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Laboratorio SUPSI PVLab

Applied Photovoltaic Research
Swiss Solar Competence

SUPSI

Alpine PV Modules: Mechanically Robust, Yet UV-Sensitive? Insights from Mechanical Load and UV Stress Testing

SUPSI Industry Day 2026

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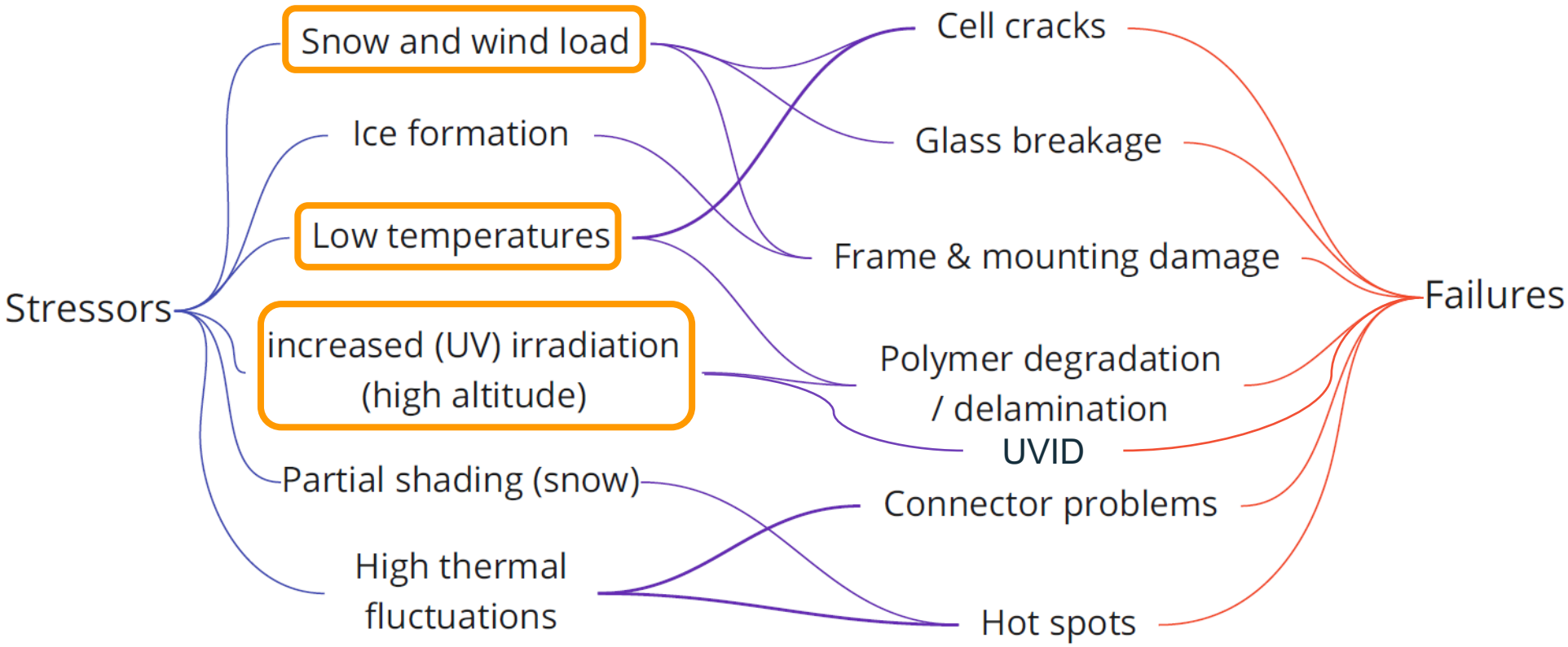
21 May 2026

Mendrisio

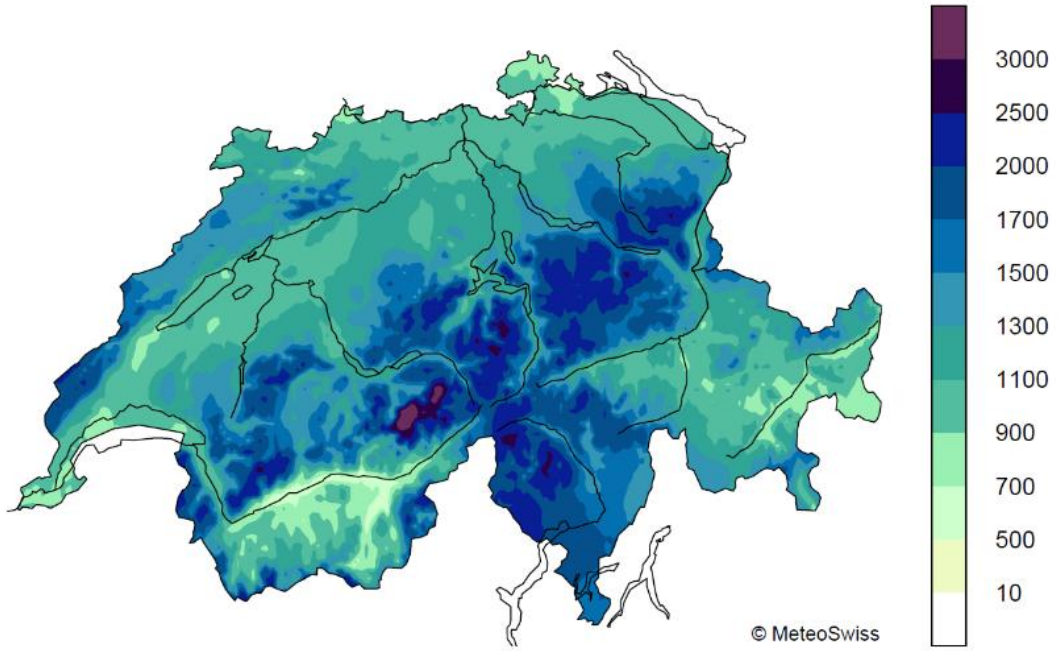
Alpine PV Stressors

Alpine PV Stressors



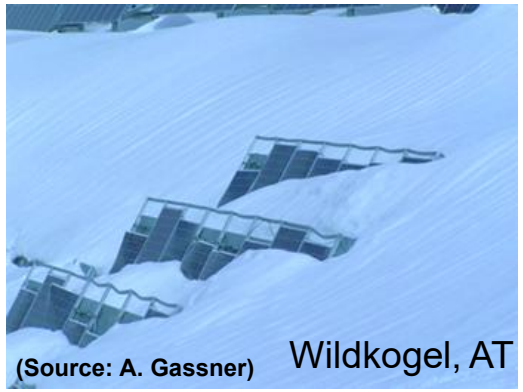
Modified from G. Friesen et al. (2025), Optimisation of Photovoltaic Systems for Different Climates, PVPS Task 13 Report

Snow Loads (Static Mechanical Load)

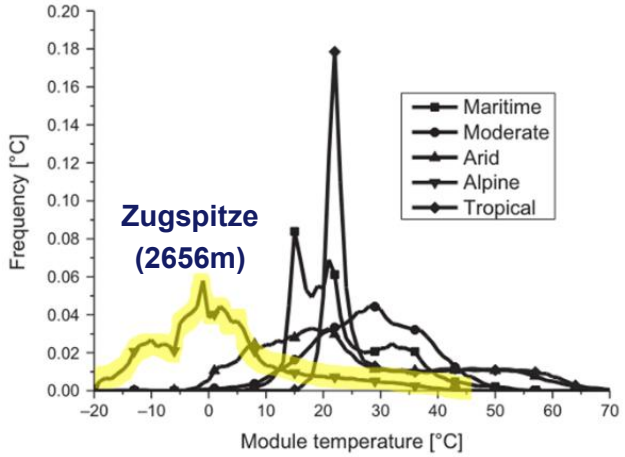


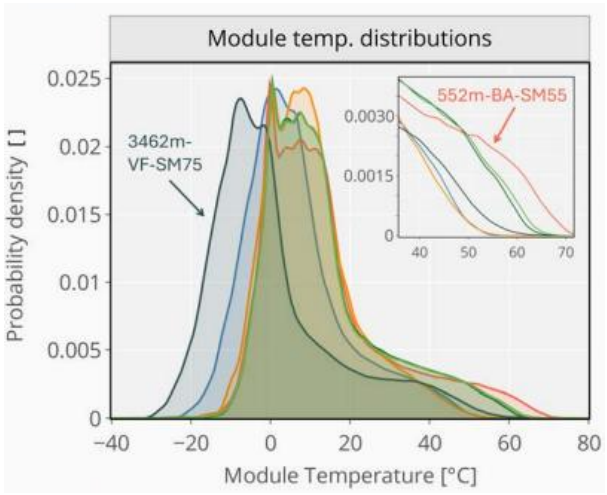
Annual total precipitation in Switzerland [mm]

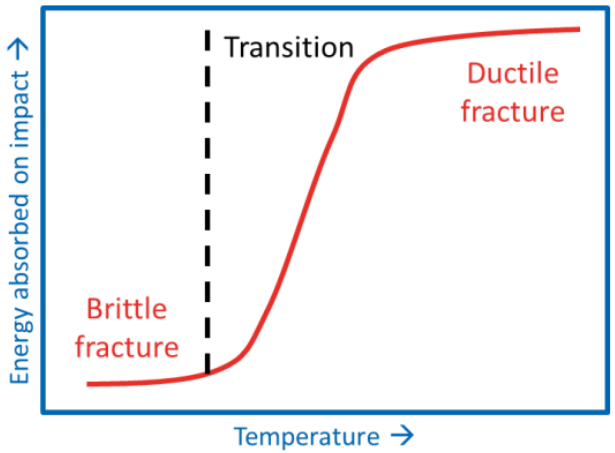
- Snow accumulation (after 1200-1500 masl, snow is the dominant precipitation)
- Higher mechanical stress
- **Solutions → Module, mounting and system design**



Low Temperatures



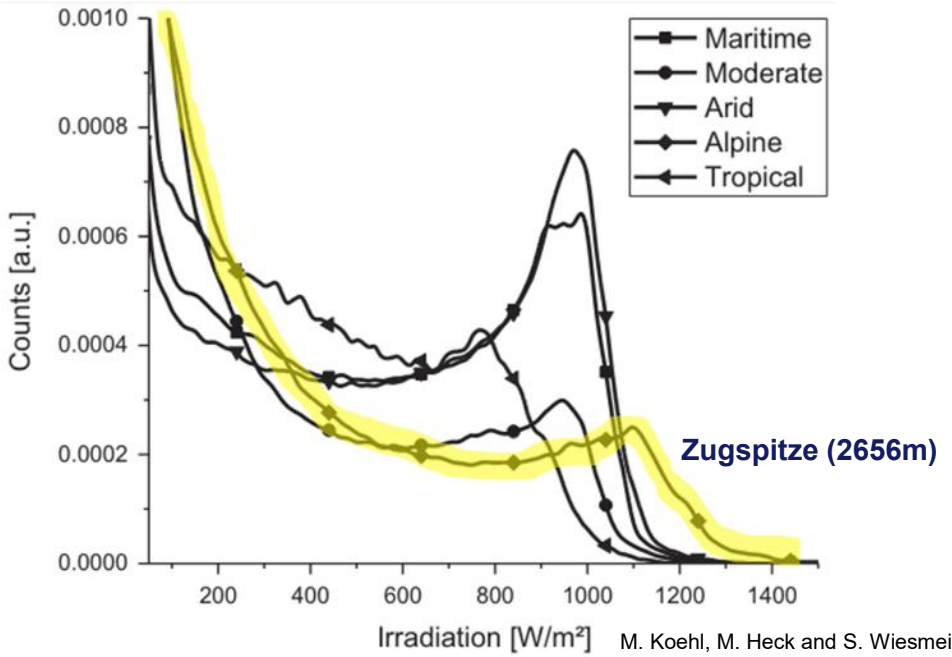




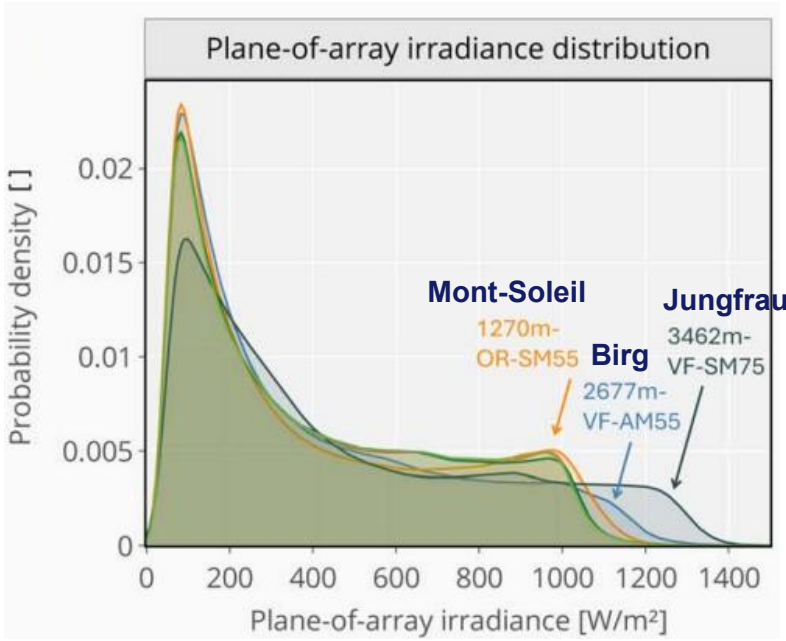
IEA Task 13: Optimisation of Photovoltaic Systems for Different Climates

- Very low temperatures (< -15 ˚C)
- At low temperatures, polymers are in a glassy state, indicating that the material is **rigid and brittle** → stiff encapsulant cannot deform as easily to absorb and distribute mechanical loads → higher stress concentrations in the solar cells and interconnections

High Irradiance (*High UV Irradiance*)



M. Koehl, M. Heck and S. Wiesmeier, En. Sci. & Eng., 2018, doi: 10.1002/ese3.189



E. Özkalay, H. Quest, A. Gassner, et al., doi: 10.1039/D4EL00040D

Birg & Jungfraujoch are only facade!

- High irradiance *(Front-side >1600 W/m² from private discussions in CH)*
- Front+Rear Irradiance >1800 W/m² expected
- High current due to high albedo + bifaciality
- **Stress on busbars/ribbons and bypass diode**

- High altitude → high UV
- Snow albedo is UV rich [1]
- **Stress on polymeric materials**
- **Stress on UV-sensitive solar cell technologies (i.e. TOPCon, PERC, HJT, BC)**

[1] M. P. Brennan et al., "Effects of spectral albedo on solar photovoltaic devices," Sol. Energy Mater. Sol. Cells, doi: 10.1016/j.solmat.2014.01.046.

