Faculty of Engineering
School of Photovoltaic and Renewable Energy Engineering

Beyond the Standard: What Your Module Qualification Isn't Telling You

PV ModuleTech USA, Napa Valley, USA, 16-17 June 2026

Bram Hoex

School of Photovoltaic and Renewable Energy Engineering, UNSW Sydney, Kensington, 2052, Australia

School of Photovoltaic & Renewable Energy Engineering

World-Leading PV Research Translated into Real Solutions

50+
Years of PV research excellence

PERC & TOPCon
Invented at UNSW

World Records
Solar cell efficiencies

200+
Researchers & 400+ students

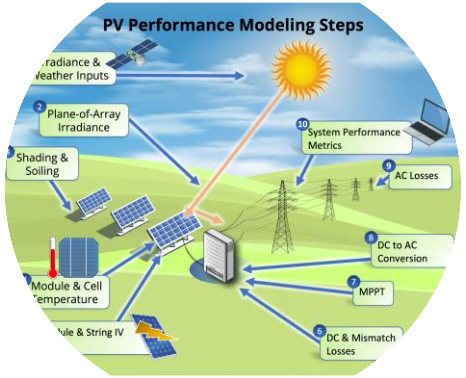
Strong commercialisation track record
Spin-offs, licensed IP, and industry partnerships delivering real-world impact

COMMERCIAL SPIN-OFFS UNSWHOEXGROUP

Foresight PV

Energy Yield & Degradation Modelling

Highest-precision energy yield modelling for utility-scale solar — advanced degradation analytics to maximise plant lifetime & returns.



Developers | Asset Owners | Module Mfrs

P2AgentX

AI Solar Operations Platform

AI brain and robotic hands that make solar farms self-operating, efficient, and effortless.

LIVE: 18 utility-scale solar farms across MENA now live

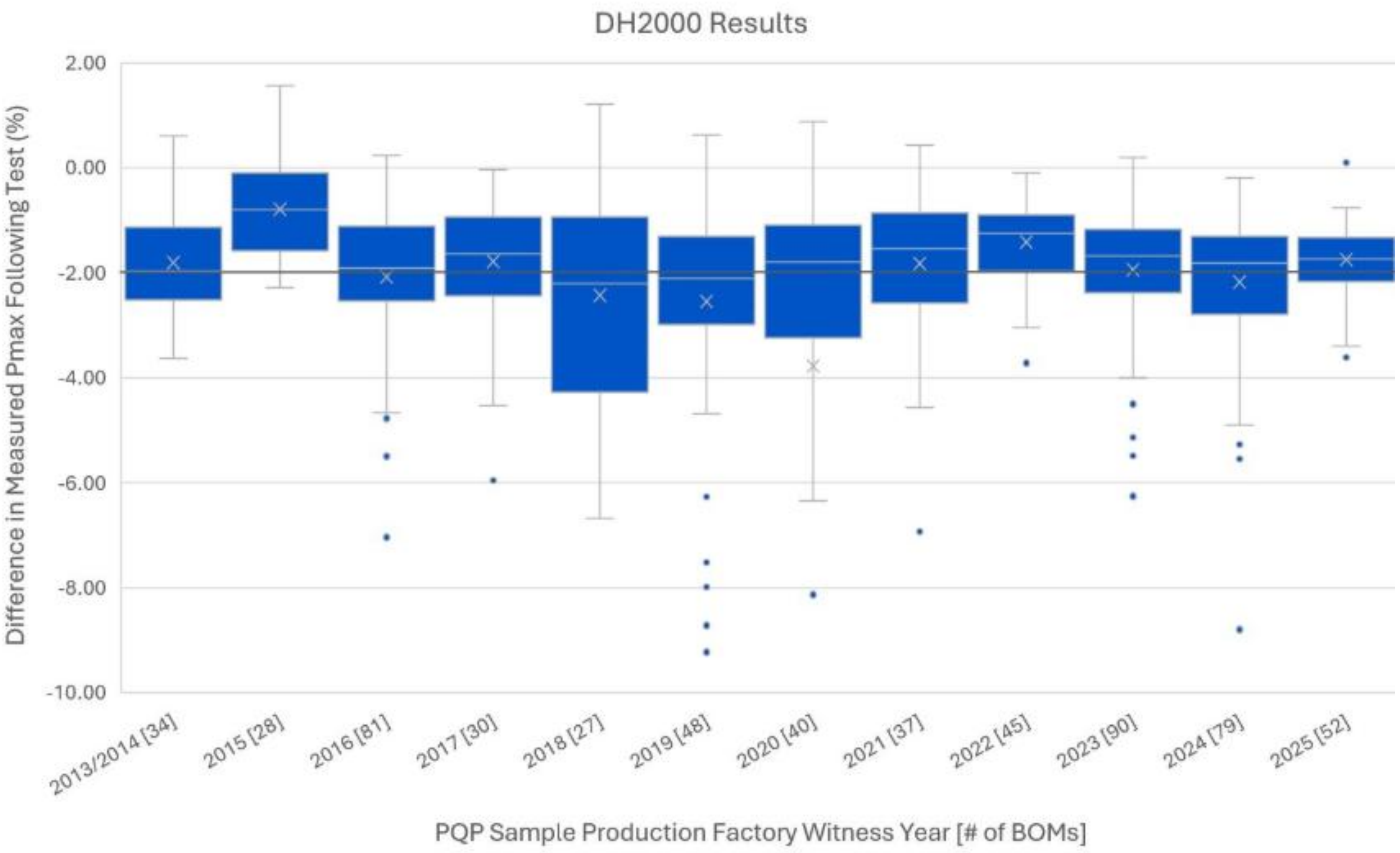
Stress Factors

- Humidity
- UV
- High temp
- T-cycling
- High voltage
- Mechanical

Drivers of loss	Occurrence/Examples	Leads to
Degradation of packaging materials	♦ Glass breakage ♦ Dielectric breakdown ♦ Bypass diode failure ♦ Encapsulant (discoloration, elasticity) ♦ Backsheet cracking/delamination	♦ Performance failure ♦ Safety hazard (electric shock) ♦ Ground faults/current leakage ♦ Electrochemical corrosion
Loss of adhesion	♦ Delamination: • Glass-to-encapsulant • Cell-to-encapsulant • Encapsulant-to-backsheet	♦ Optical decoupling (reduced light transmission) ♦ Inefficient heat dissipation ♦ Reverse-bias cell heating ♦ Higher operating temperatures
Degradation of cell/module interconnects	♦ Change in joint geometry ♦ Thermomechanical fatigue ♦ Solder bond failure ♦ Broken interconnect	♦ Increased series resistance ♦ Increased heating & Localized hot spots ♦ Burns (solder joints, backsheet, encapsulant) ♦ Arcing due to opencircuit
Degradation caused by moisture intrusion	♦ Corrosion of metallization ♦ Delamination	♦ Failed gridline-to-cell adhesion ♦ Increased electrical conductivity of materials ♦ Increased current leakage ♦ PID
Degradation of semiconductor device	♦ Cracks in cells ♦ Diffusion of impurity to cell surface	♦ Electrical isolation

Eventually results in safety issues, performance reduction, or failure

Latest results from PVEL scorecard – Damp Heat Degradation



Top performers above the line

But (too) many (far) below the line

[Damp Heat Test | Kiwa PVEL PV Module Reliability Scorecard]

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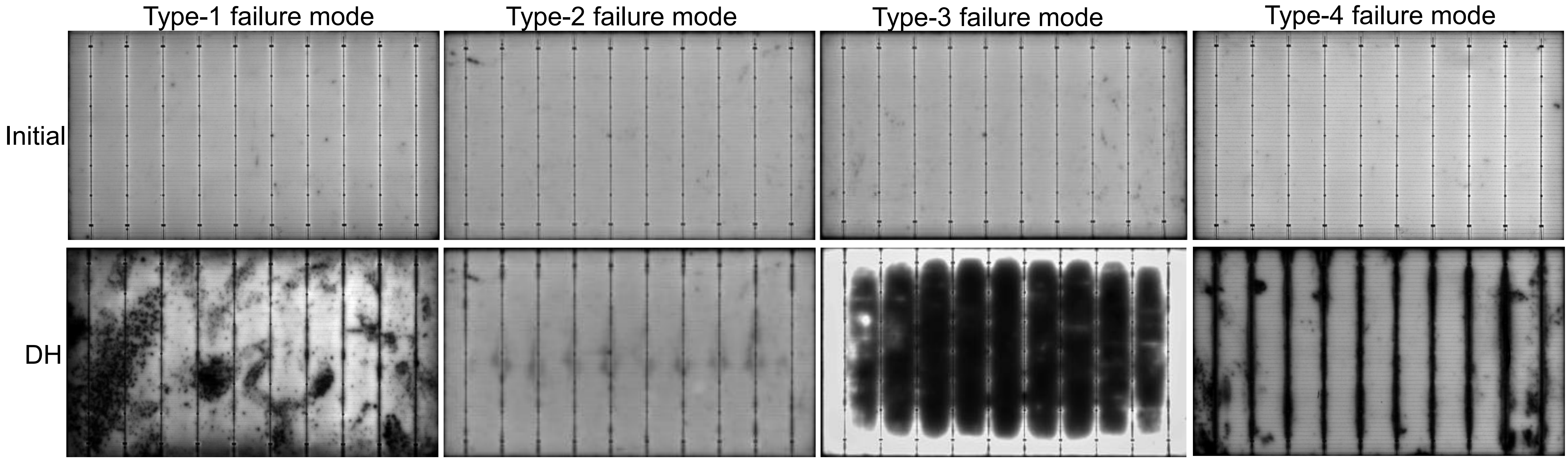
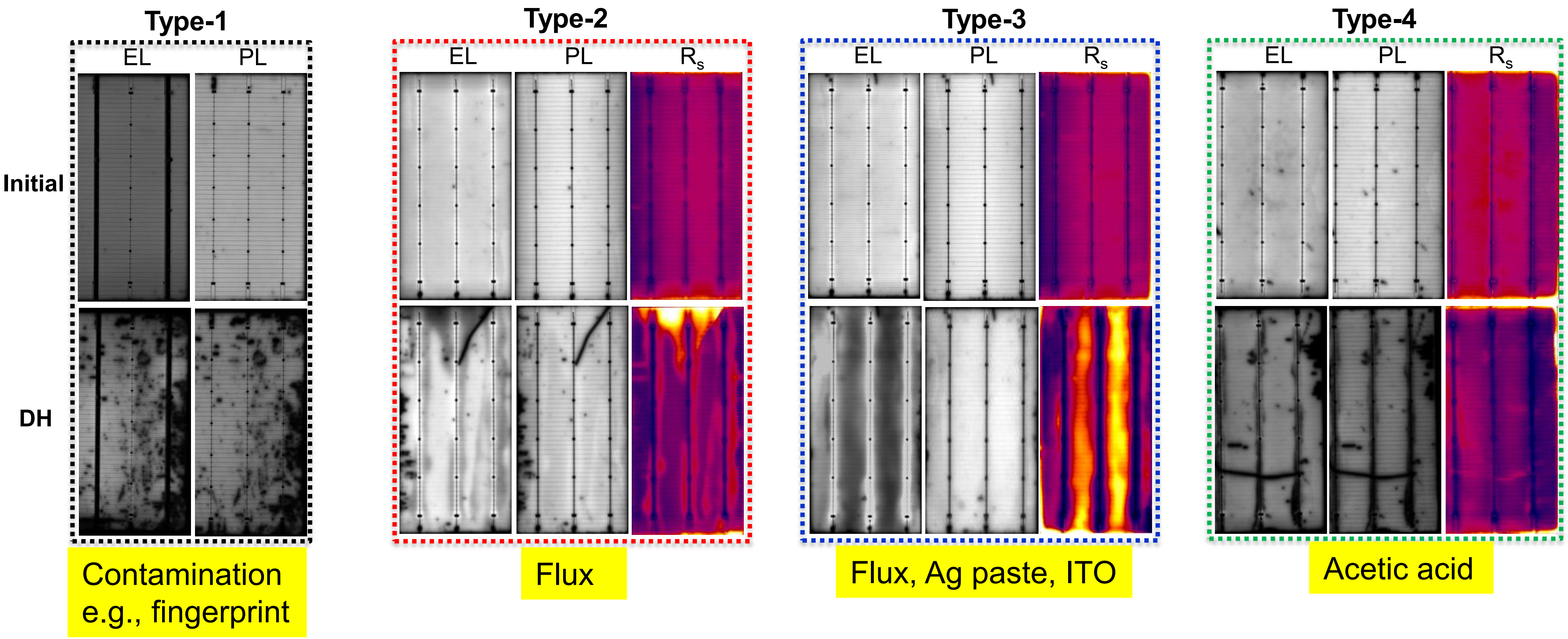
Four novel damp-heat failure modes in HJT solar cells



