Advanced accelerated stress testing for alpine applications
PVDETECT project

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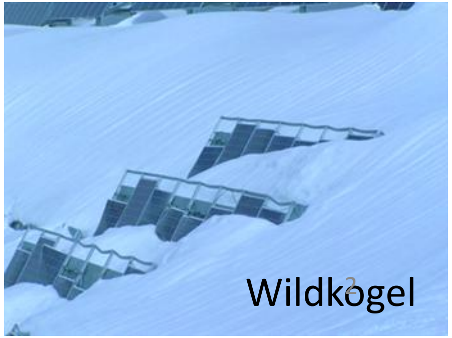
Motivation

- PV deployment is expanding to unconventional climate zones[1]
  - Example: Alpine region
- PV systems are exposed to harsher conditions there
  - Module failures occur
- Standard tests are insufficient for selecting the most suitable module types
  - → **Climate-adapted, accelerated aging tests are requested**


Madrisa Solar


Pitztaler Gletscher


Wildkogel

1 Gabi Friesen, et al. (2025), *Optimization of Photovoltaic Systems for Different Climates*. PVPS Task 13 report

Climate Specific Testing

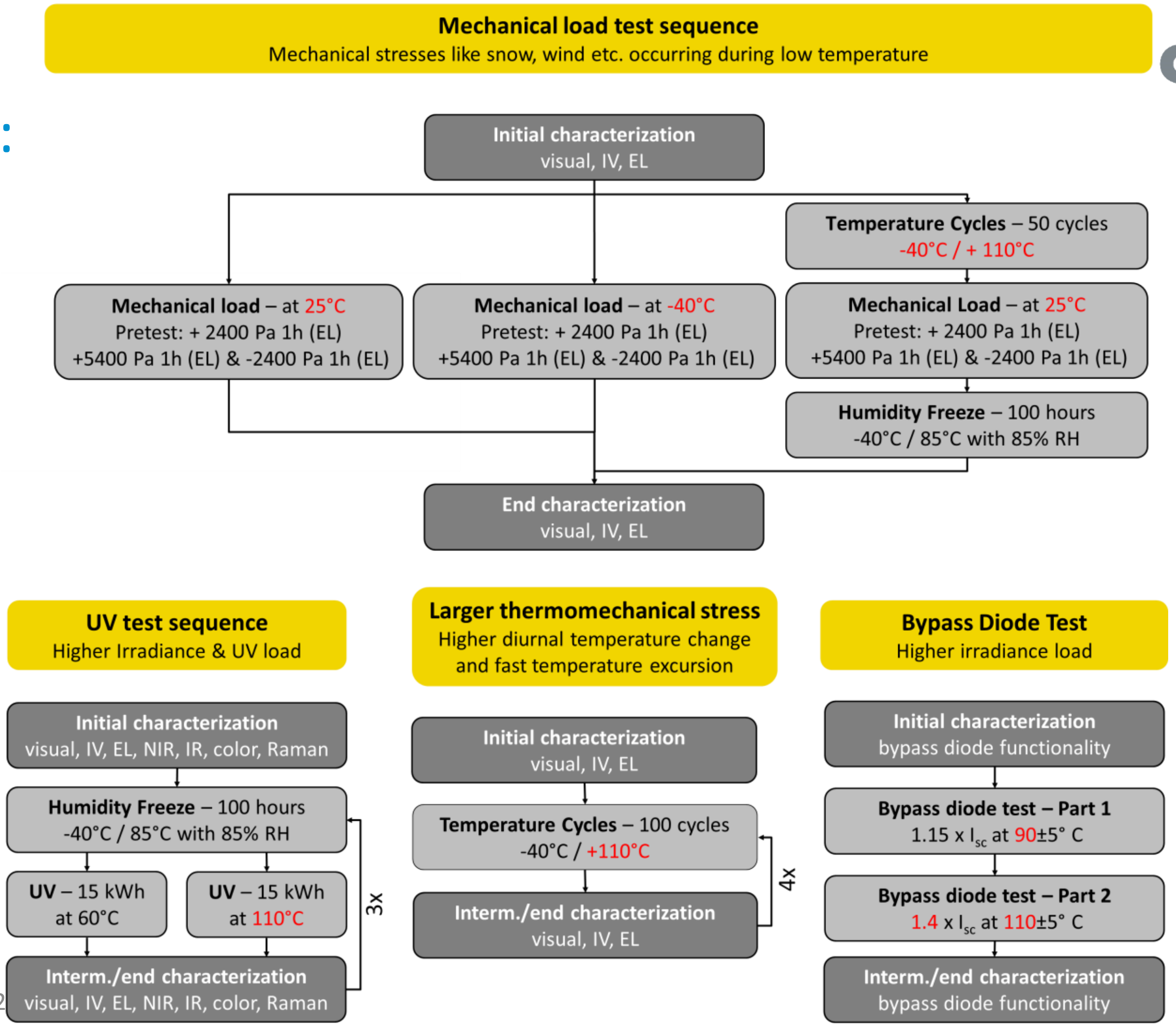
Identification of alpine stressors → Detect typical failures → Material test → Pre-tests on mini modules → Test matrix for alpine climate

