Ref. Ares(2026)414659 - 15/01/2026

D4.4 – Roadmap for the eco-design of silicon solar cells & modules technologies



Co-funded by
the European Union

Co-Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them.

Document control sheet

Project	**RESiLEX** – Resilient Enhancement for the Silicon Industry Leveraging the European matrix
Call identifier	HORIZON-CL4-2021-RESILIENCE-01-07
Grant Agreement Number	101058583
Coordinator	Iberian Sustainable Mining Cluster (ISMC)
Work package N°	4
Work package title	Sustainable, eco-design solar cells & modules
Work package leader	CSEM
Document title	D4.4 - Roadmap for the eco-design of silicon solar cells & modules technologies
Lead Beneficiary	CSEM
Dissemination level	Public
Authors	Alexis Barrou, Laurie-Lou Senaud, Lison Marthey, Adeline Lanterne, Timéa Béjat, Pia Vasquez
Contributors	Agata Lachowicz, Marie Nicolle, Ricardo Magdanela
Reviewer(s)	Adeline Lanterne, Timéa Béjat (CEA) Diego Lozano, Laura Quijano (ISMC)
Issue date	January 2026

Version control table

Version	Date	Main changes
V1	01.12.2025	Initial draft with Ecodesign regulations for PV actualized (2.2), part 3.Cells updated with results and recycling
V2	18.12.2025	Executive summary, introduction, conclusion, module results added and milestone, general layout
V3	07.01.2026	General review by CSEM, modification of part 4. Modules and new conclusion
V4	09.01.2026	Review by CEA
FINAL	15.01.2026	Final version submitted after review by ISMC

Index

Executive Summary 4

1. Introduction 6

2. Eco-design concept, main regulations, environmental impacts and strategies for PV 8

2.1 Ecodesign and Life Cycle Assessment concepts 8

2.2 Ecodesign regulations for PV 9

2.3 PV environmental impacts 14

2.4 Eco-design strategies for PV 15

3. Eco-design developments for c-Si solar cells 19

3.1 Scenarios & LCA results 19

3.2 Performance investigations 21

3.3 Reliability investigations 28

3.4 Recyclability 34

4. Eco-design developments for PV modules 35

4.1 Scenarios & LCA results 35

4.2 Eco-design bill of materials investigation 40

4.3 Performance and reliability investigations 43

4.4 Recyclability 51

5. Milestone 15: eco-designed 60 cells module demonstrator 54

5.1 Selection of the module components 54

5.2 Module manufacturing 57

6. Conclusion 62

7. References 64

Executive Summary

Deliverable **D4.4** provides a consolidated roadmap for implementing eco-design strategies in photovoltaic (PV) technologies within the RESILEX project. It builds on the interim roadmap presented in **D4.1**, integrating updated regulatory frameworks, technical developments, and sustainability assessments to guide the PV industry toward designs that combine high performance with reduced environmental impact.

The report addresses three main dimensions:

- **Regulatory and environmental context:** Updated analysis of EU and international regulations, including the **Ecodesign for Sustainable Products Regulation (ESPR)**, **Net Zero Industry Act (NZIA)**, and **Critical Raw Materials Act (CRMA)**, which set ambitious targets for carbon footprint reduction, recyclability, and resource efficiency. Life Cycle Assessment (LCA) results highlight key environmental hotspots in PV manufacturing, notably wafer production, module assembly, and metallization.
- **Eco-design strategies and achievements:** At the **cell level**, strategies include reducing wafer thickness, use of recycled silicon, as well as replacing critical materials such as silver and indium with copper and alternative indium-free transparent conductive oxides. At the **module level**, innovations focus on introducing bio-based, recycled and fluorine-free materials for module components, such as the frame, frontsheet, backsheet and encapsulant. In addition, eco-design strategies such as non-crosslinking encapsulants to facilitate recycling as well as alternative interconnection technologies, that reduce lead and silver consumption, are investigated. These approaches were validated through environmental study, technical developments and reliability tests.
- **Performance, reliability, and circularity**: Demonstration of eco-designed modules featuring optimized bill of material (BoM) and compliance with IEC reliability standards. Important focus on moisture ingress which could remain a challenge for certain BoM. Recycling analysis confirms positive impacts on PV recyclability for fluorine-free materials and non-crosslinking encapsulants, while highlighting trade-offs such as reduced economic value from silver-free designs.

A major milestone was achieved with the fabrication of a **60-cells demonstrator module**, combining In-less and Ag-less solar cells with a wooden frame, TPO encapsulant, and fluorine-free backsheet. This demonstrator illustrates the feasibility of integrating multiple eco-design strategies into a large-scale PV product.

Next steps include scaling up validated strategies, optimizing reliability for bio-based components and sustainable approaches, and deepening end-of-life assessments to ensure full circularity. By combining technical innovation, regulatory compliance, and sustainability principles, D4.4 sets a clear pathway for reducing the environmental footprint of PV systems and strengthening Europe's resilience in the solar value chain.

1. Introduction

Photovoltaic (PV) technology is central to achieve global climate targets, offering a scalable and versatile solution for clean electricity generation. Its rapid deployment, already beyond the terawatt scale, positions PV as a cornerstone of the energy transition. However, as production accelerates toward multi-terawatt levels, sustainability challenges become an increasing source of concern. Addressing these challenges requires a shift from conventional design practices to **eco-design**, ensuring that PV products minimize environmental impacts throughout their life cycle while maintaining high efficiency and durability.

The European Union has reinforced this direction through ambitious regulatory initiatives such as the **Ecodesign for Sustainable Products Regulation (ESPR)**, which introduces mandatory requirements for durability, recyclability, and carbon footprint; the **Net Zero Industry Act (NZIA)**, which promotes resilient and sustainable manufacturing; and the **Critical Raw Materials Act (CRMA)**, which targets secure and responsible sourcing of key materials. These frameworks, complemented by international standards and national policies, are reshaping the PV industry toward circularity and resource efficiency.

Within this context, the RESILEX project aims to strengthen the resilience and sustainability of the silicon value chain in Europe. Work Package 4 (WP4) focuses on developing and validating eco-design strategies for silicon-based solar cells and modules (Figure 1). These strategies were previously selected in D4.1, technically evaluated in D4.2 (for PV modules) and D4.3 (for solar cells), and environmentally evaluated in D7.2 (see table 1). Building on the interim roadmap presented in D4.1 and on the three previous deliverables (D4.2, D4.3, D7.2), this deliverable D4.4 consolidates the latest achievements and defines a forward-looking roadmap that integrates the following topics: (i) updated regulatory and environmental requirements relevant to PV eco-design; (ii) technical developments for reducing critical material use (silver, indium, silicon), (iii) introducing alternative eco-design materials and processes; (iv) reliability and recyclability assessments to ensure that eco-design strategies do not compromise long-term performance or lifetime of the PV devices as well as their recycling. The roadmap presented in this deliverable D4.4 combines scenario-based analysis, experimental results, and sustainability evaluations to guide industry adoption of eco-design principles. It serves as a reference for stakeholders seeking to align PV manufacturing with circular economy objectives and emerging EU regulations, paving the way for a more sustainable and competitive solar sector.

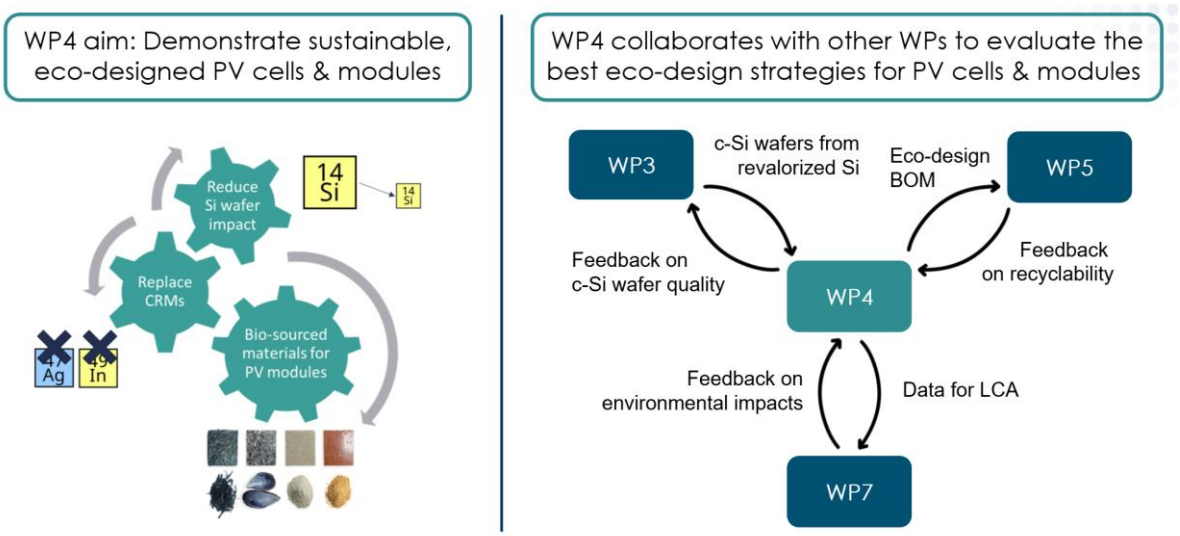


Figure 1: WP4 aim and collaboration within the RESILEX project.

Table 1: Previous deliverable used as input for D4.4.

Shortname	Longname	Publication date
D4.1	Interim roadmap for the eco-design of silicon solar cells & modules and silicon-based tandem technologies	February 2025
D4.2	First report on bio-sourced materials & module components performance	April 2025
D4.3	Report of the CRM-free, low environmental footprint Si production cells	May 2025
D7.2	Interim Comparative Environmental Sustainability Assessment	April 2025

2. Eco-design concept, main regulations, environmental impacts and strategies for PV

2.1 Ecodesign and Life Cycle Assessment concepts

As introduced in deliverable D4.1, eco-design is a systematic approach that integrates environmental considerations into product design and development with the goal of reducing negative impacts throughout the entire life cycle [Ekwa2001]. In particular, the 3R approach — Reuse, Recycle, Reduce — (detailed in Figure 2 below) constitutes a core principle of eco-design, aiming to minimize environmental impacts while maximizing product's circularity.

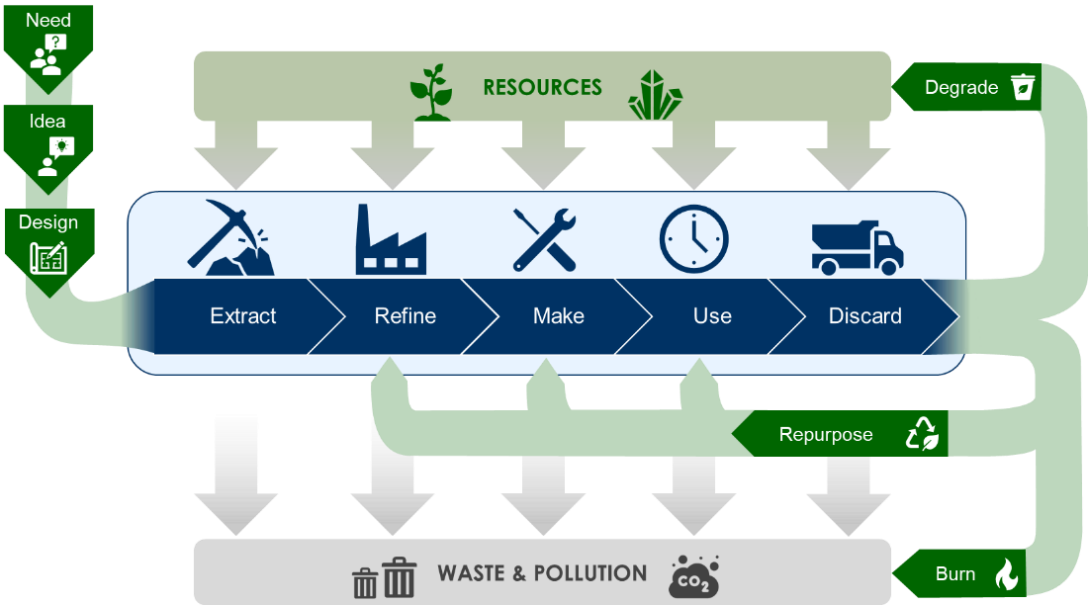


Figure 2: Ecodesign and life cycle schematic.

The foundation of eco-design is reliable environmental data. This data is obtained through Life Cycle Assessment (LCA), a standardized method for evaluating a product's environmental footprint across its entire life cycle [ISO14040]. The product is evaluated along its life stages, from raw material extraction to end-of-life treatment on a various number of impact categories (such as climate change and water use), providing a detailed overview of its environmental impact. Additionally, LCA provides a clear picture of a product's hotspots, such as processes, materials or components, contributing significantly to the overall product's environmental footprint.

By pinpointing these hotspots, LCA provides a robust basis for creating more sustainable products by identifying the greatest areas for improvement. In addition to LCA, eco-design principles are also embedded in a variety of regulations to ensure meaningful reductions in environmental impacts.

2.2 Ecodesign regulations for PV

Key eco-design regulations for PV have been detailed in D4.1 and are summarized in the table below. New regulations and evolution of previously presented regulations are also introduced.

2.2.1 Summary table of PV eco-design regulations

A broad variety of regulations exist for the eco-design of PV in Europe, and it is crucial to follow their rapid evolution to be compliant with PV eco-design standards. The regulations presented in the following table can be split into three main categories having different influence on the PV industry and its products:

- Broad regulations in favour of EU autonomy for energy supply (NZIA) and raw material supply (CRMA), leading to objectives and targets for the PV industry;

- EU regulations to make eco-design and sustainable products, notably durable, recyclable and low carbon-footprint PV products based on the ESPR that will replace in 2027 the eco-design directive and integrate work of the eco-design & Energy labelling working plan;

- World (EPEAT) and country specific (CRE and EPR for France) regulations defining eco-design thresholds and criteria for PV products.

Overall, the broad variety of eco-design strategies for PV can be populated based on the following objectives (also presented in D4.1):

- Reduction of CO_2 emissions
- Reduction of critical resource consumption
- Reuse of materials in their second life
- Extension of product lifespan
- Recycling and recovery

Table 2: Summary of eco-design regulations and their implications for PV.

Name of Regulation	Entry into action date	Region Validity	Main Objective	Main Targets	Applicable for PV & specificities
Critical Raw Materials Act (CRMA) [CRMA2024]	March 2024	EU	Securing, diversifying, and make sustainable supply of critical raw materials	Compared to Annual EU consumption: > 10% EU extraction > 40% EU processing > 25% recycling capacity < 65% share for 3rd country	Yes, all targets applicable for PV for materials like silicon metal and copper
Net Zero Industry Act (NZIA) [NZIA]	June 2024	EU	Ensure access to a secure and sustainable supply of net-zero technologies	>40% annual EU deployment met by EU manufacturers by 2030 >15% share of world production by 2040 Resilience criterion	Yes, increase in PV production capacity, simplification of procedures, sustainability and resilience criteria, support innovation and competitiveness and develop skills
Eco-design Directive (2009/125/EC) [ECO2009]	2009	EU	Ensure eco-design for energy-related products	Establish minimum requirements for energy performance and sustainability for energy-related products	Yes, applicable until 31th December 2027. Defines methods to set specific eco-design requirements
EPEAT Ecolabel [EPEAT2023]	March 2023 (PV criteria)	World	Certify electronic products based on environmental impact	Defines Criteria to certify various types of electronic products	Defines list of criteria for PV modules. Carbon footprint thresholds for PV modules (≤630 $kgCO_2e/kWp$ for Bronze, ≤400 for Gold) [NSF2024]
Simplified Carbon Evaluation (CRE) [CRE2023]	October 2021 (updated 2024)	France	Evaluate carbon footprint of PV panels in tenders	Carbon footprint threshold: < 550 kgCO2-eq/kWp < 740 kgCO2-eq/kWp (new methodology)	Mandatory for eligibility in France national tenders and tariffs
Extended Producer	January 2025	France	Promote circular	Assign producers' responsibility to	SOREN applies eco-modulation

Responsibility (EPR) [EPR]			economy and waste reduction	Finance the end-of-life products, organise waste prevention and the gestion of end-of-life of their products	bonuses/penalties based on eco-design criteria: Carbon footprint PV < 450kgCO2-eq/kWp; >14mg/Wp of Silver; >3% recycled material <0.1% lead in PV module
Ecodesign for Sustainable Products Regulation (ESPR) [ESPR]	July 2024 (January 2027 for PV)	EU	Provide harmonized EU framework for product's eco-design and sustainability	Various criteria gathered in the Digital Product Passport: durability, recyclability, repairability, energy performance, recycled content, traceability, carbon footprint	Yes, applicable for PV after 31st December 2026, with various specificities (detailed in the text below), based on the Ecodesign & Energy Labelling working plan for PV
Waste of Electrical and Electronic Equipment (WEEE) [WEEE]	August 2012	EU	Preventing the creation of WEEE, promote reuse, recycling and recovery of WEEE	Separate collection and proper treatment of WEE with, after 2019: >85% collection of WEEE generated >65% collection rate of the total weight of EEE sold in the past 3 years	Specific category (4.b) introduced in 2019 for PV products: Recovery rate >85% Reuse & recycling rate >80% Revision scheduled in December 2026 to adapt to PV market

2.2.2 Description of regulations and their evolutions

Since the release of deliverable D4.1, several changes of the regulation have occurred. The Ecodesign Directive 2009/125/EC [ECO2009] has been replaced by the Ecodesign for Sustainable Products Regulation (ESPR) [ESPR] that came into effect in July 2024. For PV panels, the ESPR sets a transition period until 31st December 2026 under which the measures continue to be covered by the Ecodesign Directive 2009/125/EC. After 2027, PV products will have to comply with the ESPR. In parallel, the Ecodesign & Energy Labelling working plan [ESPRELWP] is setting criteria and methodologies that will be used in the ESPR for PV products.

1) Ecodesign for Sustainable Products Regulation (ESPR)

The Ecodesign for Sustainable Products Regulation (ESPR) is part of the package of rules introduced under the 2020 Circular Economy Action Plan, itself being a key component of the European Greendeal [GREEN]. ESPR is crucial for PV eco-design, as it provides a harmonized EU framework aimed at improving product's sustainability across the entire life cycle. In particular, the ESPR requires PV products to meet strict criteria on durability, recyclability, repairability and energy performance, ensuring that PV panels are designed for longer lifetimes and easier recycling at end-of-life.

In the case of PV panels, which involve significant material use (such as glass, silicon, metals), the ESPR promotes resource efficiency and circularity by encouraging the use of recycled materials and reducing waste, in line with EU circular economy targets. Additionally, the ESPR advocates transparent reporting of carbon footprint and material sourcing for PV products, supported by mandatory LCA and Digital Product Passport to ensure full traceability. Overall, the ESPR harmonizes rules across the EU, preventing fragmented national regulations, and drives innovation and sustainable designs among PV manufacturers.

