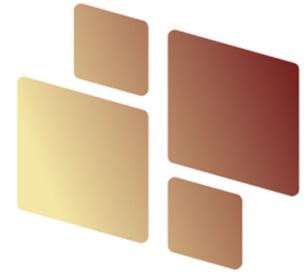


**DELIVERABLE REPORT**



**VALHALLA**

**Demonstrate real-world (outdoor) TRL5  
perovskite module stability matching  
that of Si-based modules**

**Deliverable D4.2  
DEC-2025**

**PREPARED BY  
3SUN, UVEG, CSEM, VTT, UOXF  
COORDINATED BY  
UVEG**



**Funded by  
the European Union**



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VALHALLA aims to develop perovskite solar cells and modules with power conversion efficiencies above 26 % (modules > 23 %) and extrapolated operational lifetime > 25 years, following an eco-design approach: employing harmful-solvent-free perovskite deposition, optimized use of materials, circularity, recyclability, scalable and low-cost manufacturing processes, to create a viable economic pathway for the European commercialization of this sustainable technology.

VALHALLA is formed by a multi-disciplinary consortium: 12 partners from 8 European countries; 3 industrial partners & 9 RTOs, covering the whole value chain of innovation from research centres to technology providers, end-users and market and policies.

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## Abbreviations and acronyms list

Abbreviation	Meaning	Abbreviation	Meaning
PCE	Power conversion efficiency	HTL	Hole Transport Layer
FA	Formamidinium	ETL	Electron Transport Layer
MA	Methylammonium	MPP	Maximum Power Point
Cs	Cesium	GHI	Global Horizontal Irradiance
EDAI	Ethylenediammonium Diodide	PL	Photoluminescence
ITO	Indium Tin Oxide		



## 1. Executive Summary

This document contains the final outdoor stability assessment of the perovskite cells and minimodules developed within the Valhalla project. Outdoor testing was carried out over several months in four different locations (South of Italy, Spain, Switzerland, and North of Finland), covering a wide range of environmental stress conditions. Over the monitoring period, continuous in-situ weather data (i.e., temperature, humidity, irradiance) and electrical performance metrics (i.e., maximum power point tracking, IV curves) were collected and analysed by the involved partners.

The Valhalla modules demonstrated promising power conversion efficiencies of up to 18% on an active area of approximately 15.75 cm<sup>2</sup>. As it will be discussed, such minimodules represent a suitable platform to investigate service lifetime aspects.

Despite the encouraging initial efficiencies, the minimodules exhibited rapid degradation within a few weeks of outdoor operation. In contrast, parallel monitoring of pixelated single-cell laminates revealed that selected device configurations can retain a substantial fraction of their initial performance, depending on location and architecture. Notably, a best T80 value (defined as the time required to reach 80% of the initial outdoor efficiency) exceeding 1.5 years was achieved for a set of hybrid-processed cells monitored in Switzerland, with the measurement campaign still ongoing. These results indicate that the underlying material systems and device concepts can be inherently robust.

The significantly faster degradation observed in minimodules is primarily attributed to the additional complexity and degradation pathways introduced during device upscaling, which are analysed in detail throughout the deliverable. These findings and degradation trends align well with literature reports and international datasets, confirming that the observed degradation is consistent with the current state of perovskite PV technology.

While the technological concept has been successfully validated, real-world module stability remains insufficient to meet TRL 5 requirements. Based on the strong performance demonstrated at single-cell level, the Valhalla technology is assessed to be in the TRL 4-5 transition, exhibiting initial evidence of relevant environmental performance beyond TRL 4, but not yet meeting the reliability benchmarks expected for TRL 5.

### 1.1. Description of the deliverable content and purpose

The purpose of this deliverable is to demonstrate outdoor performance and degradation trends of perovskite cells and minimodules developed within the Valhalla project under real-world conditions, thereby assessing progress toward Objective O4.1, i.e., the demonstration of TRL 5 modules with PCE > 23% and expected lifetime exceeding 25 years (matching that of Si-based modules).

The document is structured to first describe the outdoor monitoring methodologies and environmental conditions across the different test locations, with initial focus on single-cell devices monitored at multiple sites under a broad range of climatic stress factors. Subsequently, the analysis focuses on minimodules, which represent the primary technological target for TRL 5 demonstration, and discusses their outdoor performance, degradation behavior, and associated upscaling challenges.

### 1.2. Relation with other activities in the project

This deliverable is directly linked to Task 4.1 of Work Package WP4, which focuses on the long-term outdoor monitoring of perovskite minimodules in different locations. It builds upon the developments achieved in WP1 (materials), WP2 (device architecture), and WP3 (module engineering), providing a comprehensive assessment of how they translated into outdoor performance at module level.

By assessing progress toward Objective O4.1, this deliverable consolidates the outcomes of WP4. In



doing so, it also fulfils Milestone M11 “Final Module Performance Review,” offering a comprehensive overview of the current technological maturity of perovskite photovoltaics within the Valhalla project.

### 1.3. Device structures and encapsulation methods

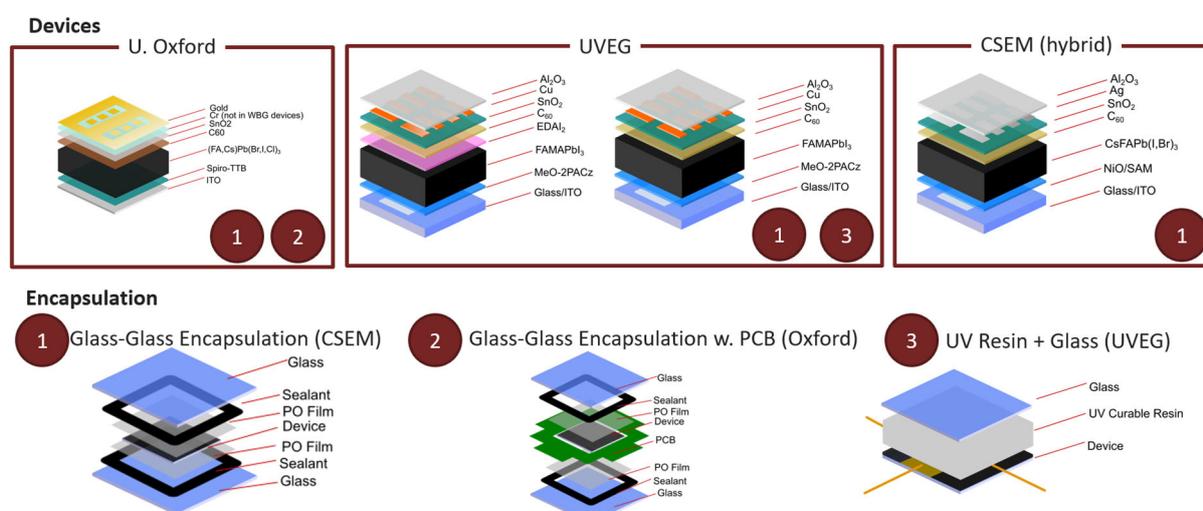
The perovskite devices developed within the Valhalla project for outdoor stability studies comprise single cells (active area  $\leq 1 \text{ cm}^2$ ) and minimodules (active area  $\approx 16 \text{ cm}^2$ ), featuring different device layouts, perovskite deposition methods, and encapsulation strategies established in the previous stages of the project. The devices were fabricated by UOXF, UVEG, and CSEM, and their architecture and compositions are illustrated in **Figure 1**.

