



## D4.1 – Interim roadmap for the eco-design of silicon solar cells & modules and silicon-based tandem 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	D.4.1 – Interim roadmap for the eco-design of silicon solar cells & modules and silicon-based tandem technologies
Lead Beneficiary	CSEM
Dissemination level	Public
Authors	Laurie-Lou Senaud, Lison Marthey, Adeline Lanterne, Timea Béjat, Pia Vasquez
Contributors	Nouha Gazbour, Alexis Barrou, Agatha Lachowicz
Reviewer(s)	CEA (Nouha Gazbour and Adeline Lanterne for CSEM parts), CSEM (Laurie-Lou Senaud for CEA and LMGP parts) ISMC (Francisco J. Luque)
Issue date	February 2025

## Version control table

Version	Date	Main changes
V1	10/02/2025	Frist Draft from Alexis Barrou and Laurie-Lou Senaud
V2	17/02/2025	Review and contribution from Nouha Gazbour
V3	21/02/2025	Addition of contribution from Laurie-Lou Senaud, Lison Marthey, Adeline Lanterne, Timea Béjat, Pia Vasquez, Agatha Lachowicz
V4	28/02/2025	Last Review from Adeline Lanterne and Laurie-Lou Senaud
VFINAL	28/02/2025	Review from ISMC (Francisco J. Luque)
VFINAL2	06/10/2025	Addition of Version control table and reviewers' names

## Index

1. Executive summary	4
2. Introduction	4
3. Sustainability: Definition and Tools	5
3.1. Definition	5
3.2. Tools	6
4. Environmental Directives and Regulations in the Photovoltaic Sector	11
4.1. Critical Raw Material Act (CRMA) legislative	11
4.2. Net Zero Industry act (NZIA)	12
4.3. Eco-design directive	13
4.4. EPEAT Ecolabel	13
4.5. Simplified Carbon Evaluation	14
4.6. Extended Producer Responsibility (EPR)	15
4.7. Conclusion	15
5. PV technology and eco-design considerations	16
5.1. PV manufacturing value chain	16
5.2. SHJ solar cells and modules – challenges and considerations	21
5.3. General strategies for eco-design PV	27
6. RESILEX solutions and Scenarios	31
6.1. Solar cells	31
6.2. PV modules	35
7. Milestone M11: Proof-of-principle eco-designed mini-module	39
7.1. Modules with eco-designed backsheet (CSEM)	39
7.2. Second proof of concept of eco-designed module with low In and low Ag containing cells (CEA)	42
8. Conclusions	44
References	45

# 1. Executive summary

The deliverable D4.1 for the RESILEX project, outlines the current state and future directions for the eco-design of silicon solar cells and modules, focusing on sustainability and regulatory compliance. It highlights the importance of photovoltaic (PV) technology in mitigating climate change and contributing to a sustainable global energy system. Key areas covered include:

1. **Sustainability Definition and Tools:** Emphasizes the need for sustainable development and introduces tools like the Sustainable Development Goals (SDGs) and the circular economy model.
2. **Environmental Directives and Regulations:** Discusses various European and national regulations, including the Critical Raw Material Act (CRMA), Net Zero Industry Act (NZIA), and the Eco-design directive, which aim to enhance the environmental profile of PV systems.
3. **PV Technology and Eco-design Considerations:** Reviews the PV manufacturing value chain, challenges in producing silicon-heterojunction (SHJ) solar cells, and general strategies for eco-design in PV technology.
4. **RESILEX Solutions and Scenarios:** Presents eco-design solutions and scenarios for solar cells and PV modules developed within the RESILEX project, focusing on reducing the use of critical materials like silver and indium, and improving recyclability and sustainability.

# 2. Introduction

To overcome the worldwide challenges of climate change mitigation, photovoltaic (PV) technology is expected to play a significant role in global electricity production and to be a key contributor to a sustainable global energy system. Its extensive use across all geographic regions, versatility in applications, and scalability facilitate a socially acceptable energy transition by providing distributed electricity generation, creating jobs, and opening new business opportunities [ETIPV2023]. By 2022, the global deployment of photovoltaic (PV) systems had surpassed the terawatt threshold, with exponential growth continuing steadily. Following this trend, the PV industry is approaching a critical juncture, poised to become a major, and in some regions, dominant energy source. In this context, addressing the environmental impact of this technology is crucial for enhancing industrial competitiveness, sustaining sector

growth, and addressing societal challenges. In response to these concerns, both national and European legislations, along with industrial alliances, strongly advocate for the adoption of an eco-design approach. In addition, various environmental initiatives have been introduced in the PV sector to enhance the environmental profile of PV systems.