The specific eco-design requirements for PV modules under the ESPR are the following:

- **Carbon Footprint Limits** with maximum embedded carbon footprint thresholds, calculated over the entire lifecycle. Methodology will likely use functional units based on lifetime energy yield (kWh) rather than nominal capacity (kWp). [JRC 2025]
- **Durability & Reliability** with minimum standards for product lifetime, including resistance to degradation and environmental stress (temperature, humidity, UV exposure). In addition, requirements for quality assurance in manufacturing are included to ensure long-term performance.
- **Recyclability & Material Recovery** with design for easy disassembly and recycling, especially for glass, aluminium frames, and silicon wafers as well as defined targets for the recovery of critical raw materials (e.g., silver, silicon).
- **Digital Product Passport (DPP)** with mandatory information disclosure on:
    - Material composition
    - Carbon footprint data
    - Recycling instructions
    - Repair and maintenance guidelines
- **Circularity & Resource Efficiency** with the encouragement of recycled content in module components and restrictions on hazardous substances to facilitate safe recycling.

- **Energy Labelling** with the Introduction of an Energy Label for PV modules, providing consumers with energy yield performance and environmental impact indicators.

2) Ecodesign & Energy Labelling working plan

Ecodesign and energy labelling working plan [ESPRELWP] provides strategic roadmap for introducing sustainability requirements and consumer information tools for PV products (PV modules and inverters) that are mentioned in the ESPR. This work, requested by the EU commission in parallel to the Ecodesign and ESPR regulations, was initially planned from 2022 to 2024. Since then, it has been extended, and work is currently ongoing to define a recyclability index for PV panels, as well as standardized methodologies for evaluating the carbon footprint of bifacial PV modules and the energy labelling of PV products [EDELPV]. The outcomes of this work will be used to complete ESPR guidelines for PV products.

3) Waste of Electrical and Electronic Equipment (WEEE)

The WEEE Directive (Directive 2012/19/EU) was adopted in 2012 and mandates that producers finance and organize the collection, treatment, recovery, and recycling of Electrical and Electronic Equipment to prevent environmental damage, recover valuable materials, and reduce hazardous waste [WEEE]. Since 2012, PV panels have been classified under Category 4 ("consumer equipment & photovoltaic panels") and need to meet the following targets after 2018: 85% of PV panel should be recovered and 80% prepared for reuse and recycled [Photorama].

The directive has been incorporated into the national legislation of EU member states since 2014. However, its implementation varies across countries, creating inconsistencies within the single market and leading to different levels of success. One key issue is the interpretation of the term "producer," which can refer to manufacturers, importers, resellers, or installers depending on the member state. Moreover, the PV industry has requested a separate collection target from other WEEE categories due to the long lifespan of solar panels and the market's volatility. Current targets are considered overly ambitious and difficult to meet, as they depend on national conditions and are calculated based on the current or previous three years' market data. To improve reporting under Directive 2012/19/EU, Commission Implementing Decision 2019/2119 introduced sub-categories, with photovoltaic waste classified under 4.b, requiring separate reporting [Photorama].
Regarding recovery and recycling ratios, the EU's minimum requirements have been a positive step toward establishing recycling practices. However, given that PV panels contain only small amounts of critical and valuable materials (such as indium, silver, and silicon), meeting these targets is relatively easy without recovering these

elements. This results in their permanent loss, posing an environmental challenge. A mandatory review of the directive is due by December 2026, potentially leading to more PV-specific frameworks, aligned with other eco-design directives previously mentioned.

2.3 PV environmental impacts

The environmental impacts of PV modules were evaluated by WP7, which focuses on sustainability assessment across economic, social, and environmental dimensions, using LCA methodologies. Their evaluation considers the environmental impact of manufacturing 1 m² of a silicon heterojunction (SHJ) PV module, which is the PV technology studied in the RESILEX project.

Figure 3 illustrates the relative contribution of the three major steps in PV module manufacturing: 1-4 wafer production, 5 cell manufacturing and 6 module production, for six impact categories (climate change, freshwater ecotoxicity, carcinogenic human toxicity, non-carcinogenic human toxicity, resource use fossils, as well as resource use minerals and metals). The use phase was not considered here, as it presents negligible environmental impacts compared to resource extraction and manufacturing stage, which both account for the majority of PV modules' impact. In addition, recycling was not included, even though it could provide environmental benefits, as introduced in D4.1.

Wafer production shows the highest impacts in the first four categories, primarily due to the energy-intensive silicon purification processes. Module production has a significant impact on climate change and the greatest impact in terms of "resource use, fossils", driven by the aluminium frame and glass components. Finally, cell manufacturing shows the highest impact on "resource use, mineral and metals" due to the indium and silver required for the solar cell contacts.

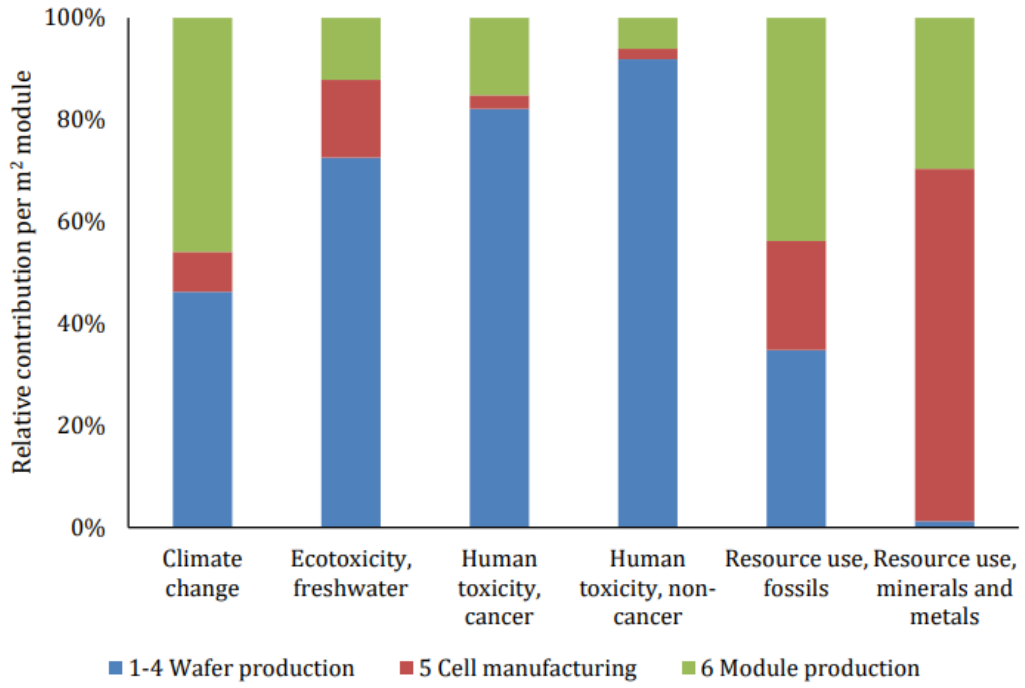


Figure 3: Relative contribution of the steps wafer production, cell manufacturing and module production to the environmental impacts of 1 m2 SHJ module (based on D7.2).

2.4 Eco-design strategies for PV

The RESILEX roadmap presented in D4.1 outlines eco-design strategies to lower the carbon footprint and minimize the use of critical raw materials based on the previously mentioned eco-design regulations and challenges to make a sustainable PV industry. Building on this, RESILEX WP4 focuses on implementing practical eco-design strategies for solar cells and modules which are summarized in Tables 3 and 4 below. At the cell level, the eco-design strategies of RESILEX WP4 focus on reducing the wafer thickness, use of recycled silicon, replacing silver with copper as well as removing indium content in transparent conductive oxides. At the module level, the strategies focus on introducing bio-based, recycled and fluorine-free materials for module components, such as the frame, frontsheet, backsheet and encapsulant. In addition, eco-design strategies such as non-crosslinking encapsulants to facilitate recycling as well as alternative interconnection technologies, that reduce lead and silver consumption, are investigated.

Table 3: Eco-design strategies for PV cells' manufacturing implemented in RESILEX WP4.

Solar cells material	Main Strategy Description	Expected Positive Outcome for Eco-Design	Potential Negative Outcome
Silicon	Use of silicon wafer made from revalorized silicon waste (T4.1) produced with a carbon-free aluminothermic process (WP3)	Reduces the carbon footprint of wafer production; promotes circular economy, limit wastes	May reduce the quality (level of purity and lifetime) of the wafer and cells performances
Silicon	Use thinner silicon wafer	Lowers material use, energy consumption, and carbon footprint	May affect mechanical strength, performances and handling during manufacturing
Silver	Use of copper-based pastes deposited by screen-printing	Reduces cost and environmental impact; lowers reliance on critical materials	Copper may oxidize; lower conductivity than silver, may impact module reliability
Silver	Use of copper electroplating process	Reduces cost and environmental impact; lowers reliance on critical materials	Copper may oxidize; lower durability compared to silver
Indium	Use of thinner indium-based TCO layer	Reduces reliance on indium, lowers environmental impact	Lower conductivity and stability under humidity may arise with thinner ITO layer
Indium	Use of In-free TCO deposited by PVD	Suppress reliance on indium; lowers environmental impact	In-free TCOs may have lower stability and conductivity; reliability concerns under humidity
Indium	Use of SnO2 film (In-free TCO) deposited using AP-SALD	Suppress reliance on indium. Costs and environmental impact reduction thanks to lower electricity needs and no vacuum needs	Implementation by PV manufacturers is challenging

Table 4: Eco-design strategies for PV modules manufacturing implemented in RESILEX WP4.

PV module	Main Strategy Description	Expected Positive Outcome for Eco-Design	Potential Negative Outcome
Aluminium Frame	Use of bio-based materials (e.g., wood)	Reduces CO_2 footprint; promotes renewable material use	Fire resistance, mechanical stability and recycling challenges
Glass (Frontsheet)	Remove glass and use polymeric frontsheet	Reduces module weight and CO_2 footprint	Lower mechanical stability; higher cost; recycling complexity
Encapsulant	Use non-cross-linking thermoplastic olefin (TPO) instead of EVA	Easier recycling; reshaping possible; lower environmental impact	Needs reliability testing; potential moisture ingress issues
Metallization	Lead-free interconnection with 0BB (zero busbar) or ECA	Reduces silver and lead use; improves performance and reliability	Requires process adaptation; potential durability concerns
Backsheet	Use fluorine-free and bio-based materials (e.g., PET, PP, flax composites)	Easier recycling; lower environmental and economic impact at end-of-life	Reduced UV protection and durability; may require new protective layers
Frontsheet	Use custom fluorine-free polymeric materials	Reduces GWP and fluorine-related recycling issues	May have lower mechanical and UV resistance /reduce durability compared to glass

In addition to these eco-design strategies applied to PV cell and module manufacturing, extended PV module lifetime and high PV module recyclability are also important eco-design measures to consider. Both strategies aim to maximize the energy and material value of each PV module, reduce waste and replacement needs, and enable the recovery of valuable resources at end-of-life. Thus, the combination of long lifetime, high recyclability, as well as eco-designed strategies for PV cells and modules manufacturing provides a strong pathway to reduce the overall environmental footprint of PV systems and supports a more circular and sustainable energy sector.

The methodology applied in the RESILEX project to develop sustainable and eco-designed PV solar cells and modules is guided by the following steps:

- Definition of scenarios based on eco-design strategies (led by WP4)
- Life cycle assessment of the different scenarios to quantify the environmental benefits of eco-design strategies (led by WP7)
- Technical results of eco-design strategies (led by WP4)
- Reliability tests of eco-design strategies (led by WP4)
- Evaluation of the impact of eco-design strategies on the recycling (led by WP5)

In the RESILEX project, LCA and technical results are used to validate the proposed eco-design scenarios for cells and modules, guide trade-offs between environmental benefits and technical durability, and support compliance with emerging EU regulations that set carbon footprint thresholds and recyclability metrics. By applying LCA early and systematically, the project ensures that innovations lead to PV modules that are both high-performing and environmentally responsible. In the following sections, the RESILEX PV scenarios, including eco-design strategies, as well as LCA and technical results are presented for both solar cell and module manufacturing.

3. Eco-design developments for c-Si solar cells

Eco-design developments for solar cells developed in WP4 were presented in table 3. The following section (3.1) presents the LCA results of the reference and eco-design scenarios defined in D4.1. The research and initial performance results of eco-designed solar cells are presented in section 3.2. Section 3.3 explores their stability and reliability through dedicated tests. Finally, section 3.4 highlights the implications of the different eco-design strategies for recycling through insights from COMET, a recycling partner leading RESILEX WP5.

3.1 Scenarios & LCA results

Based on the eco-design considerations and investigations detailed in deliverable D4.1, three main scenarios for processing solar cells were presented and are recalled in Figure 4.

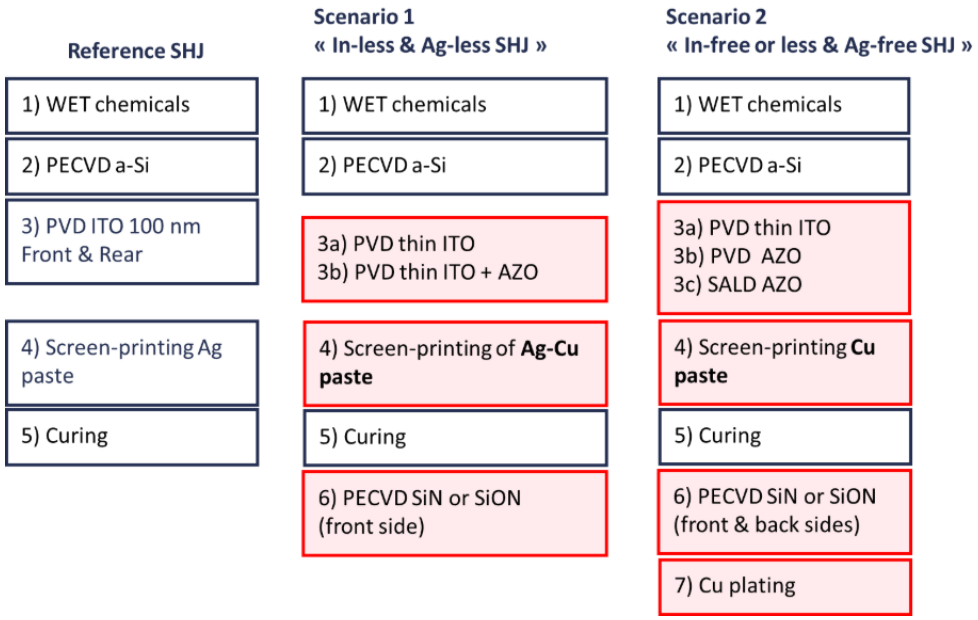


Figure 4: Schematic of the different process steps for the three scenarios investigated in WP4 for a specific technology (SHJ) of silicon-based solar cells. Standard processes are used in reference SHJ scenario while Scenario 1 represents an In-less, Ag-less cell and Scenario 2 an In-free or Ag-free cell.

These scenarios aim to reduce the solar cell's environmental impact and decrease the use of critical raw materials. The first scenario describes the reference SHJ solar cells of the RESILEX project, the second scenario describes SHJ solar cells with indium and silver reduction and the third one describes indium-free and silver-free solar cells (more details are given in D4.1). These three scenarios have been shared with the RESILEX WP7 team for a complete assessment of their economic, environmental, and societal impacts.

The results of the environmental assessment comparing the reference design and Scenario 1 are presented in Figure 5 and were originally reported in Deliverable D7.2. Scenario 1 significantly reduces environmental impacts compared to the reference design, with a 30% decrease in climate change potential and a 44% reduction in mineral and metal resource use.

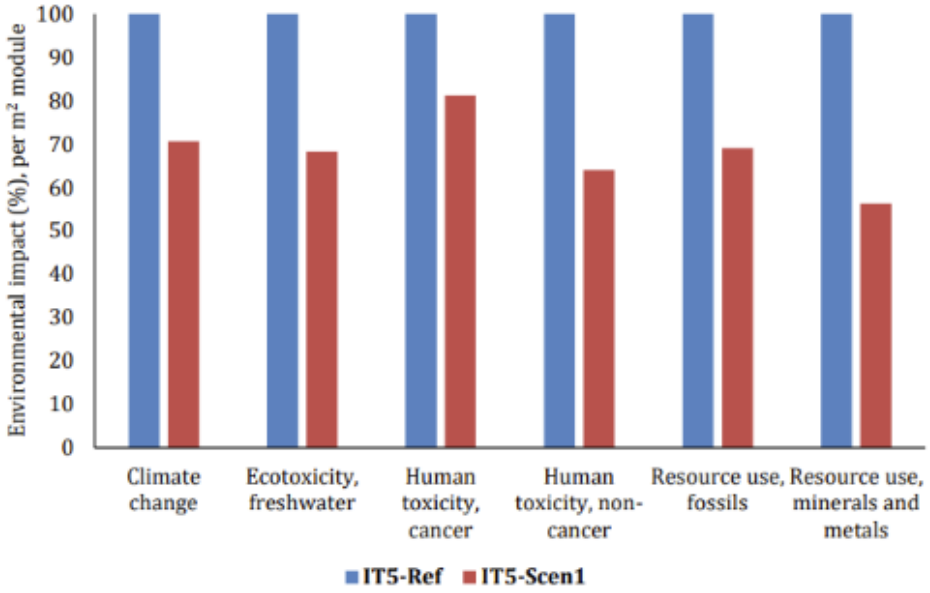


Figure 5: Relative environmental impact of alternative cell manufacturing (IT5-Scen 1) compared to the reference (IT5-Ref) and expressed per m2 of PV module (based on D7.2).

These improvements are mainly due to:

- Partial substitution of silver with copper, lowering the environmental footprint and reducing metal supply impacts.
- Reduction of indium tin oxide (ITO) layer thickness, which decreases both metal demand and energy consumption during physical vapor deposition.

Impact reductions are primarily linked to metal supply reduction for climate change and human toxicity categories, while for fossil resource use, improvements come from lower energy demand due to thinner ITO.

This analysis highlights several critical aspects that guide the developments of this work. One of the most significant findings is the potential to further reduce the environmental impact of solar cell manufacturing. Among the different contributors, the metal supply chain, particularly indium and silver, emerges as a key area for improvement.

Scenario 2, illustrated in Figure 4, addresses this challenge by eliminating both silver and indium from the solar cell design. In this approach, indium tin oxide (ITO) is replaced by aluminium-doped zinc oxide (AZO), deposited using PVD or SALD

techniques, thereby removing indium entirely. Additionally, the metallization process of scenario 2 relies on pure copper: a thin seed metallic grid is screen-printed on both sides using copper paste, followed by an additional copper plating step to complete the grid, eliminating silver from the cell.

The evaluation of this scenario has not been fully performed yet and LCA results will be made available in the next LCA deliverable of WP7. Nonetheless, literature review [Louwen2015] and recent research carried at CSEM suggests that copper plating should further reduce the environmental impact of solar cell production compared to reference scenario, especially for the resource use of minerals and metals impact category due to the suppression of silver.

