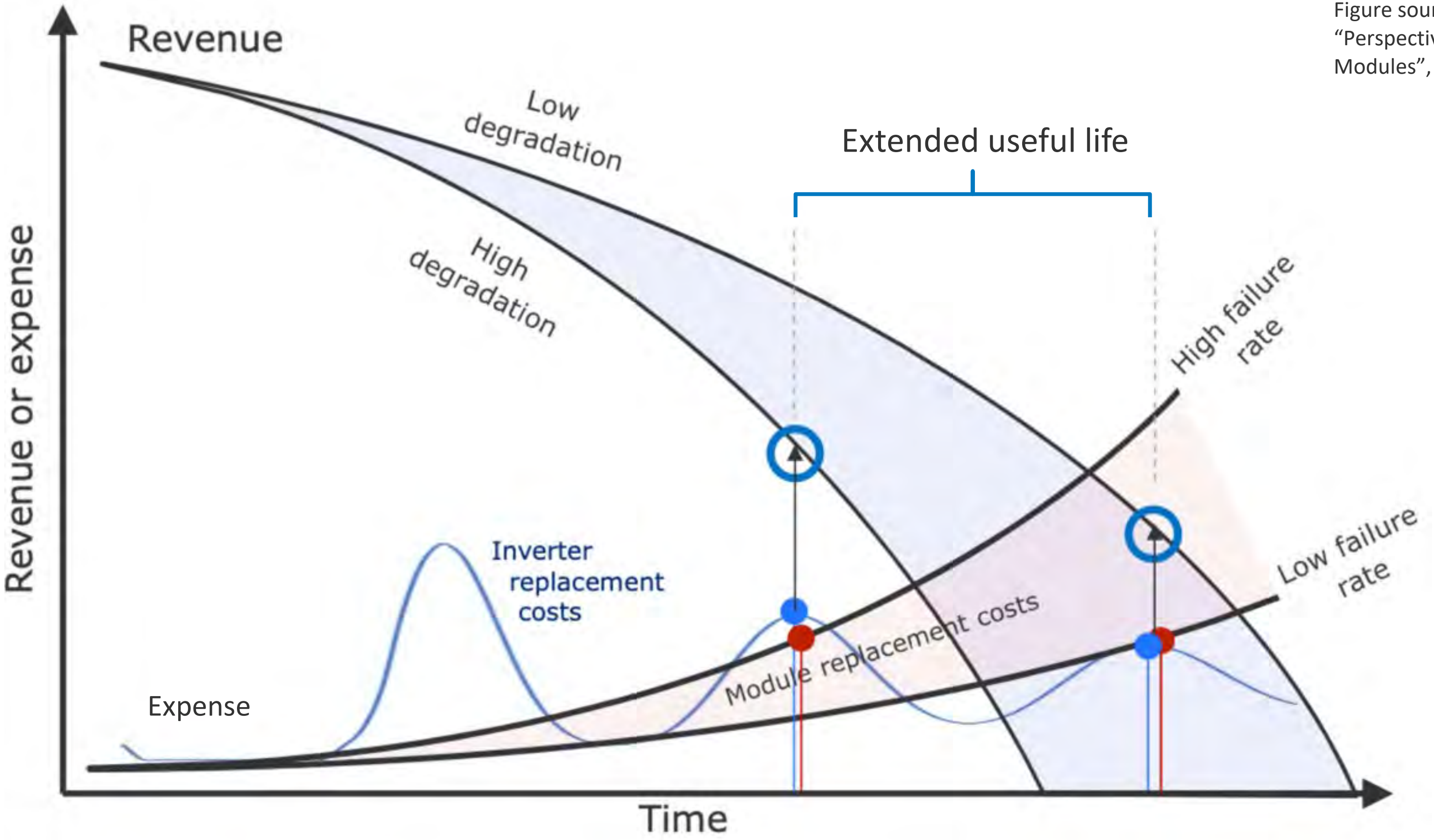
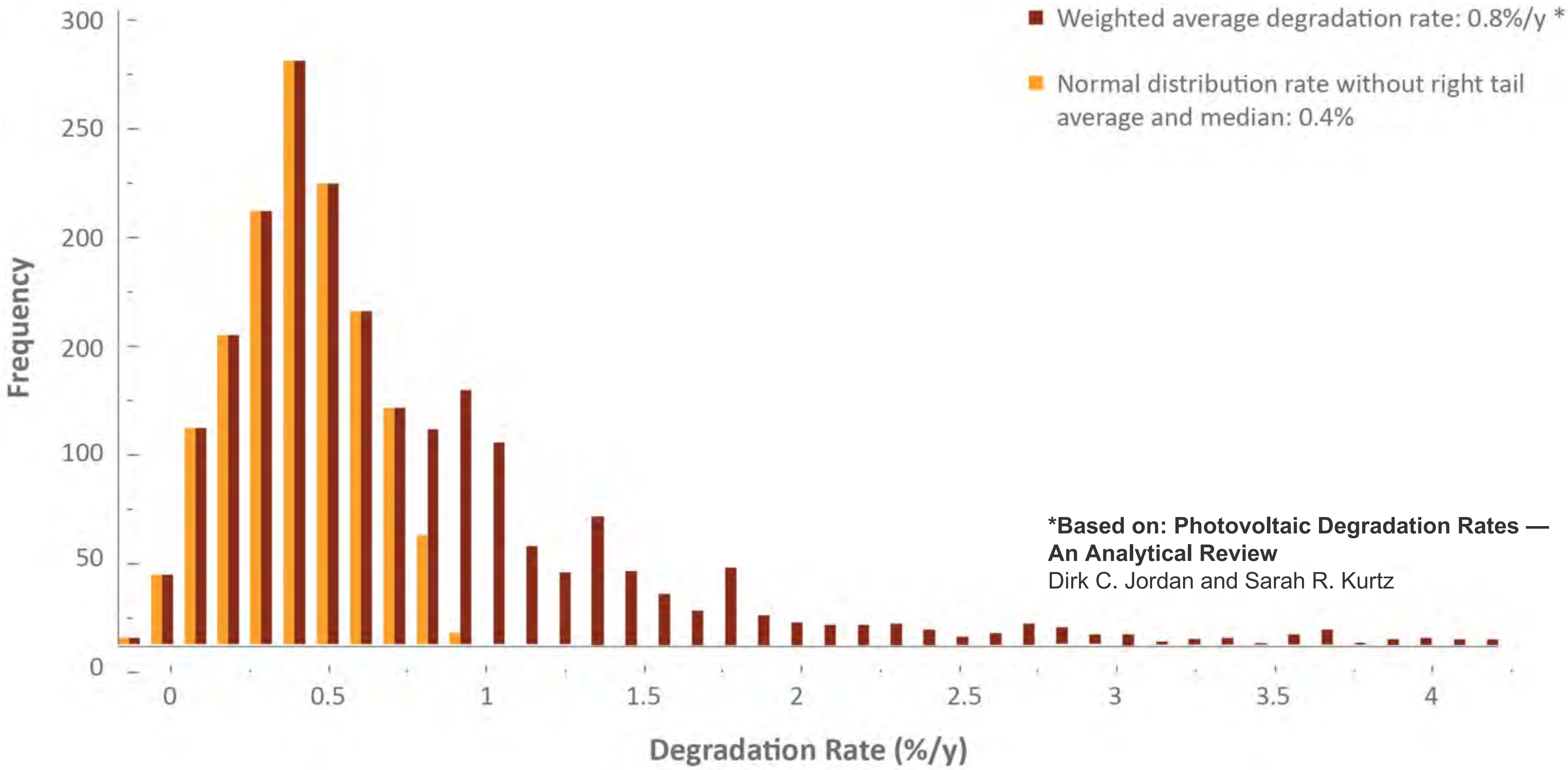


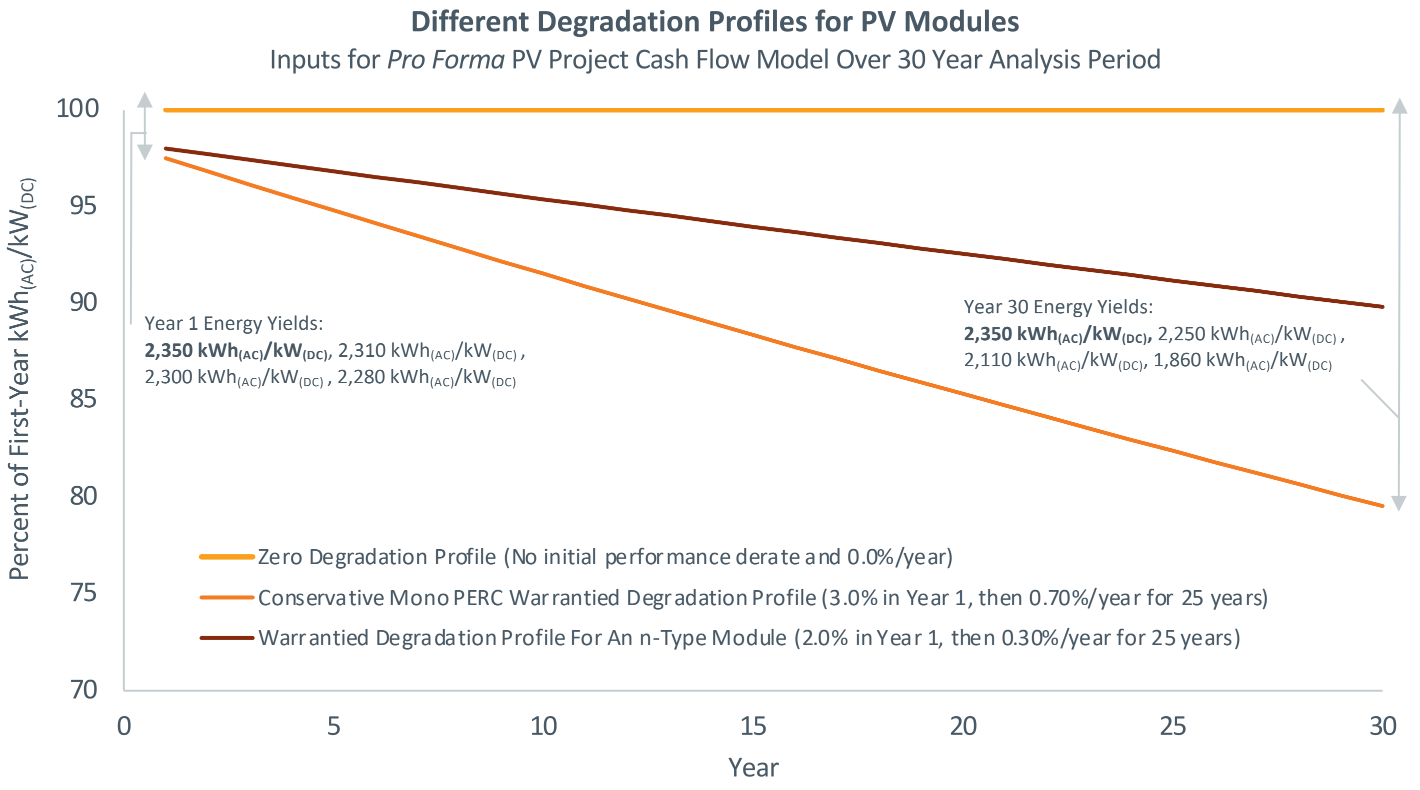
Figure source: Henry Hieslmair "Perspectives on the Useful Life of Modules", Presentation at the 2020 PVRW

Distribution of Degradation Rates for PV Systems



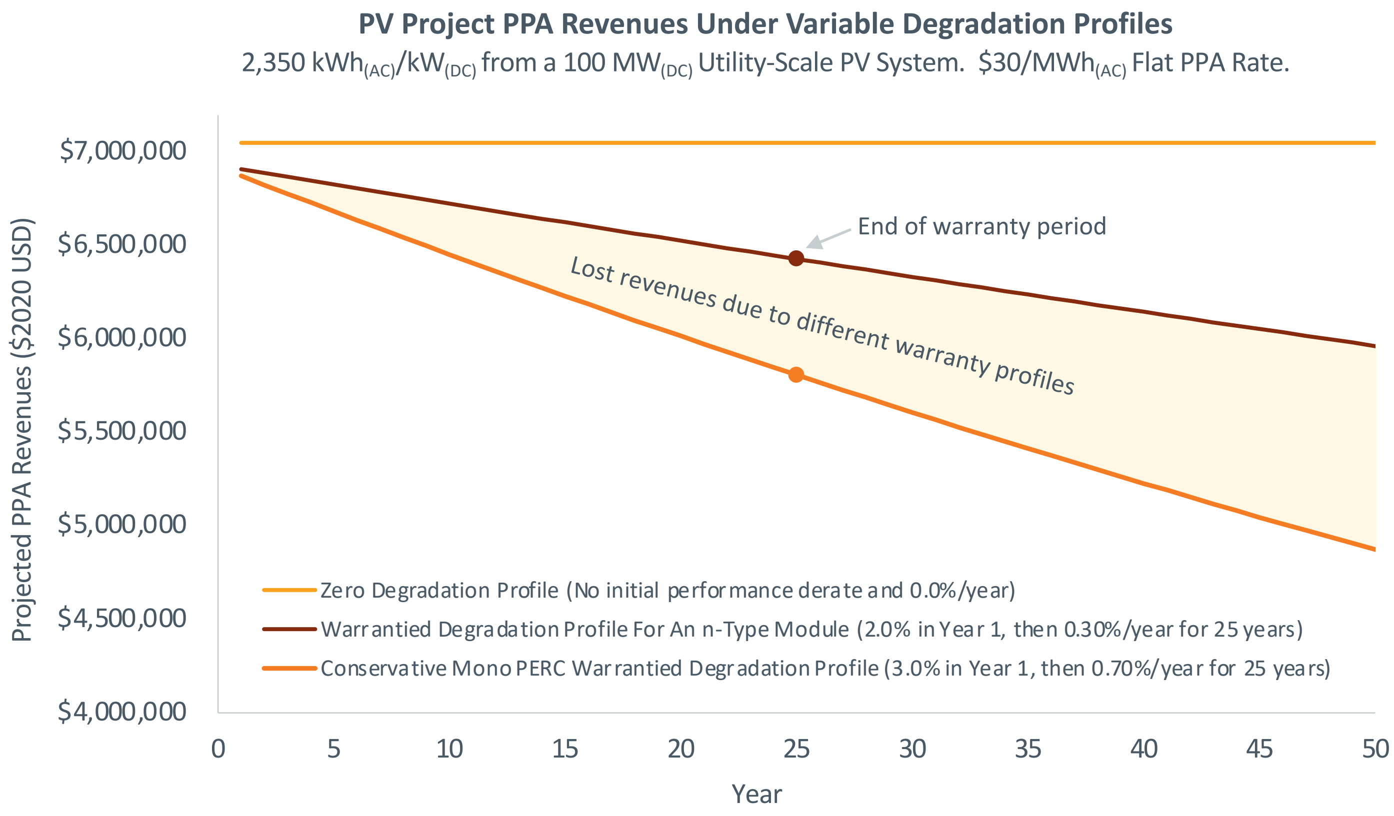
***Based on: Photovoltaic Degradation Rates — An Analytical Review**
Dirk C. Jordan and Sarah R. Kurtz

Degradation Profiles Used for the Project Cash Flow Model



In SAM, degradation profiles are applied against first-year $kWh_{(AC)}/kW_{(DC)}$ energy yield.

