DELIVERABLE REPORT

NEXUS

D3.2: BOM definition for eco-designed PVSK/Si tandem modules passing IEC tests

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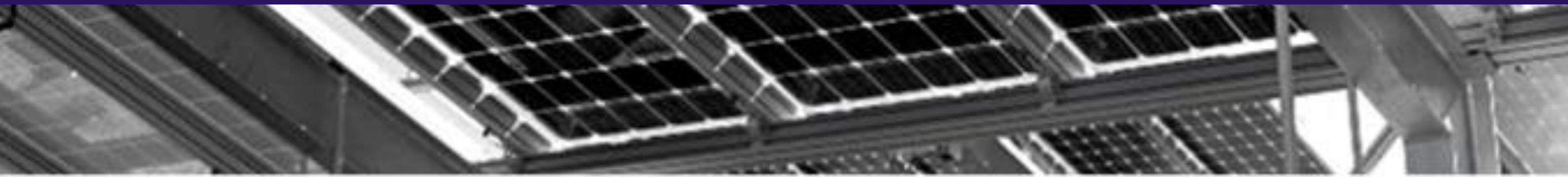

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NEXUS aims to accelerate Europe's energy transition by developing perovskite-silicon tandem photovoltaic technology, via a new European paradigm: an eco-design approach, based on efficiency, cost, sustainability, circularity and social aspects and using abundant materials. NEXUS aims to develop stable, 2-terminal perovskite-silicon tandem solar cells and modules with high power conversion efficiencies, using sustainable, coherent and competitive European PV production, to create a viable economic pathway for the European commercialisation of this technology.

NEXUS is formed of a multi-disciplinary consortium: 13 partners from 10 countries; 6 industrial partners & 7 RTOs, covering the whole value chain of innovation from research centres to technology providers, end-users and market and policies.

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NEXUS Consortium

Organization name	Short name	Country
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ACCADEMIA EUROPEA DI BOLZANO	EURAC	IT
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Abbreviations and acronyms list

Abbreviation	Meaning	Abbreviation	Meaning
BoM	Bill of Material	PCE	Power Conversion Efficiency
CtM	Cell to Module	POE	Poly-Olefin Elastomer
DH	Damp Heat	PV	Photovoltaic
DSC	Differential Scanning Calorimetry	PVSK/Si	Perovskite/Silicon
ECA	Electrically Conductive Adhesive	TC	Thermal Cycle
FF	Fill Factor	TPO	Thermoplastic poly-olefin
IEC	International Electrotechnical Commission	VOC	Volatile Organic Compounds
Jsc	Short Circuit Current Density	Voc	Open Circuit Voltage

1. Executive Summary

Perovskite tandem solar cells offer significant potential for enhancing photovoltaic efficiency, surpassing the limits of traditional silicon-based cells. However, their commercial adoption faces several key challenges, particularly in adapting industrial processes for interconnection and lamination.

1. **Interconnection Technology Adaptation:** Perovskite tandem cells require adaptation in interconnection methods, as their structural and electrical properties differ from standard silicon cells. The use of traditional soldering or conductive adhesives must be optimized to avoid damaging the delicate perovskite layers, which are sensitive to high temperatures.
2. **Lamination Adaptation:** Laminating perovskite tandem cells presents another major challenge due to their sensitivity to heat and moisture. Standard lamination process used for silicon modules involve high temperatures and long exposure times, which can degrade perovskite materials. Therefore, new encapsulation materials and lamination conditions, including low-temperature lamination and advanced moisture barriers, are needed to protect the perovskite layers without compromising module durability or efficiency.
3. **Stability and Durability:** Beyond process adaptation, perovskite and interface layers remain vulnerable both to environmental stress factors induced degradation and intrinsic degradation. For example, even minor process-induced stresses during interconnection or lamination can accelerate degradation, reducing module lifetime.

Overcoming these interconnection and lamination challenges is crucial for scaling up perovskite tandem cell production while maintaining high efficiency and long-term performance. Continued research into process optimization and material innovations is key to unlocking the full potential of perovskite tandem solar technology.

1.1. Description of the deliverable content and purpose

The deliverable *Bill of Material (BoM) definition for eco-designed Perovskite/Silicon tandem modules* aims to provide a detailed framework for selecting materials and processes that ensure the tandem modules meet environmental sustainability goals while passing the IEC certification tests, namely TC (Thermal Cycle) and DH (Damp Heat). The purpose of the report is twofold: first, to define the specific materials and components needed to create tandem modules that are both high-performing and environmentally friendly, and second, to validate that these eco-designed modules comply with international standards for durability and performance, as set by the IEC 61215.