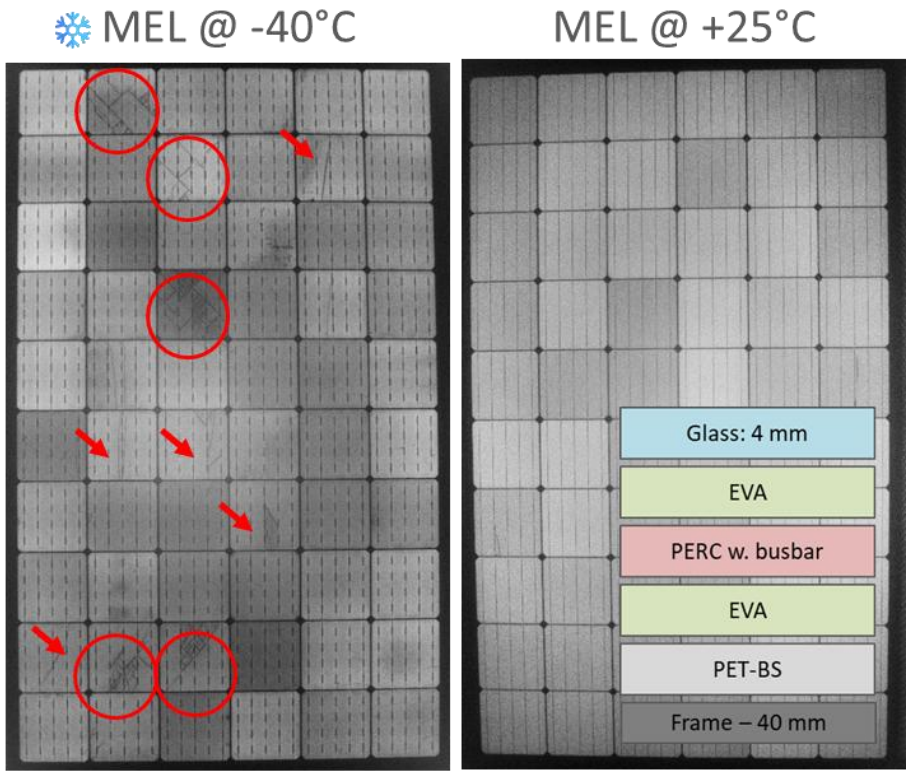
Alpine PV Module Testing within ALIENCE Project

Alpine PV Module Testing – PV Modules

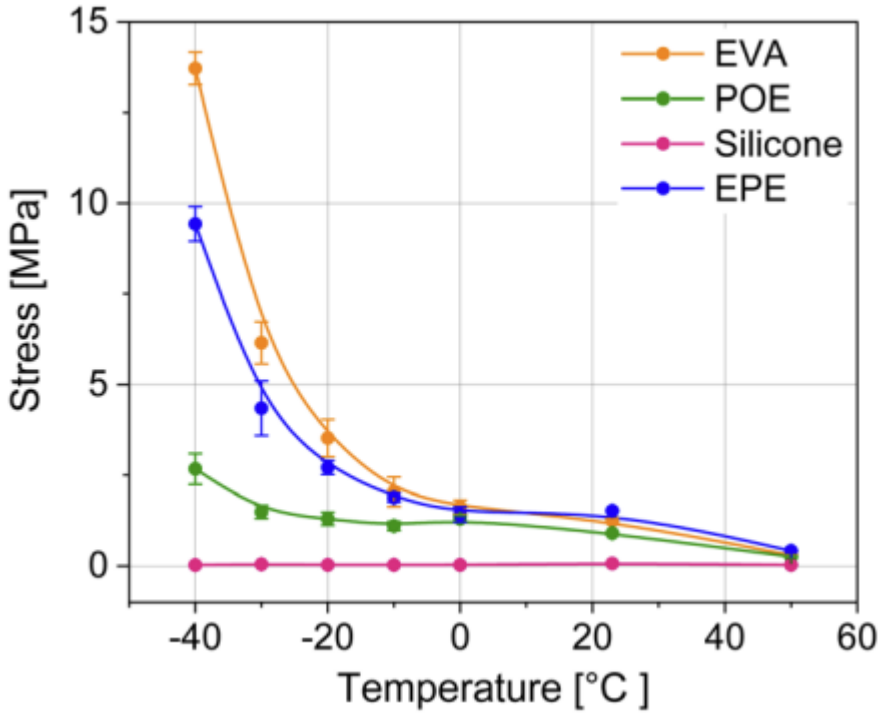
	Module Construction	Glass Thickness	Frame	Solar Cell	Encapsulant	Number of cells
Module-1 (Standard module)	Glass / Glass	2 mm / 2 mm	35 mm aluminum frame	TOPCon / half-cell	EVA	108
Module-2 (Alpine-relevant)	Glass / Glass	3.2 mm / 3.2 mm	Reinforced 40 mm aluminum frame	TOPCon / half-cell	EPE	108
Module-3 (Alpine-relevant)	Glass / Glass	2.8 mm / 2.8 mm	Reinforced 35 mm aluminum frame	TOPCon / half-cell	EPE	108
Module-4 (Alpine-relevant)	Glass / Glass	3.2 mm / 3.2 mm	Reinforced aluminum frame	TOPCon-based Back Contact / half-cell	EPE	108
Alpine-relevant: *Either designed for Alpine conditions, planned to install or installed in Alpine conditions in Switzerland.*						

Alpine PV Module Testing – Mechanical Load (MEL) Test Sequence

EL images after +5400 Pa

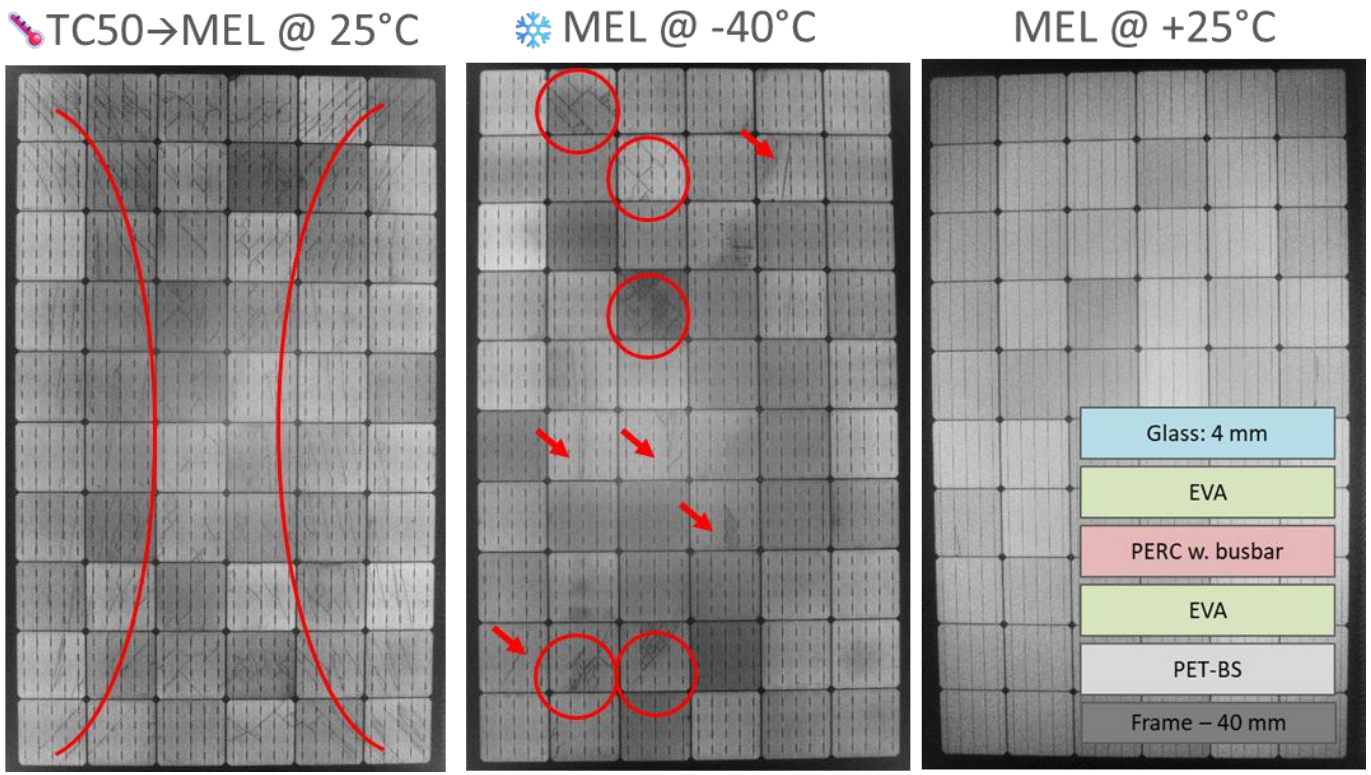


A. Gassner et al., “Enhanced Mechanical Load Testing of Photovoltaic Modules for Cold and Snowy Climates”, 2026, EES Solar

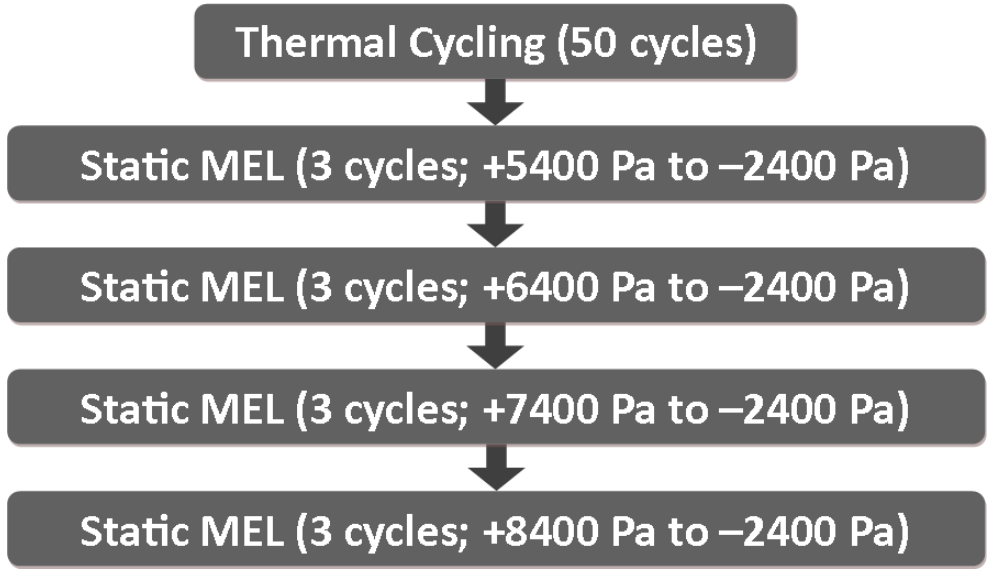


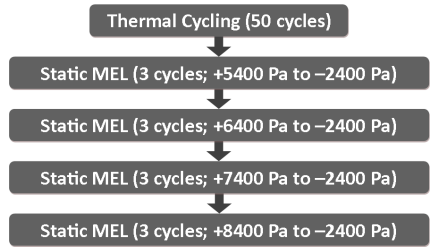
Alpine PV Module Testing – Mechanical Load (MEL) Test Sequence

EL images after +5400 Pa

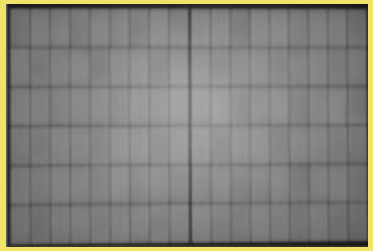
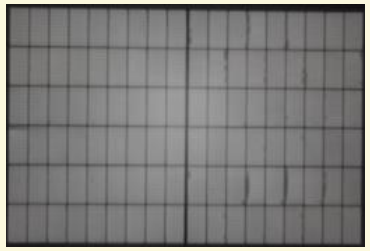
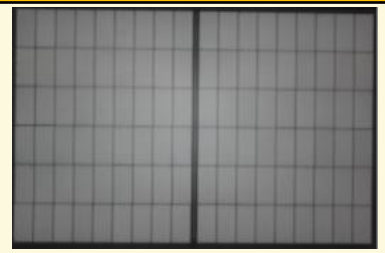
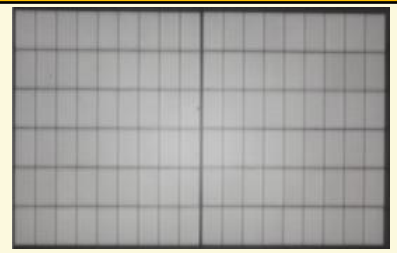
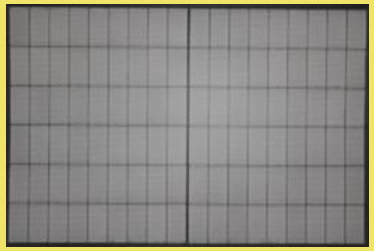
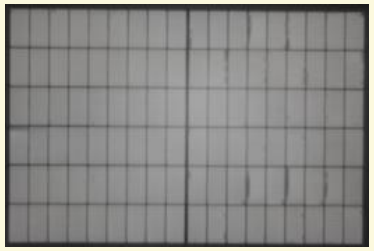
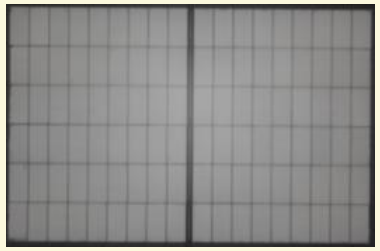
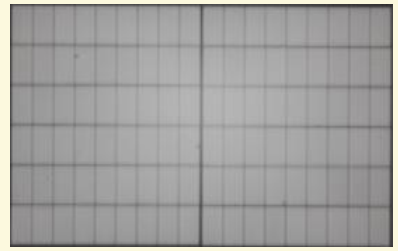
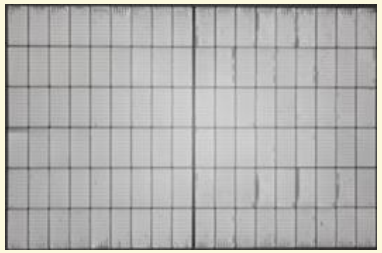
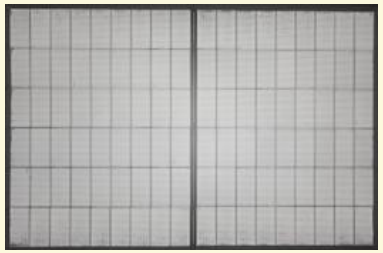
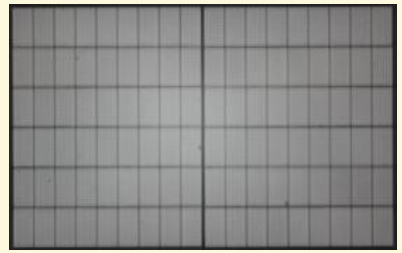


A. Gassner et al., “Enhanced Mechanical Load Testing of Photovoltaic Modules for Cold and Snowy Climates”, 2026, EES Solar





