



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Federal Department of the Environment,
Transport, Energy and Communications DETEC

Swiss Federal Office of Energy
Energy Research and Cleantech

Final report from 4 December 2025

PV-DETECT

Accelerated product development for
unconventional PV-applications through
advanced reliability testing combined with
early degradation detection



University of Applied Sciences and Arts
of Southern Switzerland

SUPSI

Publisher:

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Berne
www.energy-research.ch

Subsidy recipients:

Scuola universitaria professionale della Svizzera italiana (SUPSI)
CH-6850 Mendrisio
www.supsi.ch

Authors:

Ebrar Özkalay, SUPSI, ebrar.oezkalay@supsi.ch
Anika Gassner, OFI, anika.gassner@ofi.at

SFOE project coordinators:

Stefan Oberholzer, Swiss Federal Office of Energy, stefan.oberholzer@bfe.admin.ch

SFOE contract number: SI/502484

The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.



Summary

In countries such as Switzerland and Austria, the expansion of conventional ground-mounted photovoltaic (PV) installations in lowland areas is limited by competing land-use demands. Consequently, PV deployment is increasingly shifting toward alternative applications, including building-integrated photovoltaics (BIPV), infrastructure-integrated systems, multipurpose installations, and ground-mounted systems in alpine regions. PV systems installed in alpine environments and BIPV applications are exposed to operating conditions that differ significantly from those of conventional ground-mounted PV systems. Alpine installations experience high irradiance, strong UV exposure, snow and wind loads, and low operating temperatures, while BIPV systems often operate at elevated temperatures and are more frequently affected by shading and thermomechanical stresses. These conditions can lead to specific degradation mechanisms that are not fully addressed by existing standard qualification tests. The aim of the project PV-DETECT was, therefore, to develop and evaluate advanced reliability testing approaches combined with sensitive early-stage degradation detection methods to accelerate PV product development for these demanding environments.

A key innovation of the project was the systematic combination of highly accelerated ageing tests with advanced characterisation techniques to detect degradation mechanisms at an early stage. Within the framework of the Solar ERA.NET programme, the project involved international collaboration with research partners and industry, including the Austrian Research Institute for Chemistry and Technology (OFI) and the module manufacturer Sonnenkraft. Together, considering field data and experience collected from representative PV systems, new test sequences were developed and applied to a set of PV modules with different designs and material combinations. The work focused on ultraviolet (UV) exposure, thermal cycling (TC), hot spot endurance (HSP) testing, bypass diode testing and static mechanical load (SML) testing.

The project demonstrated that several standard qualification tests can be significantly accelerated while still reproducing relevant degradation mechanisms. TC and SML tests were successfully accelerated by more than a factor of three, with the SML procedure adapted to better represent realistic alpine conditions. UV degradation of polymeric materials was accelerated by increasing module temperature and/or UV irradiance, allowing earlier identification of material weaknesses such as backsheet degradation. HSP tests showed only limited acceleration under the investigated conditions but revealed that advanced material diagnostics can detect early chemical changes in polymer backsheets, particularly for PET-based materials. Bypass diode testing showed that the investigated procedures represent realistic BIPV conditions but should be further intensified to represent the extreme irradiance levels encountered in alpine environments.

Analysis of the test results also identified module design features that are particularly suitable for alpine PV applications. Modules designed for alpine environments benefit from polyolefin elastomer (POE) encapsulation, glass/glass structures, framed module designs, multi-wire metallization, and bypass diodes with higher current capacity. These design characteristics improve mechanical stability and reduce the likelihood of cell cracking under snow loads, wind stress, and low-temperature conditions, while also ensuring safer operation under high irradiance levels typical of alpine environments.

Overall, the results contribute to improved reliability assessment and product development for PV modules intended for BIPV and alpine installations. Manufacturers can use the developed testing approaches to identify material weaknesses earlier in the design process and to optimise module architectures for application-specific stresses. The insights gained in the project were disseminated through collaboration with international research partners, scientific publications, and direct exchange with PV industry stakeholders, thereby supporting the development of more reliable PV technologies for challenging operating environments.



Zusammenfassung

In Ländern wie der Schweiz und Österreich ist der Ausbau konventioneller, bodenmontierter Photovoltaik-(PV)-Anlagen in Tieflandregionen durch konkurrierende Flächennutzungsansprüche begrenzt. Daher verlagert sich der PV-Ausbau zunehmend auf alternative Anwendungen, darunter gebäudeintegrierte Photovoltaik (BIPV), in Infrastruktur integrierte Systeme, Mehrfachnutzungsanlagen sowie bodenmontierte Anlagen in alpinen Regionen. PV-Systeme, die in alpinen Umgebungen sowie in BIPV-Anwendungen installiert sind, sind Betriebsbedingungen ausgesetzt, die sich deutlich von denen konventioneller bodenmontierter PV-Systeme unterscheiden. Alpine Installationen sind durch hohe Einstrahlung, starke UV-Belastung, Schnee- und Windlasten sowie niedrige Betriebstemperaturen gekennzeichnet, während BIPV-Systeme häufig bei erhöhten Temperaturen betrieben werden und stärker von Verschattung sowie thermomechanischen Belastungen betroffen sind. Diese Bedingungen können zu spezifischen Degradationsmechanismen führen, die durch bestehende Standardqualifikationstests nicht vollständig abgedeckt werden. Ziel des Projekts PV-DETECT war es daher, fortschrittliche Zuverlässigkeitsprüfmethoden in Kombination mit empfindlichen Verfahren zur frühzeitigen Erkennung von Degradation zu entwickeln und zu bewerten, um die Produktentwicklung von PV-Modulen für diese anspruchsvollen Einsatzbedingungen zu beschleunigen.

Eine zentrale Innovation des Projekts war die systematische Kombination hochbeschleunigter Alterungstests mit fortschrittlichen Charakterisierungsmethoden, um Degradationsmechanismen frühzeitig zu erkennen. Im Rahmen des Solar ERA.NET-Programms umfasste das Projekt eine internationale Zusammenarbeit mit Forschungspartnern und Industrie, darunter das Österreichische Forschungsinstitut für Chemie und Technik (OFI) sowie der Modulhersteller Sonnenkraft. Unter Berücksichtigung von Felddaten aus relevanten Einsatzumgebungen wurden neue Testsequenzen entwickelt und auf eine Reihe von PV-Modulen mit unterschiedlichen Designs und Materialkombinationen angewendet. Die Arbeiten konzentrierten sich auf ultraviolette (UV) Bestrahlung, thermisches Zyklieren (Thermal Cycling, TC), Hot-Spot-Dauertests, Bypassdiodentests sowie mechanische Belastungstests (Static Mechanical Load, SML).

Das Projekt zeigte, dass mehrere Standardqualifikationstests deutlich beschleunigt werden können, während gleichzeitig relevante Degradationsmechanismen reproduziert werden. TC- und SML-Tests konnten erfolgreich um mehr als den Faktor drei beschleunigt werden, wobei das SML-Verfahren angepasst wurde, um realistische alpine Bedingungen besser abzubilden. Die UV-bedingte Degradation polymerer Materialien wurde durch eine Erhöhung der Modultemperatur und/oder der UV-Bestrahlungsstärke beschleunigt, wodurch Materialschwächen wie beispielsweise die Degradation von Rückseitenfolien früher identifiziert werden konnten. Hot-Spot-Tests zeigten unter den untersuchten Bedingungen nur eine begrenzte Beschleunigung, machten jedoch deutlich, dass fortschrittliche materialanalytische Verfahren frühe chemische Veränderungen in polymeren Rückseitenfolien erkennen können, insbesondere bei PET-basierten Materialien. Bypassdiodentests zeigten, dass die untersuchten Verfahren realistische Bedingungen für BIPV-Anwendungen darstellen, jedoch weiter verschärft werden sollten, um die extremen Einstrahlungsniveaus in alpinen Umgebungen abzubilden.

Die Analyse der Testergebnisse ermöglichte zudem die Identifikation von Moduldesignmerkmalen, die sich besonders für alpine PV-Anwendungen eignen. PV-Module für alpine Umgebungen profitieren von einer Verkapselung mit Polyolefin-Elastomer (POE), Glas/Glas-Modulstrukturen, gerahmten Moduldesigns, Multi-Wire-Metallisierung sowie Bypassdioden mit höherer Stromtragfähigkeit. Diese Designmerkmale verbessern die mechanische Stabilität und verringern die Wahrscheinlichkeit von Zellrissen unter Schnee- und Windlasten sowie bei niedrigen Temperaturen und ermöglichen gleichzeitig einen sicheren Betrieb unter den hohen Einstrahlungsniveaus, die für alpine Standorte typisch sind.



Insgesamt tragen die Ergebnisse zu einer verbesserten Zuverlässigkeitsbewertung und Produktentwicklung von PV-Modulen für BIPV- und alpine Anwendungen bei. Hersteller können die entwickelten Testansätze nutzen, um Materialschwächen bereits in frühen Phasen des Designprozesses zu identifizieren und Modulararchitekturen für anwendungsspezifische Belastungen zu optimieren. Die im Projekt gewonnenen Erkenntnisse wurden durch die Zusammenarbeit mit internationalen Forschungspartnern, wissenschaftliche Publikationen sowie den direkten Austausch mit Akteuren der PV-Industrie verbreitet und tragen damit zur Entwicklung zuverlässigerer PV-Technologien für anspruchsvolle Betriebsumgebungen bei.

Main findings («Take-Home Messages»)

- Photovoltaic (PV) modules designed for alpine environments benefit from polyolefin elastomer (POE) encapsulation, glass/glass structures, framed modules, multi-wire metallization, and bypass diodes with higher current capacity; these features together enhance mechanical stability and reduce the likelihood of cell cracking under snow load, wind stress, and low temperature conditions, offering safer operation under high irradiation conditions.
- POE encapsulants are preferable to ethylene vinyl acetate (EVA) for alpine PV applications because their lower glass transition temperature maintains elasticity at low temperatures, providing better protection of solar cells to mechanical stress over a wider temperature range.
- Several standard reliability tests were successfully accelerated without introducing unexpected degradation mechanisms. Ultraviolet (UV) exposure, Thermal Cycling (TC), and Static Mechanical Load (SML) tests were effectively accelerated considering operating conditions in Alpine PV and BIPV applications.
- Static Mechanical Load tests performed after 50 cycles of thermal cycling or at -40°C , instead of the standard 25°C condition, better replicate alpine stress conditions and accelerate the occurrence of relevant failure modes, achieving acceleration factors greater than three. Laboratories that lack very large climatic chambers to accommodate their SML setups can perform the tests at room temperature after 50 cycles of TC and still obtain comparable outcomes to doing such tests at -40°C .



Contents

| | |
|---|-----------|
| Summary | 3 |
| Zusammenfassung | 4 |
| Main findings («Take-Home Messages») | 5 |
| Contents | 6 |
| List of figures | 7 |
| List of tables | 8 |
| List of abbreviations | 9 |
| 1 Introduction | 11 |
| 1.1 Context and motivation..... | 11 |
| 1.2 Project objectives..... | 12 |
| 2 Approach, method, results and discussion | 13 |
| 2.1 Enhanced stress emergence in Alpine PV and BIPV applications and resulting degradation modes and failures (Task 2.1)..... | 14 |
| 2.2 Identification of methods for sensitive degradation detection (Task 2.2)..... | 16 |
| 2.3 Initial Test Matrices (Task 2.3, Task 2.4, WP3)..... | 17 |
| 2.3.1. Initial Accelerated Ageing Test Sequence..... | 18 |
| 2.3.2. Low temperature behaviour of encapsulants and modules | 21 |
| 2.3.3. Overall Evaluation of the Initial Test Sequences | 22 |
| 2.4 Developed Alpine and BIPV Specific Test Sequences (Task 2.3, Task 2.4, WP3)..... | 23 |
| 2.4.1. Test Sequences | 23 |
| 2.4.2. Modules | 24 |
| 2.4.3. UV Test Sequence (Alpine & BIPV-roof)..... | 25 |
| 2.4.4. Mechanical Load Test Sequence (Alpine)..... | 26 |
| 2.4.5. Thermal Cycling (TC) Test Sequence (Alpine & BIPV)..... | 28 |
| 2.4.6. Hot Spot Endurance Test Sequence (Alpine & BIPV)..... | 33 |
| 2.4.7. Bypass Diode Test Sequence (Alpine & BIPV)..... | 34 |
| 2.5 Defining advanced methodology for accelerated reliability testing (T4.2)..... | 34 |
| 2.6 Evaluation of Diagnostic Tools for Early Failure Detection (T4.3)..... | 35 |
| 2.7 Characterisation and failure analysis of field-aged PV modules (T4.1)..... | 36 |
| 3 Conclusions and Impact | 39 |
| 3.1 Conclusions | 39 |
| 3.2 Impact..... | 39 |
| 4 National and international cooperation | 42 |
| 5 Publications and other communications | 42 |
| 6 References | 44 |



List of figures

| | | |
|------------|---|----|
| Figure 1: | Examples of pilot projects for PV in an alpine environment: (a) "Monte Rosa SAC Hut", (b) 2.2 MW PV system dam Muttsee, (c) "Lac des Toules" in Switzerland and (d) BIPV (façade) system in Austria. | 11 |
| Figure 2: | Work packages and tasks of each work package. | 14 |
| Figure 3: | Initial accelerated ageing test sequence..... | 19 |
| Figure 4: | Developed microcracks and cell cracks in the mini-modules..... | 20 |
| Figure 5: | EL images of all 4-cell test mini-modules after four test cycles..... | 20 |
| Figure 6: | Tensile strength measurements of encapsulants. Lower tensile strength corresponds to a more elastic encapsulant..... | 21 |
| Figure 7: | Appearance of first cell cracks during the static three-point mechanical load test on mini-modules at various temperatures..... | 22 |
| Figure 8: | Developed Alpine PV and BIPV Test Sequences. | 23 |
| Figure 9: | Mini-modules undergoing UV exposure. (left) Metal halide irradiation (300–2500 nm) at $\approx 110^{\circ}\text{C}$ module temperature. (right) UVA irradiation (300–400 nm, intensified irradiance peak at 340 nm) at $\approx 60^{\circ}\text{C}$ module temperature. | 26 |
| Figure 10: | Electroluminescence images of modules a-c) with busbars and d) with wires after the static mechanical load test under different conditions..... | 27 |
| Figure 11: | Light microscopic image of cross sections of G/BS modules comparing (left) PERC cells with busbars and (right) TOPCon cells with multi-wires. | 27 |
| Figure 12: | Change in normalized maximum power and fill factor (FF) for (top) G/PERC/G (4mm/4mm) and (bottom) G/PERC/BS (4mm/BS) modules during and after Standard (-40°C to $+85^{\circ}\text{C}$) and Highly Accelerated (-40°C to $+110^{\circ}\text{C}$) thermal cycling tests..... | 29 |
| Figure 13: | Change in normalized maximum power and fill factor (FF) for G/HJT/BS modules during Standard (-40°C to $+85^{\circ}\text{C}$), Accelerated (-40°C to $+95^{\circ}\text{C}$), and Highly Accelerated (-40°C to $+110^{\circ}\text{C}$) thermal cycling tests. | 31 |
| Figure 14: | Module temperature (blue), hot spot temperature (red), and their difference (green) recorded during 15 hours of hot spot endurance test conducted at a controlled module temperature of 55°C | 33 |
| Figure 15: | Module temperature (blue), hot spot temperature (red), and their difference (green) recorded during 15 hours of hot spot endurance test conducted at a controlled module temperature of 75°C | 33 |
| Figure 16: | G/PERC/BS, G/IBC/BS and G/HJT/BS modules with shadow masks on the outdoor test stand..... | 34 |
| Figure 17: | (left) FTIR-measurements of the backsheets of a PV installation at Dobratsch. (right) NIR measurement of a module..... | 37 |