The report discusses the selection of low-temperature materials, such as lead-free conductive adhesives and TPO encapsulants, along with the process adaptations required to operate below 150°C. Additionally, it presents initial results demonstrating the module's ability to meet critical tests of IEC 61215 certification standard.

1.2. Relation with other activities in the project

This report outlines the work carried out in Task 3.1 of Work Package 3 (WP3). The latest perovskite/silicon (PVSK/Si) tandem cells developed in WP1 and WP2 have been provided for integration into modules. Feedback from this process has enabled the WP1 and WP2 teams to refine and enhance the cell design. Additionally, the modules fabricated in WP3 have been deployed to various locations for outdoor performance assessments, which allow the WP3 team to further optimize their material and process selections.

2. Module development

The interconnection and lamination of perovskite-silicon (PVSK/Si) tandem cells present specific challenges due to the unique properties of both perovskite and silicon materials. Unlike standard silicon solar cells, which are typically interconnected using soldering methods at temperatures around 180°C, perovskite-based cells are much more temperature-sensitive. This is because the perovskite layer can degrade at relatively low temperatures, necessitating interconnection techniques that operate below 150°C [1], [2], [3]. The most common alternative to high-temperature soldering in tandem cells is the use of electrically conductive adhesives (ECA). These adhesives, typically composed of a polymeric matrix embedded with conductive particles (e.g., silver or copper), allow for low-temperature interconnections, making them suitable for fragile perovskite layers. However, ensuring strong adhesion and good electrical contact through ECAs requires optimization of curing times and temperatures, often based on thermal analysis such as Differential Scanning Calorimetry (DSC) [4], [5], [6].

In addition to interconnection, the lamination process is crucial for ensuring the long-term stability of tandem modules. Lamination typically involves encapsulating the cells between layers of protective glass and a polymeric encapsulant to shield them from moisture and environmental degradation. For perovskite-silicon tandems, encapsulants like POE (polyolefin elastomer) or TPO (thermoplastic polyolefin) can still be used, as they can be processed at lower temperatures and form robust bonds with the module's materials. EVA is not ideal for tandem PV modules because it can break down under heat and UV light, releasing acetic acid. This acid can corrode metal contacts and interconnections and accelerate the degradation of perovskite layers, which are especially sensitive to chemical and environmental damage. Moreover, to ensure the integrity of the module, especially in demanding

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conditions such as high humidity, edge sealants are used to prevent oxygen and moisture ingress in a G/G module configuration. The selection of the right encapsulant and edge sealant, coupled with optimized lamination parameters, is essential to avoid defects like delamination or bubble formation, which can compromise the module's performance [7].

Different studies have demonstrated that while current interconnection techniques like ECAs are promising, there are still challenges to be addressed. Issues such as poor adhesion between the ribbons and metallization layers, or degradation in device performance after lamination, remain common. For instance, various studies report that metallization layers can peel off or show weak adhesion, especially when the perovskite top layer has insufficient mechanical robustness [2].

Looking ahead, continuous improvement in both material selection and process adaptation is required to enable the large-scale production of durable, high-efficiency perovskite-silicon tandem modules. This involves not only perfecting interconnection and lamination techniques but also conducting rigorous long-term aging tests to assess the reliability of these materials under real-world conditions

2.1. Interconnection process

2.1.1. Interconnection choice

To ensure the compatibility of high-efficiency perovskite-silicon (PVSK/Si) tandem cells with industrial tools and processes, we initially focused on the silicon bottom cell to adapt existing processes. Traditional interconnection methods using tin/lead alloy soldering are no longer feasible, as they require temperatures above 180°C (the eutectic melting point). While soldering with low-melting-point alloys, such as bismuth or indium, is an option, we decided against it for two main reasons (see D3.1 and D3.4:

- Bismuth and indium are critical materials that cannot support large-scale production, and recycling dispersive materials like solder is technically and economically challenging.
- Ultra-low-temperature silver pastes, employed for the metallization of tandem cells, are less compatible with soldering techniques, a limitation we had previously observed with low-temperature silver pastes in HJT cells (poor wetting)

Therefore, we opted to use Electrically Conductive Adhesive (ECA), a polymer matrix with embedded conductive particles, for our interconnection needs.