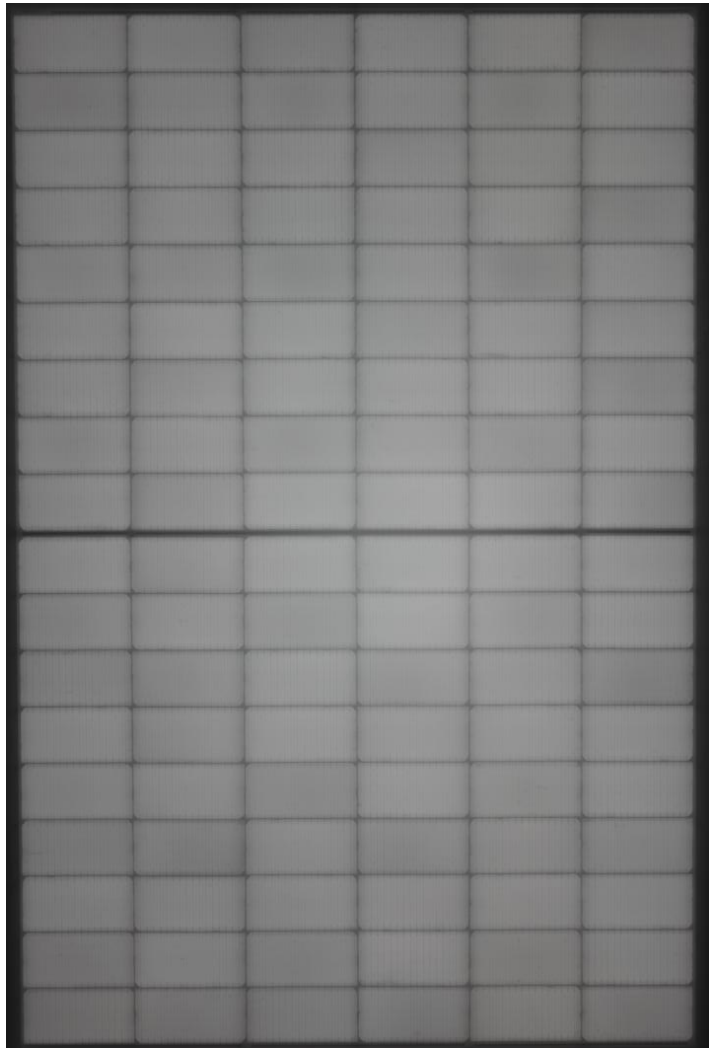
Alpine PV Module Testing – Mechanical Load (MEL) Test Sequence

	Module-1 (Standard)	Module-2 (Alpine-relevant)	Module-3 (Alpine-relevant)	Module-4 (Alpine-relevant)
Initial				
3 X +5400 Pa & -2400 Pa				
3 X +8400 Pa & -2400 Pa	-			
Result	✗ FAIL	✓ PASS	✓ PASS	✓ PASS
Key Observation	Glass breakage at +5400 Pa	Pre-existing + load-induced damages (damaged soldering and cell fingers)	Load-induced microcracks, damaged cell fingers & darkening on interconnection areas	Load-induced minor changes (small dark areas) in EL images

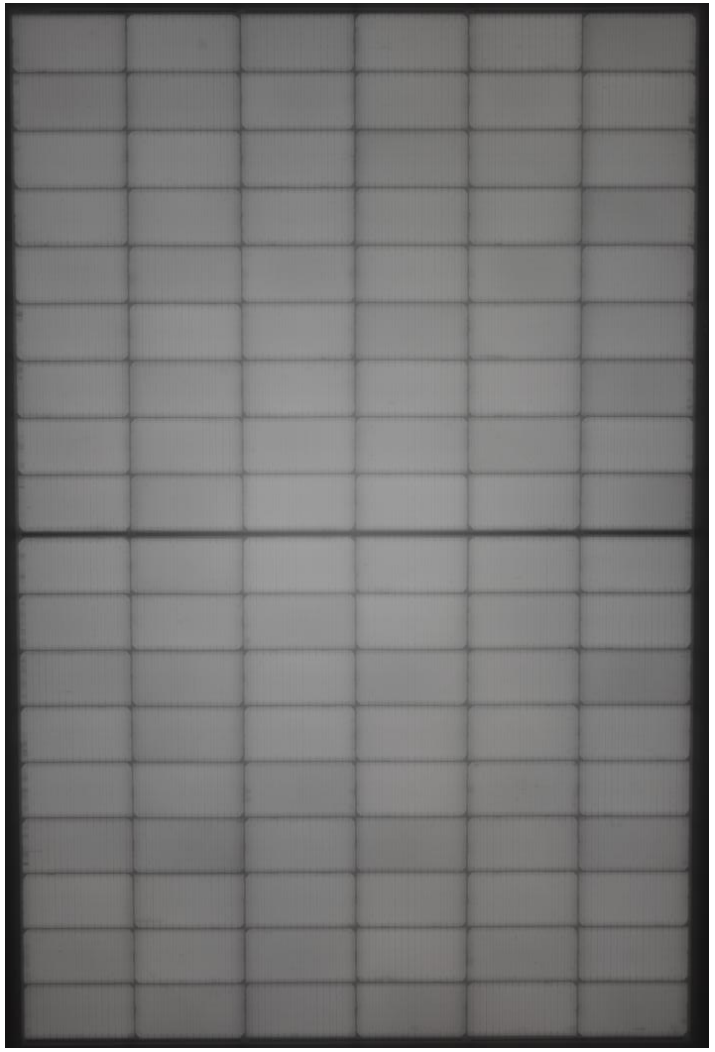
Mechanical Load (MEL) Test Sequence
Module-1 (Standard) (2 mm / 2 mm)

Thermal Cycling (50 cycles)
↓
Static MEL (3 cycles; +5400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +6400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +7400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +8400 Pa to –2400 Pa)

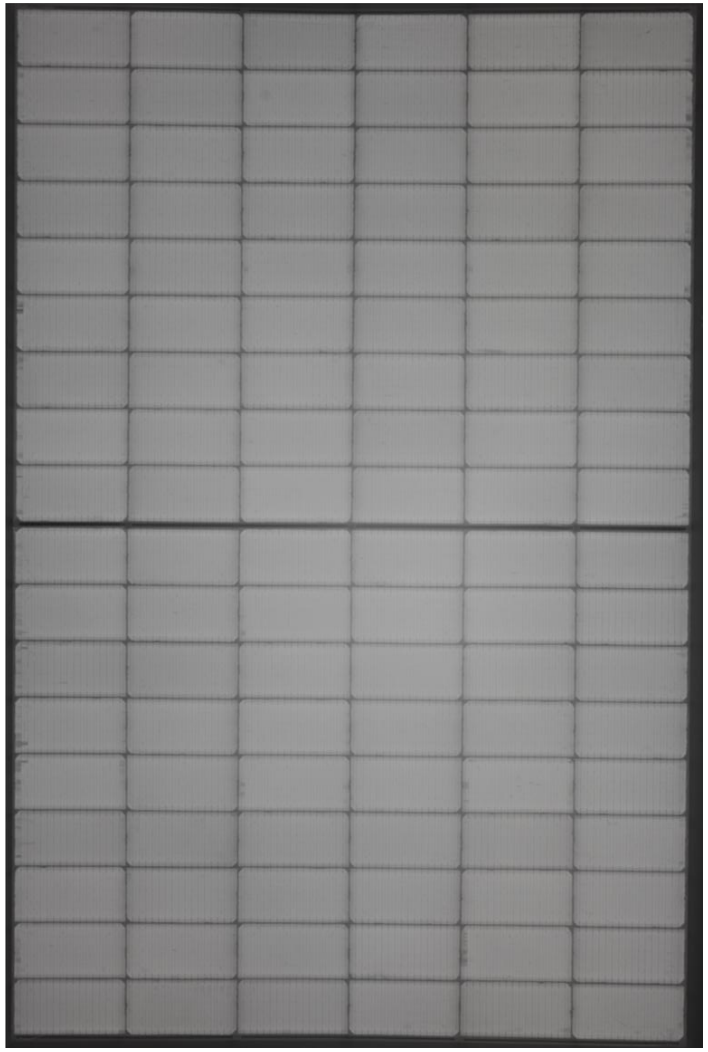
Initial



TC50

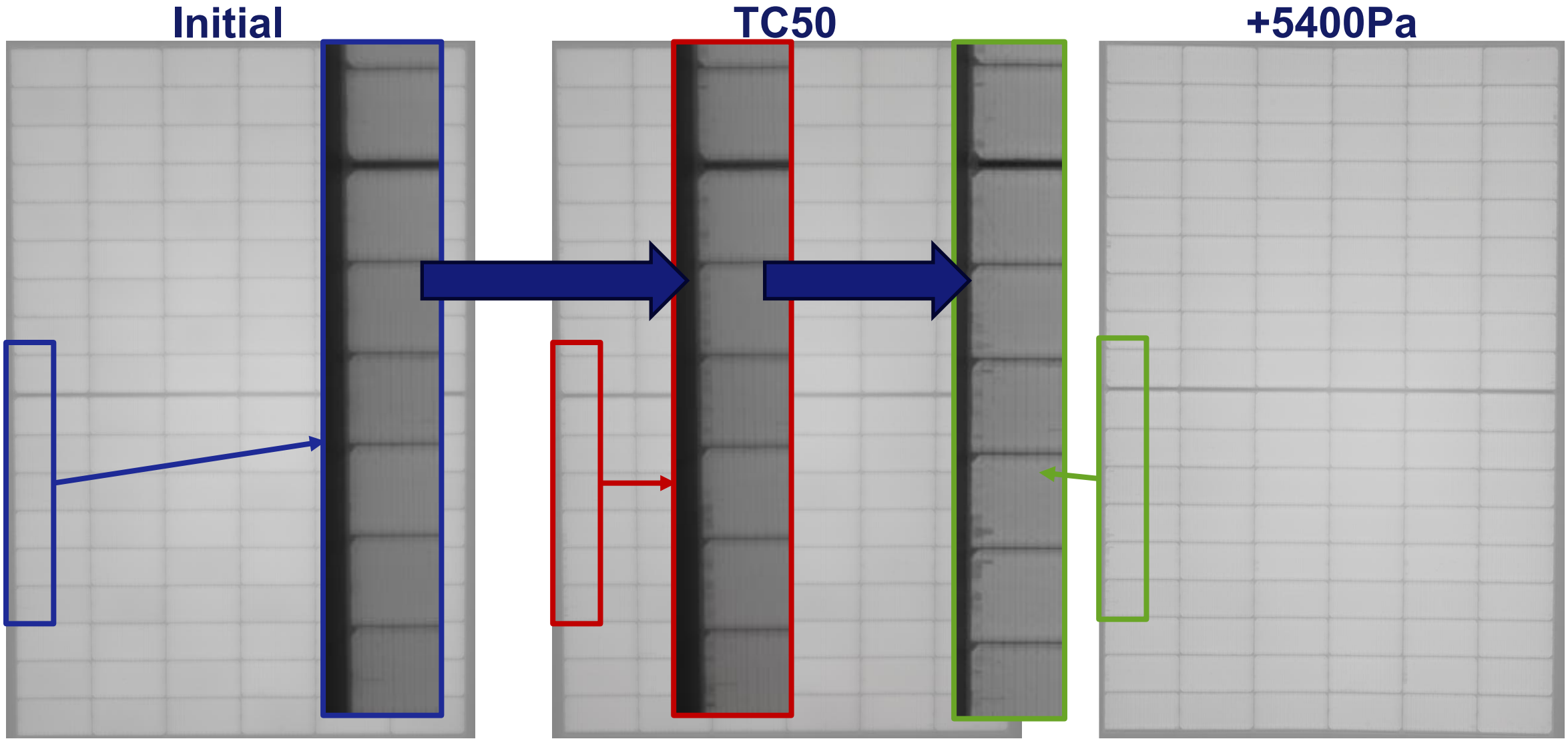


+5400Pa



Mechanical Load (MEL) Test Sequence
Module-1 (Standard) (2 mm / 2 mm)

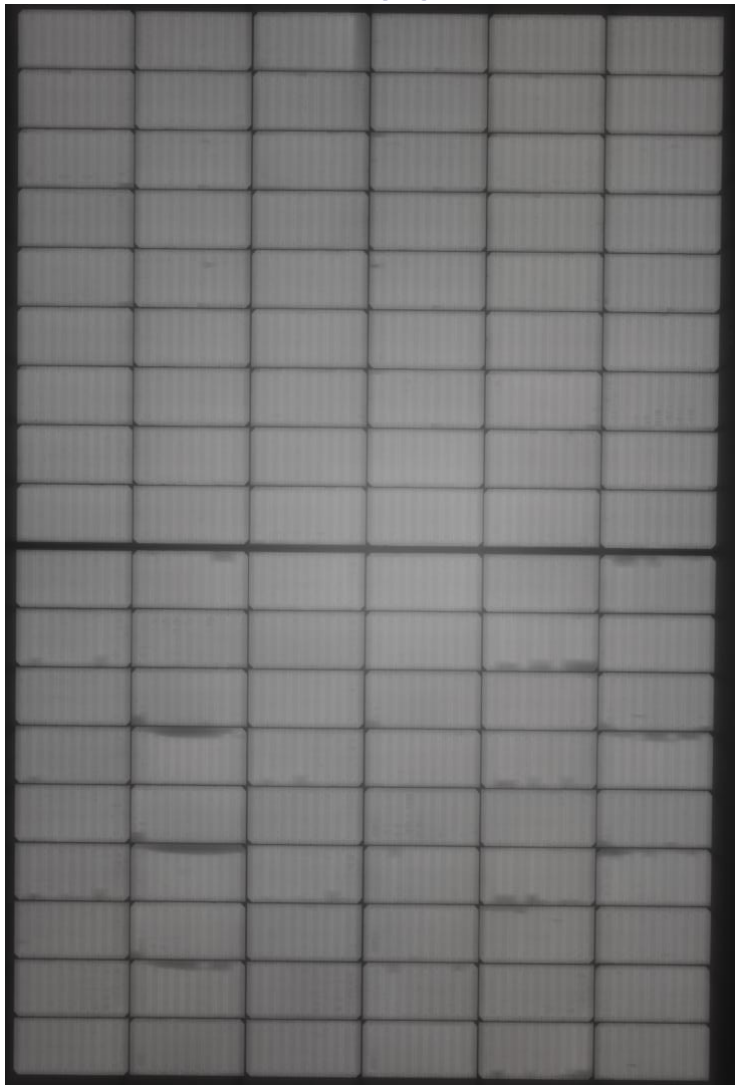
Thermal Cycling (50 cycles)
↓
Static MEL (3 cycles; +5400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +6400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +7400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +8400 Pa to –2400 Pa)



Mechanical Load (MEL) Test Sequence
Module-2 (Alpine-relevant) (3.2 mm / 3.2 mm)

Thermal Cycling (50 cycles)
↓
Static MEL (3 cycles; +5400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +6400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +7400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +8400 Pa to –2400 Pa)