Figure 18: Overview of indoor and outdoor measurement results for all analysed systems in the published work. The figure shows: (i) the module degradation rates of maximum power based on indoor PM measurements (box plots with underlying data points), and (ii) the system PLR calculated from outdoor monitoring data using the multi-YoY method, with 95% CI. Systems are ordered by altitude zones indicated at the top. For the site 533m-VR-SM55(HO), which is composed of 94% SM55-HO modules and 6% SM55 modules, both types are shown for the indoor I–V results. The minority type is displayed in a faded colour for clarity, as it is less representative of the system behaviour..... 38

Figure 19: The Loser PV system (1560 m). 41

List of tables

Table 1: Alpine-specific environmental stressors, related failure modes, and applicable IEC standards..... 15

Table 2: BIPV-specific environmental stressors, related failure modes, and applicable IEC standards..... 16

Table 3: List of the bill of materials (BOM) of the tested mini-modules..... 18

Table 4: List of the final test samples produced within the project..... 25

Table 5: Summary of the modules tested in Thermal Cycling test sequence. 28

Table 6: Electroluminescence images of G/PERC/G (4 mm / 4 mm) and G/PERC/BS (4 mm / BS) modules taken before, and after 400 cycles of Standard (–40°C to +85°C) and Highly Accelerated (–40°C to +110°C) thermal cycling tests. 30

Table 7: Electroluminescence images of G/HJT/BS modules before, and after 200, 300, and 600 cycles of Standard (–40°C to +85°C), Accelerated (–40°C to +95°C), and Highly Accelerated (–40°C to +110°C) thermal cycling tests..... 32

Table 8: Acceleration factors of ATC and HATC for modules showing performance changes after TC tests and increase in test duration due to modified conditions..... 33

Table 9: Summary of the test conditions, observed degradation modes, the corresponding identification methods, and the key outcomes of each test sequence investigated in this project 35

Table 10: Evaluation of the degradation identification tools. 36



List of abbreviations

| | |
|----------|--|
| AL-BSF | Aluminium Back Surface Field |
| ATC | Accelerated Thermal Cycling |
| ATR-IR | Attenuated Total Reflectance Infrared |
| BIPV | Building-Integrated Photovoltaics |
| BOM | Bill of Materials |
| BS | Backsheet |
| DH | Damp Heat |
| DML | Dynamic Mechanical Load |
| DSC | Differential Scanning Calorimetry |
| EL | Electroluminescence |
| EPE | Ethylene-Propylene Elastomer |
| EVA | Ethylene-Vinyl Acetate |
| FF | Fill Factor |
| G | Glass |
| GW | Gigawatt |
| HATC | Highly Accelerated Thermal Cycling |
| HF | Humidity Freeze |
| HJT | Heterojunction |
| IBC | Interdigitated Back Contact |
| IEC | International Electrotechnical Commission |
| IEA PVPS | International Energy Agency Photovoltaic Power Systems Programme |
| IR | Infrared |
| I_{sc} | Short-Circuit Current |
| ISO | International Organization for Standardization |
| I-V | Current–Voltage |
| kWh | Kilowatt-hour |
| MW | Megawatt |
| MQT | Module Qualification Tests |
| NIR | Near-Infrared |



| | |
|----------|---|
| OFI | Austrian Research Institute for Chemistry and Technology |
| PET | Polyethylene Terephthalate |
| POE | Polyolefin Elastomer |
| PERC | Passivated Emitter and Rear Contact |
| PV | Photovoltaic |
| SaTC | Standard Thermal Cycling |
| SFOE | Swiss Federal Office of Energy |
| SML | Static Mechanical Load |
| SUPSI | University of Applied Sciences and Arts of Southern Switzerland |
| TC | Thermal Cycling |
| TD-GC/MS | Thermo-Desorption Gas Chromatography / Mass Spectrometry |
| TGA | Thermogravimetric Analysis |
| TOPCon | Tunnel Oxide Passivated Contact |
| TS | Technical Specification |
| TW | Terawatt |
| UVA | Ultraviolet A |
| UV | Ultraviolet |
| UVF | Ultraviolet Fluorescence |
| UVID | UV-Induced Degradation |
| V_{oc} | Open-Circuit Voltage |
| WP | Work Package |
| ZAMG | Central Institution for Meteorology and Geodynamics |



1 Introduction

1.1 Context and motivation

Solar photovoltaic (PV) technology is among the most promising renewable energy sources, with total installed capacity reaching 1 terawatt (TW) in 2022 and 2.2 TW in 2024, including an additional 602 gigawatts (GW) installed in 2024 [1]. Despite this rapid growth, the large-scale deployment of conventional ground-mounted PV systems in lowland areas is constrained in mountainous countries such as Switzerland and Austria due to limited land availability and competing land-use demands (e.g., agriculture, settlements, and environmental protection). To further expand PV capacity in these regions, installations must increasingly rely on alternative deployment pathways. These include:

- (i) integrated solutions in the built environment (e.g. building roofs, façades, and infrastructure),
- (ii) dual-use applications that combine energy generation with existing structures (e.g. PV on infrastructure), and
- (iii) ground-mounted PV systems in mountainous areas, where larger installations are technically feasible but exposed to harsh environmental conditions (Figure 1).



Figure 1: Examples of pilot projects for PV in an alpine environment: (a) "Monte Rosa SAC Hut", (b) 2.2 MW PV system dam Mutsee, (c) "Lac des Toules" in Switzerland and (d) BIPV (façade) system in Austria.

Additionally, maintaining a high level of electricity supply security, particularly for winter electricity, is of great importance. Winter supply gaps are becoming more pronounced due to seasonal mismatches between electricity demand and PV production, as well as the gradual transformation of the energy system.



In this context, appropriately designed PV installations in alpine areas represent a targeted solution rather than a general expansion pathway. At elevations above the fog layer, higher solar irradiation, increased albedo from snow reflection, and lower ambient temperatures can enhance winter energy yields. This improved winter performance is the primary justification for Alpine PV installations, despite their substantially higher investment costs compared to systems in the lowlands.

However, PV systems operating in such harsh and demanding environments are exposed to stresses exceeding those encountered in moderate climates [2]. High UV irradiation, strong temperature fluctuations, snow and ice loads, and mechanical stress from wind can challenge long-term reliability. Depending on the application type and environmental conditions, additional stresses – such as increased UV exposure in alpine environments [3, 4] or enhanced thermal stress in building-integrated PV (BIPV) systems [5, 6] – may exceed the parameter limits covered by standard International Electrotechnical Commission (IEC) qualification tests. These conditions can accelerate specific degradation modes and potentially reduce service lifetime.

For the design qualification and type approval of PV modules, a compilation of required module qualification tests (MQT) is specified in IEC 61215-2:2021 [7]. The tests were originally developed to qualify conventional flat-plate PV modules installed in a ground-mounted system under moderate climatic conditions. Their primary objective is to identify early-life failures and ensure high durability, rather than to predict long-term performance or lifetime under site-specific stress conditions.

In recent years, however, the boundary conditions for PV deployment have changed significantly. The increasing deployment of PV systems in alpine regions, desert climates, coastal environments, floating installations and building-integrated applications has raised concerns about whether the existing MQT sequences adequately represent the relevant stress factors. Research institutions, certification bodies, and industry stakeholders have therefore initiated discussions on extending or adapting qualification procedures. Within the IEC framework, dedicated working groups, particularly in IEC Technical Committee 82, are actively evaluating macro- and micro-climate-specific stress profiles and potential modifications to existing standards [8, 9, 10]. Parallel efforts are being pursued by research organizations, which investigate accelerated stress testing, combined stress sequences, and climate-specific durability assessment methods [11, 12, 13].

At the same time, the need for more advanced testing methodologies is increasingly driven by industry. Manufacturers developing modules for alpine installations, BIPV, floating PV, or other unconventional applications face higher mechanical, thermal, and UV stresses than those represented in standard MQTs. Investors, insurers, and system operators are requesting improved reliability data and more robust lifetime predictions [14, 15].

Product development plays a critical role in ensuring the long-term reliability and economic viability of PV modules, particularly for operation in demanding environments such as alpine regions or BIPV applications. Module lifetime and performance are largely determined during the design phase through material selection, module architecture, and bill of materials decisions. Standard qualification tests verify minimum durability requirements but do not optimise designs for application-specific stress combinations, such as intensified UV exposure, severe thermo-mechanical cycling, or mechanical loads at low temperatures. Therefore, advanced and application-oriented product development methodologies are required to identify weaknesses early, enable rapid design iterations, and ensure robust long-term performance. Accelerated, reliability-driven product development is essential to reduce time-to-market while increasing confidence in durability for high-investment PV applications.

1.2 Project objectives

The main objective of the PV-DETECT project is to develop an advanced testing methodology for accelerated and optimised product development of PV modules for the unconventional applications (Alpine PV and BIPV), ensuring that increased investment costs under harsh conditions are justified by demonstrably improved long-term performance and durability. The planned work is based on **(i) improved and**



accelerated reliability testing with (ii) sensitive analytical tools for early failure and degradation detection.

The acquired know-how is passed on to the PV module manufacturer (i.e. project partner Sonnenkraft, an Austrian PV module manufacturer) so that the advanced methodology can be used to implement efficient, accelerated product development for modules designed for operation in unconventional applications. Additionally, through the dissemination of our results during the project, several PV installers and module manufacturers focusing on unconventional operating conditions approached us to request know-how transfer. Reduced reliability testing times, achieved through enhanced stress testing and early-stage degradation detection, enable an accelerated product development process (optimised module architecture and bill of materials). A reduction in product development time by a factor > 3 is targeted.

SUPSI's motivation to develop advanced testing methodologies arises from its applied research mandate and its close collaboration with industry partners in module manufacturing and system integration. By developing reliability-oriented approaches, SUPSI aims to bridge the gap between academic research on PV reliability and industrial product development.

As a Solar ERA-NET project, PV-DETECT was implemented through an international collaboration. SUPSI worked closely with the Austrian Research Institute for Chemistry and Technology (OFI), contributing expertise in polymer science and PV module reliability, and with Sonnenkraft GmbH (previously KIOTO), an Austrian PV module manufacturer with BIPV and Alpine PV modules in its portfolio. This collaborative framework ensured a direct link between advanced laboratory testing, material-level degradation analysis, certification expertise, and industrial module development for demanding applications. It also guarantees that the developed methodologies are directly transferable to industrial development processes and aligned with concrete market needs.

2 Approach, method, results and discussion

The project was structured into four work packages (WPs) (Figure 2). WP1 covered project coordination, technical alignment between partners, and dissemination activities throughout the project duration.

WP2 focused on the technical preparation of the study. This included a targeted literature review and analysis of operating conditions in unconventional PV applications (Alpine PV and BIPV systems), definition of application-specific stress test matrices, and systematic selection and screening of suitable characterisation methods for early degradation detection. In addition, dedicated test modules were designed and manufactured, and relevant PV systems were identified to perform measurements in WP4.

WP3 comprised the core experimental work. Accelerated ageing tests – defined in WP2 based on realistic and application-specific stress levels – were performed on newly manufactured test modules. Electrical, mechanical, and material characterisation was conducted before, during, and after the stress sequences. This enabled monitoring of degradation progression, identification of failure mechanisms, and evaluation of the bill of materials and the sensitivity of the selected diagnostic tools.

WP4 focused on analysing the data generated in WP3 and on detailed on-site or laboratory characterisation of field-aged modules using the same diagnostic toolbox applied in WP3. By correlating known operating conditions with observed degradation patterns and systematically comparing field and laboratory ageing results, the project identified which diagnostic methods are most suitable for detecting specific degradation mechanisms. Based on this combined analysis, an advanced testing methodology for early degradation detection and reliability-driven product development was derived.

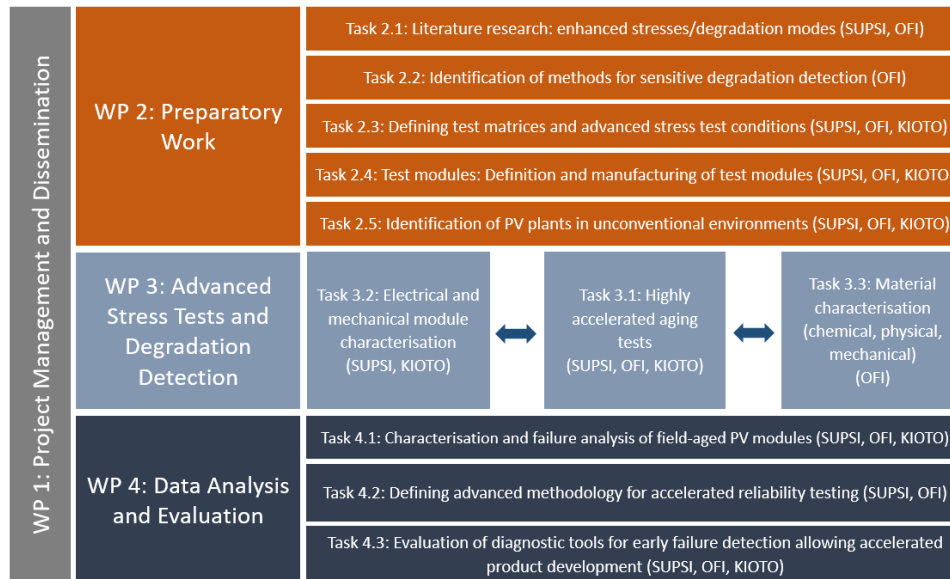


Figure 2: Work packages and tasks of each work package.