- High mechanical loads (snow and/or wind)
- Ice formation
- Low temperatures (< -30°C)
- Fast temperature fluctuations
- Higher irradiance (> 1600 W/m^2)
- High albedo

→ high current &UV

Özkalay, E.*, Quest, H. *, Gassner, A.*, et al. (2025), *Three decades, three climates: environmental and material impacts on the long-term reliability of photovoltaic modules*. EES Solar, Advance Article

Alpine Test Matrix:

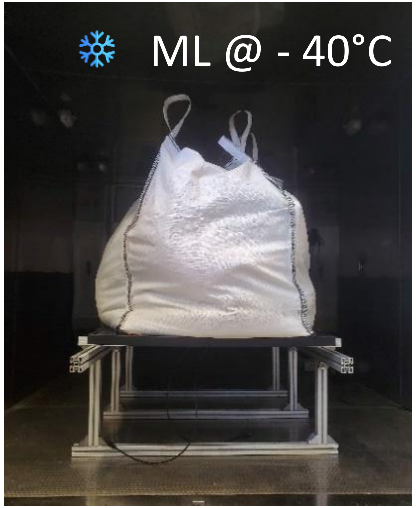


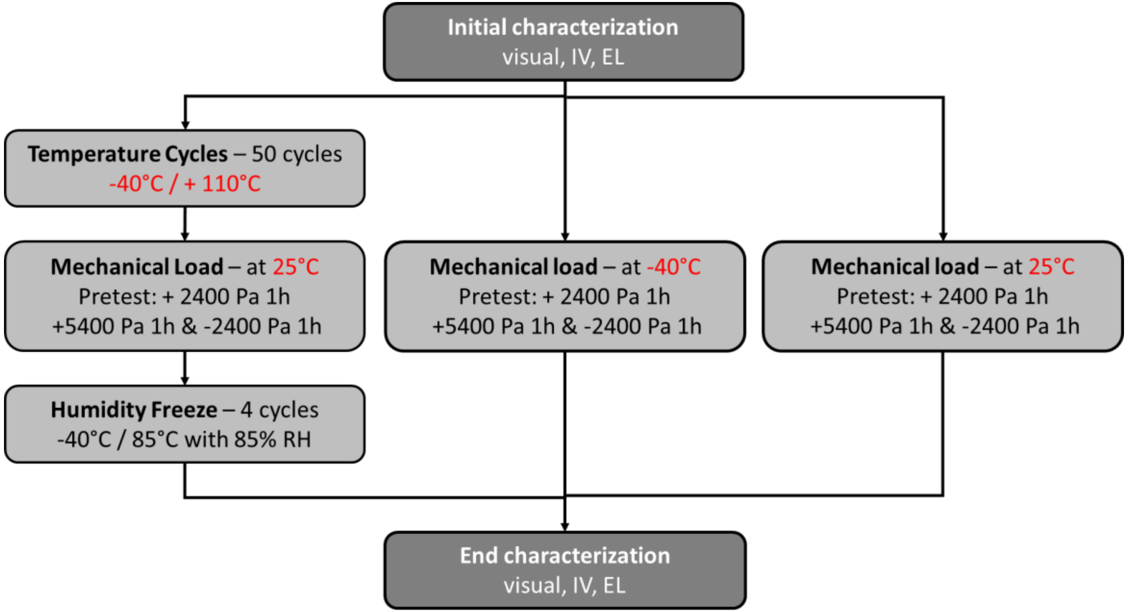
Adapting IEC 61215 for Alpine Conditions

Test	IEC 61215	PVDetect	Achieved?
Mechanical load	min 2400 Pa at 25°C	5400 Pa front, 2400 Pa back a) **at -40°C** b) **after TC**	✓ more realistic
UV test	1x 15 kWh/m^2	3x 15 kWh/m^2 (front & back) T_{mod} = 60°C (UVA lamp) T_{mod} = **110°C** (MH lamp)	~ backside ✓ front: not enough
Thermal Cycling	200 cycles: -40°C/85°C	400 cycles: -40°C/**110°C**	✓ on average roughly: 3.9 x acceleration
Bypass Diode	1.25 x Isc at 75°C	**1.4 x** Isc at **110°C**	**X** Suggestion: **2 x Isc** at 75°C

Adapted Mechanical Load (ML) Test

- ML after temperature cycles
- ML @ -40°C
- Reference: ML @ 25°C (MQT 16)





