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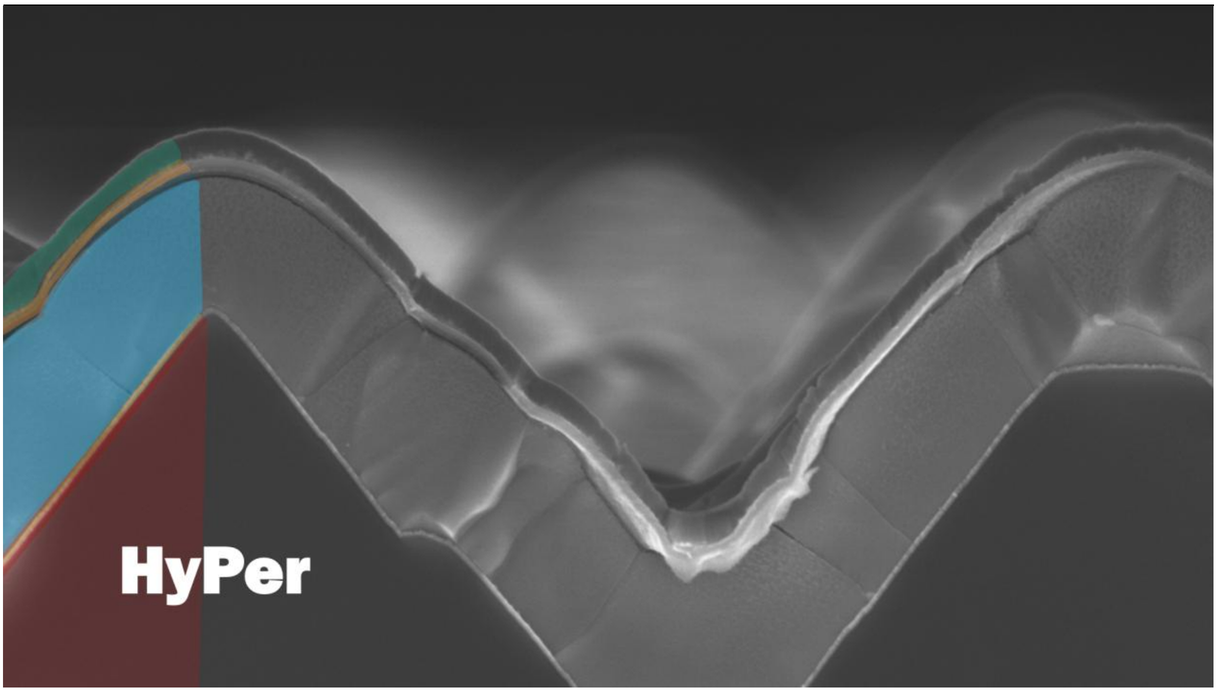
Interim report from 12 December 2025

HyPer

Hybrid Approach for Perovskite-Silicon Tandem Solar Cells



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Summary

This intermediate report (end of the first year) summarizes the contribution of the Centre d'Electronique et de Microtechnique (CSEM) to the HyPer ("**Hy**brid Approach for **Per**ovskite-Silicon Tandem Solar Cells") project.

The HyPer project aims to industrialize high-efficiency, stable 2-terminal perovskite-silicon tandem solar cells by developing scalable deposition processes for large-area devices. Its overarching goal is to raise the technology readiness level from TRL 4 to TRL 6 by demonstrating >30% power conversion efficiency on M10-size silicon heterojunction (SHJ) wafers (>250 cm² active area) using industrially relevant methods.

The project focuses on adapting the hybrid two-step perovskite deposition route evaporating an inorganic scaffold followed by a dispensing of an organohalide precursor to processes compatible with large wafers and high throughput. Three scalable second-step methods (inkjet printing, slot-die coating, and close-space sublimation) will be benchmarked to ensure uniform, high-quality perovskite films on textured silicon substrates. Achieving these objectives will help overcome major bottlenecks in scaling, moving beyond small-area spin-coated devices that currently dominate record efficiencies.

A second central aim is to improve the operational stability of perovskite/silicon tandems. HyPer targets <5% relative degradation after 3000 h damp-heat testing (85 °C/85% RH), 600 thermal cycles (−40 to 85 °C), and >2000 h of light soaking, ultimately aiming for <1 % absolute annual degradation outdoors in Central Europe. This will be achieved by developing more stable Formamidinium-(FA-) based perovskite formulations, suppressing defect migration and phase segregation, implementing improved transport layers (including spatial-ALD SnO_2 buffers), and establishing robust glass-glass encapsulation. These material, interface, and encapsulation innovations will enhance tandem solar cell reliability and demonstrate the technology's viability for real-world use. The project is strongly aligned with the CETPartnership Call on advanced renewable energy technologies, addressing efficiency, cost reduction, and technological sovereignty for Europe. By enabling scalable, high-performance tandem manufacturing, HyPer directly supports the deployment of low-cost clean electricity and reduces reliance on non-European PV supply chains. The consortium also integrates gender-balanced research teams and adopts an open-science approach, committing to rapid dissemination of results, open-access publications, and public release of indoor and outdoor stability data. Together, these advances establish a credible pathway toward commercial perovskite-silicon tandem modules and contribute to Switzerland and Europe's long-term renewable energy and energy-security goals.

Zusammenfassung

Dieser Zwischenbericht (Ende des ersten Projektjahres) fasst den Beitrag des Centre d’Electronique et de Microtechnique (CSEM) zum HyPer-Projekt („Hybrid Approach for Perovskite-Silicon Tandem Solar Cells“) zusammen.

Das HyPer-Projekt zielt darauf ab, hocheffiziente und stabile 2-polige Perowskit-/Silizium-Tandemsilizium-solarzellen zu industrialisieren, indem skalierbare Abscheideverfahren für großflächige Bauelemente entwickelt werden. Das übergeordnete Ziel besteht darin, den Technologie-reifegrad von TRL 4 auf TRL 6 zu erhöhen, indem ein Wirkungsgrad der Leistungsumwandlung von >30 % auf Silizium-Heterojunction-Wafern (SHJ) im M10-Format (>250 cm² aktive Fläche) mit industriell relevanten Verfahren demonstriert wird.

Der Schwerpunkt des Projekts liegt auf der Anpassung des hybriden Zweistufen-Perowskit-abscheideverfahrens - Verdampfung eines anorganischen Gerüstes gefolgt von der Applikation eines Organohalid-Precursors - an Prozesse, die mit großen Wafern und hohem Durchsatz kompatibel sind. Drei skalierbare Zweitschritt-Verfahren (Inkjet-Druck, Slot-Die-Beschichtung und Close-Space-Sublimation) werden miteinander verglichen, um eine gleichmäßige, hochwertige Perowskitschicht auf texturierten Siliziumsubstraten sicherzustellen. Die Erreichung dieser Ziele wird helfen, zentrale Engpässe bei der Skalierung zu überwinden und über kleinflächige, spin-beschichtete Bauelemente hinauszugehen, die derzeit die Rekordwirkungsgrade dominieren. Ein zweites zentrales Ziel ist die Verbesserung der Betriebsstabilität von Perowskit-Silizium-Tandems. HyPer strebt <5 % relative Degradation nach 3000 Stunden Feuchte-Wärme-Belastung (85 °C / 85 % r. F.), 600 Temperaturzyklen (−40 bis 85 °C) und >2000 Stunden Lichtbelastung an und zielt letztlich auf <1 % absolute jährliche Degradation unter Außenbedingungen in Mitteleuropa ab. Dies soll durch die Entwicklung stabilerer Formamidinium (FA)-basierter Perowskitformulierungen, die Unterdrückung von Defektmigration und Phasensegregation, die Implementierung verbesserter Transportschichten (einschließlich räumlicher ALD-SnO_2-Pufferschichten) sowie durch eine robuste Glas-Glas-Kapselung erreicht werden. Diese Material-, Interface- und Verkapselungs-innovationen erhöhen die Zuverlässigkeit und belegen die Praxistauglichkeit der Technologie. Das Projekt steht in engem Einklang mit dem CETPartnership-Call zu fortgeschrittenen erneuerbaren Energietechnologien und adressiert Effizienz, Kostenreduktion und technologische Souveränität Europas. Durch die Ermöglichung skalierbarer, leistungsstarker Tandemfertigung unterstützt HyPer direkt den Ausbau kostengünstiger, sauberer Elektrizität und verringert die Abhängigkeit von nicht-europäischen PV-Lieferketten. Das Konsortium setzt zudem auf ausgewogen zusammengesetzte Forschungsteams und verfolgt einen Open-Science-Ansatz mit rascher Ergebnisverbreitung, Open-Access-Publikationen und öffentlicher Bereitstellung von Stabilitätsdaten aus Labor- und Außentests. Zusammengenommen schaffen diese Fortschritte einen glaubwürdigen Pfad hin zu kommerziellen Perowskit/Silizium-Tandemmodulen und tragen zu den langfristigen Zielen der Schweiz und Europas in den Bereichen erneuerbare Energie und Energiesicherheit bei.

Résumé

Ce rapport intermédiaire (fin de la première année) résume la contribution du Centre d'Electronique et de Microtechnique (CSEM) au projet HyPer (« Hybrid Approach for Perovskite/Silicon Tandem Solar Cells »). Le projet HyPer vise à industrialiser des cellules solaires tandem pérovskite-silicium à 2 terminaux, à haut rendement et avec une meilleure stabilité, en développant des procédés de dépôt pour des cellule solaire tandem sur grande surface.

L'objectif principal est de faire passer le niveau de maturité technologique (Technology Readiness Level) de TRL 4 à TRL 6 en démontrant une efficacité supérieure à 30 % sur des cellules solaires de silicium à hétérojonction (SHJ) au format M10 (>250 cm² de surface active) en utilisant des méthodes pertinentes au niveau industriel. Le projet se concentre sur l'adaptation de la voie hybride de dépôt de la pérovskite en deux étapes - évaporation d'une couche inorganique suivie de l'application d'un précurseur organohalogéné - à des procédés compatibles avec des cellules solaires industrielles et un volume de production élevé. Trois méthodes de déposition pour cette seconde étape (impression jet d'encre, slot-die et sublimation en espace clos) seront comparées afin de garantir des couches de pérovskite homogènes et de haute qualité sur des substrats de silicium texturés. L'atteinte de ces objectifs permettra de lever des verrous majeurs liés à l'industrialisation de cette technologie et de d'obtenir des rendements énergétiques comparable aux cellules solaires de petites taille déposés par spin-coating qui dominent actuellement les records d'efficacité.