2.1 Enhanced stress emergence in Alpine PV and BIPV applications and resulting degradation modes and failures (Task 2.1)

The project started with a structured literature review to identify (i) environmental stressors specific to alpine and BIPV applications, (ii) corresponding degradation mechanisms and failure modes of PV modules, and (iii) existing accelerated testing approaches addressing these stressors. The review covered:

- peer-reviewed scientific publications on climate-specific degradation (e.g., UV-induced degradation, thermo-mechanical fatigue, moisture ingress, snow-load-induced mechanical damage, etc.),
- reports on long-term monitoring of alpine PV installations in Switzerland, Austria and neighbouring countries,
- climate data sources (e.g., Central Institution for Meteorology and Geodynamics (ZAMG) and comparable meteorological databases) to quantify relevant environmental loads such as irradiation intensity, temperature cycling amplitude, and snow loads,
- existing standards and technical specifications (e.g., IEC 61215 and other related norms), and
- publications discussing extended or combined accelerated testing procedures beyond standard IEC qualification.

The objective was not only to gather norms, but to systematically link application-specific stress factors (e.g., high UV exposure, large temperature gradients, static and dynamic mechanical loads, limited rear ventilation in BIPV) with observed degradation modes, such as encapsulant discolouration, solder fatigue, cell cracking, delamination, or backsheet embrittlement. The identified stress-degradation relationships were structured and summarized in Table 1 and Table 2. The tables list:

- environmental stressors in alpine and BIPV applications,
- corresponding degradation mechanisms and failure modes reported in the literature, and
- existing standard accelerated ageing tests.



This structured analysis allowed the identification of gaps between real operating conditions in unconventional applications and the stress profiles represented in current IEC qualification tests. The results also contributed to an international report within IEA PVPS Task 13 (“Optimisation of Photovoltaic Systems for Different Climates”), where climate-specific optimisation strategies are discussed [16].

Table 1: Alpine-specific environmental stressors, related failure modes, and applicable IEC standards

| Alpine stressors | Typical Failure Modes | Relevant Tests | Applicable IEC Standards / Technical Specifications (TS) |
|------------------------------|--|---|--|
| High UV exposure | <ul style="list-style-type: none"> • Degradation of backsheet and encapsulant • UV-induced degradation (UVID) of cells | <ul style="list-style-type: none"> • UV preconditioning / UV exposure test | <ul style="list-style-type: none"> • IEC 61730-2:2023 (for backsheet) • IEC TS 63126:2020 (extended UV for hot climates) |
| High irradiance | <ul style="list-style-type: none"> • Bypass diode failure • Increased hot spot risk | <ul style="list-style-type: none"> • Bypass diode test • Hot spot endurance test | <ul style="list-style-type: none"> • IEC 61215-2:2021 (hot spot test, bypass diode test) • IEC TS 63126:2020 (extended stress levels) |
| Low temperature | <ul style="list-style-type: none"> • Increased encapsulant stiffness • Cell cracking | <ul style="list-style-type: none"> • Thermal Cycling (TC) • Humidity Freeze (HF) • Cold conditioning | <ul style="list-style-type: none"> • IEC 61215-2:2021 (TC, HF) • IEC 61730-2:2023 (cold conditioning) |
| Rapid temperature excursions | <ul style="list-style-type: none"> • Interconnect failures • Backsheet and encapsulant damage | <ul style="list-style-type: none"> • Thermal Cycling (TC) • Extended Thermal Cycling | <ul style="list-style-type: none"> • IEC 61215-2:2021 (TC) • IEC 62892:2019 (Extended TC) |
| Snow load | <ul style="list-style-type: none"> • Glass breakage • Cell cracking • Mechanical deformation | <ul style="list-style-type: none"> • Static Mechanical Load (SML) • Non-uniform snow load test | <ul style="list-style-type: none"> • IEC 61215-2:2021 (SML) • IEC 62938:2020 (non-uniform snow load) |
| Ice formation | <ul style="list-style-type: none"> • Frame deformation or breakage | <ul style="list-style-type: none"> • Humidity Freeze (HF) • Mechanical frame testing | <ul style="list-style-type: none"> • IEC 61215-2:2021 (HF) |
| Wind load | <ul style="list-style-type: none"> • Cell cracks • Mounting structure damage • Ribbon/interconnect fatigue | <ul style="list-style-type: none"> • Dynamic Mechanical Load (DML) • Static Mechanical Load (SML) | <ul style="list-style-type: none"> • IEC 62782:2016 (DML) • Post-DML sequences: TC50 + HF10 and/or Damp Heat (DH) per IEC 61215-2:2021 • IEC 61215-2:2021 (SML) |
| Hail impact | <ul style="list-style-type: none"> • Glass fracture • Cell damage | <ul style="list-style-type: none"> • Hail impact test | <ul style="list-style-type: none"> • IEC TS 63397:2022 • Recommended stress sequence: DH → Hail → DML → TC → HF |



Table 2: BIPV-specific environmental stressors, related failure modes, and applicable IEC standards.

| BIPV stressors | Typical Failure Modes | Relevant Tests | Applicable IEC Standards / Technical Specifications |
|------------------------------------|--|--|---|
| Elevated Operating Temperature | <ul style="list-style-type: none">• Degradation of back-sheet and encapsulant• Metallisation corrosion and solder fatigue• Cell degradation• Bypass diode failure | <ul style="list-style-type: none">• UV preconditioning / UV exposure test• Thermal Cycling (TC)• Hot spot endurance test• Bypass diode thermal test | <ul style="list-style-type: none">• IEC 61215-2:2021 (UV, TC, hot spot, bypass diode test)• IEC TS 63126:2020 (extended stress levels) |
| High diurnal temperature variation | <ul style="list-style-type: none">• Thermo-mechanical fatigue of cells• Interconnect fatigue• Metallisation damage | <ul style="list-style-type: none">• Thermal Cycling (TC)• Extended Thermal Cycling | <ul style="list-style-type: none">• IEC 61215-2:2021 (TC)• IEC TS 63126:2020 (Extended stress levels of TC)• IEC 62892:2019 (Extended TC) |
| Frequent partial shading | <ul style="list-style-type: none">• Hot spots• Encapsulant or back-sheet degradation• Cell damage or glass cracking• Bypass diode failure | <ul style="list-style-type: none">• Hot spot endurance test• Bypass diode test | <ul style="list-style-type: none">• IEC 61215-2:2021 (hot spot test, bypass diode test)• IEC TS 63126:2020 (extended stress levels) |

2.2 Identification of methods for sensitive degradation detection (Task 2.2)

To enable a highly accelerated product development approach, sensitive and early-stage degradation detection is essential. Therefore, a systematic screening of diagnostic and characterisation methods was performed to identify the most suitable techniques for monitoring degradation for each highly accelerated stress testing sequence.

All relevant measurement methods available at the participating project partners were compiled and assessed with respect to (i) sensitivity to early degradation, (ii) suitability for non-destructive testing, and (iii) compatibility with accelerated testing sequences. The screened methods were grouped into three categories

Material characterization

- Visual inspection / light microscopy of failures
- Near-infrared (NIR) Spectroscopy
- Infrared (IR) Spectroscopy
- Raman Spectroscopy
- Colour measurement
- Thermo-desorption gas chromatography/mass spectrometry (TD-GC/MS)
- Thermal analysis (differential scanning calorimetry - DSC)
- Thermo-mechanical analysis (thermogravimetric analysis - TGA)



Imaging Methods

- Electroluminescence (EL) image
- Ultraviolet-Fluorescence (UVF) image
- Thermography
- Ultrasonic microscopy
- ATR-IR imaging (on cross-section)

Electrical characterization

- Current-voltage (I-V) measurement

The rationale for including this broad range of methods was to establish a direct link between specific accelerated stress factors and the most sensitive diagnostic technique. Different stress conditions (e.g., enhanced UV, thermal cycling, mechanical loading, or hot spot formation) activate different degradation pathways at the material, interface, or cell level. No single method can detect all relevant early-stage defects.

Therefore, during the first accelerated stress sequence (in Section 2.3), these techniques were systematically applied and evaluated. The objective was to identify which techniques provide the earliest and most reliable indication of degradation. This screening process forms the basis for defining a reduced and application-oriented highly accelerated product development methodology.

2.3 Initial Test Matrices (Task 2.3, Task 2.4, WP3)

Before developing the complete Alpine PV and BIPV test matrices, exploratory investigations were carried out to better understand relevant degradation mechanisms and suitable diagnostic approaches.

First, **an initial accelerated ageing test sequence** (in Section 2.3.1) was developed with the objective of intentionally triggering known or anticipated alpine stress-related failure modes under intensified stress conditions. This sequence was not intended to represent the final project test matrix, but rather to investigate different accelerated ageing mechanisms and to evaluate the applicability and sensitivity of the characterisation methods described in Task 2.2 (Section 2.2).

Second, **three-point bending tests at different temperatures** (in Section 2.3.2) were conducted to investigate the low-temperature behaviour of different materials and module assemblies. These tests aimed to analyse changes in stiffness and crack susceptibility at sub-zero temperatures representative of alpine operating conditions.

Both test series were therefore preparatory in nature and did not constitute the main stress sequences of the project. Instead, they served to:

- improve understanding of stress–degradation relationships under intensified conditions,
- screen and validate diagnostic tools for early degradation detection, and
- evaluate the mechanical behaviour of encapsulants and module stacks at low temperatures.

Test Samples

An initial set of 4-cell test samples (Table 3) was manufactured by Sonnenkraft and subjected to the (i) initial accelerated ageing test sequence and (ii) three-point bending tests at different temperatures. For each module type, three samples were manufactured (unless otherwise specified).



The tested mini-module configurations varied in:

- Module structure (glass/backsheets, glass/glass)
- Encapsulant type (EVA, POE)
- Backsheet material (PET DS460, Tedlar)

These mini-modules were used to:

- Investigate material- and design-dependent degradation mechanisms under intensified stress conditions.
- Benchmark characterisation techniques with respect to their suitability for detecting chemical, mechanical, and electrical degradation.

The knowledge gained from these exploratory investigation tests was subsequently used to (i) **develop a complete test matrix for alpine and BIPV systems** (Section 2.4) and (ii) **define the bill of materials (BOM) for the test modules** manufactured for the core experimental phase.

Table 3: List of the bill of materials (BOM) of the tested mini-modules.

| Name | Module Structure | Encapsulant | Backside | Number of cells | Number of modules |
|----------|------------------|-------------|-----------|-----------------|-------------------|
| DeEP-11 | Glass/Backsheet | EVA | PET DS460 | 4 | 5 |
| DePP-12 | Glass/Backsheet | POE | PET DS460 | 4 | 3 |
| DeEG-13 | Glass/Glass | EVA | Glass-1 | 4 | 3 |
| DePG-14 | Glass/Glass | POE | Glass-1 | 4 | 3 |
| DeET-15 | Glass/Backsheet | EVA | Tedlar | 4 | 3 |
| DePT-16 | Glass/Backsheet | POE | Tedlar | 4 | 3 |
| DeEG-17 | Glass/Glass | EVA | Glass-2 | 4 | 3 |
| DePG-18 | Glass/Glass | POE | Glass-2 | 4 | 3 |
| DeEP-19a | Glass/Backsheet | EVA | PET DS460 | 4 | 1 |
| DePP-20a | Glass/Backsheet | POE | PET DS460 | 4 | 1 |

G: Glass, EVA: ethylene-vinyl acetate, POE: polyolefin elastomer, PET: Polyethylene Terephthalate, Tedlar: Polyvinyl fluoride.

2.3.1. Initial Accelerated Ageing Test Sequence

Based on prior experience from research activities at SUPSI and OFI, an initial accelerated ageing test sequence was defined with stress parameters exceeding those specified in standard IEC qualification procedures. The objective was twofold:

- To explore the response of PV modules under intensified stress conditions.
- To evaluate the robustness of the stress protocol and the effectiveness of the associated diagnostic methods.

Four test rounds of the accelerated ageing sequence were conducted under the conditions summarised in Figure 3. Mini-modules were subjected to the defined stress steps. After each stress step, the mini-



modules were characterised using the diagnostic methods identified in Task 2.2 (Section 2.2). This procedure allowed a dual screening process:

- **Screening of stress tests**, to assess which stress combinations most effectively trigger relevant degradation modes under accelerated conditions.
- **Screening of identification methods**, to determine which analytical techniques provide the earliest and most reliable detection of emerging defects.

The iterative execution enabled refinement of both the stress protocol and the diagnostic toolbox, forming the basis for the subsequent development of the highly accelerated methodology.

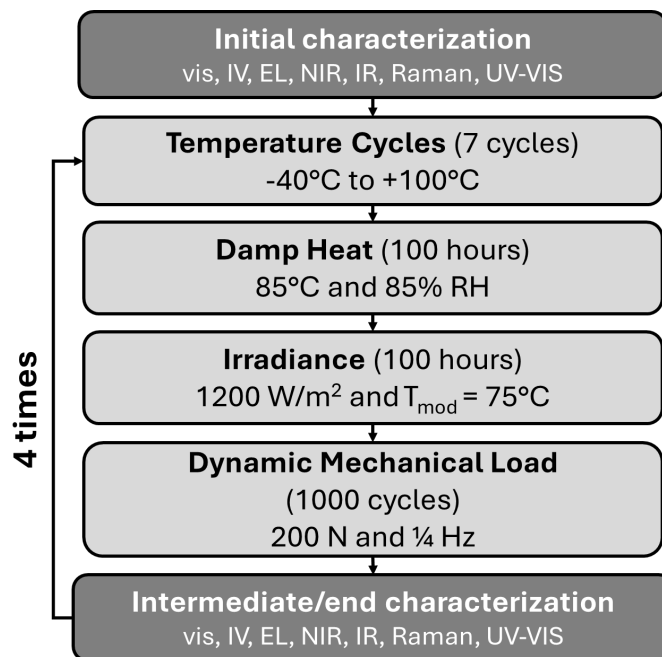


Figure 3: Initial accelerated ageing test sequence.

After four cycles (49 days total), the material and electrical measurements indicated initial signs of degradation in the test mini-modules. In particular, the dynamic mechanical load steps induced cell cracking, despite the applied pressure being only approximately 2000 Pa (around 0.1 m² sample area) (Figure 4). EL imaging was performed after the first, third, and fourth cycles. By the end of the sequence, six of eight modules exhibited new microcracks or cell cracks of varying severity (Figure 5). These defects resulted in maximum power degradation between -3.3% and -8.2%.

To assess potential degradation of polymeric embedment materials, spectroscopic analyses were conducted. Raman spectroscopy showed increased fluorescence intensity with exposure time, indicating early-stage polymer ageing. However, no clear evidence of chemical degradation was observed.