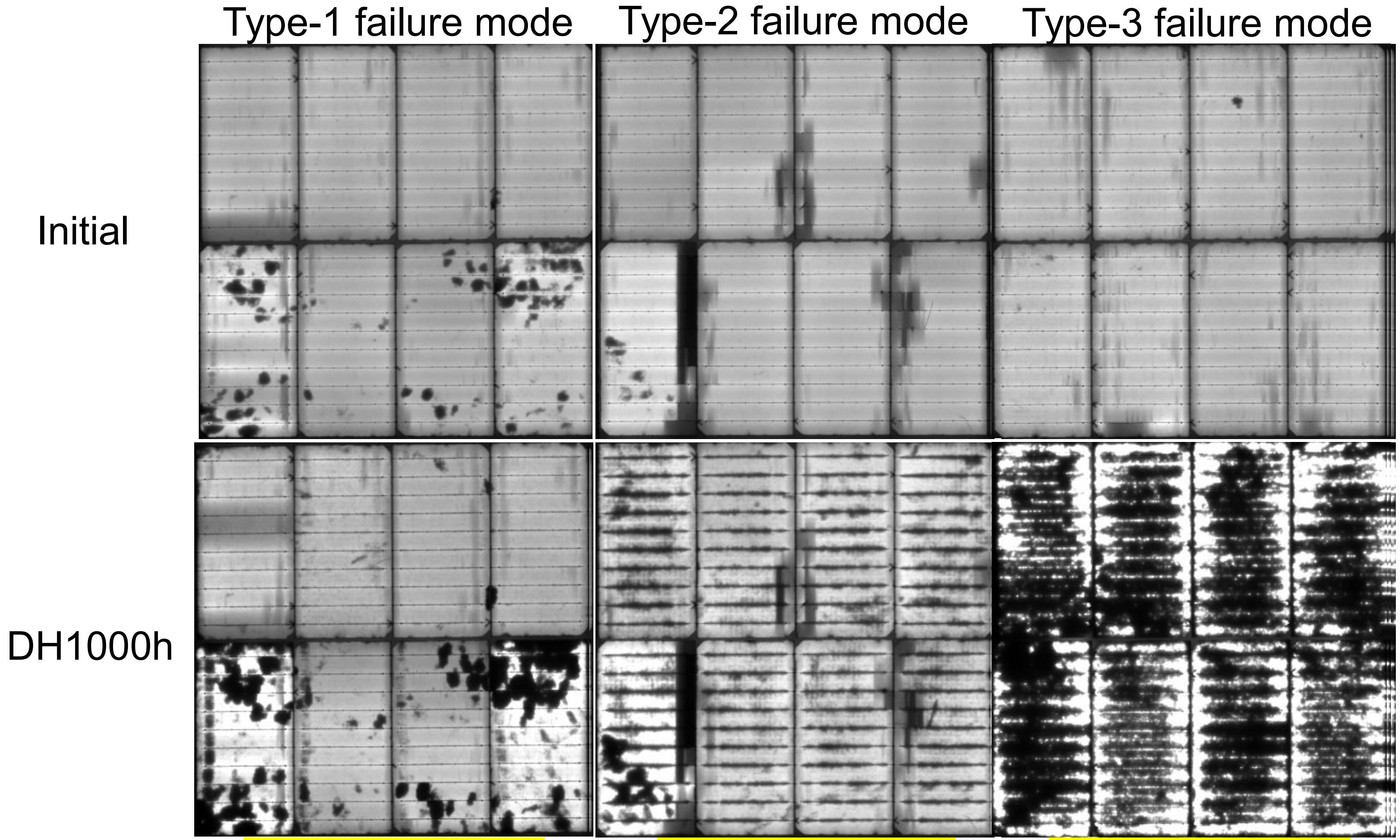
- **Four main failure modes found on HJT glass-backsheet modules after the humidity test**
  - Type-1 : **Point** failure (P_{max} loss of up to ~40%$_{rel}$)
  - Type-2 : Failure **around** the interconnection of the busbar and ribbon (P_{max} loss ~5% $_{rel}$)
  - Type-3 : Failure **between** interconnection of busbar and ribbon (P_{max} loss of up to ~50% $_{rel}$)
  - Type-4 : Failure **at/on** the interconnection or busbar and ribbon (P_{max} loss of up to ~16% $_{rel}$)
- **Each failure mode required different approaches to detect and eliminate at the cell level**

Four novel damp-heat failure modes in HJT solar cells



- All four failure modes can be reproduced in the non-encapsulated cells
- Root causes responsible for each failure mode have been identified
- Cell-level testing is one order of magnitude quicker than module-level testing

Three failure modes in TOPCon modules



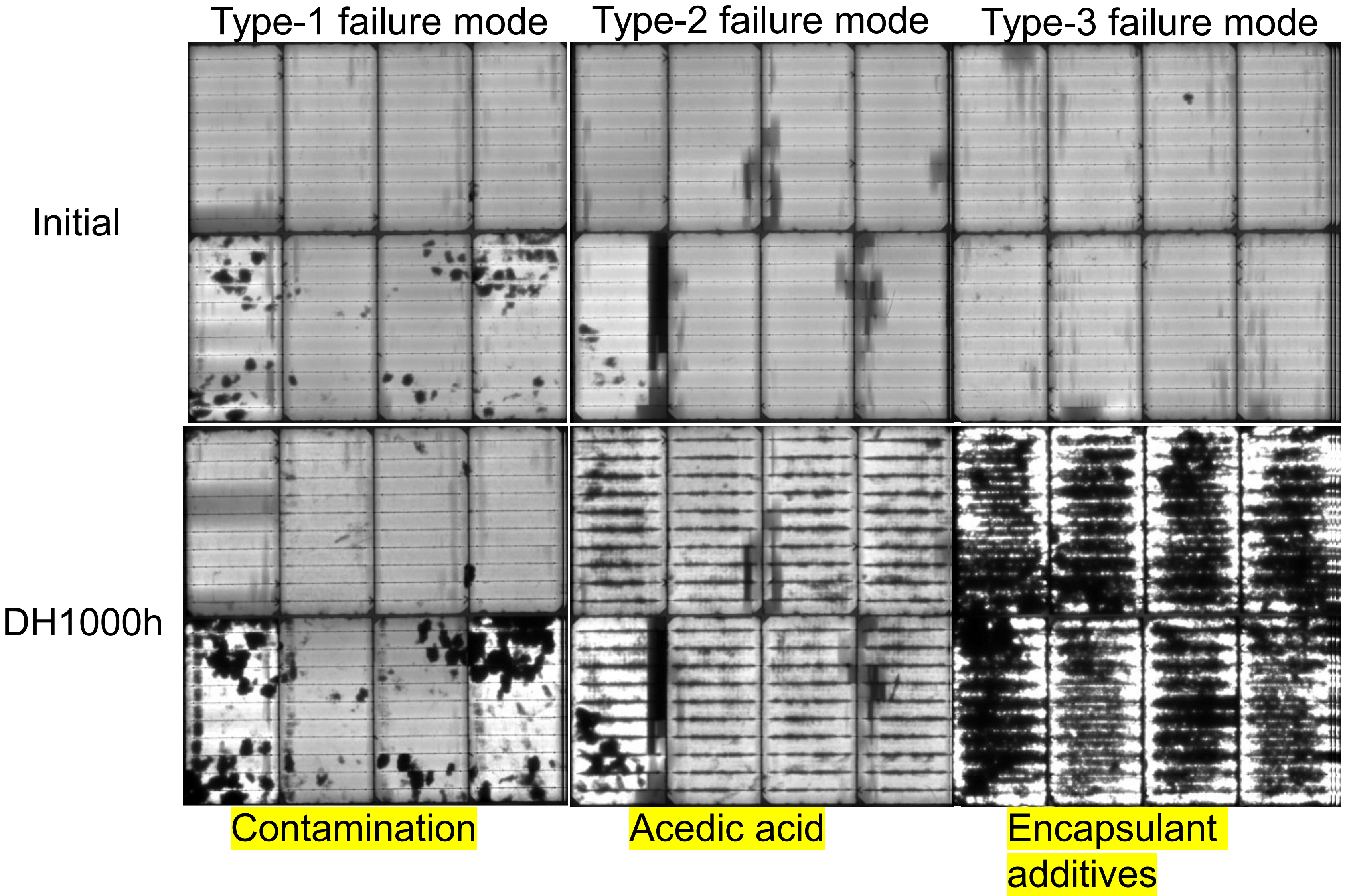
P_{max} loss ~15%$_{rel}$ | P_{max} loss ~11%$_{rel}$ | P_{max} loss ~65%$_{rel}$

Type-1 failure mode: point-localized failure
Type-2 failure mode: failure at/around the interconnection point
Type-3 failure mode: failure across the entire area of cells/module

- Three failure modes have been realised in TOPCon modules, but absent in PERC modules
- These failure modes are quite similar to HJT modules

Sen, Wang, Khan, Hoex et al., 10.1016/j.solmat.2024.112877

Three failure modes in TOPCon modules

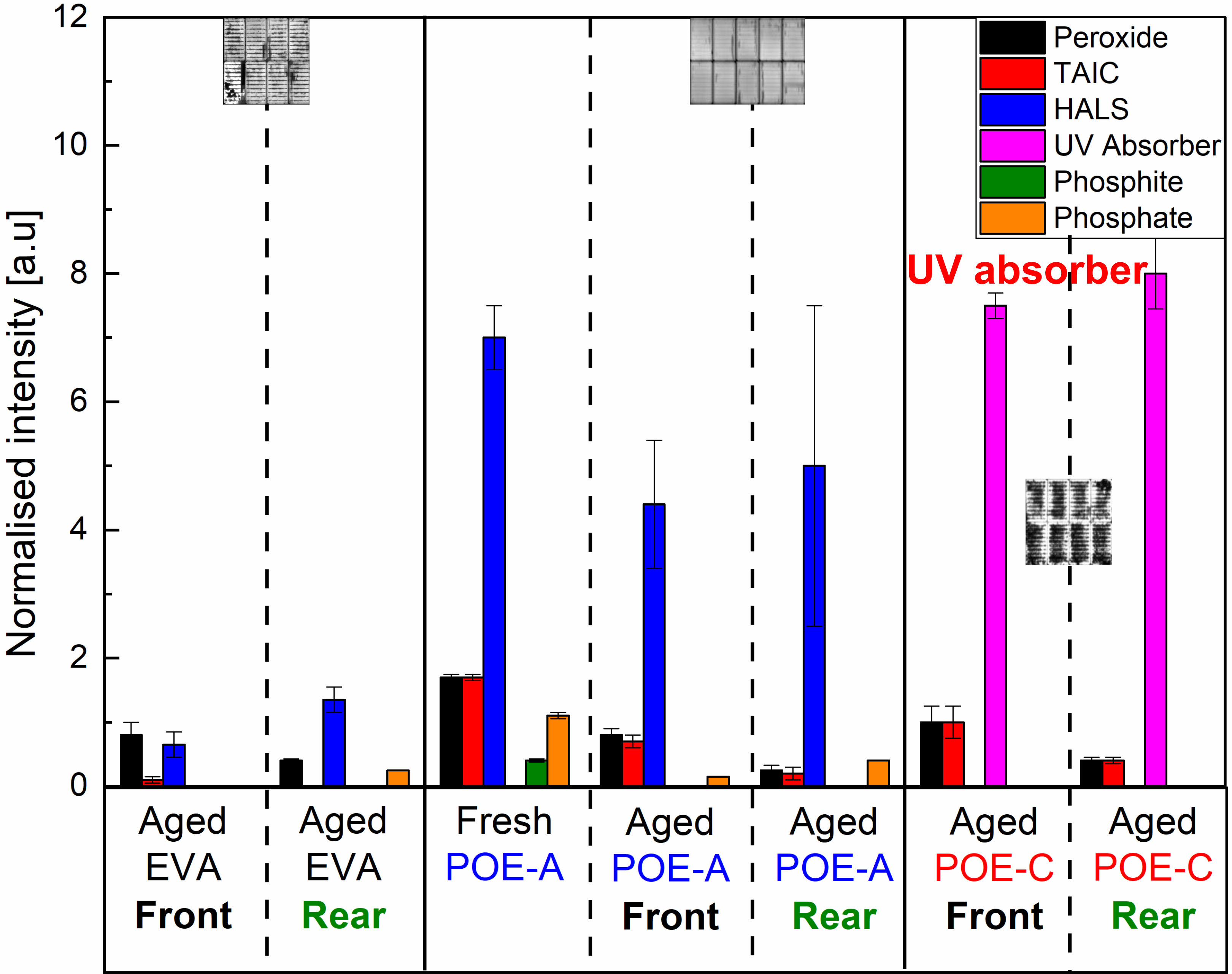


Type-1 failure mode: point-localized failure
Type-2 failure mode: failure at/around the interconnection point
Type-3 failure mode: failure across the entire area of cells/module

The Encapsulant Is a Chemical Reactor, Not Just Glue!