Un deuxième objectif central est d'améliorer la stabilité opérationnelle des tandems pérovskite/silicium. HyPer vise une dégradation relative inférieure à 5 % après 3000 h d'essais en chaleur humide (85 °C / 85 % HR), 600 cycles thermiques (−40 à 85 °C) et plus de 2000 h de vieillissement sous illumination, avec pour ambition finale une dégradation absolue annuelle inférieure à 1 % en conditions extérieures en Europe centrale. Cet objectif sera atteint grâce au développement de formulations de pérovskite à base de Formamidinium (FA) plus stables, à la suppression de la migration des défauts et de la ségrégation de phase, à la mise en œuvre de couches de transport améliorées (y compris des couches barrière de SnO_2 déposées par ALD spatial) et l'encapsulation verre-verre robuste. Ces innovations au niveau des matériaux, des interfaces et de l'encapsulation renforceront la fiabilité et démontreront la viabilité de la technologie pour des applications réelles. Le projet est fortement aligné sur les objectifs du CETPartnership concernant les technologies avancées d'énergie renouvelable, en répondant aux enjeux d'efficacité, de réduction des coûts et de souveraineté technologique pour l'Europe. En rendant possible une fabrication de tandems performants à grande échelle, HyPer soutient directement le déploiement d'une électricité propre à faible coût et réduit la dépendance vis-à-vis des chaînes d'approvisionnement photovoltaïques non européennes. Le consortium intègre en outre des équipes de recherche équilibrées du point de vue du genre et adopte une approche de science ouverte, avec une diffusion rapide des résultats, des publications en libre accès et la mise à disposition publique de données de stabilité en laboratoire et en extérieur. Ensemble, ces avancées établissent une trajectoire crédible vers des modules tandem pérovskite/silicium commerciaux et contribuent aux objectifs à long terme de la Suisse et de l'Europe en matière d'énergies renouvelables et de sécurité énergétique.

Contents

List of abbreviations

ALD	Atomic Layer Deposition
CETP	Clean Energy Transition Partnership
CSEM	Centre Suisse d'Electronique et de Microtechnique
CSS	Close-Space Sublimation
CTM	Cell-to-Module
Cz	Czochralski (silicon wafer growth method)
DH	Damp Heat
DLIT	Dark Lock-In Thermography
DPI	Drops Per Inch
EDX	Energy-Dispersive X-ray Spectroscopy
EL	Electroluminescence
EQE	External Quantum Efficiency
FA	Formamidinium
FF	Fill Factor
F-ISE	Fraunhofer Institute for Solar Energy Systems
Fz	Float-Zone (silicon wafer growth method)
HTL	Hole Transport Layer
ISOS	International Summit on Organic Solar Cells Stability (test protocols)
ITO	Indium Tin Oxide
IV	Current-Voltage
J-V	Current Density-Voltage
KIT	Karlsruhe Institute of Technology
MB	Meyer Burger
MPP / MPPT	Maximum Power Point / Maximum Power Point Tracking
NiOx	Nickel Oxide
PCE	Power Conversion Efficiency
PL	Photoluminescence
PV	Photovoltaic
QCM	Quartz Crystal Microbalance
RJ	Recombination Junction
SAM	Self-Assembled Monolayer
SFOE	Swiss Federal Office of Energy
SHJ	Silicon Heterojunction
SnO_2	Tin Oxide
TCO	Transparent Conductive Oxide
TRL	Technology Readiness Level
UVEG	University of Valencia
WP	Work Package

1 Introduction

1.1 Context and motivation

The HyPer project emerges from the need to overcome the efficiency limitations of conventional silicon photovoltaics. While silicon solar cells approach their theoretical efficiency limit of 29.4%, perovskite-silicon tandem architectures offer a path toward substantially higher power conversion efficiencies (>30%) thanks to the complementary optical properties of perovskites.

However, current record tandem devices are fabricated on small areas using non-scalable methods such as spin coating, creating a major bottleneck for industrial adoption. Additionally, perovskite materials face key stability challenges: sensitivity to moisture, heat, ion migration, and phase segregation all threaten long-term reliability under real-world operating conditions.

The motivation for HyPer is therefore twofold:

- Scaling up tandem solar cell technology to industrial wafer formats (M10, >250 cm²) using deposition techniques suitable for high-throughput manufacturing.
- Improving material and device stability to meet industry-relevant reliability standards and to enable outdoor deployment with annual degradation below 1%abs/year in Central Europe.

By addressing these challenges, HyPer supports Switzerland and Europe's strategic goal of strengthening its PV manufacturing ecosystem and reducing dependency on non-European supply chains, while enabling cleaner and more efficient renewable electricity generation.

1.2 Project objectives

The HyPer project aims to bring industrial monolithic 2-terminal perovskite-silicon tandem cells from TRL 4 to TRL 6 through the development of scalable, high-performance, and stable deposition processes. The core objectives are:

1. Develop scalable perovskite deposition technologies

    HyPer will adapt the hybrid two-step perovskite formation route, evaporation of an inorganic scaffold followed by deposition of an organohalide precursor, to industrial conditions. Three large-area compatible deposition methods (inkjet printing, slot-die coating, close-space sublimation) will be benchmarked to produce uniform perovskite layers on textured M10 wafers.

2. Demonstrate high-efficiency, large-area tandem devices

    The project targets a power conversion efficiency >30% on >250 cm² active area SHJ bottom cells processed using industry-ready methods, exceeding current state-of-the-art values.

3. Achieve industry-relevant stability and reliability

    HyPer aims to meet stringent accelerated aging criteria, including:
    <5% relative degradation after 3000 h damp-heat (85 °C/85% RH).
    <5% relative degradation after 600 thermal cycles (−40 to 85 °C).
    Robust light-soaking resistance (>2000 h at ≥65 °C).
    A long-term outdoor degradation rate below 1%abs/year is targeted.

4. Strengthen the Switzerland and Europe's PV value chain

By enabling scalable tandem cell manufacturing, HyPer supports European technological sovereignty, reduces reliance on external supply chains, and accelerates deployment of low-cost renewable energy technologies in alignment with CETPartnership goals.

2 Approach, method, results and discussion

The HyPer project is organized into seven work packages designed to raise perovskite/silicon tandem solar cell technology from TRL 4 to TRL 6 through scalable deposition processes, enhanced device stability, and industrial integration.

WP1 provides the administrative foundation of the project through coordinated management, dissemination, exploitation planning, and gender/risk monitoring.

WP2 ensures alignment with the CETPartnership through structured reporting and participation in the Knowledge Community.

Technology development begins with **WP3**, which focuses on scaling the inorganic scaffold deposition to pilot-line linear evaporation systems, ensuring compatibility with textured M10 SHJ wafers. In parallel, **WP4** develops industrially scalable second-step perovskite deposition techniques (inkjet printing, slot-die coating, and close-space sublimation) to synthesize uniform, high-quality perovskite films on large areas.

In **WP5**, these layers are integrated onto silicon heterojunction bottom cells to construct full monolithic tandem devices with active areas >250 cm², targeting efficiencies above 30%. **WP6** supplies advanced characterization tools to identify optical and electrical losses, map degradation pathways, and provide iterative feedback to optimize material and process development.

Finally, **WP7** addresses module integration and reliability, including encapsulation, interconnection, accelerated aging (damp heat, thermal cycling, light soaking), and outdoor field testing. The goal is to demonstrate modules with <1% absolute annual degradation, fulfilling industrial lifetime requirements.

Together, these WPs form a coherent pathway from fundamental process innovation to industrial validation, positioning the HyPer project as a major step toward commercial perovskite-silicon tandem solar module production in Europe.

In more detail, the activities are distributed as follows:

WP1 - Management, Dissemination & Exploitation
- Coordinate consortium activities and communication
- Administrative & financial management
- Data management plan, gender & risk monitoring
- Dissemination (website, publications, events)
- Exploitation strategy & partner IP management

WP2 - Reporting & CETP Knowledge Community
- Produce mandatory CETP reports
- Exchange results with CETPartnership Knowledge Community
- Participate in evaluation panels and working groups
- Ensure compliance with CETP open-science requirements

WP3 - Deposition of Inorganic Scaffold
- Develop scalable vacuum evaporation of PbX_2/CsX scaffolds
- Transfer from point-source to linear-source pilot-line equipment
- Optimize texture conformality on M10 SHJ wafers
- Develop scalable HTL deposition (evaporated SAM-based layers)
- Ensure compatibility with downstream organic deposition methods

WP4 - Deposition of Organic Components
- Develop organohalide precursor deposition via three pathways:
  - Inkjet printing
  - Slot-die coating
  - Close-space sublimation (CSS)
- Optimize ink formulation & wet-film control
- Achieve uniform crystallization on textured Si
- Benchmark the 3 approaches for industrial scalability

WP5 - SHJ Bottom Cells & Large-Area Tandems

- Provide industrial M10 silicon heterojunction bottom cells (textured)
- Develop recombination junction (RJ) stack
- Integrate WP3+WP4 perovskite layers to complete tandem devices
- Demonstrate >30% efficiency on >250 cm^2 active area
- Prepare routes for industrial transfer to manufacturing

WP6 - Characterization & Diagnostics

- Standard JV, EQE, iVoc, Suns-Voc characterizations
- Identify optical/electrical bottlenecks
- Advanced diagnostics (e.g., PL, EBIC, ToF-SIMS)
- Map degradation pathways and guide material/process improvements
- Provide feedback loops to WP3-WP5

WP7 - Module Integration & Reliability

- Develop glass/glass encapsulation with UV-blocking interlayers
- Cell-to-module (CTM) interconnection methods
- Validate stability under:
    - Damp-heat (3000 h, 85°C/85% RH)
    - Thermal cycling (600 cycles, −40→85 °C)
    - Light soaking (>2000 h at ≥65°C)
- Outdoor testing in Central Europe conditions
- Demonstrate <1% absolute annual degradation

This intermediate scientific report outlines the progress made by CSEM in the Hyper project, focusing primarily on work packages 3 to 7. Work packages 1 and 2 are not covered in the results section.

WP3: Deposition of the Inorganic scaffold

The goal of this work package is to focus on the vacuum deposition of the inorganic template on textured Silicon substrates. CSEM is responsible for identifying one promising scaffold for textured tandem processing (MS 3.2 [M15]). In addition, CSEM should provide guidelines to control the thermal evaporation of the lead template using Quartz Crystal Microbalance (QCM) (D-3.2 [M18]). The inorganic scaffolds produced in this work package will be used in WP4 by the different partners.

Objectives

This WP focuses on the vacuum deposition of the inorganic PbX_2/CsX scaffolds (where X = I, Br or Cl) on textured Si substrates. These scaffolds will be converted into a perovskite phase in WP4.