2.1.2. ECA selection

The first step in material selection was identifying suitable ECAs that could be processed at temperatures below 150°C. To determine this, we performed thermal characterization of various ECA materials using Differential Scanning Calorimetry (DSC) experiments. DSC measures how a material’s heat capacity changes with temperature, revealing key properties like melting and curing temperatures. This data is essential for determining optimal processing conditions, especially for materials in photovoltaic applications that must withstand specific thermal limits. This allowed us to assess the curing temperature of each ECA. Through additional characterization, we could also predict the kinetic behavior of these materials. Figure 1 presents the theoretical curing times for different ECAs at varying temperatures, enabling us to optimize the process parameters for each material. Each point represents the estimated time required for complete curing of the ECA at a specified temperature. We defined a process window by a maximum temperature of 150°C and a duration of 30s (green zone - Figure 1), ensuring that the materials are processed without exceeding its thermal limits that could compromise their structural integrity or functional properties, while still allowing adequate time for necessary curing or bonding to occur (in a standard industrial stringer, curing time is limited to 30 seconds to maintain high production throughput. We can observe that ECAs D and F fall outside the green zone, thus excluding them from our candidate selection for processing PVSK/Si tandem cells.

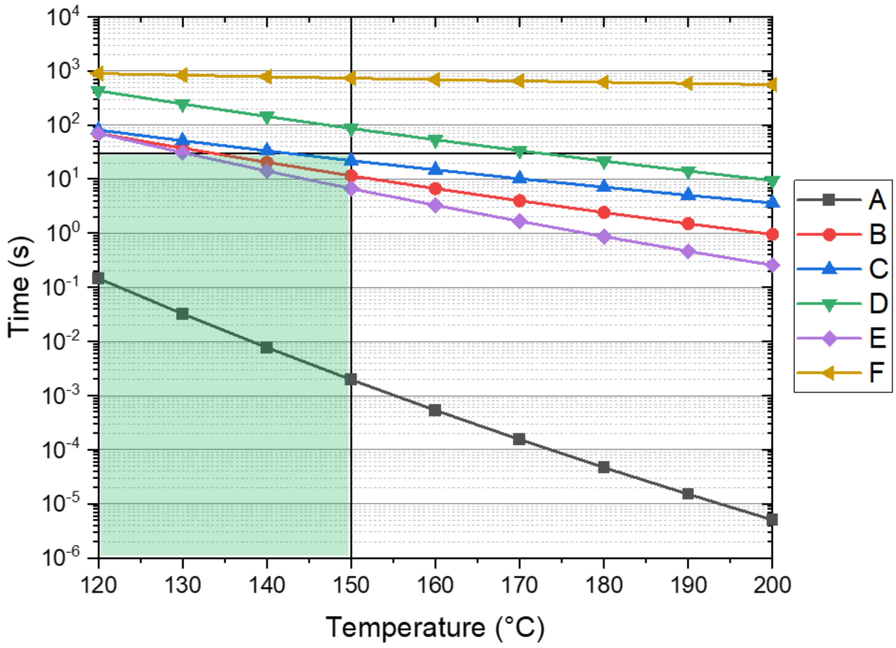

Figure 1: Theoretical curing times for various ECAs at different temperatures. The green zone indicates the optimal processable conditions for PVSK/Si tandem cell

The four remaining ECAs were tested on our industrial stringer, with the curing step set at 150°C (20s), to validate the feasibility of manufacturing cell strings with a silicon bottom cell. We evaluated the adhesion of ribbons on the strings to confirm the suitability of the ECAs for use, thanks to 90° peel testing (> 0.5N/mm). ECA A, serving as our reference, was selected for the first interconnection test on the perovskite/silicon (Pk/Si) tandem cell.

2.1.3. ECA PVSK/Si tandem cell ribbons connection

PVSK/Si tandem cells have been provided up to now by two consortium partners, UOXF and UVEG, and the design and composition of the metallization have evolved over time. Initial attempts to establish contact with the cells revealed new types of failures not typically seen in silicon solar cells. As previously documented in the literature [2], we encountered new types of failures related to cell interconnection. During the initial trials, delamination was observed, with the ribbons showing very poor adhesion to the cell. Typically, in standard silicon cells, ribbon failure occurs due to an issue at the ECA/ribbon interface. In NEXUS PVSK/Si tandem cells, however, failures occurred at the interface between the cell and the metallization, or even below, indicating that the issue was unrelated to the ECA process.