Additive class	Typical chemistries (examples)	Primary role(s)
Organic peroxides (crosslinkers)	Dicumyl peroxide (DCP); TBEC; DBPH (Luperox/Trigonox 101)	Generate radicals during lamination to crosslink polymer (raise gel content), improving creep and thermal resistance
Crosslinking coagents	TAIC (triallyl isocyanurate); TAC (triallyl cyanurate); TMPTMA	Boost crosslink efficiency/density and heat resistance at a given peroxide level; shorten lamination time
UV absorbers (UVAs)	Benzotriazoles (e.g., Tinuvin P/327/360); Benzophenones (UV-531); Hydroxyphenyl-triazines (HPTs)	Filter UV (≈240–360 nm) to slow photo-oxidation and yellowing
HALS (hindered amine light stabilizers)	Tinuvin 770/292/123; reactive/grafted HALS	Catalytically quench radicals; synergistic with UVAs for long-term weatherability
Antioxidants — primary & secondary	Primary phenolics (Irganox 1010/1076); Secondary phosphites (Irgafos 168)	Limit thermo-oxidative degradation during processing and service; phenolics trap radicals, phosphites decompose hydroperoxides
Adhesion promoters (silane coupling agents)	γ-MPS/A-174 (3-methacryloxypropyl-trimethoxysilane); VTMS; silane-grafted tie-layers	Form covalent Si–O–Si bridges to glass/metal oxides → durable adhesion
Acid scavengers / neutralizers	Calcium stearate, Magnesium stearate, Magnesium oxide; Hydrotalcites (e.g., Mg-Al carbonate)	Neutralize acidic species (notably acetic acid from EVA hydrolysis) to mitigate corrosion/PID risk
Fillers / nanoparticles (optional)	Al_2O_3, SiO_2, ZnO, graphene (research)	Tune barrier/mechanical/UV shielding; processing aids
Luminescent down-shifting (UV-DS) materials	Phosphors (YAG:Ce, $Sr_2SiO_4:Eu^{2+}$); Quantum dots (e.g., $AgInS_2$/ZnS, InP/ZnS); organic dyes (coumarins/perylene)	Convert UV/near-UV photons to visible → boost short-wavelength response and reduce UV stress (UVID)

Root Cause for Catastrophic Failure Identified

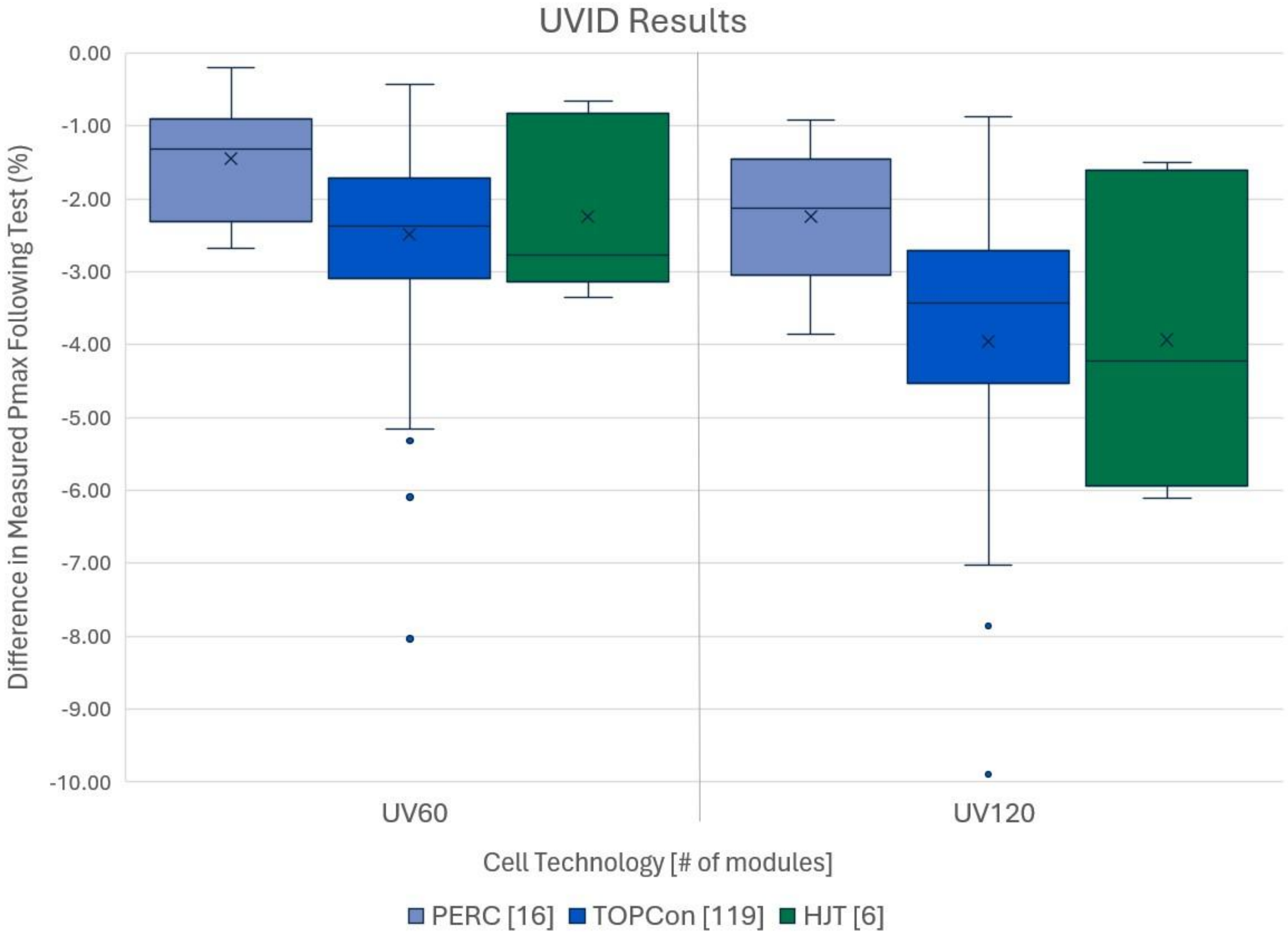


POE-C:

- **Contains UV absorber**
- No Phosphite/Phosphate (antioxidant)

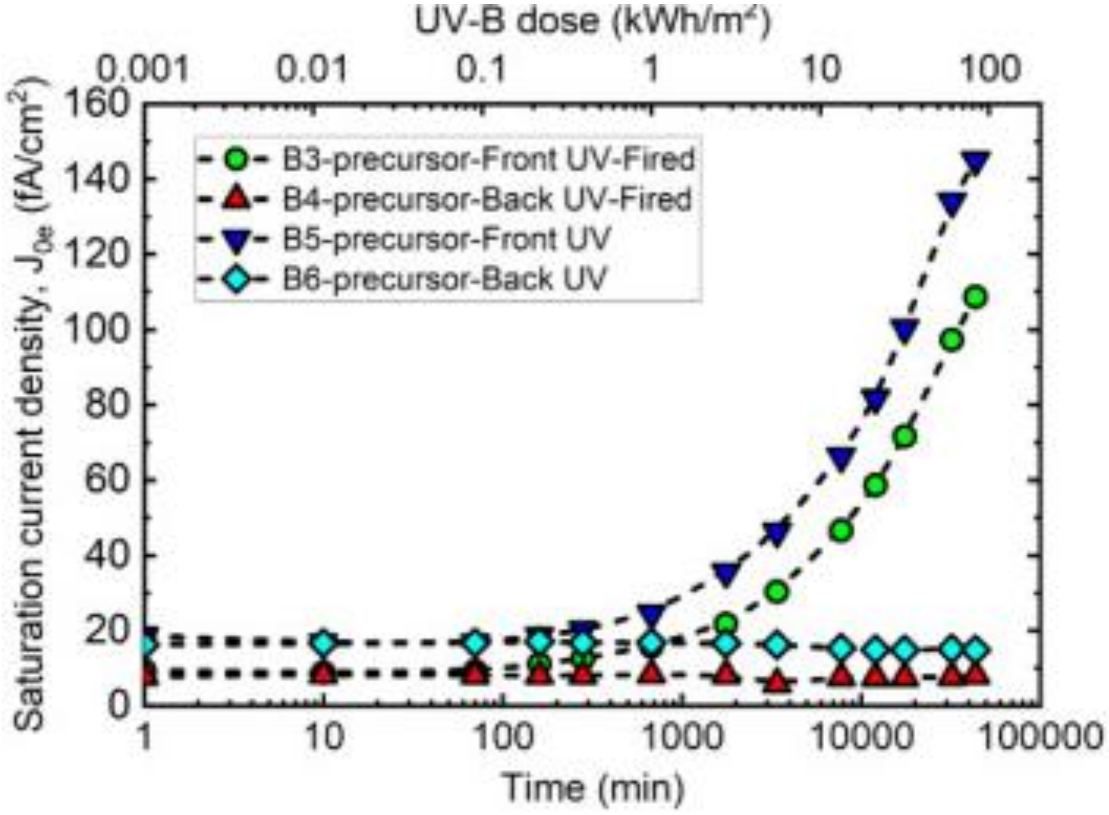
  → **Additive degrades, leads to acid formation -> degrades metallisation**

UVID Is a Fleet-Scale Problem Across All Technologies

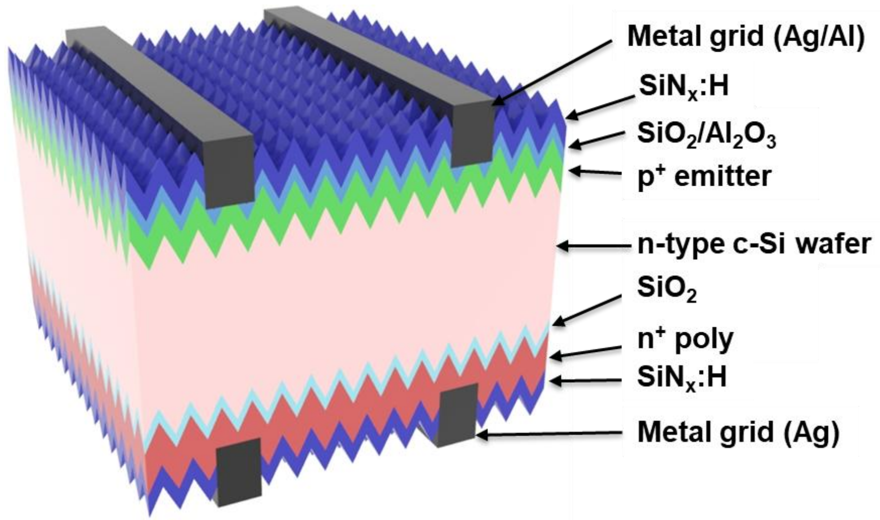


[UVID Test | Kiwa PVEL PV Module Reliability Scorecard](#)