More specifically, the main objectives of WP3 are as follows:

O3.1: To identify an industrially applicable process to deposit the hole transport layer (HTL) on industrial textured Si bottom cells at high quality and rate. The HTL should ensure good adhesion and optimal growth of the PbX_2/CsX scaffold deposited on top (T3.1).

O3.2: Using R&D equipment, develop process recipes for the PbX_2/CsX scaffold that i) enable a precise control over composition and thickness, ii) yield high homogeneity across the substrate size, and iii) excellent batch-to-batch reproducibility (T3.2).

O3.3: Based on insights retrieved above, develop process recipes enabling the deposition at high throughput of PbX_2/CsX scaffolds reaching the targeted properties (composition, thickness, homogeneity) using the linear evaporation system of F-ISE (T3.3).

Milestones and Deliverables

MS-3.1 Identification of the HTL and Si textures to be used throughout the project (KIT) [M9] (submitted)

MS-3.2 Identification of at least one promising scaffold for textured tandem processing (CSEM) [M15] (on-track, results presented in this report).

D-3.1 Benchmark of HTL materials in terms of properties (thickness, microstructure, chemistry, adhesion of scaffold, tandem performance) and industrial potential (deposition method) (KIT) [M9] (submitted).

D-3.2 Guidelines to precisely control the thermal evaporation of scaffolds (composition, thickness) using QCMs (CSEM) [M18] (on-track, results presented in this report).

D-3.3 Report detailing high-throughput scaffold processing conditions yielding best textured tandem performance, homogeneity and reproducibility on textured M10 wafers (F-ISE) [M27] (not started).

MS-3.2 Identification of at least one promising scaffold for textured tandem processing (CSEM) [M15]

For milestone **MS-3.2**, CSEM is responsible for identifying one promising scaffold for textured tandem processing. CSEM employs point sources for lead iodide and cesium bromide precursors. These precursors were selected because they have already demonstrated strong potential for achieving higher-efficiency perovskite/silicon tandems using textured bottom cells [1]. The introduction of a cesium source helps prevent the formation of undesirable non-perovskite phases [2].

At CSEM, the point sources for lead iodide (PbI_2) and cesium bromide (CsBr) are positioned on opposite sides of the evaporation chamber (Figure 1a), which could lead to deposition inhomogeneities. To evaluate this concern, we deposited the scaffold on several samples placed along the diagonal of the rotating substrate holder during evaporation.

The inorganic scaffold thickness was measured by profilometry, revealing a variation of approximately 7% between the center and the edge of the substrate holder. This difference is likely due to the chamber design and could be mitigated by using linear sources for scaffold deposition.

Chemical homogeneity was assessed by energy-dispersive X-ray spectroscopy (EDX), comparing atomic ratios (Pb vs. I and Cs vs. Br) as a function of substrate position. No significant differences were observed, indicating that source positioning does not introduce a spatial gradient across the M10 wafer size (182 × 182 mm²).

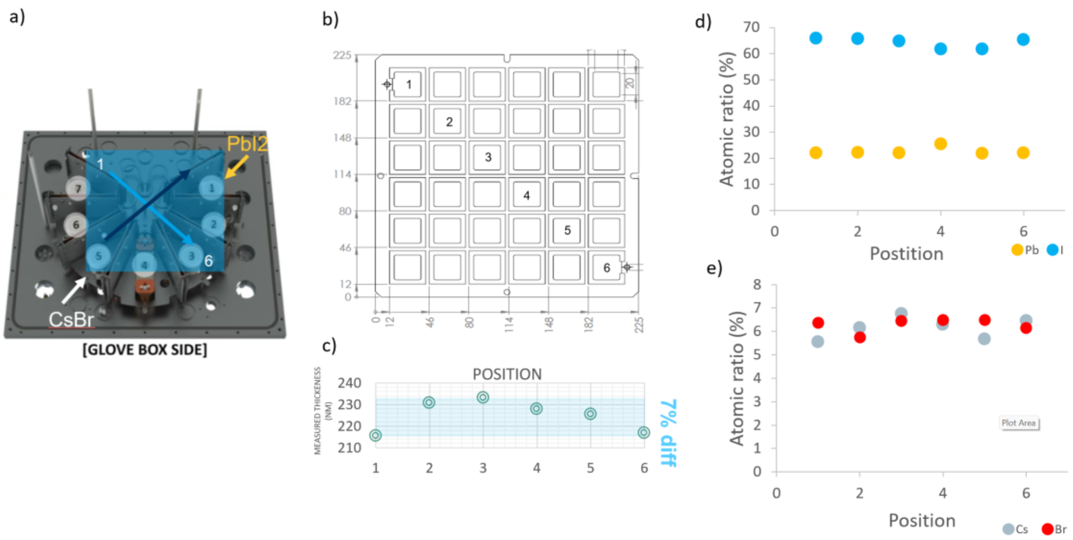


Figure 1 (a) Position of the CsBr and PbI_2 sources within the deposition chamber. The blue rectangle indicates the substrate holder. (b) Substrate holder with six samples arranged along the diagonal. (c) Thickness of the lead-based scaffold measured along the diagonal by profilometry (target thickness: 220 nm). (d) Atomic ratio of lead and iodine measured along the diagonal by EDX. (e) Atomic ratio of cesium and bromine measured along the diagonal by EDX.

One potential concern is that the amount of material (PbI_2) loaded into the crucible could affect the evaporation ballistic cone, potentially introducing spatial variations in thickness. To investigate this, two successive depositions were performed: the first with the lead iodide crucible filled to more than three-quarters of its height, and the second with the crucible filled to one-quarter of its height (Figure 2). The thickness of the inorganic template was measured by profilometry in both cases. The difference between the center and the edge of the substrate holder was less than 7%, confirming that the amount of lead iodide in the crucible does not create a thickness gradient and therefore does not cause batch-to-batch variations.

A major concern for industrializing the hybrid method is the potential degradation of inorganic precursors after multiple evaporation cycles. In Figure 3, we analysed the composition of both PbI_2 and CsBr precursors before and after repeated scaffold depositions (five evaporations for lead iodide and ten for CsBr) using EDX. In both cases, the EDX spectra remained similar, indicating no chemical degradation of the precursors. Atomic ratios differed by only a few percent between pristine and aged materials, suggesting that both precursors maintain their chemical integrity over multiple evaporations. This is an important information in view of future scaling efforts with a linear source.

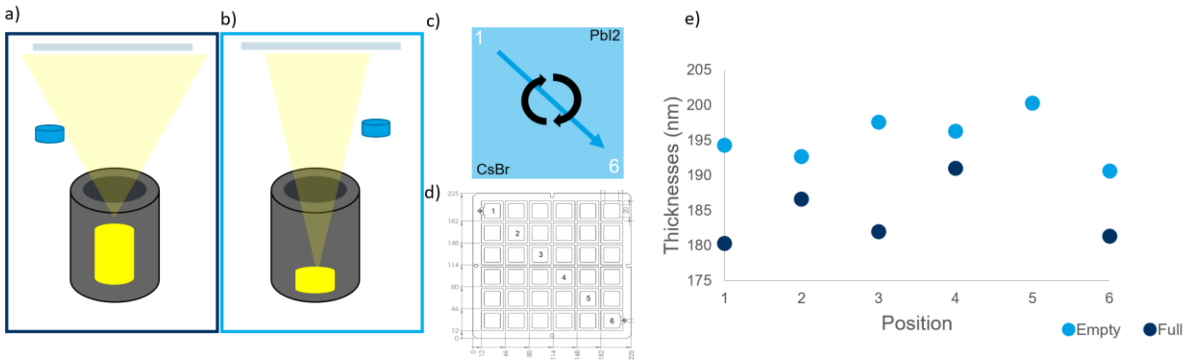
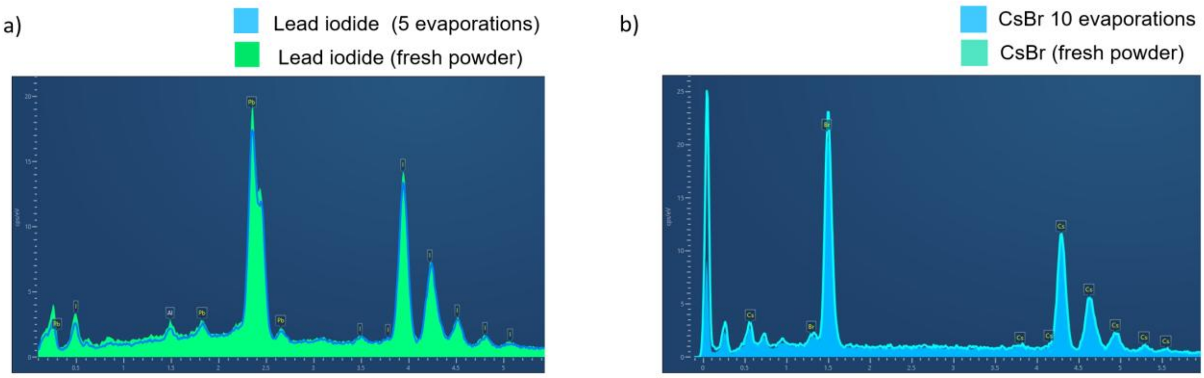


Figure 2 Schematic of the lead iodide source with the crucible filled (a) and nearly empty (b). (c) Schematic of the substrate holder showing the positions of the CsBr and PbI_2 sources. (d) Substrate holder with sample positions indicated. (e) Thickness of the scaffold measured along the diagonal by profilometry (target thickness: 200 nm) for both full and nearly empty crucible conditions.



	I (%)	Pb (%)
Fresh	73.71	26.29
Evaporated	73.18	26.82

	Cs (%)	Br (%)
Fresh	61.07	38.93
Evaporated	63.78	36.44

Figure 3 (a) EDX spectra of fresh PbI_2 powder and PbI_2 powder left in the crucible after 5 evaporations scaffolds evaporation, (b) EDX spectra of fresh CsBr powder and CsBr powder left in the crucible after 10 evaporations scaffolds evaporation.

Most reported hybrid fabrication processes use relatively low evaporation rates for the lead-based template, typically 0.5-1 Å/s for the inorganic scaffold. This results in long processing times of 40-100 minutes per evaporation. In contrast, we evaluated the possibility of evaporating the inorganic scaffold at 10 Å/s, reducing the processing time by a factor of ten (from about 100 minutes to only 10 minutes).

Figure 4 shows that increasing the evaporation rate (from 1 Å/s to 10 Å/s) does not significantly affect the morphology of the inorganic scaffold, whether deposited on textured silicon or flat silicon substrates. Achieving similar morphologies at high rates is a key requirement for enabling high-throughput tandem fabrication in industrial settings. The next steps will evaluate whether the performance of perovskite/silicon tandem solar cells is influenced by the evaporation rate of the inorganic template.