Initial



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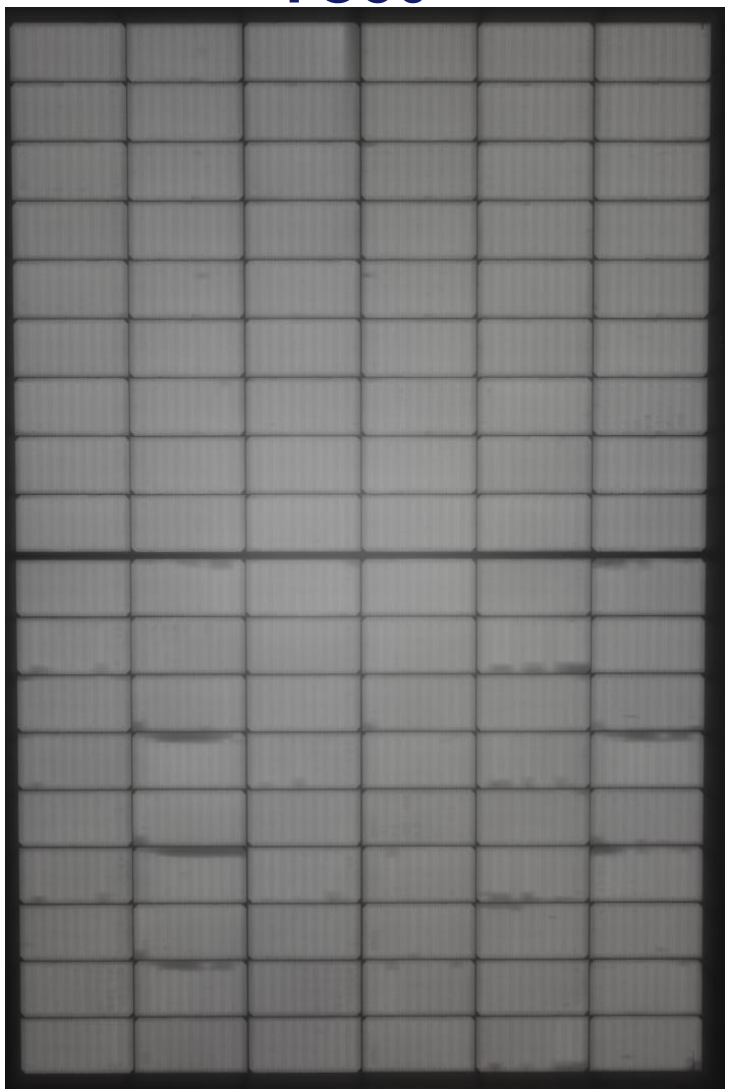
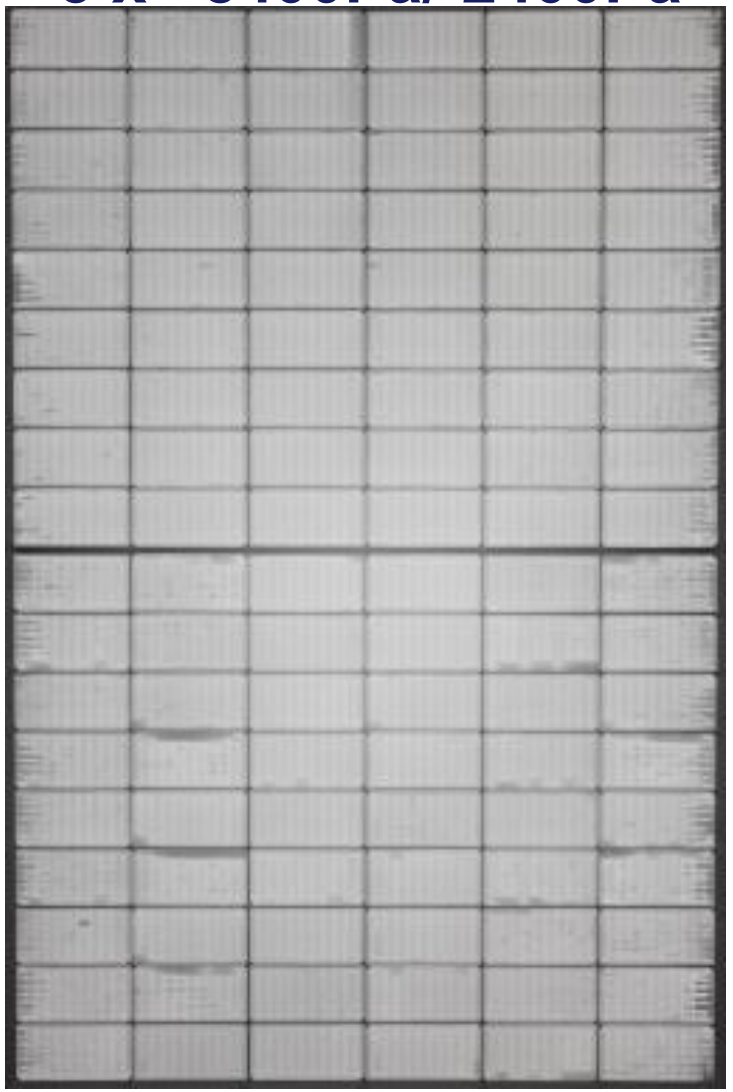
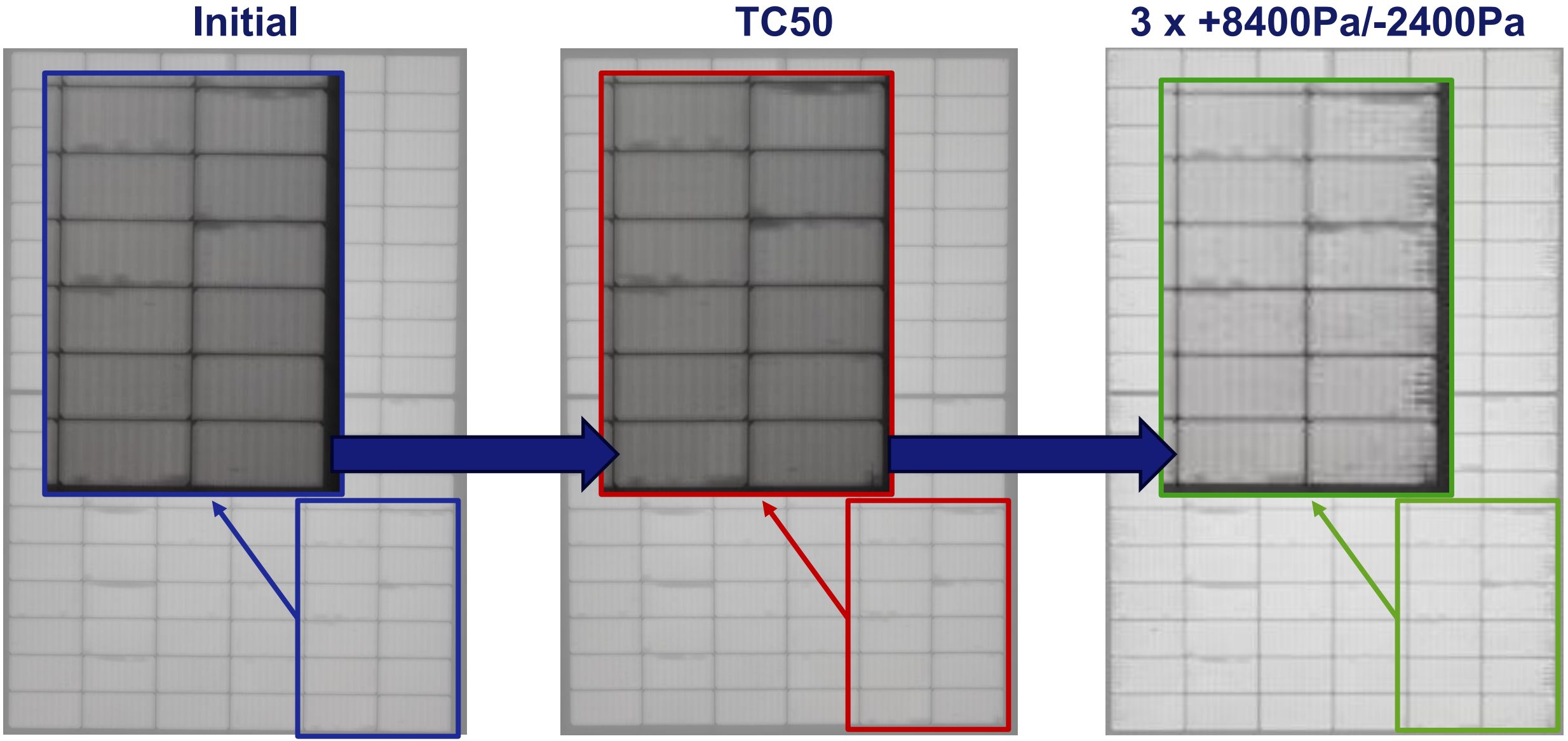


3 x +8400Pa/-2400Pa



Mechanical Load (MEL) Test Sequence
Module-2 (Alpine-relevant) (3.2 mm / 3.2 mm)

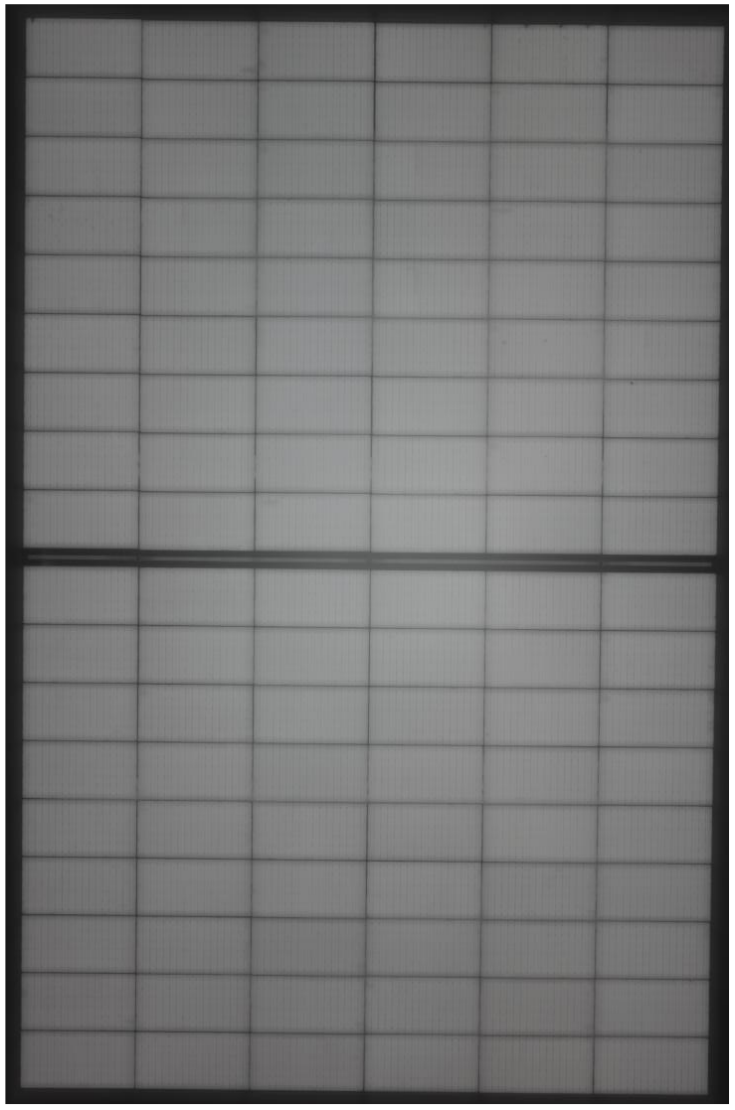
Thermal Cycling (50 cycles)
↓
Static MEL (3 cycles; +5400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +6400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +7400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +8400 Pa to –2400 Pa)



Mechanical Load (MEL) Test Sequence
Module-3 (Alpine-relevant) (2.8 mm / 2.8 mm)

Thermal Cycling (50 cycles)
↓
Static MEL (3 cycles; +5400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +6400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +7400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +8400 Pa to –2400 Pa)

Initial



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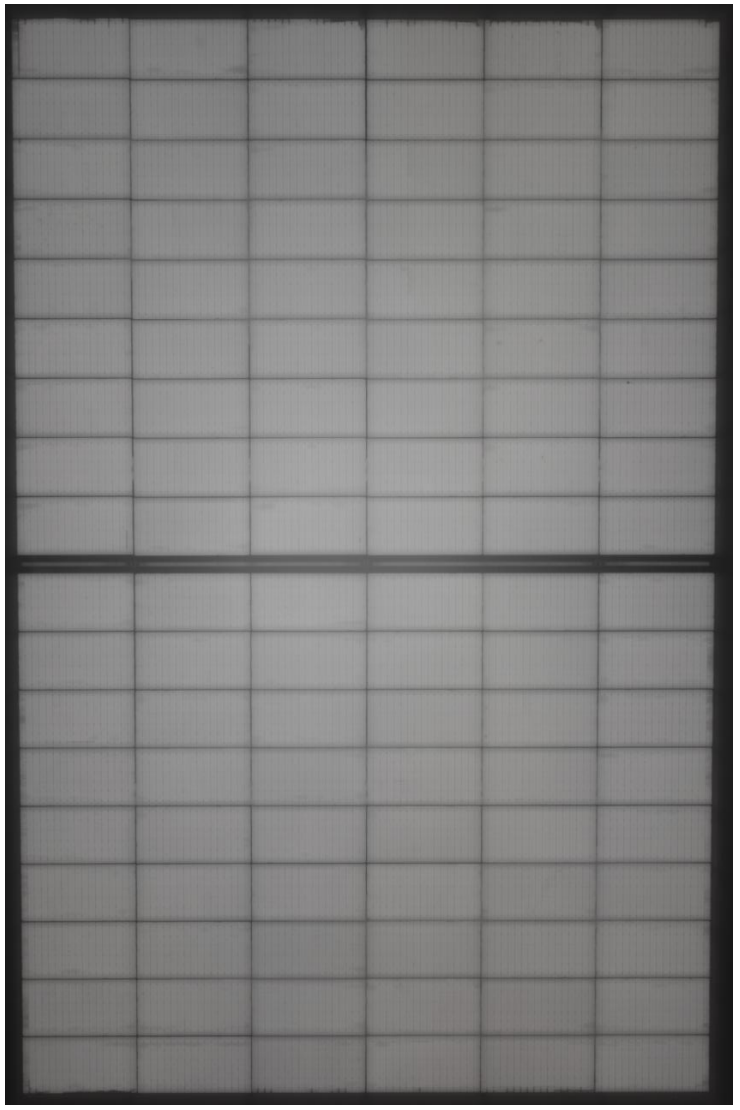
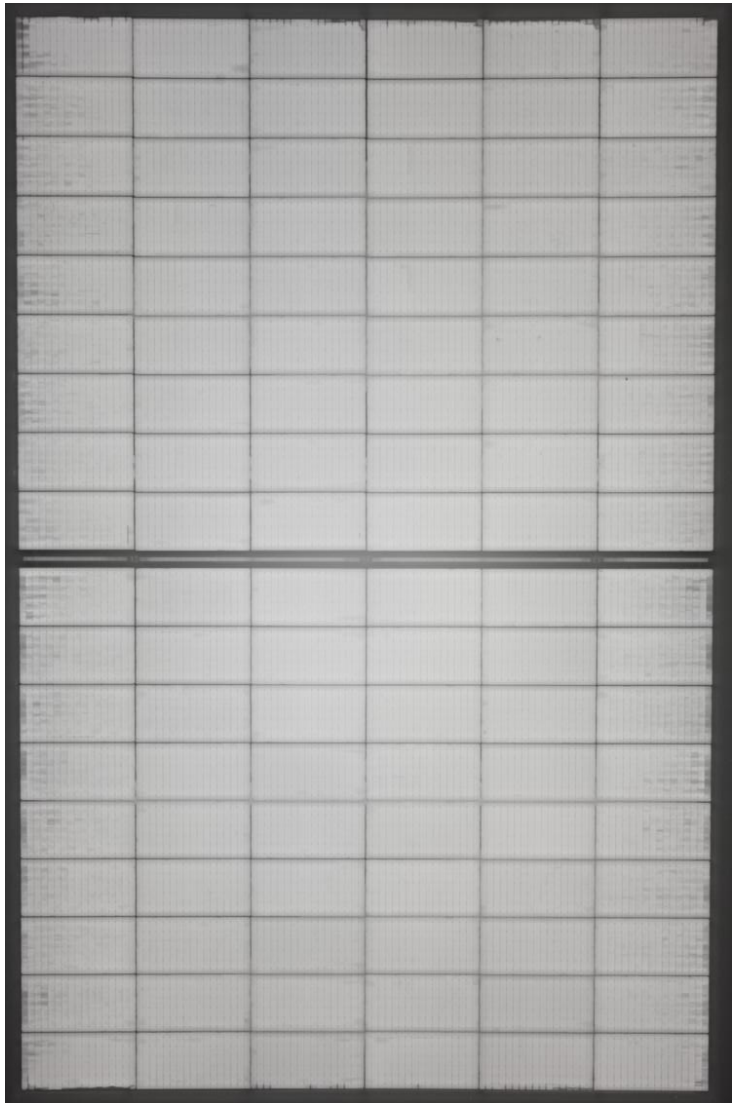
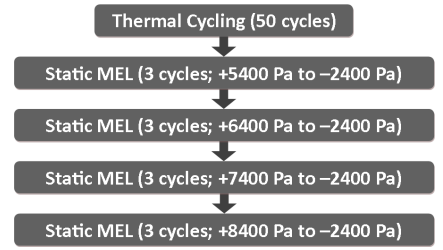