For UOXF and UVEG, devices were prepared using full-vacuum processes, where the perovskite layer is formed by co-evaporation of the precursors. In contrast, CSEM devices are producing using a hybrid route, prepared via a sequential approach: co-evaporation of  $\text{PbI}_2$  and  $\text{CsBr}$ , followed by spin-coating or slot-die coating of FAI and FABr in alcohol and a final annealing step to crystallize the perovskite absorber.

Encapsulation Method 1 (CSEM) consists of laminating the device substrate between two glass encapsulation layers, using a butyl-based edge sealant applied around the perimeter of the lamination glasses. A commercial thermoplastic polyolefin foil is used as the lamination material on both sides of the device. For cells fabricated by UOXF, an additional layer of edge sealant was incorporated to account for the increased glass thickness. This encapsulation method has been used for all the minimodules reported in this document.

Encapsulation Method 2 (UOXF) adopts a concept similar to the glass–glass lamination employed in Method 1 but introduces an internal printed circuit board (PCB) structure between the two glass layers. This PCB insert facilitates the routing of electrical contacts through the encapsulation, ensuring reliable wiring while maintaining the mechanical and environmental integrity of the encapsulation.

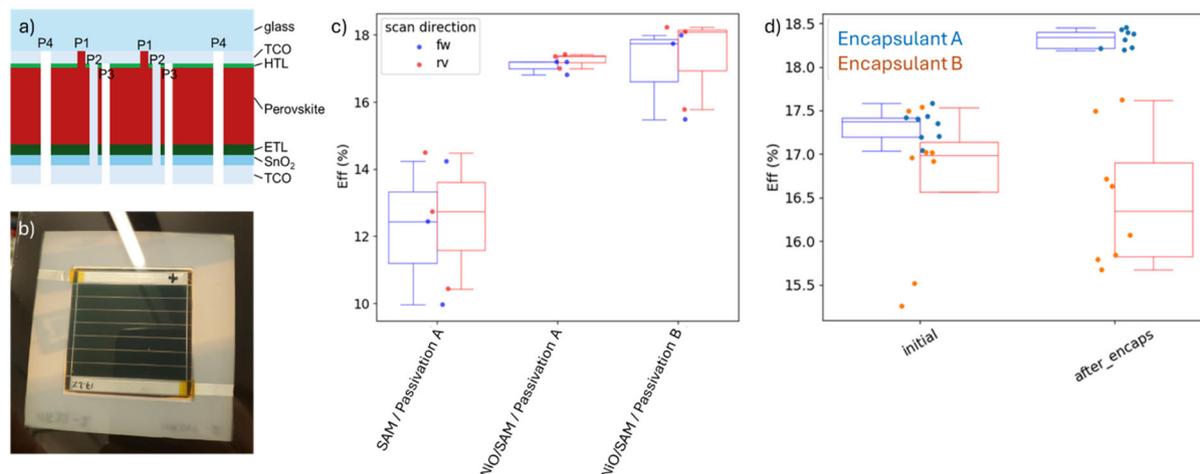
Encapsulation Method 3 (UVEG) is based on UV-curable resin and glass as the encapsulation medium, and it was initially implemented as an alternative in-house encapsulation strategy. This approach allowed UVEG to encapsulate their own devices on site, avoiding shipment to external partners and thereby reducing handling time and device degradation. The method yielded good results as well, as will be shown in the next section.



**Figure 1.** Schematics showing the layouts of the devices fabricated by UOXF, UVEG, and CSEM, and reported in this deliverable. The three different encapsulation strategies used are also highlighted.



**Figure 2a-b** shows the minimodule architecture, as well as the best power conversion efficiencies (PCEs) obtained with minimodules of around 16 cm<sup>2</sup> in active area (18%, using the hybrid method, Figure 2c). Encapsulation Method 1 was adopted for all minimodules analysed in this deliverable, leading to minimal efficiency losses, as shown in Figure 2d. Within the Valhalla WP3, larger-area modules of up to 100 cm<sup>2</sup> were also successfully demonstrated. However, minimodules with an active area of ~16 cm<sup>2</sup> were selected for the outdoor stability assessment, as they are fully representative of module-level processing steps (e.g., laser scribing), while offering increased practicality in terms of fabrication yield, handling, and shipment between partners.



**Figure 2.** a) Schematic view of the mini-modules produced in VALHALLA, alongside b) corresponding picture of an encapsulated 15.75 cm<sup>2</sup> module; c) power conversion efficiency of hybrid-processed modules with different hole transport layer (HTL) stack (SAM or bilayer NiO/SAM) and passivation interlayer at the perovskite/electron transport layer (ETL); d) power conversion of hybrid-processed modules before/after encapsulation in a glass/glass stack with an edge sealant (see picture in b).