Accelerated cell-level UVID: Days, Not Months

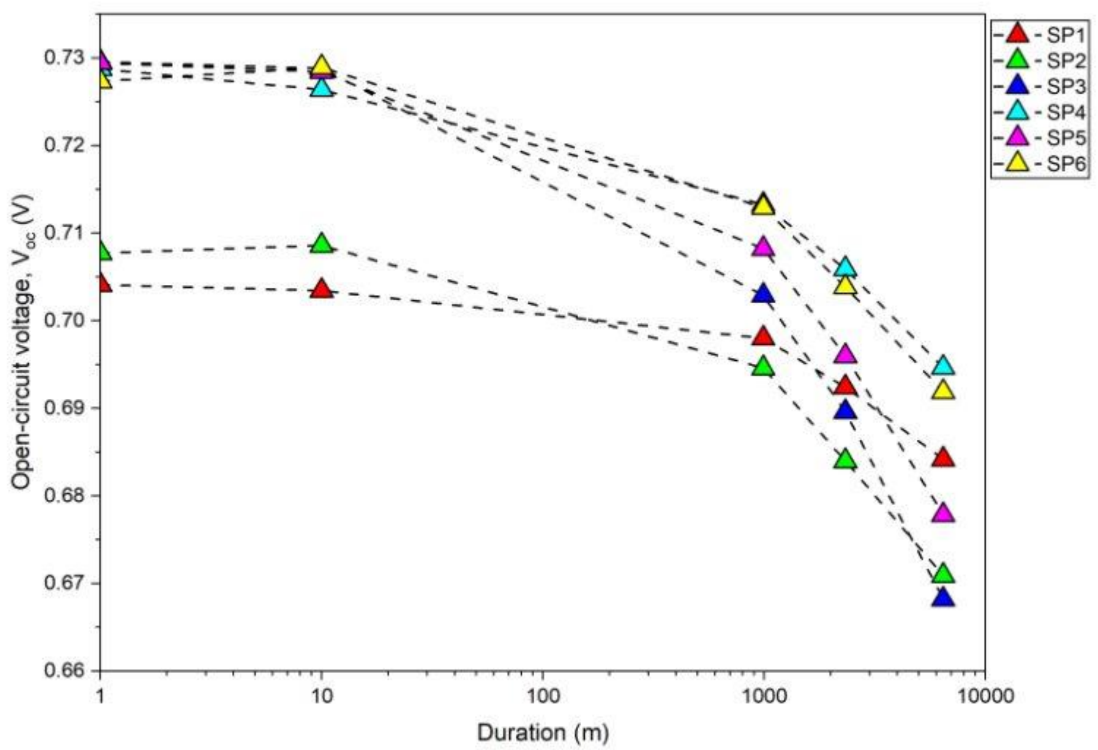


- We can accelerate UVID using UV-B compared to UV-A
- Only degradation at the **TOPCon front**, no degradation at the TOPCon rear as UV is fully absorbed in the poly-Si layer (this may change when using poly fingers in the near future)

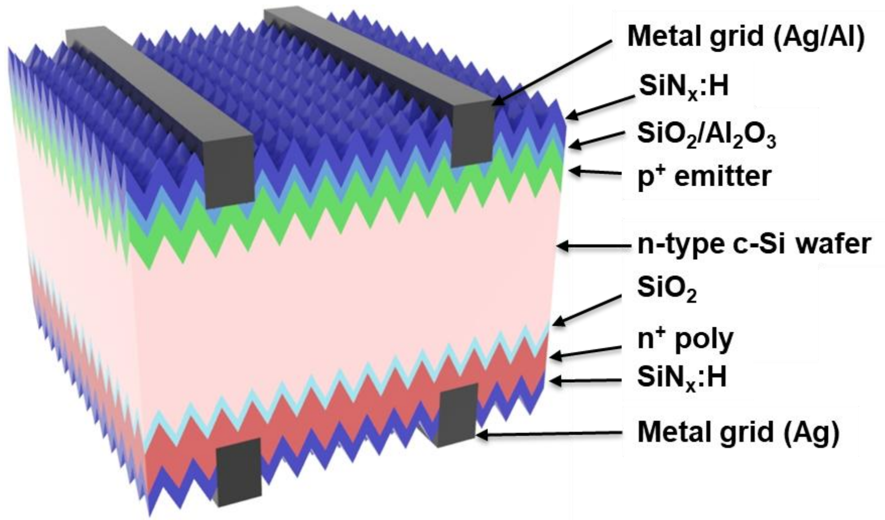


Source: Khan, Hoex, *et al.*, SEMSC, **294**, 113895 (2025)

Accelerated cell level UVID: Days, Not Months



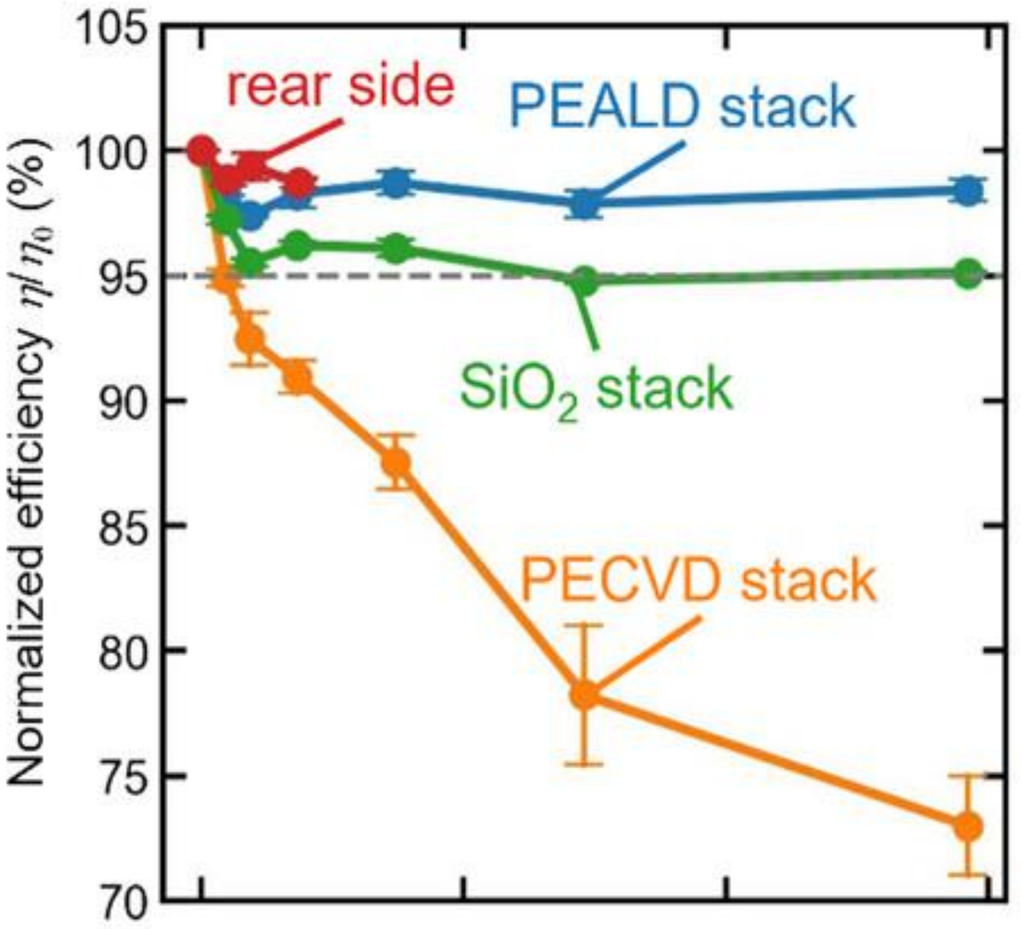
- We accelerate UVID using UV-B compared to UV-A
- Test can be used to check your supply chain
- Significant spread in cell UVID sensitivity observed in our testing (up to a factor of 5!)



Unpublished

Reducing UVID at the cell level

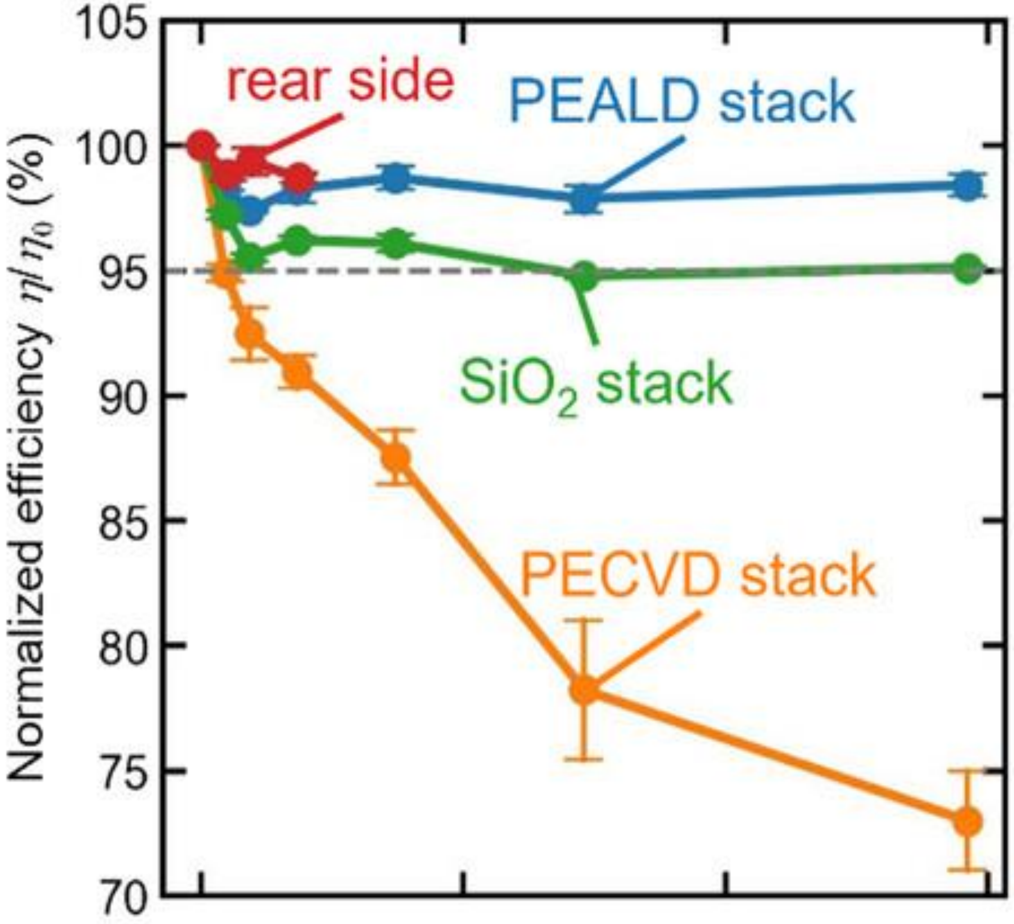
- Significantly higher UVID when using PECVD vs ALD for AlO_x film deposition
- Higher quality silicon oxide (SiO_2) film reduces UVID

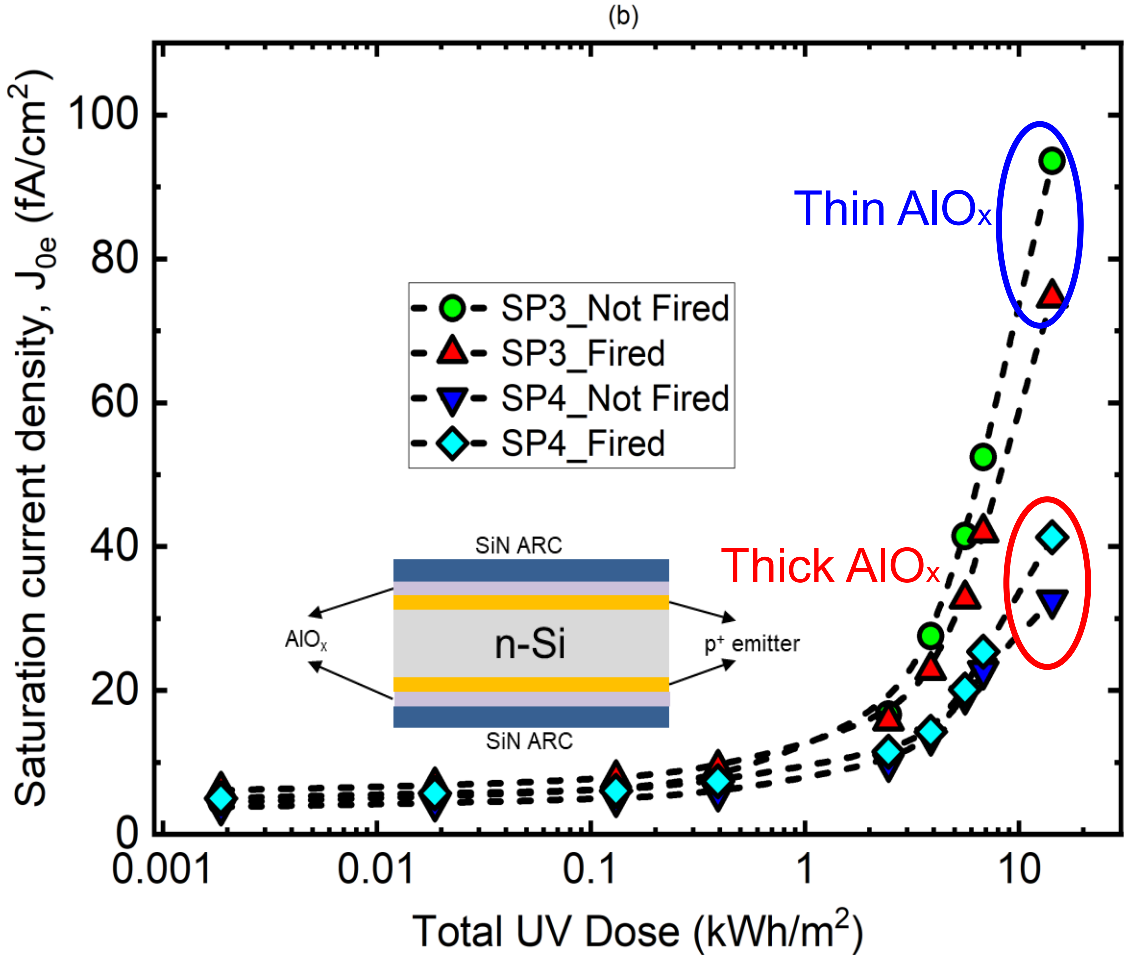


Hollemann *et al.*, Solar RRL,
https://doi.org/10.1002/solr.202500510 (2025)