In addition, we investigated sequential evaporation of CsBr and PbI_2. Co-evaporation of these precursors is more challenging to control industrially because precise rate control is required to maintain the desired composition. Furthermore, co-evaporation typically leads to higher material waste due to deposition rate stabilization requirements. Sequential evaporation may therefore offer advantages over coevaporated recipes. To explore this, different CsBr seed layer thicknesses (0-100 nm) were deposited prior to the PbI_2 layer (Figure 5). The resulting inorganic scaffold morphology appears more porous compared to that obtained with co-evaporation (Figure 4a).

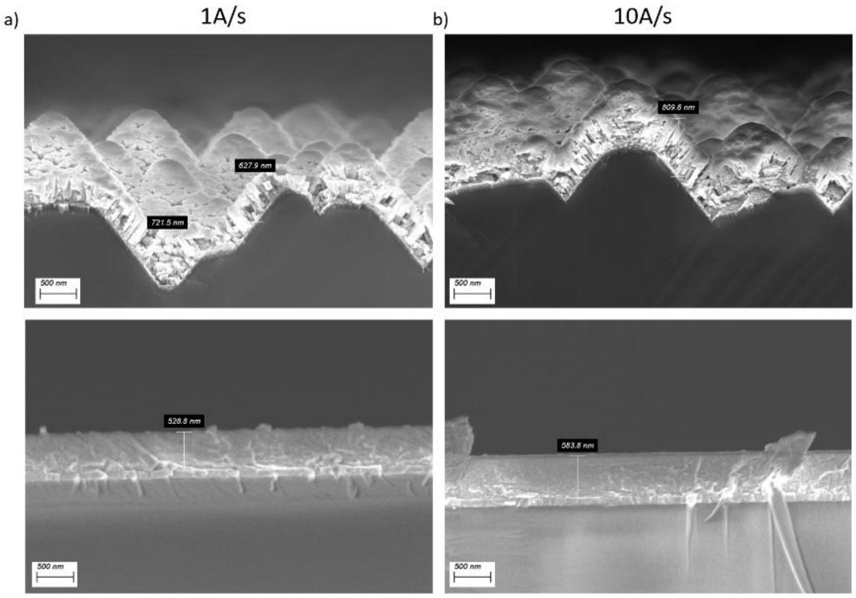


Figure 4 (a) SEM images of the inorganic scaffold deposited at 1 Å/s, on textured silicon (top) on flat silicon surface (bottom). (b) SEM images of the inorganic scaffold deposited at 10 Å/s, on textured silicon (top) on flat silicon surface (bottom).

Conversion to the perovskite layer using ethanol and iso-butanol resulted in conformal perovskite growth on the silicon pyramids. Notably, the absence of CsBr (0 nm) led to the formation of pinholes in the perovskite layer for both solvent systems. This is attributed to the tendency of hexagonal phases to form when CsBr, a smaller cation than formamidinium, is missing. In contrast, CsBr seed layers of 25-100 nm enabled uniform, conformal perovskite coating. The next steps will assess whether perovskite fabricated by sequential evaporation delivers opto-electronic properties comparable to those obtained with co-evaporation recipes.

Finally, inorganic templates fabricated by sequential evaporation at higher rates (1 Å/s for CsBr and 10 Å/s for PbI_2) were produced (Figure 6). This configuration appears most suitable for industrialization with linear sources, as precise rate control becomes less critical, material usage is optimized, and source cross-contamination is minimized. The morphology of the lead-based template is similar to that obtained at lower evaporation rates (1 Å/s for the scaffold, Figure 5). After conversion using an organohalide solution dissolved in ethanol, a conformal perovskite layer was achieved on the silicon texture. However, some pinholes were observed in the sequentially evaporated scaffold (highlighted by green circles), likely originating from increased porosity of the inorganic template. This issue could be mitigated by optimizing the solvent system and improving the conversion process.

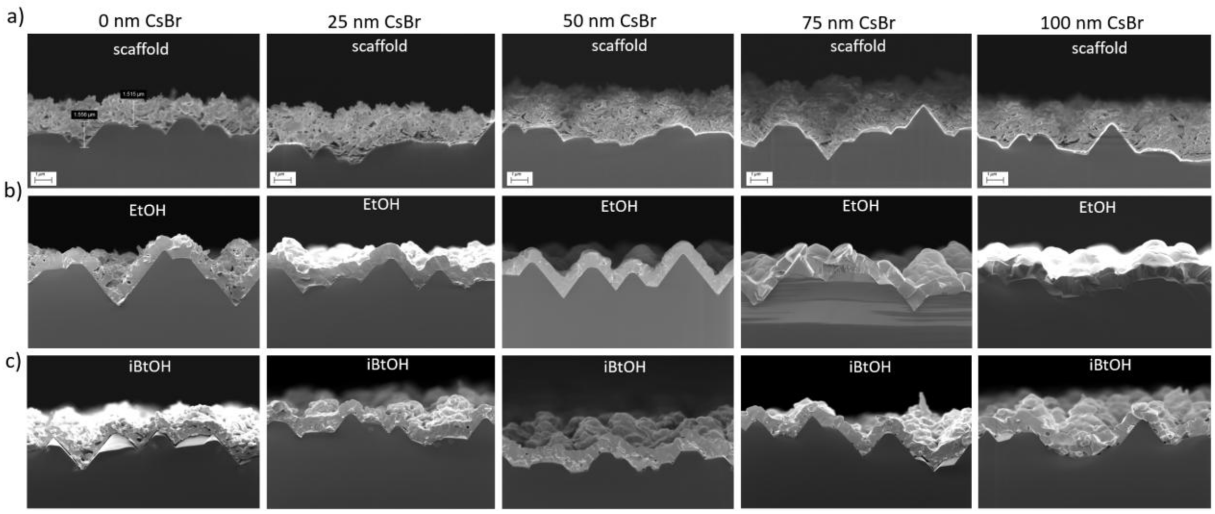


Figure 5 (a) SEM images of the inorganic scaffold deposited sequentially (CsBr and PbI_2) on textured silicon with different CsBr seed layer thicknesses. (b) corresponding SEM images of perovskite layers converted by an organohalide solution dissolved in ethanol. (c) corresponding SEM images of perovskite layers converted by an organohalide solution dissolved in iso-butanol.

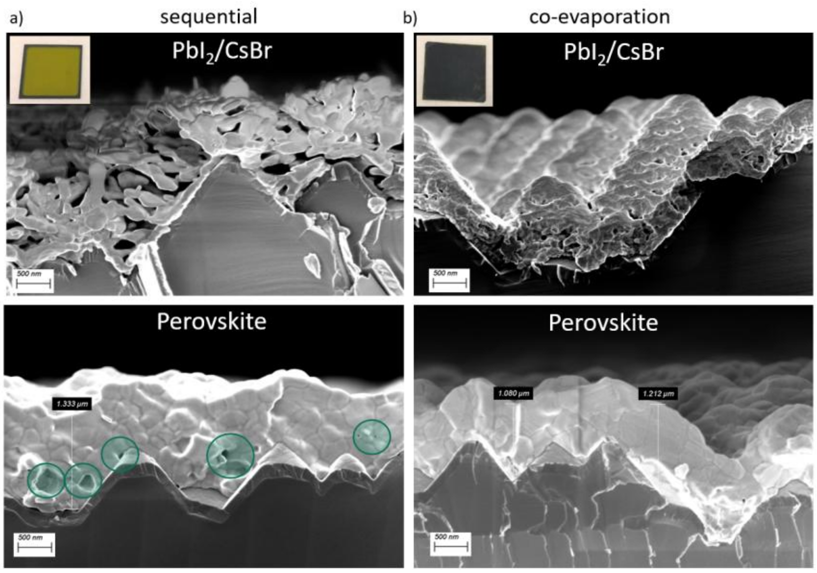


Figure 6 (a) SEM images of the inorganic scaffold deposited sequentially (CsBr and PbI_2) on textured silicon at 10 Å/s (top) and the corresponding conversion to the perovskite (bottom). (b) SEM images of the inorganic scaffold deposited by co-evaporation (CsBr and PbI_2) on textured silicon at 10 Å/s (top) and the corresponding conversion to the perovskite (bottom).

WP3: conclusion and next steps

In this intermediate report CSEM showed that using a R&D deposition system, the deposition of the inorganics scaffold composed of 10% cesium bromine and 90% lead iodide led to homogeneous coating (in terms of thicknesses and stoichiometry) over M10 wafers sizes (>180 x 180 mm^2). In addition, the quality of the precursor was assessed by EDX after 5 evaporations without any degradation of the precursor observed. In addition, pathways for having a more industrially relevant inorganics scaffold are investigated, mainly increasing the deposition rate of the scaffold to 10 Å/s (a 10-fold increase compared to most of the scaffold fabrication reported) led to similar scaffold morphologies and perovskite conversion. Finally, sequential evaporation, where a seed layer of CsBr is first evaporated and then PbI_2 was evaporated on top this seed layer was investigated. The morphology of the template was significantly more porous when using sequential evaporation.

CSEM will commission early 2026 a new evaporation system that should lead to shorter process durations, as well as even better control over the film properties.

WP4: Deposition of the organic components

The goal of this work package is to develop scalable deposition techniques for the organic precursors over a large area (100 cm^2). CSEM is responsible for the deliverables D-4.3 (Month 30). Demonstration of multiple 1-cm^2 tandems co-processed on large area Si wafers (100 cm^2 or above) reaching an average PCE>30% and extended stability in ISOS L2 test conditions (CSEM) [M30]. CSEM is mainly investigating the deposition of the organic precursors by inkjet printing.

Objectives

This WP focuses on developing scalable fabrication processes for the organic precursors and the subsequent formation of the perovskite thin film during post treatment. Three processes are in focus, namely inkjet printing (KIT), slot-die coating (TNO) and close-space sublimation (UVEG). These processes will be developed with the target to optimize the perovskite thin film quality, the homogeneity, the process rate and the process yield.

More specifically, the main objectives of WP4 are as follows:

O4.1: Define process window for solution-based deposition techniques (i.e. inkjet printing (KIT), slot-die coating (TNO), and close-space sublimation (UVEG)) to deposit the organic components onto the inorganic scaffold from WP3 to form a high-quality perovskite layer (T4.1, T4.2 and T4.3). This includes optimal process conditions of the respective post-process for each method (e.g., solvent extraction processes, annealing steps, etc.)