Figure 2 illustrates an example of contact failure after ECA was used to connect the ribbons. The adhesion of the ribbons is weak, due both to the very small contact pads and, as shown in the image, poor adhesion of the upper layer of the top cell.

Adhesion was assessed qualitatively, as the ribbon adhesion was too weak to be measured accurately

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or even to allow safe handling of the cell

Figure 2: Examples of contact failure occurring both with the metallization and the top cell layer are ripped off.

It was also possible to observe differences based on the origin of the PVSK/Si tandem cells

- On UVEG's devices: we were able to achieve good mechanical contact on the device
- On UOXF's devices: we were unable to successfully attach the contact ribbons to the front (polished) side, as the evaporated silver layer peels off when the ribbons are applied. However, on the back (textured) side, the adhesion works well. This issue is something we've also observed internally when metallizing cells through screen-printing, where poor adhesion of the screen-printing ink occurs on flat surfaces.

After multiple exchanges with the partners who supplied the tandem cells, we were finally able to achieve reproducible results in connecting them. In particular, they modified the top cell process by depositing an insulating silicon oxide layer on the edges of the silicon substrate, around the active area of the top cell, and by masking the substrate during the deposition of the top cell layers. In the end, the contact pads lie on the silicon oxide layer, ensuring much better adhesion of the metal to be contacted with the ribbons.

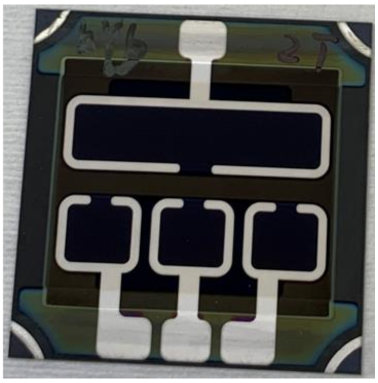

Figure 3: UOXF tandem cell with modified design (top cell layer-free area below the metal pads that lie on a silicon oxide layer deposited on the bottom silicon cell substrate).

2.2. Lamination step

Lamination in photovoltaic (PV) modules is crucial as it provides both structural support and environmental protection, ensuring module durability and performance over time. By embedding the solar cells between layers of encapsulant and protective materials (such as glass and backsheet), lamination shields the cells from moisture, oxygen, UV exposure, and mechanical stress. It involves

heating and compressing layers within the module—typically, glass, encapsulant materials like EVA or POE, solar cells, more encapsulant, and a backsheet or second glass layer—so they bond securely without air pockets or moisture ingress. This process usually occurs in a lamination machine, where a vacuum is applied to remove air before heating and pressing the stack under controlled conditions.
During lamination, the encapsulant material melts and flows around the cells, filling any gaps to create a protective seal around the delicate parts of the module. Afterward, the encapsulant cools and solidifies, securing the module structure. The exact parameters, such as temperature, vacuum levels, and duration, vary based on the materials used and the module design. Proper lamination is crucial for module longevity, as it ensures stability against environmental factors like UV exposure, moisture, and temperature changes.

Our next focus was on developing the lamination process specifically for tandem cells. We selected an industrial encapsulant, initially a polyolefin elastomer (POE), designed for processing temperatures above 150-160°C. This encapsulant was chosen as a start as it is a reference encapsulant for HJT technology.
We then had to optimize our lamination recipe to reduce the process temperature in order to preserve the perovskite material. Optimization was performed to ensure proper adhesion between the glass and encapsulant, as well as optimal crosslinking, as demonstrated in Figure 4.