Project PPA Revenues for the Different Warranty Profiles

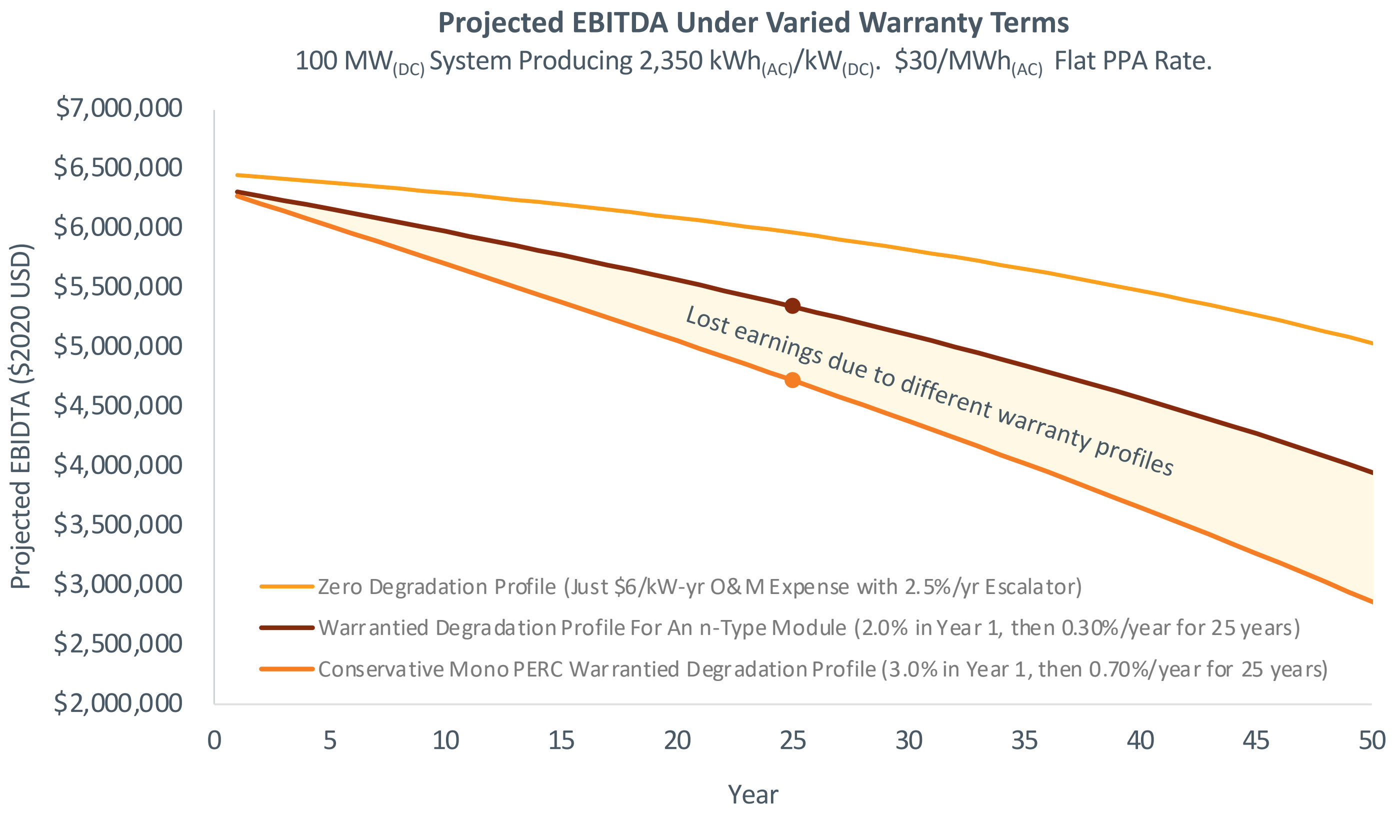


In SAM, degradation profiles are applied against first-year $kWh_{(AC)}/kW_{(DC)}$ energy yield.

Project PPA revenues ($):

- $\$/kWh_{(AC)}$ (or $\$/MWh_{(AC)}$) PPA rate *times*
- $kWh_{(AC)}/kW_{(DC)}$ energy yield *times*
- System size (DC)

Project EBITDA for the Different Warranty Profiles



In SAM, PV Project Earnings Before Interest, Taxes, Depreciation, and Amortization (EBITDA)

EBITDA = PPA Revenues – Operations and Maintenance (O&M) expenses

Impacts and Breakeven Analysis for the Warranty Profiles

Impact Upon 1H 2020 Baseline U.S. Utility Scale PV Projects After-tax with 5-Year MACRS and 26% ITC (2020 qualification). 30-Year analysis period. $0.95/$W_{(DC)}$ Capital Cost, $6/$kW_{(DC)}$-yr direct O&M expense, and 2,350 $kWh_{(AC)}/kW_{(DC)}$ nameplate energy yield.	
Assume the *n*-type warranty profile for the PV project—instead of the conservative mono PERC warranty profile	Increase project IRR by 93 basis points (bps) ($30/$MWh_{(AC)}$ Levelized PPA Rate) Lower LCOE by $1.3/$MWh_{(AC)}$ (6.0% nominal discount rate)
Assume the *n*-type warranty profile carries an associated premium above the conservative mono PERC warranty profile (for example, a higher module price or an insurance product)	Breakeven net present value equivalent to $0.05—0.06/$W_{(DC)}$

But what about module failures?

Module “failures” can be unpredictable and could impact PV project cash flows to a greater degree than simple degradation rate assumptions.

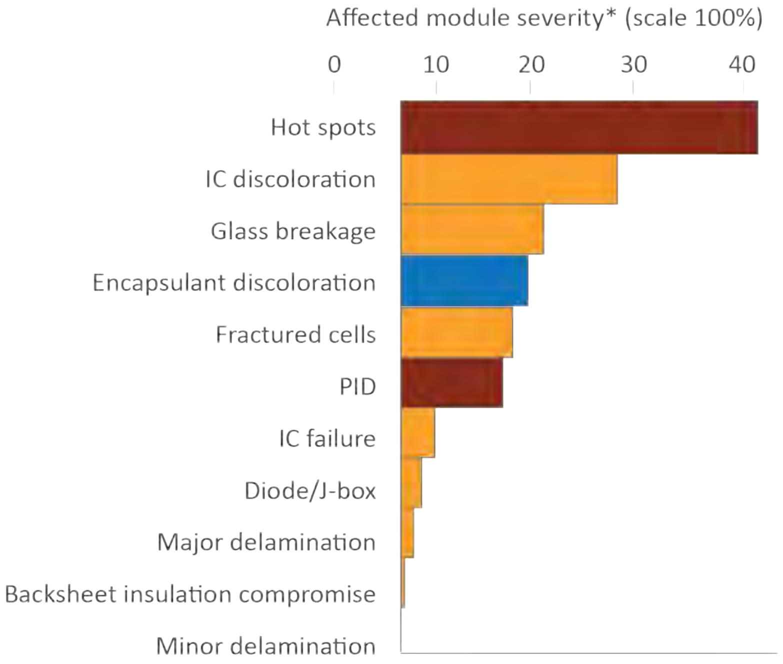


Figure source: D Jordan, T J Silverman, J H Wohlgemuth, S R Kurtz, and K T vanSant “Photovoltaic failure and degradation modes”, PIP, 2017.

Problem Statement: Conceptual Project Cash Flows Considering Varied Degradation and Failure Rates

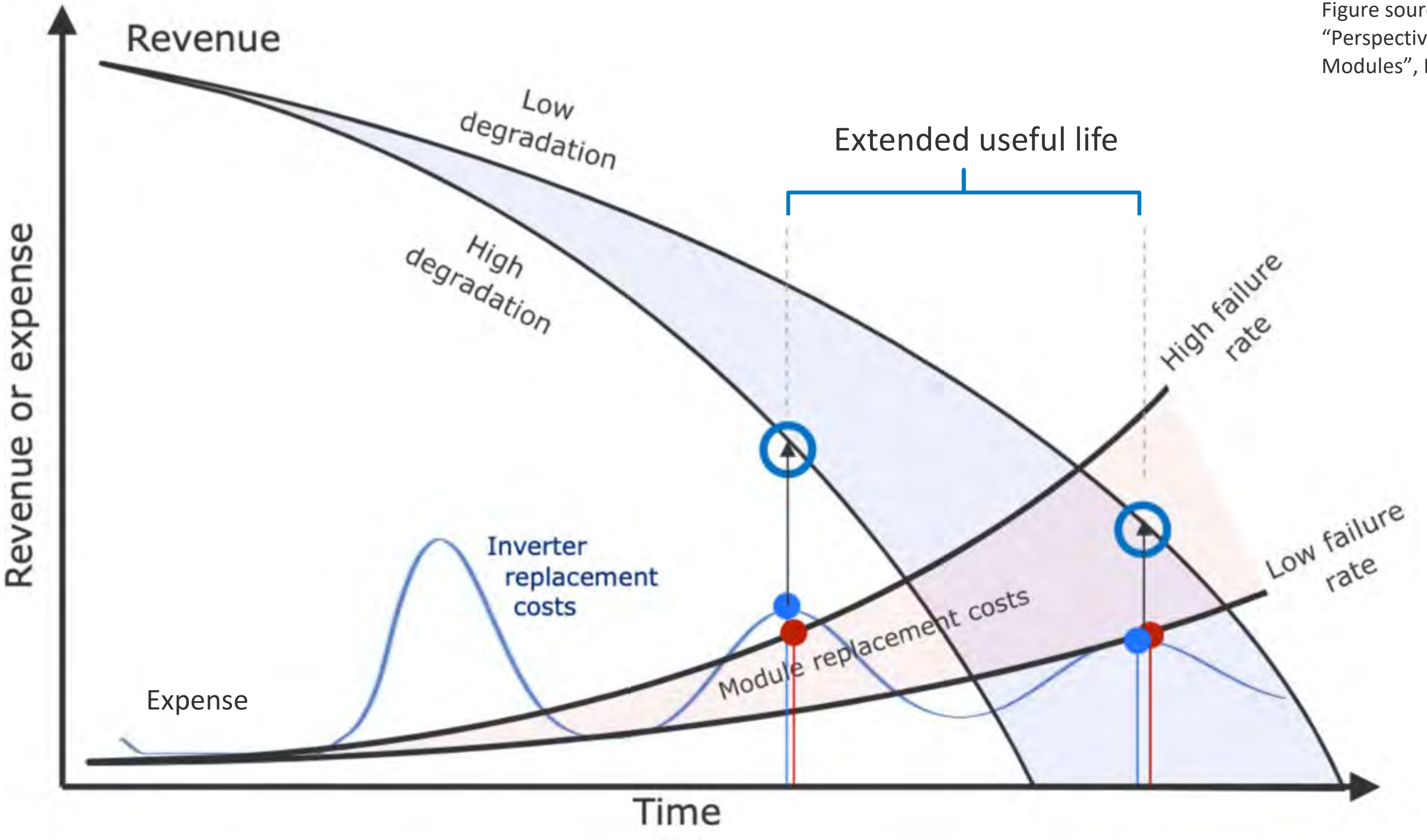


Figure source: Henry Hieslmair "Perspectives on the Useful Life of Modules", Presentation at the 2020 PVRW

What about module failures?

Finding: Module "failures" can be unpredictable and may significantly impact PV project cash flows.

Analytical challenge: Relative to simple degradation profiles, consideration of module failures significantly complicates the PV project cash flow analysis.

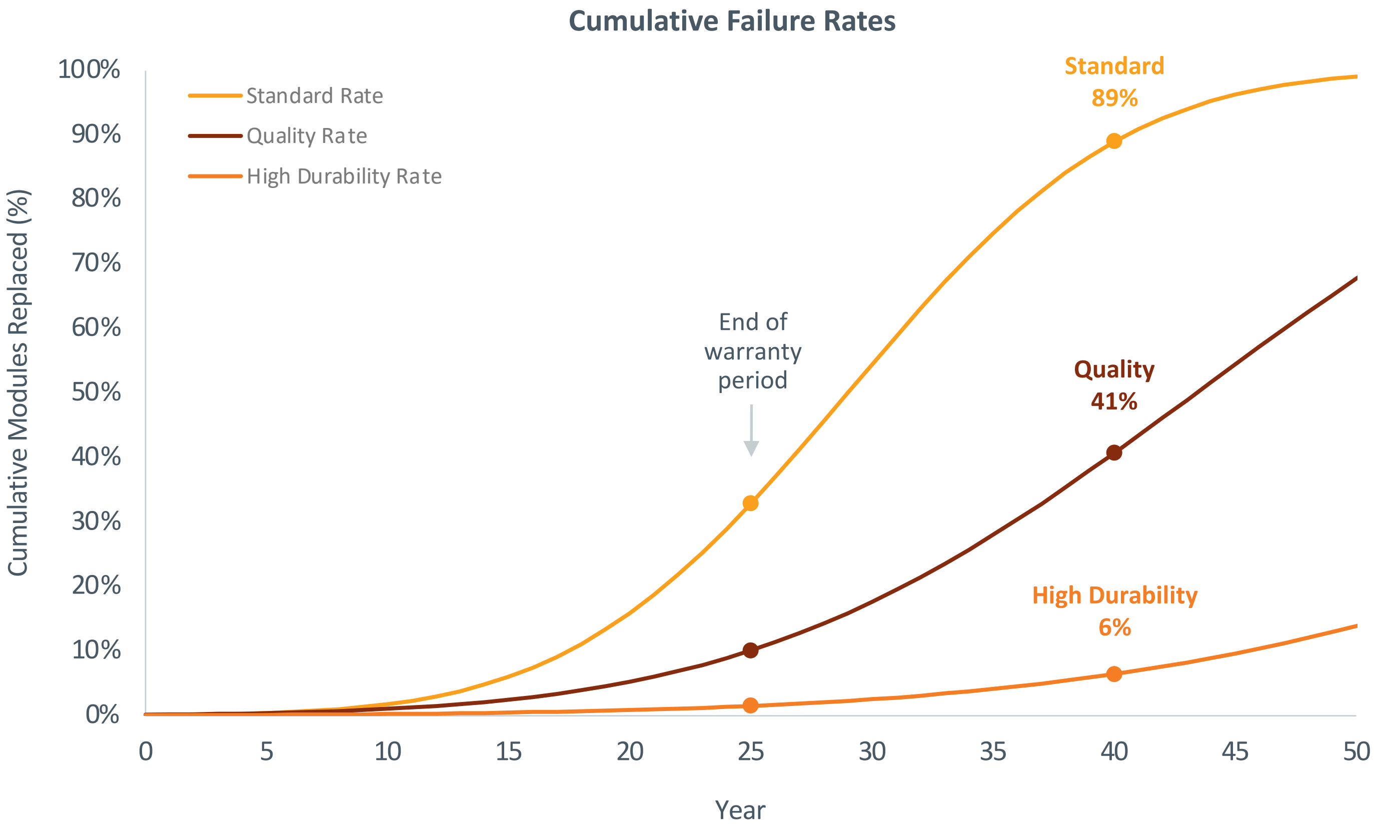
One must first qualify a module "failure" that may necessitate replacement:

- Determine the acceptable amounts of module-level power losses. Energy yield models suggest losses due to cracked cells, for example.
- Consider string level power losses and the net impacts to system-wide $kWh_{(AC)}$ power production. One failed module pulls down the entire string, which can consist of 12—18 modules.

Versus:

- Module replacement costs, which are a function at least three factors:
  1. Current and projected module pricing and size. Replacement modules may or may not be covered by warranty, and how about variability in module efficiency and sizes going forward?
  2. Direct labor time and expense. Is a truck roll required? How many modules can be replaced per unit time?
  3. System engineering and overhead (e.g., monitoring and engineering module replacements and procurement, as well as potential warranty enforcement costs)

Cumulative Module Replacements for the Different Degradation Profiles

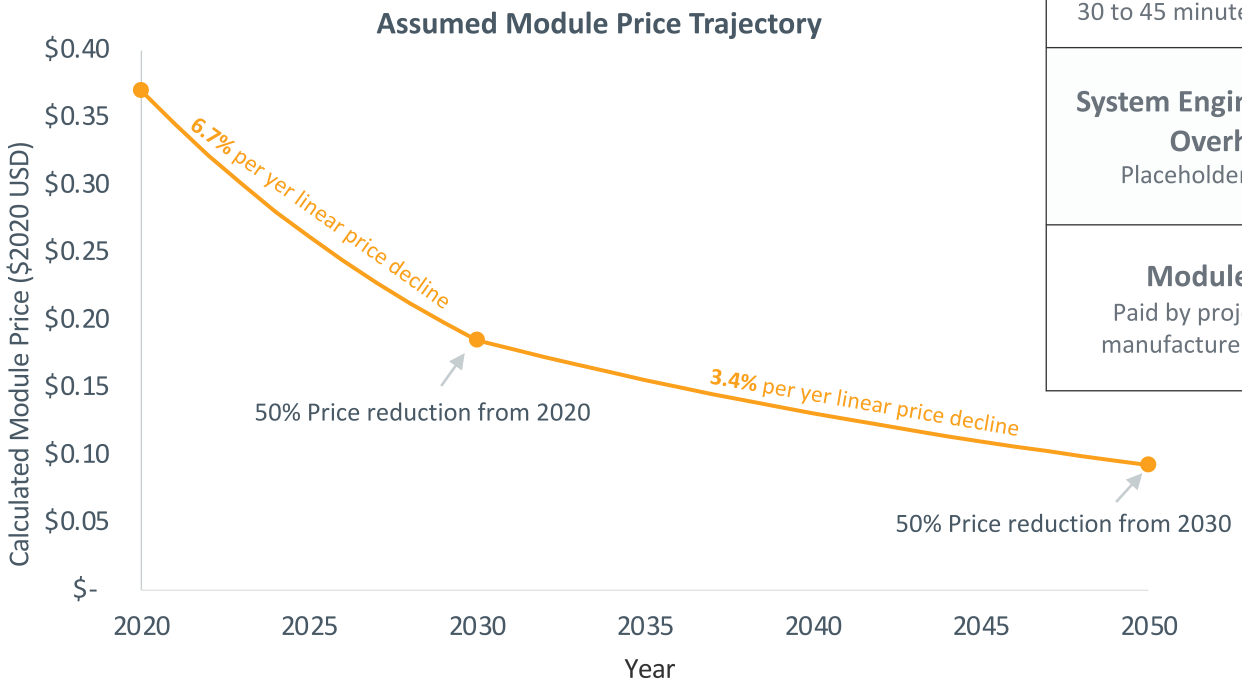


Module failures can impact project cash flows to a greater degree than degradation alone.