Reducing UVID at the cell level

- Significantly higher UVID when using PECVD vs ALD for AlO_x film deposition
- Higher quality silicon oxide (SiO_2) film reduces UVID
- Thicker ALD films reduce UVID

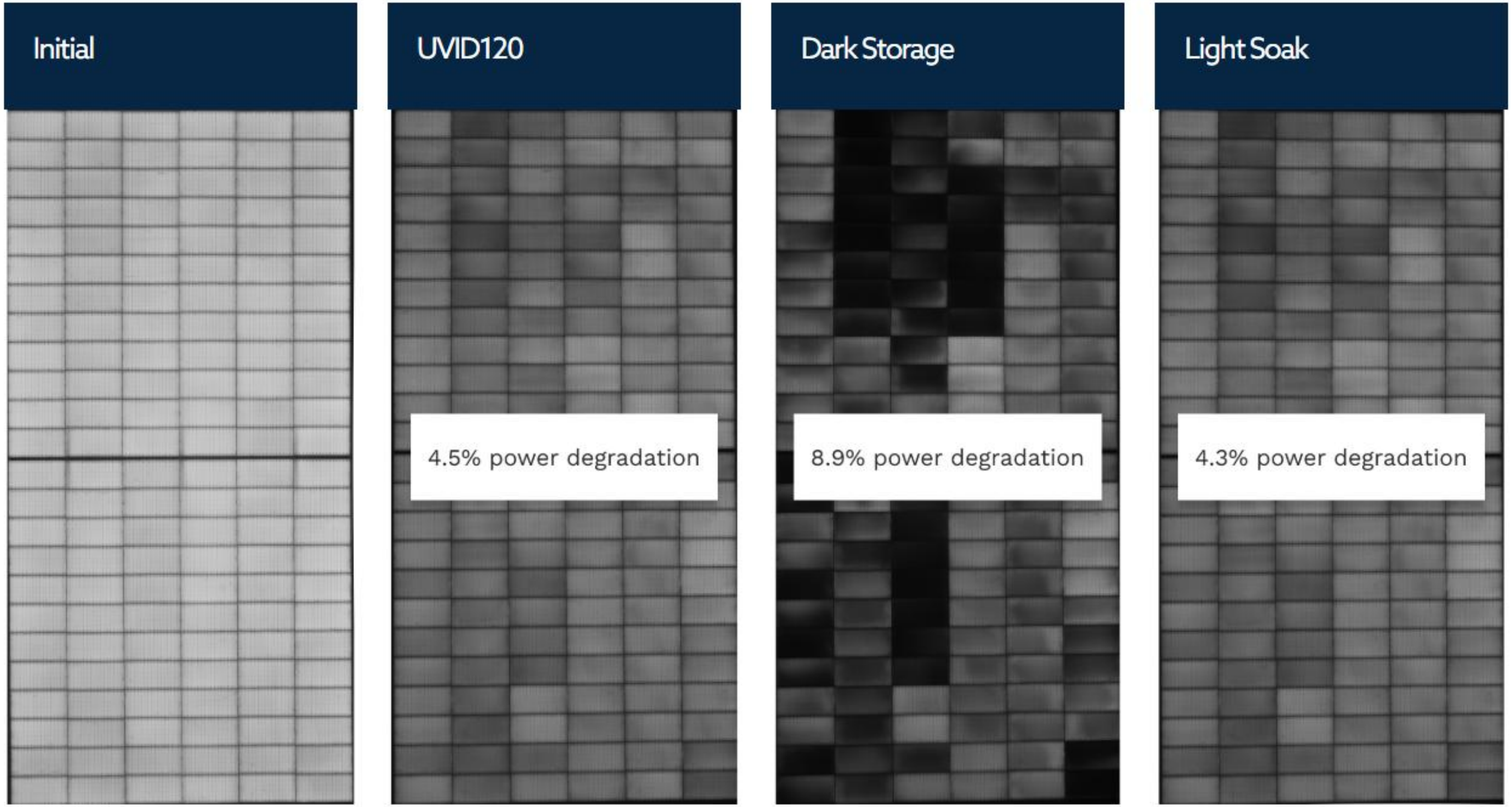




Hollemann *et al.*, Solar RRL, https://doi.org/10.1002/solr.202500510 (2025)

Khan, Hoex, et al. SOLMAT ***298,*** *114149 (2026)*

Dark Storage Metastability: Challenge for Testing



[UVID Test | Kiwa PVEL PV Module Reliability Scorecard]

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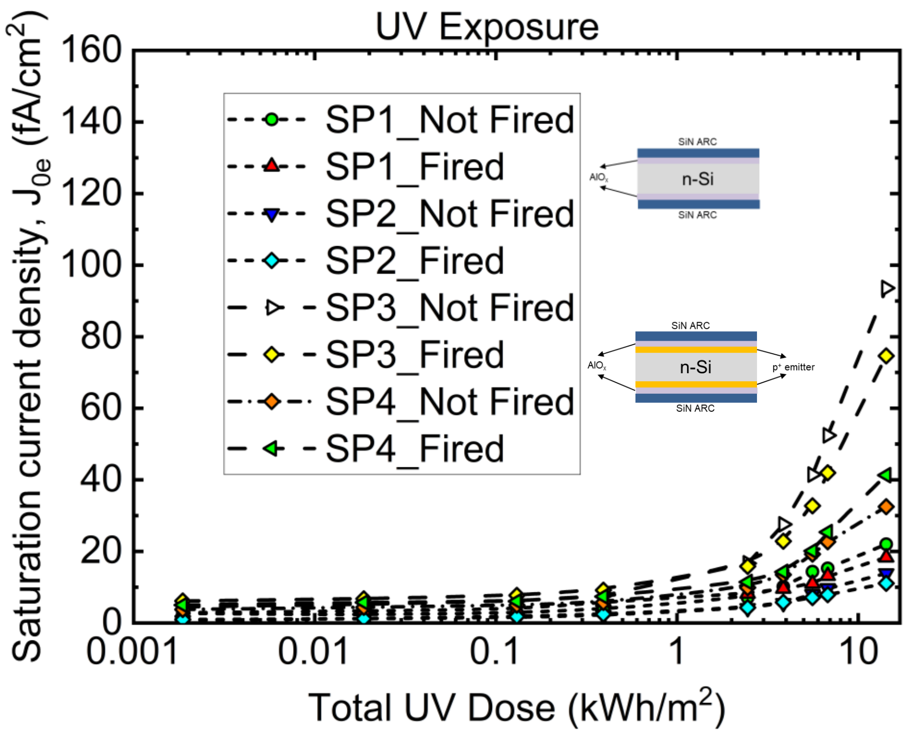
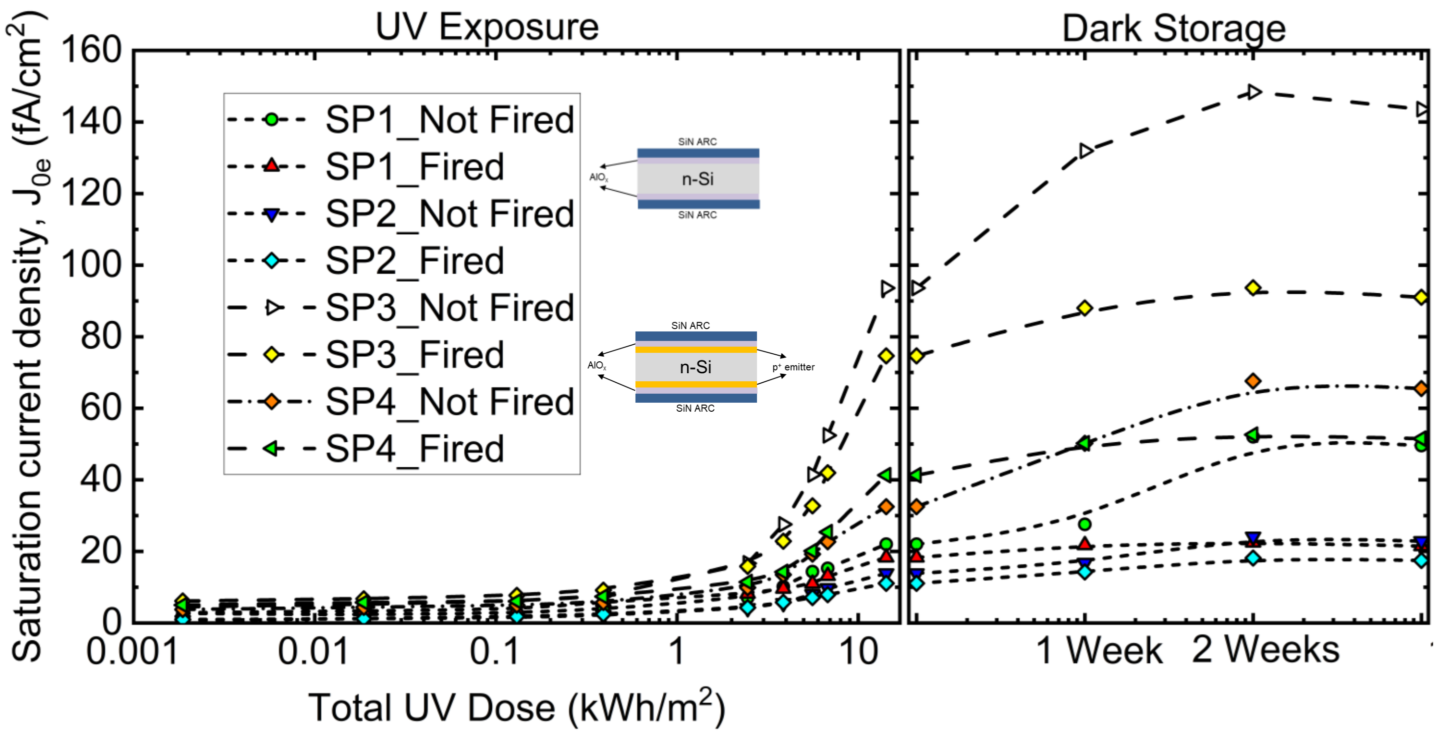
Metastability: Degradation Continues in the Dark, Recovers on Anneal



- **UV:** Rapid rise in recombination

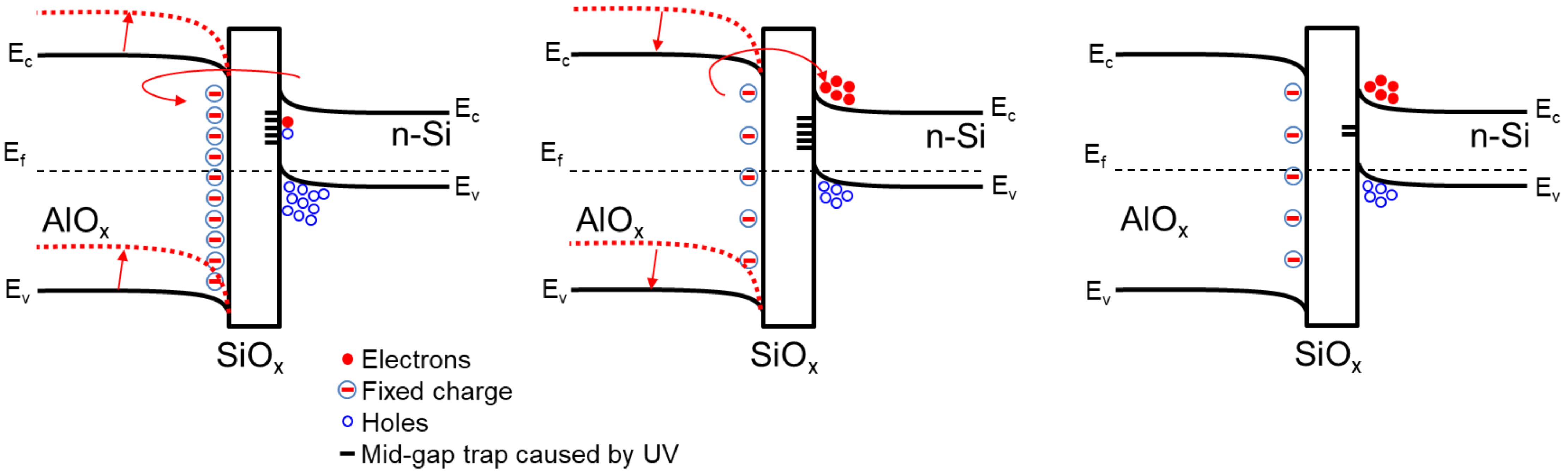
Metastability: Degradation Continues in the Dark, Recovers on Anneal



- **UV:** Rapid rise in recombination
- **Dark storage:** Degradation continues, worst in unstable samples
- **Annealing:** Low-T anneal restores J_{0e} to near initial values

Khan, Sen, Wang, Wang, Hoex, et al. SOLMAT ***298,*** *114149 (2026)*

Proposed UVID mechanism



- **UV:** Si–H bond breakage in SiN_x and interface ↑D_{it}, but charge trapping boosts Q_f
- **Dark storage:** D_{it} stable; Q_f released → higher recombination
- **Recovery:** Anneal diffuses H, ↓D_{it}, restores passivation.