## 1.4. Test conditions and single-cell performances

### 1.4.1. Outdoor testing in Valencia (UVEG)

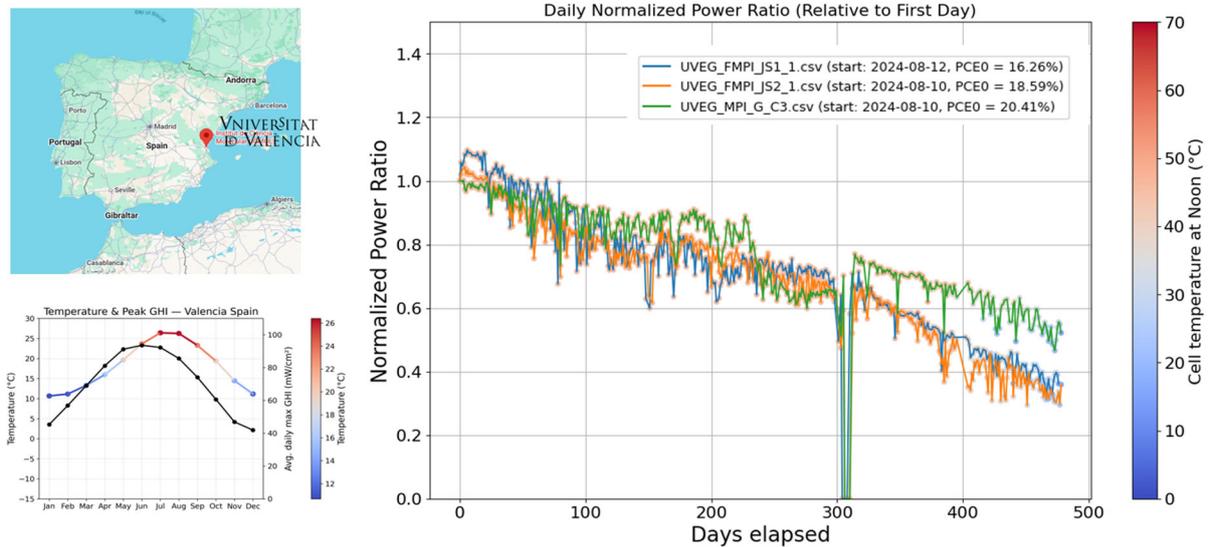
For outdoor testing at UVEG site in Valencia, the solar cells were kept at their Maximum Power Point (MPP) using two  $\mu$ MPP Tracker MP0205M24 (maximum current  $\pm 10$  mA and  $\pm 100$  mA) from LPVO, University of Ljubljana, using the “perturb and observe” algorithm. The global irradiance in the plane of the array was monitored with a Hukseflux SR15-D1 pyranometer. Air temperature and humidity was measured with a meteorological station; cell temperature was measured with a laminated black body with a PT-100 temperature sensor.

Valencia has one of the harshest climates among the test sites in the project. This place has a typical Mediterranean coastal climate with high solar irradiance, hot summers, and low precipitation. The site experiences approximately 45–55 rainy days per year and 450–500 mm of annual rainfall, mainly concentrated in autumn (September-October). Summers are characterized by persistent clear-sky conditions, high Global Horizontal Irradiance (GHI), and maximum temperatures typically reaching 30–33 °C. Devices tested here have reached temperatures as high as 65 °C during summer.

To monitor the devices, the “Power Ratio” approach was used in this case because it considers the performance of the device during the whole day. By dividing the integrated generated power of the solar cells by the integrated irradiance data per day, the performance of the solar cells can be displayed as a function of time. Although more than 30 devices between their own devices and from other partners were tested in the location, three among of the best devices are displayed in **Figure 3**. Orange



and blue lines represent FAMAPI devices without EDAI and encapsulated using the Glass-Glass Method 1 (Fig. 1), meanwhile one MAPI device with Encapsulation Method 3 is represented in green. All the devices showed a quasi-linear decay in time, with the FAMAPI devices reaching the T80 around the 100-120 days, while the MAPI device surpassed the 200 days. After a restart around the 300 days due to monitoring issues, some of the devices recovered and even improved their performance.



**Figure 3.** (left) Map showing the test location, with an inset displaying the average ambient temperature and peak GHI during the monitoring period. (right) Outdoor performance of the single cells monitored in Valencia over time, expressed as the daily normalized power ratio, calculated as the integrated electrical power generated by the cell divided by the total incident irradiance. Devices with the best initial PCEs and longest lifetimes are shown.

#### 1.4.2. Outdoor testing in Neuchatel (CSEM)

Outdoor stability measurements at the CSEM test site in Neuchatel (Switzerland) were conducted under real environmental conditions representative of a temperate central European climate. The test site is equipped with a continuous monitoring system that records in-situ weather data throughout the measurement campaign. The devices were maintained at their MPP using electronic boards and algorithms provided by the LPVO, University of Ljubljana.

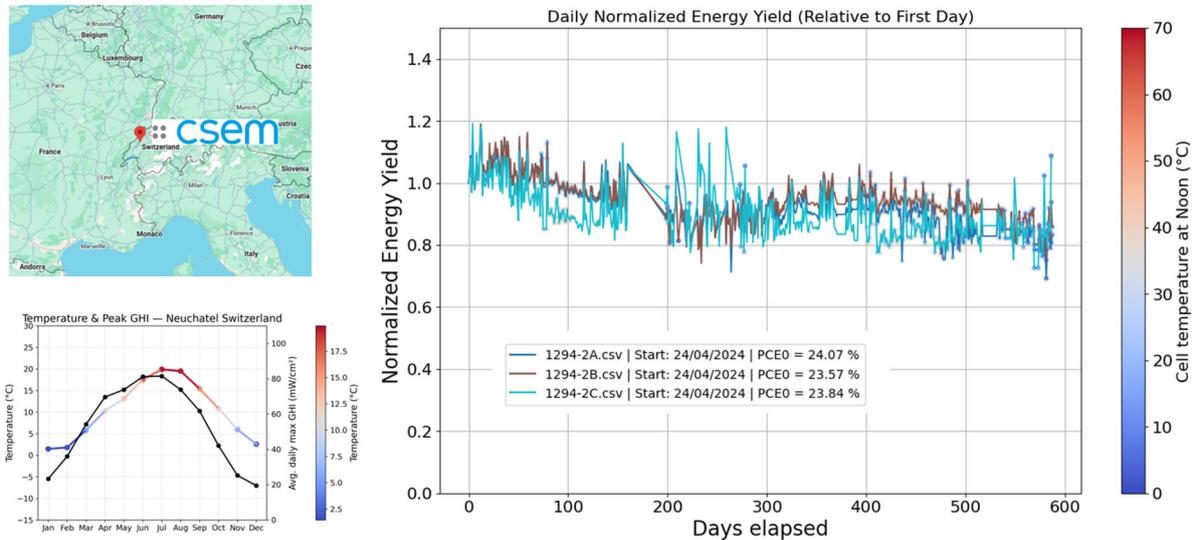
During the monitoring period, daily peak GHI typically ranged between 40–100 W/cm<sup>2</sup>, while average ambient temperatures fluctuated seasonally from approximately 0 °C in winter to 25 °C in summer (see **Figure 4**). Figure 4 also shows the outdoor performance of some of the best-performing devices monitored at CSEM, expressed as normalized efficiency over time.