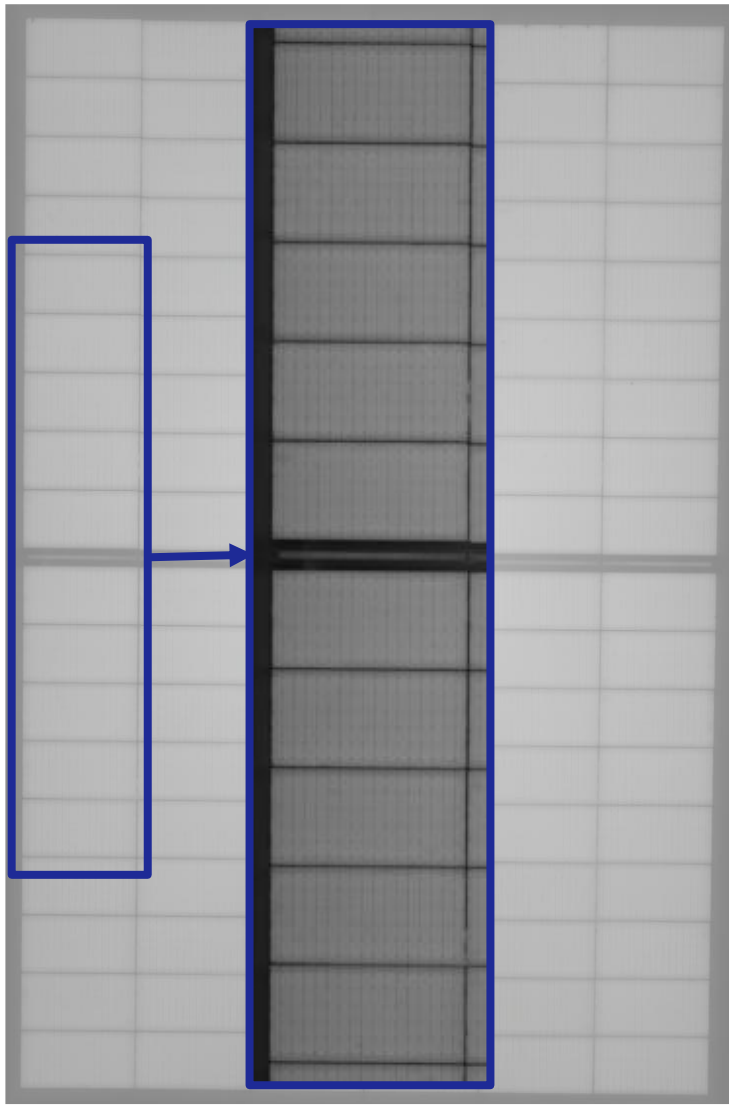
3 x +8400Pa/-2400Pa



Mechanical Load (MEL) Test Sequence
Module-3 (Alpine-relevant) (2.8 mm / 2.8 mm)



Initial



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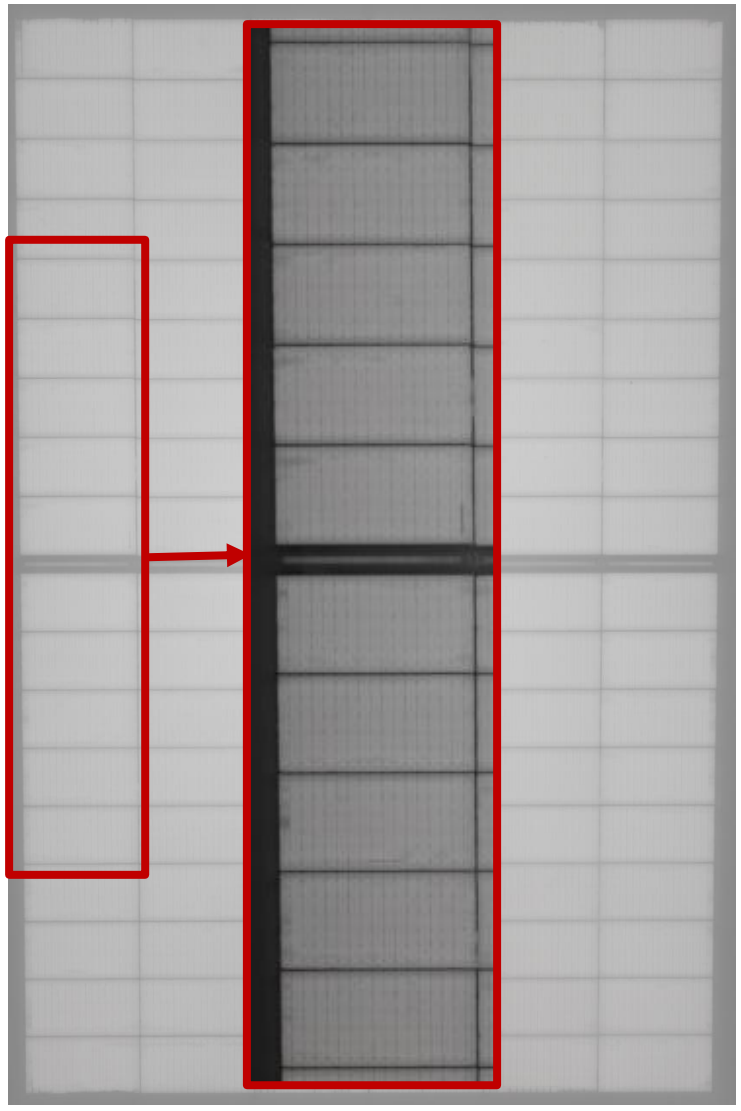
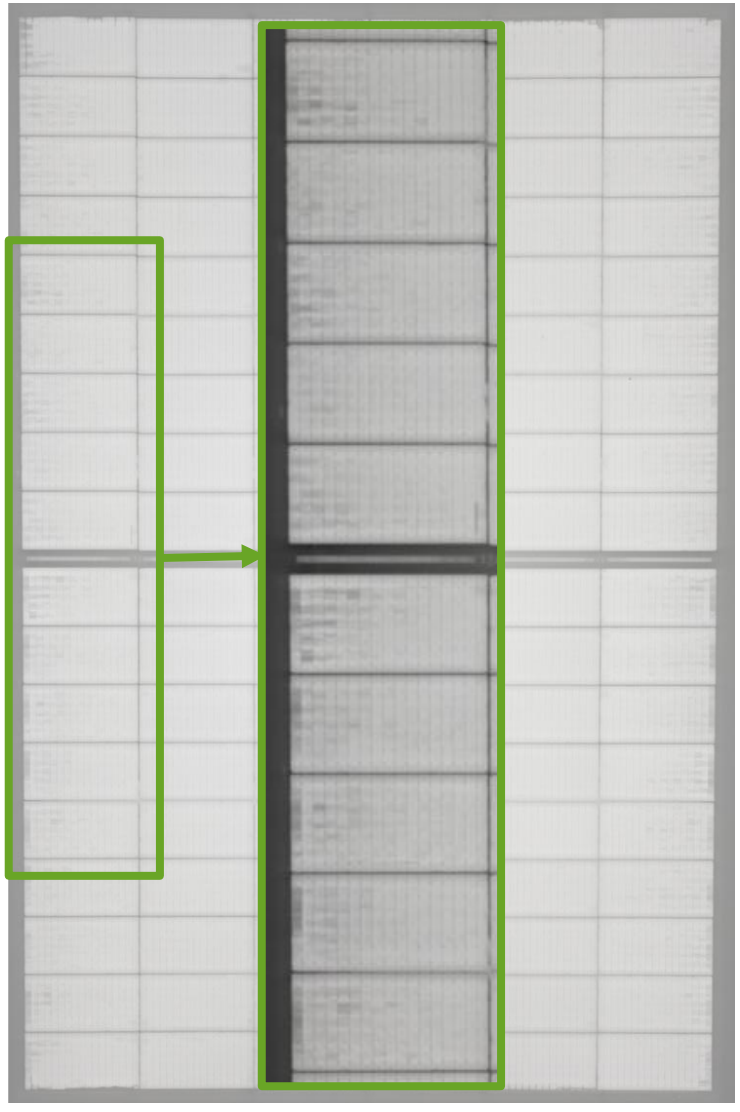


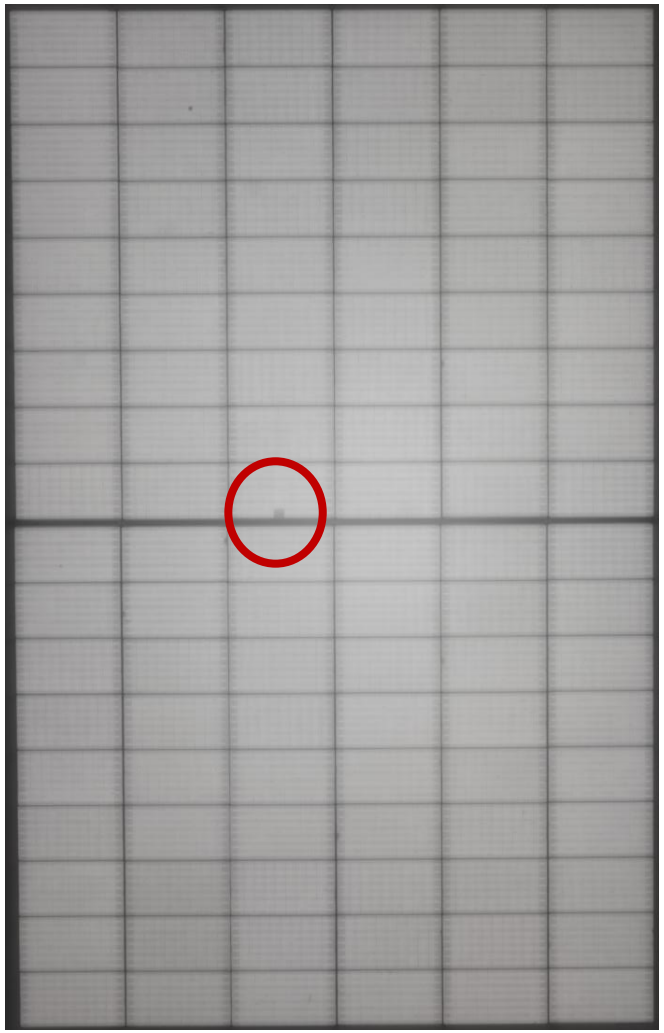
3 x +8400Pa/-2400Pa



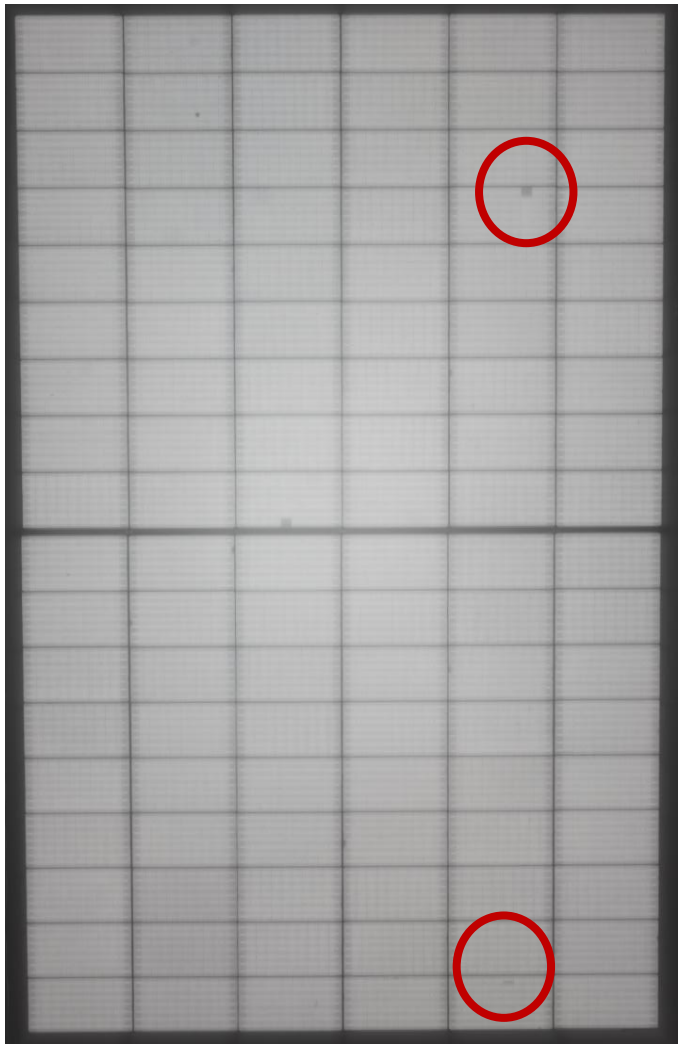
Mechanical Load (MEL) Test Sequence
Module-4 (Alpine-relevant) (3.2 mm / 3.2 mm)