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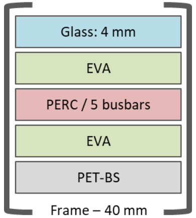
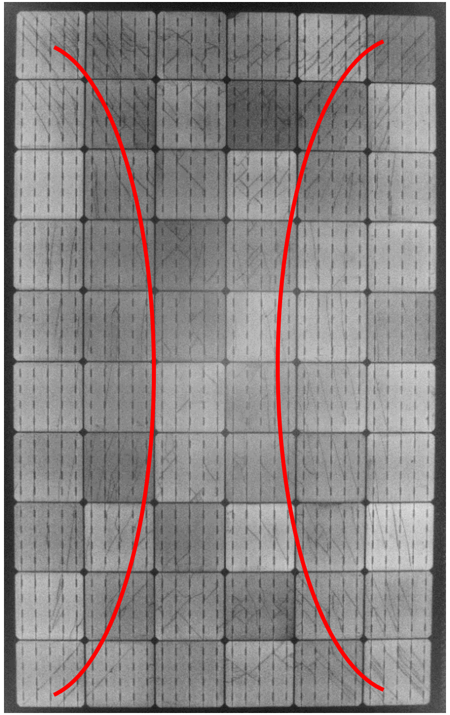


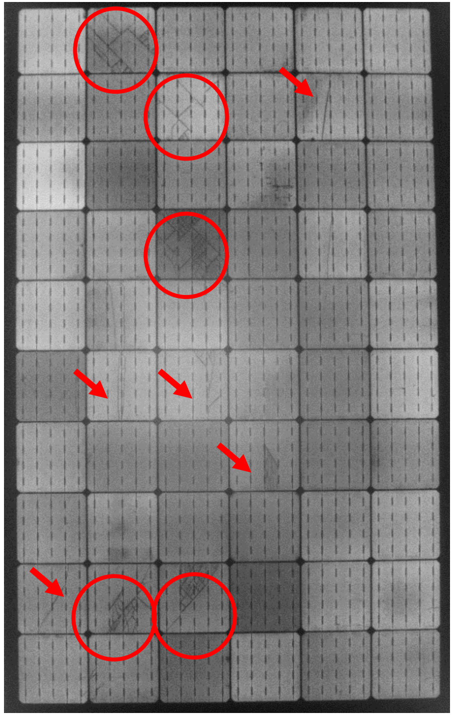
Results ML: G/BS Modules

EL images after +5400 Pa

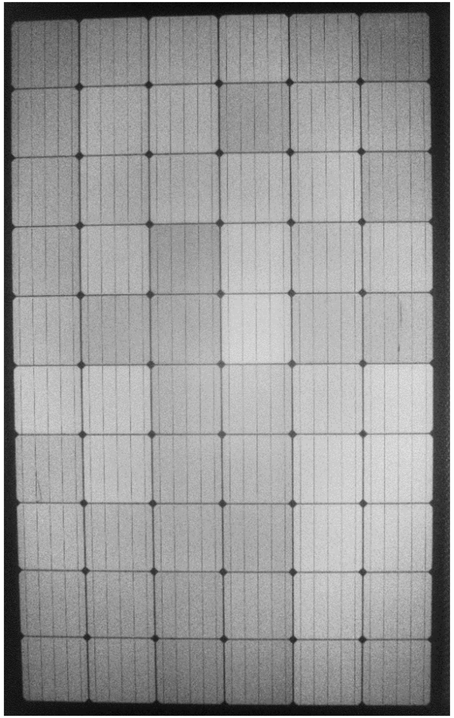
TC50 → ML @ 25°C

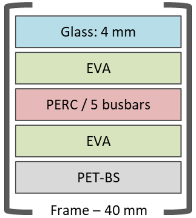


ML @ -40°C



ML @ +25°C





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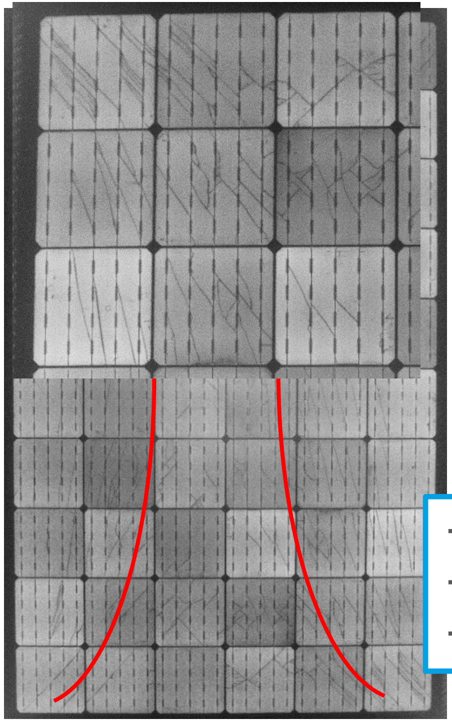
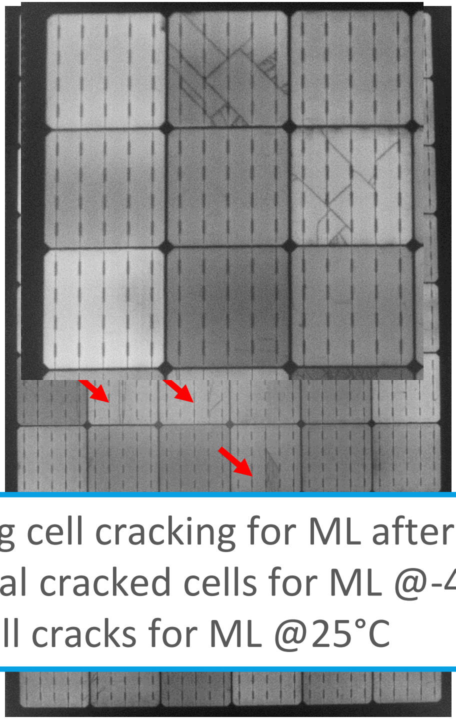