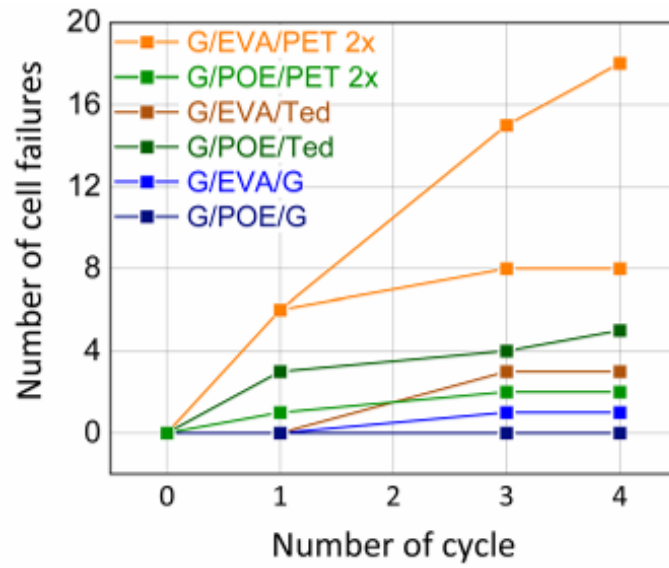


Figure 4: Number of failures (cell cracks, micro cracks and solder bond failures) in the eight mini modules after each cycle of the accelerated test sequence including dynamic mechanical loading [17].

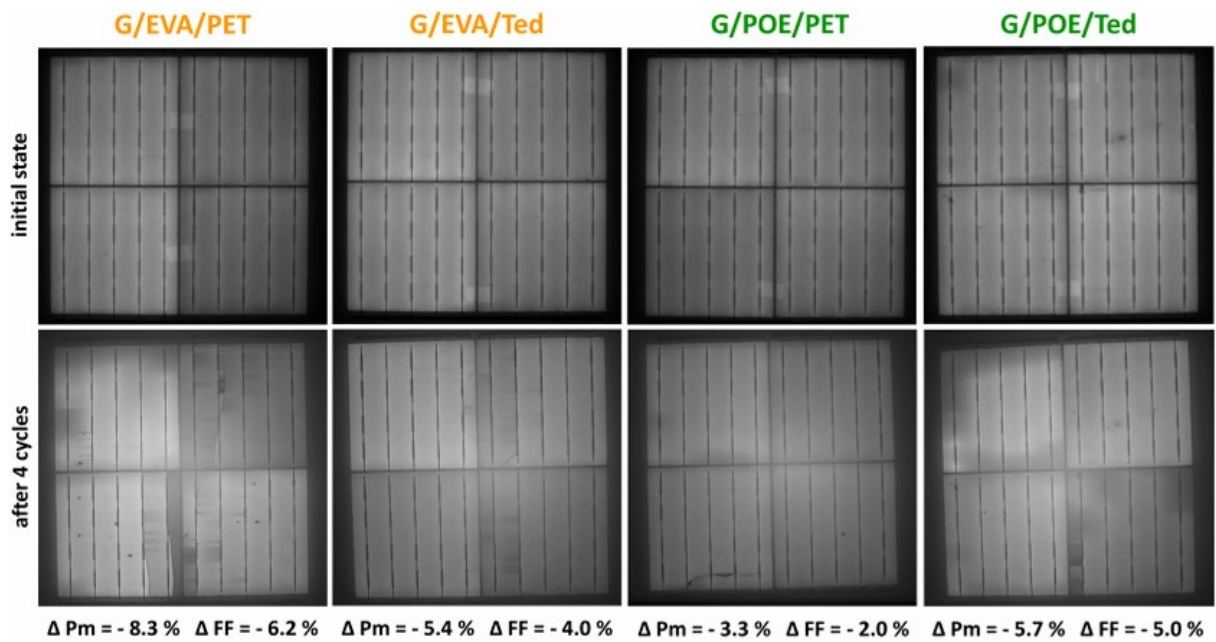


Figure 5: EL images of all 4-cell test mini-modules after four test cycles [17].



2.3.2. Low temperature behaviour of encapsulants and modules

In a separate test sequence, the low temperature behaviour of PV module encapsulants were analysed at both material and mechanical levels. Material characterisation included thermal and thermo-mechanical analyses to assess temperature-dependent changes in stiffness and stability. Four widely used encapsulation materials were evaluated:

- ethylene-vinyl acetate (EVA),
- ethylene-propylene elastomer (EPE),
- polyolefin elastomer (POE), and
- silicone.

The glass transition temperatures determined by differential scanning calorimetry (DSC) are:

- EVA: -30°C
- POE: -50°C
- Silicone: -122°C
- EPE: -30°C and -51°C

Tensile strength tests were then carried out according to ISO 527-2 at various temperatures. The tensile strength at 100% elongation was compared across different encapsulants and temperatures (Figure 6). Encapsulants with lower glass transition temperatures, such as POE or silicone polymers, maintain their elasticity even at low temperatures, providing optimal protection for the cells against high mechanical loads, particularly in situations with high snow loads and wind during cold weather.

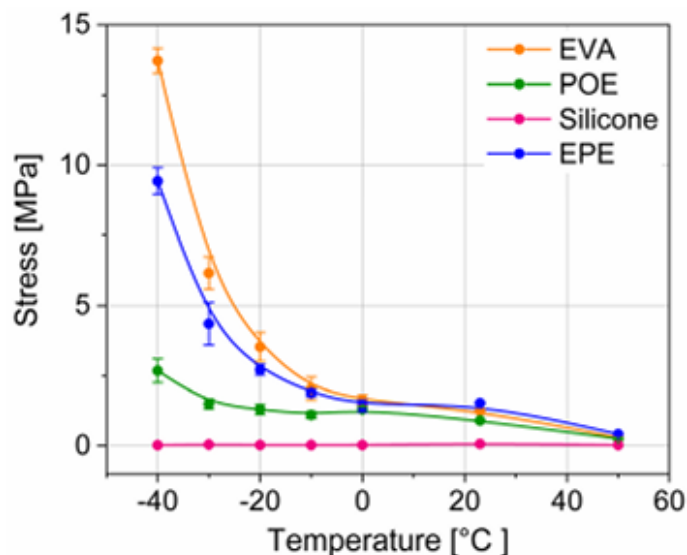


Figure 6: Tensile strength measurements of encapsulants. Lower tensile strength corresponds to a more elastic encapsulant [17].



Afterwards, static three-point mechanical tests were performed in a climate chamber at temperatures from +20°C to -50°C to evaluate low-temperature mechanical stability across module structures and encapsulants under a load of 5400 Pa. The temperature was decreased in steps of 10 °C, and at each step, a load was applied for one hour. EL imaging was performed between temperature steps to detect newly formed cell cracks and to correlate crack initiation with encapsulant behaviour and temperature-dependent stiffness changes. The results showed (Figure 7):

- Glass/glass modules exhibited significantly lower deflection than glass/backsheet modules.
- At 5400 Pa, the average deflection of glass/glass samples was 0.27 mm, compared to 0.64 mm for glass/backsheet samples.
- The combination of glass/glass architecture and POE encapsulant showed the lowest crack susceptibility at low temperatures.

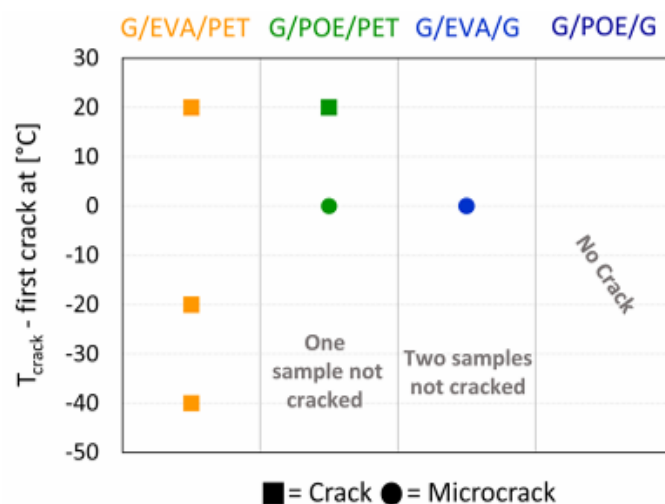


Figure 7: Appearance of first cell cracks during the static three-point mechanical load test on mini-modules at various temperatures.

2.3.3. Overall Evaluation of the Initial Test Sequences

Based on the initial results, the most effective analytical tools for degradation characterisation were selected, and the best-suited BOM for the **alpine environment** was identified. Key findings include:

- POE is the preferred encapsulant over EVA for alpine environments, as EVA's elasticity decreases significantly at low temperatures.
- Glass/glass module structures demonstrate better stability under mechanical loads compared to glass/backsheet structures.

Using insights from the first test runs, optimised complete alpine and BIPV test sequences were developed addressing the primary stressors in these environments (wind, snow, cold weather, high irradiance, UV radiation, and temperature fluctuations) (in Section 2.4.1, Figure 8). Test samples with various BOM and design (Glass/glass, glass/backsheet, EVA, POE, EPE, with/without frames) were produced and characterised (in Section 2.4.2, Table 4).



2.4 Developed Alpine and BIPV Specific Test Sequences (Task 2.3, Task 2.4, WP3)

2.4.1. Test Sequences

Based on insights from the initial accelerated ageing sequence and low-temperature investigations (in Sections 2.3.1 and 2.3.2, respectively), complete Alpine and BIPV-specific test sequences were developed (M22, D2.1). The developed sequences (Figure 8) include:

- Intensified UV exposure test
- Mechanical load test sequence (Alpine-specific)
- Extended and accelerated thermal cycling
- Extended hot spot endurance testing
- Bypass diode stress testing

The mechanical load sequence specifically addresses alpine snow and wind loads. The UV, thermal cycling, hot spot, and bypass diode sequences are relevant for both Alpine PV and BIPV applications due to elevated irradiance, partial shading, and temperature-related stresses. All test campaigns were conducted in the third project year.

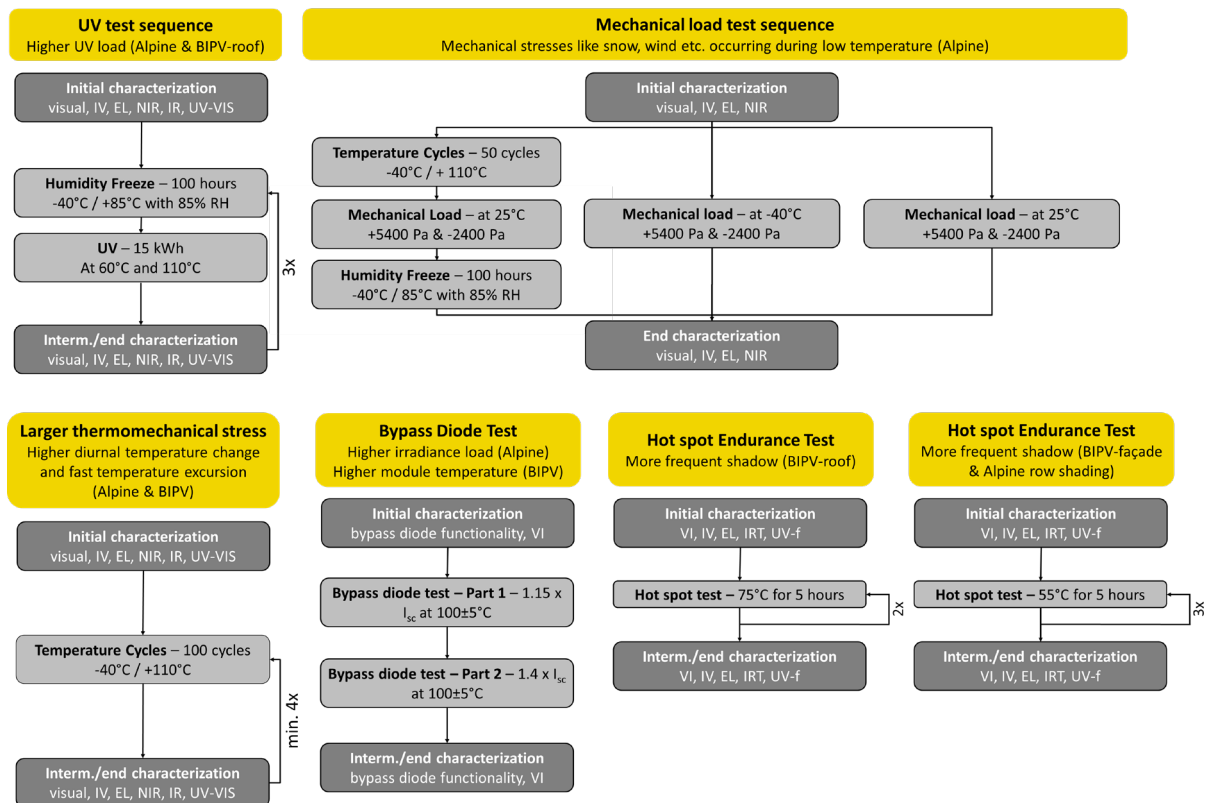


Figure 8: Developed Alpine PV and BIPV Test Sequences. For each test sequence, the aimed PV application is indicated in parentheses.



2.4.2. Modules

More than 50 full-size and 14 mini-modules, including dark-stored reference samples, were manufactured and allocated to the developed test sequences (Table 4). The samples varied mainly in:

- Module structure (glass/glass, glass/backsheet)
- Cell technology (PERC, TOPCon, IBC, HJT, AI-BSF)
- Encapsulant (EVA, POE, EPE)
- Glass thickness (3–6 mm)
- Framed vs unframed design

The selection criteria were tailored to each test sequence in Figure 8.