Thermal Cycling (50 cycles)
↓
Static MEL (3 cycles; +5400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +6400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +7400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +8400 Pa to –2400 Pa)

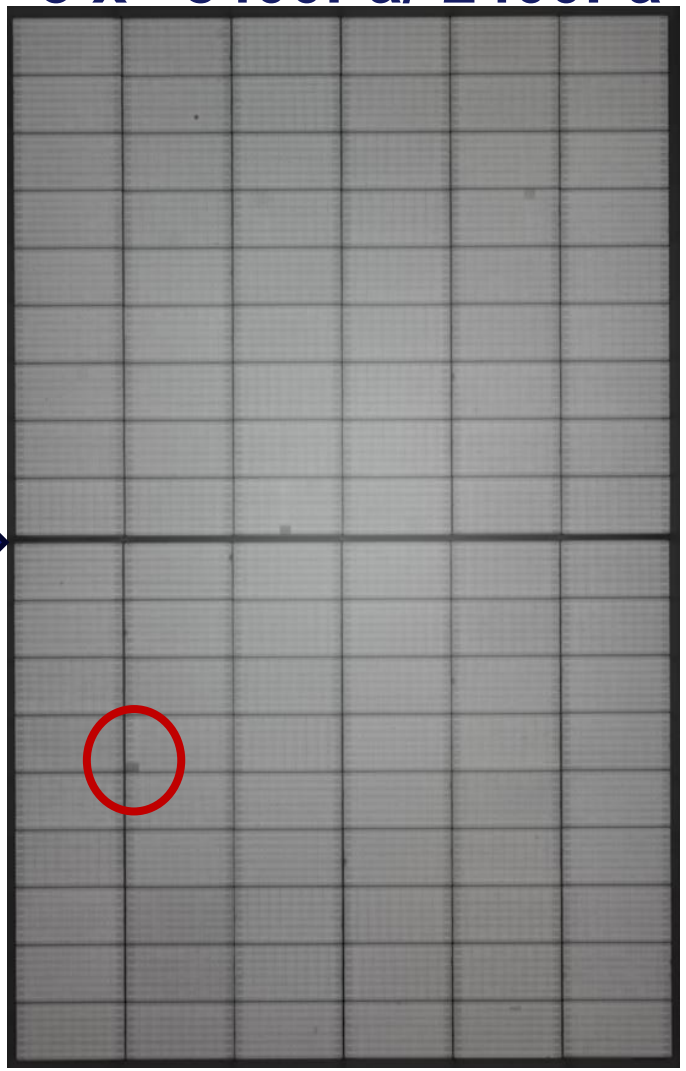
Initial



TC50



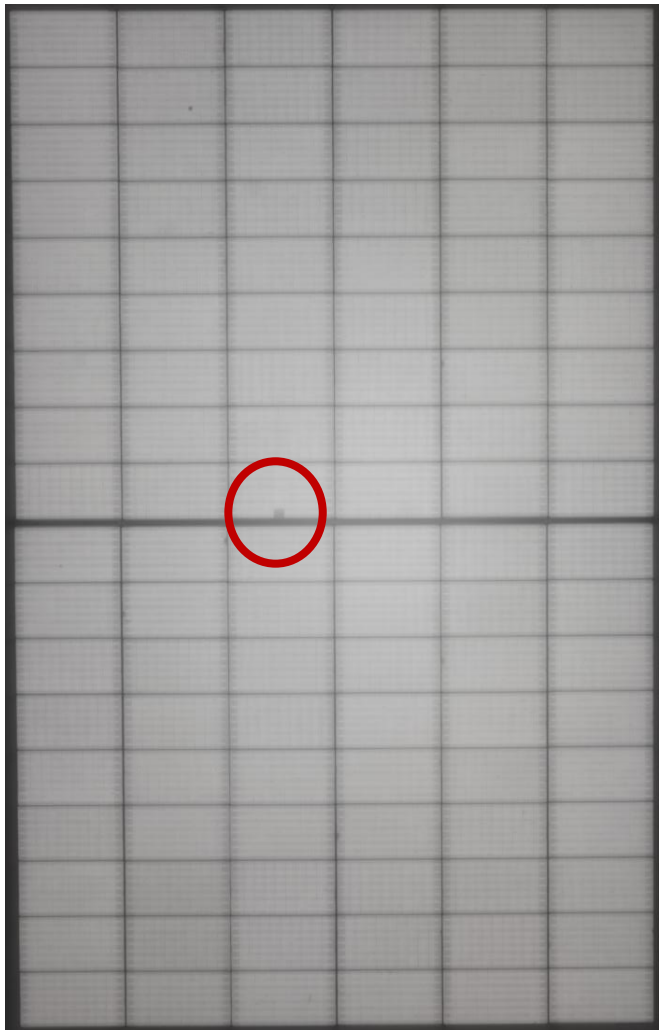
3 x +8400Pa/-2400Pa



Mechanical Load (MEL) Test Sequence
Module-4 (Alpine-relevant) (3.2 mm / 3.2 mm)

Thermal Cycling (50 cycles)
↓
Static MEL (3 cycles; +5400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +6400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +7400 Pa to –2400 Pa)
↓
Static MEL (3 cycles; +8400 Pa to –2400 Pa)

Initial



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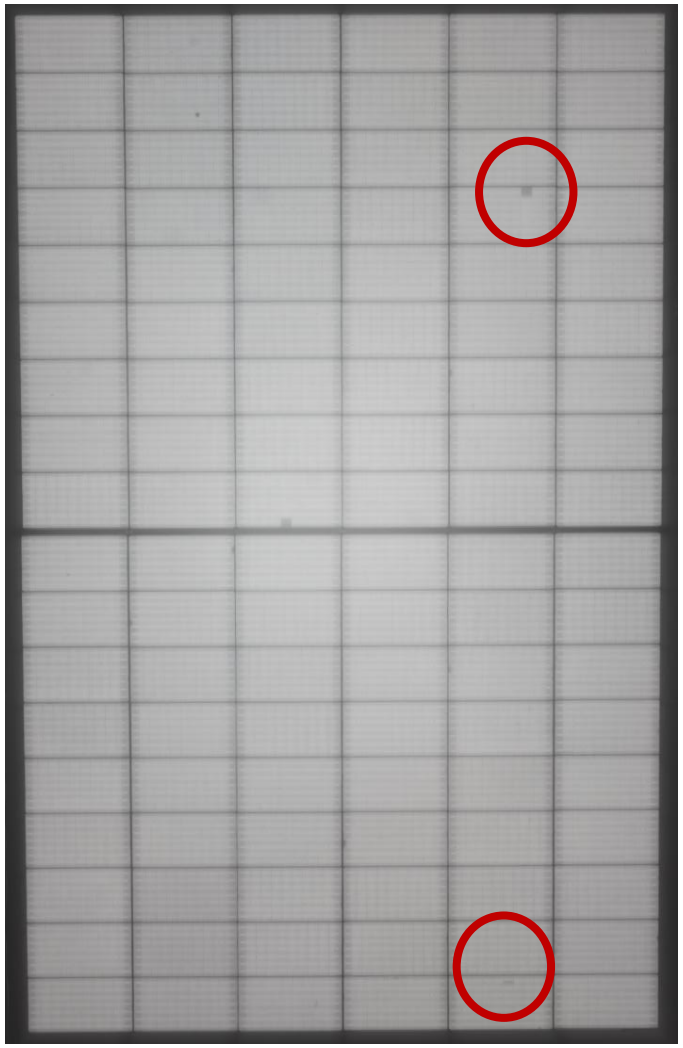
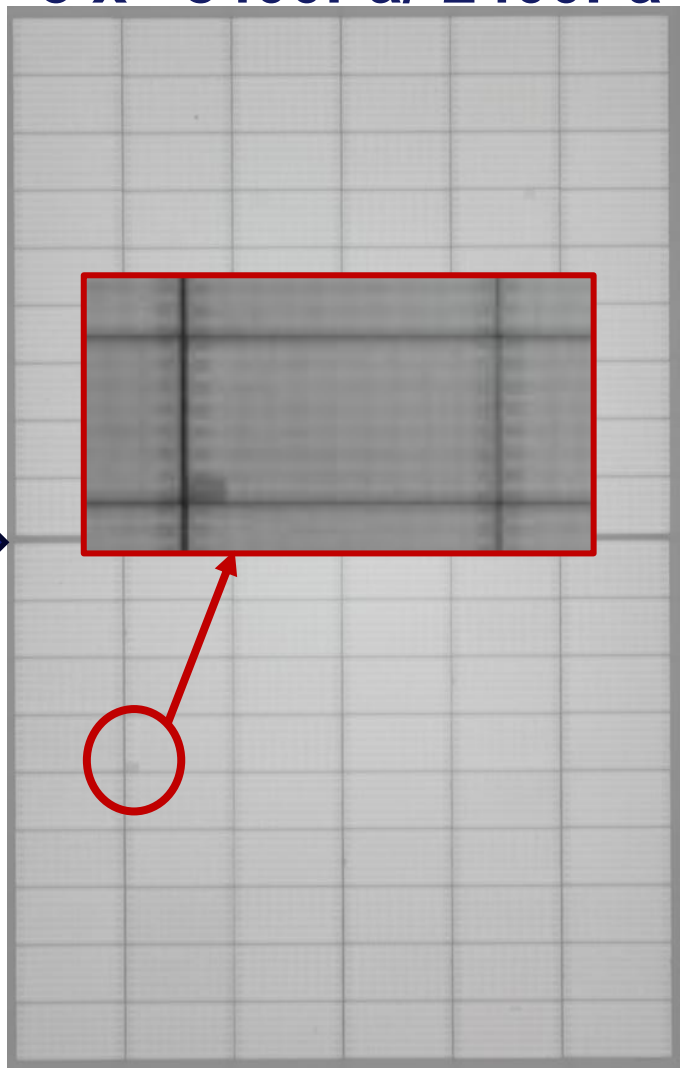
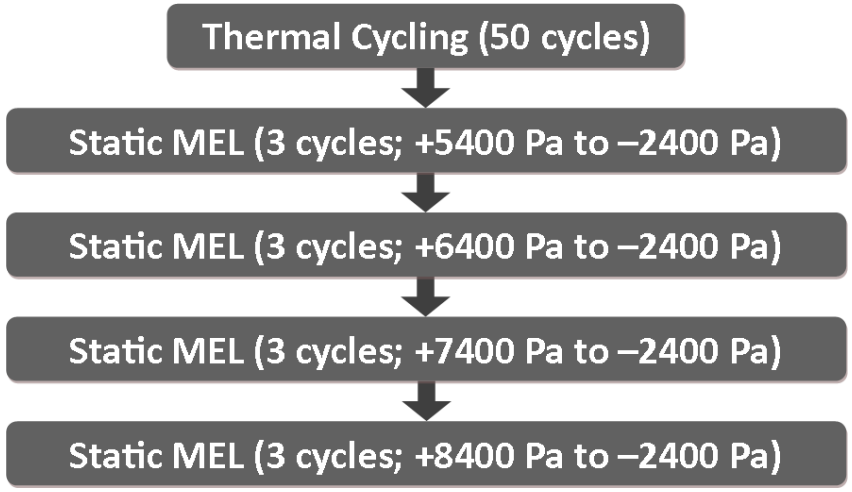


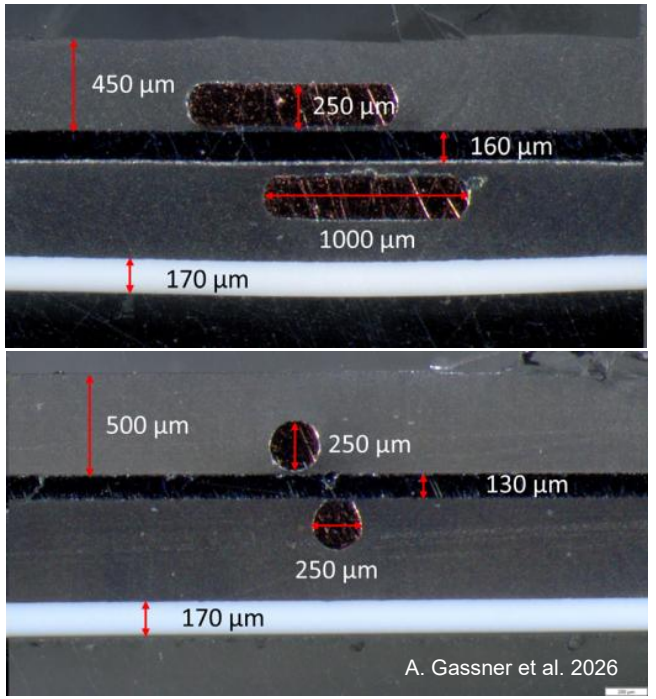
3 x +8400Pa/-2400Pa



Mechanical Load (MEL) Test Sequence

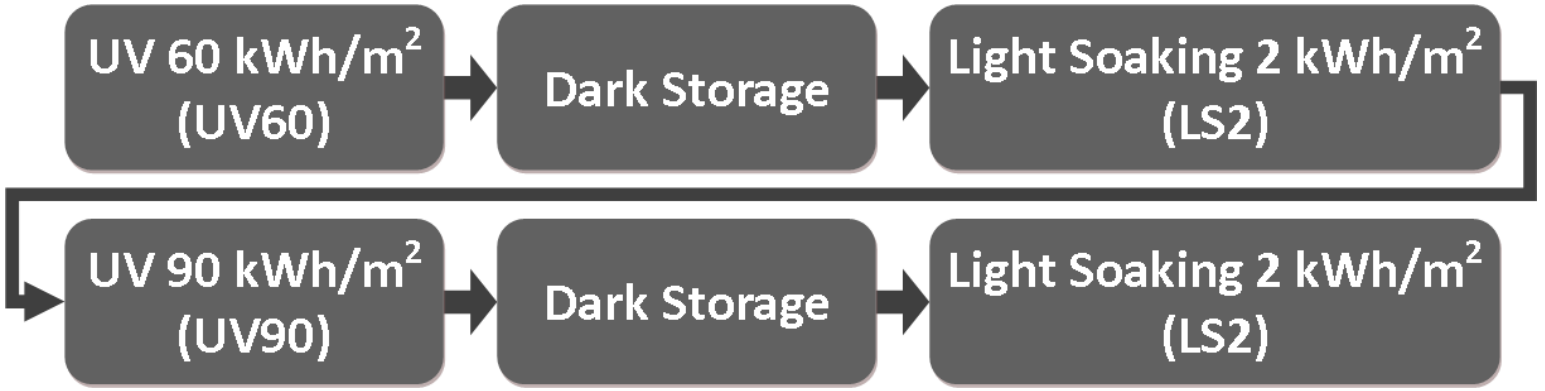
- The standard PV module design is insufficient for sustained high mechanical loads.
- High-load-resistant PV modules can be successfully designed and manufactured.
- Manufacturing quality and process control are critical to mechanical reliability.
- Observed finger damage may be linked to thin wire interconnections replacing wider busbars.