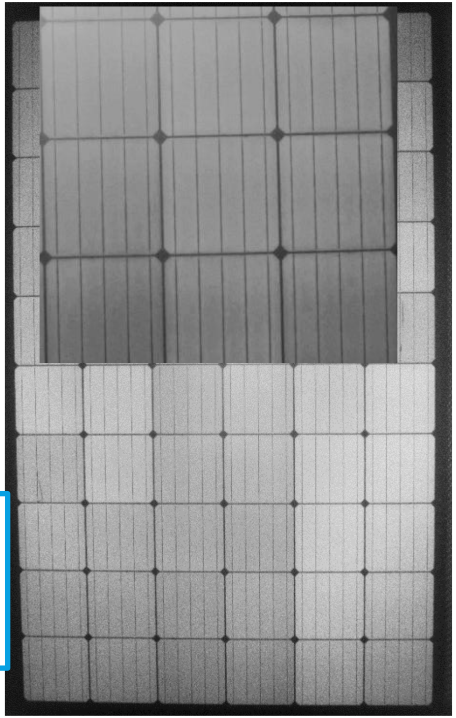
ΔP_m = -9.1 %; ΔFF = -4.1 %

ML @ -40°C



ΔP_m = -6.0 %; ΔFF = -1.9 %

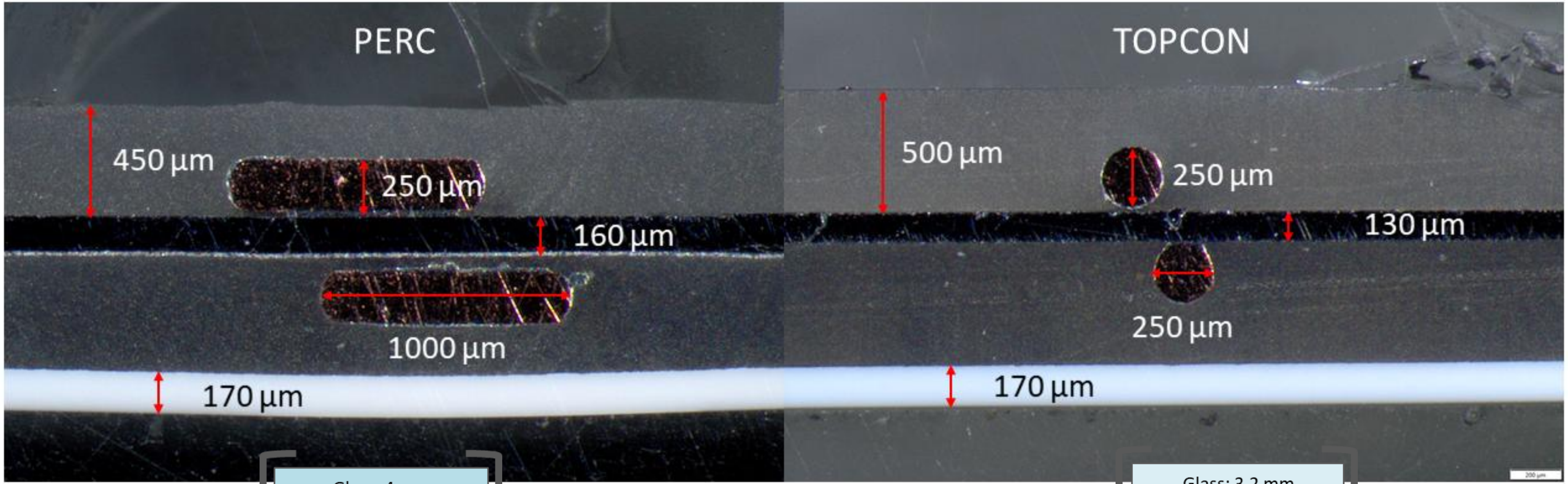
ML @ +25°C



ΔP_m = -2.5 %; ΔFF = -0.18%

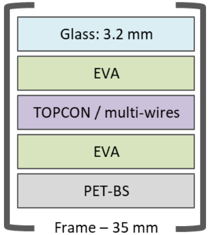
- → Strong cell cracking for ML after TC
- → Several cracked cells for ML @-40°C
- → No cell cracks for ML @25°C