Of particular interest are the results obtained with the 1-cm<sup>2</sup> hybrid-type single-cells fabricated by CSEM and encapsulated using Method 1, some of which exhibited the highest T80 values observed in the project, reaching more than 1.5 years (test ongoing, see Figure 4). Encapsulation Method 1 effectively protects the devices against moisture induced degradation, as well as against thermal cycles, and reached an efficiency on the order of 18% despite not involving any perovskite/ETL passivation interlayer. The absence of passivation interlayer is likely one of the main reasons behind this good operational stability, as will be further discussed in the following sections.

It is also worth noting that the Neuchatel climate is moderate compared to the harsher conditions at southern Mediterranean sites, which may partially contribute to the comparatively higher stability observed for these devices. Nonetheless, these results are very promising relative to the limited



outdoor stability data currently available in literature, where real-world T80 values for perovskite devices remain under active investigation and show substantial variability depending on climate and device architecture.



**Figure 4.** (left) Map showing the CSEM test location, with an inset displaying the average ambient temperature and peak GHI during the monitoring period. (right) Outdoor performance of single-cell devices monitored in Neuchatel, expressed as the daily normalized power ration over time. Devices with the best initial PCEs (18% in standard test conditions) and longest lifetimes are shown.

#### 1.4.3. Outdoor testing in Catania (3SUN)

Outdoor stability monitoring at the 3SUN site in Catania (Italy) was conducted under real-world operating conditions representative of a hot Mediterranean climate. Environmental conditions were monitored using a local meteorological station, recording ambient temperature, relative humidity, and irradiance data. Similarly to Valencia, the site is characterized by high annual solar irradiance, extended clear-sky periods, and elevated summer temperatures typical of southern Mediterranean climates. **Figure 5** (left) reports the evolution of average ambient temperature and peak GHI over the same monitoring period.

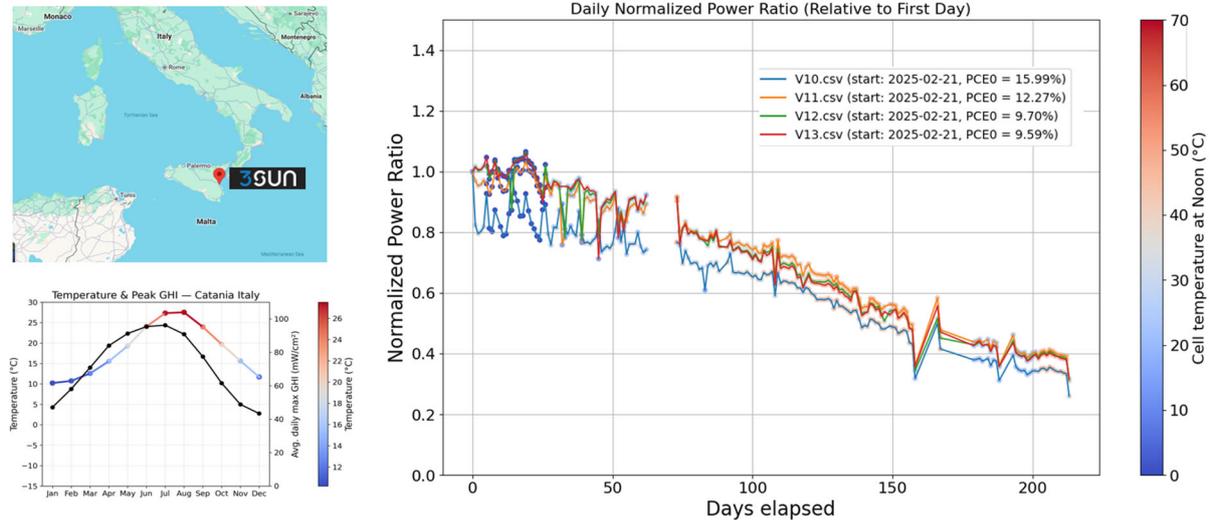
At Catania site, Valhalla single-cell devices were continuously tracked at their MPP using a 24-channel  $\mu$ MPPT board developed by LPVO, University of Ljubljana. This setup, installed in 2024 and continuously operating since then, was suitable exclusively for single cells due to the voltage operating limits of the system ( $-1.6$  V to  $+2$  V). To enable outdoor monitoring of minimodules with higher operating voltages, a dedicated system upgrade was implemented at the 3SUN site and became operational in summer 2025. The upgraded setup consists of five Ossila Source Measure Units (SMUs,  $\pm 10$  V) connected to a dedicated PC running MPPT control software developed by UVEG.

The single-cell devices monitored at the 3SUN site were mainly fabricated by UVEG. All of them incorporated EDAl-based passivation and were encapsulated using CSEM Encapsulation Method 1, as illustrated in Figure 1. Device performance was analyzed using the same Power Ratio approach as already described in Section 1.3.1. This normalization enables a meaningful comparison of device performance over time by mitigating the impact of day-to-day irradiance variability. Figure 5 (right) shows the normalized power ratio over time for the monitored single cells.

All monitored single-cell devices exhibited T80 values below 100 days, with the best performing devices reaching approximately 75 days. While the cell architecture and fabrication process were



comparable to those of devices monitored at the UVEG (Valencia) site, a key difference is that only EDAl-passivated cells were tested in Catania. The relatively low T80 values observed at the 3SUN site can therefore be attributed to the combined effect of high thermal/irradiance stress and the specific perovskite passivation strategy.



**Figure 5.** (left) Map showing the 3SUN test location, with an inset displaying the average ambient temperature and peak GHI during the monitoring period. (right) Outdoor performance of the single cells monitored in Catania over time, expressed as the daily normalized power ratio, calculated as the integrated electrical power generated by the cell divided by the total incident irradiance. Devices with the best initial PCEs and longest lifetimes are highlighted.