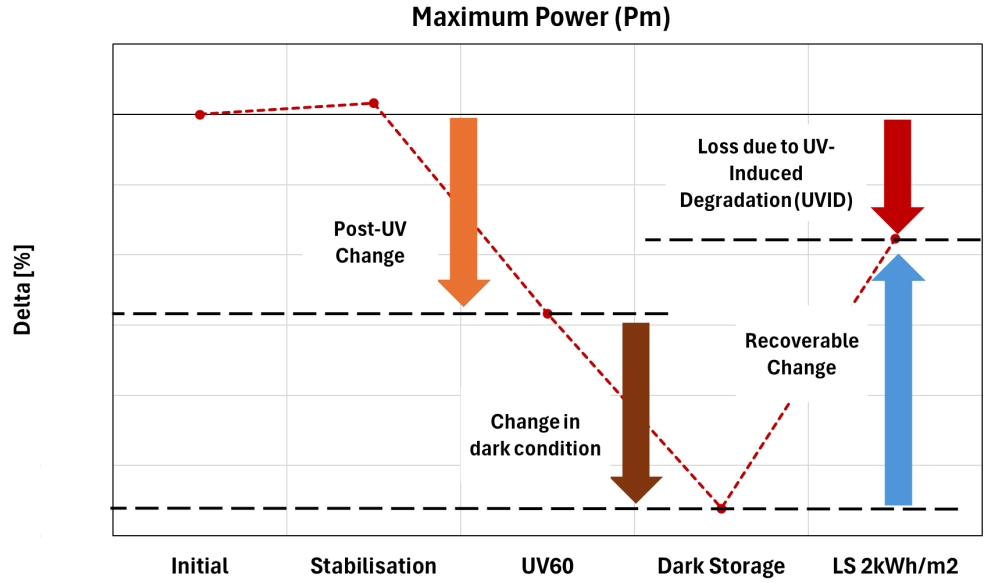


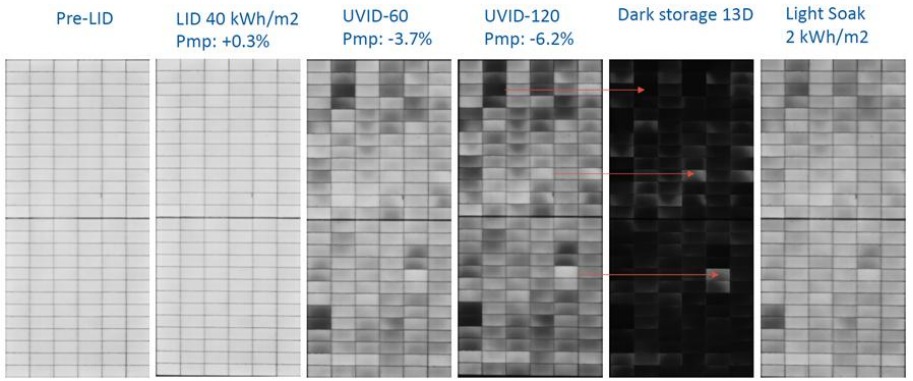


Alpine PV Module Testing – UV Stress Test Sequence

- High UV irradiance
- High albedo (snow albedo is UV rich) + Bifaciality
- New technologies are UV sensitive (especially rear sides) [1,2]



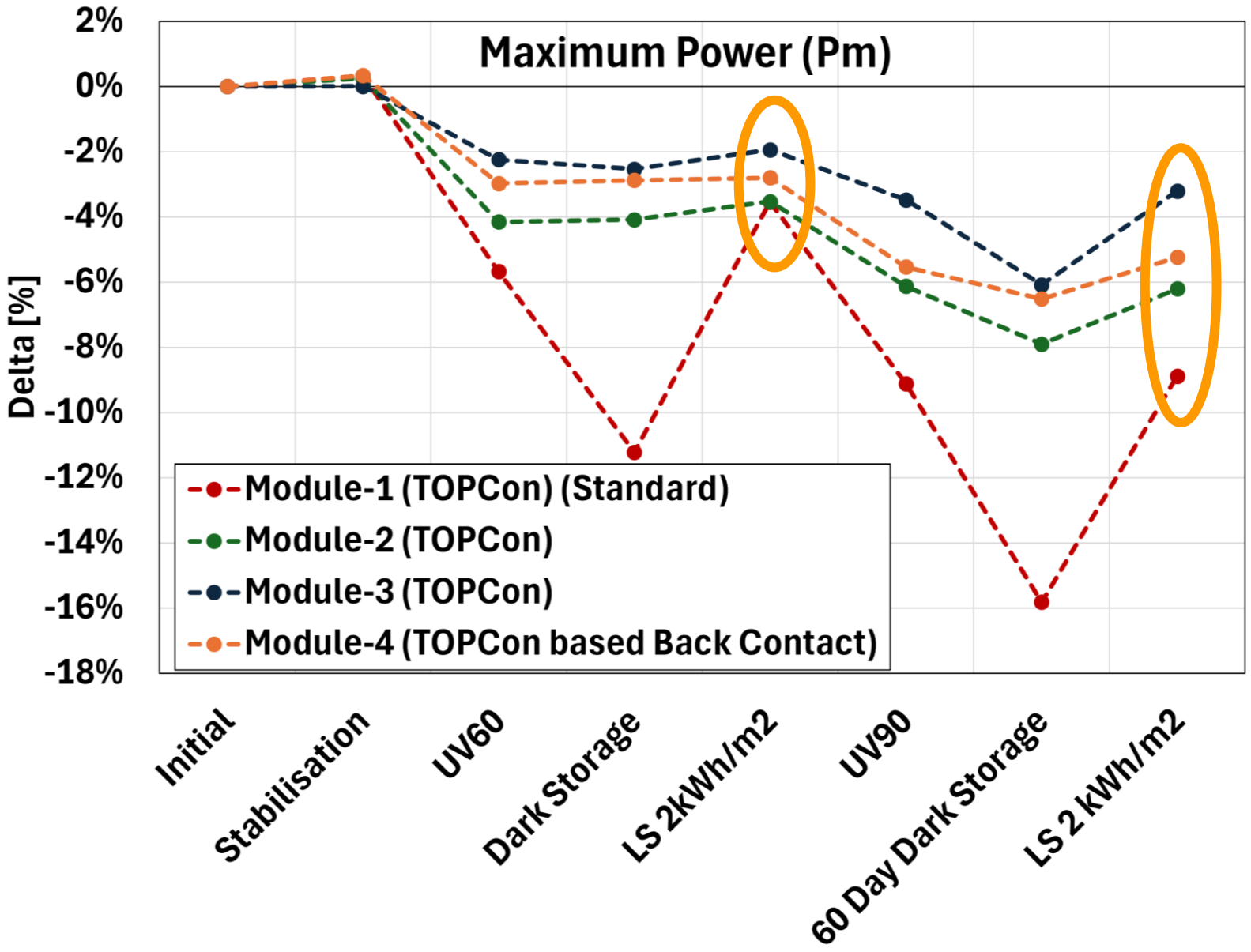




KIWA PVEL

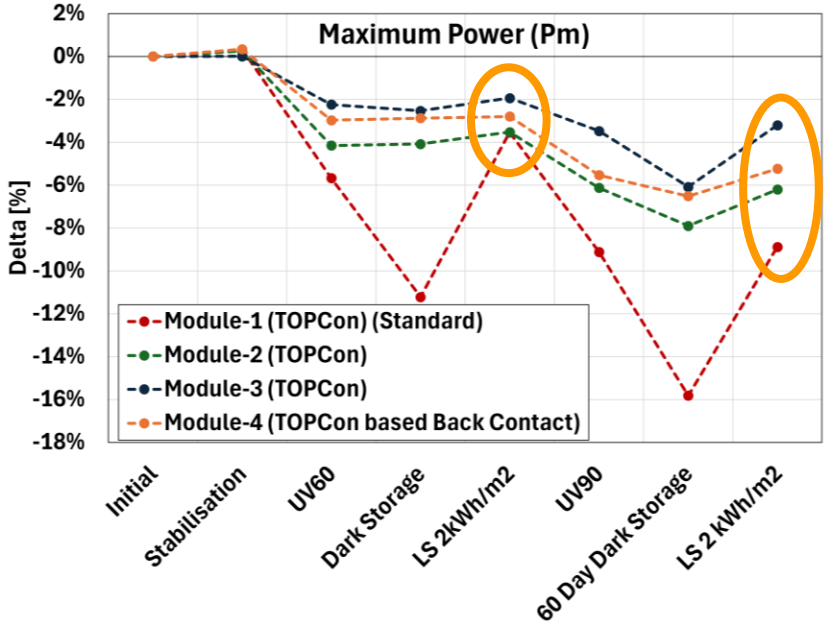
[1] P. Gebhart et al., PiP, 2024
[2] KIWA PVEL

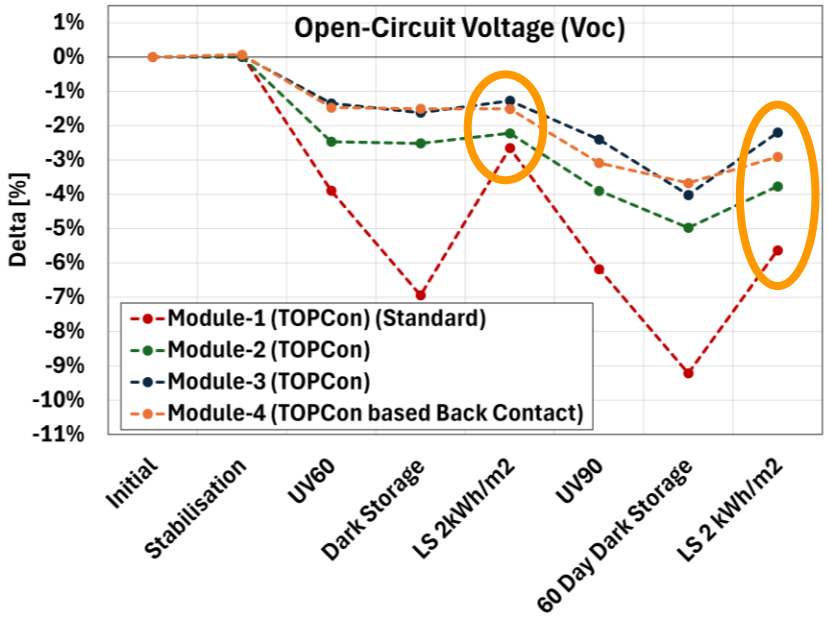
UV Stress Test Sequence

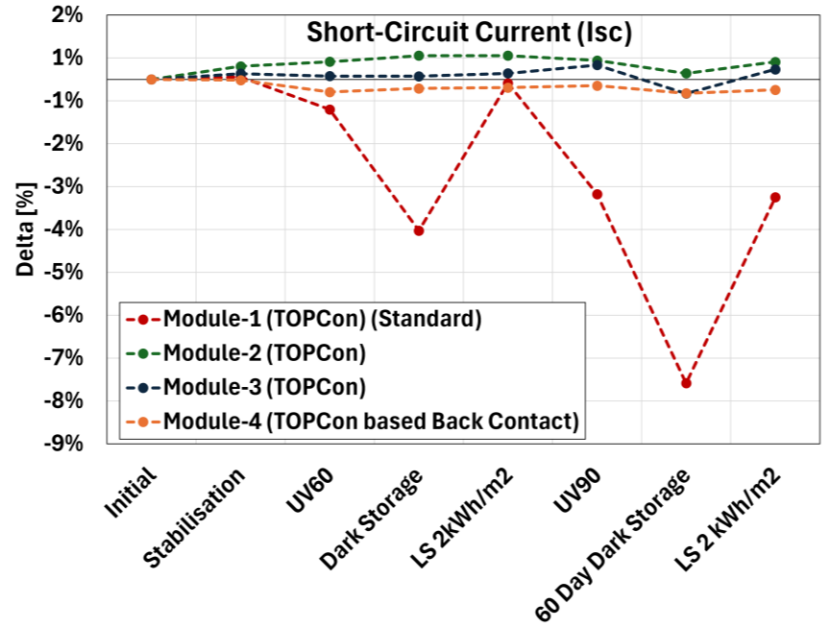


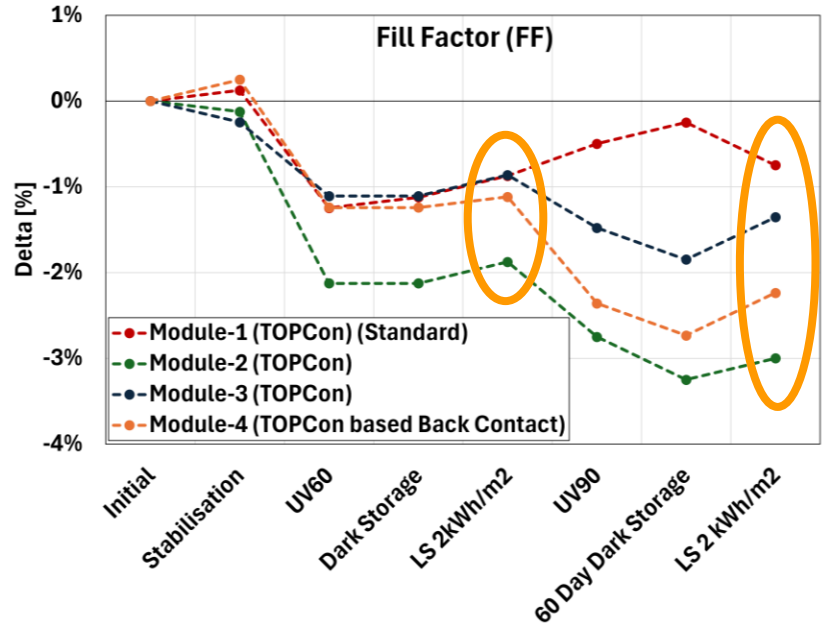
- All modules show UV sensitivity.
- Significant degradation already at 60 kWh/m² (~2–4%), primarily from Voc and FF losses.
- After 150 kWh/m² exposure, total losses reach ~3.2–9%.
- Checkered EL pattern observed in all modules due to UVID.