Additional factors to consider:

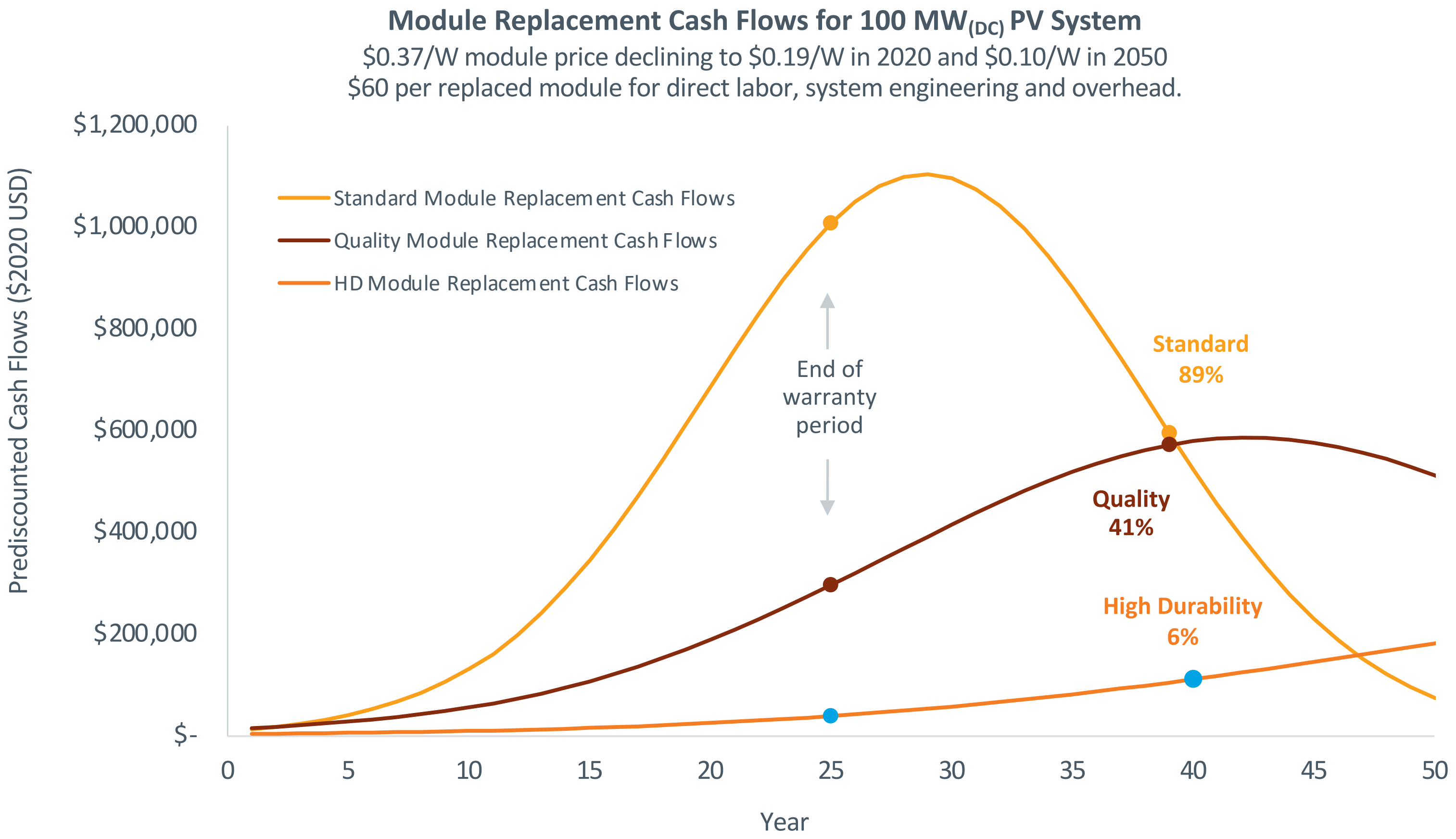
1. Warranty terms and enforcement (if applicable)
2. Downtime. String-level power losses significantly impact energy yield.
3. Pre-purchase modules vs projecting future module pricing (and efficiency and size)

Factors That Affect Cash Outflows for Module Replacements



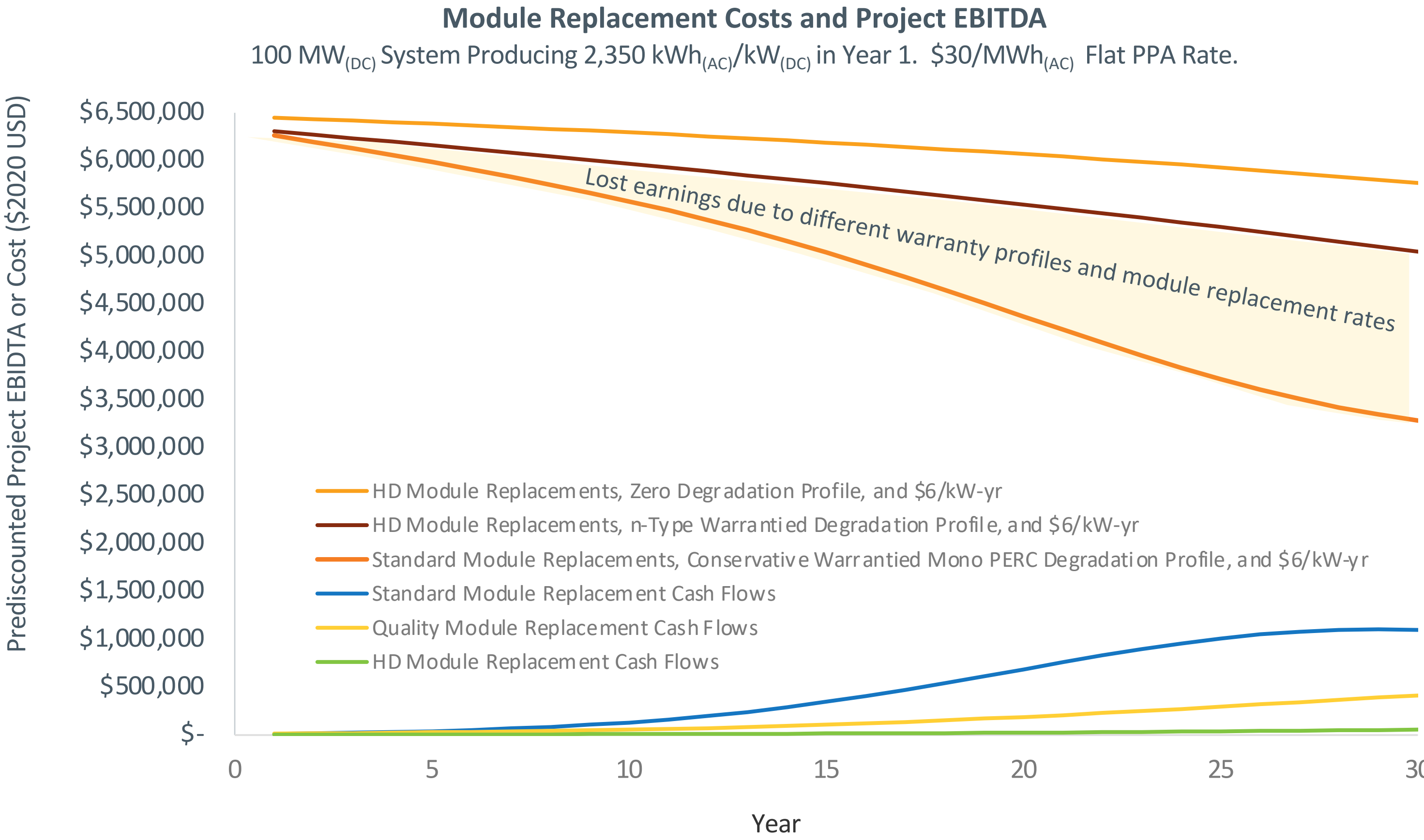
Direct Labor 2 laborers at $25 to $35/hr burdened rates 30 to 45 minutes per module	$25—50 per module replaced =$0.05—0.15/W of replacements using 350 W to 450 W module power ratings
System Engineering and Overhead Placeholder Estimate	$18—28 per module replaced =$0.04—0.08/W of replacements using 350 W to 450 W module power ratings
Module Price Paid by project owner, manufacturer, or insurer	See chart

PRELIMINARY Module Replacement Cash Flows



Note: The pre-discounted cash flows shown in these scenarios do not include replacements of replacements. 30-year analysis periods are used in subsequent analyses.

PRELIMINARY Project EBITDA Calculations for the Different Degradation and Failure Profiles



In SAM, PV Project Earnings Before Interest, Taxes, Depreciation, and Amortization (EBITDA)

EBITDA = PPA Revenues − Operations and Maintenance (O&M) expenses

DRAFT analysis completed June 3, 2020

Impacts Analysis for the Warranty and Failure Profiles

Impact Upon 1H 2020 Baseline U.S. Utility Scale PV Projects After-tax with 5-Year MACRS and 26% ITC (2020 qualification). 30-Year analysis period. $0.95/W$_{(DC)}$ Capital Cost, $6/kW$_{(DC)}$-yr direct O&M expense, and 2,350 kWh$_{(AC)}$/kW$_{(DC)}$ nameplate energy yield.	
Assume the *n*-type warranty profile for the PV project and the high durability module replacement costs—instead of the conservative mono PERC warranty profile and standard module replacement costs	Increase project IRR and lower LCOE
Assume the *n*-type warranty profile carries an associated premium above the conservative mono PERC warranty profile (for example, a higher module price or an insurance product)	Increase breakeven net present value

Review of the major causes of module failures

Module “failures” can be unpredictable and may impact PV project cash flows to a greater degree than simple degradation rate assumptions

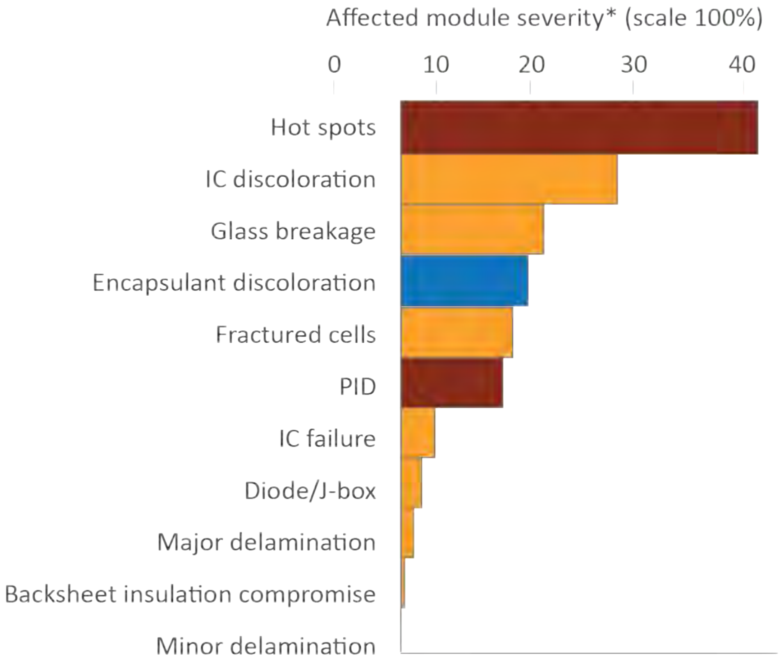


Figure source: D Jordan, T J Silverman, J H Wohlgemuth, S R Kurtz, and K T vanSant “Photovoltaic failure and degradation modes”, PIP, 2017.

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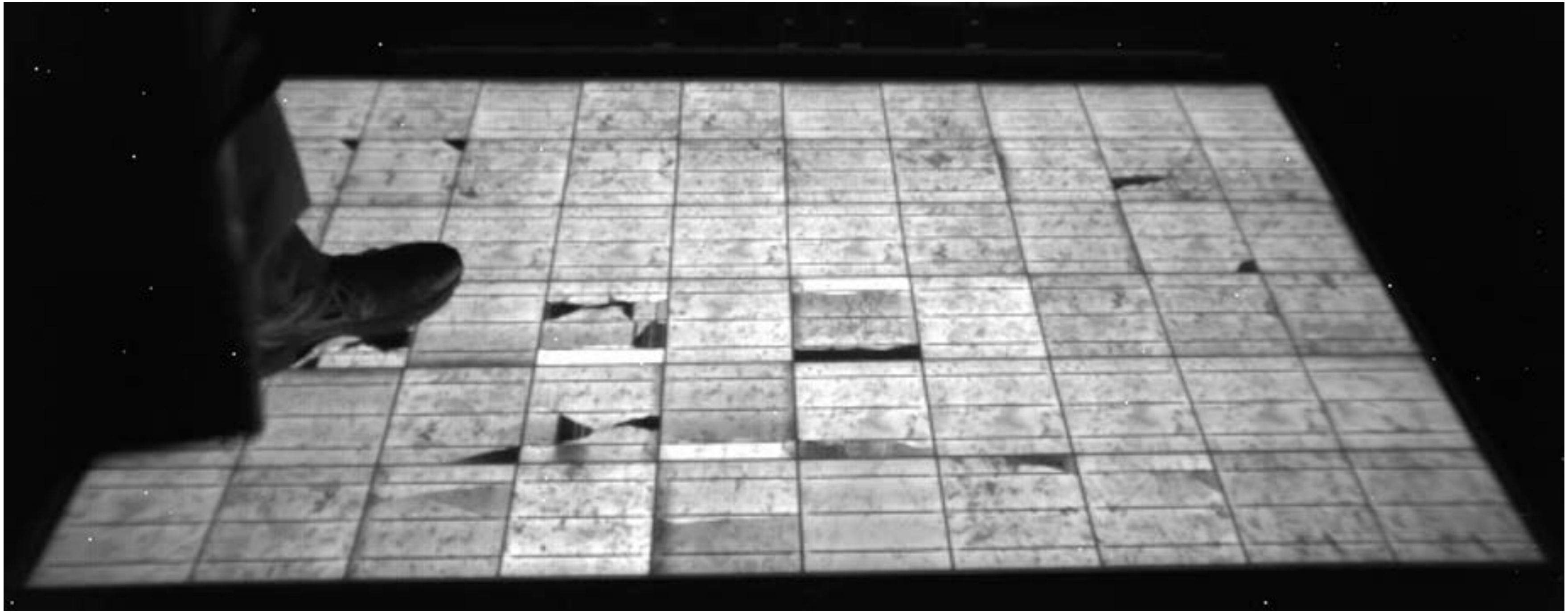
Cell Cracks – What Can Happen?



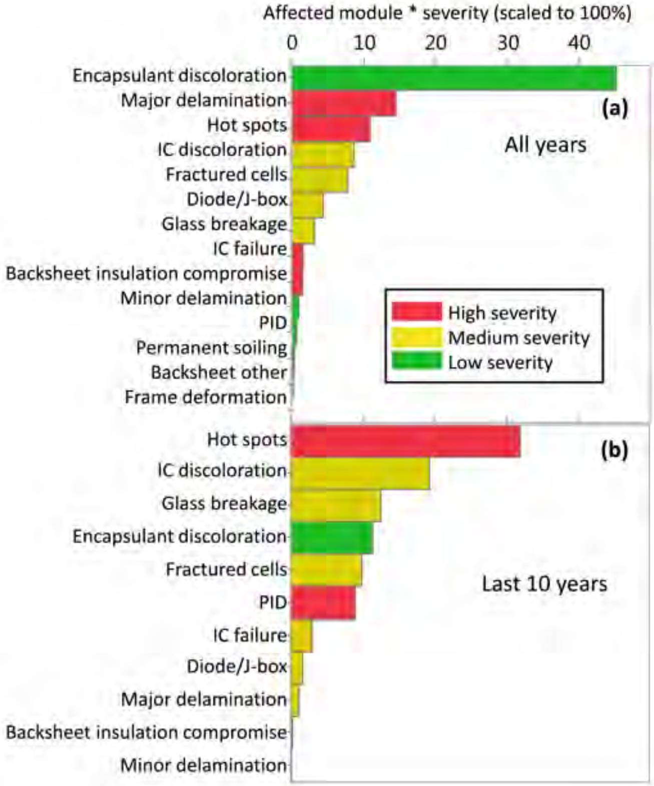
Electroluminescence video by T. Silverman, https://www.youtube.com/watch?v=-qdyxIybmoc (2017).