O4.2: Optimize the perovskite thin film formation for processing on textured Si bottom solar cells including method-specific deposition parameters, solvent extraction, annealing steps (type, duration, temperature) or additives (T4.1, T4.2 and T4.3).

O4.3: Demonstrate homogenous perovskite films on an area of at least 100 cm^2 with a thickness variation of less than 5% and an average implied open circuit voltage (iV_{oc}) potential of >1.2 V (T4.1, T4.2 and T4.3).

O4.4: Fabricate 2T tandem devices with an average PCE of >30% (e.g. 1 cm^2 devices co-processed on substrates 100 cm^2 or larger) with extended stability during light soaking in 1-sun conditions at >65 °C (T4.4).

Milestones and Deliverables

MS-4.1: Identification of optimal process parameters for all three methods to deposit the organic precursor materials (KIT) [M15] (started).

MS-4.2 Selection of the organic precursors deposition method to scale-up in WP5 (TNO) [M24] (started).

D-4.1 Report comparing the industrial compatibility (performance, throughput, stability) of the three deposition methods used to deposit the organic components of the perovskite (TNO) [M24] (on-track)

D-4.2 Perovskite films processed on industrial wafers with an area of 100 cm^2 with an iV_{oc} of >1.2 V and a thickness variation of <10%rel (KIT) [M24] (started).

D-4.3 Demonstration of multiple 1-cm^2 tandems co-processed on large area Si wafers (100 cm^2 or above) reaching an average PCE>30% and extended stability in ISOS L2 test conditions (CSEM) [M30] (started).

Preliminary tests were conducted using inkjet printing as the second step of the hybrid method to deposit the organohalide layer. Inkjet printing was selected at CSEM as a promising technique for scaling up this step, given its strong industrial track record as a deposition method.

A proof-of-concept perovskite/silicon tandem device with an efficiency of 27.5% on 1 cm² was achieved using silicon bottom cells polished on the front side (Figure 7). This demonstrates the potential of the hybrid approach, combining a thermally evaporated inorganic scaffold with an inkjet-printed organohalide layer deposited in air (relative humidity: 50%).

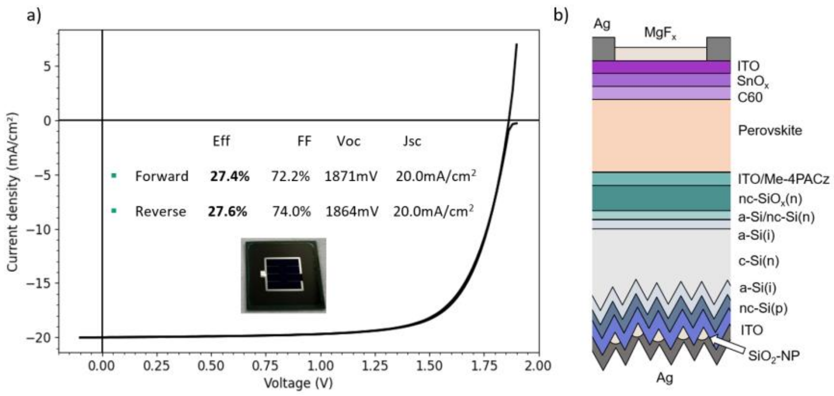


Figure 7 (a) Current-density/voltage characterization of 1 cm^2 perovskite/silicon tandem with a flat front surface produced with the hybrid method and with the organohalide deposited by inkjet printing and evaporated silver. (b) schematic of perovskite/silicon tandem solar cell.

Next, a 100 cm² single-junction perovskite solar cell was deposited on a polished M10 crystalline silicon wafer (>180 × 180 mm²) using the same PVD-inkjet printing process (Figure 8). In this demonstration, the hole transport layer was deposited by evaporation, a scalable technique suitable for industrial implementation. A stabilized maximum power point (MPP) efficiency of 8.2% was achieved after 100 seconds of tracking at the proof-of-concept stage. Dark lock-in thermography (DLIT, Figure 8c) revealed substantial local shunts (“hot spots”) that reduce overall device performance. Further investigation is needed to understand and mitigate these defects to improve cell efficiency. Nevertheless, this demonstration showcases the feasibility of using the hybrid PVD-inkjet printing method for manufacturing functional large-area perovskite/silicon tandem solar cells.

Initial tests were performed on textured bottom cells using the hybrid method, where the second organohalide deposition step was carried out by inkjet printing (Figure 9). The conversion of the inorganic scaffold strongly depends on the drop-per-inch (DPI) setting during inkjet printing. Full conversion, i.e., when PbI_2 is no longer observed at the bottom of the perovskite layer, was achieved when tuning DPI values (Figure 9c). Images of the printed textured tandem reveal drying marks of the organohalide solution at high DPI, suggesting that organohalide may accumulate at the surface of the perovskite. This issue could be mitigated by different approaches that are being investigated.

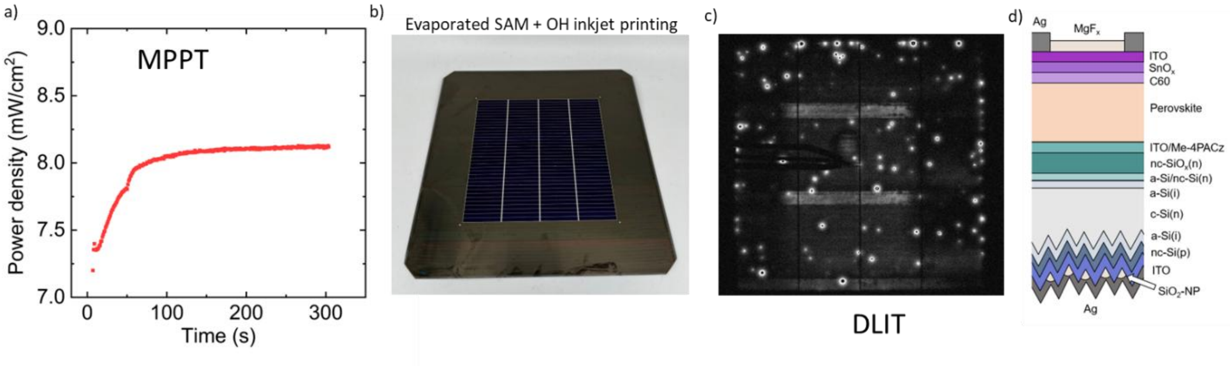


Figure 8 (a) Maximum power point tracking (MPPT) of 100 cm^2 perovskite/silicon tandem with a flat front surface produced with the hybrid method with the organohalide deposited by inkjet printing. (b) picture of the tandem device. (c) Dark lock-in thermography (DLIT) of the 100 cm^2 perovskite/silicon tandem solar cell. (d) schematic of perovskite/silicon tandem solar cell.

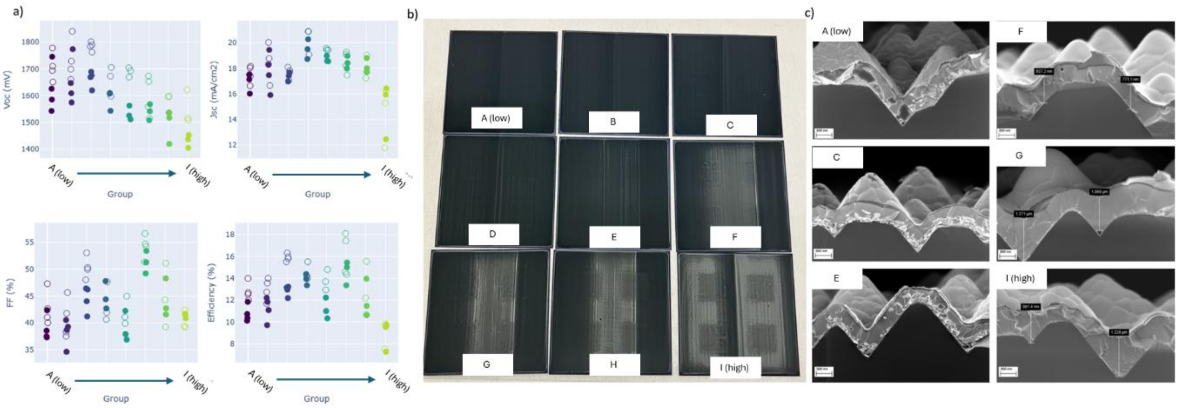


Figure 9 (a) *J-V* parameters of the 1 cm^2 perovskite/silicon tandem produced by thermal evaporation (inorganic scaffold) and inkjet printing (organohalide) with different drop per inch (from low - A, to high - I). (b) corresponding picture of the tandem devices. (c) corresponding SEM images.

To assess the overall performance of the perovskite/silicon tandem solar cell, reference devices were fabricated using spin-coating for the organohalide deposition step (Figure 10). First, thermally evaporated silver was employed as the metallization on 1 cm² devices. A concentration screening in the organohalide solution was performed. Figure 11 shows SEM images of the perovskite top cell on textured silicon bottom cells. Residual inorganic template is visible at the bottom of the pyramid valleys for low concentrations, which correlates well with the *J-V* parameters observed in Figure 10a.

Additionally, perovskite/silicon tandem solar cells with screen-printed metallization were fabricated (Figure 10b). Developing screen-printed metallization is essential for large-scale production and is already an industry standard. However, the power conversion efficiency was lower compared to devices with evaporated metallization, primarily due to reduced fill factor (FF) and increased hysteresis. While the root cause of this difference is still under investigation, it was observed that screen printing introduces perovskite degradation beneath the metallization bus bars (Figure 10c). This degradation may lead to shunting and charge extraction issues. Addressing this challenge will be a key focus in the upcoming phases of the Hyper Project.