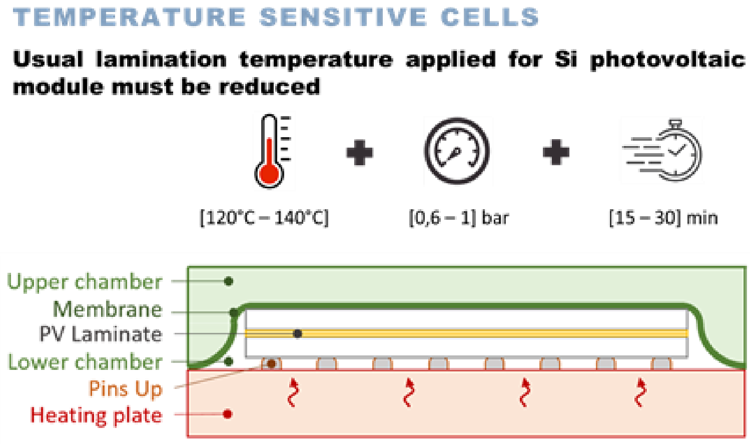

Figure 4: Standard membrane chamber laminator with time/temperature process conditions applied to tandem cells

We monitored the temperature profile for each lamination recipe to ensure it remained below 140°C, as shown in Figure 5. The two process parameters were adjusted as follows:

- The degassing and heating steps were determined by the melting temperature of the encapsulant.
- The time under pressure was defined by the degree of cross-linking in the encapsulant (POE) and/or the adhesion between the encapsulant and the glass. The cross-linking of the encapsulant is determined using a standardized method developed by CEA, ensuring consistent and accurate assessment of the material's curing process [8].

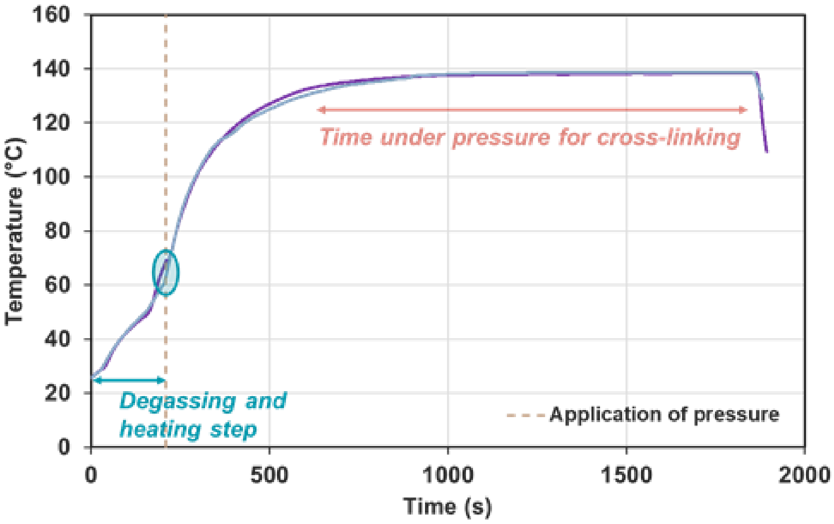

Figure 5: Temperature monitoring of a glass-glass lamination process

We then applied edge sealant to hermetically seal the module and effectively protect the tandem cells from oxygen and moisture ingress. However, we encountered an unexpected issue with bubbles forming inside the edge sealant after lamination. Since these bubbles could act as initiation points for defects, we needed to identify their cause and eliminate them. Extending the degassing time did not resolve the issue. Significant improvement was observed when we reduced the time under pressure, resulting in a lower degree of cross-linking in the POE (Figure 6). We attributed the formation of bubbles to the Volatile Organic Compounds (VOCs) generated during cross-linking, which became trapped by the edge sealant (demonstrating its hermeticity in an unusual way…) [9]. As a result, it appeared more effective to work with thermoplastic polyolefin (TPO) or ionomer encapsulants, which do not require cross-linking, for edge sealant implementation.

Figure 6: Lamination of POE encapsulants with edge sealant (POE under crosslinked is equivalent to TPO materials)

Adhesion tests were conducted to evaluate the encapsulant's bond to the glass, both in its initial state and after 1000 hours of Damp Heat (DH) exposure. Mechanical shear tests were also performed to assess the integrity of the edge sealant/glass interface (Figure 7).