500 mm

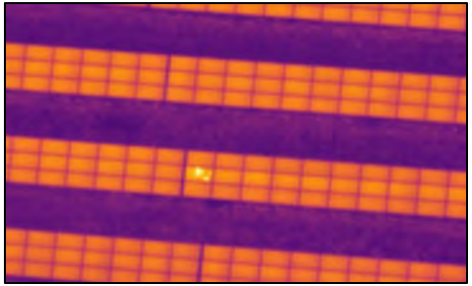
The module continues working even after major cell breakage, but… cracks eventually lead to power loss over time.


This could happen to you!

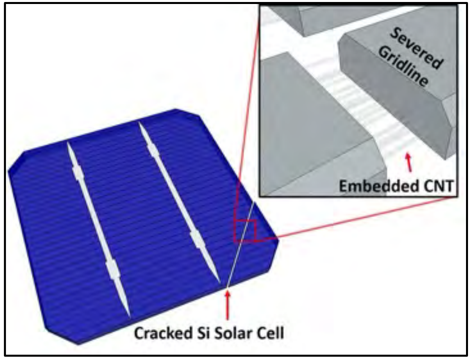
DEGRADATION DUE TO HOT SPOTS AND CELL CRACKS IN TERRESTRIAL PV CELLS



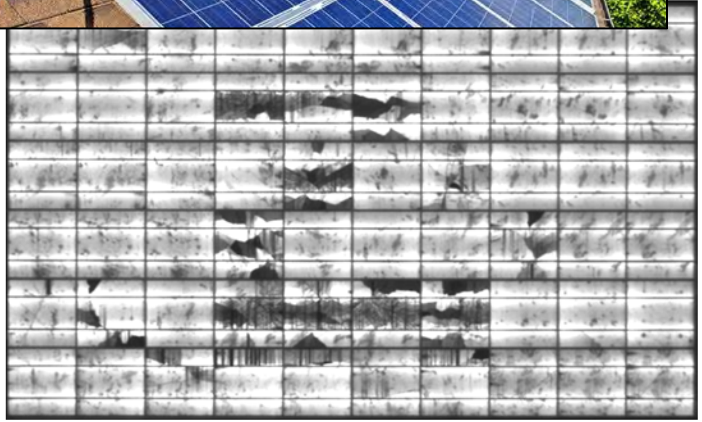
Jordan *et al.*, *Prog. Photovolt. Res. Appl.* **25**, 318-326 (2017).



R. Andrews, 2018 NREL PV Reliability Workshop, Lakewood, CO (2018).



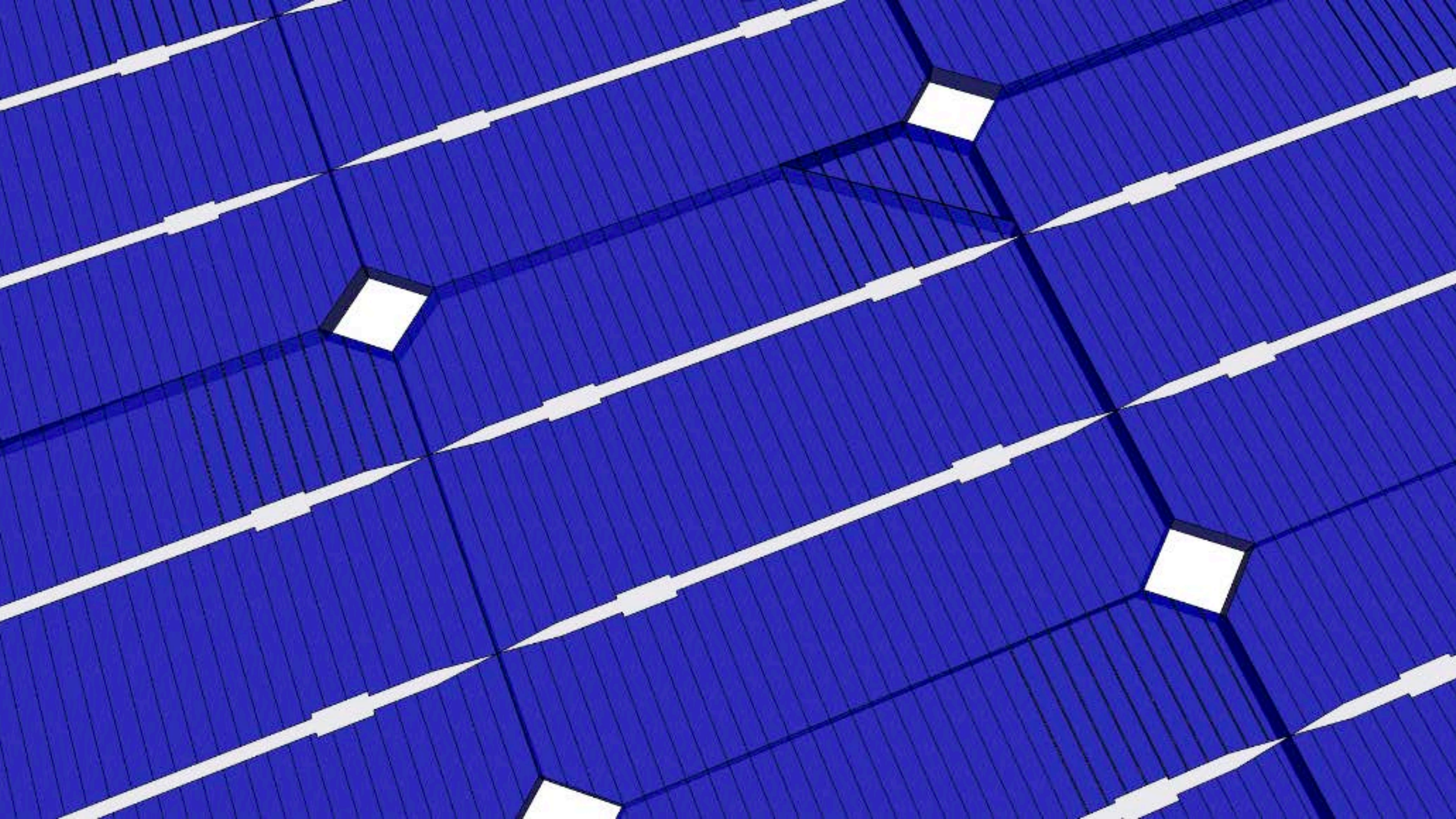
http://energyinformative.org/best-solar-panel-monocrystalline-polycrystalline-thin-film/

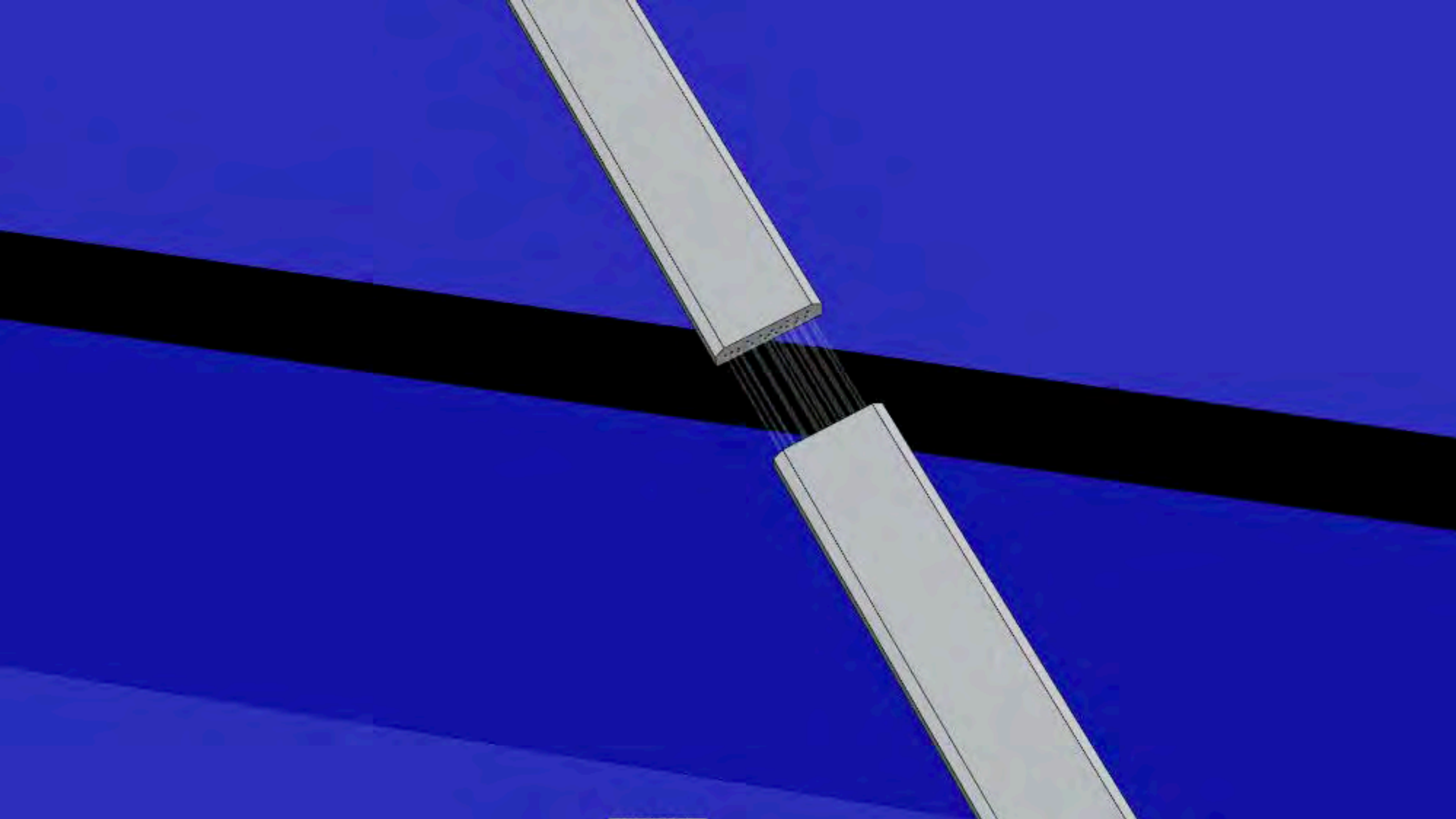


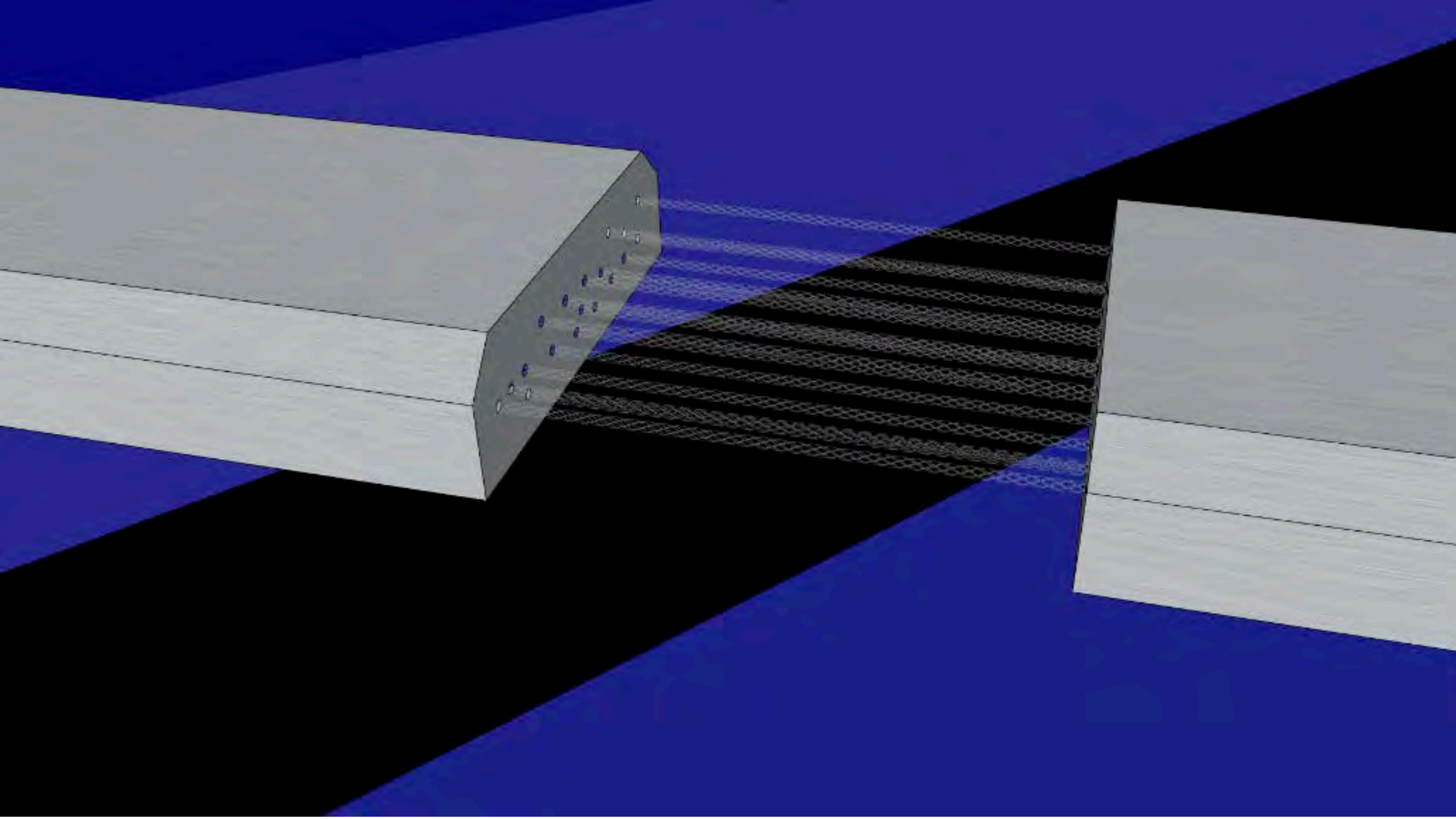
Könges *et al.*, 26th EU PVSEC, 3290-3294 (2011).