While reducing environmental impact is essential, these changes must not compromise the primary function of solar cells: delivering high efficiency and long-term performance when integrated into modules. The challenge lies in achieving eco-design improvements without sacrificing energy conversion efficiency. Furthermore, reliability over decades of operation remains a critical requirement, as solar cells and modules are expected to produce electricity consistently throughout their lifespan. The investigations on those topics are tackled in section 3.2 and 3.3.

3.2 Performance investigations

As introduced previously, several strategies have been studied in the project to remove (or reduce by more than 70%) the indium and silver contents in silicon heterojunction solar cells as well as reducing the impact of the silicon material. These strategies include:

- For Indium:
  1) The reduction of In-based TCO layer thickness
  2) Use of AZO layer (In-free TCO)
  3) Use of SnO_2 films (In-free TCO) using AP-SALD deposition

- For Silver:
  4) Use of copper-containing paste deposited by screen-printing
  5) Use of copper electroplating process

- For Silicon:
  6) The use of thinner wafers
  7) The use of silicon wafers integrating recycled silicon

The results of the developments performed by CEA, CSEM and LMGP for each strategy and for the combination of In and Ag reduction have been first reported in deliverable D4.3. A summary of the result presented in D4.3 for each development can be found below, along with new results obtained since M36.

1) <u>The reduction of the In-based TCO layer thickness, for In reduction above 70%</u>

The reduction of Indium by this approach was a success. For the first time, the possibility to reduce Indium content in SHJ solar cells by 77.2% while decreasing the cell efficiency by less than 0.1% absolute was demonstrated (see Figure 6). State-of-the art developed ultra-thin ITO of 15 nm was used on the front side for this demonstration, with an additional SiN_x anti-reflective layer, combined with a reduced and optimized IMO:H (indium metal oxide) layer of only 30 nm on the rear side. The performance losses were minimized thanks to the use of nc-Si:H selective layers. The robustness of the approach was confirmed several times on CEA pre-industrial line. The processing of several large-scale batches has enabled us to raise the TRL of the approach to level 7, while using a particularly low In content as compared to other research. Finally, the process was also proven to be compatible with silver and silicon reductions, as detailed in deliverable D4.3. The assessment of these "In-less" SHJ at module level were then conducted. Results can be found in the next section.

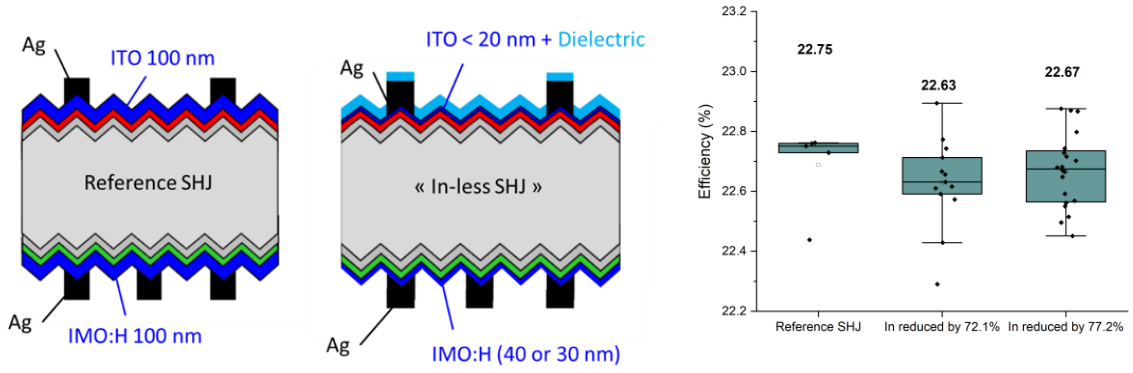


Figure 6: Schematic SHJ solar cell structure with standard indium consumption (reference) and reduced indium quantity (In-less SHJ), and best results obtained with thin ITO, published in [Lanterne 2024].

2) <u>The development of AZO layers as In-free TCO by PVD</u>

Concerning developments of indium free TCOs by PVD, we demonstrated aluminum zinc oxide (AZO) layers with interesting electrical properties resulting in high solar cells performances both at CSEM and CEA. At CSEM, we developed AZO layers to achieve high-quality electro-optical properties for optimal integration into SHJ-IBC solar cells. The deposition parameters were optimized to obtain high transparency together with electrical properties that ensure effective contact with both the

underlying PECVD layers and the metallic grid on top. Using a silver grid, we demonstrated that the optimized AZO led to an efficiency increase of approximately +0.2% compared to the reference AZO (see Figure 7.1).

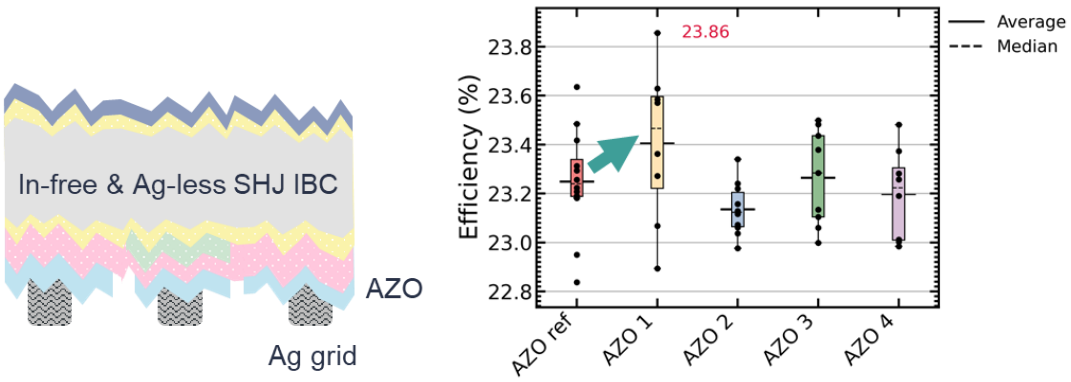


Figure 7.1: Schematic SHJ IBC solar cell structure with AZO developed in the RESILEX project and silver grid (reference, left) as well as the best efficiency obtained (right).

Additionally, the AZO layer deposition was developed on CEA pre-industrial PVD equipment and integrated into a pilot-line process for standard SHJ. Layers with promising performance were obtained and implemented on the front side and/or rear side of SHJ cells. In this way, we successfully demonstrated the integration of a "Front In-free" SHJ solar cell on the CEA pilot line, without efficiency loss, as well as a fully "In-free" SHJ cell with an efficiency loss of only 1.2% (see Figure 7.2). As with the previous approach, the stability of these cells under humidity is of particular importance, results are presented in the next section.

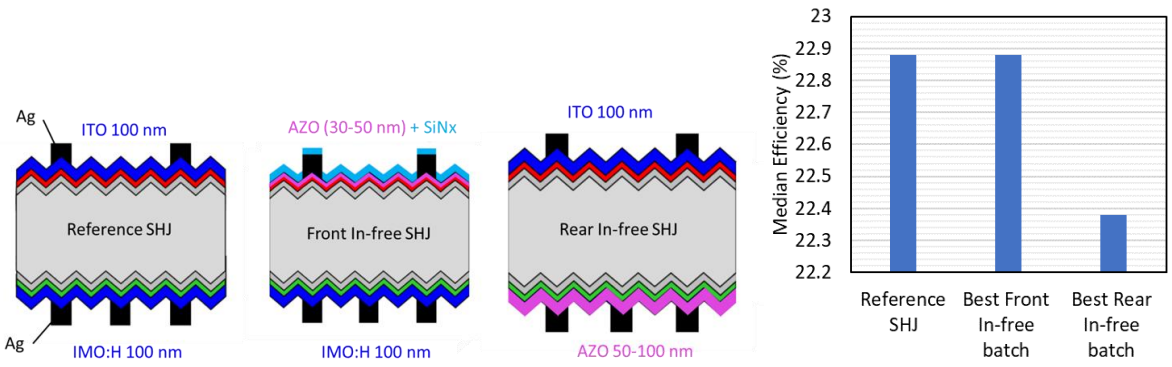


Figure 7.2: Schematic SHJ solar cell structure with standard indium consumption (reference) and SHJ structures with AZO layers tested in RESILEX and best performances obtained [Gageot 2025].

3) <u>The development of SnO_2 films as In-free TCO using an atmospheric pressure, low temperature and low environmental footprint spatial atomic layer deposition technique (AP-SALD):</u>

Regarding the development of In-free TCO by means of AP-SALD, we have investigated the applicability of SnO_2 thin films as transparent electrode in SHJ solar cells. We have demonstrated that low electron mobility is the main limiting factor resulting in lateral sheet resistances, about one order of magnitude higher than state of the art ITO films. We have proposed and explored ways for improving the electrical properties of SnO_2 through doping, hydrogenation and tuning of chemical composition. In addition, we have developed a SALD doping module that allow us to deposit mixed cation films with precise control in thickness and composition, and currently we are working on applying this setup on the fabrication of doped SnO_2 thin films. Hydrogenation of SnO_2 thin films points out to a passivating effect of H_2 on the thin films,can potentially help in increasing electron densities without an effect in mobility. Additionally, we have worked on the optimization of the deposition process to achieve deposition rates that are more compatible with industrial processes.

In this project, efforts have been axed in three critical aspects:

- Lowering deposition temperature for SHJ process compatibility (T_{dep}<230 °C)
- Reducing electrical resistivity to the order of 10^{-3}–10^{-4} Ω.cm, keeping transmittance up to 80% in the VIS-IR range of the solar spectrum
- Increasing deposition rates (0.02 Angstrom/s in the beginning of this task) to increase process compatibility with industrial production.

We have tested deposition of SnO_x using different oxidant precursors, of variable reactivity. Best results are obtained using a non-toxic, mixed precursor based in H_2O at 70%. The increased reactivity of the mixture, deposited at 220 °C, allow to increased deposition rates up to 0.64 nm/s. At the same time, electrical resistivity is decreased up to $5.5x10^{-3}$ Ω.cm for glass-deposited samples and up to $1.0x10^{-3}$ Ω.cm for samples deposited on intrinsically doped Si and SHJ precursors. A summary of the growth properties, and optical-electrical properties of different O-precursor content at two temperatures compatible with SHJ applications is shown in Figure 8.

Furthermore, we proposed AP-SALD as a less energy intensive alternative deposition technique to PVD. In AP-SALD setup, no pumping groups are needed as the entire deposition process is performed at ambient pressure. Additionally, the spatial separation between pulse-purge ALD steps (instead of time in traditional ALD) allows process development with competitive deposition rates, in contrast to traditional ALD.

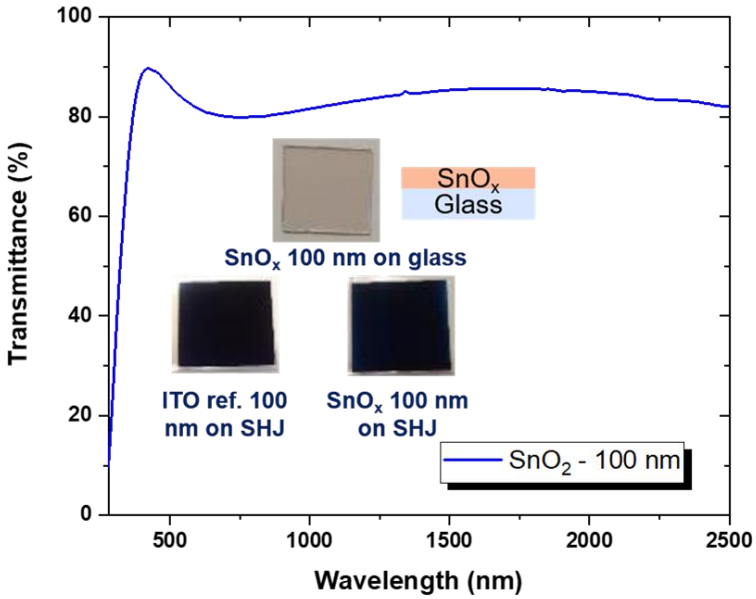


Figure 8: Transmittance spectrum of SnOx (250-2500 nm) deposited on silica glass substrate. Inset: Pictures of SnOx deposited on glass, and on SHJ compared to reference ITO.

4) <u>The use of copper containing paste deposited by screen-printing</u>

Regarding the use of copper-containing paste deposited by screen-printing, results have demonstrated the robustness of the process with large batches of solar cells processed on CEA pre-industrial line. A continuous improvement in silver reduction and performance was achieved during the project, thanks to industry efforts in developing new Ag/Cu paste formulations. By using these new pastes and applying tighter control over the screen-printing process, the latest results obtained on the pre-industrial line demonstrated the feasibility of achieving a total silver consumption as low as 10.9 mgAg/W, while maintaining an efficiency loss limited to 0.04%. Compared to the industrial reference of 24.6 mgAg/W at the beginning of the project, this result represents a 55% reduction in silver usage without compromising performance. The best results conducted to silver consumption as low as 6.8 mgAg/W in the RESILEX project (corresponding to a 72% Ag reduction). These results are ahead of current industrial practices and in line with achievements from other institutes.

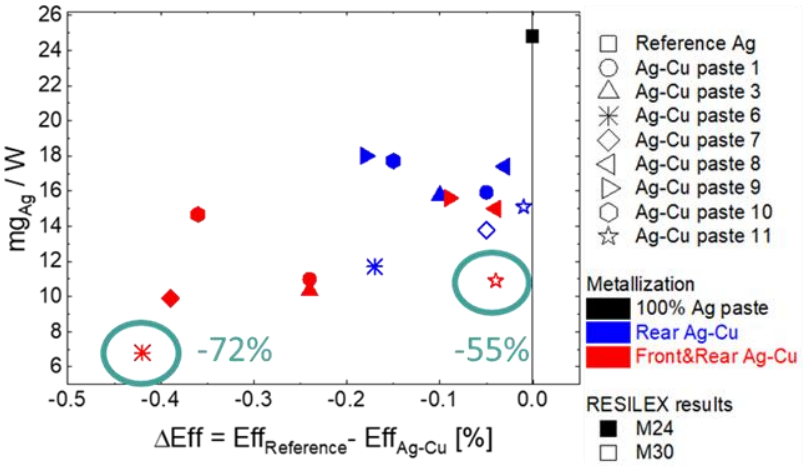


Figure 9.1: Ag consumption per watt-peak of the solar cell in correlation of the median efficiency loss for the rear only and the front & rear integration of the Ag/Cu pastes published in [Lanterne2 2024] (based on D4.3)

In addition, silver–copper (Ag/Cu) pastes were investigated at CSEM for the integration into SHJ IBC solar cells. Combining the optimized AZO layers presented in section 3.2.2 with the most promising Ag/Cu paste, we demonstrated indium-free and silver-less (with a silver reduction >70%) IBC solar cells up to 24.12% efficiency (see Figure 9.2). These developments demonstrated further the strong potential of SHJ IBC architecture to be an alternative for In-free and Ag-less solar cells.

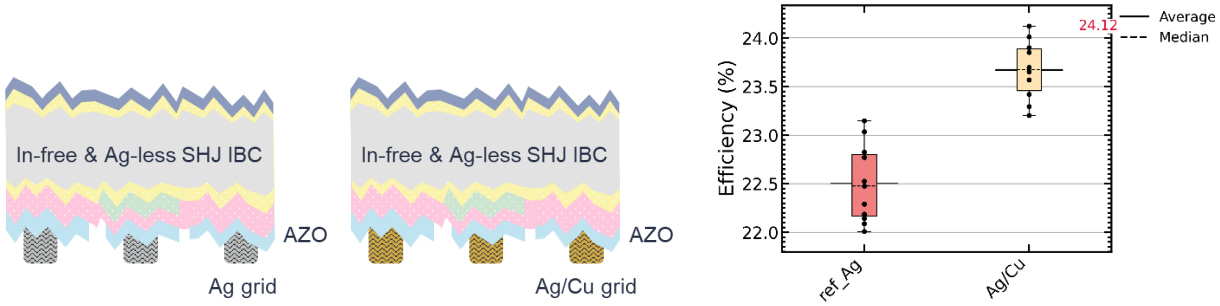


Figure 9.2: Schematic SHJ IBC solar cell structure with standard silver grid (reference, left) and with silver-copper grid (middle) tested in RESILEX as well as the best efficiency obtained on 4 cm^2 solar cells (right).

5) <u>The use of copper electroplating process</u>

Regarding the development of copper-plating process, we demonstrated that this process is a very promising solution to significantly reduce both indium and silver consumption in SHJ solar cells at the same time. Copper-plated SHJ solar cells with strong indium reduction (>70%) demonstrated efficiencies close to the references during our different investigations. In addition, this work allowed for significant optimization of the copper-plating process at different levels with a demonstration of (i) optimized Ag/Cu seed-grid and preliminary results of full copper seed-grid, (ii) optimized dielectric masking layers allowing for avoiding gosht plating, improved anti-

reflecting coating, providing TCOs re-hydrogenation and allowing for optimal copper fingers growth, as well as (iii) optimized copper-plating process with technological solutions close to industrial processes.

As main achievement, industrial indium-less and silver-less SHJ precursors were processed to assess the industrial potential of copper electroplating. Different ITO thicknesses and seed-grid configurations were tested. Dielectric layer deposition demonstrated again an increase in current and voltage, while slightly decreasing FF. The copper electroplating step substantially improved FF due to higher finger conductivity, leading to an overall efficiency increase despite a small current loss from added shading (see Figure 10). The best Cu-plated cell of this lot achieved 22.81% efficiency, approaching the reference group's average (22.95%), demonstrating further that Cu-plating can deliver high-performance In-less and Ag-less cells.

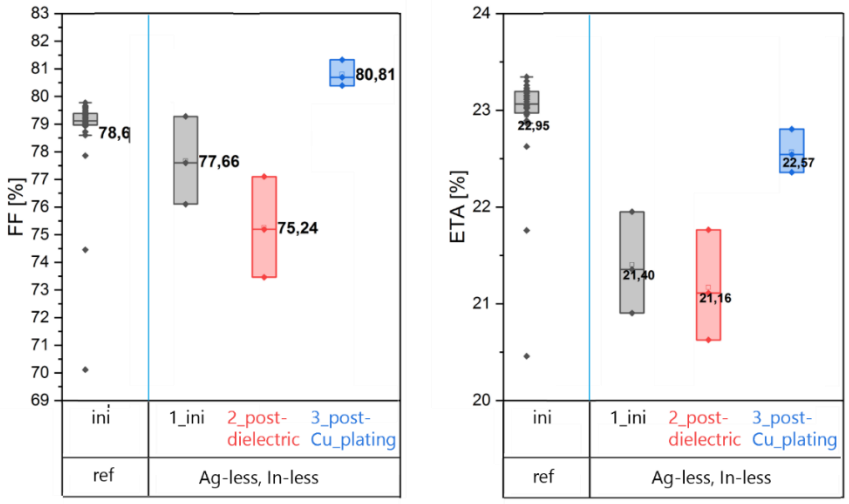


Figure 10: Field Factor (FF) and efficiency (ETA) of reference solar cell versus Ag-less, In-less solar cells using Cu plating.