#### 1.4.4. Outdoor testing in Oulu (VTT)

Outdoor monitoring was also conducted at the VTT test site in Oulu (Finland), representing a cold, high-latitude climate with strong seasonal variations in irradiance, temperature, and daylight duration.

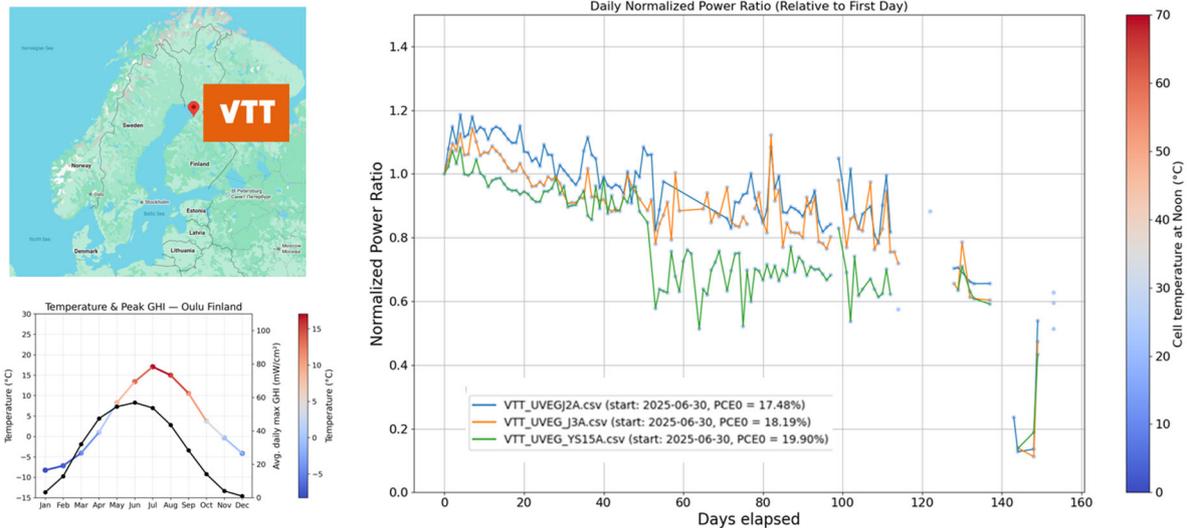
The outdoor monitoring setup, built during the project, comprises 16 measurement channels, suitable for both single cells and minimodules. Electrical performance was monitored through periodic IV-curve measurements, acquired every 30 minutes when the irradiance exceeded 1 mW/cm<sup>2</sup>. Between successive IV scans, devices were held under a constant electrical bias corresponding to the V<sub>MPP</sub> extracted from the previous IV sweep, enabling quasi-continuous operation close to maximum power conditions.

Environmental conditions were monitored in parallel. Due to the northern latitude, the site experienced rapidly decreasing day length and irradiance during autumn, with the first snowfall occurring in mid-November. During winter conditions, some devices became partially or fully covered by snow and ice. The daily normalized power ratio (Figure 6) data get more scattered as length of the day decreases, mainly due to a reduced number of data points per day. The first days when irradiance remained under the measurement limit (1 mW/cm<sup>2</sup>) were observed in mid-October, which shows as discontinuities in the normalized power ratio plots. Despite these challenging operating conditions, the Oulu site provides a valuable contrast to southern European locations by enabling outdoor stability assessment under low-temperature, low-irradiance, and intermittent illumination regimes. Figure 6 (left) shows the geographical location of the VTT site together with the average ambient temperature and peak GHI recorded during the monitoring period.

Among the devices monitored at the Oulu site were single cells closely comparable to those tested at the 3SUN site in Catania, including the use of EDAl-based perovskite passivation. **Figure 6** (right)



reports the outdoor performance of these devices; also in this case, device performance was analyzed using the power ratio approach. Despite the inclusion of EDAI passivation, the devices typically reached T80 values of up to approximately 100 days, exceeding those observed for analogous devices tested in Catania. The reduced thermal stress and lower cumulative irradiance characteristic of the Oulu site seem to mitigate degradation pathways that are accelerated under hot and high-irradiance Mediterranean conditions, underscoring the influence of climatic factors on the outdoor stability of passivated perovskite devices.



**Figure 6.** (left) Map showing the VTT test location, with an inset displaying the average ambient temperature and peak GHI during the monitoring period. (right) Outdoor performance of the single cells monitored in Oulu, expressed as the daily normalized power ratio, calculated as the integrated electrical power generated by the cell divided by the total incident irradiance. Devices with the best initial PCEs and longest lifetimes are highlighted.