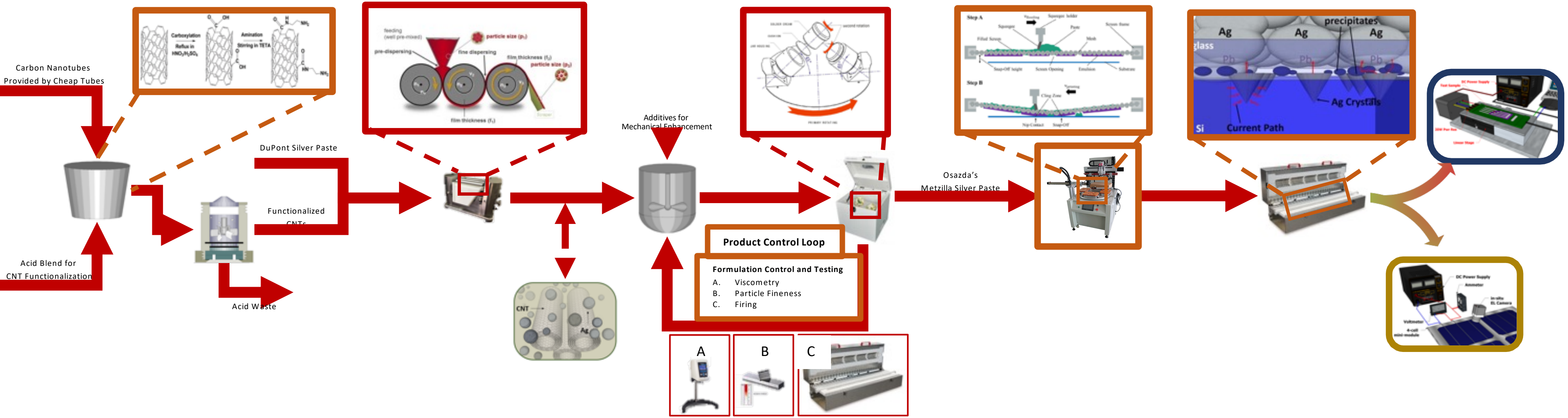
✓ Solder bond failures and cracked cells are suspect for hot spots.[1]

[1]Jordan *et al.*, *Prog. Photovolt. Res. Appl.* and **25**, 318-326 (2017) and **25**, 583-591 (2017).









osazda
ENERGY

Multi-Walled Carbon Nanotube (MWNT) Functionalization

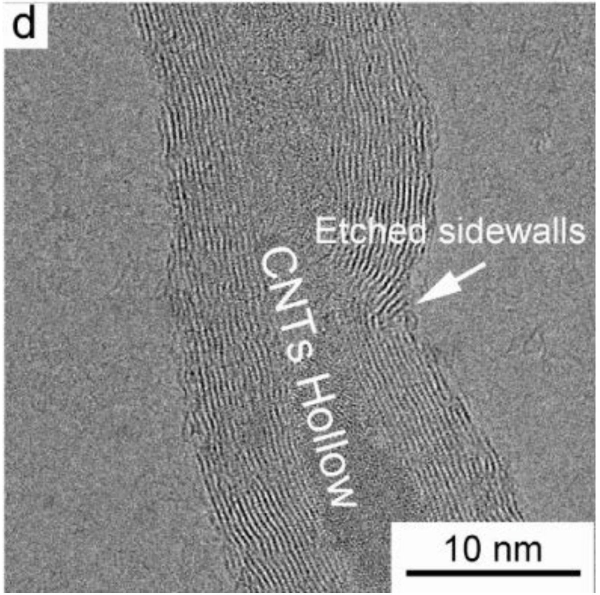


Figure 1: HRTEM image of etched sidewalls from HNO3 H2SO4 treatment, From: “Enhanced Mechanical Properties of Aluminum Based Composites Reinforced by Chemically Oxidized Carbon Nanotubes” by Guo, B., Zhang, X., Cen, X., Chen, B., Wang, X., Song, M., Ni, S., Yi, J., Shen, T., Du, Y., 2018, Reprinted with Permission

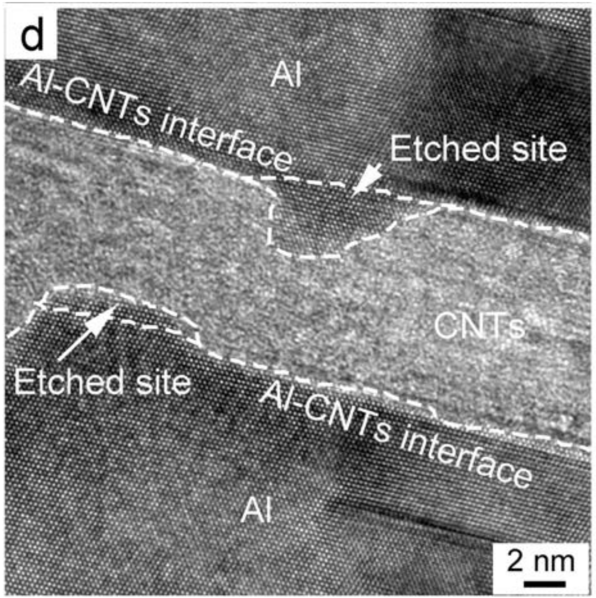


Figure 2: HRTEM image of etched sidewalls from HNO3 H2SO4 treatment, now combined with aluminum, From: “Enhanced Mechanical Properties of Aluminum Based Composites Reinforced by Chemically Oxidized Carbon Nanotubes” by Guo, B., Zhang, X., Cen, X., Chen, B., Wang, X., Song, M., Ni, S., Yi, J., Shen, T., Du, Y., 2018, Reprinted with Permission

Balancing Load Transfer and Fragmentation

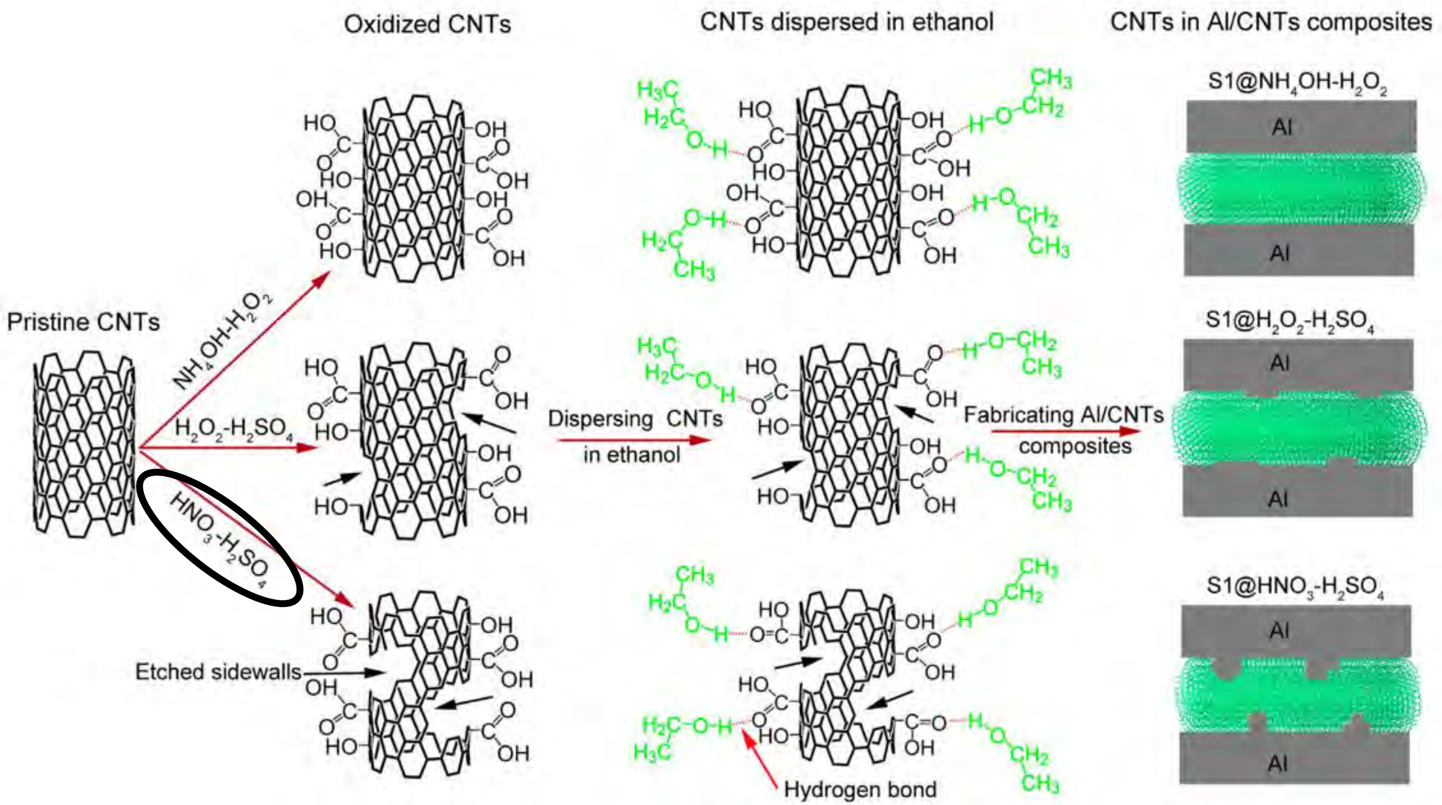
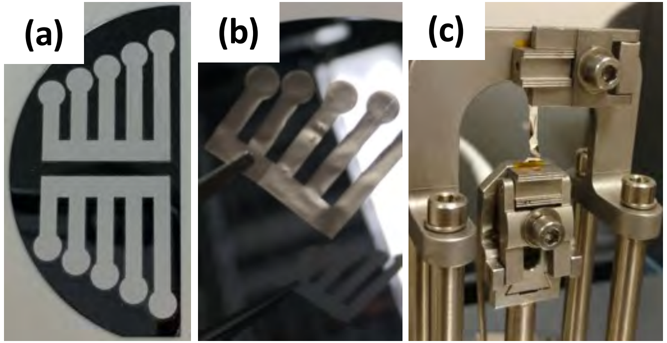


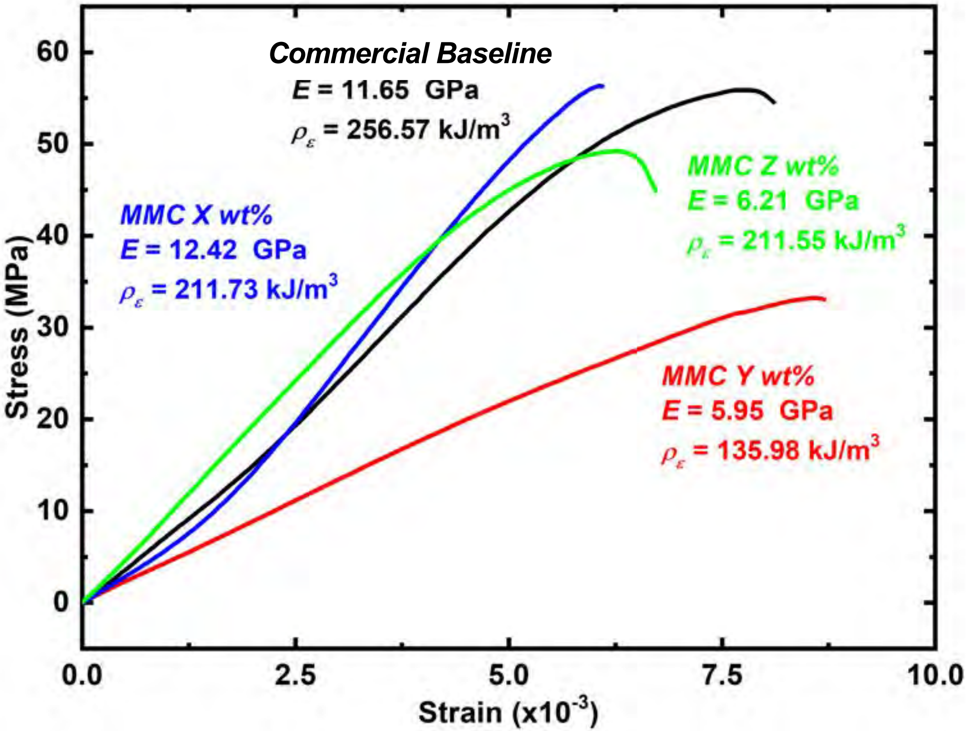
Figure 3: Displaying various mechanisms for functionalizing carbon nanotubes and the resulting features, From: “Enhanced Mechanical Properties of Aluminum Based Composites Reinforced by Chemically Oxidized Carbon Nanotubes” by Guo, B., Zhang, X., Cen, X., Chen, B., Wang, X., Song, M., Ni, S., Yi, J., Shen, T., Du, Y., 2018, Reprinted with Permission

Dynamic Mechanical Analysis (UNM)

(a) (b) (c)



(d)



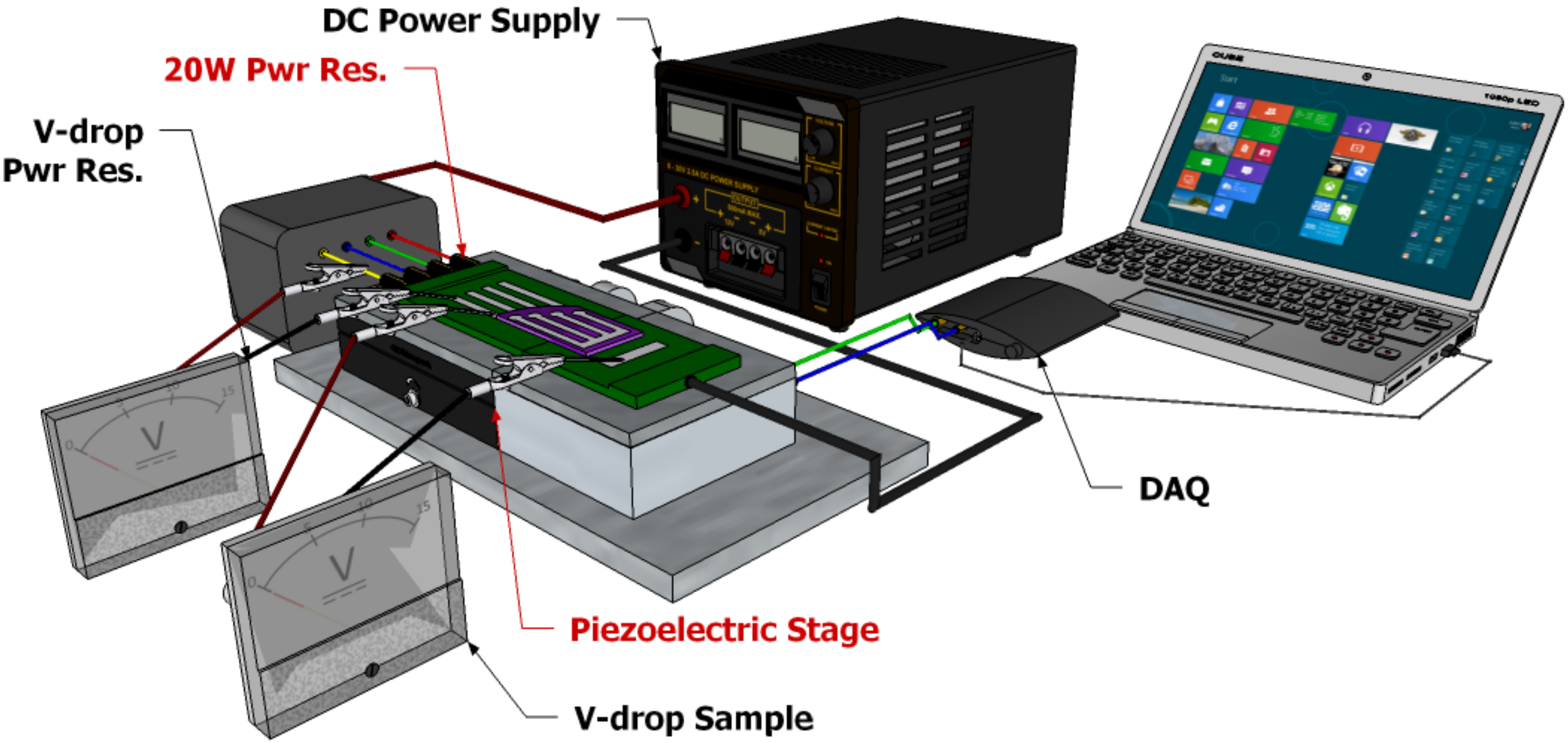
MetZilla™ for Al-BSF cells –

- 4% decrease in elastic modulus
- 16% increase in modulus of toughness
- Increase in ductility

MetZilla™ for PERC cells – in progress

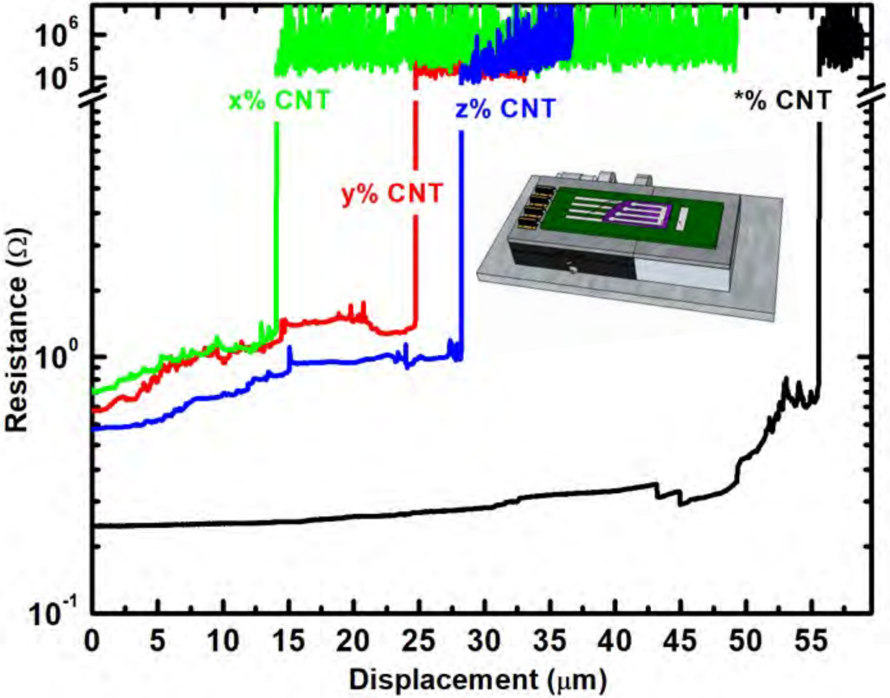
- Elastic modulus control is possible
- Ductility control is possible
- CNT wt% optimization is needed to Increase modulus of toughness