6) The use a thin wafer to reduce Silicon

In the RESILEX project, we investigated the impact of indium reduction by processing "In-less" SHJ solar cells on thin silicon wafers. Conclusions highlight similar behaviours of the cell's current and Voc when wafer is reduced from 165 µm to 65 µm, for the "In-less" SHJ solar cells process than for a "Reference" SHJ process. But in the end, the efficiency loss when reducing wafer thickness to 65 µm is more pronounced for the "In-less" SHJ (a loss of 4.8%abs, compared to 3.1%abs for the reference) due to larger FF losses and large dispersion in this parameter. Results highlight additional issue in the manufacturing of the "In-less" process on 65 µm wafers, such as breakages, that could be related to the addition of a PECVD step.

3.3 Reliability investigations

The long-term stability and reliability of the solar cells developed in RESILEX was assessed through standard module aging tests such as Damp Heat (85% humidity and 85°C), thermal cycling (-40°C/+85°C) and UV test. Two lead-free innovating interconnection technologies were used for these tests: i) ribbons glued with electrically conductive adhesive (ECA) was tested at CEA ; ii) 0BB technology was tested at CSEM.
At CEA, three solar cells innovation were assessed with ECA: i) the use of ultra-thin ITO layers to process "In-less SHJ", ii) the use of AZO (PVD) layers used in "front or rear In-free SHJ" and iii) the use of Ag-Cu screen-printed pastes to process "Ag-less SHJ". At CSEM the copper plating approach was assessed with the 0BB technology.

1) Stability of "In-less" SHJ with ultra-thin In-based TCO:

During the development of the bilayer approach to reduce indium on the front side of the cell, reliability tests on modules with ultrathin ITO layers were carried out by CEA. The impact of thin ITO layers of 5, 10 and 15 nm on the UV reliability was assessed for three selective layers (a-Si:H, nc-Si:H and nc-SiOx:H). The cells were integrated into one-half cell mini-modules in a glass/backsheet architecture. The results highlight an enhanced reliability against UV for thinner ITO layers and show that the nc-SiOx:H selective layer is unstable upon UV exposure. DH tests were subsequently performed on the UV-exposed modules. They did not raise any particular concern regarding the usage of ultrathin ITOs of 15 nm and 10 nm on the front side. However, a strong deterioration is observed for the 5 nm layers. In addition, the highest module efficiency after UV + DH was achieved with nc-Si:H layers in combination with 15 nm ITO on the front side.

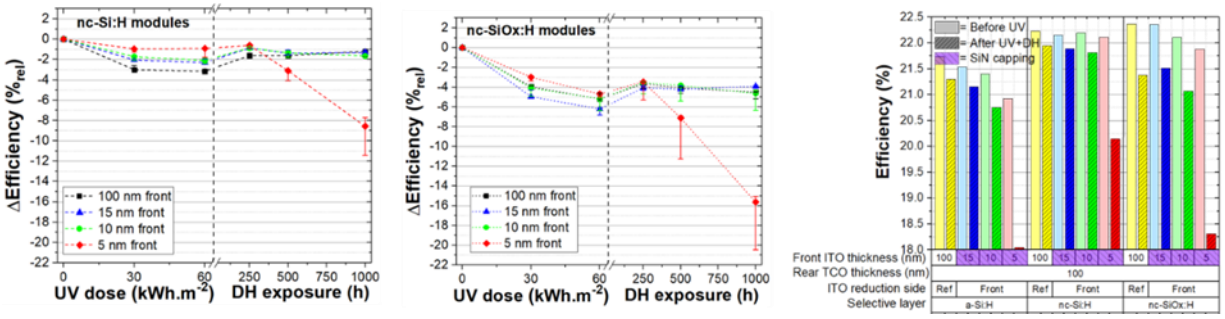


Figure 11: (left) Relative efficiency losses of modules with ultrathin front ITOs on nc-Si:H and nc-SiOx:H and (right) absolute efficiency variations after 60 kW h.m-2followed by 1000h of DH exposure. The points represent the median module, and positive and negative error bars best and worse modules respectively (results published in [Gageot2023].

Following these results, the combination of 15 nm of ITO with SiNx layer on the front and an IMO:H layer of 40 nm on the rear was further studied, as it became our standard "In-less" process in RESILEX. It corresponds to an Indium reduction of 72%.

The behavior under UV degradation was thus studied in 1 ½ cell glass-backsheet mono-module with TPO encapsulant (as tested as new material in this project for eco-designed BoM of the module). Results that were published in [Lanterne 2024] confirm an improved UV stability for "In-less" SHJ modules as compared to reference modules with thick ITO. This was previously observed in our work and shows an additional benefit of using thin ITO. In addition, a second study was focused on the damp heat (DH) test of In-less SHJ in 2 ½ glass-glass mini-module configuration using POE encapsulant. Results were very promising with P_{max} losses limited below 5% after 3000h of damp heat exposure (85% humidity and 85°C) below the standard for all the modules. However, after 2000h of DH, a clear trend of larger impact of humidity on the low indium content modules is observed (see Figure 12.1 below).

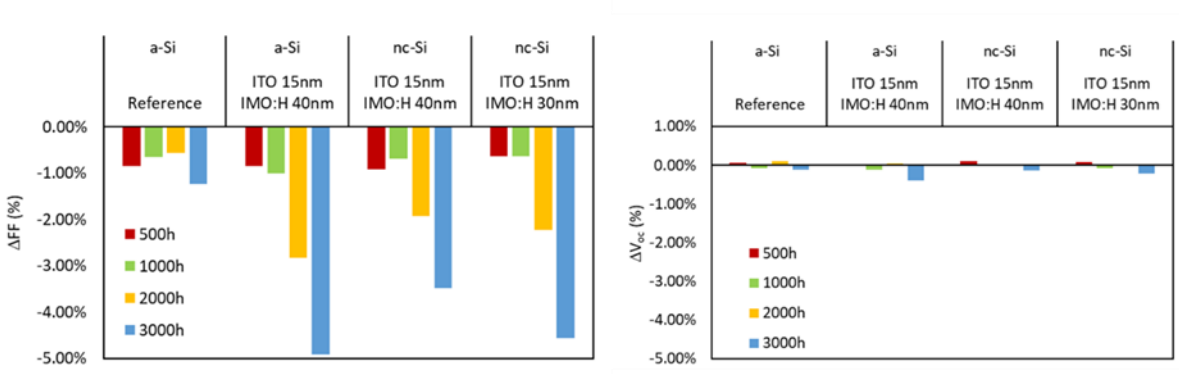


Figure 12.1: FF and Voc relative variation after DH exposure. Average values of three mini-module cf. [Lanterne 2024].

In conclusion, results concerning thin-ITO approach raise no concern for industrial transfer at this stage as all standards passed. However, the results highlight a higher sensitivity to humidity for these cells than for reference SHJ. Thus, using alternative material for the module fabrication with higher permeability may have a stronger impact on these cells than standard ones. Alternatively, the addition of the SiNx layer on the rear side may reduce further the humidity effect on these cells and should be investigated.

2) Stability of front or rear "In-free" SHJ with AZO layers:

The reliability of the most promising process of SHJ solar cells with AZO layers on the front and rear side was studied at CEA with ECA interconnection in one half cell mini-modules and glass/backsheet architecture (6 modules per condition). The module stability under damp heat (85% humidity and 85°C) was studied up to 1000h (one time the standard) and can be seen on the Figure 12.2 below from [Gageot 2025].

On the rear side, the condition with 100 nm of AZO layer was assessed. As compared to 100 nm of In-based TCO, only a slight increase of the FF deterioration is observed. The modules passed one time the standard under DH, which is very promising for this approach. Its integration is now limited by the efficiency losses at the cell level (0.5% loss) which is not acceptable for industry and implies pursuing the layer development for rear integration.

For the front side, the stability of three thicknesses of AZO from 30 to 50 nm was studied. One batch without SiNx:H capping layer was also processed in order to see the impact of this dielectric on the module reliability.A direct impact of the AZO thickness on the module stability was observed with higher FF degradation measured at 30 nm than 50 nm. We also measured better stability under DH without the SiNx:H capping layer. The results for 50 nm of AZO are promising with a similar degradation than In-based TCO at 1000h. Also, the negative impact of the capping layer opens the way of improvement with the test of another dielectric. If 50 nm of AZO must be used for reliability, a less absorbent AZO layer must be developed to use a thicker layer without impacting efficiency.

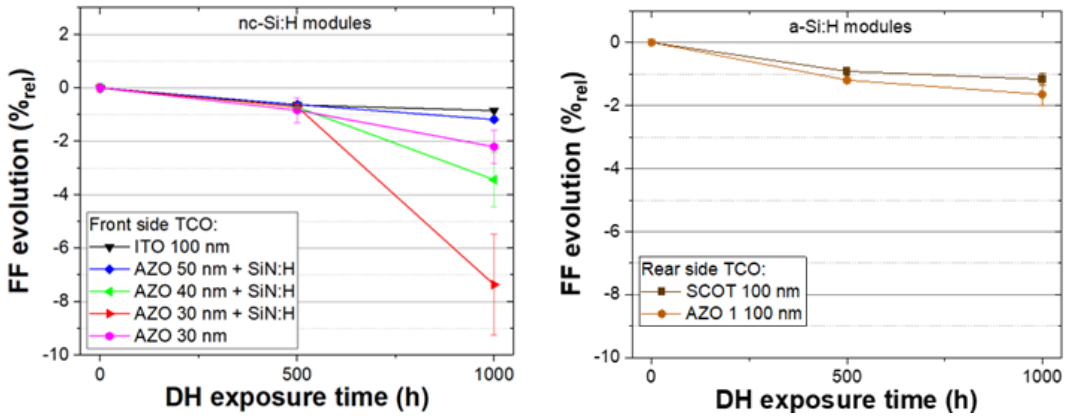


Figure 12.2: FF relative variation after DH exposure for module with AZO on the front (left) and module with AZO on the rear (published in [Gageot 2025]).

In conclusion, the thick AZO layers (above 50nm) show promising stability performances and passed one time the IEC standards for the DH test. However, it was the thinner layer of 30nm that allowed integration without efficiency losses. Reducing the absorption of thicker layers seems then necessary or investigate alternative capping dielectric to improve the humidity stability of thinner ones.

3) Stability of "Ag-less" SHJ with Ag/Cu pastes based metallization:

The use of copper-based pastes (Ag/Cu) is a very promising solution for reducing silver consumption, but one of the main concerns is the stability of the metallization and interconnection under humidity, meaning that processing and reliability issues need to be resolved before mass production can begin.

The reliability of the Ag/Cu paste based metallization was assessed in RESILEX after interconnection and module integration at CEA. For selected Ag/Cu pastes, mini-modules were fabricated with ECA bonding, glass-glass module configuration, and POE encapsulant. To assess the impact of silver reduction on the module performances and reliability, the module Pmax and FF were measured after thermal cycling (-40°C/+85°C) and DH exposure.

The first Ag/Cu paste assessed in RESILEX shows promising module results with a slow degradation of the FF of only 2% after 600 thermal cycle and a Pmax loss less than 2.5% after 1000h of DH. Three other Ag/Cu paste were then assessed under DH (see Figure 13) up to 2000h. Results of paste 1 and 2 highlight the problematic of the larger humidity degradation that is measured for some Ag/Cu pastes with larger power loss than the silver metallization at 2000h.

However, for one more recent Ag/Cu paste (paste 3), similar degradation than silver reference after 2000h was obtained. This is an excellent result, as this paste passed two times the IEC standards with similar behavior to Ag paste.

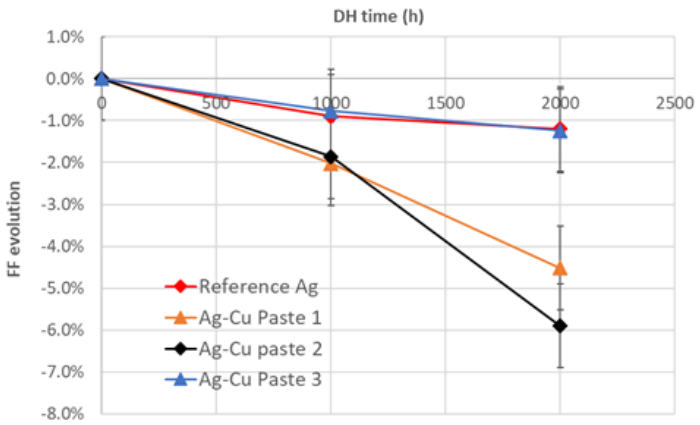


Figure 13: FF relative variation after DH exposure for various Ag/Cu paste.

Following these first tests, the reliability of this approach was further studied at CEA outside the scope of the RESILEX project. The results published in [Monna 2025], confirm what was observed in RESILEX. Indeed, two other recent Ag/Cu pastes demonstrate similar degradation than Ag paste under 2000h of DH and 400 TC, opening the way for massive industrialization of this approach.

4) Damp heat aging of Cu-plated cells:

Cu-plated cells combined with various dielectric layers deposited at CSEM and CEA were investigated using low-temperature zero busbar (0BB) interconnection.

Given the known sensitivity of copper metallization to humidity, Cuplated cells incorporating various dielectric layers deposited at CSEM and CEA were investigated. The cells were encapsulated in a minimodule configuration using lowtemperature zerobusbar (0BB) interconnection and exposed to dampheat (DH) conditions for up to 2000 hours. Results indicate that the reference module fails after 2000 hours in DH, while Cu-plated modules exhibit an average performance loss of about -2%, with no significant differences among the tested dielectrics (see Figure 14). The degradation observed in the reference module is primarily due to interconnection failures, as illustrated in Figure 15, and the presence of dielectric layer could improve the adhesion.

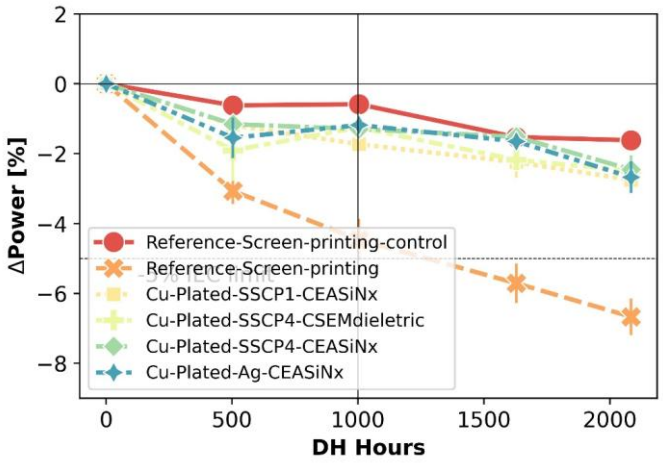


Figure 14: Relative percentage power loss of Cu-plated modules with 0BB interconnection under damp heat (DH) exposure

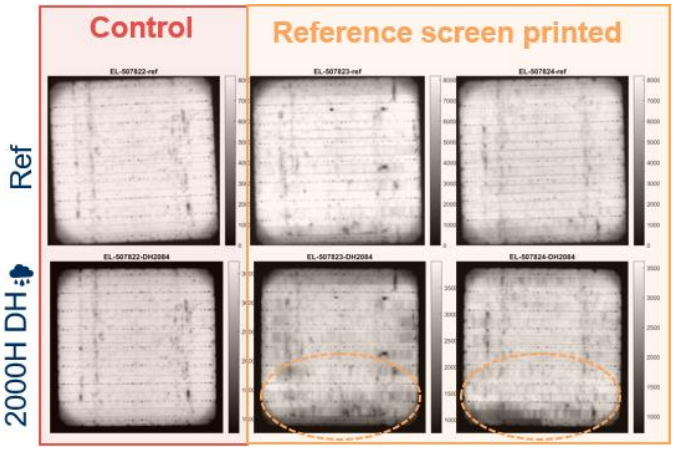


Figure 15: EL of screen-printed PV modules after degradation

5) UV aging of Cu-plated cells:

To complete the DH aging study, the reliability of mini-modules integrating Cu-plated cells under UV exposure was investigated. Cu-plated solar cells made at CSEM with industrial precursors (from task 4.2) were interconnected with 0BB interconnection technology and implemented in mini-modules with a glass-glass configuration.

Three different types of cells were encapsulated in glass-glass modules:

- Reference cell (group 1) with Ag metallization, 80nm front ITO and no dielectric deposition and no Cu-plating.
- In-less cell (group 2) with 50nm front ITO, Ag seed-grid with dielectric layer and Cu-plating.
- In-low cell (group 5) with 30nm front ITO, Ag see-grid with dielectric layer and Cu-plating.

The initial performance of the modules was evaluated, with mini-module efficiency ranging from 19.59% to 21.84%, and a cell-to-module ratio between 89% and 97%. After manufacturing and initial measurements, all mini-modules were placed in a UV chamber, except three modules (one per group) acting as control modules, which were stored in a dark place with ambient air. After a given time in the UV chamber, the modules were removed, measured, and the results analysed before placing them back into the UV chamber. This process was repeated multiple times to achieve a final UV dose of 150 kWh/m² for all modules. Figure 16 below presents the power relative variation as a function of the UV dose.

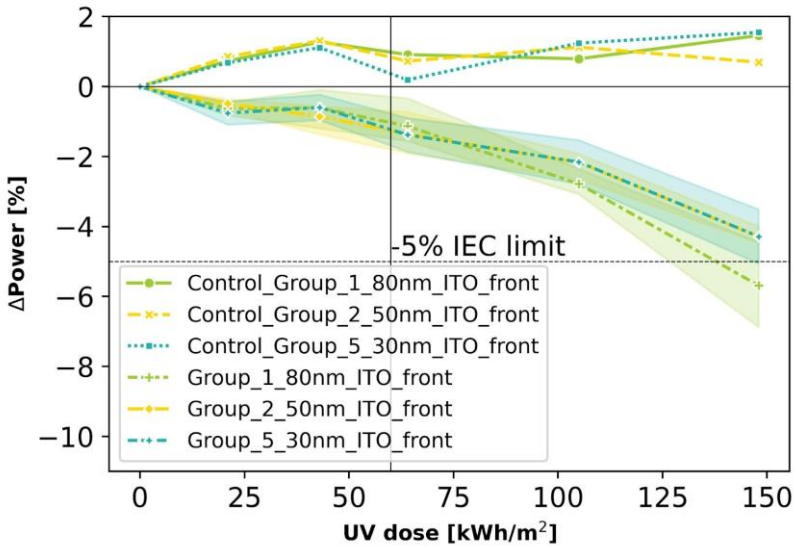


Figure 16: Relative power variation as a function of the UV dose for the different groups.