G/BS module cross-section



Glass: 4 mm
EVA
PERC / 5 busbars
EVA
PET-BS
Frame – 40 mm

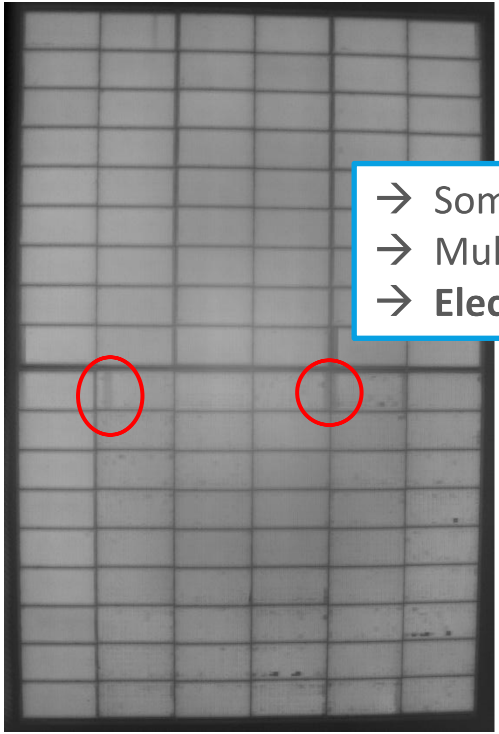
Glass: 3.2 mm
EVA
TOPCON / multi-wires
EVA
PET-BS
Frame – 35 mm



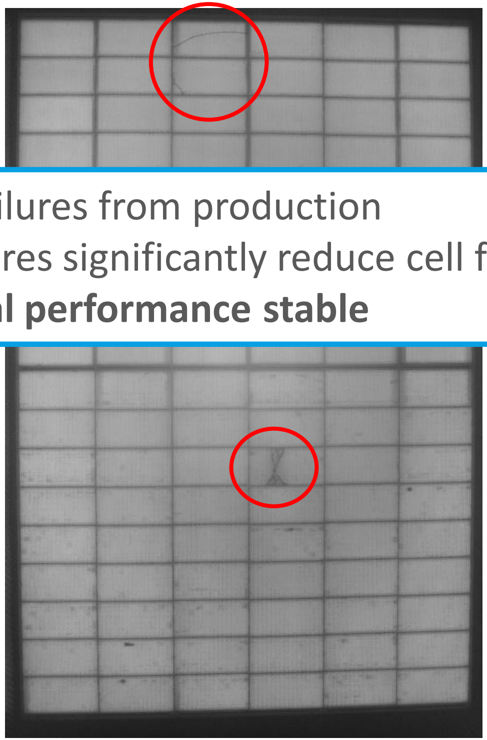
Results: G/BS modules – TOPCON w. multiwires

EL images after +5400 Pa

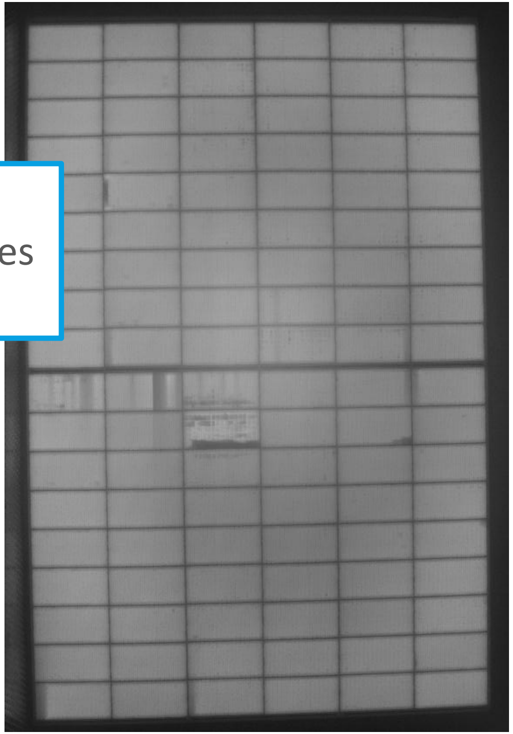
TC→ML @ 25°C



ML @ - 40°C



ML @ + 25°C



- → Some failures from production
- → Multi-wires significantly reduce cell failures
- → **Electrical performance stable**