Table 4: List of the final test samples produced within the project.

| Test | Application | Test Sample | Glass Thickness | Frame | Module Dimensions [mmxmm] | Number of Samples |
|--|------------------------|--------------------------------------|-----------------|-------|---------------------------|-------------------|
| UV Test Sequence | Alpine and BIPV | G/POE/PERC/POE/PET | 4mm/PET | no | 4-cells | 3 |
| | | G/POE/PERC/POE/G | 4mm/4mm | no | 4-cells | 3 |
| | | G/POE/TOPCon/POE/PET | 4mm/PET | no | 4-cells | 3 |
| | | G/POE/TOPCon/POE/G | 4mm/4mm | no | 4-cells | 3 |
| | | G/POE/Al-BSF/POE/PET | 4mm/PET | no | 4-cells | 2 |
| Mechanical Load (static) Test Sequences | Alpine | G/EVA/PERC/EVA/G | 6mm/6mm | no | 2020x1015 | 3 |
| | | G/EVA/PERC/EVA/G | 4mm/4mm | no | 1700x995 | 3 |
| | | G/EVA/PERC/EVA/G | 3mm/3mm | no | 1700x995 | 3 |
| | | G/EVA/PERC/EVA/PET | 4mm/PET | yes | 1680x1015 | 3 |
| | | G/EVA/TOPCon/EVA/PET | 4mm/PET | yes | 1748x1143 | 3 |
| | | G/POE/TOPCon/POE/PET | 4mm/PET | yes | 1748x1143 | 3 |
| | | G/EPE/TOPCon/EPE/PET | 3.2mm/PET | yes | 1748x1143 | 3 |
| Extended and Accelerated Thermal Cycling Test Sequence | Alpine and BIPV | G/POE/PERC/POE/G | 4mm/4mm | no | 1700x1090 | 4 |
| | | G/POE/PERC/POE/G | 3mm/3mm | no | 1700x995 | 4 |
| | | G/POE/PERC/POE/PET | 4mm/PET | yes | 1680x1002 | 4 |
| | | G/PERC/BS | 3.2mm/PET | yes | 1769x1052 | 3 |
| | | G/IBC/BS | 3.2mm/PET | yes | 1690x1046 | 3 |
| | | G/HJT/BS | 3.2mm/PET | yes | 1721 x 1016 | 3 |
| Extended Hot Spot Endurance Test Sequence | BIPV roof | G/POE/PERC/POE/G | 4mm/4mm | no | 1700x1090 | 1 |
| | | G/POE/PERC/POE/PET | 4mm/PET | yes | 1680x1002 | 1 |
| | | G/POE/TOPCon/POE/G | 3mm/3mm | no | 1766x1165 | 1 |
| | | G/PERC/BS | 3.2mm/PET | yes | 1769x1052 | 1 |
| | | G/IBC/BS | 3.2mm/PET | yes | 1690x1046 | 1 |
| | | G/HJT/BS | 3.2mm/PET | yes | 1721 x 1016 | 1 |
| | Alpine and BIPV façade | G/POE/PERC/POE/G | 4mm/4mm | no | 1700x1090 | 1 |
| | | G/POE/PERC/POE/PET | 4mm/PET | yes | 1680x1002 | 1 |
| | | G/POE/TOPCon/POE/G | 3mm/3mm | no | 1766x1165 | 1 |
| | | G/PERC/BS | 3.2mm/PET | yes | 1769x1052 | 1 |
| | | G/IBC/BS | G/PET | yes | 1690x1046 | 1 |
| | | G/HJT/BS | 3.2mm/PET | yes | 1721 x 1016 | 1 |
| Bypass Diode Test | Alpine | Potted and not potted junction boxes | NA | NA | NA | 6 |
| | BIPV | Potted and not potted junction boxes | NA | NA | NA | 6 |

G: Glass, EVA: ethylene-vinyl acetate, POE: polyolefin elastomer, PET: Polyethylene Terephthalate, TOPCon: Tunnel Oxide Passivated Contact, PERC: Passivated Emitter and Rear Contact, IBC: Interdigitated Back Contact, HJT: Heterojunction and Al-BSF: Aluminium Back Surface Field.

2.4.3. UV Test Sequence (Alpine & BIPV-roof)

Alpine environments exhibit elevated UV doses due to high altitude and UV-rich snow albedo (up to 90% reflection). BIPV roof systems can additionally reach higher operating temperatures, accelerating UV-induced polymer degradation.



Mini-modules were exposed to:

- 100 hours of humidity-freeze (HF) pre-UV
- Three cycles of 15 kWh UV dose
- Metal halide irradiation (300–2500 nm) at $\approx 110^{\circ}\text{C}$ module temperature (Figure 9 left)
- UVA irradiation (300–400 nm, intensified irradiance peak at 340 nm) at $\approx 60^{\circ}\text{C}$ module temperature (Figure 9 right)

Non-destructive (IR, NIR, Raman) and destructive (ATR-IR imaging, DSC) analyses at OFI were performed alongside electrical characterisation.

Key Findings:

- Backsheet surface degradation was severe, particularly under intensified UVA exposure.
- Backsheet bulk degradation was stronger at higher module temperature (110°C), showing a crystallisation peak shift of $+12^{\circ}\text{C}$ (vs. $+6^{\circ}\text{C}$ at 60°C), **indicating polymer chain scission**.
- POE encapsulant showed no detectable degradation, as it is a very stable material.
- Electrical degradation trends were inconclusive due to sample diversity and limited statistical base. Slightly stronger degradation was observed for TOPCon compared to PERC (V_{oc} and FF losses).

Higher module temperatures significantly accelerated the degradation of module materials. However, the applied UV dose (in total 60 kWh/m^2 , less than a year in relevant environments) was likely insufficient to represent long-term alpine exposure. Extended UV testing is planned in follow-up projects, such as [ALIENCE](#) (alpine) and [COLOUR](#) (BIPV).



Figure 9: Mini-modules undergoing UV exposure. **(left)** Metal halide irradiation (300–2500 nm) at $\approx 110^{\circ}\text{C}$ module temperature. **(right)** UVA irradiation (300–400 nm, intensified irradiance peak at 340 nm) at $\approx 60^{\circ}\text{C}$ module temperature.

2.4.4. Mechanical Load Test Sequence (Alpine)

In the alpine climate, mechanical loads from wind and snow are among the strongest stressors, especially when combined with low temperatures or rapid temperature fluctuations. Through material and mini-module testing, we learned that encapsulant flexibility, even at low temperatures, is crucial for solar cell protection. We also found POE to be advantageous for this task due to its lower glass transition temperature. Full-size module tests conducted as described in the test matrix (Figure 8) showed interesting results:

- Severe cell cracking occurred in glass/backsheet modules under static mechanical loading after thermal cycling (Figure 10a) and at -40°C (Figure 10b), causing significant power loss.
- Reference glass/backsheet modules loaded at room temperature did not develop cracks (Figure 10c).



- Glass/glass modules showed no cell cracking, but frameless designs were susceptible to glass breakage under high loads.
- Multi-wire metallisation (TOPCon) reduced crack propagation (Figure 10d) because the smaller wire volume, compared with wide busbars (PERC), applies less stress on the solar cells (Figure 11).
- From a module design perspective, the findings highlight that POE encapsulation, glass/glass structures, framed modules, and multi-wire metallisation provide improved robustness under mechanical load.

Testing under realistic low-temperature conditions induced representative failure modes earlier than standard testing. **Based on EL and power degradation analysis, the effective acceleration factor exceeded three compared to conventional room-temperature load testing.** Detailed outcomes of the mechanical load tests have been published in a [peer-reviewed paper](#) [17].

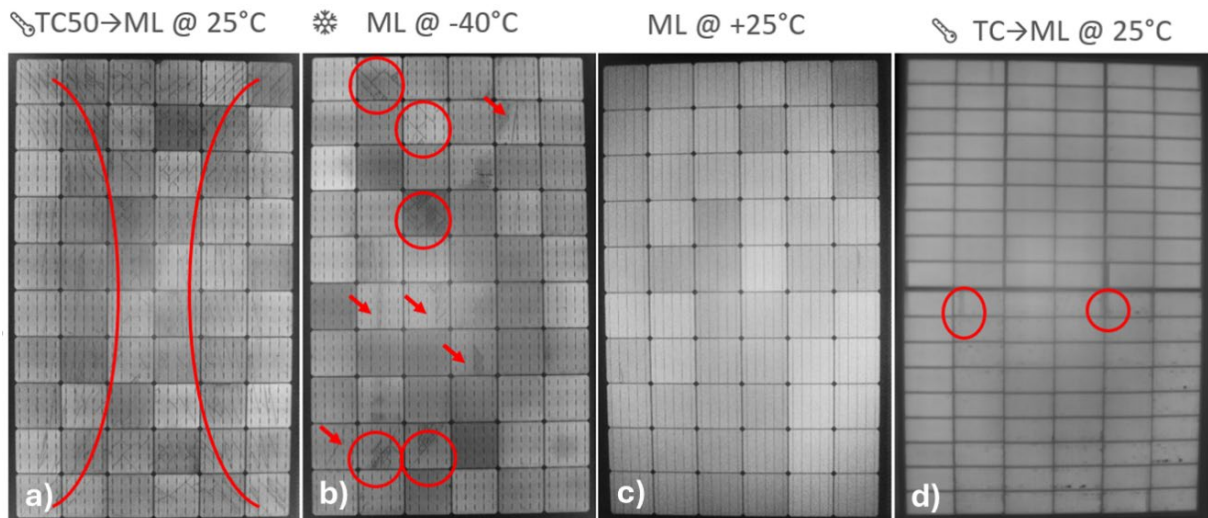


Figure 10: Electroluminescence images of modules **a-c)** with busbars and **d)** with wires after the static mechanical load test under different conditions.

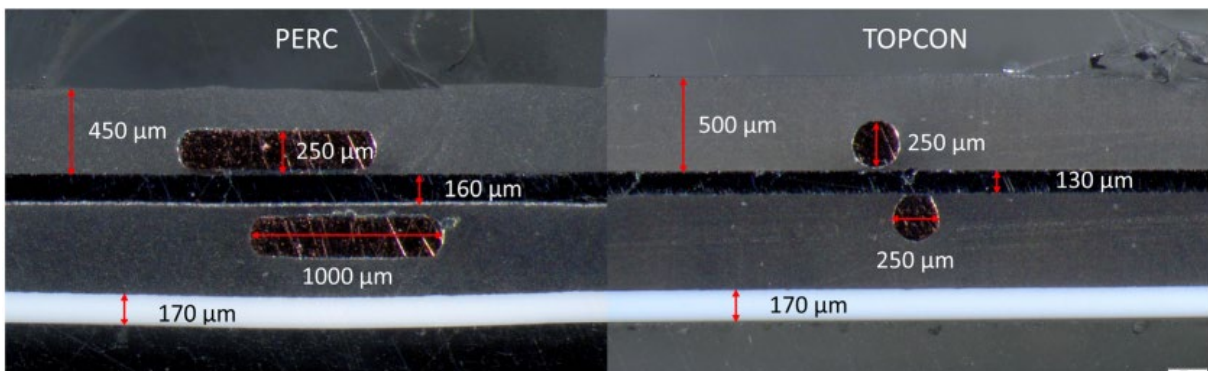


Figure 11: Light microscopic image of cross sections of Glass/Backsheet modules comparing **(left)** PERC cells with busbars and **(right)** TOPCon cells with multi-wires.



2.4.5. Thermal Cycling (TC) Test Sequence (Alpine & BIPV)

Table 5 summarises the modules tested, their testing conditions, and the number of cycles within each test sequence. For the **standard TC (StTC)** sequence, I-V and EL measurements were performed after every 200 cycles. For the **accelerated TC (ATC)** and **highly accelerated TC (HATC)** sequences, I-V and EL measurements were performed after every 100 cycles.

Table 5: Summary of the modules tested in Thermal Cycling test sequence.

| Module Type | Standard TC (StTC) (-40°C to +85°C) | Accelerated TC (ATC) (-40°C to +95°C) | Highly Accelerated TC (HATC) (-40°C to +110°C) |
|---------------------------------|--|---|--|
| G/PERC/BS 3 mm / 3 mm | 400 cycles | - | 400 cycles |
| G/PERC/BS 4 mm / BS | 400 cycles | - | 400 cycles |
| G/PERC/G 4 mm / 4 mm | 400 cycles | - | 400 cycles |
| G/PERC/BS 3.2 mm / BS | 600 cycles | 600 cycles | 300 cycles |
| G/IBC/BS 3.2 mm / BS | 600 cycles | 600 cycles | 300 cycles |
| G/HJT/BS 3.2 mm / BS | 600 cycles | 600 cycles | 300 cycles |

G: Glass, BS: Backsheet, PERC: Passivated Emitter and Rear Contact, IBC: Interdigitated Back Contact, HJT: Heterojunction

Figure 12 shows that the G/PERC/G (4 mm / 4 mm) and G/PERC/BS (4 mm / BS) modules exhibit a larger change in maximum power under HATC, primarily due to fill factor losses caused by metallization damage, as shown in Table 6. HATC successfully accelerated the degradation of the relevant parameters (power and fill factor, without causing unexpected issues) and induced the expected failure modes (e.g., damaged fingers and solder bonds), needing fewer cycles compared to the standard sequence. The G/PERC/G (3 mm / 3 mm) module showed no noticeable performance changes and is therefore not included here.