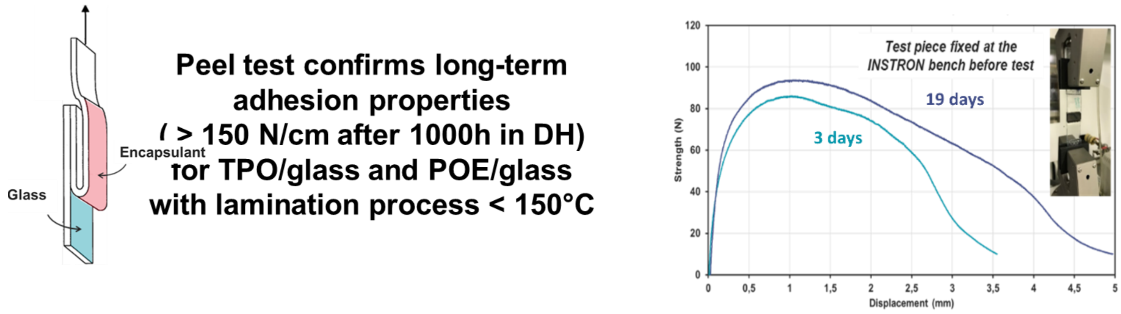

Figure 7: presentation of the adhesion test for the Encapsulant/Glass and the Edge Sealant/Glass interface

After successfully integrating the edge sealant, we assessed the module's sealing efficiency using moisture-sensitive paper. As shown in Figure 8, the edge sealant proves to be an effective barrier against humidity, ensuring proper protection of the tandem cells.

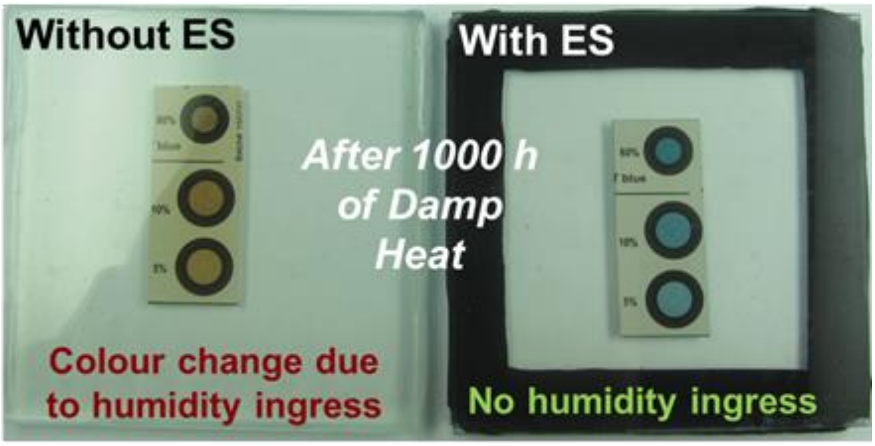

Figure 8 : Validation of Edge Sealant implementation with TPO material

2.3. Module step

Following the initial phase of material selection, done on the silicon bottom cell (conductive adhesive, encapsulant, and PIB edge sealant) and the development of a process to maintain temperatures below 150°C, we finalized a specific Bill of Materials (BoM) designed to address the new challenges posed by PVSK/Si tandem solar cells (Table 1). We then carried out the first module integration of these device.

Module BoM	
Front cover	100 x 100 x 3mm glass
Encapsulant	TPO
Rear cover	100 x 100 x 3mm glass
Edge sealant	PIB 10mm x 650µm
ECA	Acrylate
Ribbons	800 x 200µm

Table 1: BoM used on the first NEXUS tandem modules

However, during our first complete module processing (interconnection and lamination), although the visual appearance of the tandem module was satisfactory, the device was non-functional, as demonstrated in Figure 9.