UV Stress Test Sequence









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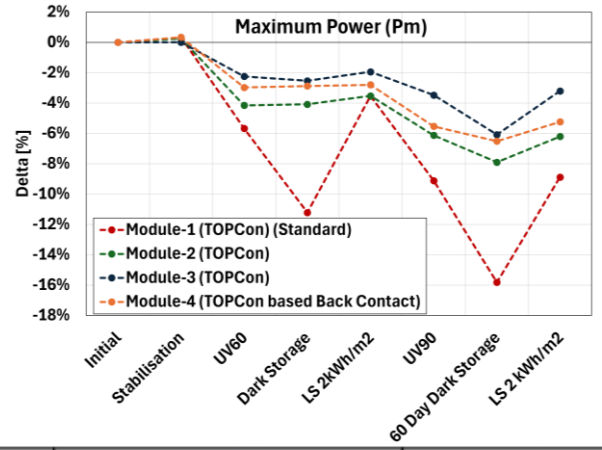
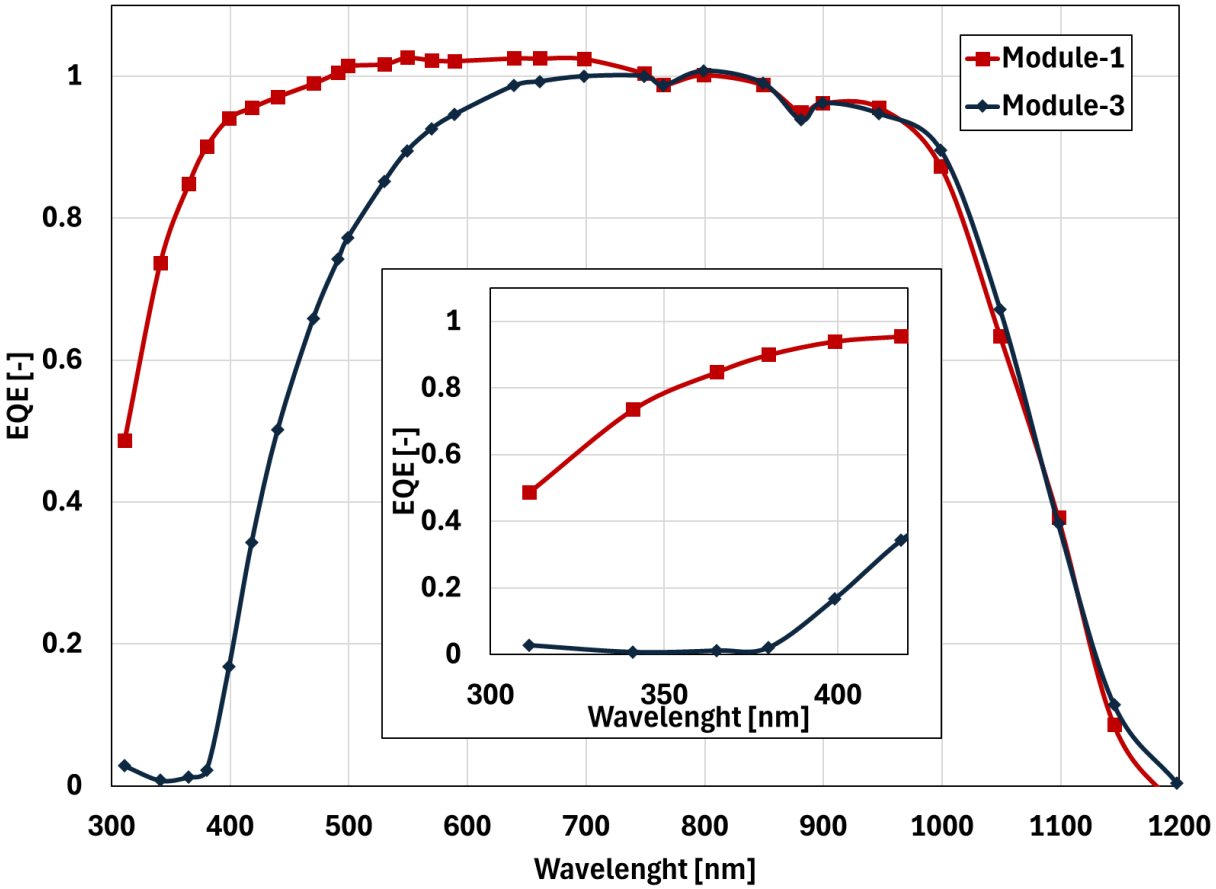
UV Stress Test Sequence

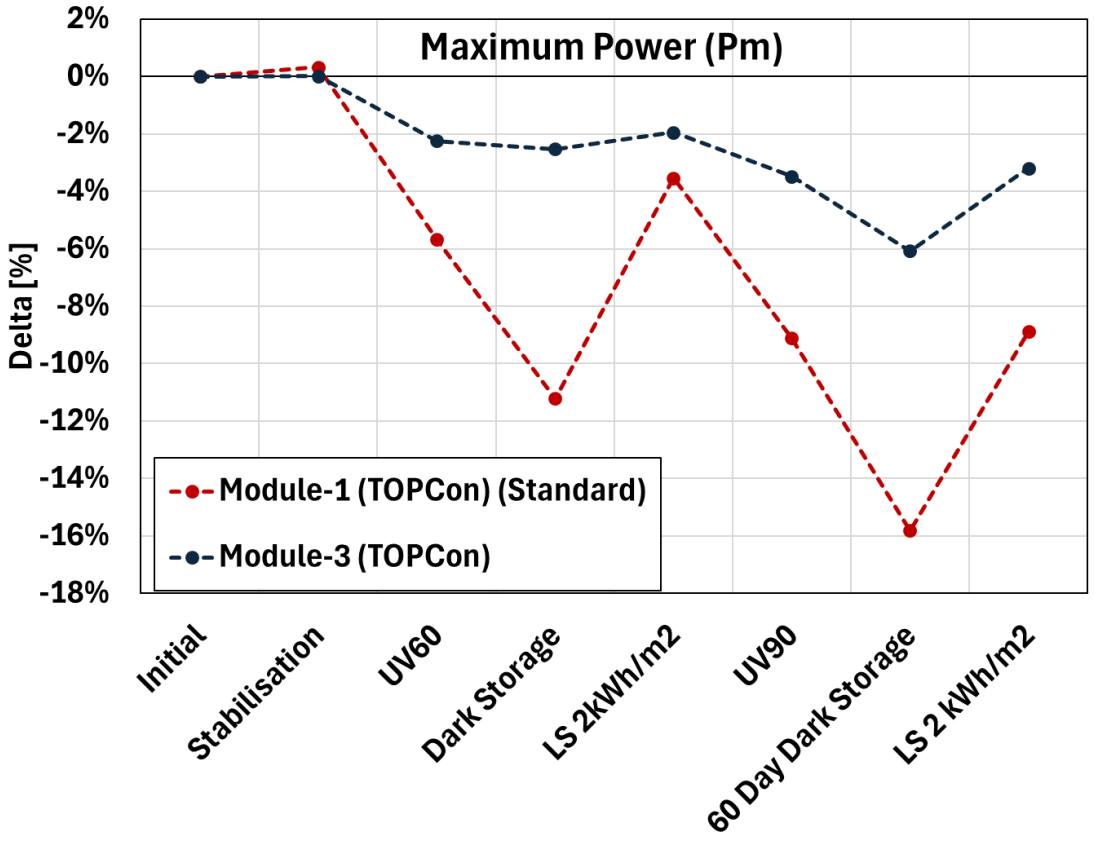


	Initial	UV60 (front)	Dark Storage	LS 2kWh/m²	UV90 (front)	Dark Storage	LS 2kWh/m²
Module-1							
Module-2							
Module-3							
Module-4							

UV Stress Test Sequence

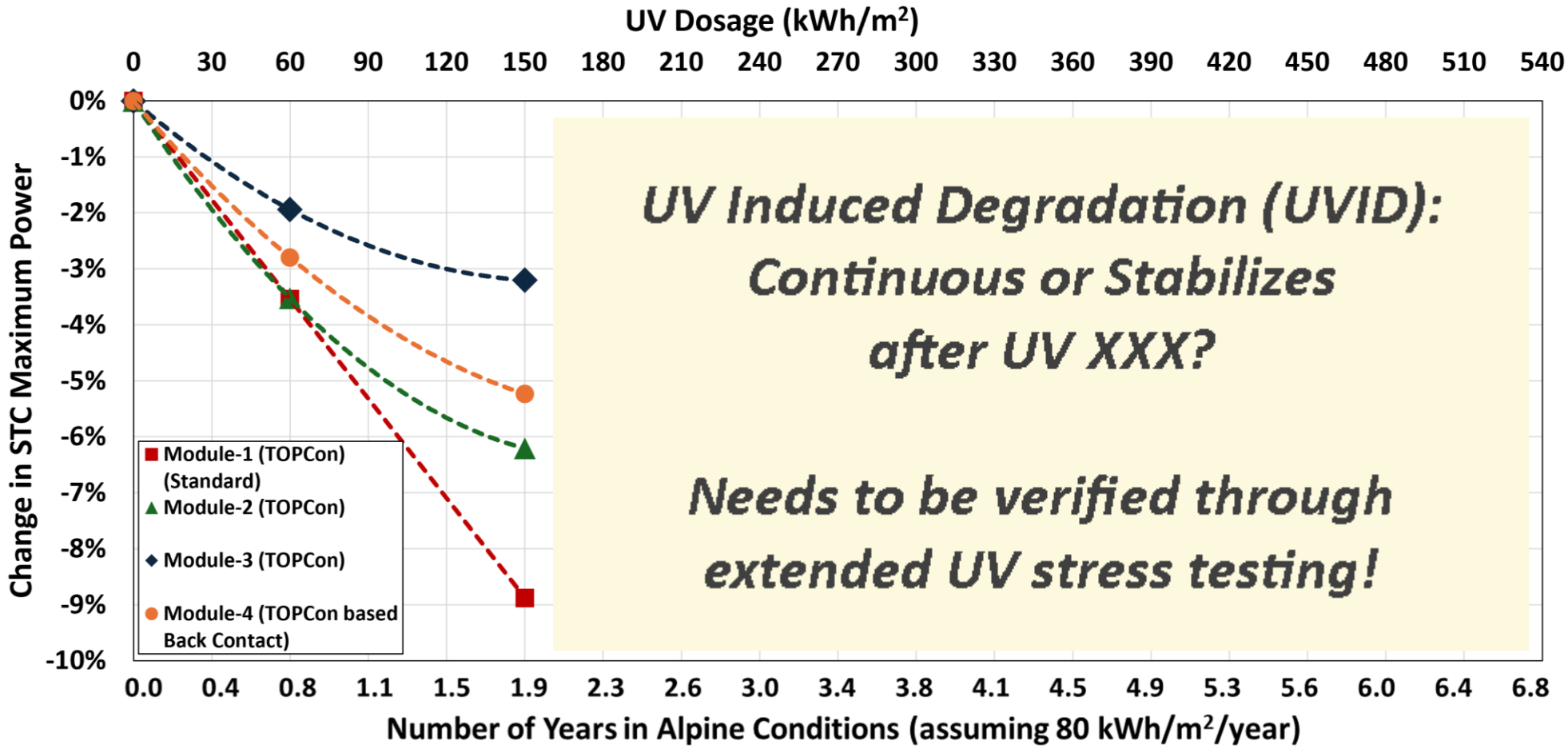
- Effect of encapsulant with UV cutoff?





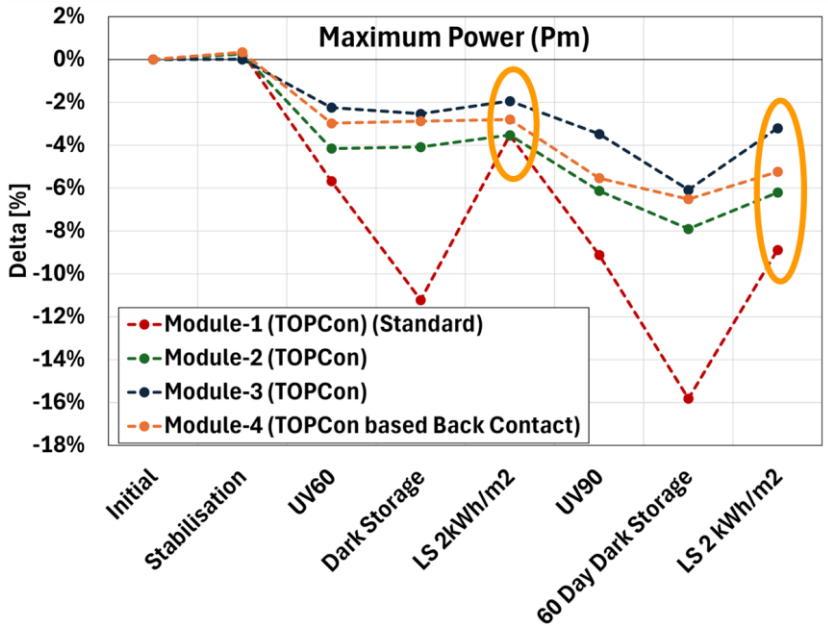
UV Stress Test Sequence

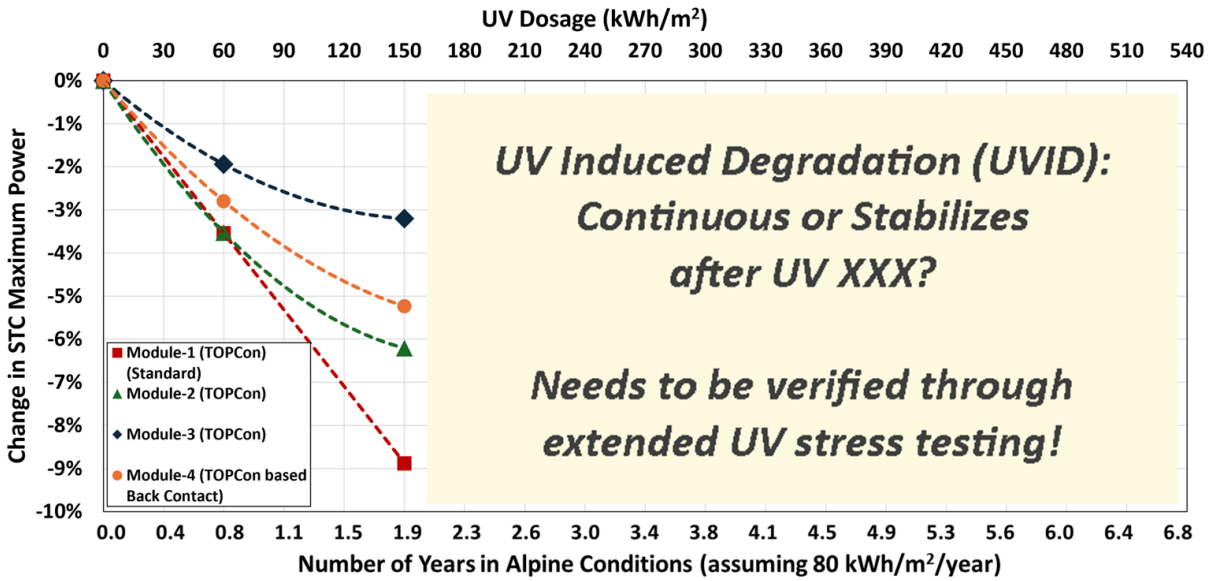
- UVID: continuous or stabilizes after XXX UV??? → extended testing necessary



UV Stress Test Sequence

- All tested modules exhibited measurable UV sensitivity. Modern high-efficiency cell architectures are vulnerable to UV-induced degradation despite UV-cutoff encapsulants.
- Alpine-relevant modules with UV-cutoff encapsulants showed approximately 3.2–6.2% power loss after 150 kWh/m² UV exposure (equivalent to roughly 2 years of Alpine operation).
- The influence of UV-cutoff encapsulants on UVID requires further investigation.
- Long-term stabilisation behaviour of UVID remains an open question.





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Thank you for your attention!

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