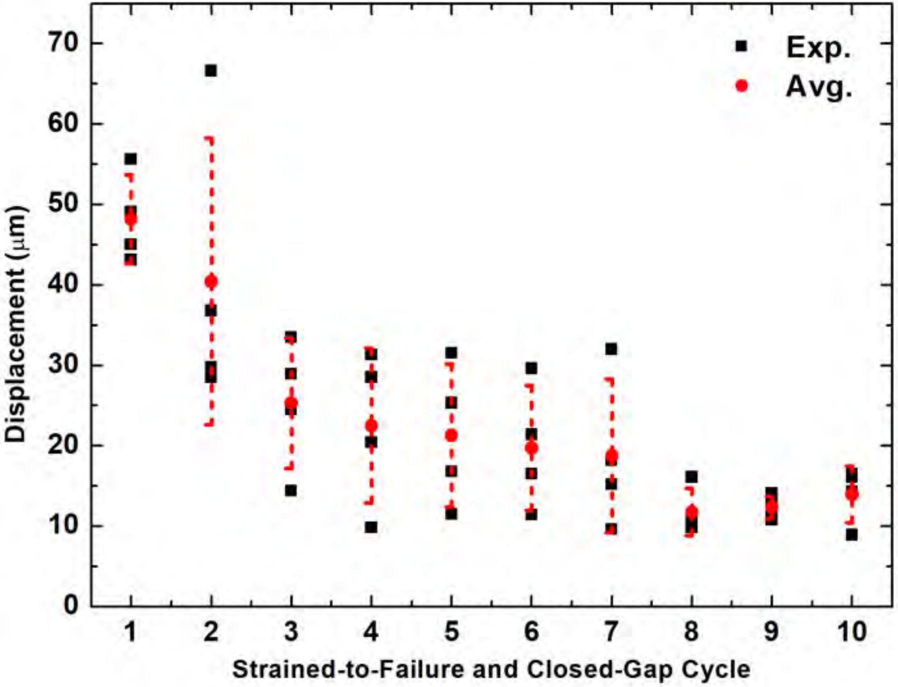
RACK (RESISTANCE ACROSS CLEAVES & CRACKS) MEASUREMENTS



RACK (RESISTANCE ACROSS CLEAVES & CRACKS) – GAP BRIDGING & SELF-HEALING

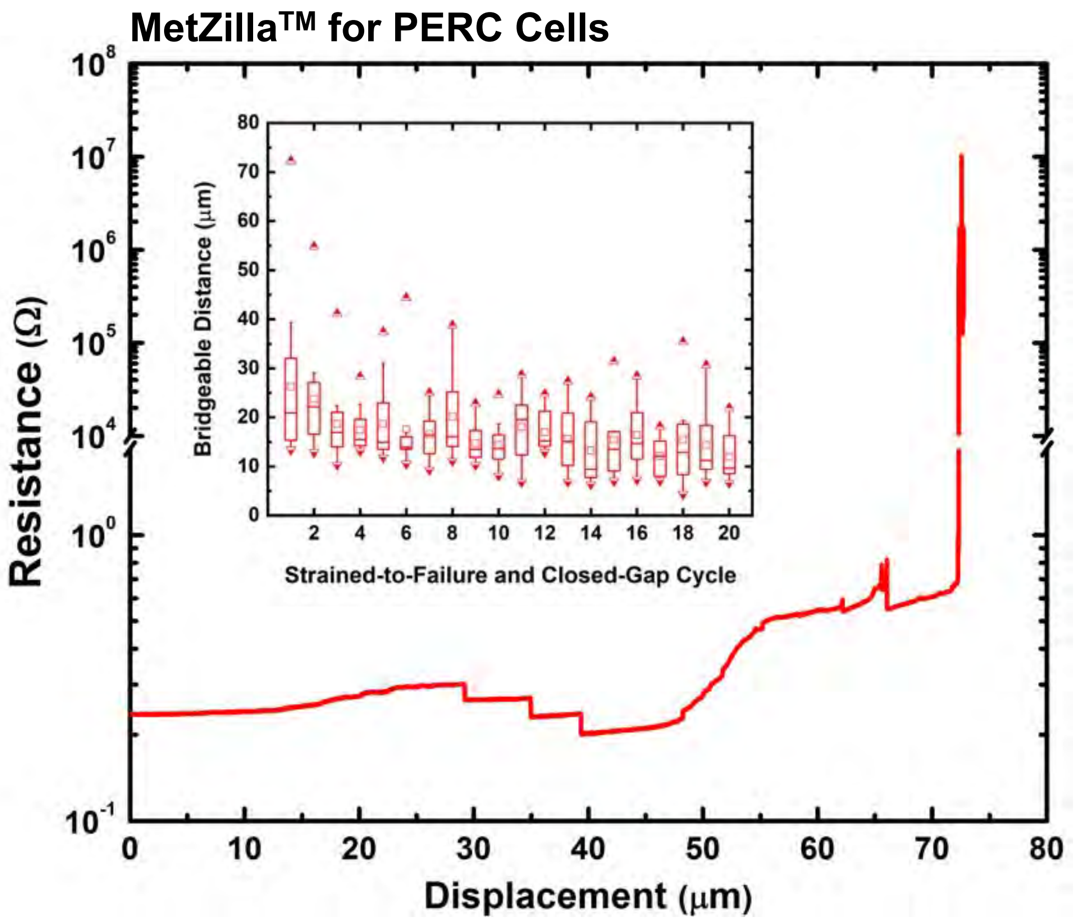
MetZilla™ for Al-BSF Cells





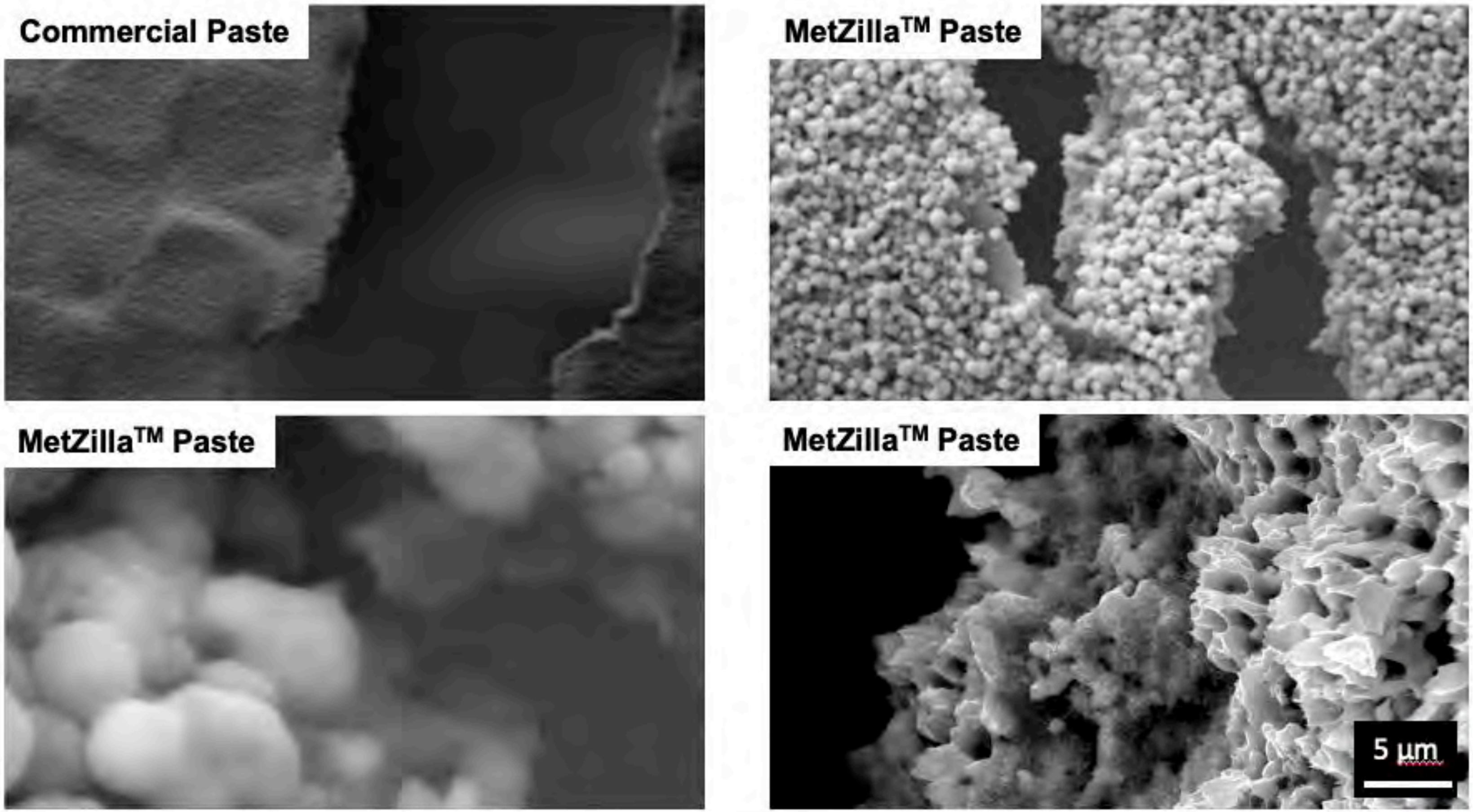
- >50 μm maximum bridgeable gap with optimum CNT loading
- "Self-healing" to bridge ~20 μm gaps repeatably

RACK (RESISTANCE ACROSS CLEAVES & CRACKS) – GAP BRIDGING & SELF-HEALING

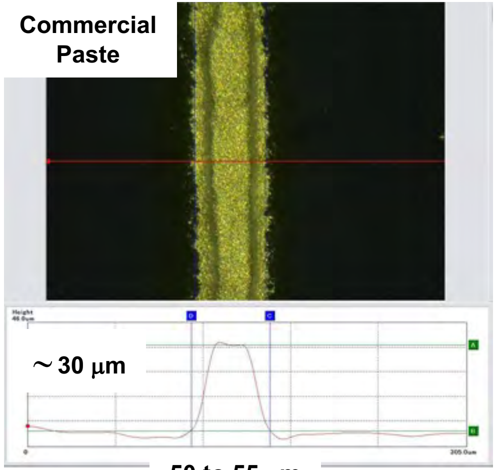


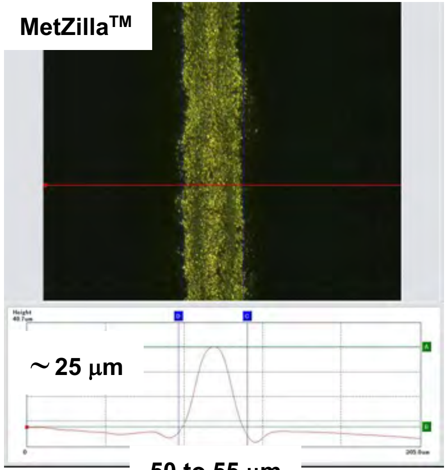
- **20 to 30 μm** average gap and **>70 μm** maximum bridgeable gap
- "Self-healing" to bridge ~10 to 20 μm gaps repeatably
- CNT wt% and firing schedule optimization needed

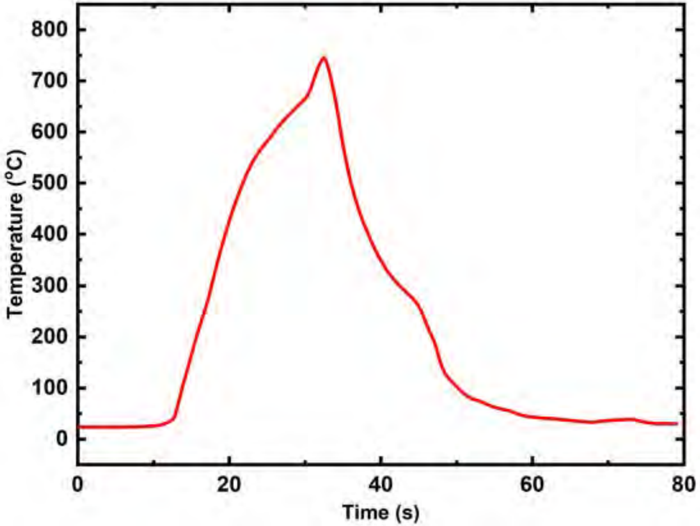
In Situ Scanning Electron Microscopy During Strain Test (CINT)



Screen Printing and Firing (Georgia Tech)



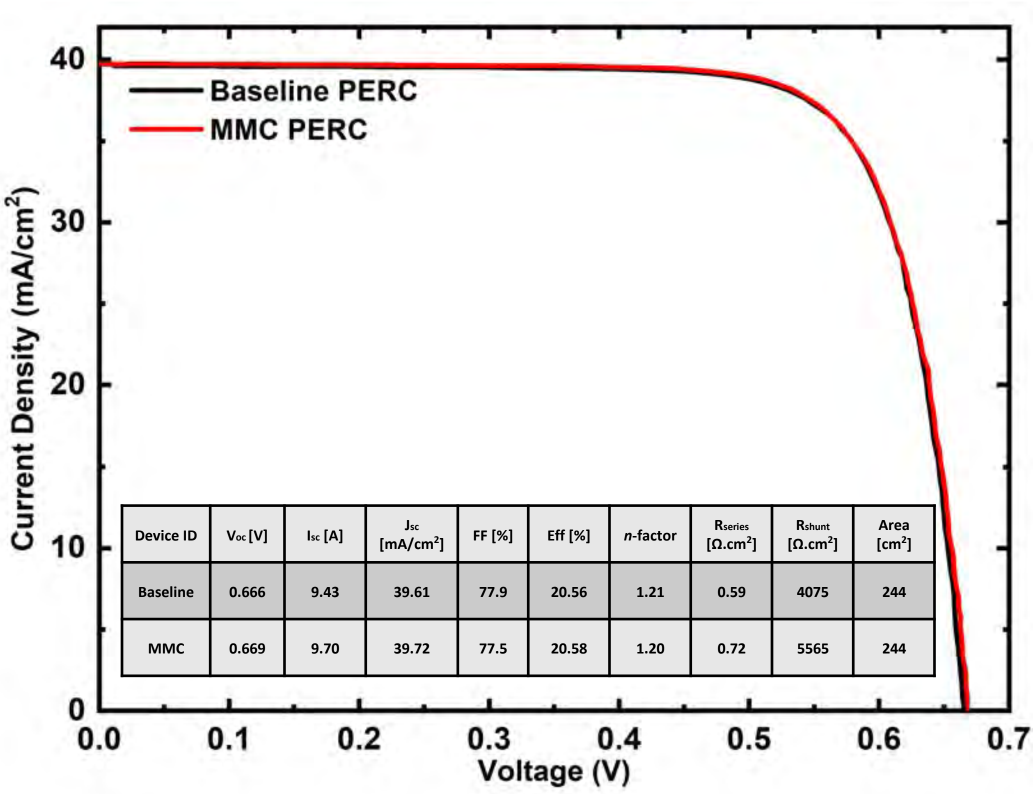




	R_c ($\Omega.cm^2$)	$R_{bus\text{-}to\text{-}bus}$ ($\Omega.cm^2$)	Laydown Weight Wet (g)	Laydown Weight Dry (g)
Commercial Paste	7.800	0.041	0.161	0.130
MetZilla™ Paste	8.700	0.056	0.151	0.115 – 0.125

- Plug-in solution to a standard industrial process
- Line uniformity, laydown weight, contact and bus-to-bus resistance need improvement

CELL PERFORMANCE – SILVER PASTE MMC



Device ID	V_{oc} [V]	I_{sc} [A]	J_{sc} [mA/cm^2]	FF [%]	Eff [%]	*n*-factor	R_{series} [Ω.cm^2]	R_{shunt} [Ω.cm^2]	Area [cm^2]
Baseline	0.666	9.43	39.61	77.9	20.56	1.21	0.59	4075	244
MMC	0.669	9.70	39.72	77.5	20.58	1.20	0.72	5565	244