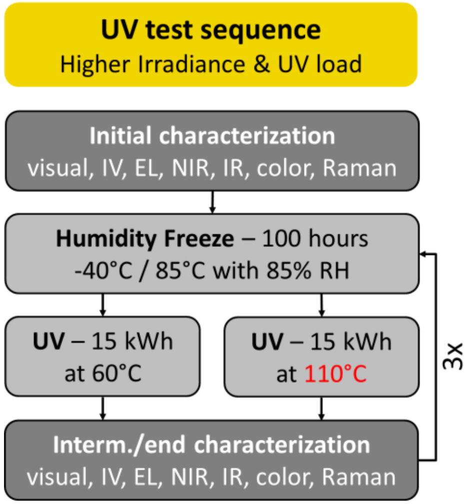
UV Test for Alpine Conditions

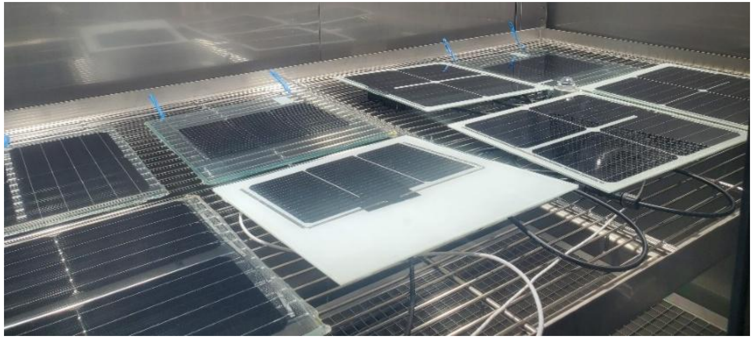
Higher irradiance & high albedo → higher UV dosage

- Accelerated via module temperature increase
- Multiple cell technologies tested (PERC, Topcon, Al-BSF)

→ No clear differentiation observed

Further investigation required
→ Work done by SUPSI in ALIENCE project





Further work : Alience -Project
https://alpine-pv.ch/wiki/module-testing/uv-stress-test/

UV Testing: Backsheet Degradation

UVA Fl lamps

300-400 nm (peak 340 nm)