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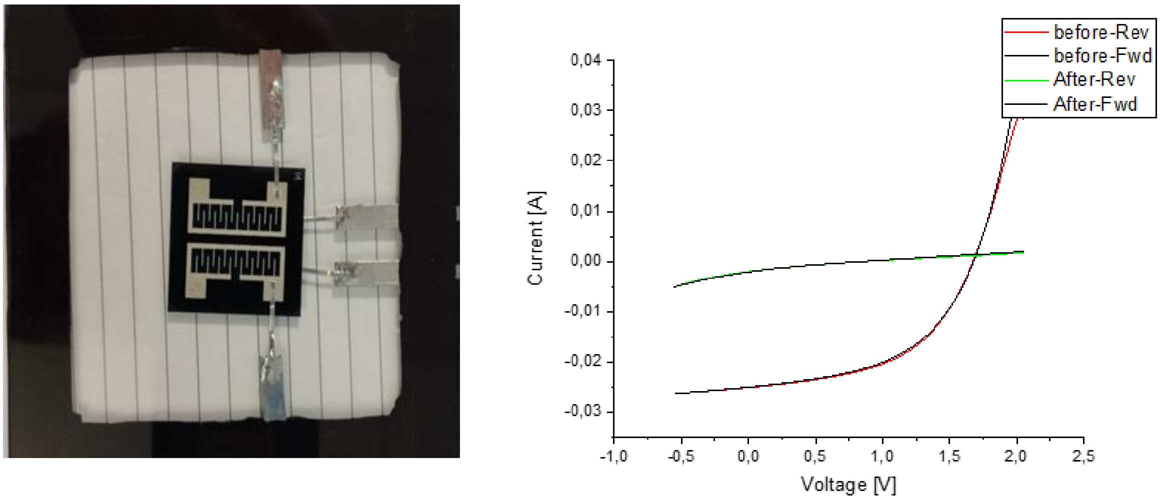
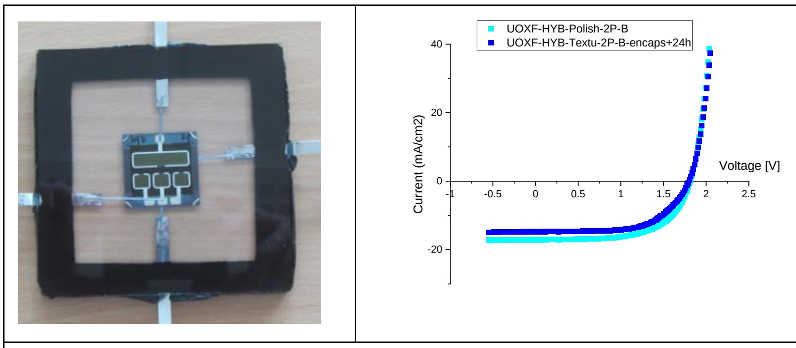


Figure 9: Images of a connected module showing failure after both the interconnection and lamination steps (right) – IV curve of the cells before and after module assembly (left)

Once again, we collaborated with the partners who supplied the tandem cells to improve the metallization and the upper layer of the top cells. After several metallization design enhancements, we were finally able to successfully connect and laminate a device while preserving its performance. Figure 10 shows an image of the functioning device along with its associated electrical characterization. The fill factor (FF) and open-circuit voltage (Voc) of the device remained unaffected by the module assembly process, indicating that the procedure was efficient and did not compromise the integrity of the cells. This demonstrates a well-optimized manufacturing process that ensures the preservation of electrical performance during the assembly. The reduced short-circuit current density (Jsc) could be attributed to reduced optical management in current matching.



	Cell	Module
PCE (%)	19.0	16.4
Voc (V)	1.81	1.80
Jsc (mA/cm²)	17.1	14.73
FF (%)	61.3	62.0

Figure 10: Images of a functioning connected module after both the interconnection and lamination steps (right) – IV curve before and after modules assembly (middle) – Table displaying the IV electrical parameters of the cells before and after module assembly (left).

In parallel, we have also worked on larger PVSK/Si cells fabricated at CEA (9cm²). Using the same BoM, we successfully integrated the cell into module with even a gain in current showing good optical management and current matching of the bottom and the top cell Figure 11. This result demonstrates that with effective optical management of current matching within the module, it is feasible to boost the short-circuit current density (Jsc) at the module level.