*Khan, Sen, Wang, Wang, Hoex, et al. SOLMAT **298,** 114149 (2026)*

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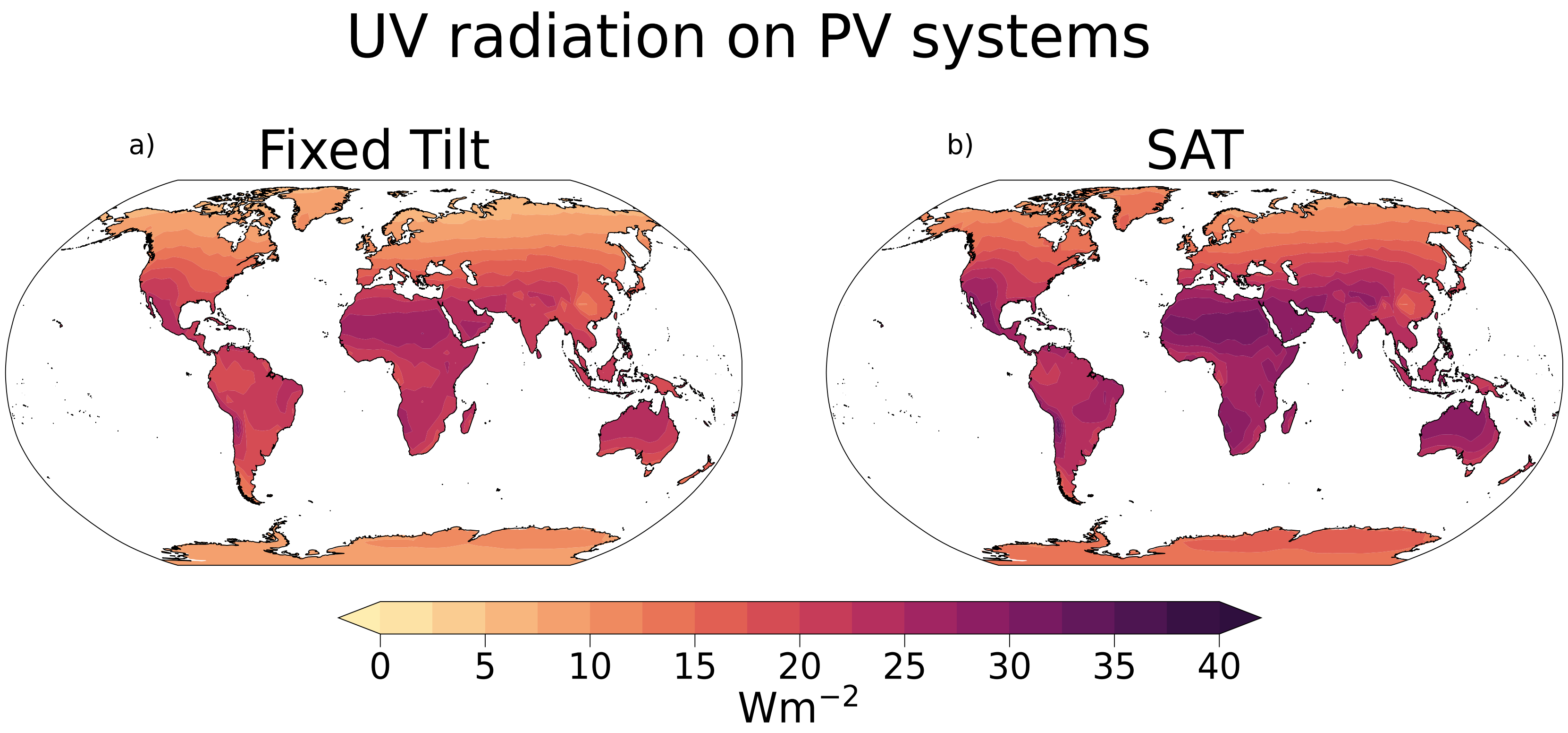
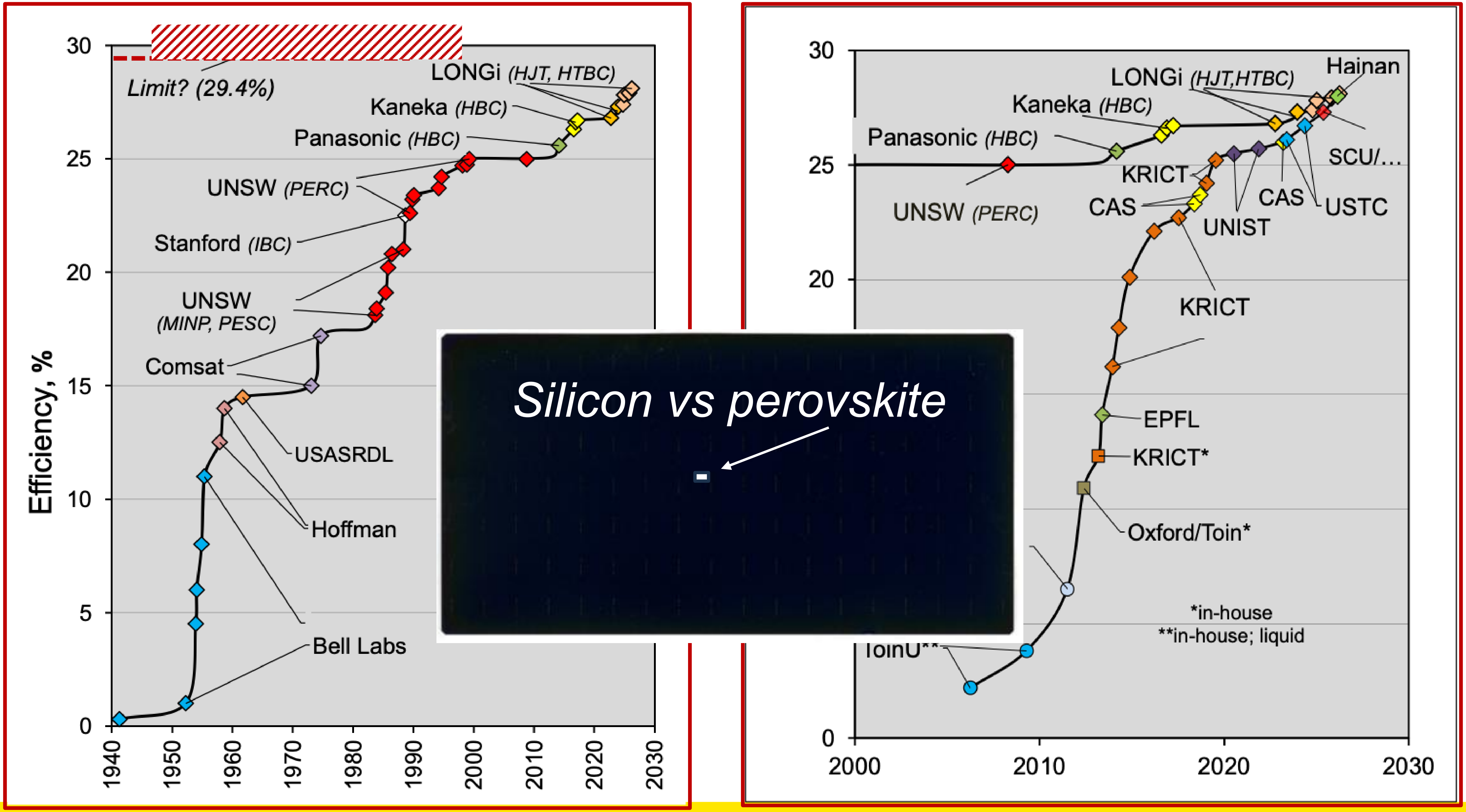
Global Scale UV modelling



- Previous models could only model global UV
- We developed a model to calculate angle- and wavelength-dependent UV from satellite data that is as accurate as resource-intensive ray tracing

Poddar, Hoex, *et al.*, IEEE JPV, DOI: 10.1109/JPHOTOV.2026.3668778 (2026)



Green *et al.*, SNEC Plenary, 2026

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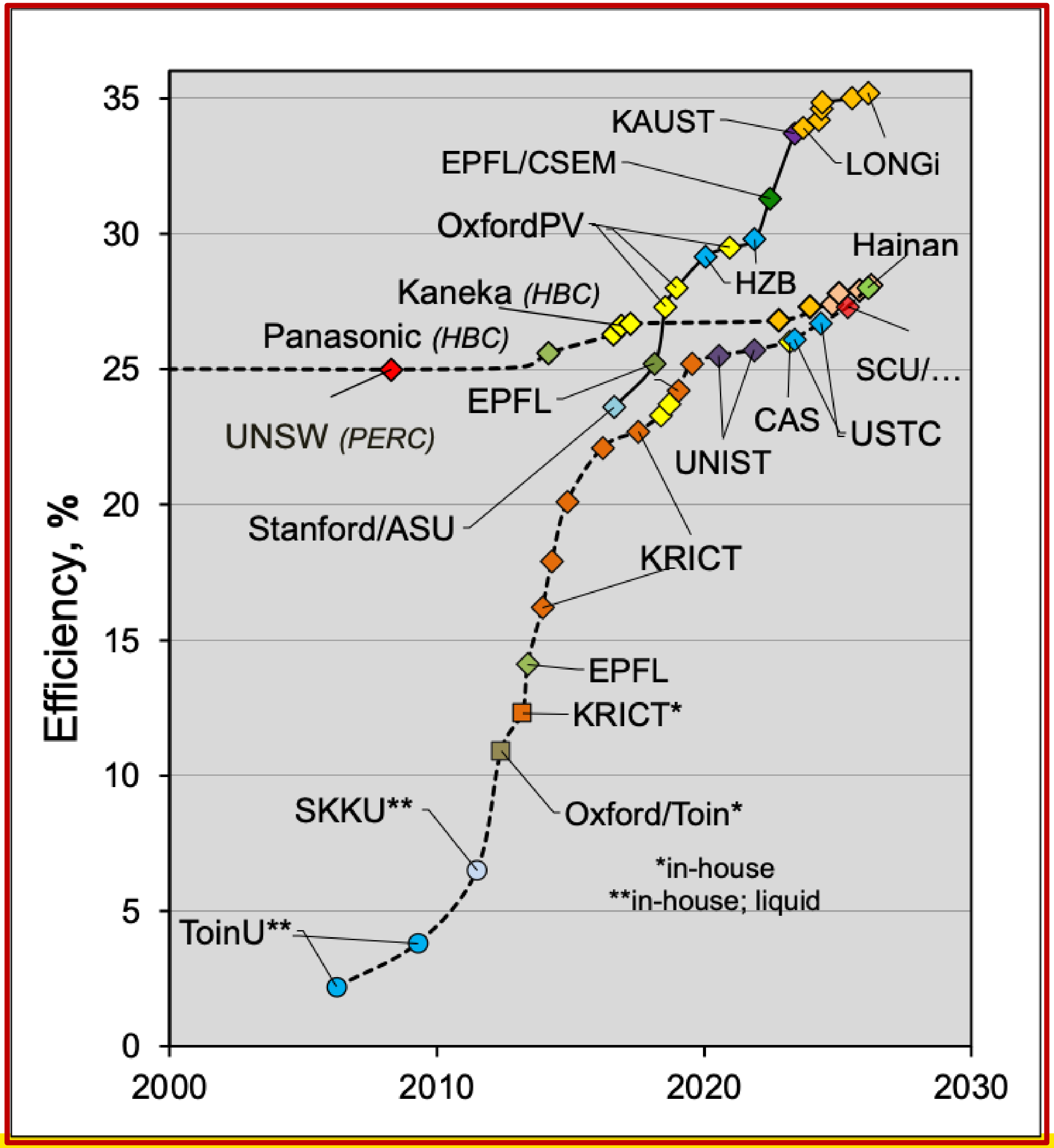