✓ Similar cell performance with CNT incorporation

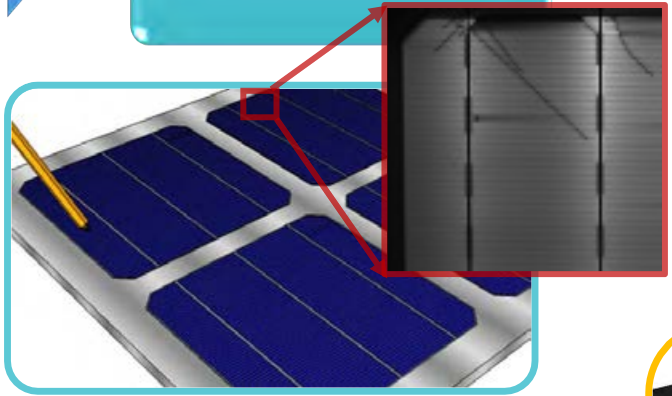
Description on Module Testing

Module Construction

- Physical layout
- Ribbon tabbing
- Bottom encapsulant

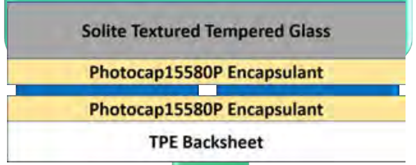
Initial Defects

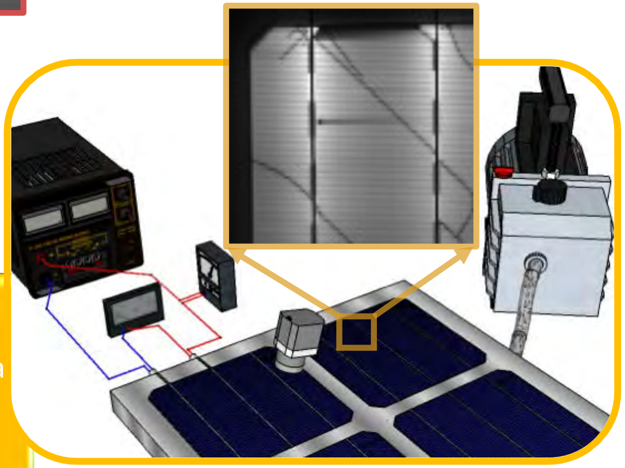
- Diamond scribe used to manually introduce cracks



Module Construction

- Top encapsulant
- Sample lamination



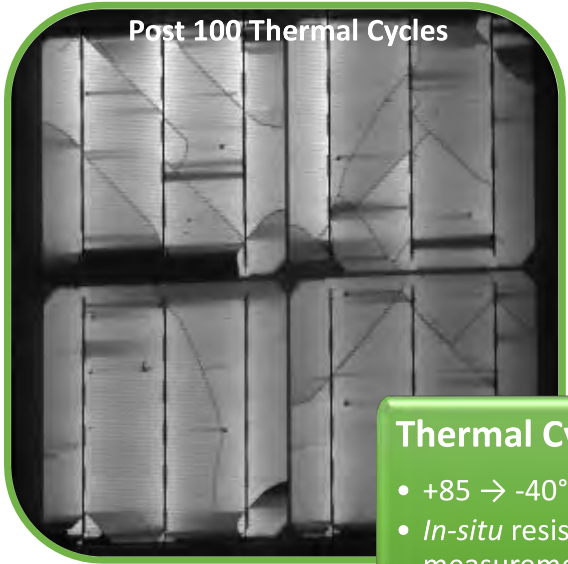


Vacuum Cracking

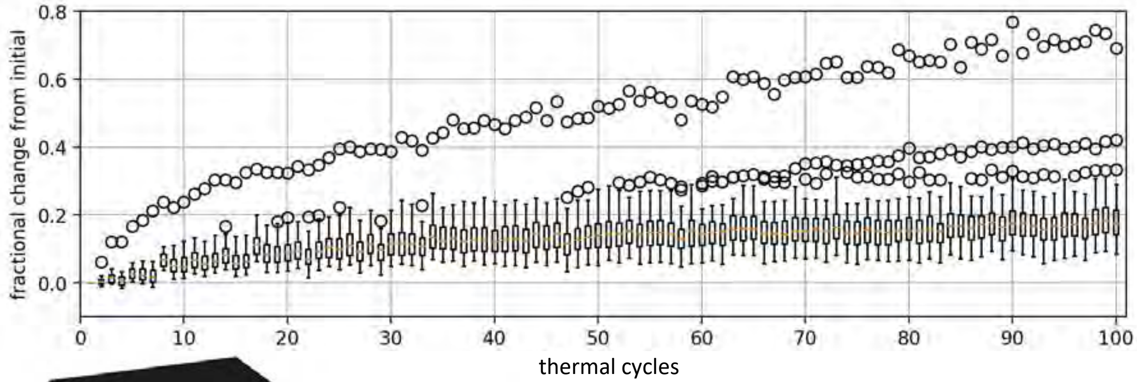
- Vacuum applied 0 – 15 kPa
- EL and resistance measurements post-crack

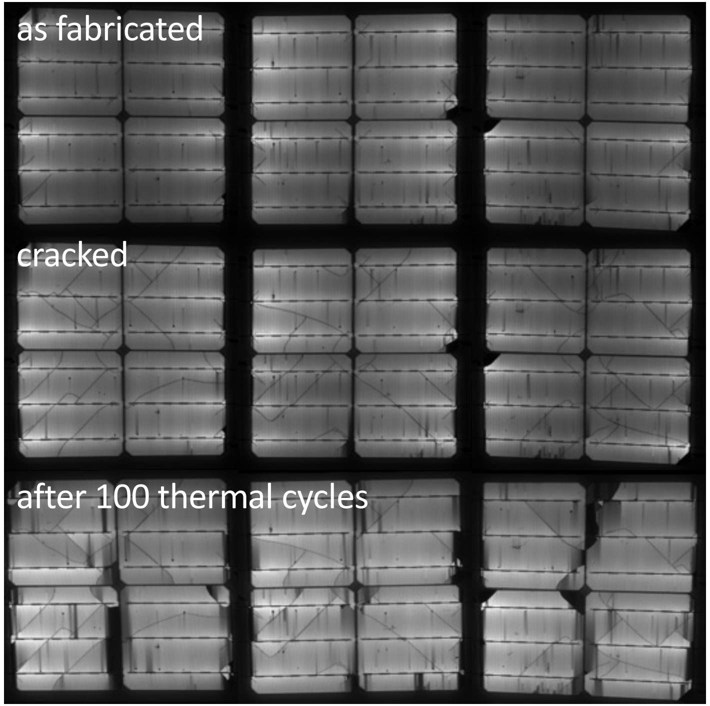
Thermal Cycling

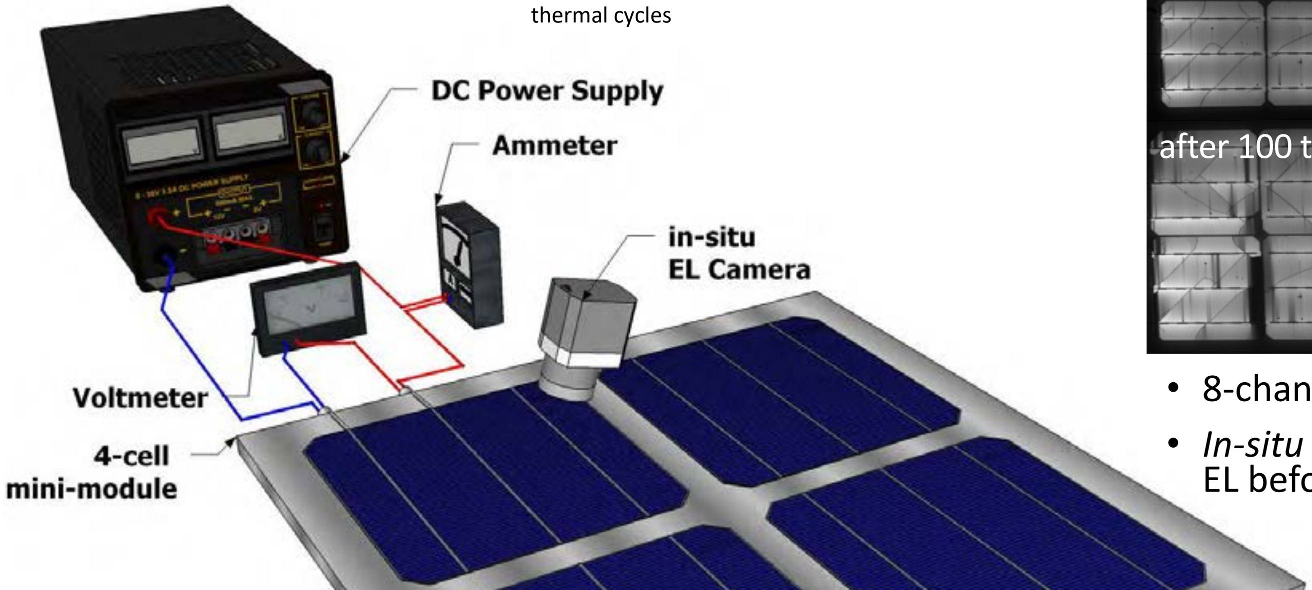
- +85 → -40°C
- *In-situ* resistance measurements



Baseline Module Testing

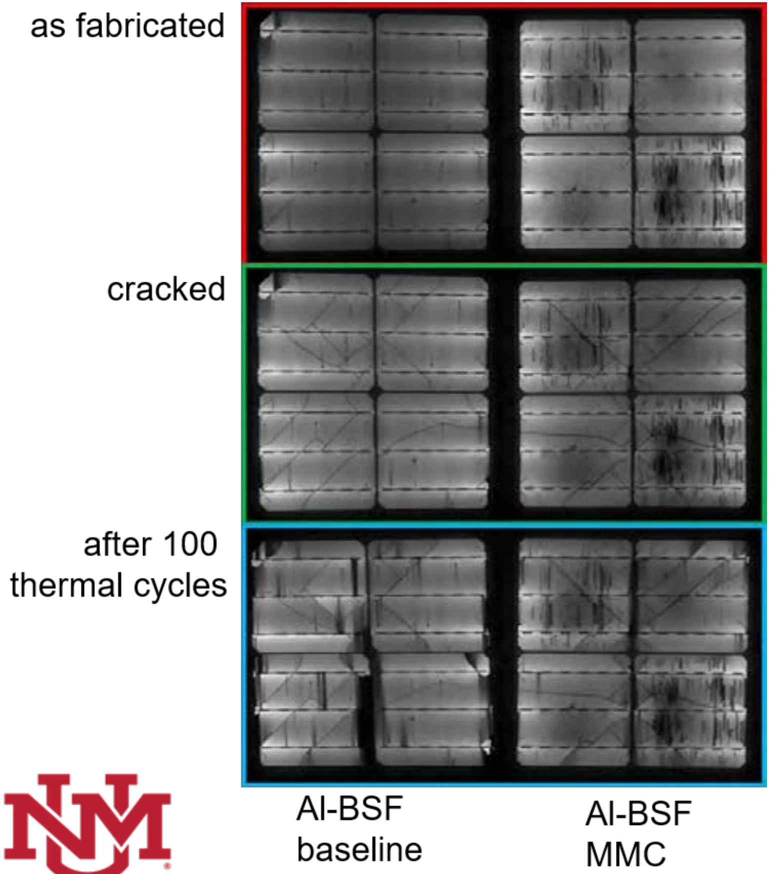


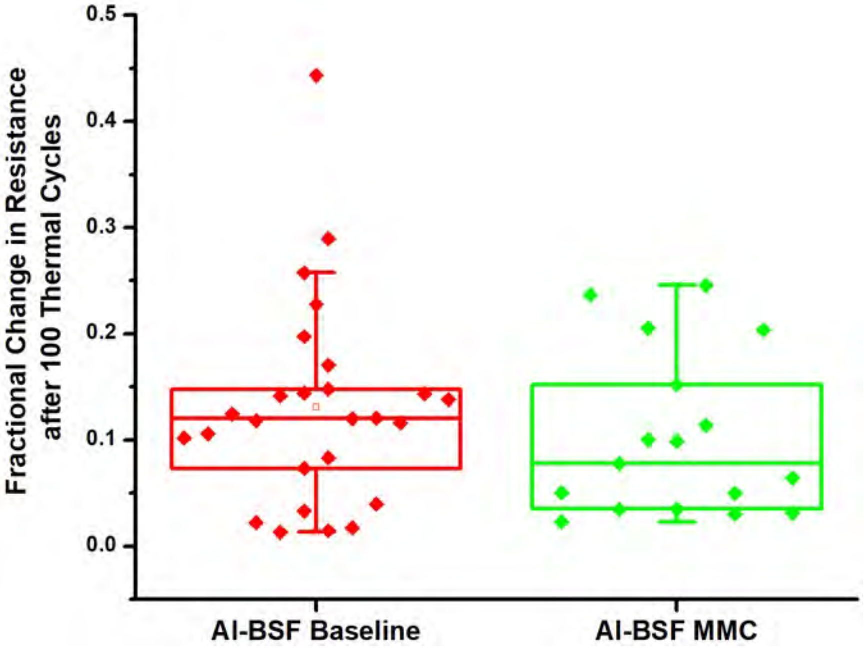




- 8-channels measurement per module
- *In-situ* resistance measurements and EL before and after thermal cycling

Module Integration – Accelerated Testing



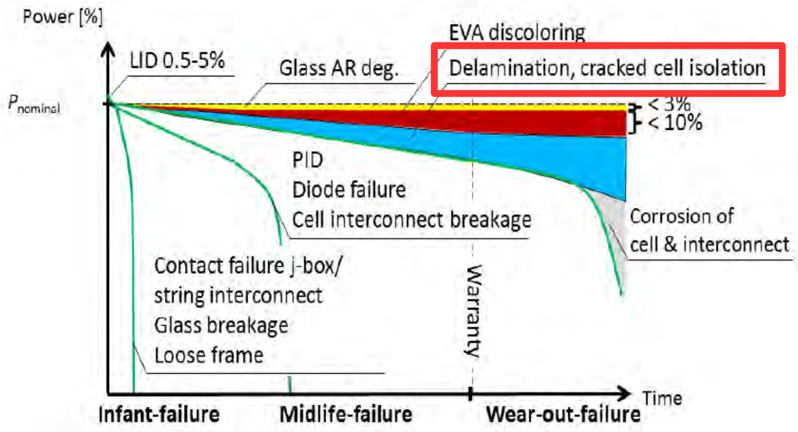


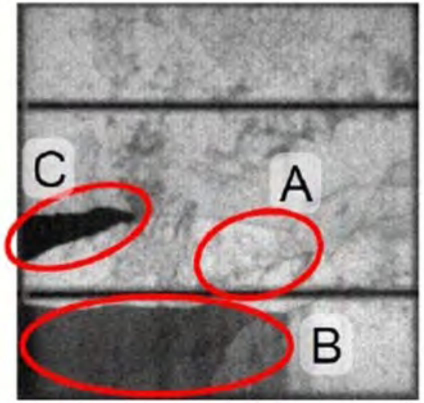
- Commercial Ag paste as baseline
- MMC shows slower degradation
- Future testing with PERC

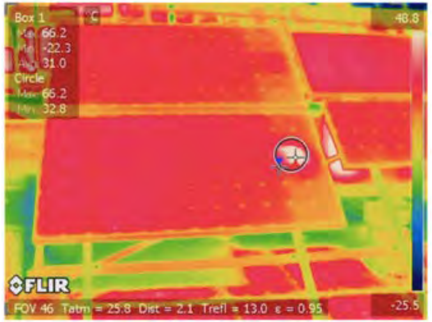
Conclusions

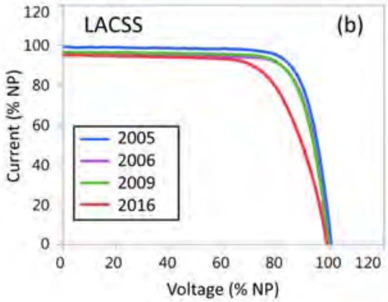
- Fracture toughness increases with CNT incorporation.
- MMC-enhanced metallization can provide > **50 µm** gap bridging capability.
- "Self-healing" occurs when the fractured composite gridlines are brought together.
- "Self-healing" is repeatable and settles at **10 to 20 µm**.
- Beginning-of-life cell performance is approximately the same with and without the MetZilla™ integration.
- MetZilla™-enhanced Al-BSF modules degrade at a slower rate compared to baseline modules.
- Accelerated testing will be conducted on PERC mini-modules.

Terrestrial Solar degradation Trends









Cell cracks leading to current loss and contributing to hot spots is the primary degradation problem.

Presentation Outline

- Introduction (Teresa Barnes, DuraMAT Director, 5 minutes)
- Problem Statement by Henry Hieslmair, DNV GL (10 minutes)
- Impacts to a Portfolio of PV Projects (Mike, 15 minutes)
- Overview of the Osazda Energy Solution to Cell Cracking (Sang, 10 minutes)
- **Quantified Value Proposition of Reducing Cell Cracking (Mike, 10 minutes)**
- Conclusions, Next Steps, and Questions (Everyone, 10 minutes)

How Do Cracked Cells Occur?