## 1.5. Module performance assessment

### 1.5.1. Degradation trends at different locations

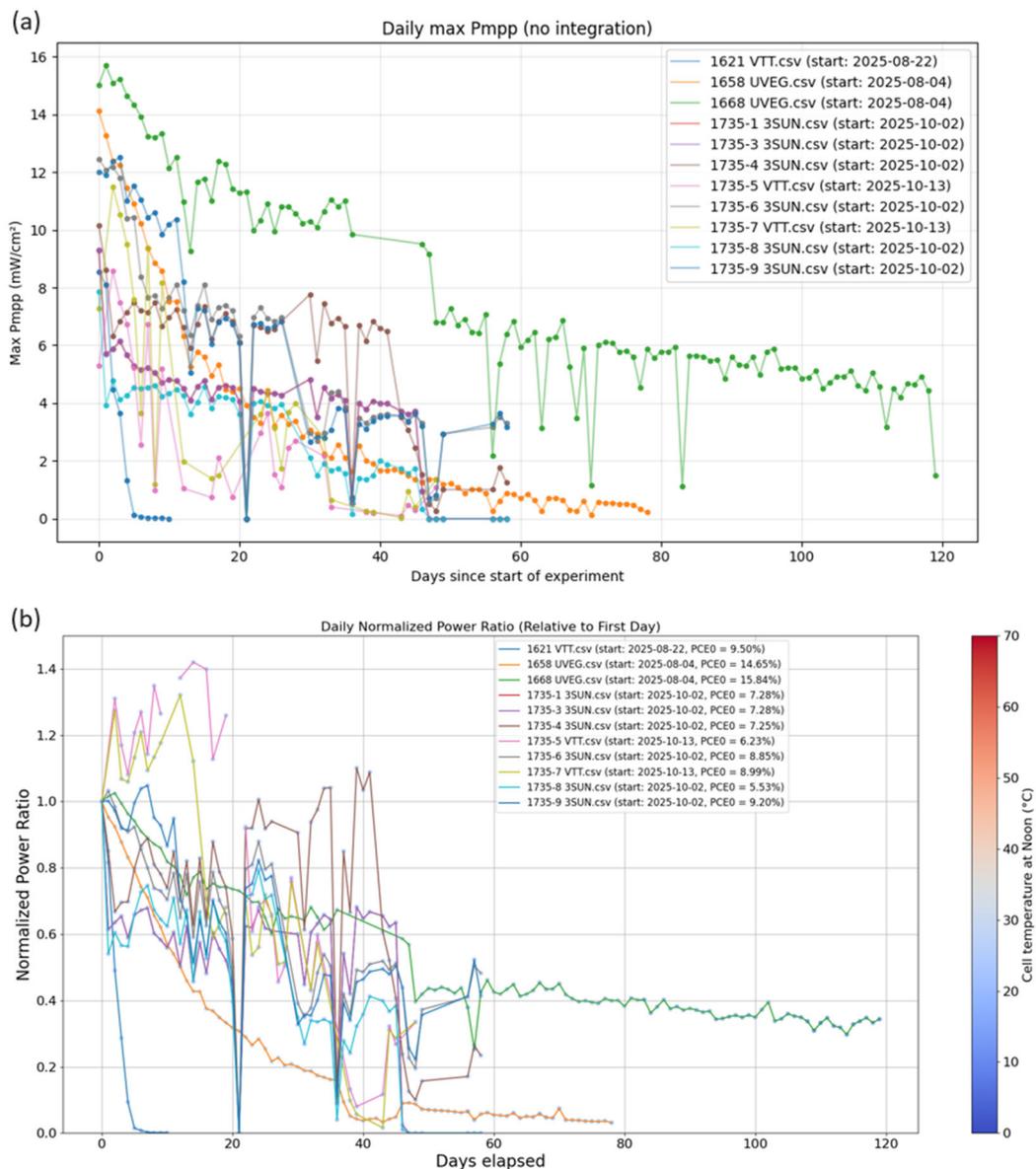
Various Valhalla minimodules were monitored under outdoor conditions at three sites (Catania, Valencia, and Oulu), operated at their MPP. Particular focus was placed on minimodules of Hybrid-type fabricated by CSEM, which had previously shown the highest stability at the single-cell level. In Figure 2 an overview of the minimodule architecture is shown.

**Figure 7a** shows the evolution of the maximum  $P_{mpp}$  per day over time for these minimodules, monitored during the second half of 2025 until the end of the project (unless evident degradation occurred earlier). Applying the Power Ratio method proved to be very challenging in this case due to difficulties in synchronizing irradiance and power data; consequently, daily maximum power output was initially chosen as the most reliable metric to visualize module performance over time. All devices exhibited a rapid decay in maximum  $P_{mpp}$  with values dropping below 80% of their initial output in less than one month, confirming the faster degradation of the mini-modules compared to single cells. A notable variability in the degradation behaviour is observed across individual modules, with some devices showing fluctuations or temporary recoveries, making precise interpretation challenging.

To reduce the influence of meteorological conditions and irradiance levels, the Power Ratio method was also applied to these minimodules following the same methodology as before. The dataset was



post-processed to exclude days with very low irradiance, and outliers – defined as data points deviating by more than  $\pm 20\%$  relative to both the preceding and subsequent days – were removed. The resulting normalized power ratio per day as a function of time is shown in Figure 7b. Based on these normalized trends, we estimate that all monitored minimodules reached T80 values within 7 weeks, confirming the relatively rapid decay of the scaled-up devices while acknowledging some uncertainty due to data dispersion and measurement limitations.



**Figure 7.** Outdoor performance of Valhalla minimodules monitored at three different locations (Catania, Valencia, Oulu). (a) Evolution of maximum power output ( $P_{mpp}$ ) per day over time. (b) Daily normalized power ratio over time, calculated as the integrated electrical power generated by the cell divided by the total incident irradiance. The modules were tested at the locations indicated at the beginning of their respective codes.

Both module-specific and process-related degradation mechanisms were found to contribute to the rapid performance loss observed, as will be discussed in the next section. In addition, it is worth noting that all minimodules investigated here incorporate a passivation layer at the ETL/perovskite interface.



While such passivation strategies are known to enhance initial device performance by reducing interfacial recombination and increasing PCE, they have also been reported to negatively impact long-term operational stability by accelerating interfacial degradation processes. This trade-off between efficiency and stability is consistent with previous observations, including the faster degradation observed for devices monitored in Catania compared to those tested at the UVEG site.

More broadly, the rapid  $P_{\text{mpp}}$  decline observed in all the Valhalla minimodules is consistent with trends reported in the literature and in standardized outdoor datasets such as those collected by the Perovskite PV Accelerator for Commercial Technologies (PACT) initiative (Sandia National Laboratories, publicly available dataset: <https://pvfact.sandia.gov/results-and-data/>). While PACT includes a wide range of perovskite single junction minimodules from multiple partners, the majority of these devices exhibit T80 values below 10 weeks at peak efficiencies comparable to those achieved in Valhalla, showing that short-term outdoor degradation is common. Only a small fraction of PACT modules retains significant efficiency over longer periods, but it should be noted that the dataset includes devices fabricated using various layouts and perovskite fabrication methods including full wet-based approaches, making a direct comparison challenging. By contrast, Valhalla modules are produced with hybrid and full-vacuum deposition techniques, avoiding the use of toxic coordinating solvents. This comparison confirms that Valhalla technology behaves consistently with the general performance of perovskite modules under real-world conditions and underscores the need for further improvements at the module level to bridge the gap between cell and module stability to reach long-term outdoor operation.

#### 1.5.2. Analysis of factors limiting device stability

To gain deeper insight into the degradation mechanisms observed during outdoor testing, a subset of minimodules was analyzed in more detail. In particular, two out of the six minimodules monitored at 3SUN were disconnected and returned to CSEM for in-depth characterization aimed at identifying the dominant failure modes. Three main degradation modes were identified as summarized in **Figure 8**.