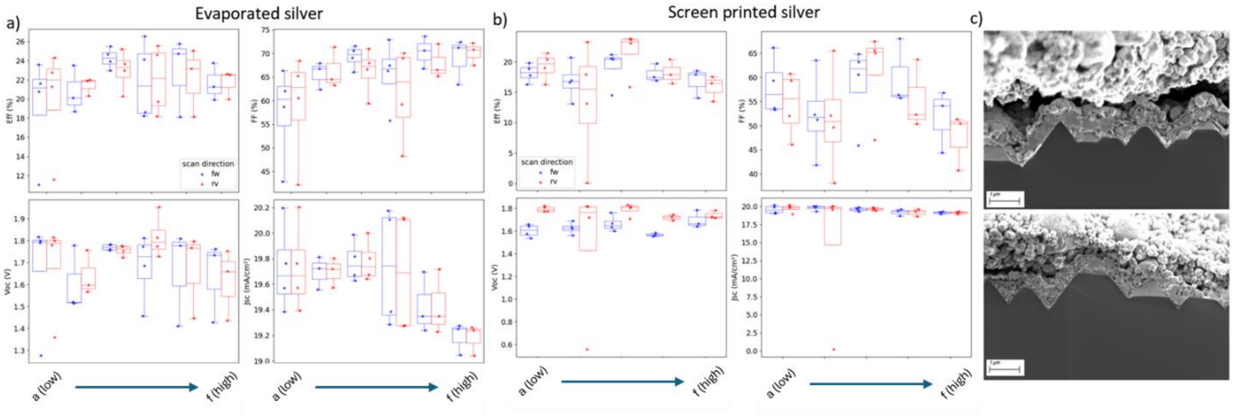


Figure 10 (a) *J-V* parameters of the 1 cm^2 perovskite/silicon tandem produced by thermal evaporation (inorganic scaffold) and spin-coating (organohalide) with different molarities (from a - low, to g - high) with an evaporated silver metallization grid). (b) *J-V* parameters of the 1 cm^2 perovskite/silicon tandem produced by thermal evaporation (inorganic scaffold) and spin-coating (organohalide of low to high molarity) with a screen-printing metallization grid. (c) SEM images of the perovskite below the screen-printed bus bar.

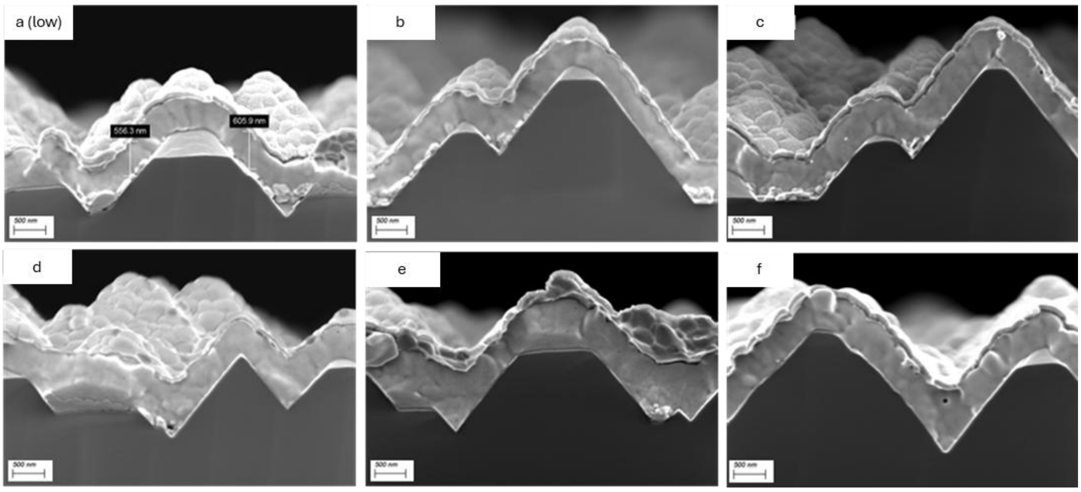


Figure 11 SEM images of the spin-coated perovskite top cell on textured silicon with different organohalide concentration.

WP4: conclusion and next steps

Preliminary results demonstrate the strong potential of the hybrid PVD-inkjet printing approach for scalable perovskite/silicon tandem solar cells, achieving up to 27.5% efficiency on 1 cm^2 devices. However, challenges remain in optimizing organohalide deposition, mitigating local shunts, and improving metallization reliability. Moving forward, efforts will focus on (1) enhancing the perovskite/silicon tandem efficiency toward 30% on 1 cm² cells, (2) refining inkjet printing parameters to ensure full conversion and uniformity on large-areas, and (3) investigating and resolving issues linked to screen-printed silver contacts that currently reduce device performance. These steps will be critical to achieving industrial-scale, high-efficiency tandem solar cells.

WP5: Silicon heterojunction bottom cells and large-area tandem solar cells developments

The goal of this work package is to develop large-area silicon bottom cells and to fabricate prototype tandem solar cells on full wafer size (approximately 250 cm²). CSEM is not responsible for any deliverables or milestones in this work package and has only limited allocated hours per month.

However, following the withdrawal of Meyer Burger from the project, CSEM can contribute to the development of several tasks within this work package. Importantly, CSEM is not affected by Meyer Burger's bankruptcy, as it maintains a stock of more than 200x M10 wafers and also has the capability to fabricate its own bottom cells.

Objectives

This work package deals with the development of large-area silicon bottom cells and the realization of the manufacturing processes of prototype tandem solar cell scaled to full wafer size (i.e. 250 cm²).

The main objectives of this work package are:

O5.1: Develop adapted industrial both-sides textured silicon heterojunction solar cells (SHJ), which will serve as the bottom cells in a monolithic, two-terminal tandem configuration (T5.1).

O5.2: Develop efficient recombination and tunnel junctions (RJ) to minimize optical and electrical losses at the interconnection between the top and bottom solar cells (T5.2).

O5.3: Detail the full process flow to produce large-area (>250 cm²) perovskite-silicon tandem solar cells, including pre-conditioning steps and cell shipments between partners (T5.3).

O5.4: Integrate the perovskite absorber developments from WP3-WP4 into large-area (>250 cm²) perovskite/silicon tandem solar cells (T5.4).

Milestones and Deliverables

MS-5.1 Decision on cell design (masks for TCOs, grid...), for small, medium and large cell sizes (Meyer Burger) [M6] (submitted).

MS-5.2 Final processing sequence for the top cell processing and the transport concept for large area cells (F-ISE) [M18] (on-track, still needs to be defined in M18).

MS-5.3 Decision of material stack and deposition methods for high efficiency (>30%), large-area tandem cells (250 cm^2) (F-ISE) [M24] (decision to be made at the end of the second year).

D-5.1 Realization of adapted industrial silicon heterojunction solar cell with optimized surface morphology (Meyer Burger) [M18] (with Meyer Burger out of the project, project partners will use standard bottom cell provided by Meyer Burger in year 1).

D-5.2 Realization of effective RJ allowing efficient carrier recombination, contacting to HTL and homogeneous and pinhole-free deposition of the overlying layers. (Meyer Burger) [M12] (Perovskite/silicon tandem with efficiencies above 27% reached by different partners on standard silicon heterojunction solar cell with ITO recombination junction).

D-5.3 Realization of large-area (250 cm^2) tandem cells with an efficiency of >30 % and passing the reliability criteria of WP7 (F-ISE) [M36] (not started).

The main contribution of CSEM to WP5 so far was to the assessment of Meyer Burger bottom cells. Here, silicon heterojunction solar cells (SHJ) fabricated by CSEM were used as a benchmark to Meyer Burger bottom cells. Figure 12 presents SHJ bottom cells received from Meyer Burger at different illumination (1 sun, 0.5 sun and 0.1 sun). Screen-printed metallization was carried out at CSEM.

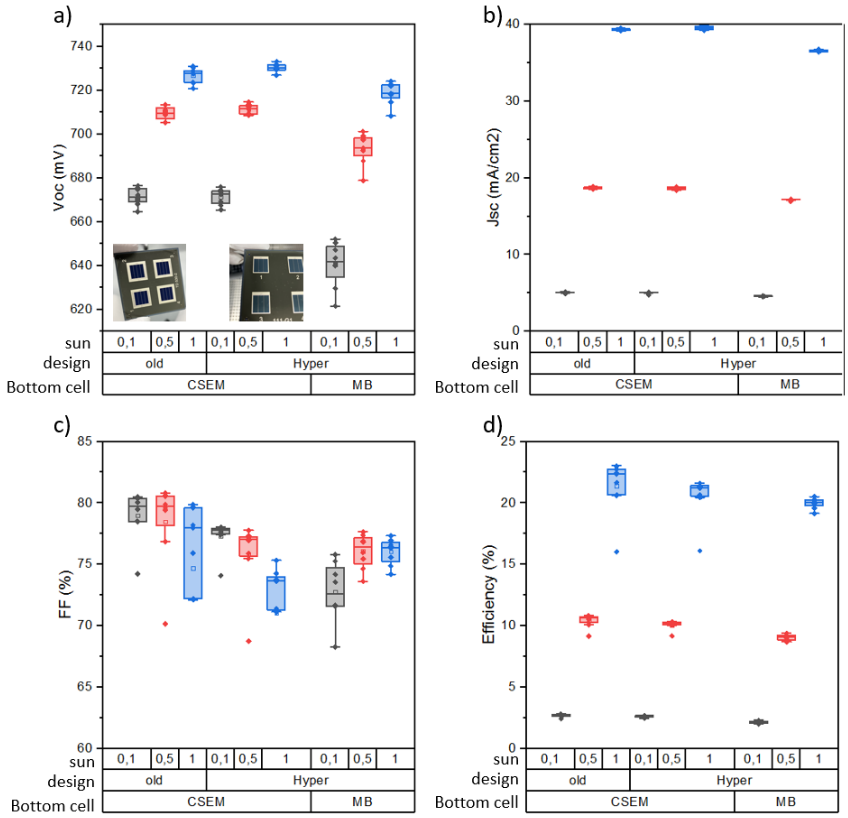


Figure 12 *J-V* parameters of the 1 cm^2 silicon single junction measured a different illumination. Comparison of Meyer Burger bottom cells (Cz wafer) and CSEM bottom cell (FZ wafer), featuring a bus bar all around the cell (old design) and a bus bar on one side of the cell (HyPer design).

Meyer Burger SHJ solar cells (based on Cz wafers) exhibit lower performance compared to CSEM reference cells (based on FZ wafers). The main differences arise from reduced open-circuit voltage (Voc) and fill factor (FF), particularly at half-sun illumination (0.5 sun), a condition most relevant for tandem configurations where the perovskite top cell absorbs approximately half of the incident light.

At low illumination (0.1 sun), the Meyer Burger bottom cells appear to have a lower shunt resistance, which likely explains the observed decrease in FF as illumination decreases.

Despite these differences, the efficiency gap is not considered critical for tandem fabrication. Meyer Burger bottom cells maintain a power conversion efficiency of 9-10% under halved illumination, which is suitable for tandem applications with a perovskite top cell. This performance level should still enable perovskite/silicon tandem solar cells with efficiencies exceeding 30%.

WP5: conclusion and next steps

In this work package, we assessed the performance of Meyer Burger bottoms cells to CSEM SHJ reference. We concluded that the use of Meyer Burger (Cz wafer) bottom cells might lead to lower perovskite/silicon tandem solar cell efficiencies in comparison to CSEM reference. Still, efficiencies above 28-30% are possible with the bottom cells provided by Meyer Burger. CSEM acquired a stock of 200 M10 silicon wafers prior to Meyer Burger filing for bankruptcy. This number of wafers is considered sufficient in order to complete the project (considering a 100 wafers per year consumption). In addition, CSEM has its own capability to fabricate tailored bottom cells for its needs. Risks regarding the accomplishment of the objective of this work package are high considering the withdrawal of Meyer Burger from the project. Objectives might be adjusted by the CETP committee. CSEM can provide its help in reaching the deliverables.