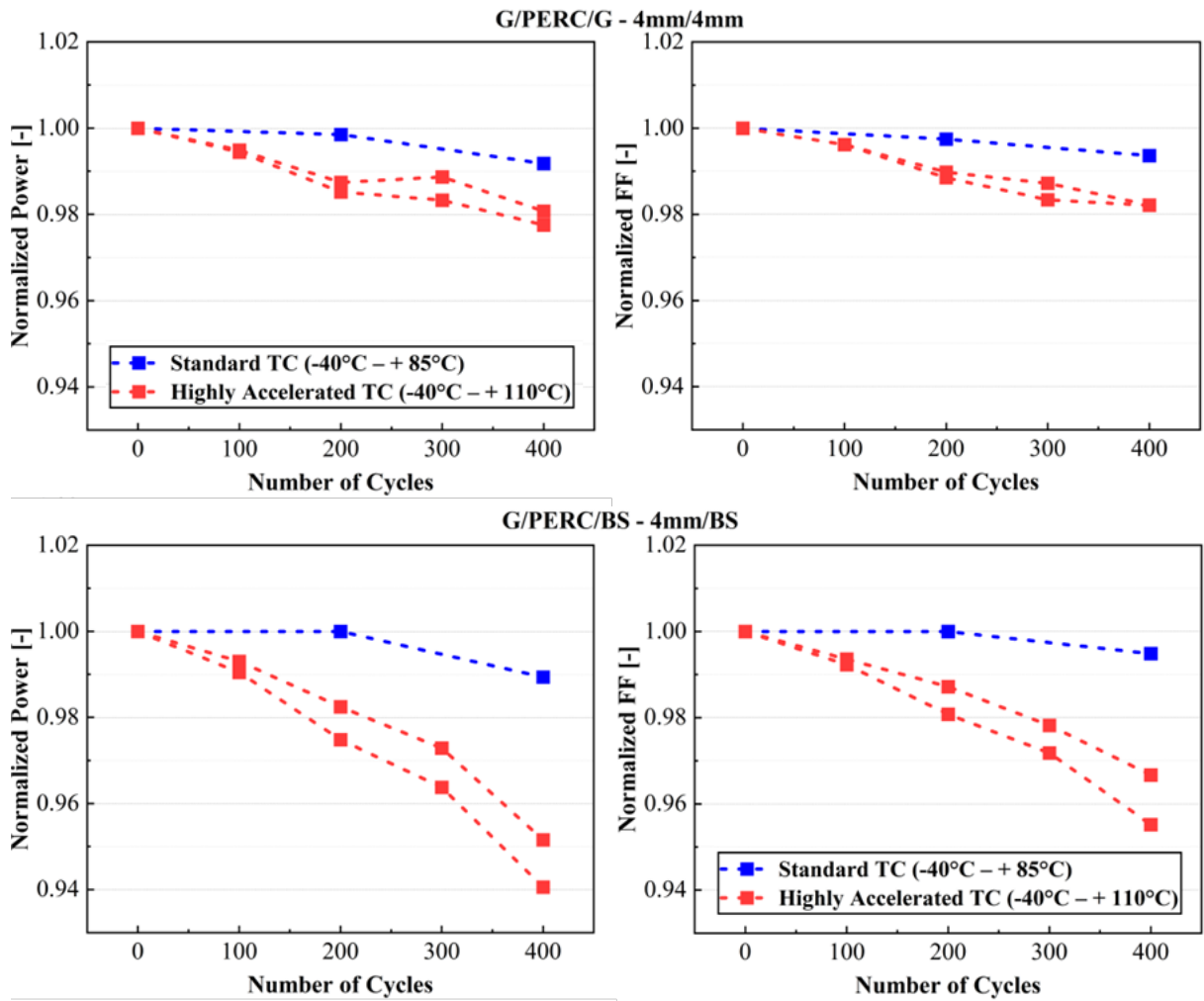
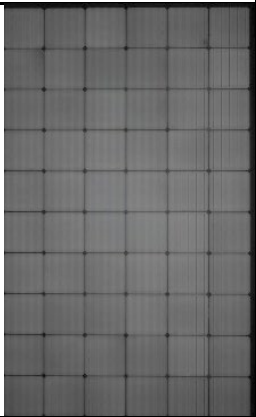
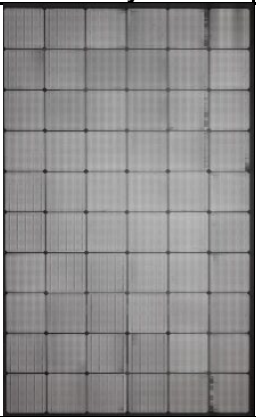
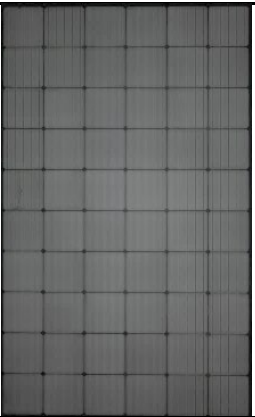
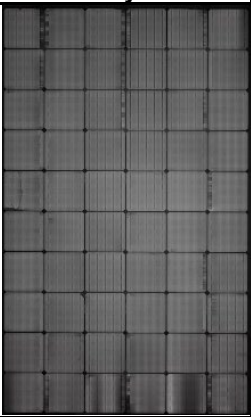
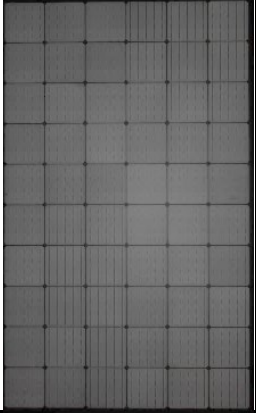
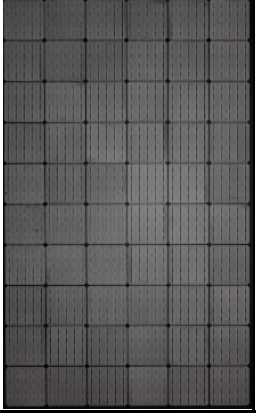
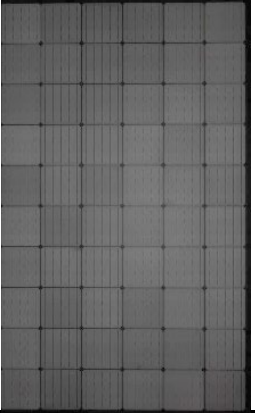


Figure 12: Change in normalized maximum power and fill factor (FF) for **(top)** G/PERC/G (4 mm / 4 mm) and **(bottom)** G/PERC/BS (4 mm / BS) modules during and after Standard (-40°C to +85°C) and Highly Accelerated (-40°C to +110°C) thermal cycling tests.



Table 6: Electroluminescence images of G/PERC/G (4 mm / 4 mm) and G/PERC/BS (4 mm / BS) modules taken before, and after 400 cycles of Standard (-40°C to +85°C) and Highly Accelerated (-40°C to +110°C) thermal cycling tests.

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

G/PERC/BS (3.2 mm / BS) and G/IBC/BS (3.2 mm / BS) modules did not show any significant performance changes, so they are not shown here. However, as illustrated in Figure 13, G/HJT/BS modules experienced notable performance degradation due to thermomechanical stresses. All three modules showed damaged fingers (Table 7). When the TC test was performed under more demanding conditions by increasing the maximum temperature, the thermomechanical stress intensified, resulting in a greater amount and severity of the damage. This accelerated the drop in fill factor, leading to a faster decline in maximum power, without causing unexpected failures.



G/HJT/BS

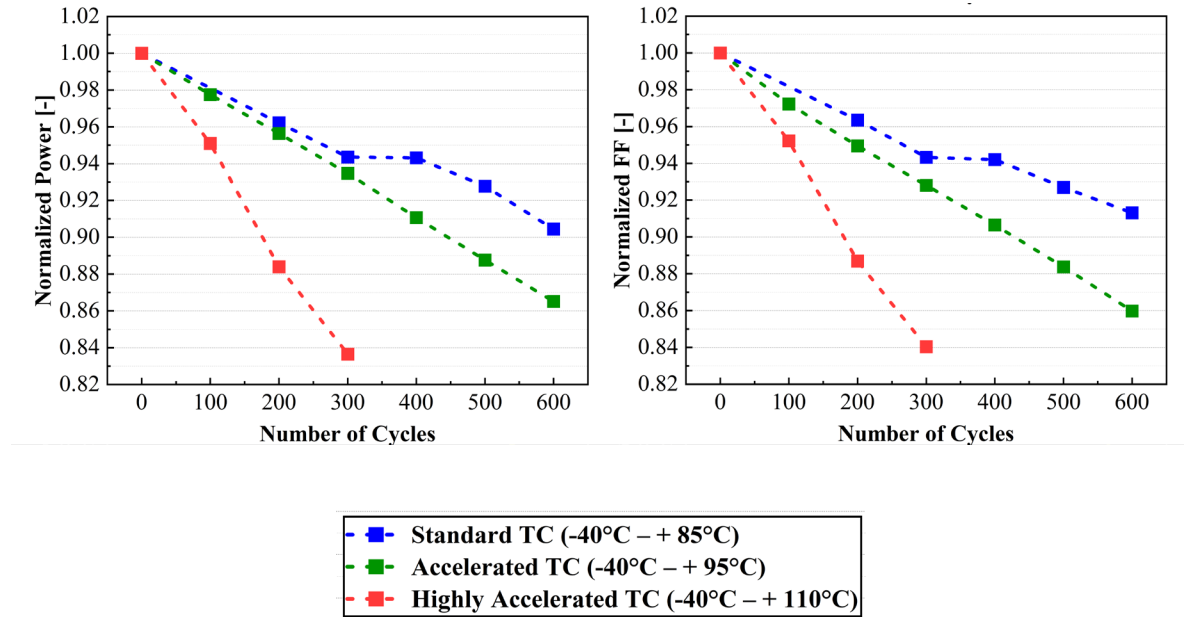

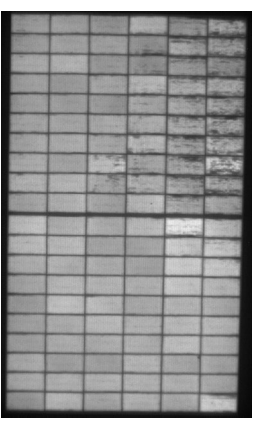
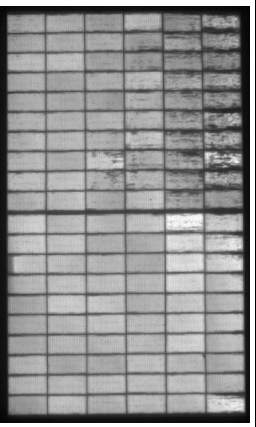

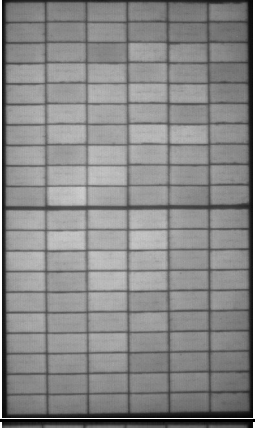
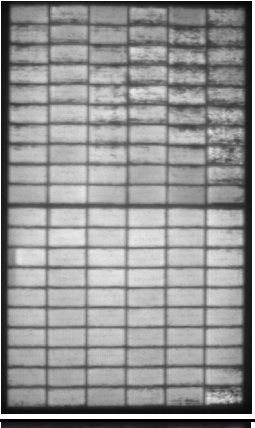
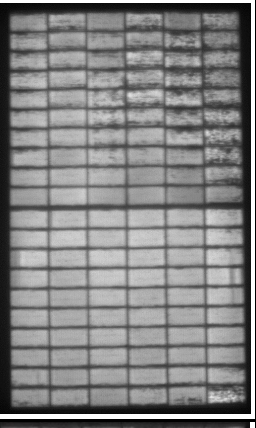
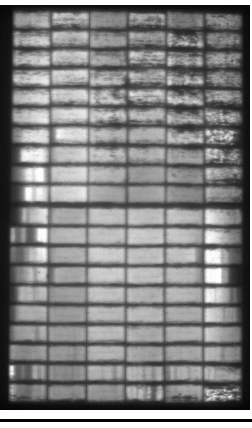
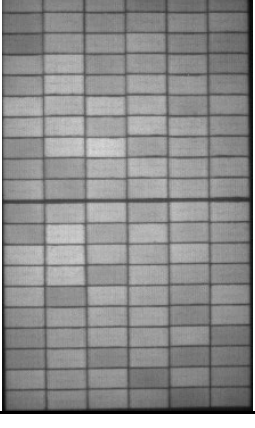
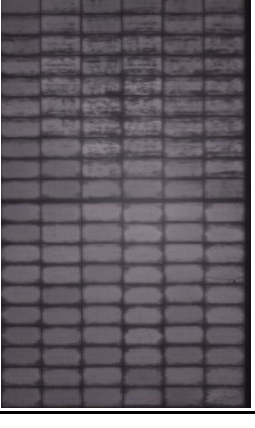
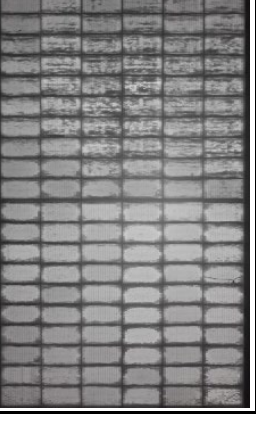
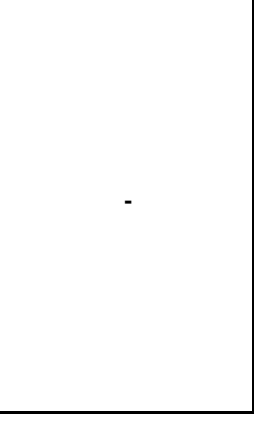


Figure 13: Change in normalized maximum power and fill factor (FF) for G/HJT/BS modules during Standard (-40°C to +85°C), Accelerated (-40°C to +95°C), and Highly Accelerated (-40°C to +110°C) thermal cycling tests.



Table 7: Electroluminescence images of G/HJT/BS modules before, and after 200, 300, and 600 cycles of Standard (-40°C to +85°C), Accelerated (-40°C to +95°C), and Highly Accelerated (-40°C to +110°C) thermal cycling tests.

| | Initial | 200 cycles | 300 cycles | 600 cycles |
|---|---|---|--|---|
| Standard TC (-40°C to +85°C) |  |  |  |  |
| Accelerated TC (-40°C to +95°C) |  |  |  |  |
| Highly Accelerated TC (-40°C to +110°C) |  |  |  |  |

Acceleration was evaluated by using the FF change per cycle. Three of the six module types showed measurable degradation. **The acceleration factors averaged 3.9 times and reached up to 7.4 times, while test duration increased by only 7–20%** (Table 8). The accelerated tests reproduced the same failure modes observed in the standard TC tests without introducing non-representative damage, demonstrating successful and efficient proportional acceleration.



Table 8: Acceleration factors of ATC and HATC for modules showing performance changes after TC tests and increase in test duration due to modified conditions.

| | Accelerated TC (-40°C to +95°C) | Highly Accelerated TC (-40°C to +110°C) |
|---|---------------------------------|---|
| Acceleration Factor for G/PERC/BS – 4 mm / 4 mm | - | 7.4 (±1.4) |
| Acceleration Factor for G/PERC/G – 4 mm / BS | - | 2.9 (±0.5) |
| Acceleration Factor for G/HJT/BS – 3.2 mm / BS | 1.6 (±0.2) | 3.7 (±0.5) |
| Test duration versus standard | +7% | +20% |

2.4.6. Hot Spot Endurance Test Sequence (Alpine & BIPV)

Hot spot tests at standard, 55C, and elevated, 75C, module temperatures (Figure 8) were carried out for up to 15 hours in 5-hour increments on glass/glass and glass/backsheet PERC, HJT, IBC, and TOP-Con modules (Table 4). Figure 14 and Figure 15 present the module and hot spot temperatures. Due to differences in breakdown voltages across the four cell technologies and in BOMs, the modules exhibited different hot spot temperatures. No significant performance losses were observed after testing. Only two modules showed darker regions in the EL images at the hot spot location, indicating localized metallization damage caused by the elevated temperatures.

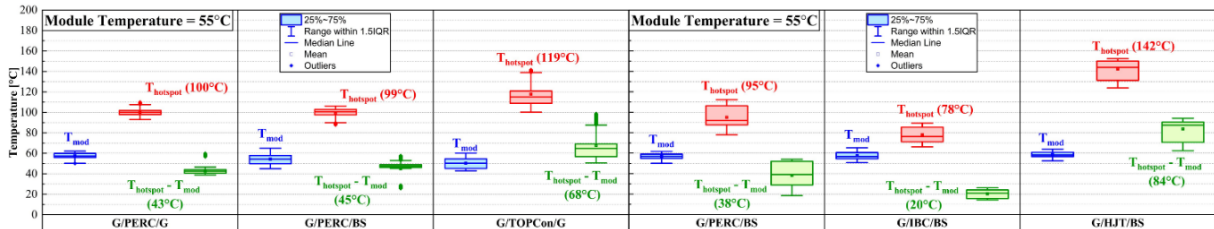


Figure 14: Module temperature (blue), hot spot temperature (red), and their difference (green) recorded during 15 hours of hot spot endurance test conducted at a controlled module temperature of 55°C.