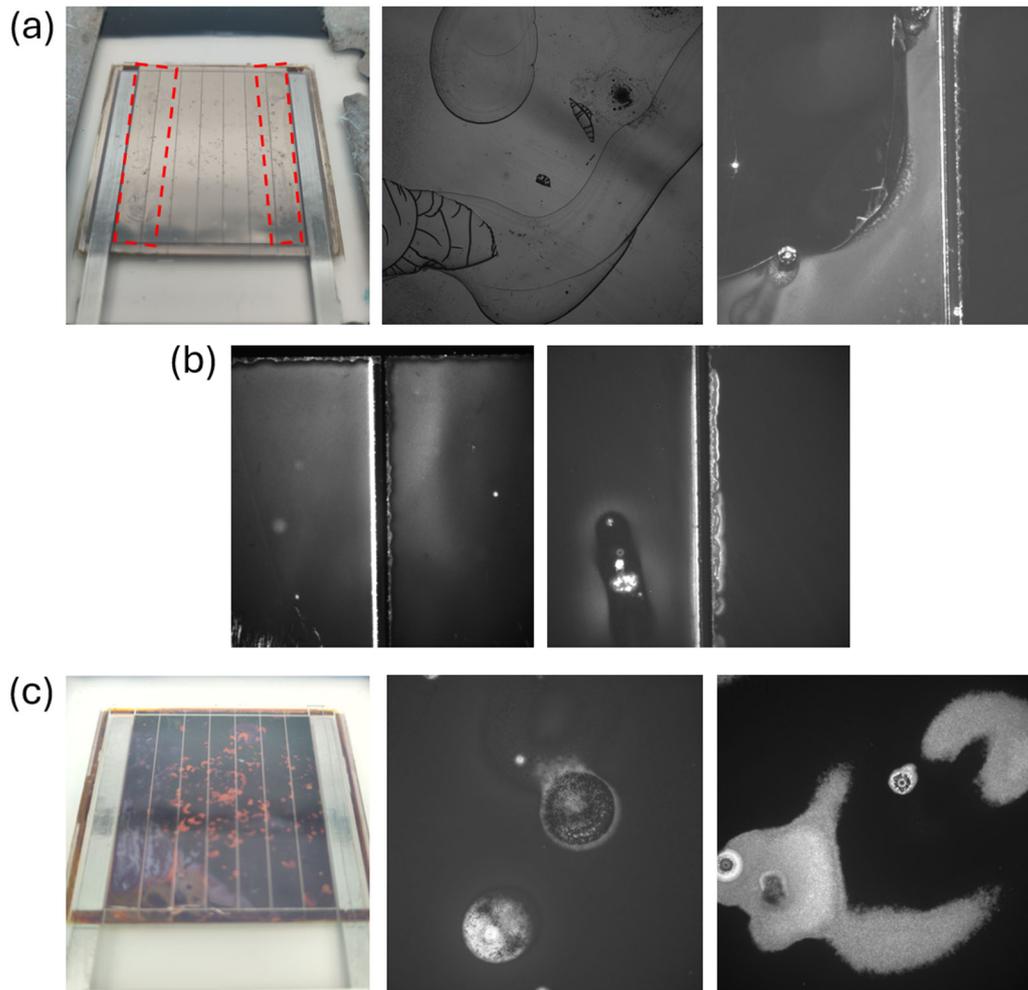
The first failure mode is delamination occurring in proximity to the ribbons, as shown in Figure 8a. Delamination was clearly observed from the film side and under microscopic inspection, corresponding to bright regions in photoluminescence (PL) images. No extensive delamination was detected elsewhere in the modules, indicating that this failure mode is primarily induced by local thermo-mechanical stress associated with the ribbons. Although spatially localized, this delamination obstructs the current flow and therefore affects the electrical performance of the entire module.

The second failure mode is scribe-line degradation, illustrated in Figure 8b. This degradation mechanism is commonly observed in perovskite minimodules and is associated with the laser scribing steps used for module patterning (P1, P2, and P3, see Figure 2a). In the analyzed samples, the degradation appeared to originate specifically from the P3 laser scribe line; it was observed only in one of the two returned modules and only in localized regions. Notably, degradation along the scribe line was more pronounced in areas where nearby particles were present, suggesting that local defects or contamination can exacerbate scribe-related degradation pathways.

The third failure mode is particle-induced degradation, shown in Figure 8c. This batch of minimodules was significantly affected by an unidentified form of particle contamination. In two-step perovskite deposition processes, such particles are known to disrupt film formation, often leading to comet-like features during spinning and resulting in locally altered stoichiometry. In the analyzed modules, particle centers looked heavily degraded, which can be associated with a shunting behavior. Unlike the first two failure modes, this degradation mechanism is not linked to module integration but is instead related to the perovskite deposition process itself. In principle, it can also affect single-cell devices, although the likelihood of encountering these defects increases with the size of the active area.



This analysis highlights that minimodule degradation arises from both module-specific and process-related mechanisms. In particular, the ribbon-induced delamination and scribe-line degradation are strongly linked to module fabrication and were not observed in single-cell devices, whereas particle-induced degradation reflects more general process-related issues. This explains why minimodules show significantly lower outdoor stability compared to single cells: two out of the three main degradation modes appear only at the module level. This underscores the need for further optimization and engineering at the module scale.