WP6: Characterization

The goal of this work package is to tackle the characterization of the tandem cells produced during the project. From fast IV-measurements to the development of imaging methods to assess the homogeneity and quality of the perovskite coating over large area. CSEM is mainly responsible for the deliverable D-6.1 Report on fast measurement routine (CSEM) [M13].

Objectives

This work package focuses on analyzing perovskite/silicon tandem solar cells to support WPs 3,4,5 and 7 with an emphasis on cell scalability and stability.

CSEM and F-ISE will work towards the following objectives:

O6.1: Establish a common fast current-voltage (IV*)* characterization routine for accurate evaluation of the temperature-dependent tandem performance on all cell dimensions (1 cm² to 250 cm²).

O6.2: Develop a sub-cell-selective iV_{oc}-imaging technique to quantify internal voltage losses.

O6.3: Provide advanced characterization methods to identify degradation pathways and provide in return these inputs for WPs to optimize the stability of tandem devices.

Milestones and Deliverables

MS-6.1 Common (fast) IV-protocol on how to measure cells transferred to partners (CSEM) [M12] (on track, will be submitted soon).

D-6.1 Report on fast measurement routine (CSEM) [M13] (on track, will be submitted soon).

D-6.2 Report on quantitative imaging of each sub-cells (F-ISE) [M24] (on track, will be submitted on M24).

D-6.3 Characterization and classification of fundamental degradation modes of HyPer cells (F-ISE) [M36] (not started).

Task 6.1: Assessment of global cell performance (CSEM, F-ISE) [M1-M36]

Global cell measurements (EQE, IV) will be adapted to accommodate the different cell sizes produced in the project, including large-area devices. A central focus of this task for CSEM is the definition of fast *J-V* measurement routines that can be implemented in a production environment, where throughput is critical. The challenge with perovskite-based devices lies in ensuring the accuracy of these fast routines, as such devices are prone to metastable effects caused by mobile ions.

In this task, CSEM will report on a fast measurement protocol for perovskite/silicon tandems, targeting power conversion efficiency measurements within 100-500ms. Perovskite solar cells are known to exhibit transient artifacts due to capacitive effects and ion migration.

The current standard measurement protocol at CSEM (Figure 13a) includes:

- Three sets of reverse and forward scans (11 s each): two at 1 sun illumination (before and after MPP tracking) and one at low illumination (0.04 sun).
- Maximum power point tracking for 60-120 s.

The total duration is 2-3 minutes per tandem cell, which is orders of magnitude longer than typical industrial routines (~100 ms). Increasing measurement speed by reducing integration time and delay introduces hysteresis and inconsistencies for scans faster than 2 s (Figure 13b).

In a second experiment, tandem cells were light-soaked for 10 s prior to measurement (Figure 13c). Notably, faster scans (500 ms to 2 s) showed reduced hysteresis and minimal performance deviation compared to slower scans. These results suggest that fast measurement routines could be viable in production if preceded by a short light-soaking step. This approach could be implemented in a production line by adding a light-soaking module before the characterization stage.

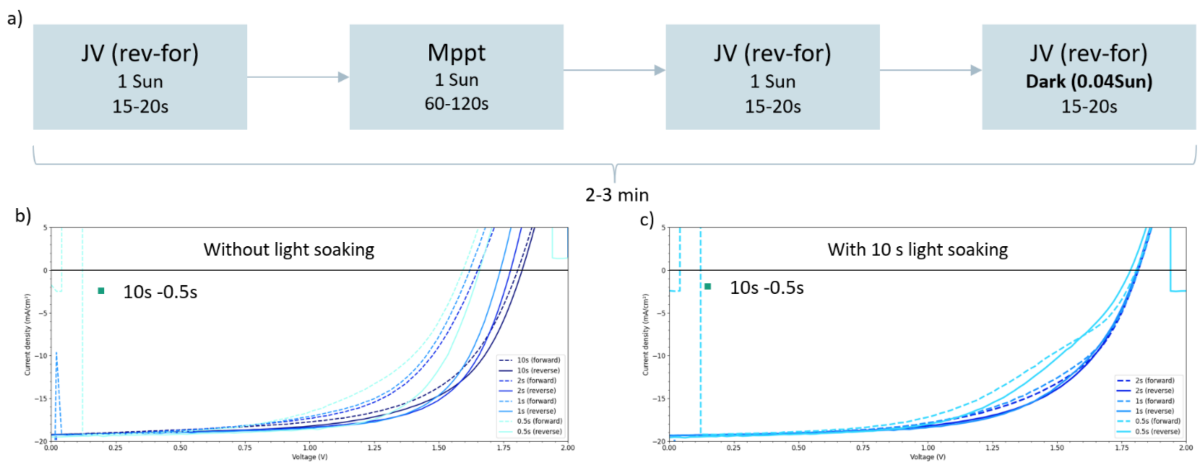


Figure 13 (a) Standard measurement protocol at CSEM. (b) Voltage/Current-density measured at different scan-speed (from 10s to 0.5s) without light soaking. (c) Voltage/Current-density measured at different scan-speed (from 2s to 0.5s) with light soaking of 10s before the measurements.

The perovskite/silicon tandem solar cells presented in Figure 13 are current limited by the perovskite top cell, which is important to consider when analyzing measurement results. It is well established that the impact of tandem fill factor (FF) and shunt resistance is dictated by the current-limiting sub-cell [3].

To investigate this, *J-V* measurements were performed on tandem devices under blue- and red-light bias (Figure 14). The data indicate that hysteresis and shunt resistance effects are more pronounced when the silicon bottom cell limits the current. This is expected, as the bottom cell typically exhibits higher shunt resistance and FF compared to the perovskite top cell.

These findings suggest that production-grade tandem solar cells should be designed to operate under bottom-cell-limited conditions, as this configuration could make fast measurement routines more feasible and robust.

Further experiments using light bias will be conducted in the next steps of the project. Additionally, Fraunhofer ISE (F-ISE) will provide a model for ion migration to support the analysis of metastable effects during cell measurements.

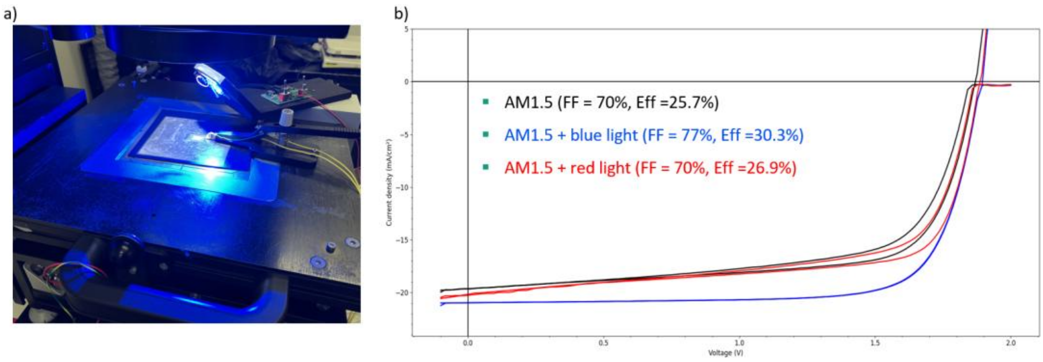


Figure 14 (a) picture of the light-bias *J-V* measurement setup. (b) *J-V* measurements of perovskite/silicon tandem solar cells with different light bias.

Task 6.2: Assessment of process scalability (F-ISE, CSEM) [M1-M36]

In Task 6.2, CSEM and Fraunhofer ISE will provide camera-based imaging methods to assess the homogeneity and quality of HyPer solar cells. These methods will enable sub-cell selective photo- and electroluminescence (PL/EL) analysis to identify process-induced inhomogeneities.

CSEM has a bi-chromatic PL/EL system capable of selectively imaging the perovskite top cell and silicon bottom cell. This system can map the entire tandem cell area across different sizes (from 1 cm² to 200 cm²). Figure 15 shows photoluminescence images of the perovskite and silicon heterojunction sub-cells for the batch presented in Figure 10. Clear inhomogeneities are visible in both sub-cells. This imaging technique provides valuable insights into the deposition quality of the perovskite top cell using scalable methods and helps detect precursor inhomogeneities caused by substrate handling or process issues.

This characterization tool is available for analyzing tandem solar cells produced in WP4 by different partners and benchmarking various scalable organohalide deposition methods. Additionally, it can be applied in WP3 to assess the homogeneity of the inorganic scaffold. Finally, the system can operate in electroluminescence mode to study transient effects under different current injection levels.

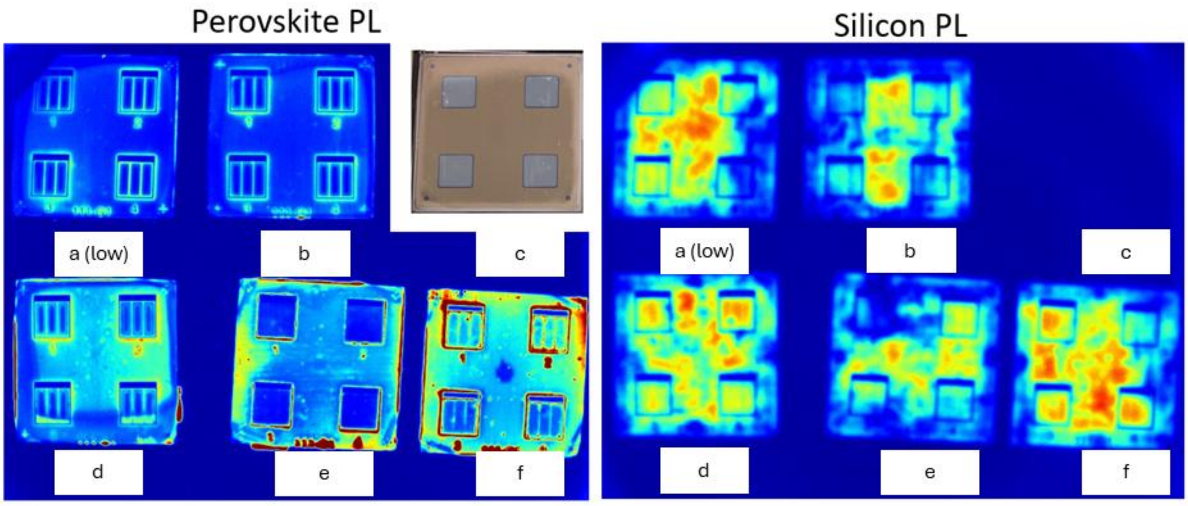


Figure 15 Bi-chromatic photoluminescence (PL) of the perovskite and bottom cell with different organohalide concentrations (from a - low, to f - high).