Similar trends for group 1, group 2 and group 5 are observed with a great power stability (<4% loss for 100 kWh/m² UV exposure). In particular, group 2 (50 nm ITO with Cu-plating) and group 5 (30 nm ITO with Cu-plating) show degradation below 5% after 150 kWh/m² UV dose. These results demonstrate strong potential for adopting copper

plating process using a dielectric layer to ensure module stability under UV-induced degradation, while maintaining high efficiency over time.

3.4 Recyclability

The eco-design strategies applied to c-Si solar cells in this project impact not only the cell supply chain and manufacturing processes but may also impact PV recycling operations. To assess their influence on the recyclability of PV solar cells and modules, these strategies have been analysed and discussed in collaboration with COMET, a mechanical recycler and consortium partner leading Work Package 5.

- **In-less and In-free solar cells**: Reducing, or even removing, the indium content of SHJ solar cells has a negligeable impact on PV module recyclability. No specific interest in indium was expressed by smelters working with COMET and the quantity of indium in a PV module is negligeable in any case.

- **Ag-less and Ag-free solar cells**: Reduction of silver content reduces the economic value made through PV panel recycling. Silver is present in small quantities in today's recycled PV modules (<0.5% content) but has a high economic value. Silver is currently part of a poly-metallic concentrate that is sold by COMET to smelters. The economic value of the concentrate is proportional to the content of valuable metals, such as silver. By reducing the amount of silver, less economic value can be generated by PV recyclers from PV module recycling. Nevertheless, copper is a metal of interest to replace silver, as it possesses a lower, but still notable economic value and is easily recovered and recycled, limiting partly the reduction of the economic value of the concentrate of metals containing less or no silver.

- **Si-less solar cells**: The reduction of wafer thickness will lead to a reduction of silicon content. The silicon represents 4% of the mass of c-Si PV modules recycled in 2025 [SOREN]. Over the years, PV industry has seen an increase of mono-silicon vs poly-silicon and a reduction of wafer thickness. This trend is affecting PV recyclers with a delay of 20-30 years due to PV module lifetime. For now, valorisation of silicon at the end-of-life is being evaluated by multiple recyclers, such as ROSI or COMET. If the reuse of silicon from aged PV modules appears to be possible and economically viable, the silicon wafer thickness reduction could have a negative impact on the economic viability of PV module recycling in the long-term.

4.Eco-design developments for PV modules

The strategies explored in the project to develop eco-designed PV modules are organized into several research and development directions, as presented below:

- Material selection and development for low environmental impact bill of materials (BoM)
- Extended material analysis of selected materials
- Study of the reliability and compatibility of new materials in PV module configuration
- Production of modules with eco-designed BoM

The results of the developments performed by CEA and CSEM for each R&D directions have been first reported in deliverable D4.2. A summary of the results presented in D4.2 for each development can be found below, along with new results obtained since M36.

Eco-design strategies for PV modules developed in WP4 were presented in table 4. The following **section (4.1)** discusses the **LCA results** of the reference and eco-design scenarios as well as bio-based materials. The research and **selection of eco-design materials** for PV modules are presented in **section 4.2**. The **eco-designed BoM** of PV modules as well as their initial **performance and reliability** are presented in **section 4.3**. Finally, **section 4.4** highlights the implications of the different eco-design strategies for **recycling** through insights from COMET, a recycling partner leading RESILEX WP5.

4.1 Scenarios & LCA results

Previous section showed that various materials are candidates for eco-design bill-of-materials. To assess their potential, the environmental footprint of three main scenarios was evaluated. In addition, bio-based materials appear to play a central role in the eco-design solutions studied and are widely promoted for reducing environmental and carbon impacts. A thorough LCA evaluations was carried to validate their true sustainability potential.

1) Resilex Scenarios & LCA results

Based on the eco-design considerations and investigations detailed in deliverable D4.1, three main scenarios for the PV module composition were proposed and are detailed in table 5. The reference scenario represents the reference glass-backsheet PV module with components corresponding to the mainstream PV module composition. Scenario 1 represents a glass-glass module with copper wire and ECA interconnections, a TPO encapsulant and aluminium frame. Scenario 2 is identical to scenario 1 except that the aluminium frame is replaced by a wooden frame, and the backsheet is a PET fluorine-free backsheet. Note that the different materials employed in the module composition will be detailed later in this report.

Table 5. Overview of the module's composition for reference, scenario 1 and 2. ECA = Electrically Conductive Adhesive, TPE = Thermoplastic Elastomer, PET = Polyethylene terephthalate, EVA = Ethylenevinyl Acetate, TPO = Thermoplastic Olefin

Compartment	IT6-Reference	IT6-scenario 1	IT6-scenario 2
Cell interconnection	Multiwire brazing	Cu ribbons with ECA	Cu ribbons with ECA
Frontsheet	Glass	Glass	Glass
Backsheet	TPE	Glass	PET without fluorine
Encapsulant	EVA	TPO	TPO
Frame	Aluminium	Aluminium	Wood

These three scenarios were shared with the RESILEX WP7 team for a complete assessment of their economic, environmental, and societal impacts. The results of the environmental assessment of the three scenarios are detailed in the Figure 17 based on deliverable D7.2.

A net tendency arises for climate change, human toxicity (cancer and non-cancer), land use and use of fossil resources, for which the scenario 2 has always the lowest impact. The reference scenario features always the highest impact, followed by a slightly lower impact for scenario 1 (94-98%). For freshwater ecotoxicity, the Scenario 1 has the highest impact, while for the use of mineral and metal resources, scenarios 1 and 2 present highest impact than the reference.

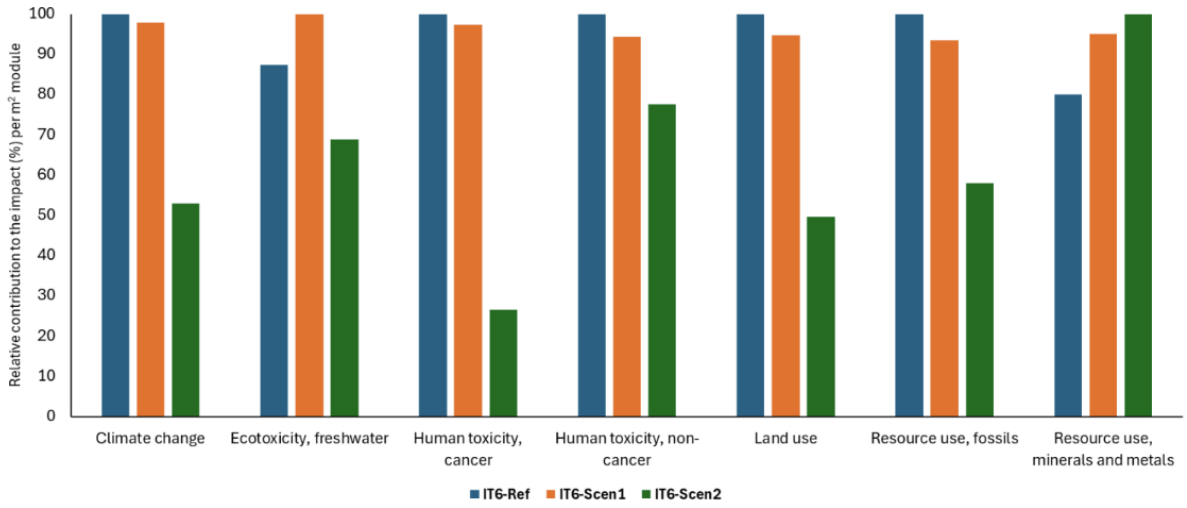


Figure 17: Environmental impact of the reference (IT6-Ref) and alternative scenarios (IT6-Scen 1 & 2), expressed by m2 of SHJ module. The impact of each scenario is expressed in percentage relative to the highest impact in each impact category.

Detailed results are presented in D7.2 deliverable. As major conclusion:

- The use of **aluminium** as a **frame** contributes significantly to the total impact of module assembly for climate change, fossil resource use, freshwater ecotoxicity, human toxicity-cancer and land use. When aluminium is substituted with wood, the frame's contribution to the total impact becomes almost negligeable across all impact categories, except for land use.

- **Cell interconnections** are the major contributor to the module impact on non-cancer human toxicity and on minerals and metals resource use. When replacing multi-wire brazing by copper ribbons and ECA, the impact is stable for human toxicity and land use but rises for the other impact categories. This rise is due to the higher content of silver in the ECA and copper ribbons solution compared to the multiwire brazing solution.

- **Frontsheet** and **backsheet** are important contributors of the PV module impact on climate change, ecotoxicity freshwater, resource use fossils and land use. Polymer sheets have overall a lower environmental footprint than glass sheets. Nevertheless, the environmental impact of the frontsheet-backsheet couple is similar, being it either glass-glass or glass-polymer. The reason is that the use of a polymer backsheet requires a thicker glass sheet to maintain the rigidity of the PV module compared to the glass sheet thickness of a glass-glass configuration.

- **Encapsulant** have a small contribution to the PV module assembly impact. This contribution is superior to 10% of the total for the use of fossil resources and climate change. By replacing EVA with TPO, the impact of the encapsulant is reduced for all impact categories.

Building on the previously discussed LCA results, it becomes evident that further reductions in the environmental impact of PV module assembly could be achieved by combining specific material and design changes. For instance, replacing the aluminium frame with a wooden alternative, opting for TPO instead of EVA as the encapsulant, and eliminating silver from the interconnection process all appear to significantly lower the overall footprint of the module.

2) LCA of different BOM configuration (focus on frontsheet-backsheet changes)

To guide further our developments, a preliminary LCA study was performed to assess the eco-design BoM's potential to reduce environmental impact. Figure 18 compares the global warming potential of an eco-designed module integrating flax backsheet, PO encapsulant and non-fluorinated frontsheet with conventional glass/glass and glass/backsheet designs. Double-glass modules show the highest impact due to glass, while the eco-design module features the lowest impact. Although the flax backsheet has a higher CO_2 impact than conventional backsheets, it enables glass removal, significantly lowering overall impact, in addition to eliminate fluor content, which improves recyclability. These results highlight that not only the components themselves matter for reducing the environmental impact, but that their smart combination and integration are also crucial. In addition, as mentioned previously, the lifetime of the eco-designed PV module will determine its overall environmental impact and is a central focus of this project.

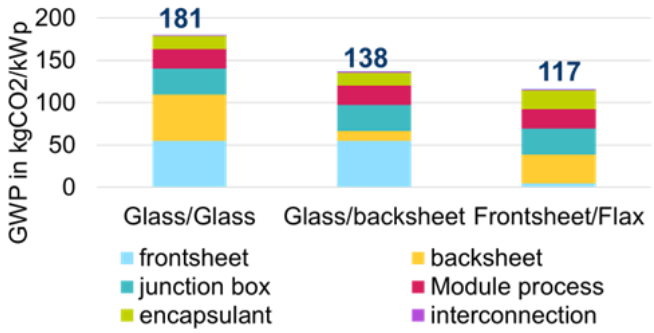


Figure 18: Global warming potential (GWP) of PV modules with three different BoM.

3) Bio-based materials and LCA

Bio-based materials are not yet widely used in PV modules and represent a relatively new area of research and development. To deepen this investigation, a comprehensive literature review was carried out to assess the potential benefits of incorporating bio-based materials into PV modules within eco-design approaches and completed with our expertise. Our findings indicate that substituting certain PV module components with bio-based materials is technically feasible, with the backsheet being the most frequently assessed element. However, these substitutions have rarely been evaluated in terms of their impact on module electrical performance and reliability. Furthermore, the environmental implications of such substitutions have generally not been addressed.

Our own research shows that replacing conventional PV polymers (encapsulant and backsheet) with bio-based alternatives does not automatically reduce the carbon footprint of solar electricity. This is due to several factors:

- The carbon footprint of bio-based polymers is not inherently lower than that of fossil-based polymers and must be assessed on a case-by-case basis.
- The contribution of encapsulant or backsheet materials to the overall carbon footprint of electricity generation is relatively small (approximately 1%).
- Any substitution must be accompanied by a comprehensive evaluation of module performance and lifetime. If durability is compromised, the overall environmental impact could increase. For example, biodegradable materials such as PLA fail to provide a long-term stability and are therefore unsuitable.

Beyond carbon emissions, the use of bio-based materials raises other sustainability concerns, such as land use and water consumption. Our estimates indicate that supplying the PV industry with first generation biobased polymers (i.e., derived from eatable resources) for encapsulant and backsheet production, would require twice the land area needed to install these modules, approximately 2.4Mha, or 1.6% of global arable land. Water consumption varies significantly depending on crop type and location, ranging from 6% to 61% of the water demand associated with PV module production.

We therefore recommend a case-by-case evaluation of the use of biobased materials in PV. Among the options explored, replacing aluminum frames with wood appears to be the most promising approach in terms of bio-based material use. A paper has been submitted on bio-based materials for PV topic and should be published soon.

4.2 Eco-design bill of materials investigation

Previous section assessed the environmental impact of various eco-design configurations and materials. PV module components have defined properties and characteristics that eco-design materials must meet to ensure their suitability as reliable eco-design PV components. This section highlights the main eco-design strategies and their potential to replace materials currently used in PV module production.

As presented in D4.2, literature review showed important research on substituting polymeric backsheet with bio-based composites, and fewer on substituting fossil-based with bio-based alternatives (for polymer production). To select relevant bio-based materials for PV, we defined a methodology, including material screening, testing and implementation at the module level as well as environmental evaluation.

Based on the material screening, Figure 19 highlights the materials that were identified as particularly relevant for deeper eco-design potential assessment. In addition to the bio-based materials for sheets, frame and encapsulant, fluor-free polymers are evaluated as well as lead-free (possibly Ag-less) interconnections (0BB, ECA and Cu ribbon) and eco-designed solar cells developed by WP4 team.

PV module component	Mainstream materials	Eco-design materials
Encapsulant	EVA polymer: • Non-bio-based • Cross-linking	Polymer: • Bio-based • Low cross-linking
Front and backsheet	TPE Polymer • No bio-based Glass	• Bio-based and fluor-free Polymers • Composites: wood, flax, ... • Thin or recycled glass
Frame	Metal: • Aluminium	Bio-based: • Wood
Interconnection	Metalic interco.: • Multi-wire brazing with silver and lead	Alternative interco.: • 0BB and ECA • Copper ribbons • Lead-free
Solar cell	SHJ solar cells: • Indium • Silver • Silicon	Eco-design SHJ solar cells: • Indium-less/free • Silver-less/free • Silicon-less

Figure 19: Eco-design developments evaluated in WP4.

1) Bio-based frame (wood to substitute aluminium):

The objective of frame study was to analyse the feasibility of replacing existing PV module frames with an eco-designed alternative featuring a reduced environmental footprint. To this aim, we targeted a bio-based solution—namely, a **timber frame**. To evaluate the stress constraints of the frame based on wood, CEA developed a numerical model. This model demonstrated theoretical similar mechanical performance by replacing the aluminium frame with one made of local wood species. However, this alternative is heavier for equivalent performance (approximately 35 % increase in weight) as wood density is higher than aluminium one. Outside the scope of RESILEX, CEA also performed material and module level qualification to select the best wood species for frame. Results published in [Bejat 2024] suggests Acacia, widely available in Europe, as the most promising wood species for bio-based frame.

Significantly this study demonstrated that the manufacture of PV modules with natural fibre could be relevant for certain applications. However, total lifetime estimates are not yet possible at this stage of the work and will be addressed in the next steps of the study. Indeed, understanding the durability of assemblies, which can have an impact on frame stability, is essential. Future optimization should focus on frame assembly techniques to ensure high resistance to weather-induced degradation. In addition, a comprehensive qualification process will have to be carried out to determine the extended performance of wood frames compared with aluminium frames. This work aims to pave the way towards exploration of novel material types for framing to ensure a massive reduction of environmental footprint of PV modules.

2) Fluor-free polymer frontsheet to replace glass:

As presented in Figure 19, replacing the glass frontsheet in a PV module with a polymer alternative can reduce the module's CO_2 intensity. However, this substitution does not guarantee long term durability, which could ultimately increase the environmental impact of solar electricity if the module lifetime is shortened. Despite this limitation, polymer frontsheet are valuable for lightweight applications, such as vehicle integration or rooftops that cannot support the weight of conventional glass-based modules. Currently, most polymer frontsheet used in lightweight PV application contain fluoropolymers, which pose significant challenges for recycling and material recovery as discussed in previous sections. To address this issue, a flexible, non-fluorinated polymer frontsheet was developed and extruded at CSEM. Due to its flexibility, this frontsheet requires a rigid backsheet to ensure mechanical

stability of the module. To comply with eco-design strategies, this fluor-free frontsheet was tested in combination with the composite flax based backsheet (see next section), demonstrating a potential pathway toward more sustainable lightweight PV designs.

3) Fluorine-free materials:

- Fluor-free flexible backsheet (alu-PET):

Backsheets have historically contained fluoropolymers to enhance resistance to outdoor stressors. Recent studies showed that the use of fluoropolymers can result in PFAS pollution at several stages of the backsheet's lifetime. To avoid this, we turned toward fluorine-free polymers. To reduce the environmental footprint, we opted for a European fluorine-free multi-layer backsheet. During material testing and module integration, we used a partially recycled fluorine-free backsheet from a European manufacturer. Despite research efforts, this backsheet had to be discarded for further application as its damp-heat performance was too poor. For the final demonstrator, we used a PET-core fluorine-free backsheet with a thin aluminium layer to improve moisture-ingress resistance.

- Fluor-free rigid backsheet (bio-based with reinforced polymer):

Since none of the PV modules containing bio-based materials described in the literature have been evaluated through both reliability and environmental studies, we developed our own bill of materials and conducted an assessment for a lightweight application. In this configuration, the backsheet can be a rigid composite, enabling the substitution of the front glass with a polymer frontsheet.

A composite backsheet incorporating natural fibres was selected for investigation. It is made of woven natural flax fibres combined with a polypropylene (PP) thermoplastic resin. A key advantage of this composite is that the PP resin is recyclable, unlike the epoxy resins commonly used in composite materials.

4) Zero busbar and lead-free interconnection:

It is possible to reduce the silver consumption at module level by using an interconnection technology without busbar (0BB), allowing to significantly decrease the use of metal (silver in most cases). In addition, this interconnection scheme brings more advantages regarding performance and reliability compared to standard multi-busbar brazing interconnection. Lead-free interconnections are also under investigation, by replacing conventional lead-based solders with alternative lead-free solutions. Adhesive bonding or lead-free 0BB interconnection, helps reduce the environmental and health risks associated with lead. Moreover, these alternatives enable lower process temperatures.

Another lead-free commercially available alternative of soldering to interconnect solar cells is using ribbons gluing with Electrically Conductive Adhesive (ECA), which is a promising interconnection technology. It is indeed a lead-free (along with bismuth or indium free) material. As a polymer material, its thermomechanical properties can be tuned and being a low-temperature interconnection technology, it offers low mechanical stresses, which facilitates the integration of tandem cells or other thin, stress-sensitive cell architectures. As ECA are composite materials consisting of a polymer matrix (acrylate, epoxy or silicone based) and by conductive particles (with different shape or materials), a proper material characterization and qualification are indispensable prior to its application in stringing. To remain sustainable, the interconnection of ECA ribbons must minimize Ag consumption at module level, with joint optimization of metallization at cell and module level and aim to use less harmful polymer matrix than actual ones (epoxy).