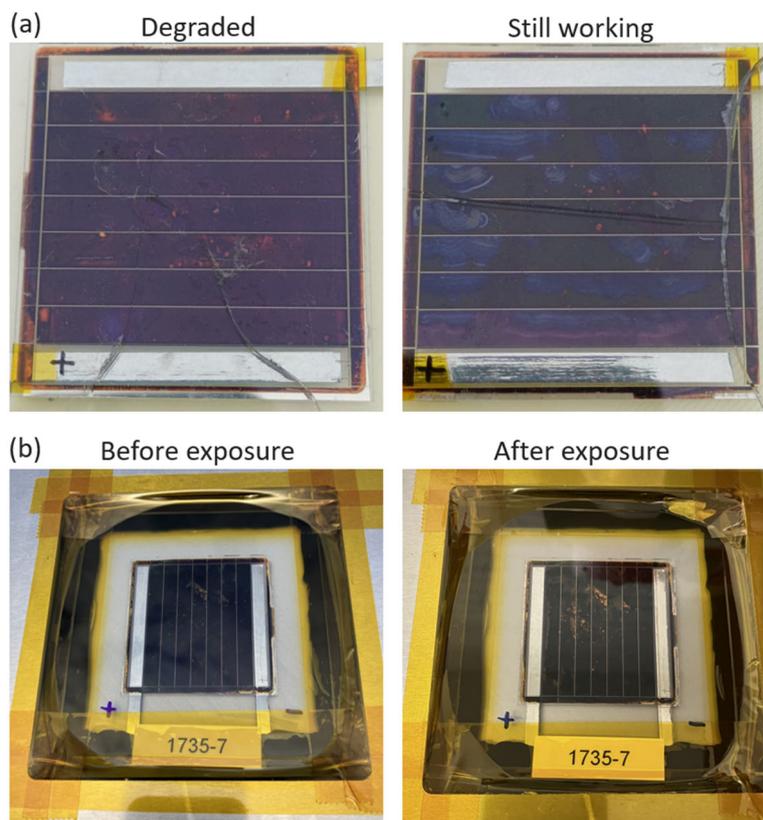
**Figure 8.** Representative images of the analyzed Valhalla minimodules previously monitored at 3SUN site, showing the three main degradation modes: (a) ribbon-induced delamination, visible both from the film side and under microscopic inspection; (b) scribe-line degradation, originating from the P3 laser scribe line, observed only in localized regions and exacerbated by nearby particles; (c) particle-induced degradation, caused by particle contamination during the two-step perovskite deposition process, leading to locally disrupted stoichiometry and shunting.

To further assess the relevance of the identified failure modes, devices at other test sites were visually inspected. Representative images are shown in Figure 9 for devices from the UVEG and VTT sites. At the UVEG site, regions of yellowing in degraded minimodules were observed (a clear indicator of perovskite degradation), mainly near the laser scribe lines and likely exacerbated by nearby particle contamination. This pattern suggests a strong link with degradation mode 2 (scribe-line degradation), with a possible contribution from mode 3 (particle-induced degradation). Figure 9a compares a picture



of a degraded device with that of a device still functioning; in the latter, initial defects are visible, but they are fewer in number and remain localized primarily near the scribe lines, consistent with the trends observed in the more degraded minimodules. Glass breakage was also observed, highlighting the presence of significant residual stress in the packaged modules after encapsulation. Adjusting the lamination foils thicknesses and overall encapsulation conditions could mitigate the issue. As a result of the glass breaking, the mini-modules were no longer protected from interaction with ambient atmosphere which likely contributed to the degradation of the mini-modules.

Similarly, the images from the VTT site highlight reproducible degradation patterns. Figure 9b compares the same minimodule before and after 65 days of outdoor exposure in Oulu. Prior to exposure, the device shows a few localized imperfections, primarily near the scribe lines. After 65 days, a pronounced pattern of yellowing has developed, mainly spreading from the laser scribe regions. This supports the interpretation that scribe-line-related pathways are a dominant contributor to outdoor performance decay, potentially aggravated by environmental factors and particles contamination. The analogous degradation observed across different sites reinforces the need to address these failure mechanisms in module design and fabrication to improve long-term outdoor stability.



**Figure 9.** (a) At the UVEG site: on the left, a degraded device showing prominent yellowing, particularly near the laser scribe lines, indicative of perovskite degradation; on the right, a still-functioning device from the same site, where initial defects are visible but remain limited in number and primarily localized near the scribe lines. (b) At the VTT site: the same minimodule before (left) and after 65 days of outdoor exposure (right). Prior to exposure, a few localized imperfections are visible near the scribe lines; after exposure, pronounced yellowing has developed and propagated from the scribe region.

## 2. Conclusions

The perovskite minimodules developed and characterized within the Valhalla project, free of any toxic



solvent, have demonstrated promising PCEs of up to 18% for an active area close to 16 cm<sup>2</sup>. However, outdoor tests revealed a rapid performance degradation within a few weeks regardless of device layout or test location, with all minimodules reaching T80 within 7 weeks. Both single cells and minimodules were monitored: notably, some individual cells exhibited encouraging outdoor stability, reaching T80 values of more than 1.5 years, as observed for a hybrid perovskite cell fabricated by CSEM and monitored in Neuchatel (test still ongoing). These results demonstrate that careful selection of materials, interfaces, and encapsulation strategies can effectively mitigate key degradation mechanisms such as moisture ingress. Nevertheless, scaling up from pixelated cells to minimodules evidently introduces additional degradation pathways and complexities, highlighting the challenges of translating laboratory-level performance to larger, practically relevant devices.

The primary objective of this deliverable was to demonstrate outdoor TRL 5 module stability comparable to silicon PV, where reliable operation in relevant environments with predictable long-term degradation is expected. Based on the current data, the Valhalla minimodules do not yet meet this benchmark. While the observed efficiencies confirm the validity of the technological concept, the insufficient outdoor stability prevents the technology from reaching the targeted TRL level.

It is important to emphasize that achieving silicon-comparable outdoor stability remains a central challenge for the entire perovskite research community, with ongoing efforts worldwide focused on optimizing materials, interfaces, encapsulation strategies, and device architecture. To provide context on the current worldwide status, our results were compared with outdoor data collected by initiatives such as the PACT program. The reference data and degradation trends from PACT align with our observations in this deliverable, with most single-junction perovskite minimodules typically showing T80 values below 10 weeks at comparable peak efficiency levels. These results are particularly relevant considering that the Valhalla project focuses on perovskite deposition techniques (i.e., hybrid and full-vacuum) that are less mature than some of the highest-performing full-wet laboratory processes which are included in the PACT datasets, while offering the advantage of being free of any toxic solvent.

In conclusion, we can state that the technology developed within Valhalla can be positioned between TRL 4 and TRL 5, where the technological concept is validated, but outdoor reliability remains insufficient. While the minimodules are currently far from achieving stability comparable to silicon PV, the promising outdoor performance of some individual cells indicates that the materials and interface choices are scientifically sound. This suggests that the technological concept is already partially validated beyond TRL 4 and provides a solid basis for further optimization at the module level, supporting progress toward higher TRL levels in the near future.