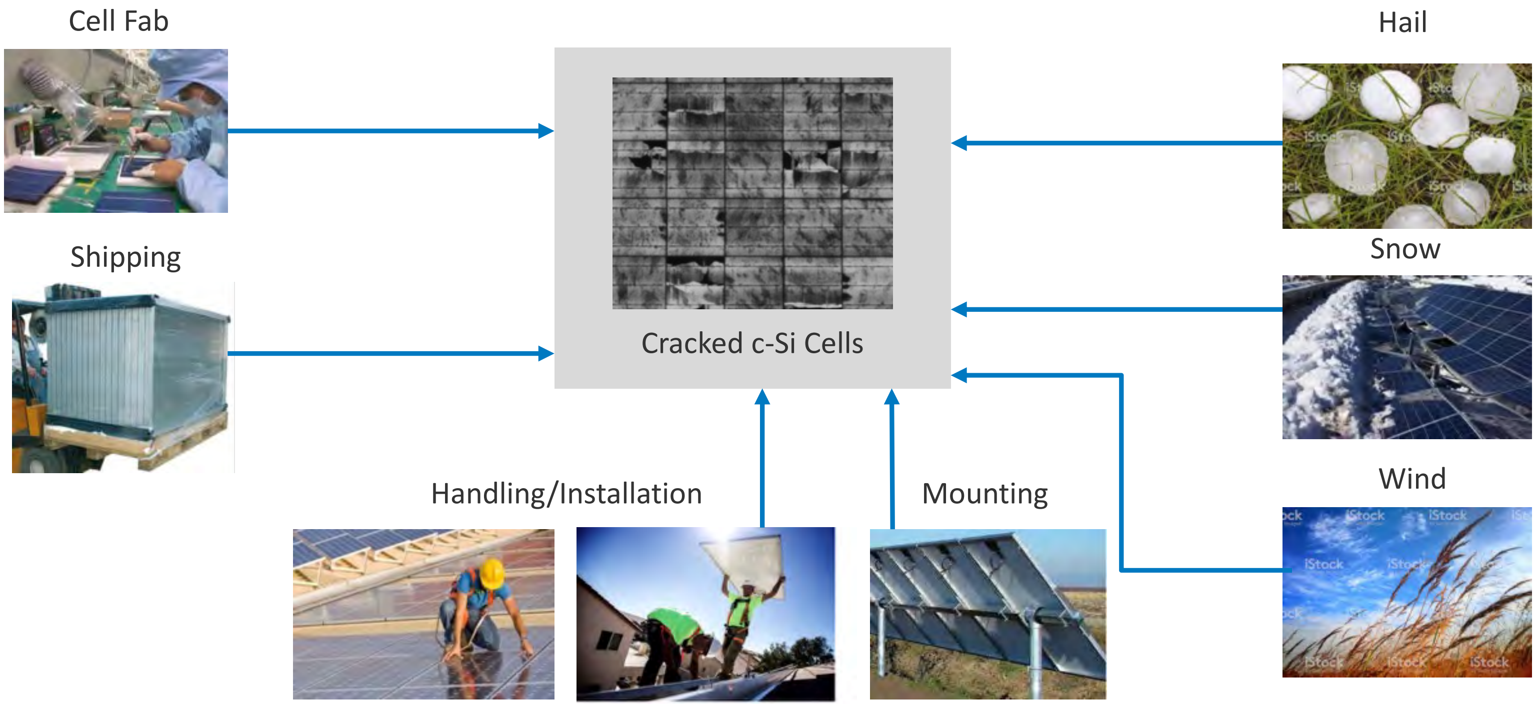


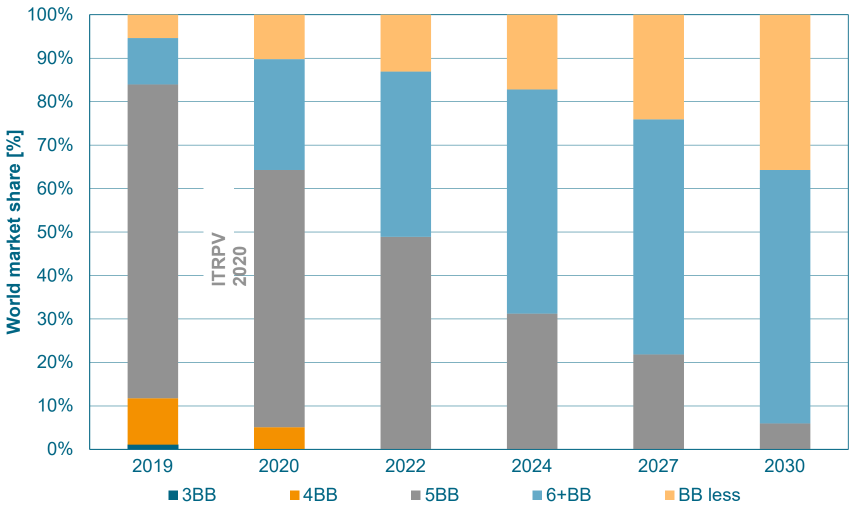
Image sources: A Gabor et al, PVRW 2017. Conceptual layout: L Trippel "Quantifying the Impacts of Cell Cracking in the Field" Webinar with PV Magazine

Technology Trends—Moving in the Right Direction

Lower Crack Risk

- Glass/Glass—no tensile stress
- Multiwire and Smartwire Connection Technologies—smaller disconnected areas
- Conductive adhesive (some shingled)—fewer microcracks
- Parallel wiring—cells less likely to enter reverse bias
- Better packaging
- More electroluminescence (EL) quality control testing—at the factory, as well as pre-installation and prior to commissioning

Busbar Technology

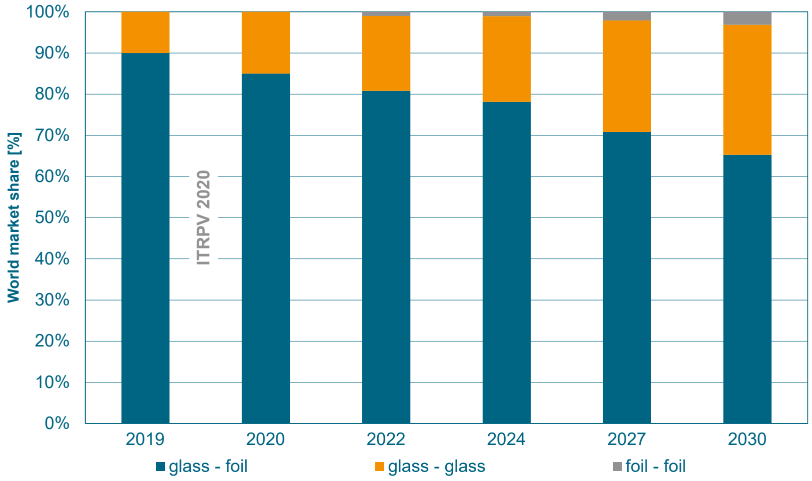


Technology projections from the 2020 ITRPV (https://itrpv.vdma.org/)

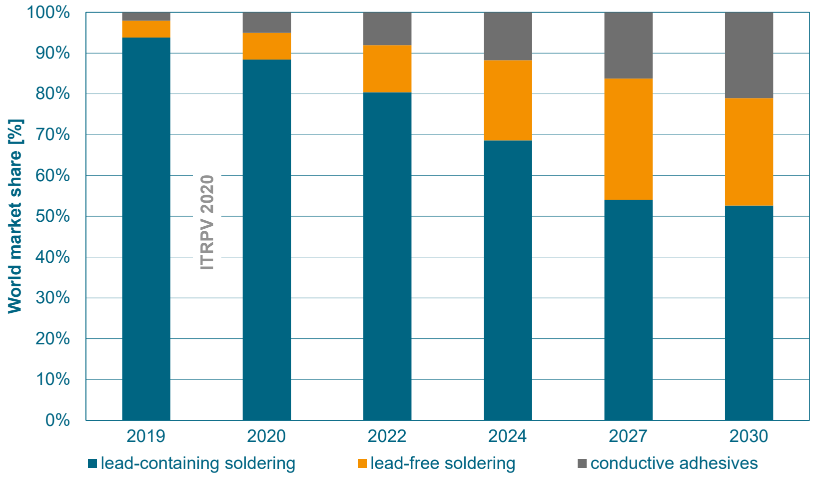
List provided by Andrew Gabor, BrightSpot Automation

Technology Trends—Moving in the Right Direction

Different cover materials for modules



Different technologies for cell interconnection



Technology projections from the 2020 ITRPV (https://itrpv.vdma.org/)

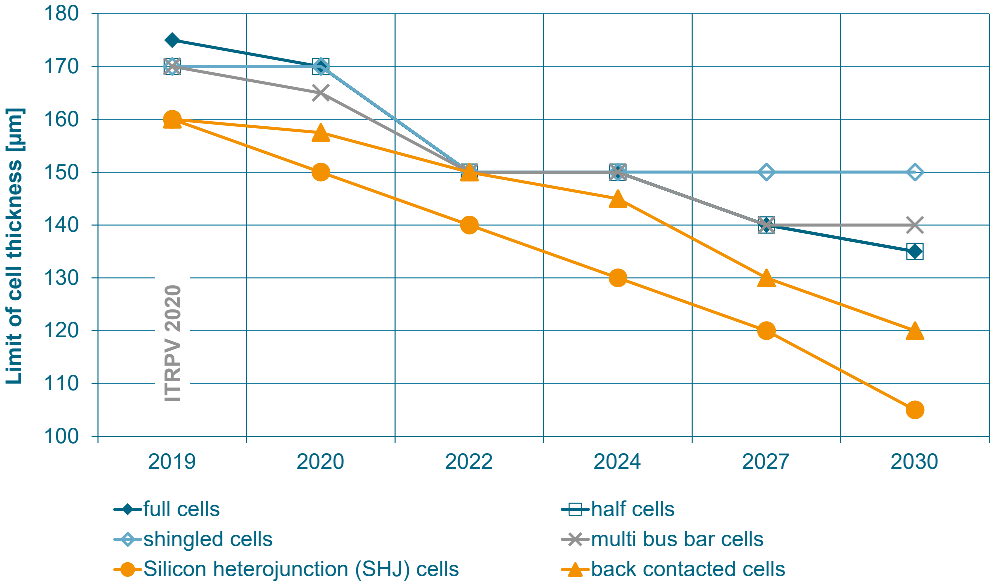
Technology Trends—Moving in Directions That Increase Cell Crack Risk

Increased Crack Risk

- Laser cut cells (half-cut, shingled)—microcracks
- Larger modules—more deflection and tensile stress
- Thinner wafers—easer crack propagation

List provided by Andrew Gabor, BrightSpot Automation

Limit of cell thickness in future module technology for different cell types

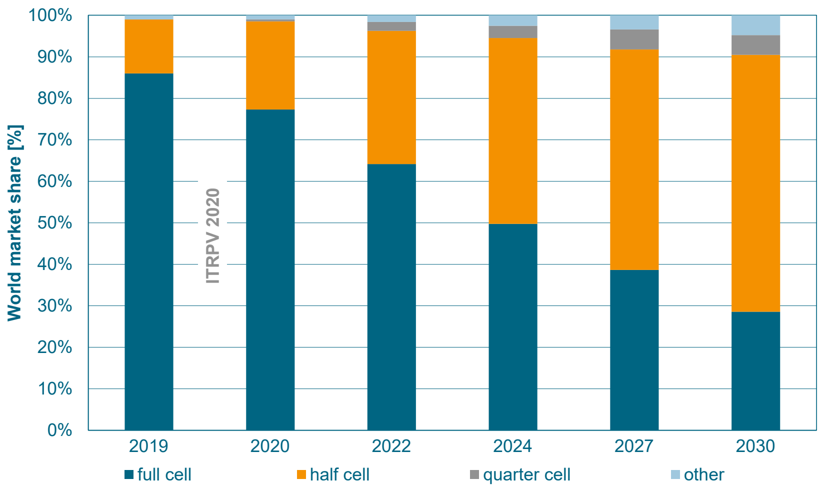


Technology projections from the 2020 ITRPV (https://itrpv.vdma.org/)

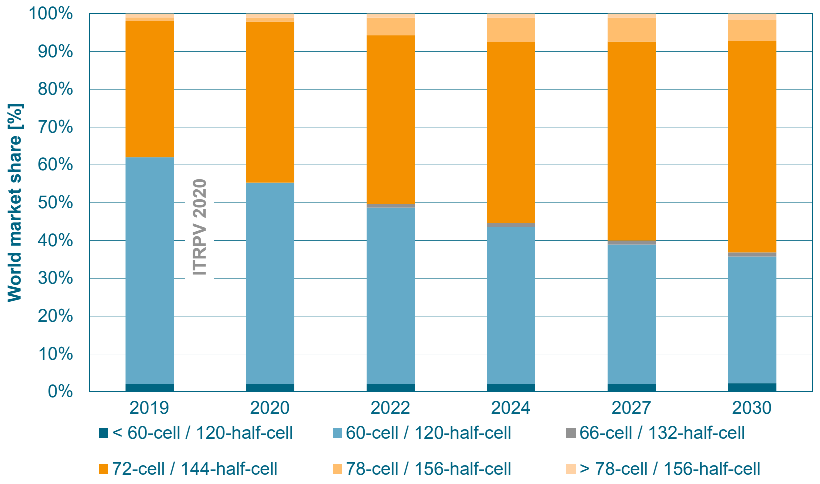
Technology Trends—Moving in Directions That Increase Cell Crack Risk

Different cell dimensions in c-Si modules

Other include shingle, 1/5th or 1/6th /8-inch



Different module sizes

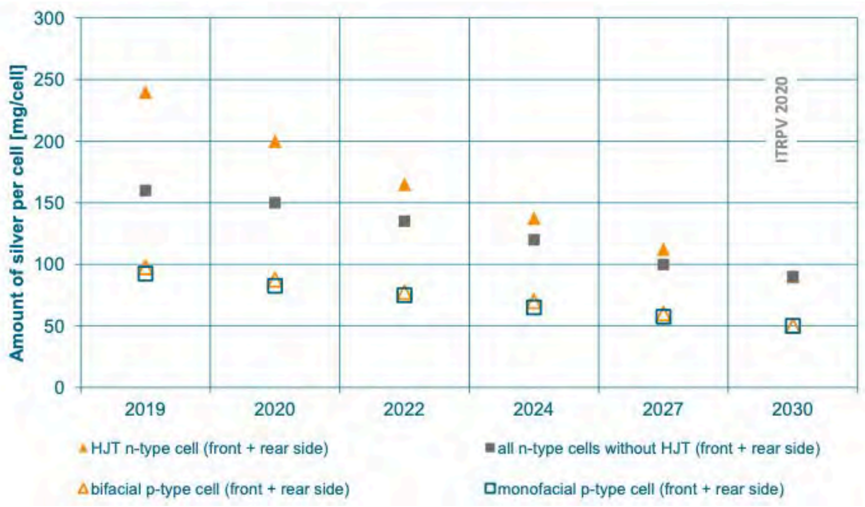


Technology projections from the 2020 ITRPV (https://itrpv.vdma.org/)

Standard and Metzilla Paste Materials Costs Calculation

Material	Consumption	Material Cost	Cost per cell
Frontside metallization paste for fingers and busbars	65 mg per cell	$550/kg	$0.0413
Backside tabbing metallization paste	22.5 mg per cell	$410/kg	$0.0092
Functionalized CNTs	1 mg per cell	$8,000/kg	$0.0080
Total Cost per Cell (M6=274.15 mm^2)	$0.0505 Standard PERC paste $0.0585 Metzilla paste		
Total Cost per Watt 22% Efficiency =6.0 W per cell	**$0.0084/W Standard PERC paste** **$0.0098 Metzilla paste**		

Trend for remaining Silver per cell incl. bus bars



Total silver paste from 2020 ITRPV: 87.5 mg per cell

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Conclusions and Proposed Next Steps

A PV module and system with greater durability carries value in many forms, including improved degradation profile and reduced operations and maintenance (O&M) expenses. Improved durability characteristics are one pathway to improve project lifecycle EBITDA, which carries a higher net present value for the project.

Next steps for this analysis:

(1) Define the characteristics for the replacement modules: What are *their* failure and degradation rate characteristics? How do different module sizes affect system engineering in the future?

(2) Resolve repowering costs: direct labor, system engineering and overhead, and module price.

(3) Deconvolute, to the extent possible, the correlation between specific failure mechanisms and resulting degradation and failure rates. This could help quantify the value proposition of specific research projects.