Green *et al.*, SNEC Plenary, 2026

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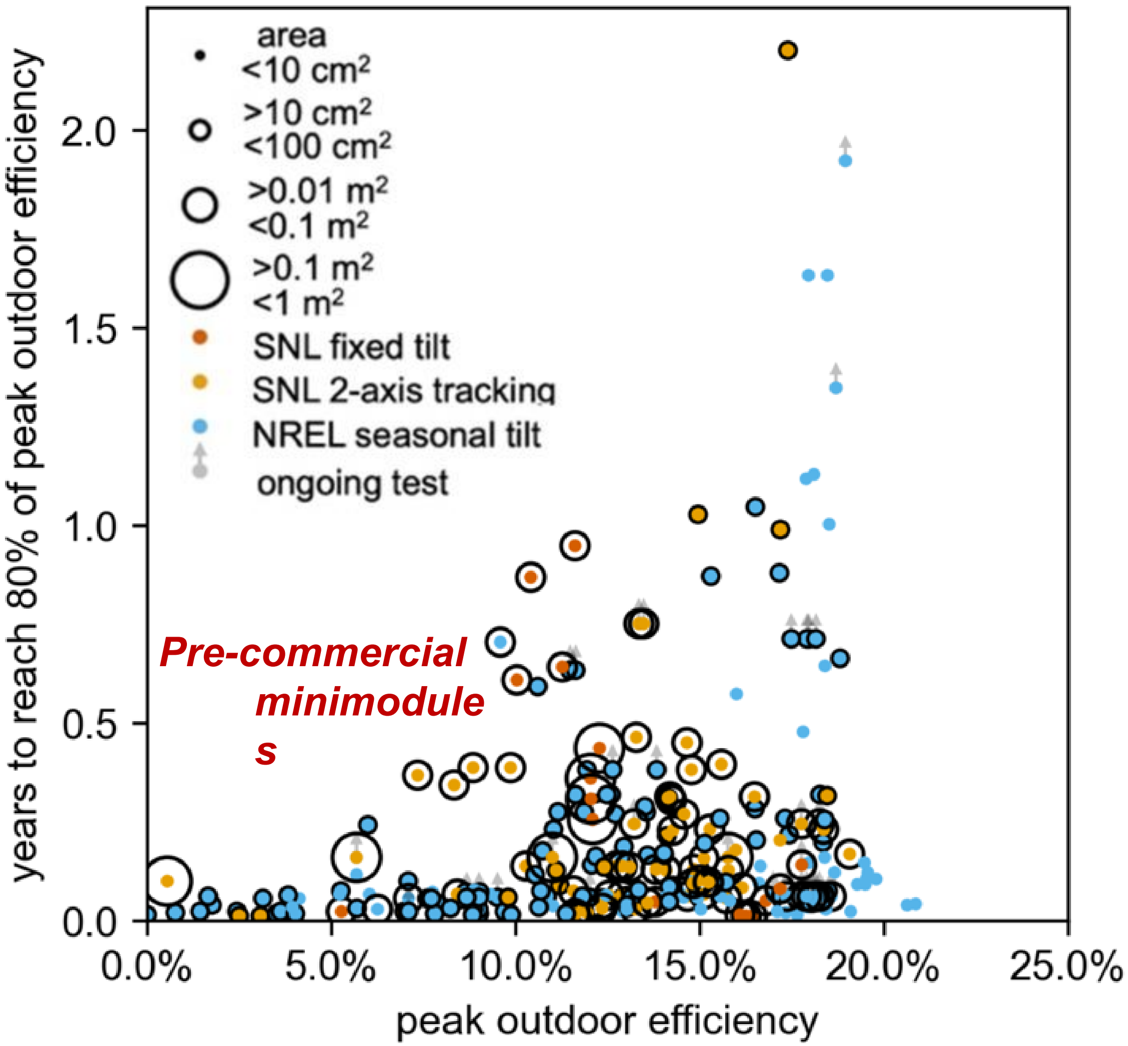
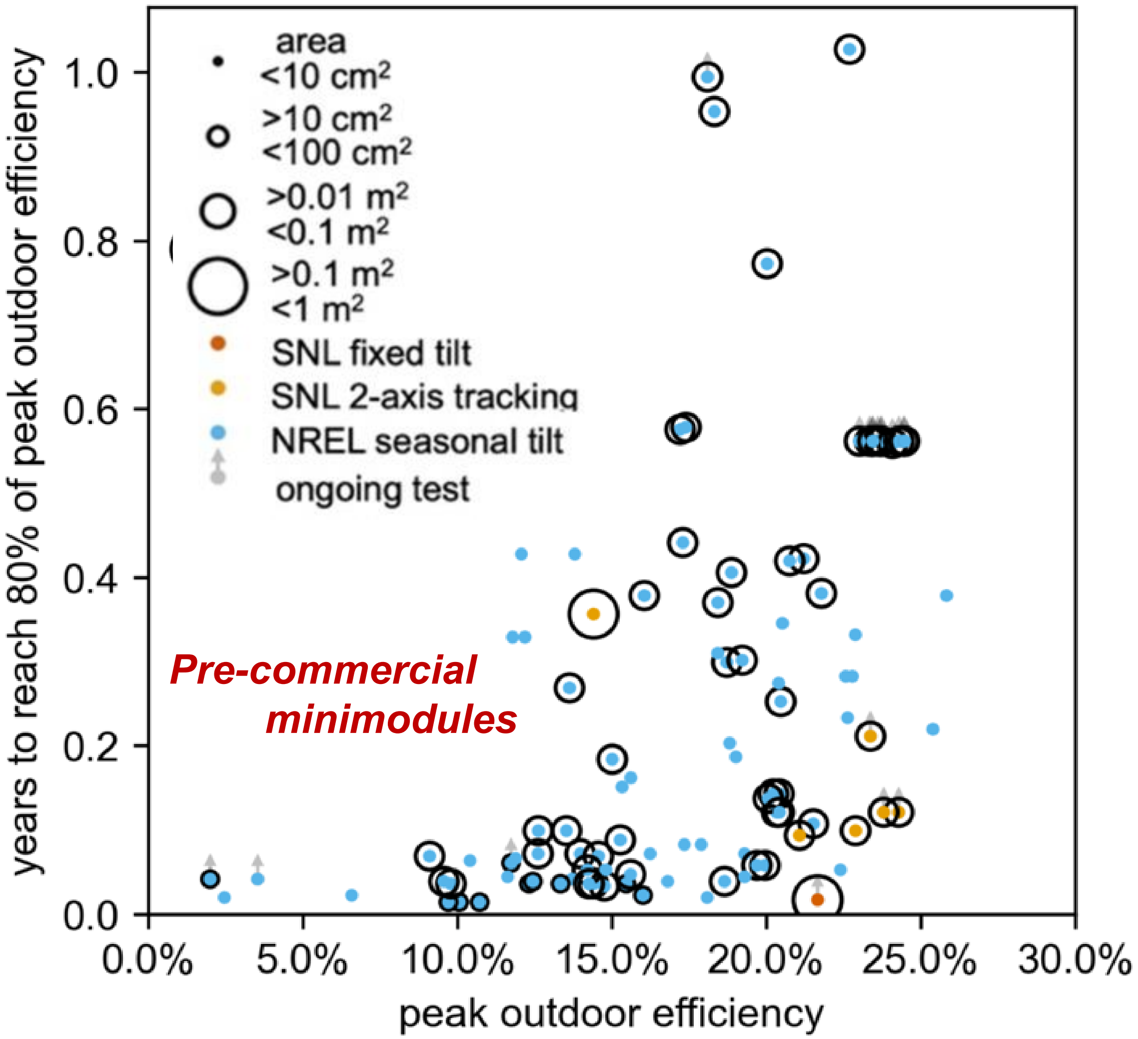
Perovskite? Stability?

Single junction



Tandem



https://pvpact.sandia.gov/results-and-data/ updated 7 May 2026

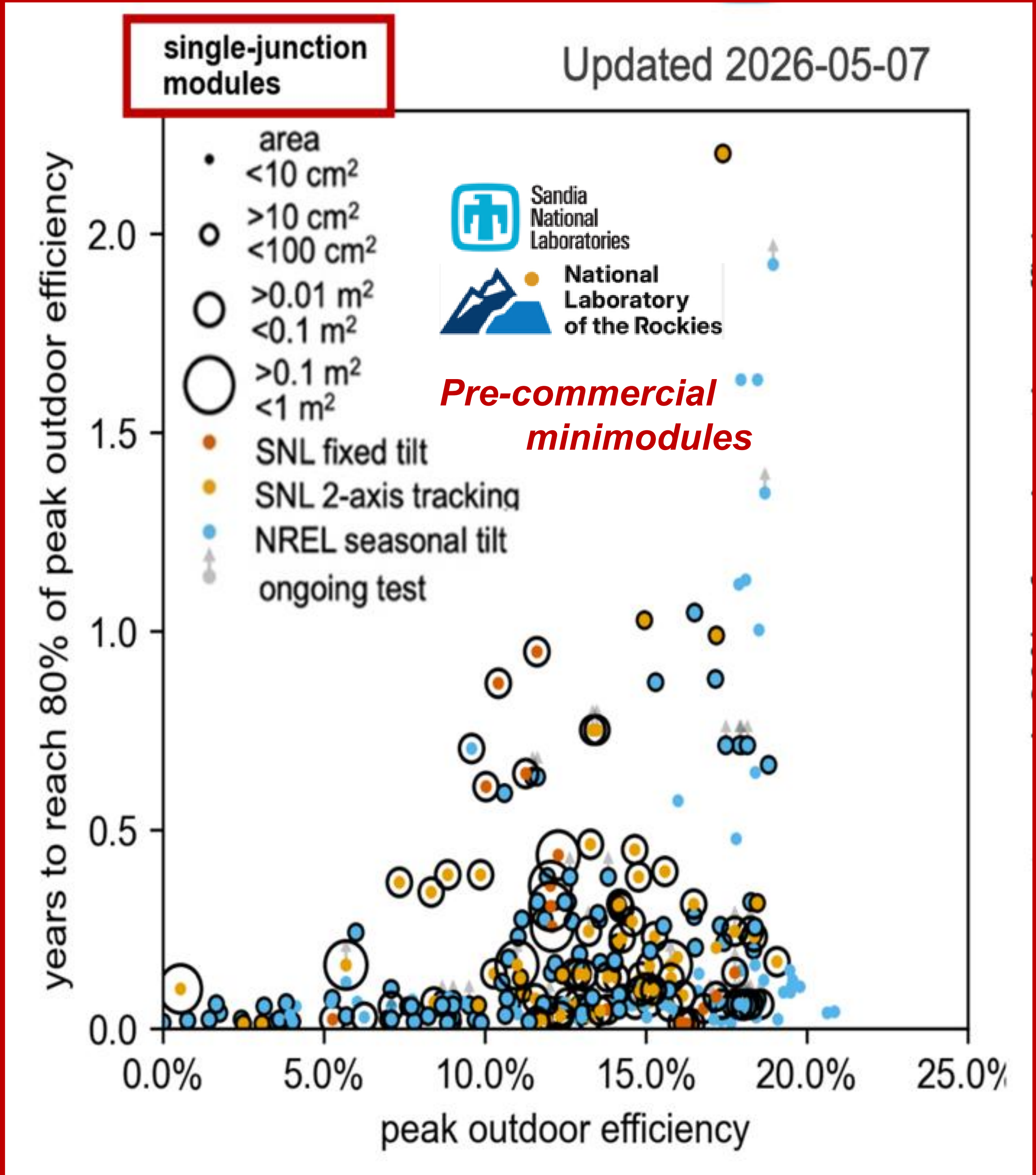
Independent third-party testing required!