4.3 Performance and reliability investigations

Reducing the environmental impact at the material level is only one part of the challenge. The evaluated eco-designed materials must also ensure that the initial performance of PV modules remains competitive with conventional designs. A module with compromised efficiency would not meet industry requirements, regardless of its sustainability benefits of its components. Furthermore, beyond initial performance, long-term reliability is a critical consideration as PV modules are expected to deliver electricity consistently over decades, even under varying environmental conditions and aging stresses. Therefore, this section highlights the investigations carried on the eco-design choices and their influence on the electrical performance and reliability of PV modules.

1) PERC, IBC, SHJ cells with 0BB interconnection with non-fluorinated frontsheet, CSEM encapsulant and bio-based composite backsheet

Dedicated experiment was designed to test modules featuring the newly developed frontsheet, CSEM encapsulant that can be bio-based, and flax backsheet (module structure in Figure 20). Additionally, three types of solar cells were tested: PERC, IBC, and SHJ with 0BB interconnection, which is the targeted cell technology in the RESILEX project.

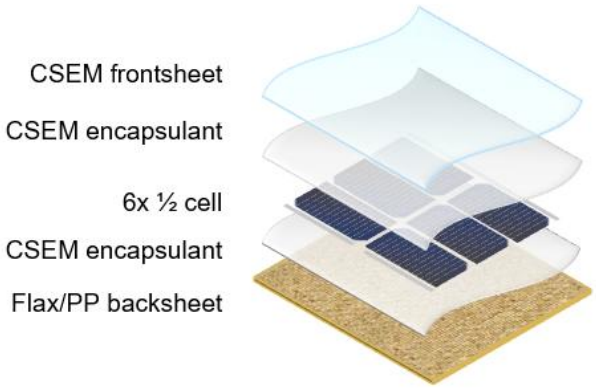


Figure 20: CSEM module stack with non-fluorinated frontsheet, CSEM encapsulant that can be biobased and a biobased composite backsheet

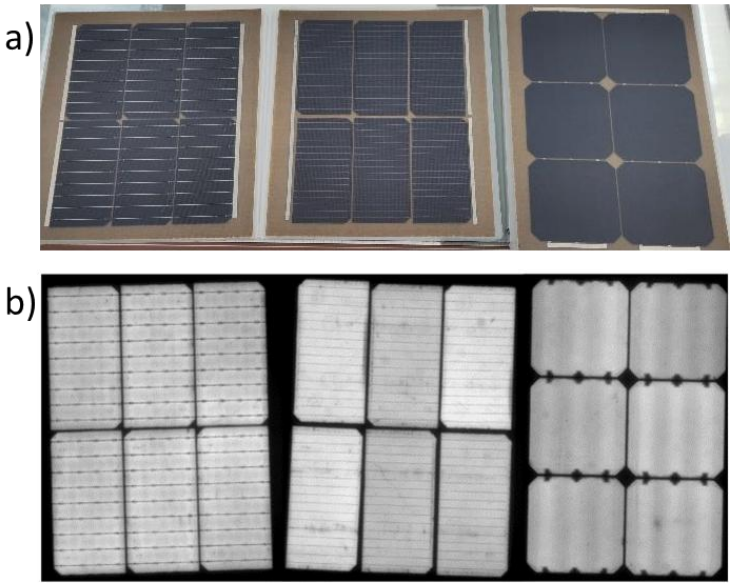


Figure 21: a) Image and b) EL of modules with, from left to right PERC, SHJ and IBC cells.

As demonstrated in Figure 21, after lamination the modules do not show visual defects or cell breakage. The materials are compatibles with one another for lamination

process. Their initial performance is shown in **¡Error! No se encuentra el origen de la referencia.**22.

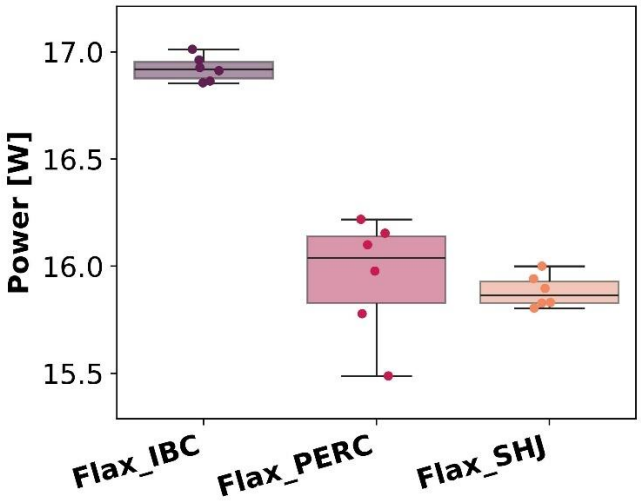


Figure 22: Initial performance of Flax modules with different commercial cell technologies.

Since module lifetime is crucial for achieving low CO_2 electricity production, reliability and durability must be thoroughly assessed. We evaluated performance under damp heat (85 °C, 85% Relative Humidity (RH)) and thermal cycling (–40 to +85 °C) according to IEC61215 standards of the flax lightweight modules. DH is particularly critical for humidity-sensitive cells such as SHJ. Thermal cycling can lead to mechanical stress and potential damage when the materials in the module have different thermal expansion coefficients. All modules passed twice the IEC requirement for TC, but PERC modules failed under DH. These results emphasize that moisture ingress through module materials is a major concern and should be minimized to prevent degradation of solar cells and interconnections. Overall, the findings are promising, though additional testing especially under UV exposure and sequential stress is needed to confirm long-term durability.

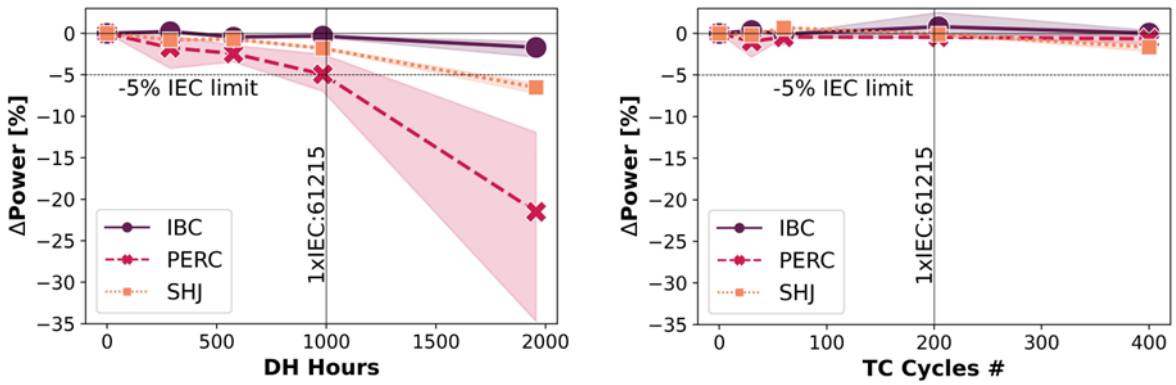


Figure 23: Performance loss of IBC, SHJ and PERC modules with the developed eco-design BoM under a) Damp Heat (DH) and b) Thermal Cycling (TC).

Additionally, some modules were placed outdoor for 9 months. As shown on Figure 24 the backsheet degrades. We tried to reproduce this degradation by placing the modules after DH and DH in UV for 60kWh/m2 (equivalent to 1 year outdoor). Unfortunately, modules did not show similar degradation.

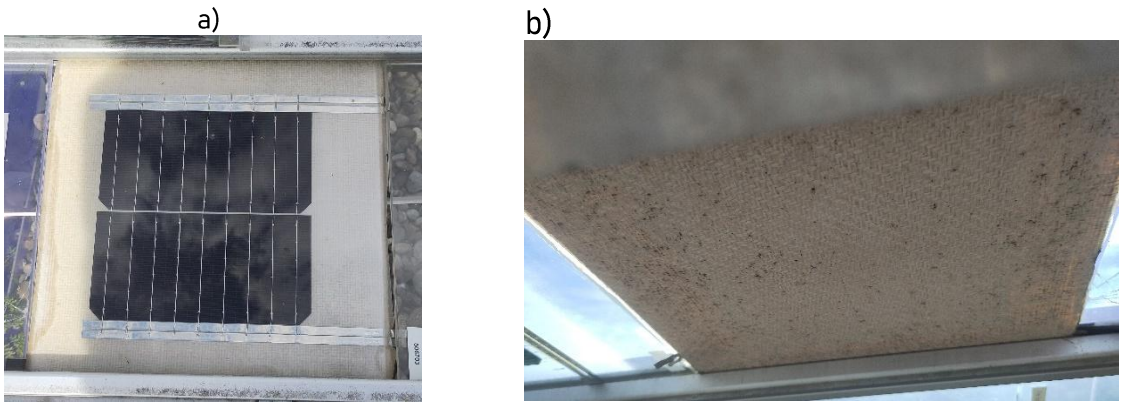


Figure 24: Picture of modules degraded outdoor after 9 months exposure: From a) the front view and b) the rear view.

2) <u>In-less SHJ cells interconnected with ECA in glass/glass vs polymer frontsheet/flax-backsheet configurations</u>

Other modules were made with indium-less SHJ cells interconnected with ECA. The same strings were used an implemented into a conventional glass/glass module and a lightweight-flax configuration. Their initial performance is shown in Figure 25. The initial performance of the lightweight BoM is higher and related to Isc, indeed the frontsheet is textured compared to glass that reflects incoming light. The modules are currently under reliability testing.

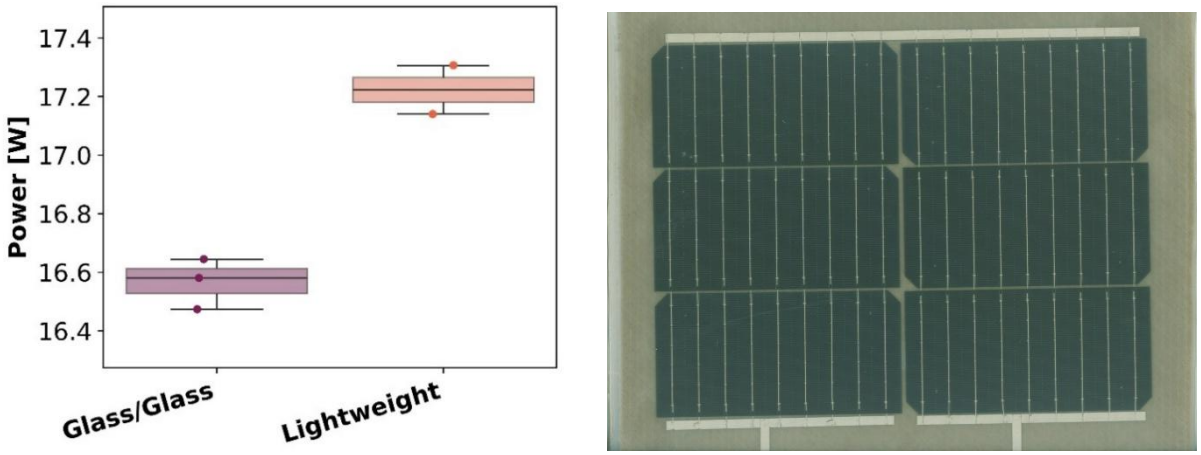


Figure 25: (Left) Initial performance of modules with In-less SHJ cells interconnected with ECA in glass/glass and lightweight flax configurations. (Right) picture of the flax lightweight module module.

3) IBC cell with polymer frontsheet, and wood-plank backsheet

Another exploratory work consists of the use of a wood plank as a backsheet as shown in Figure 26. The module passed 1xIEC in humidity freeze cycling (consisting of 10 temperature cycles varying between -60°C and + 85°C).

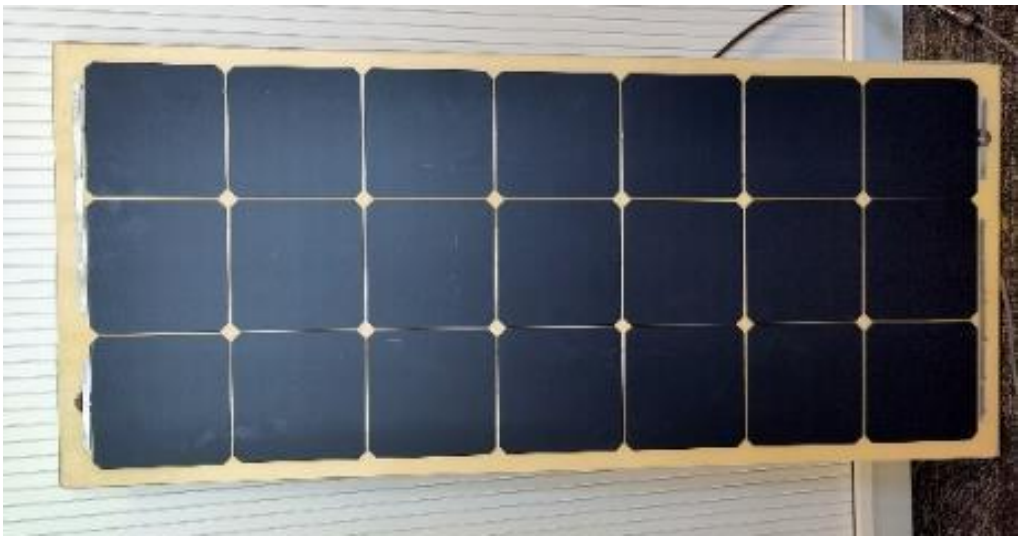


Figure 26: PV module with a wood plank as a backsheet.

4) Ag-less, (In-less) SHJ cell with ECA lead free, bio-based encapsulant in glass-glass and glass-backsheet configuration

In this first campaign we integrated SHJ solar cells with Ag/Cu metallization (silver reduced by 50% to 60%) and standard indium content (ITO of 100 nm) or an In reduction of 70% (ITO of 30 nm). The solar cells were interconnected with a ECA lead-free technology in M2 half-cell configuration.

Possibly bio based encapsulant from CSEM (CSEM TPO and CSEM TPOUV) were then laminated in glass / glass (G) or glass / backsheet (BS) configuration compared to a commercial encapsulant TPO2 in BS configuration. Accelerated DH aging tests had been launched for 3000 h with intermediate measurement steps on these modules. Variation of the performances during DH can be found on the Figures 27 and 28 below.

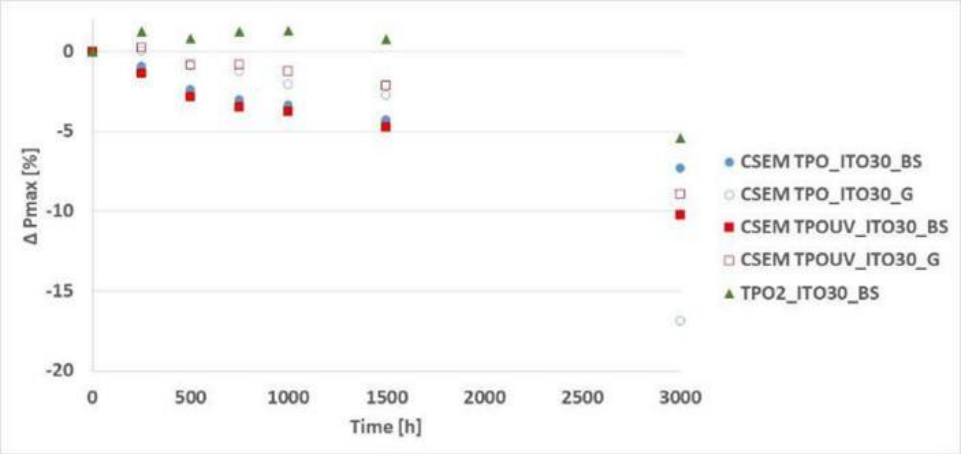


Figure 27: Variation in maximum module power output (Pmax) during DH aging – Cells with thin ITO

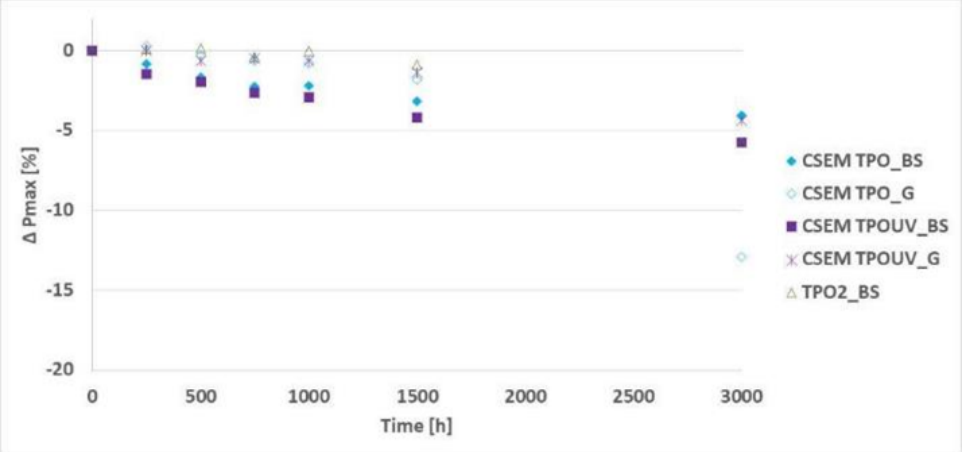


Figure 28: Variation in maximum module power output (Pmax) during DH aging – Cells with thick ITO

During this study we found that ITO thickness of 30 nm instead of 100 nm has no major influence on Pmax variation in DH aging up to 3000 h. Meanwhile, a slightly better Pmax performance belongs to thick ITO modules. The most striking result of this experimental campaign is the fact that all the studied modules passed the 1,5 x times the standard criterion in DH exposure (< 5 % Pmax loss after 1500 h DH) with European encapsulant and copper-based electrodes and two modules even had passed 3 x times the standard's requirement which is a very good result for this first trial.

The impact of the glass / backsheet configuration was also analysed for the two encapsulants in the project (CSEM TPO and CSEM TPOUV). Contrary to expectations, the glass/glass modules lost more power after 3000 h than the glass/backsheet modules with CSEM TPO encapsulant for both ITO thicknesses. It may come from premature cell degradation or glass leaching. This tendency was not recorded for CSEM TPOUV encapsulant made modules.

5) Ag-less SHJ interconnected with ECA, with bio-based polymer frontsheet, bio-based encapsulant, fluor-free recycled PET backsheet

This second experimental campaign concerned the integration of an experimental bio-based polymer frontsheet in mini module configuration with two half cells. Full polymer modules, containing different polymers at front and rear side, requires careful manufacturing process to avoid unwanted curving. For this campaign we used:

- A full bio-sourced polymer frontsheet (experimental version, not yet available on market).
- Partly bio-based encapsulant (on market).
- Fluorine free EU backsheet with third part recycled PET (on market).
- Ag-less SHJ interconnected by ECA.