WP6: conclusion and next steps

WP6 establishes essential characterization protocols for perovskite/silicon tandem solar cells, including fast IV routines and advanced imaging techniques to assess performance, scalability, and stability. Initial results show that fast measurements can be adapted for industrial use when combined with short light-soaking steps, and bi-chromatic PL/EL imaging provides valuable insights into sub-cell homogeneity and process-induced defects.

Moving forward, the focus will be on (1) refining and validating fast *J-V* protocols under production-like conditions, (2) extending sub-cell-selective imaging to larger areas and integrating it into process feedback loops, and (3) investigating metastable effects and degradation pathways through modeling and targeted experiments to support stability optimization across all work packages.

WP7: Module integration and reliability testing

The goal of this work package is to assess the encapsulation and reliability of tandem cells produced during the project. This includes:

- Interconnecting tandem cells into single laminates and mini-modules.
- Evaluating the stability of encapsulated cells under various degradation protocols.
- Investigating the long-term stability of tandem cells under outdoor conditions.

CSEM is the work package leader. The main objective is to encapsulate perovskite/silicon tandem solar cells fabricated in WP4 and WP5 and perform comprehensive stability testing on these devices.

Objectives

WP7 focuses on the interconnection, encapsulation and reliability testing of the tandems produced in the project.

The specific objectives are to:

O7.1: Develop industrially applicable interconnection and encapsulation processes yielding high efficiency encapsulated devices exhibiting extended stability (T7.1).

O7.2: Assess the stability of encapsulated perovskite-silicon tandem cells and modules through a variety of harsh accelerated aging tests performed in the laboratory and use the insights retrieved from these tests to improve the stability of the devices (T7.2).

O7.3: Validate stability improvements by demonstrating tandem modules with extended outdoor stability, with a target to limit degradation to an extrapolated value of <1%rel/year (T7.3).

Milestones and Deliverables

MS-7.1 First generation of encapsulated tandems ready for accelerated ageing & outdoor monitoring (CSEM) [M12] (first hybrid-processed perovskite/silicon tandem solar cells encapsulated, to be submitted soon).

MS-7.2 Encapsulated cells with less than 5%rel loss in efficiency after 3000 hours of DH, 600 TC, and 1000 hours of ISOS L2 testing (CSEM) [M36]. (first stability tests started, results to be reported in M36).

D-7.1 Encapsulated tandems with a CTM loss of <10%rel (F-ISE) [M27] (on-track, to be reported on M27).

D-7.2 Report summarizing the results of the indoor accelerated aging tests (CSEM) [M36] (on-track, to be reported on M36).

D-7.3 Report summarizing the outdoor monitoring data (UVEG) [M36] (not started).

MS-7.1 First generation of encapsulated tandems ready for accelerated ageing & outdoor monitoring (CSEM) [M12].

CSEM has produced the first batch of encapsulated tandem solar cells featuring different metallization schemes and substrate sizes. The encapsulation process at CSEM uses a glass/glass configuration with an encapsulant sheet on both sides of the solar cell. Electrical contact is achieved by applying self-adhesive ribbons on either evaporated or screen-printed metallization. Additionally, a butyl edge sealant is applied around the perimeter of the encapsulation glass to prevent water ingress during stability testing (Figure 16).

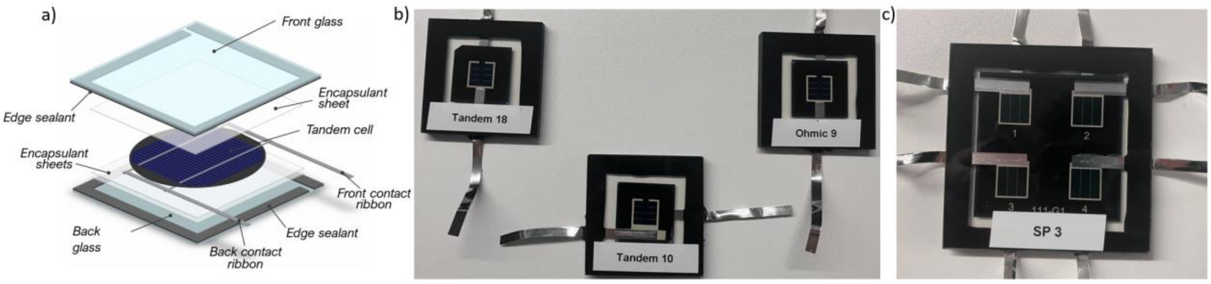


Figure 16 (a) Schematic of the encapsulation method at CSEM, (b) laminate of the 1 cm^2 with the evaporated silver. (c) laminate of the 1 cm^2 with the screen-printed silver on a 5 x 5 cm^2 substrate.

Using this encapsulation scheme, 1-step spin-coated perovskite/silicon tandem solar cells produced at CSEM were encapsulated with a cell-to-module (CTM) loss of less than 10%.

Encapsulated spin-coated tandems of CSEM have been subjected to IEC 61215 testing in the past, including:

- Thermal cycling: 250 cycles between -40°C and 85°C.
- Damp heat: 1000 hours at 80°C and 80% relative humidity.
- Light soaking: 1000 hours at 45°C under 1 sun illumination.

Results showed less than 5% relative efficiency loss after thermal cycling and damp heat testing, and less than 10% loss after 1000 hours of light soaking. These results validate the efficacy of CSEM's glass/glass lamination package and these tests will now be performed on HyPer hybrid-processed tandems.

WP7: conclusion and next steps

WP7 has successfully initiated the development of industrially relevant encapsulation and interconnection processes for perovskite/silicon tandem solar cells, achieving promising results with glass/glass encapsulation and butyl-edge sealing with spin-coated tandem references. The encapsulated tandems with a spin-coated perovskite demonstrated less than 10% CTM loss and showed suitable stability during IEC 61215 thermal cycling and damp heat tests, with efficiency losses below 5% after 1000 hours and 200 cycles, respectively.

Moving forward, efforts will focus on (1) optimizing encapsulation schemes specifically for hybrid-processed tandems, for larger modules and different metallization approaches, (2) extending accelerated aging protocols and correlating them with outdoor monitoring data to validate long-term stability, and (3) implementing design improvements based on degradation analysis to ambitious but necessary target of <1% relative annual efficiency loss in outdoor conditions.

3 Conclusions and outlook

Project Status

The project is on track across all work packages. Meyer Burger stepped down due to bankruptcy filing; however, this does not affect CSEM's ability to pursue the project. A stock of 200 M10 wafers was secured at the start of the project, and CSEM retains the capability to process its own silicon bottom cells.

On **WP3**, CSEM successfully demonstrated homogeneous deposition of PbI_2/CsBr scaffolds on M10 wafers using R&D evaporation systems, with stable precursor quality and reproducible results. Industrially relevant pathways, such as increasing deposition rates and sequential evaporation, were explored to improve scaffold porosity and organohalide infiltration. Next steps include assessing opto-electronic properties of perovskite layers formed via sequential evaporation and validating their potential for achieving 30% tandem efficiency.

For the **WP4**, hybrid PVD-inkjet printing has shown strong potential, achieving 27.5% efficiency on 1 cm² tandems - as a benchmark, spin-coating references exceeded 27% on textured silicon bottom cell. Next steps focus on (1) pushing 1 cm² tandems toward 30% efficiency, (2) optimizing inkjet parameters for uniform conversion, and (3) resolving screen-printed silver issues to enable large-scale devices.

For **WP5**, despite Meyer Burger's withdrawal, CSEM secured sufficient wafers and can fabricate tailored bottom cells. Risks remain high, but CSEM will support deliverables by contributing expertise in scalable coatings. Objectives may be adjusted by the CETP committee.

In **WP6**, fast *IV* measurement routines (0.5-1 s) and bi-chromatic PL/EL imaging were established, enabling industrially relevant characterization and defect analysis. Next steps include refining fast measurement protocols under production conditions, scaling imaging to larger areas, and modelling metastable effects to guide stability improvements.

In **WP7**, CSEM has a validated interconnection and lamination procedure, which has been shown to pass IEC 61215 thermal cycling, damp heat test criteria. This procedure is now being transposed to hybrid-processed tandems. Next steps involve optimizing encapsulation for larger modules, correlating accelerated aging with outdoor monitoring, and implementing design improvements to meet the <1% annual degradation target.

4 National and international cooperation

The HyPer project is part of the Clean Energy Transition Partnership (CETP) is a strategic initiative aimed at accelerating the transition to clean energy through collaborative research, development, and innovation across Europe and beyond of the CETP partnership. 7 institutions take part in the HyPer project, Fraunhofer ISE (F-ISE), The Netherlands Organisation for Applied Scientific Research (TNO), Karlsruhe Institute of Technology (KIT), University of Valencia (UVEG), SparkNano, Meyer Burger (MB) and the Centre Suisse d'Electronique et de Microtechnique (CSEM). Meyer Burger recently filed for bankruptcy and withdrawn from the project.

International cooperation in between the different partners includes i) monthly scientific exchanges, ii) exchange of samples and processes, iii) joined open-access publications writing and presentation at scientific European and international conferences.

5 Publications and other communications

At the conclusion of the project, a peer-reviewed publication summarizing the stability tests conducted in WP7 will be prepared and published. Additionally, collaborative publications addressing the processing of perovskite top cells on textured silicon substrates and large-area devices may be submitted to peer-reviewed journals. Scientific findings will also be showcased at prominent international photovoltaic conferences (such as EUPVSEC, PSCO, MATSUS), as well as at seminars and workshops (including the Tandem PV Workshop and BW Perovskite Workshop). Major project outcomes will be identified and categorized based on their commercial potential and exploitation opportunities.

6 References

[1] Chin X. Y. et al, “Interface passivation for 31.25%-efficient perovskite/silicon tandem solar cells.Science,” Science, pp. 59-63, 2023.

[2] Jérémie Werner, “Complex Refractive Indices of Cesium-Formamidinium-Based Mixed-Halide Perovskites with Optical Band Gaps from 1.5 to 1.8 eV,” ACS Energy Letters, pp. 742-747, 2018.

[3] M. &. B. C. Boccard, “Influence of the subcell properties on the fill factor of two-terminal perovskite-silicon tandem solar cells.,” ACS Energy Letters, vol. 5, no. 4, pp. 1077-1082., 2020.