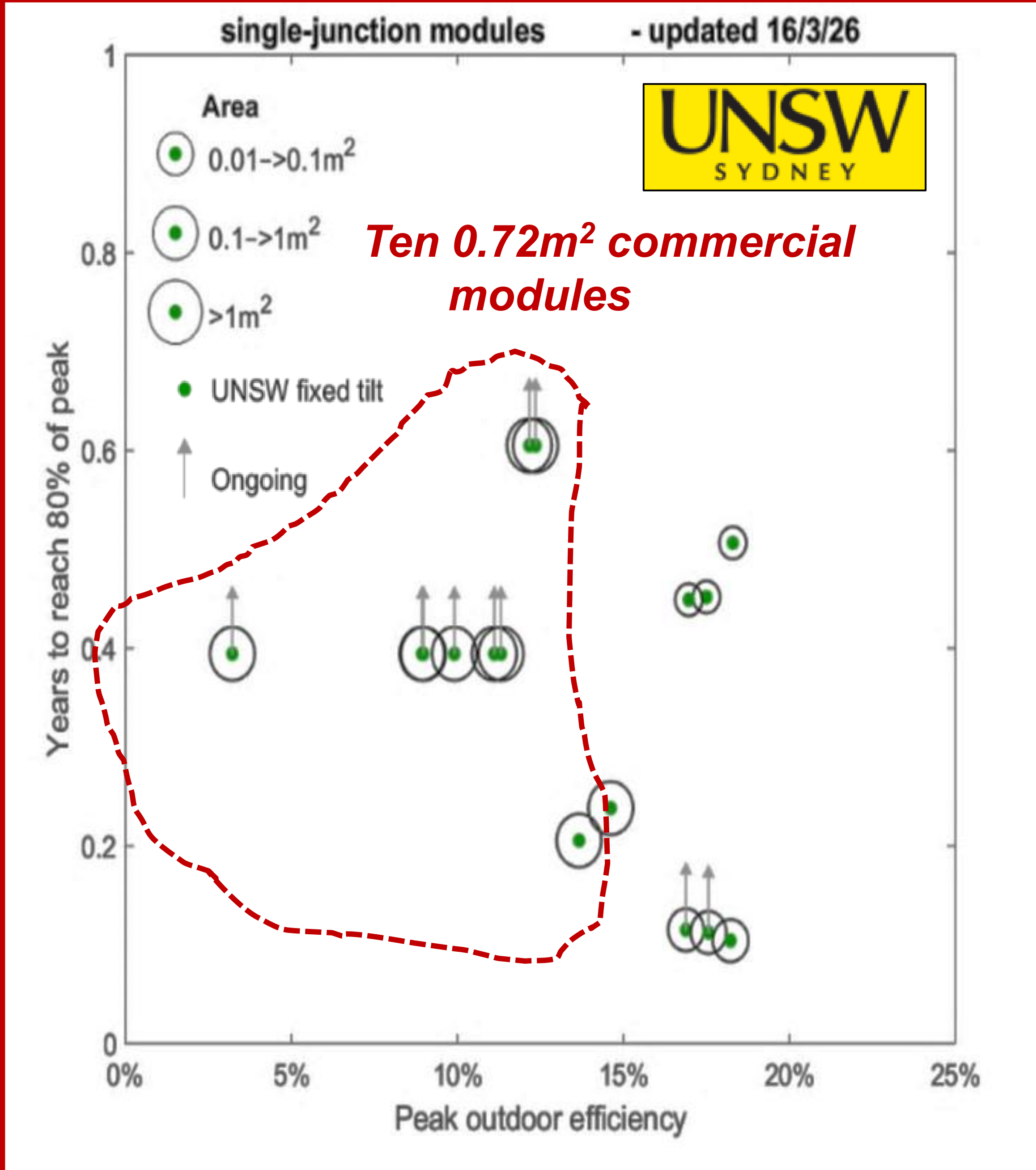
UNSW initiated this in May 2025

Green *et al.*, SNEC Plenary, 2026

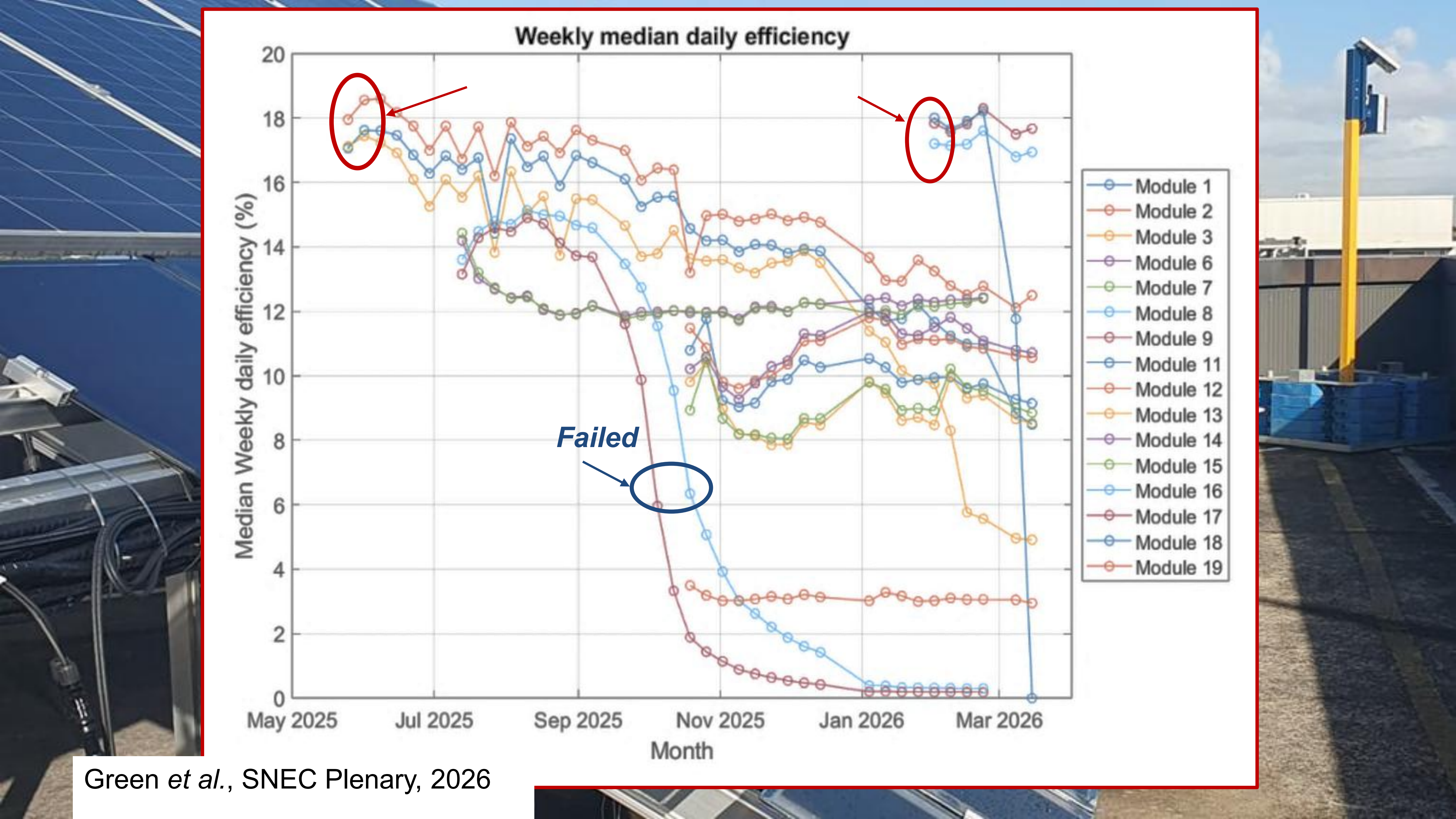
- *Field-testing commercial (& pre-commercial) perovskite modules*
- *Voluntary anonymized participation – all key players involved*
- *Quarterly reports – anonymized data for whole field*
- *Failed module diagnostics with mitigation suggestions*

Green *et al.*, SNEC Plenary, 2026

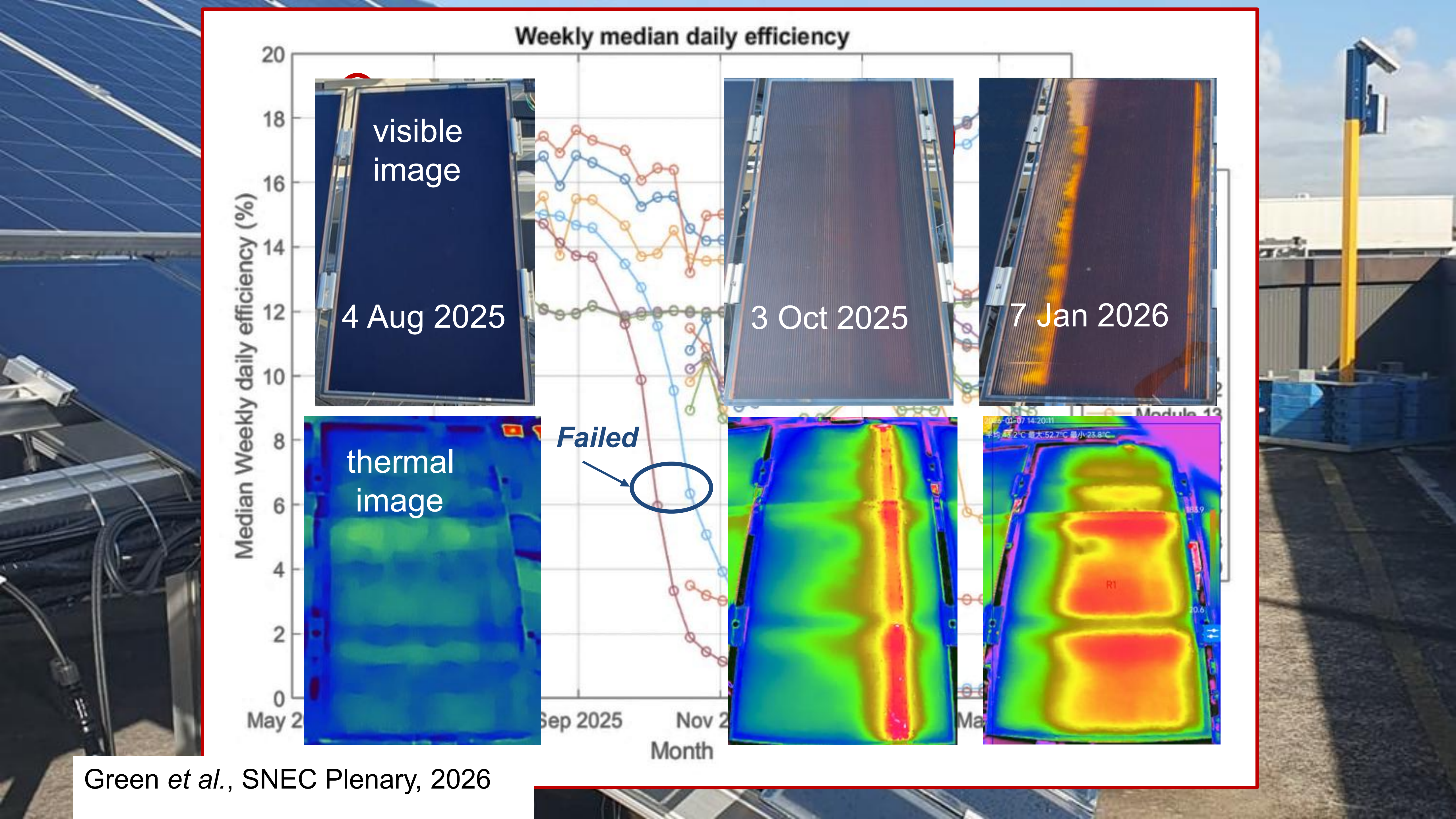




Green *et al.*, SNEC Plenary, 2026



Green *et al.*, SNEC Plenary, 2026



Green *et al.*, SNEC Plenary, 2026

Phase II

Green *et al.*, SNEC Plenary, 2026

Beyond the Standard: From Mechanism to Bankable Lifetime

Standards detect infant failures, they **don't predict or guarantee** 25+ year lifetime. **The problems are technology-specific and mechanistic, and so are the solutions.**

WHAT WE FOUND		WHAT WE CAN DO FOR YOU
HJT & TOPCon carry unique failure modes absent in PERC	→	**Cell-level failure-mode diagnostics** Reproduce your DH/field failures, identify root cause — 10–100× faster than module testing
Encapsulant additives react with metallisation & dielectric films	→	**Encapsulant & BOM screening** Flag additive–metallisation incompatibilities before they cost 25-year reliability
UVID is mechanistic — up to 5× spread across the supply chain	→	**Accelerated UVID qualification + yield modelling** Rank sensitivity in days; UVID built into lifetime predictions, not derate guesses
Perovskite has a real, unresolved reliability gap	→	**Independent perovskite field-testing** Join the anonymised program @UNSW, ahead of GW deployment

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Running in P2AgentX: our yield & degradation models give your farm's AI the means to detect and act on losses before they compound.

ARENA · Australian Government · Australian Renewable Energy Agency · ACAP · Trailblazer Recycling & Clean Energy

b.hoex@unsw.edu.au

All technical papers can be found on Publications – UNSW Hoex Group

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