Several tests were performed to develop a lamination procedure for full polymer module at CEA. Final version has no cell break. We decided to send these two modules (b) to thermal cycling aging as it is a crucial point of full polymer modules reliability analysis. One module configuration had successfully passed the test of 200 thermal cycles.

6) Standard vs In-less SHJ, glass-glass vs bio-based frontsheet-backsheet, CSEM vs commercial TPO encapsulant

CEA continued the analysis of project's materials integrated in PV modules in accelerated aging conditions. A third experimental campaign has been completed, evaluating the integration of bio-based and CSEM developed encapsulant combined with bio-based polymer frontsheet. The chosen configuration was 2x3 ½ cells modules. For this campaign 16 modules were produced:

- 2 cell types: "Standard SHJ" and "In-less SHJ"
- Configuration Frontsheet/Backsheet:
  - Glass/Glass (3,2 mm)
  - Polymer/Polymer (600 µm)
  - 2 * 3 ½ cells modules
- Recommended encapsulant from first campaign:
  - CSEM encapsulant (low UV) (TPO project)
  - Commercial TPO encapsulant (TPO2)

Once produced, the modules were put in accelerated aging under damp heat (+85°C, 85% RH) conditions for 3000h in total.

Global results & conclusion:

The IEC 61215 standard's ΔPmax<5% after 1000h of damp heat exposure criteria was passed by only 3 modules:

- CEA's Polymer as frontsheet/TPO2/SHJ/Partly recycled Polymer Backsheet

- CEA's Polymer as frontsheet/TPO2/SHJ/ CEA's Polymer as Backsheet
- Glass/POE/SHJ/Glass

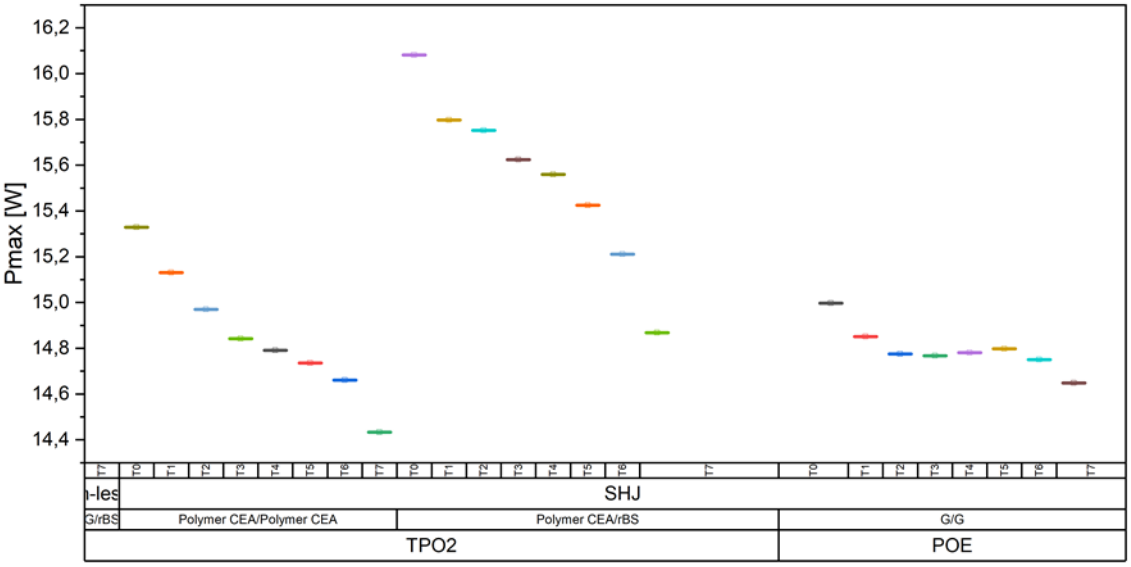


Figure 29: 3rd experimental campaign results in Pmax.

Figure 29 shows the variation of power for the 3 modules that passed the IEC norm after 1000h under DH conditions.

As major outcomes, it appears that:

- 2 cell types: "Standard SHJ" and "In-less SHJ" had been tested with eco sourced polymer components in front and back sheet (damp heat at +85°C, 85% RH) for 3000 hours.
- SHJ cells had very promising electrical performances with this partly bio-sourced BOM.
- In-less cells are more sensitive to moisture ingress thus had less good electrical performance with these materials.
- To mitigate moisture ingress' impact In-less cells could be treated by adding a SiNx layer to decrease moisture ingress into silicon.
- Partly recycled Polymer Backsheet is discarded for further investigation with In-less SHJ cells.

4.4 Recyclability

Eco-design strategies modify the materials and assembly processes, inevitably affecting recycling pathways and recovery rates. Understanding how these eco-design strategies influence recyclability is essential for closing the loop and achieving complete circularity of PV modules. As a starting point, current challenges for PV module recycler are identified based on the feedback from COMET, a mechanical recycler leading Resilex WP5.

- **Cross-linked encapsulant**, such as EVA, is a real glue, making the PV module separation process challenging for mechanical recycling. A non-crosslinking encapsulant would ease these separation processes.
- **Fluorine-based backsheets** are not recycled (despite being separated and recovered from other PV components) because of the presence of fluorine in backsheet's materials. Indeed, when applying conventional pyrolysis of fluorine-based backsheets (for energy recovery), hazardous fluorinated pollution occurs, which is forbidden by the current EU regulation [FLUO];
- **Antimony** presence in the glass hardens the post-recycling use of PV glass in Europe because of the change of EU glass manufacturing process (rolled glass to float glass), the latter being sensitive to antimony [ESIA]. More precisely, antimony, which is classified as a hazardous substance, reacts with the tin bath on which the glass is floated and pollutes the float glass production. Prior to float glass process, the rolled glass process was used in Europe and is still used in China, country from where most of the glass used in PV panels comes from. As a result, a high majority (>95%) of PV panels with glass contains antimony, which hindrances the integration of the recovered PV glass into the manufacturing of new products like flat glass in Europe, leading to a downcycling of glass (COMET's case is for bituminous applications). Nonetheless, things are starting to change in Europe and glass manufacturers are increasingly studying the integration of recycled glass into their production, with a very limited amount of antimony-containing glass for now.
- **Lead** presence in the metallization do not affect the recycling (for COMET) as lead present in the metal concentrate can be recovered by smelters afterwards. Nevertheless, lead is identified as a hazardous substance due to its impact on human health, leading eco-organization collecting PV panels to set lead content thresholds.

Overall, we observe that mechanical PV recyclers face various challenges limiting the circularity of the elements present in PV module, either due to physical or chemical properties of materials, presence of hazardous substances and important legislations [WEEE, FLUO] surrounding it.

The eco-design strategies for PV modules previously mentioned in the deliverable have an influence on the challenges faced by PV manufacturers. Three main effects may arise from the implementation of these eco-design strategies: positive, neutral and negative impact for PV recycler. The eco-design strategies evaluated by WP4 are classified below within these three categories:

1) Positive impacts for recyclers:

- **Fluorine-free materials** (used for frontsheets and/or backsheets) ease the recycling process. Additionally, using recoverable plastic (PP, PE, PS, ABS) instead of PET facilitate furthermore the recycling. Finally, flame retardant materials make unfeasible the separation of the sheet's material for standard recycling, so they should be avoided.
- **PO encapsulant**: EVA-free or non-crosslinking encapsulant will ease the mechanical separation of PV module for their recycling as EVA is a crosslinked encapsulant, appearing as a real glue which is not recyclable yet.

2) Neutral impacts for recyclers

- **Lead-free** soldering does not often influence the recycling process. Lead present in the metal concentrate can be recovered by smelters afterwards PV recycling process. Nevertheless, lead is identified as hazardous substance due to its impact on human health, leading eco-organization collecting PV panels to set lead content thresholds. Additionally, removing lead might reduce the risk of glass contamination, which can be beneficial for glass recycling;
- **Bio-based plastics** are difficult to differentiate from fossil-based plastic as the finished product is similar, leading to an identic recycling for PV recyclers. Note that recoverable plastics should be favored (PP, PE, ABS, PS) instead of PET to ease recycling.

3) Negative impacts for recyclers:

- **Alu-free** PV modules have a negative impact on PV recycling as aluminium frames are very easy to recover and recycle with a high economical value (when sold to foundries). Replacing them with bio-based frame will harden the PV module recycling process. For example, wooden frames are difficult to separate from the rest of the module as wood residues remain and require additional steps to dispose of them. Additionally, if wood frames were previously treated to resist to moisture and wood-boring insect, there valorisation afterwards might be compromised because of the presence of chemicals.
- Bio-based **backsheet** made from **natural fibers with epoxy** represent challenges to revalorize. Plastics (ABS, PP, PE, PP filled with glass fiber, talc, hemp, etc.) can be recycled by recyclers and transformed into small pellets, that are later used by compounders to make new plastic. When plastic is filled with epoxy, the pellets obtained will clogs injectors, and filters for compounders, making plastic filed with epoxy unfit as resource to make new plastics, limiting their valorization potential.
- **Glass-free** PV modules have a negative impact on the PV module recyclability. Indeed, PV manufacturers are required to meet >80% of PV weight to be reused or recycled. Without glass, it is currently not possible to reach this target. In addition glass-free PV modules are based on polymer frontsheet and backsheet, which composition could threaten the recycling process. On one hand, if the plastic is simple (PP as example), it can be recycled. On the other hand, technical plastic (with flame retardant or other chemicals) is difficult to recycle. Furthermore, glass used in PV modules could be reused instead of silica in the production of silicon wafers, improving the circularity of photovoltaic industry.

5. Milestone 15: eco-designed 60 cells module demonstrator

A 60 cells photovoltaic module has been manufactured at CEA. This module combines project's eco-design innovations at cell and module level tackled in WP4 and was identified as a key milestone in the RESILEX project.

5.1 Selection of the module components

In order to increase the module efficiency, by means of reducing the series resistance, a common technical solution is to cut solar cells in two. We followed this current practice and manufactured a 120 half-cells module as demonstrator, equivalent to a 60-cells module demonstrator.

The first step was then to select of the full process from wafer to module. Each step (wafer, solar cell, interconnection, module BoM) is detailed below.

Wafers

To reduce the CO_2 footprint of this eco-designed module to its maximum, European wafers from Norway were selected with a quite low thickness of 130 µm. This is 20 µm less than the standard used at the beginning of the project allowing a CO_2 reduction of the total carbon footprint by approximately 20 kg CO_2e/kWp. To further reduce the CO_2 impact of the wafer, other alternatives options were: 1) the use of thinner wafers as low 110 µm, that demonstrate results compatibles with mass production, but could have increased the risk of breakage for this specific eco-designed module due to alternative process for the rest of the manufacturing 2) the use of recycled silicon from NTNU SisAl process but results at this time of the project were not compatible with high efficiency module production.

Solar Cells

A solar cell process compatible with a large-scale batch was then selected with the goal to reduce both In and Ag contents as compared to standard SHJ. The solar cells were processed on CEA pilot line combining two approaches:

- The use of thin In-based TCO layers to reduce indium by 72 %
- The print of Ag / Cu pastes for the metallization to reduce Ag by 50 %

The combination of these two approaches, corresponds to solar cells scenario 1, presented in the cell's eco-design section of the report. The cells were selected for their high TRL and compatibility with industrial transfer thanks to their low or negligible impact on the cell efficiency and their good results of reliability tests obtained in RESILEX and presented before.

Indeed, recent Ag/Cu paste have shown similar behaviour than Ag paste under damp heat exposure, and thin In-based TCO have passed 3 times the standards' requirement but with more important degradation than reference. To reduce this degradation on the final 60-cells module, a SiN_x dielectric capping layer was added on the rear side of the cells.

Before the solar cells manufacturing, a solar-cell pre-test was launched to evaluate the wafer quality and its compatibility with the "In-less" and "Ag-less" process and to measure the effect of the SiN_x layer addition on the rear side. This pre-test validates the SiN_x deposition on the rear side with a positive impact on the efficiency. The test conducts to a 0.37 % efficiency loss for the selected In-less & Ag-less processes on EU wafers as compared to the reference process. The loss is larger than expected and show the necessity to adapt in the future the Ag/Cu metallization grid and process to the underneath ultra-thin and more resistive TCOs.

The 112 solar cells selected for the module manufacturing showed a median efficiency of 22.7 % and top efficiency of 23.3 % with a 6 BB design and M2 wafers size, as presented in the Figure 30 below.

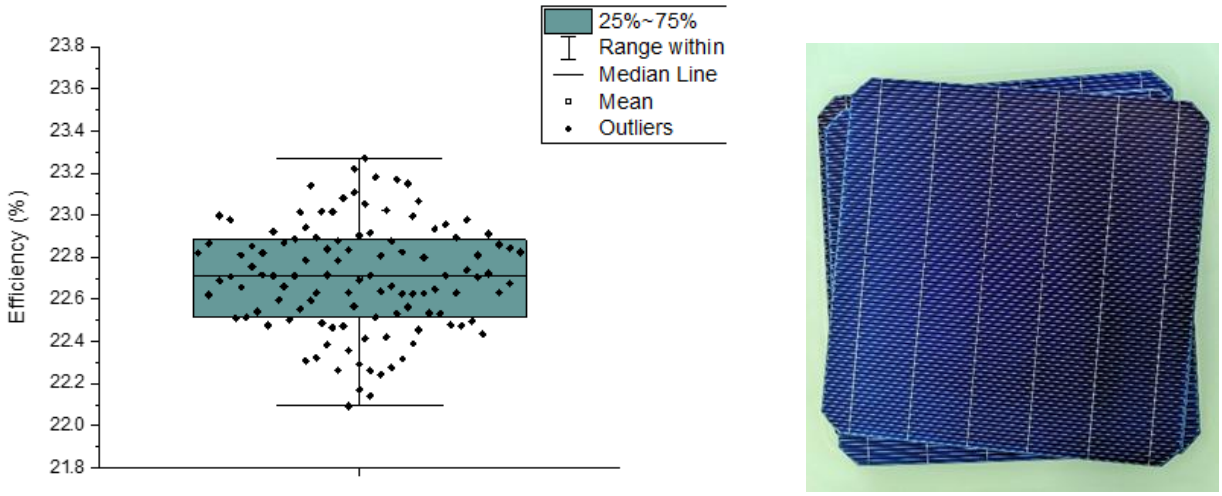


Figure 30. Efficiency scatter plot (left) and pictures (right) of the 112 solar cells fabricated for the 60 cells module.

Interconnection

To interconnect the developed solar cells, we aimed to reduce the silver content in our ECA (electrically conductive adhesive) as it was pointed out as an important drawback in the LCA analysis. Indeed, this technology uses a polymer matrix in which conductive particles are embedded to ensure electrical conductivity between solar cells and busbars. These particles were made of silver in former versions of ECAs, but today it is possible to replace silver partially or completely with copper for example. In this work, we used a **copper-based ECA and copper ribbon** to reduce Ag content to its maximum in the module.

Bill of Materials

To manufacture this demonstrator module, we followed LCA recommendations and reduced the ecological footprint of the final module as much as possible. However, we had to accept some compromises due to supply chain issues.

The **frontsheet**, which technically serves as the mechanical load-bearing layer, is usually made of glass. Today, front-glass thickness is constantly decreasing, leading to uncommon module degradation modes. At the beginning of the project, we targeted a front glass thickness of less than 2 mm, but recent field observations showed that very thin glass can undergo spontaneous breakage. The lack of understanding of this failure mode led us to use standard **3.2 mm thick glass** as the front sheet for this

manufacturing exercise. In this way, we used tempered glass, which is the optimal solution from a safety point of view.

Our search for an **encapsulant** focused on non-cross-linking polymers, as end-of-life (EoL) considerations require easy layer separation. Several polymer families allow easier separation at end of use, but the most economical solution is to use TPOs (thermoplastic olefins). Among the available products, we tested some TPOs under development and two commercially available products. For the final module, we selected a **TPO** sourced from Asia as the European one tested previously in the work package was no longer available.

Backsheets have historically contained fluoropolymers to enhance resistance to outdoor stressors. Recent studies showed that the use of fluoropolymers can result in PFAS pollution at several stages of the backsheet's lifetime. To avoid this, we turned toward fluorine-free polymers. To reduce the environmental footprint, we opted for a European fluorine-free multi-layer backsheet. During material testing and module integration, we used a partially recycled fluorine-free backsheet from a European manufacturer. Despite research efforts, this backsheet had to be discarded for further application as its damp-heat performance was too poor. For the final demonstrator, we used a **PET-core fluorine-free backsheet with a thin aluminium layer** to improve moisture-ingress resistance.

Nevertheless, our study showed the importance of finding a compromise between environmental impact optimization and module performance and durability. Specifically, multi-layer backsheet with aluminium core layer maintain PV module durability despite its higher impact compared to full polymer backsheets. For this reason, to further lower module's environmental impact, alternative backsheet materials without aluminum and fluorine are under investigation.

The common photovoltaic module **frame** material is aluminium, which has a significant impact on the module's overall LCA. To reduce this contribution, we targeted a bio-based solution—namely, a **timber frame**. This material had already been approved for this application after a long selection process in which several wood species were aged and mechanically tested (see Deliverable D4.2).

5.2 Module manufacturing

The manufacturing process consisted of several steps during which we progressed toward the final solution. Hot-vacuum lamination applies high temperature and

pressure to the assembled components. To bond all parts around the solar cells, we need to know the melting temperature of the solar encapsulant, which determines the lamination process parameters. Before this manufacturing campaign, we analysed the encapsulant polymer using differential scanning calorimetry. Once the process parameters were defined, a first lamination trial was carried out to check whether cell breakage or bubbles occurred. For this test, we used dummy solar cells.