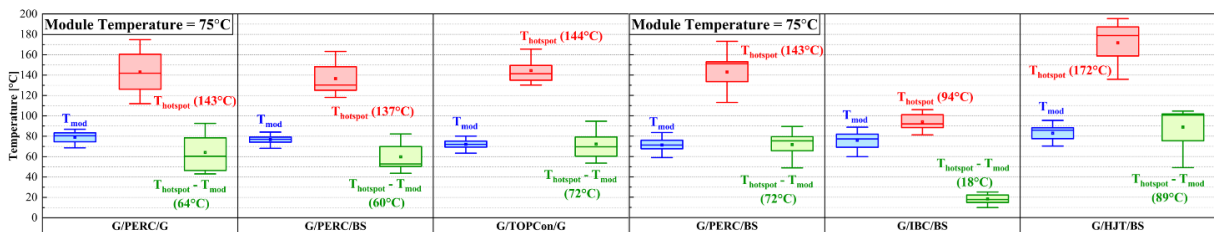


Figure 15: Module temperature (blue), hot spot temperature (red), and their difference (green) recorded during 15 hours of hot spot endurance test conducted at a controlled module temperature of 75°C.

Except for minor signals detected in the non-destructive and destructive material analyses (such as a slight colour change on the backsheet surface or the start of adhesive degradation in the multi-layer backsheet), no significant material-level changes were observed even after 15 hours of testing at a 75°C module temperature.

The same module types of three of the six modules in this campaign had previously been exposed to outdoor conditions for three years with a shadow mask as part of an earlier project called [REBIPV](#) (Figure 16) [18], allowing a comparison between hot spot endurance testing and extended outdoor ageing using shadow mask. The results indicate that although the outdoor test is also accelerated, some of the weak signals detected indoors (the adhesive degradation) may serve as early indicators of degradation.



However, these signals remain very small compared to the more severe degradation observed in the outdoor-tested modules. In these modules, destructive material tests revealed polymer chain scission in the PET core (DSC), stronger adhesive degradation between the layers (ATR-IR image) and acetic acid development in the EVA encapsulant (TD GC/MS). We suggest that even 15 hours of hot spot endurance testing at a 75°C module temperature is insufficient to represent modules operating in BIPV-insulated roof applications, where frequent shading is expected.



Figure 16: G/PERC/BS, G/IBC/BS and G/HJT/BS modules with shadow masks on the outdoor test stand.

2.4.7. Bypass Diode Test Sequence (Alpine & BIPV)

The modules tested under harsher (higher temperature and current conditions than the standard) bypass diode conditions successfully passed the tests (Figure 8). Considering typical operating conditions for BIPV modules, the applied test conditions are realistic. However, **for Alpine-specific testing, we conclude that the applied current should ideally be higher, potentially up to twice the STC I_{sc} , accounting for front irradiances up to 1600 W/m² and possibly up to 1800 W/m² or more when including rear irradiance due to high albedo.** Therefore, we recommend performing this test under higher-current conditions for Alpine-specific testing.

2.5 Defining advanced methodology for accelerated reliability testing (T4.2)

Table 9 summarizes the developed test sequences and their corresponding key outcomes. Acceleration achievements:

- **UV, Thermal Cycling (TC), and Static Mechanical Load (SML)** tests were successfully accelerated, without causing unexpected issues or mechanisms.
- The **Static Mechanical Load (SML)** test was specifically adapted to better represent Alpine low-temperature conditions.
- The **Hot Spot Endurance (HSP)** test showed only limited acceleration.
- The **Bypass Diode (BYD)** test reflected realistic BIPV conditions but did not fully represent Alpine stress levels due to potentially underestimated current loads.



Table 9: Summary of the test conditions, observed degradation modes, the corresponding identification methods, and the key outcomes of each test sequence investigated in this project.

| Test sequence | Test Conditions | Degradation Mode | Identification Tools | Key Outcomes |
|--|---|--|---|--|
| UV test sequence (Alpine & BIPV) | <ul style="list-style-type: none"> • HF 100 hours • 4 x UV15 at 110°C & 1200 W/m² UV irradiance | <ul style="list-style-type: none"> • UVID • Backsheet degradation | <ul style="list-style-type: none"> • I-V • EL • IR (surface and bulk image) • NIR | <ul style="list-style-type: none"> • Accelerated backsheet degradation (calculation of exact acceleration factor under evaluation) |
| Static Mechanical Load test sequence (Alpine) | <ul style="list-style-type: none"> • SML at -40°C • TC50→SML at 25°C | <ul style="list-style-type: none"> • Cell cracks | <ul style="list-style-type: none"> • I-V • EL | <ul style="list-style-type: none"> • >3x acceleration • More realistic Alpine representation |
| Thermal Cycling test sequence (Alpine & BIPV) | <ul style="list-style-type: none"> • Accelerated TC (-40°C to 95°C) • Highly Accelerated TC (-40°C to 110°C) | <ul style="list-style-type: none"> • Damaged solder bonds • Damaged fingers | <ul style="list-style-type: none"> • I-V • EL | <ul style="list-style-type: none"> • ≈4x acceleration under Accelerated and Highly Accelerated TC |
| Hot Spot test sequence (Alpine & BIPV) | <ul style="list-style-type: none"> • 55°C module temperature (standard) up to 15 hours (Alpine & BIPV-façade) • 75°C module temperature up to 15 hours (BIPV-roof) | <ul style="list-style-type: none"> • Adhesive degradation • Minor discoloration of backsheet | <ul style="list-style-type: none"> • ATR-IR imaging • Colour measurement | <ul style="list-style-type: none"> • Minimal acceleration • Duration too short for realistic BIPV shading |
| Bypass Diode test sequence (Alpine & BIPV) | <ul style="list-style-type: none"> • Up to 100°C, 1.15 x I_{sc} (Part 1), 1.4 x I_{sc} (Part 2) | <ul style="list-style-type: none"> • No issue | <ul style="list-style-type: none"> • Diode functionality | <ul style="list-style-type: none"> • Adequate for BIPV • Currents likely too low for Alpine scenarios, 2xI_{sc} would be more representative for Alpine |

2.6 Evaluation of Diagnostic Tools for Early Failure Detection (T4.3)

As shown in Table 10, early-stage detection relied primarily on EL imaging and I-V curve analysis especially for physical defects mainly observed in SML and TC tests. Complementary techniques, including DSC-Tcryst and TD GC/MS, provided early indications of polymer degradation and encapsulant byproducts, while ATR-IR imaging enabled early detection of inner-layer and bulk backsheet degradation. The combination of highly accelerated ageing tests and suitable diagnostic tools provides a robust framework for rapid qualification of PV modules under demanding Alpine and BIPV operating conditions.



Table 10: Evaluation of the degradation identification tools.

| Method | Relevant Tests | Detected Failures / Degradation | Non-destructive | Sensitivity / Limitation | Evaluation |
|--------------|----------------|---|-----------------|---|--|
| I-V curve | All | Electrical degradation | Yes | Detects impact, not always root cause | Essential for linking degradation to performance |
| EL | SML, TC, HSP | Cell cracks, metallization failure | Yes | Highly sensitive to cracks and inactive areas | Fast and highly informative for cell-level physical defects |
| UVF | UV, HSP | Polymeric degradation (indirect) | Yes | Interpretation required; indirect degradation indicator | Potentially useful for material degradation |
| U-ATR-IR | UV, HSP | Photo-oxidation and thermal degradation of backsheets surface | Yes | Surface-limited | Limited correlation to electrical impact |
| ATR imaging | UV, HSP | Adhesive and bulk degradation in multi-layered backsheets | No | Requires sample preparation | Highly valuable for early detection in inner-layer analysis |
| NIR | UV, HSP | Photo-oxidative degradation in backsheets | Yes | Lower sensitivity for early stages | Detects stronger degradation |
| TD GC/MS | HSP | Encapsulant degradation products | No | Requires sample preparation; destructive | Strong indicator of encapsulant degradation affecting electrical performance |
| DSC (Tcryst) | UV, HSP | Backsheet degradation (chain scission in PET) | No | Requires sample preparation; destructive | Good early indicator of polymer degradation |
| Raman | UV | Fluorescence effects | Yes | Often masked by fluorescence in polymers | Limited informative value |

2.7 Characterisation and failure analysis of field-aged PV modules (T4.1)

During the first year of the project, several alpine and BIPV systems – Kanzelhöhe, Dobratsch, Loser, Lac de Toules, and Chevenez – were analysed (Figure 17). The investigation aimed to identify degradation mechanisms characteristic of alpine PV and BIPV installations.

The analysis revealed several typical failure modes in the Alpine environment. **Glass breakage caused by mechanical loading** was observed at multiple sites, including Dobratsch and Loser. Furthermore, accelerated **degradation of polyamide-based backsheets** was detected at Dobratsch and Loser, likely driven by stronger temperature fluctuations and increased UV irradiation at high altitude.

In contrast, higher electrical degradation was observed in the low-altitude BAPV system in Chevenez compared with the same module types installed at the high-altitude site Lac de Toules.

Analysis of modules installed in different BIPV configurations showed that these systems are exposed to significantly higher (i) thermal and (ii) thermomechanical stresses, as well as (iii) more frequent shading events compared with modules installed in open-rack PV systems. These stressors can lead to (i) **accelerated photothermal degradation**, (ii) **damage to cells and metallization**, and (iii) defects such as **discolouration, glass damage, and bypass diode failure**.



Figure 17: (left) FTIR-measurements of the backsheets of a PV installation at Dobratsch. **(right)** NIR measurement of a module.

In addition, a comparative analysis of PV module performance from Jungfraujoch, Birg, Mont-Soleil, and Burgdorf (installed in the early 1990s, same age and module family) was conducted to assess performance under Alpine conditions. Here, there are two high-altitude (above 1500 m), one mid-altitude (between 1000 m and 1500 m) and several low-altitude PV systems in various mounting configurations and orientations with similar modules. We conducted various electrical (I-V and EL) and material measurements (NIR, IR, UVF, etc.), both destructive and non-destructive, on the modules when it was feasible to obtain samples from the systems. Additionally, where data was available, we analysed operating conditions - including module temperature, ambient temperature, irradiance, and temperature fluctuations - and evaluated the outdoor long-term performance of the modules through performance loss rate (PLR) analyses.

It should be noted that the analysed modules originate from installations from the early 1990s and therefore represent older PV technologies; consequently, the results are not fully representative of the behaviour of modern PV modules. Nevertheless, the long-term field data provide valuable insights into the influence of environmental stressors on PV module ageing.

Analysing the results between high and low altitude systems, PV modules installed at lower altitudes exhibited higher temperatures and correspondingly faster material ageing and performance losses than comparable modules at high-altitude sites (Figure 18). Although all systems showed low annual degradation rates ($< -0.6\%/year$), modules from the high-altitude sites exhibit lower performance losses compared to low-altitude ones. Non-destructive and destructive material analyses indicated that these elevated operating temperatures at low altitude accelerated EVA degradation (increased acetic acid formation), resulting in higher cell and metallization corrosion as well as higher adhesive degradation in the backsheet laminate. In contrast, high-altitude modules, despite higher irradiance and large diurnal temperature changes, experienced lower thermal stress, resulting in slower chemical and mechanical degradation. The results proved that when modules are built to survive the harsher conditions of the alpine climate, the conditions can be favourable for a slower material degradation and therefore also electrical degradation. Still, the bill of materials of the slight variations in the module design had the strongest effect on failures and degradation. The results underscore the strong sensitivity of PV module reliability to local climatic stressors and highlight the need for altitude- and climate-specific module design. The results have been published in a [peer-reviewed paper](#) [19].

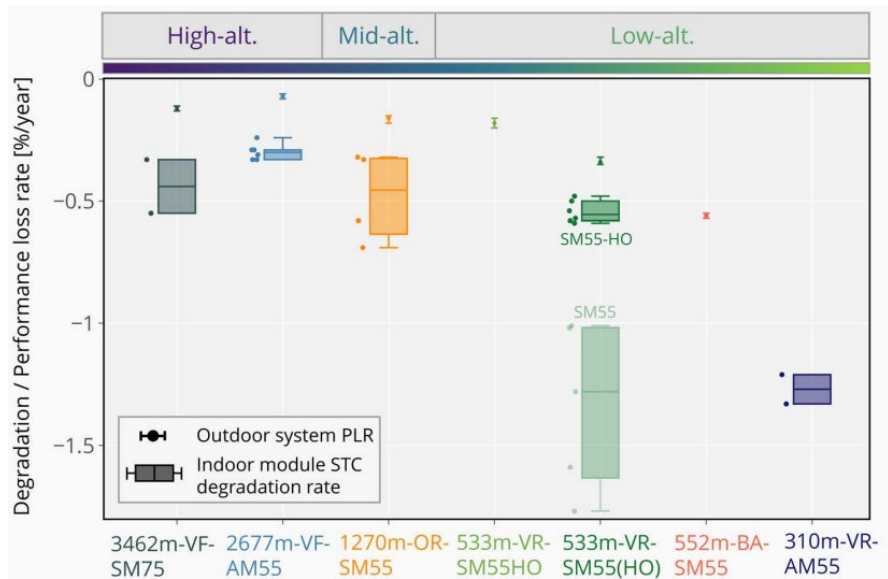


Figure 18: Overview of indoor and outdoor measurement results for all analysed systems in the published work. The figure shows: (i) the module degradation rates of maximum power based on indoor PM measurements (box plots with underlying data points), and (ii) the system PLR calculated from outdoor monitoring data using the multi-YoY method, with 95% CI. Systems are ordered by altitude zones indicated at the top. For the site 533m-VR-SM55(HO), which is composed of 94% SM55-HO modules and 6% SM55 modules, both types are shown for the indoor I-V results. The minority type is displayed in a faded colour for clarity, as it is less representative of the system behaviour.



3 Conclusions and Impact

3.1 Conclusions

This project investigated accelerated testing strategies for PV modules intended for Alpine and BIPV operating conditions, with the goal of enabling faster product development and improved reliability assessment under demanding environmental stresses.

- Several standard reliability tests were successfully accelerated without introducing unexpected degradation mechanisms. In particular, UV exposure, Thermal Cycling (TC), and Static Mechanical Load (SML) tests were effectively accelerated considering module operating conditions in Alpine and BIPV environments, and the Mechanical Load test was further adapted to more realistically represent Alpine low-temperature conditions.
- The Hot Spot Endurance (HSP) test showed only limited potential for acceleration, whereas the Bypass Diode (BYD) test reflected realistic BIPV operating conditions but may still underestimate stress levels for Alpine installations due to potentially higher current loads in such environments.
- Mechanical reliability testing showed that low-temperature loading (-40°C) or loading after TC50 produces a more critical and realistic stress scenario than mechanical load testing at the standard 25°C . Because similar results can be achieved by performing mechanical load tests after thermal cycling, as tests done at -40°C , laboratories without very large climatic chambers for their mechanical load setups can conduct the tests at room temperature following TC50 and still obtain comparable outcomes.
- The results further show that module design and material selection strongly influence crack formation and mechanical stability. PV modules intended for alpine environments benefit from POE encapsulation, glass/glass structures, framed modules, multi-wire metallisation, and bypass diodes with higher current capacity, which together improve resistance to mechanical stress and reduce crack susceptibility under snow loads, wind stress, low temperatures, and high irradiation.
- POE encapsulation proved particularly advantageous due to its lower glass transition temperature and better elasticity retention at low temperatures, reducing stress transfer to the solar cells.
- Early-stage degradation detection relied primarily on EL imaging and I-V curve analysis, which were particularly effective in identifying mechanical and electrical defects induced by SML and TC tests. Complementary diagnostic techniques including DSC-Tcryst and TD-GC/MS provided early indications of polymer degradation and encapsulant by-products, while ATR-IR imaging enabled early detection of inner-layer and bulk backsheets degradation.