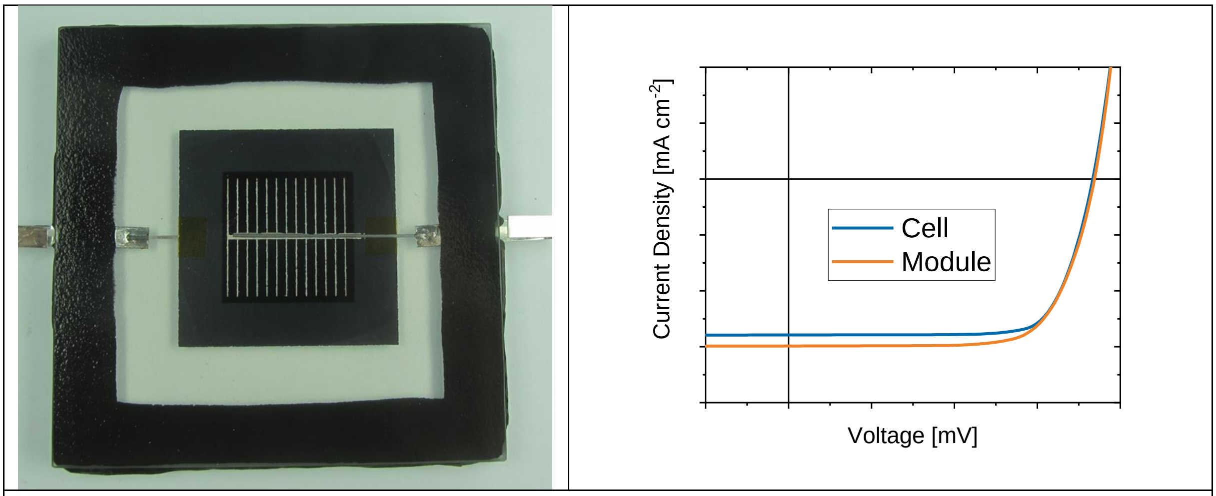


Figure 11: Images of a functioning CEA connected module after both the interconnection and lamination steps (right) – IV curve characterization before and after moduling (left).

Initial aging tests were conducted on first samples from CEA (1 DH and 2 TC). Damp Heat tests showed no degradation. Thermal Cycling tests revealed no visible delamination of the perovskite layer after 200 cycles (TC200). Nonetheless, electrical performance remains an area needing further improvement, as some devices showed stability, while others exhibited performance losses exceeding 10%.It is important to note, however, that the sample size was very limited, and the initial quality of the cells at t0 was suboptimal.

2.4. Next step

The next steps should prioritize validating the lamination process using enhanced cell samples provided by our partners. This process will involve refining the lamination technique to ensure optimal compatibility with the latest cell designs and achieving robust adhesion and protection. Stability testing will then be essential to confirm the reliability of these improvements, aiming for durable performance under varying environmental conditions. Additionally, further optimization of the lamination parameters may be needed to maximize cell performance and integrity within the module, adapting to any evolving cell characteristics from our collaborators.

In the following phase of module development, we will need to interconnect multiple cells together. This could prove challenging, as the current cell design is not optimized for series interconnection, with the top and bottom copper interconnectors not aligned. Additionally, aging tests will be conducted on the cells provided by different partners to assess their durability and performance over time.

Some single-cell modules have also be installed at different locations across the consortium's partners to assess the outdoor performance of the PVSK/Si technology and identify potential new degradation pathways. This real-world testing is critical to understanding how perovskite/silicon tandem modules behave under various environmental conditions, including variations in humidity, temperature, and UV exposure, which may not be fully captured during controlled indoor testing. By collecting data from different geographic areas, the consortium hopes to uncover unique environmental challenges and refine the module design for enhanced durability and long-term stability.

3. Conclusions

Integrating tandem perovskite-silicon (PVSK/Si) cells into modules presents significant challenges due to the sensitivity of the perovskite material and the complex process requirements. Perovskite materials are highly vulnerable to moisture, oxygen and temperature, making the lamination and encapsulation processes more delicate compared to traditional silicon cells. The interconnection of these cells also demands lower temperatures, as typical soldering methods can degrade the perovskite layers and are incompatible with low temperature metallisation pastes. Furthermore, achieving reliable mechanical and electrical contact between layers without compromising the performance is difficult due to poor adhesion in the perovskite device stack. Long-term stability, which is critical for commercial viability, is also a key concern, as perovskite cells can degrade under prolonged exposure to light, heat, and environmental stressors. Overcoming these challenges requires careful material selection and process optimization to ensure both the high efficiency and durability of the tandem modules.

In close collaboration with its NEXUS partners (UVEG & UOXF), CEA has successfully developed both the interconnection and lamination processes necessary to integrate perovskite/silicon (PVSK/Si) tandem cells into mono-cell modules. First encapsulation results are promising, showing encouraging electrical performance in the early prototypes. Initial tests show that the materials selected and the low temperature processes developed can withstand TC without delamination and prevent moisture ingress upon DH, demonstrating the relevance of the selected BoM for testing against the IEC standard. However, the long-term stability and reliability of these solutions must still be evaluated on bigger PVSK/Si devices through rigorous indoor aging tests and real-world outdoor exposure to various environmental conditions. The next phase of development will focus on scaling up from single-cell modules to four-cell interconnected modules, in order to meet one of the project's key milestones: *Encapsulated proof-of-principle 4-cell PVSK/Si module, CtM loss <10%, passing IEC stability tests.*

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