T_{module} = 60°C

- strong surface degradation

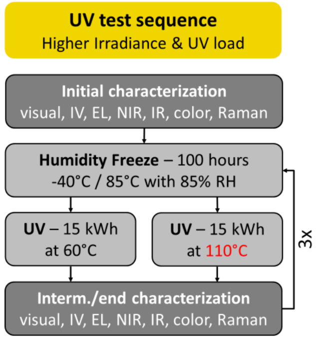
Metal halide lamps

artificial sunlight 300-2500 nm

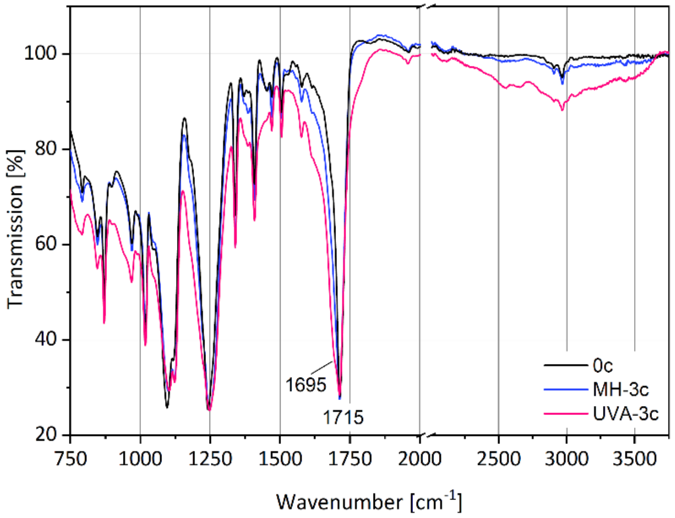
T_{module} = 110°C

- strong bulk degradation

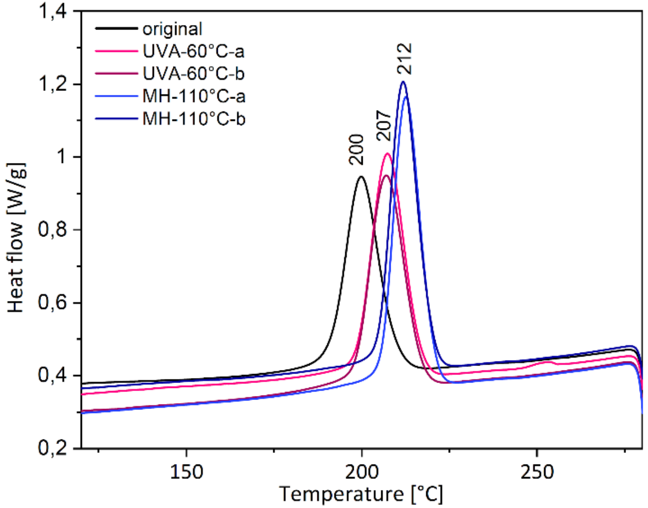
→ stronger due to **higher T_{mod}**



Surface: U-ATR-IR



Bulk: DSC

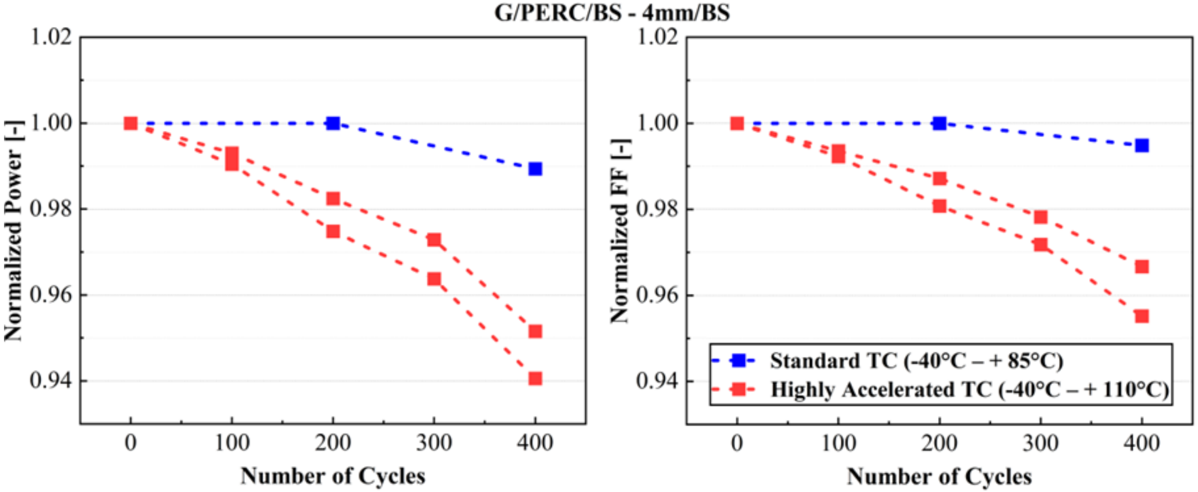


Accelerated Thermal Cycling

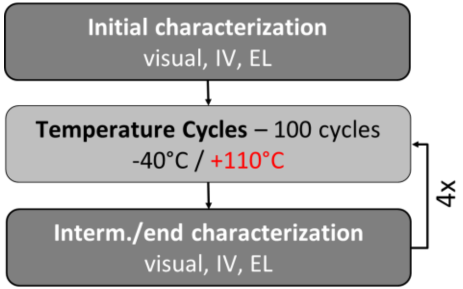
- T_{max} increased to 110°C
- Simulates high alpine temperature fluctuation

→ **3.9x acceleration (average) HATC vs TC**

→ for G/PERC/BS module 7.4x acceleration:



Larger thermomechanical stress
Higher diurnal temperature change and fast temperature excursion



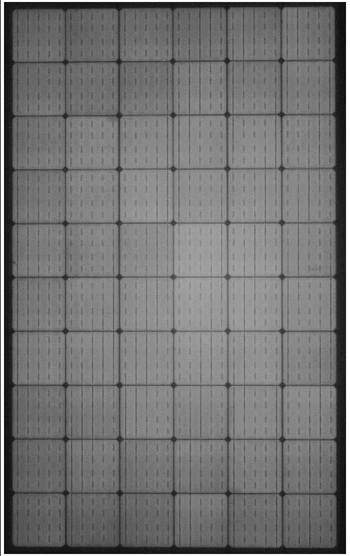
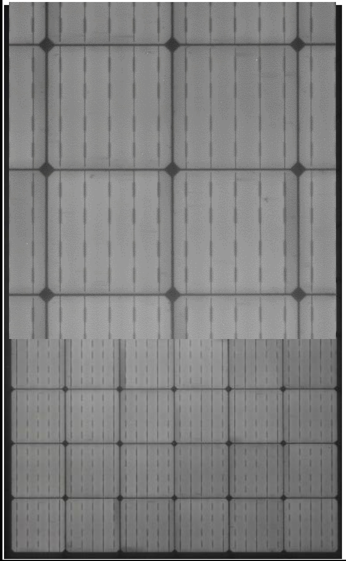
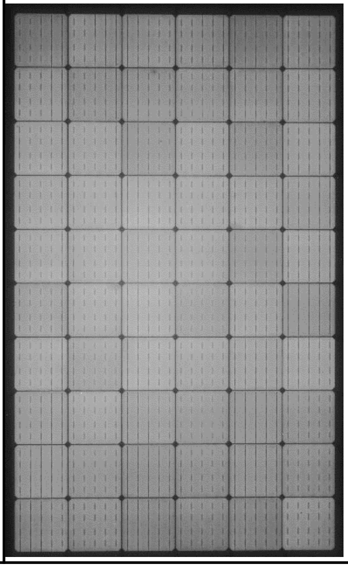
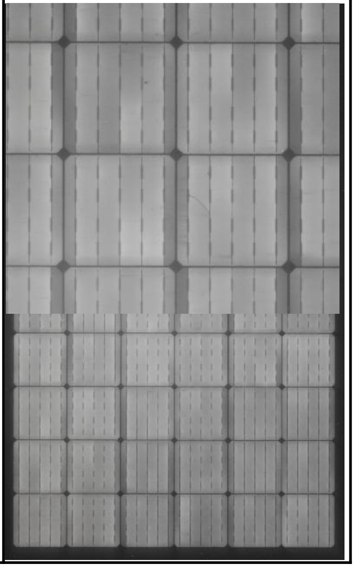
Standard TC: -40°C/+85°C