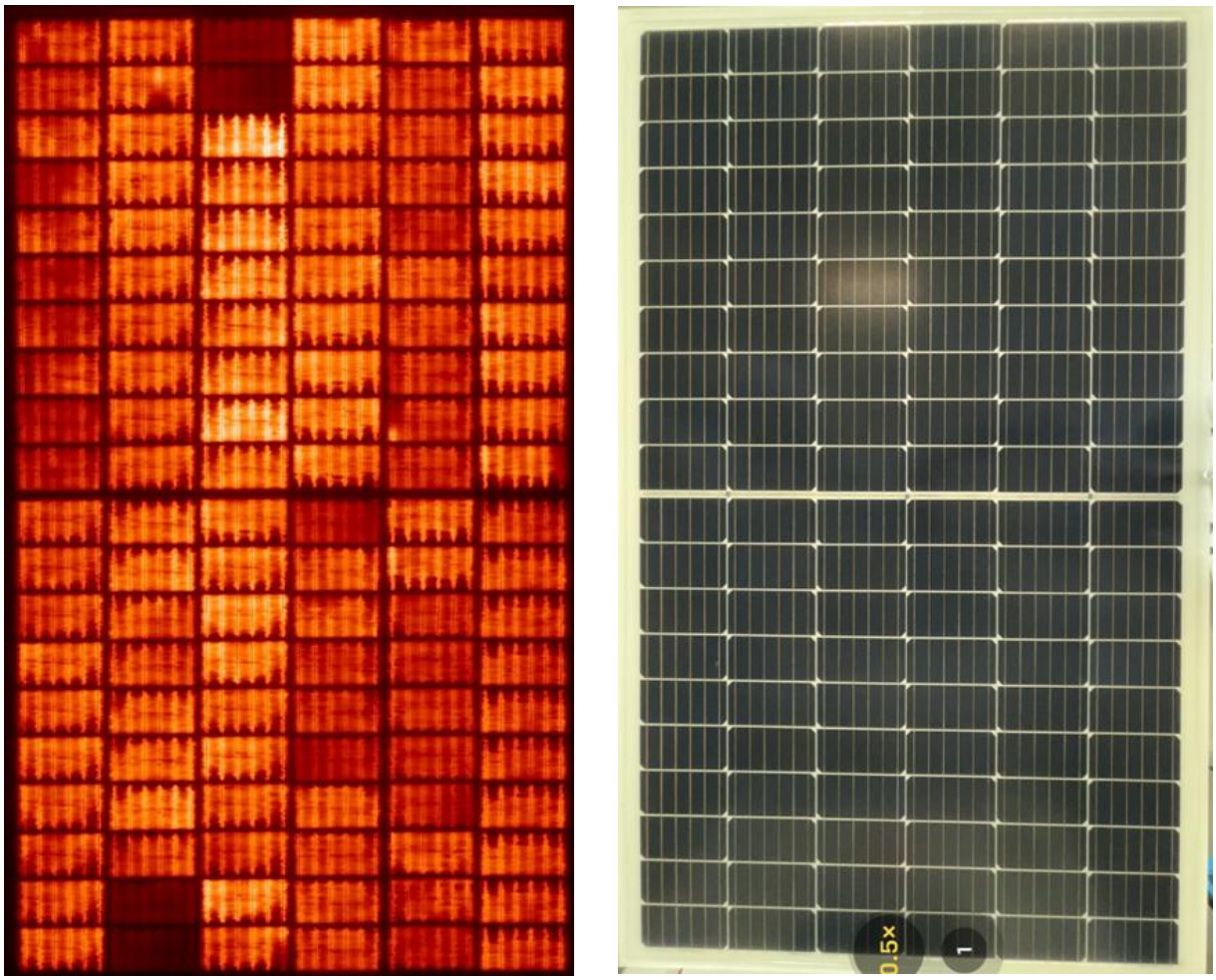


Figure 31. Trial module of first lamination test (EL (left) and picture (right)).

Final module showed no bubble or cell breakage (Figure 32). Some additional fabrication steps were added specifically to fix the timber frame. A glue was applied between the short and long sides to assemble the wooden pieces as shown in Figure 32 right. Once the drying had finished, we added the junction boxes on the rear side (3 pieces, see Figure 33).

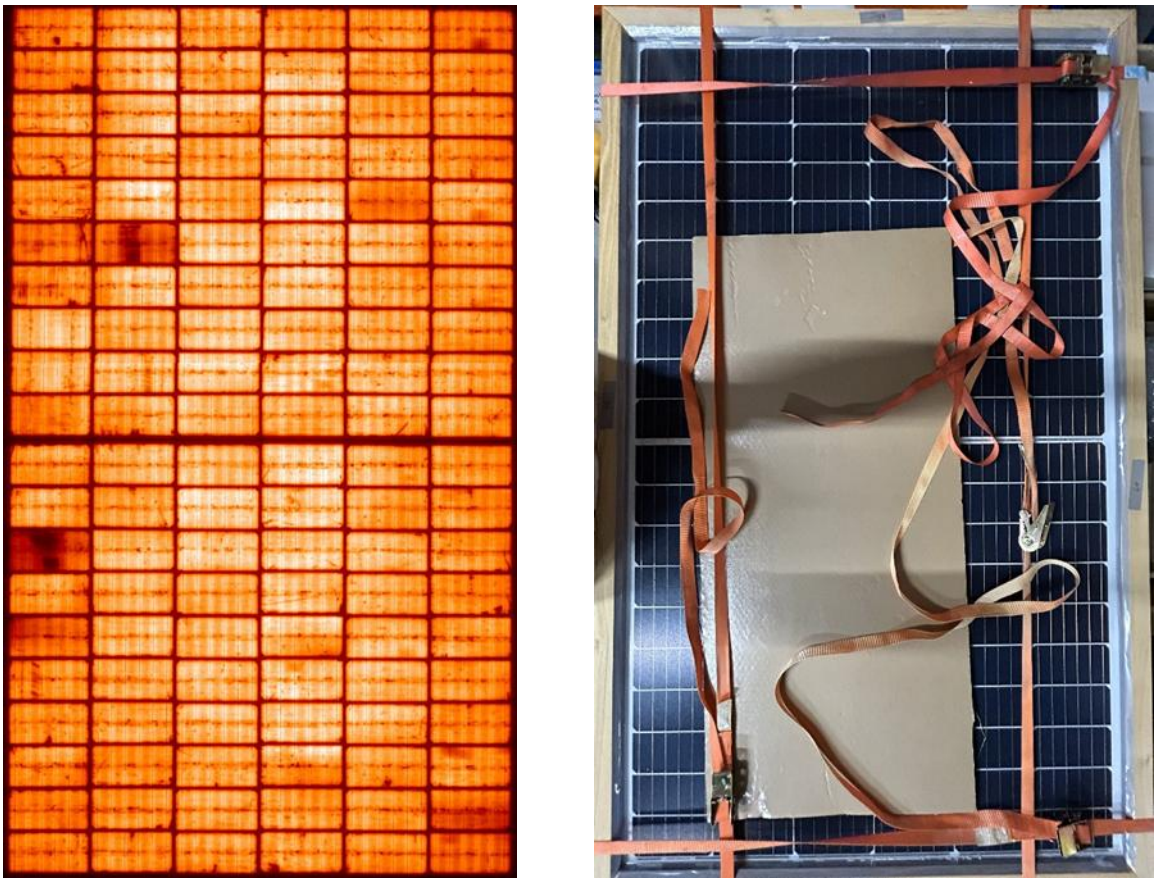


Figure 32. Final demonstrator module (EL (left) and wood frame assembly (right).

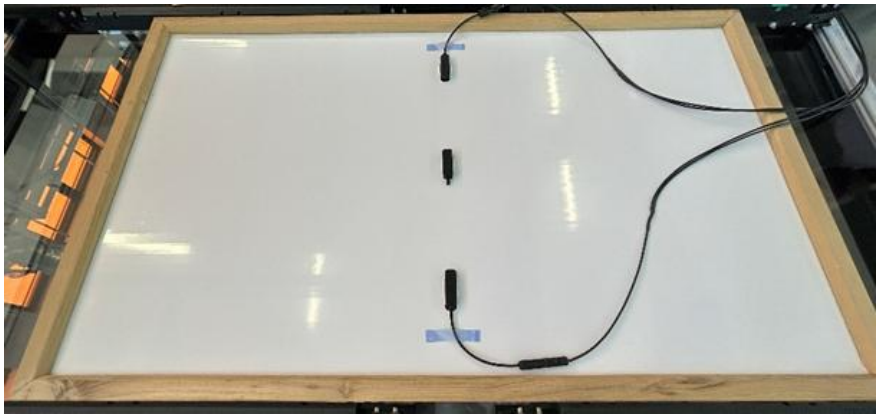


Figure 33. Junction box bending for the eco-design module.

Once the module had been finished, its electrical performance could be measured. We used a SPIRE device to determine the module's power output The I-V curve is presented in the Figure 34 and the recorded electrical parameters are shown in Table 6.

Table 6. Final demonstrator's electrical performance

Pmax [W]	325
Voc [V]	44,48
Isc [A]	9,17
FF [%]	0,758

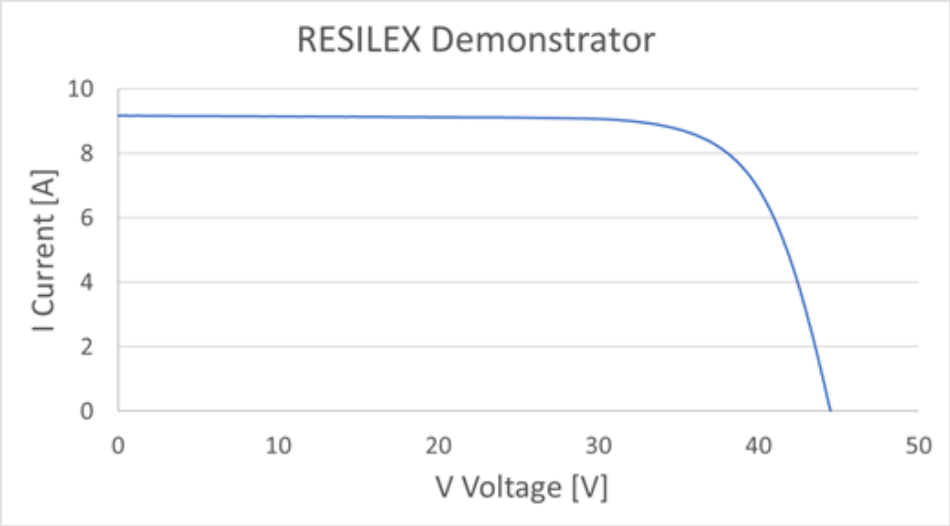


Figure 34. I-V curve of the final demonstrator.

In conclusion the manufacturing of the 60-cells eco-designed module (see Figure 35) was a success in the project. It allows us for to combine the solar cell scenario 1 (In-less and Ag-less process) and module scenario 2 (ECA interconnection with TPO encapsulant, fluor-free PET back-sheet and wooden frame) in a large-scale demonstrator. In parallel, mini-modules will be fabricated using the same solar cells in string, and same module materials to assess the reliability of this combination and perform standard aging tests. Results will be presented in deliverable D4.6.



Figure 35. The finished eco-designed module (Milestone n° 15).

6. Conclusion

Deliverable D4.4 consolidates the eco-design roadmap for c-Si solar cells and PV modules by giving a complete overview of the rapidly evolving legislations setting ambitious targets for the PV industry, notably on carbon footprint, recyclability and resource efficiency. In addition, the ecodesign strategies selected for solar cells and modules were evaluated against four lenses – environmental impact (LCA), initial performance, reliability and recyclability of the solar devices. Finally, the report presents a milestone of the Resilex project: the production of a 60 cells eco-designed PV module, combining relevant eco-design strategies.

The eco-design developments applied to SHJ **solar cells** demonstrate that critical-material reduction and environmental impact decrease is feasible with negligible impact on performance or reliability. Significant indium reduction (>70%) was achieved through thin ITO layers. The introduction of indium-free TCOs (AZO and SnO_2) demonstrated high performance and good damp-heat stability for AZO with a sufficient thickness, as well as SnO_2 emerging as a promising low-impact TCO. Silver reduction was successfully addressed using Ag/Cu pastes, reaching up to 70% Ag savings, while copper plating enabled to decrease further the silver content, demonstrating efficiencies of In-less and Ag-less solar cells close to references along with strong UV and DH stability. Finally, the use of thinner c-Si wafers was demonstrated to improve the environmental impact, but going down to 65 µm becomes challenging due to wafer handling difficulties. Across all approaches, reliability testing confirmed compatibility of these eco-optimized cells with standard module BoM and aging conditions, highlighting specific sensitivities (e.g., humidity impact on very thin TCOs) that can be mitigated. Finally, recycling considerations show that although reduced silver slightly lowers the economic value of end-of-life modules, the overall strategies positively contribute to an improved LCA.

Eco-design strategies at the **module** level show clear potential to reduce environmental impacts while maintaining high performance. LCA results confirm that replacing aluminium frames and fluorinated backsheets respectively with timber and fluorine-free polymers significantly lowers carbon footprint and resource use. Similarly, non-crosslinking encapsulants such as TPO improve recyclability by easing layer separation. Material investigations and integration in PV modules demonstrate that bio-based and recycled components are promising but require careful evaluation to ensure durability and compatibility with lamination processes. Performance tests of modules integrating flax-based backsheets, fluor-free frontsheets, CSEM encapsulant and lead-free interconnections achieved outputs comparable to conventional designs. Important remaining challenges include reliability under damp heat and thermal

cycling, which may reveal moisture-ingress sensitivity for certain module BoMs, highlighting the need for optimized barrier properties. From a circularity perspective, strategies like fluorine-free materials and non-crosslinking encapsulants provide clear benefits for recyclers, while others—such as glass-free modules or wooden frames—introduce new challenges. These trade-offs emphasize the importance of balancing environmental gains with end-of-life treatment feasibility.

Finally, our **milestone** successfully demonstrated a full-size eco-designed 60-cell PV module integrating some of the project's key innovations: thin European wafers, In-less and Ag-less SHJ solar cells (−72% In, −50% Ag), copper-based ECA interconnection, TPO encapsulation, fluorine-free PET-based backsheet, and a timber frame. The manufacturing process was validated with no cell breakage or lamination defects, and the final module reached a Pmax of 325 W, confirming that combining eco-design strategies at both cell and module level is feasible at demonstrator scale. These results clearly pave the way for next-generation eco-designed PV modules, showing that high performance and strong sustainability improvements can be achieved simultaneously. Building on these results, further studies on long-term reliability and efficiency optimization are required to continue developing this eco-designed module, following the clear development pathway identified in this work.

Overall, the developments achieved in RESILEX show that eco-design strategies for cells and modules are a practical way to meet upcoming regulatory requirements. By introducing low-environmental impact materials, integrating them into PV designs, and assessing their performance, reliability, and recyclability, this work provides a solid basis for future PV modules aligned with circular economy principles.

7. References

Section 2:

[Ekva2001] T. Ekvall & G. Finnveden "Allocation in ISO 14041—a critical review" Journal of Cleaner Production, Volume 9, Issue 3, June 2001, Pages 197-208 https://doi.org/10.1016/S0959-6526(00)00052-4

[CRMA2024] « European Critical Raw Material Act », European Commission. https://commission.europa.eu/topics/competitiveness/green-deal-industrial-plan/european-critical-raw-materials-act_en

[NZIA] « The Net-Zero Industry Act ». https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en

[ECO2009] « Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products », EUR-Lex. http://data.europa.eu/eli/dir/2009/125/oj

[EPEAT2023] EPEAT Registry. Accessed Jun. 26, 2023. EPEAT Registry

[NSF2024] « Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters », https://globalelectronicscouncil.org/wp-content/uploads/NSF-457-2019-r2024.pdf

[CRE2023] « La CRE publie les cahiers des charges des nouvelles périodes des appels d'offres dit "PPE2 Eolien", "PPE2 PV Bâtiment" et "PPE2 PV Sol" et accompagne les porteurs de projets ». https://www.cre.fr/Actualites/la-cre-publie-les-cahiers-des-charges-des-nouvelles-periodes-des-appels-d-offres-dit-ppe2-eolien-ppe2-pv-batiment-et-ppe2-pv-sol-et-accompag

[EPR] « Qu'est-ce que la responsabilité élargie du producteur », ELISE. https://www.elise.com.fr/boite-a-infos/reglementation/responsabilite-elargie-du-producteur/

[ESPR] « Ecodesign for Sustainable Products Regulation », European Commission. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/ecodesign-sustainable-products-regulation_en

[WEEE] "Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE)", EUR-Lex. http://data.europa.eu/eli/dir/2012/19/oj

[Photorama] « Eu regulation pushing forward PV recycling: the WEEE directive", Photorama project. https://www.photorama-project.eu/eu-regulation-pushing-forward-pv-recycling-the-weee-directive/

[ESPRELWP] « Ecodesign for Sustainable Products and Energy Labelling Working Plan », European Commission. https://environment.ec.europa.eu/document/download/5f7ff5e2-ebe9-4bd4-a139-db881bd6398f_en?filename=FAQ-UPDATE-4th-Iteration_clean.pdf

[GREEN] « The European Green Deal », European Commission https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

[JRC2025] Ardente et al. Harmonised rules for the calculation of the carbon footprint of photovoltaic modules in the context of the EU Ecodesign Directive, Publications Office of the European Union, Luxembourg, 2025, https://data.europa.eu/doi/10.2760/4062978 , JRC141275.

[EDELPV] « Development of standardisation methods for the eco-design and energy labelling of photovoltaic products ». https://ecodesign-pv-testing.eu/

[ESMC2023] European solar manufacturing concil, « New global certification of low-carbon PV modules », ESMC Solar. https://esmc.solar/new-global-certification-of-low-carbon-pv-modules/

Section 3:

[Louwen2015] Louwen et al. "Life cycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs" *Progress in Photovoltaics: Research and Applications*, *23*(10), 1406-1428. https://doi.org/10.1002/pip.2540

[Gageot 2023] T. Gageot, et al., "Feasibility Test of Drastic Indium Cut Down in SHJ Solar Cells and Modules using Ultra-thin ITO Layers" Solar Energy Materials and Solar Cells Volume 261, 1 October 2023, 112512, https://doi.org/10.1016/j.solmat.2023.112512 (https://hal.science/hal-04801334v1)

[Gageot 2025] T Gageot et al. "Using thin AZO layers coupled with SiN as a way to decrease Indium consumption in SHJ cells and modules" presented at Silicon PV 2025, Oxford, UK.

[Lanterne 2024] Lanterne, et al. "Indium Reduction Above 70% in SHJ Solar Cells: Study of the Module Stability" SiliconPV Conference Proceedings, 2. https://doi.org/10.52825/siliconpv.v2i.1314

[Lanterne2 2024] Lanterne, et al. "Copper-based metallization approaches for drastic reduction of silver content in SHJ Solar cells" presented at the 2024 EUPVSEC conference September 23, Vienna, Austria.

[Monna 2025] R Monna, et al. "Use of Cu ribbons and Cu-Ag HJT cell metallization on ECA based interconnection for PV modules" Solar Energy Materials and Solar Cells 287 (2025) 113594

[SOREN] "Soren met en oeuvre la filière de traitement des panneaux photovoltaïques", SOREN. https://www.soren.eco/re-traitement-panneaux-solaires-photovoltaiques/

Section 4:

[Bejat 2024] Béjat, et al. "Design for the environment: SHJ module with ultra-low carbon footprint" *Prog Photovolt Res Appl.* 2025; 33(1): 184-199. doi:10.1002/pip.3803

[FLUO] "Regulation on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU) No 517/2014", Eur-lex. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202400573

[ESIA] "European solar PV industry alliance recommentdations paper series II Adressing uncertain antimony content in solar glass for recycling", https://solaralliance.eu/wp-content/uploads/2023/10/Recommendation-on-Addressing-uncertain-antimony-content-in-solar-glass-for-recycling.pdf



Co-funded by
the European Union

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them.