Overall, the combination of highly accelerated ageing tests and advanced diagnostic techniques provides a robust framework for rapid qualification of PV modules intended for demanding Alpine and BIPV operating conditions.

3.2 Impact

The scientific results generated in this project have been – and continue to be – disseminated not only through peer-reviewed journals and conferences, but also across the broader PV community. Publications in renowned IEA PVPS Task 13, collaborations with module manufacturers and system planners in Austria and Switzerland and growing interest from public print media all underscore the strong impact of the project. Some of these examples are:



- Discussion of Alpine PV module design with two PV module manufacturers, on topics such as encapsulant choice, high irradiance conditions, UVID and mechanical strength.
- Discussion on how to test PV modules for Alpine environments, such as mechanical load testing, UV stress testing and testing considering high irradiation.
- Discussion and support for the installation of the Alpine PV test plant in Austria (Loser). More details provided below.

Reports

Results from the literature research on specific stressors as well as some of the test results were included in an IEA PVPS Task 13 report: "Optimization of Photovoltaic Systems for Different Climates" where the consortium of PV-DETECT coordinated and wrote the chapter on "Cold and Snowy climates" [16]. In the report, climate-specific stressors are analysed, and proven mitigation strategies are presented. Through this, it can serve as a practical resource for project planners and developers, striving to ensure the long-term success of PV projects worldwide.

Alpine Module Design

Various accelerated aging tests were conducted on different module materials, cell technologies, metallization, glass thicknesses, and module designs (glass/glass vs. glass/backsheet). This allowed the optimal parameters for an "alpine PV module" to be determined. Currently, only a limited number of modules are available for alpine climates. Using the project results, the project partner Sonnenkraft can develop a new alpine module with improved parameters. Our tests showed that the optimal module is a glass/glass module with POE encapsulation and multi-wire metallization, as this offers the best mechanical protection for the PV cells. Additionally, a robust frame, a high-current-capacity bypass diode, proper soldering of the metallization, and optimised clamping are required for installation.

Sonnenkraft plans to launch new alpine module in 2026

Sonnenkraft Energy GmbH develops and produces PV modules for various applications. Product development focuses on the specific requirements of each application to ensure the continued availability of high-quality products and thus guarantee the company's survival and further growth.

The results and insights from the PV-DETECT research project play a crucial role in shaping the future product portfolio. In addition to BIPV, a key application area for Sonnenkraft Energy GmbH is Alpine PV, as it is becoming increasingly important in the company's main markets. The results of the PV-DETECT project serve as the basis for the development of the new framed glass/glass alpine module, which is scheduled for launch in 2026. Furthermore, the test sequences developed within the project, specifically designed for alpine photovoltaics, will enable the rapid and efficient market launch of further variations of the new alpine module, without compromising quality.

System planners and installers

In Switzerland, the know-how generated in this project has led several Alpine PV system installation companies to seek consultation and access to the results. In addition to completed activities, ongoing collaboration is currently underway with two installers and one module manufacturer to provide further support on Alpine PV topics, mainly on module selection and testing. Due to confidentiality, the company names and system locations cannot be disclosed.

In Austria, the old (from 1988) alpine test plant at Loser (1560 m) was repowered with new modules in summer 2025 (Figure 19). The expertise developed during the project PV-DETECT could help the project planners (Energie AG— also a LOI partner of the project) to choose the best module types available.



Through close collaboration, the new system was developed, and the test site should work as a research test site for further, larger alpine systems in Austria. Five different module types were chosen with the help of the consortium. They reflect the current “alpine PV modules” on the market as well as two reference modules.



Forschungsanlage PV Loser

Die Energie AG Oberösterreich betreibt seit 1988 eine **alpine Photovoltaik-Forschungsanlage** am Loser. In den 1980er Jahren galt die Photovoltaik noch als neuartige Technologie zur Stromproduktion. Die großtechnische Erprobung in alpiner Umgebung war daher echte Pionierarbeit.

Nach über dreieinhalb Jahrzehnten Laufzeit wurde die Freiflächen-Anlage im Jahr 2025 einem sogenannten „**Repowering**“ unterzogen. Das Kraftwerk wurde mit neuen PV-Modulen unterschiedlicher Hersteller und mit neuen Wechselrichtern der oberösterreichischen Firma Fronius ausgestattet. Außerdem wurde der Standort um eine **Dach-Anlage** auf der benachbarten Bergrettungshütte erweitert. Diese versorgt den Stützpunkt der Bergrettung Aussenfeld mit erneuerbarem Sonnenstrom, welcher in einem Batteriespeicher zwischengespeichert werden kann.

Die originalen PV-Module aus dem Jahr 1988 sind an der Westseite der Bergrettungshütte ausgestellt. Heute wie damals dient die Forschungsanlage am Loser zur Erprobung von PV-Modulen in alpinen Verhältnissen.

Kennzahlen

| | |
|--------------------------|--------------------|
| Installierte PV-Leistung | 82 kW _p |
| PV-Modulfäche | 374 m ² |
| Anzahl Module | 186 Module |
| Anzahl Modultypen | 6 Modultypen |
| Inbetriebnahme | Oktober 2025 |



Wir danken den bei Fronius Mitarbeitenden für die Unterstützung der Recherche- und der Baufreigabe.

Energie. Aber Gut.



Figure 19: The Loser PV system (1560 m).

ALIENCE Project (BFH, OST, SUPSI, and ZHAW; funded by the Swiss Federal Office of Energy)

Building on the alpine PV stressor and failure analysis, as well as the test sequences and outcomes developed in the PV-DETECT project, ALIENCE project has decided to concentrate on mechanical load testing following thermal cycling (50 cycles) and extended UV testing on one standard and three alpine-relevant PV modules. The results of these tests are expected to be published on the alpine-pv.ch website in March 2026.



4 National and international cooperation

- Collaboration with OFI and Sonnenkraft in Solar ERA-NET project.
- In 2023 summer, Anika Gassner, PhD student at OFI joined SUPSI team for 3 weeks (external stay) to get more insight in the electrical characterisation expertise of this institute and perform non-destructive material measurements of some samples.
- Collaboration with BFH (Switzerland), EPFL (Switzerland), CSEM (Switzerland), OFI (Austria), and HI-ERN (Germany) to evaluate AM55 and SM55 modules that have been exposed to outdoor conditions in Switzerland for nearly 30 years, resulting in a peer-reviewed publication [19].
- Collaboration with IEA PVPS Task 13 – “Optimisation of Photovoltaic Systems for Different Climates” [16].
- Support and consultancy provided to several Swiss and Austrian PV industry stakeholders, particularly regarding Alpine PV modules and applications.

5 Publications and other communications

- A. Gassner, G.C. Eder, E. Özkalay, G. Friesen, M. Feichtner, M. Babin and F. Bleicher, “*Increased reliability for PV in alpine environment*”, poster presentation at 40th EUPVSEC Lisbon, 2023
- A. Gassner, G.C. Eder, E. Özkalay, G. Friesen, M. Feichtner, M. Babin and F. Bleicher, “*Increased reliability for PV in alpine environment*”, poster presentation at Österreichische PV Tagung, 2023
- A. Gassner, “*Accelerating the development of alpine PV modules*”, oral presentation at SUPSI Industry Day 2024, 2024
- A. Gassner, “*Herausforderungen und Randbedingungen für PV in den Alpen*”, oral presentation at TPPV Workshop: PV im alpinen Raum, 2024
- A. Gassner, “*Accelerated Ageing Tests for Alpine Photovoltaics*”, oral presentation at 10th European Weathering Symposium, 2024
- A. Gassner, E. Özkalay, G.C. Eder, G. Friesen, M. Feichtner, M. Caccivio and F. Bleicher, “*Accelerate product development for PV in alpine installations*”, poster presentation at 41th EUPVSEC Vienna, 2024
- A. Gassner, E. Özkalay, G.C. Eder, G. Friesen, and M. Feichtner, “*Accelerate product development for PV in alpine installations*”, Poster at Schweizer PV-Tagung, 2025. (Best Poster Award)
- E. Özkalay, H. Quest, A. Gassner, A. Virtuani, G. Eder, S. Vorstoffel, C. Buerhop-Lutz, G. Friesen, C. Ballif, M. Burri, and C. Bucher “*Three Decades, Three Climates: Environmental and Material Impacts on the Long-Term Reliability of Photovoltaic Modules*”, EES Solar, doi: [10.1039/d4el00040d](https://doi.org/10.1039/d4el00040d), 2025.
- Anika Gassner, Gabriele C. Eder, Ebrar Özkalay, Gabi Friesen, Markus Feichtner and Vasiliki-Maria Archodoulaki “*Enhanced mechanical load testing of photovoltaic modules for cold and snowy climates*”, oral presentation at 42nd EUPVSEC, Bilbao, 2025
- Ebrar Özkalay, Anika Gassner, Gabriele C. Eder, Gabi Friesen, Markus Feichtner “*Evaluating Hot-Spot Testing Duration for PV Modules in Shaded Environments: Insights from Real-World and Laboratory Data*”, poster presentation at 42nd EUPVSEC, Bilbao, 2025



- Anika Gassner, Gabriele C. Eder, Ebrar Özkalay, Gabi Friesen, Markus Feichtner and Vasiliki-Maria Archodoulaki “*Enhanced mechanical load testing of photovoltaic modules for cold and snowy climates*”, EES Solar, doi: [10.1039/d5el00125k](https://doi.org/10.1039/d5el00125k), 2025.
- Anika Gassner, Gabriele C. Eder, Benedikt Hufnagl, Vasiliki-Maria Archodoulaki “*NIR Spectroscopy and Chemometrics as a Tool for Non-Destructive Polymer Degradation Analysis in PV Modules*”, submitted, 2025.



6 References

- [1] International Energy Agency, “Snapshot of Global PV Markets,” IEA, 2025.
- [2] M. Koehl, M. Heck and S. Wiesmeier, “Categorization of weathering stresses for photovoltaic modules,” *Energy Science & Engineering*, vol. 6, no. 2, pp. 93-111, 2018.
- [3] G. C. Eder, Y. Voronko, W. Mühleisen, K. Knöbl, P. Kefer and C. Panhuber, “Long-term reliability of PV-modules in alpine environment,” in *37th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC)*, Lisbon, 2020.
- [4] J. Schlothauer, S. Jungwirth, M. Köhl and B. Röder, “Degradation of the encapsulant polymer in outdoor weathered photovoltaic modules: Spatially resolved inspection of EVA ageing by fluorescence and correlation to electroluminescence,” *Solar Energy Materials and Solar Cells*, vol. 102, pp. 75-85, 2012.
- [5] A. Gok, E. Ozkalay, G. Friesen and F. Frontini, “The Influence of Operating Temperature on the Performance of BIPV Modules,” *IEEE Journal of Photovoltaics*, vol. 10, no. 5, p. 1371–1378, 2020.
- [6] E. Özkalay, “Reliability and Long-term Performance of Building Integrated Photovoltaic (BIPV) Modules,” École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, 2024.
- [7] International Electrotechnical Commission, “IEC 61215-2:2021 Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 2: Test procedures,” International Electrotechnical Commission, Geneva, 2021.
- [8] International Electrotechnical Commission, “IEC TS 63126:2020 – Guidelines for qualifying PV modules, components and materials for operation at high temperatures,” IEC, Geneva, 2020.
- [9] International Electrotechnical Commission, “IEC 62892:2019 – Extended thermal cycling of PV modules – Test procedure,” IEC, Geneva, 2019.
- [10] International Electrotechnical Commission, “IEC TS 63496 – Floating photovoltaic power plants – Design guidelines and recommendations,” IEC, Geneva, Under development.
- [11] B. Adothu, S. Kumar, J. J. John and e. al., “Comprehensive review on performance, reliability, and roadmap of c-Si PV modules in desert climates: A proposal for improved testing standard,” *Progress in Photovoltaics: Research and Applications*, vol. 32, no. 8, 2024.
- [12] M. Owen-Bellini, P. Hacke, S. Spataru, D. Sulas, H. North, D. C. Miller and M. D. Kempe, “Combined-Accelerated Stress Testing for Advanced Reliability Assessment of Photovoltaic Modules,” National Renewable Energy Laboratory (NREL), Golden, CO, USA, 2020.



- [13] P. Hacke, M. Owen-Bellini, M. Kempe, D. Sulas-Kern, D. Miller, M. Jankovec, S. Mitterhofer, M. Topic, S. Spataru, W. Gambogi and T. Tanahashi, “Acceleration Factors for Combined-Accelerated Stress Testing of Photovoltaic Modules,” *Solar RRL*, vol. 7, no. 12, 2023.
- [14] R. Sastrawan, “UV testing, solar cell factory inspection now mandatory for Munich Re’s PV warranty insurance,” 12 February 2026. [Online]. Available: <https://www.pv-magazine.com/2026/02/12/uv-testing-solar-cell-factory-inspection-now-mandatory-for-munich-res-pv-warranty-insurance/>.
- [15] *Confidential communications on photovoltaic module reliability and testing with PV industry experts, 2024–2025.*
- [16] International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS), “Optimisation of Photovoltaic Systems for Different Climates,” August, 2025.
- [17] A. Gassner, G. C. Eder, E. Özkalay, G. Friesen, M. Feichtner and V.-M. Archodoulaki, “Enhanced mechanical load testing of photovoltaic modules for cold and snowy climates,” *EES Solar*, vol. 2, p. 161–173, 2026.
- [18] E. Özkalay, F. Valoti, M. Caccivio, A. Virtuani, G. Friesen and C. Ballif, “The effect of partial shading on the reliability of photovoltaic modules in the built-environment,” *EPJ Photovoltaics*, vol. 15, 2024.
- [19] E. Özkalay, H. Quest, A. Gassner, A. Virtuani, G. C. Eder, S. Vorstoffel, C. Buerhop-Lutz, G. Friesen, C. Ballif, M. Burri and C. Bucher, “Three decades, three climates: environmental and material impacts on the long-term reliability of photovoltaic modules,” *EES Solar*, vol. 1, p. 580–599, 2025.