Highly accelerated TC: -40°C/+110°C

Significant acceleration with limited test-time increase (+20%)

Accelerated Thermal Cycling

Realistic failure modes reproduced:

	Standard Thermal Cycling (-40 °C to +85 °C)		Highly Accelerated TC (-40 °C to +110 °C)	
	Initial	400 cycles	Initial	400 cycles
G/PERC/BS - 4mm/BS				

$\Delta P_m = -1\ \%$; $\Delta FF = -0.5\ \%$

$\Delta P_m = -5.4\ \%$; $\Delta FF = -3.9\ \%$

Larger thermomechanical stress
Higher diurnal temperature change and fast temperature excursion

Initial characterization
visual, IV, EL

Temperature Cycles – 100 cycles
-40°C / +110°C

Interm./end characterization
visual, IV, EL

4x

Bypass Diode Test

Higher current (irradiance + albedo)

– No failures were observed

→ For Alpine 1.4x Isc **not severe enough**

Suggested: 2x Isc at 75°C

Bypass Diode Test
Higher irradiance load

Initial characterization
bypass diode functionality

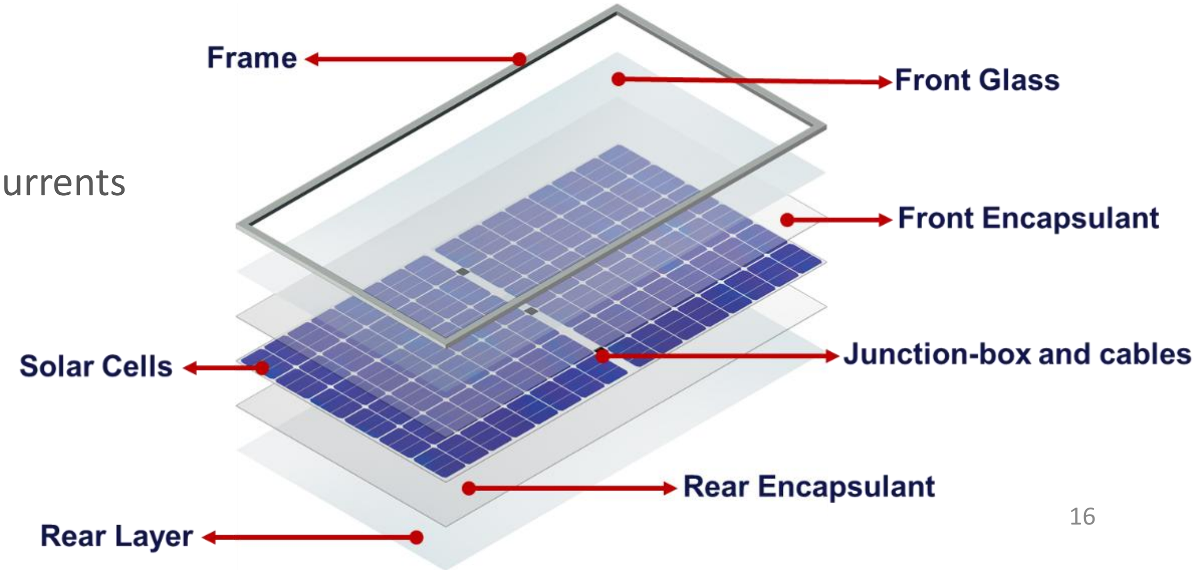
Bypass diode test – Part 1
1.15 x I_{sc} at 90±5° C

Bypass diode test – Part 2
1.4 x I_{sc} at 110±5° C

Interm./end characterization
bypass diode functionality

Optimal Design for Alpine Modules

- **Glass/Glass structure**
- **Frame**: reinforced, avoid snow accumulation
- **Glass:** tempered, thicker
- **Encapsulant:** POE, reduced stiffness at low temperature
- **Cells**: bifacial, consider UVID
- **Metallization:** multi-wire
- **Bypass diodes:** resisting high currents



Key Takeaways for Alpine PV Reliability

Standard qualification tests do not capture alpine stress conditions

- ✓ Mechanical load test at low temperatures → **more specific**
- ✓ Thermal cycling
  → can be **strongly accelerated**

- UV testing
  → longer duration / more samples
- Bypass diode test
  → higher current (>2x Isc) suggested

Climate-adapted testing enables more reliable module selection

Adapted testing → long lasting & robust modules even in harsh climates

Thank you for your attention!

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PV DETECT

Funding:

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione
Confederaziun svizra

FFG
Promoting Innovation.

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Project partners

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FORTSCHRITT IN GUTEN HÄNDEN

SONNENKRAFT

Gabi Friesen, et al. (2025), *Optimization of Photovoltaic Systems for Different Climates.* PVPS Task 13 report

Özkalay, E.*, Quest, H. *, Gassner, A.*, et al. (2025), *Three decades, three climates: environmental and material impacts on the long-term reliability of photovoltaic modules*. EES Solar, Advance Article.

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