At the European level, The EU's Net Zero Industry Act (NZIA) aims to strengthen clean technology production by incorporating resilience and sustainability criteria, such as recyclability, carbon footprint, and biodiversity. Additionally, various national legislations for eco-design PV have been recently established [NZIA]. For instance, the French Energy Regulator (CRE) has set a carbon footprint limit of approximately 550 kgCO<sub>2</sub> eq/kWp for the upcoming national tender [CRE2022]. Similarly, in the United States, the Global Electronics Council (GEC) introduced a new eco-label, EPEAT, which requires the embodied carbon of PV modules to be 630 kgCO<sub>2</sub> eq/kWp or less [EPEAT2023]. Consequently, manufacturers have intensified their efforts to comply with these regulatory requirements and to enter the market. Leading companies like REC, Voltec and Qcells are now offering low-carbon photovoltaic panels [REC2022], [Voltec], [QCells2019]. Based on the indicators present in various regulations, eco-design strategies must aim to achieve several key objectives. These include reducing CO<sub>2</sub> emissions, minimizing the consumption of fossil and critical resources, promoting the reuse of materials for a second life, extending product lifespan, and enhancing recycling and recovery processes.

Aligned with the RESILEX project's goals, the main objective of this deliverable is to define the eco-design strategies for photovoltaic (PV) modules to comply with current regulations and sustainable development goals, which will be implemented in WP4. To achieve this, WP4 employs an eco-design approach at the cell and the module level. This approach seeks to minimize environmental impact, reduce the use of critical resources, and facilitate the recycling of the PV module. The outcomes of this deliverable will provide a solid foundation for the future deliverables of WP4 and facilitate the sharing of knowledge, project objectives, and visions for the other WPs.

## 3. Sustainability: Definition and Tools

### 3.1. Definition

Worldwide, our current lifestyle is unsustainable as it stands, making it necessary to change our energy consumption and production patterns. This is the idea behind

sustainable development, which emerged in 1987 and was defined in the Brundtland Report [Brundtland] as follow:

*"...Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs and corresponds to the duties of current generations to pass on a liveable, viable, and reproducible world..."*

This concept aims to achieve a balance between societies and natural resources by ensuring development and reducing inequalities among people, which highlights three pillars of sustainable development (SD): Society, Economy, and Environment (Figure 1).

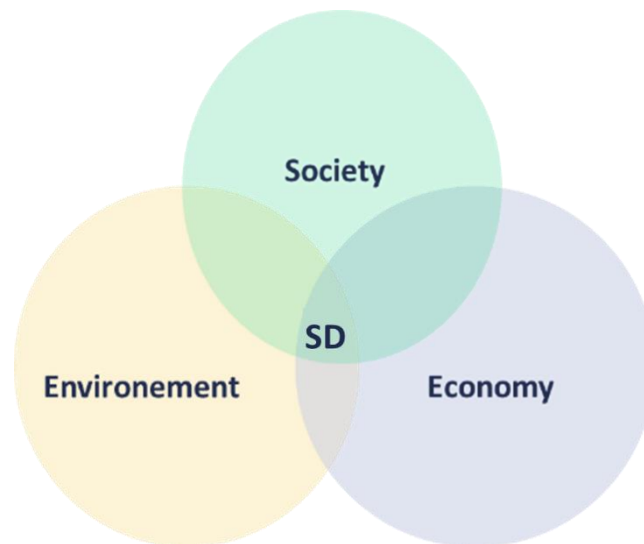


Figure 1: Pillars of sustainable development

## 3.2. Tools

Sustainable development (SD) is increasingly being integrated into decision-making processes and policy formulation. This is reflected in the development of the Sustainable Development Goals (SDGs), adopted by all UN member states in 2015 (Figure 2) [Agenda2030]. The SDG framework serves as a call to promote prosperity while respecting the planet.



Figure 2: Objectives of sustainable development

Circular economy is a concrete response to the challenges of sustainable development by offering viable economic solutions that minimize environmental impact and promote a more equitable use of resources.

### 3.2.1. Circular economy: Definition and pillars

Several definitions of the Circular Economy exist in the literature. Kirchherr et al. [Kirch2017] propose a definition that aims to be comprehensive and exhaustive:

*"...An economic system that replaces the concept of 'end of life' with the reduction, reuse, recycling, and recovery of materials in the production/distribution and consumption processes. It operates at the micro level (products, businesses, consumers), the meso level (parks, eco-industries), and the macro level (city, region, nation, and beyond), with the aim of achieving sustainable development, thereby simultaneously creating environmental quality, economic prosperity, and social equity, for the benefit of present and future generations."*

Then, the circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible [Circ2023].



Figure 3: Definition of circular economy [Circ2023]

The seven pillars of the circular economy, according to ADEME, aim to minimize environmental impact while maximizing resource efficiency at each stage of the product life cycle [ADEME2021]. Here is a summary of these principles:

- 1) **Sustainable Sourcing:** This involves using renewable, recycled, or local raw materials to reduce environmental impacts starting from the extraction of resources.
- 2) **Eco-design:** Environmental criteria are integrated from the design stage to optimize the use of materials, energy consumption, and to extend the product's lifespan.
- 3) **Industrial and territorial Ecology:** This pillar promotes resource pooling (energy, water, waste, etc.) between companies within the same territory, fostering cooperation and reducing local losses.
- 4) **Functional Economy:** The focus is on usage rather than ownership, through models based on renting, sharing, or subscription, instead of direct product purchases.
- 5) **Responsible Consumption:** It involves raising awareness among consumers about the environmental impact of their choices and promoting durable, repairable, and eco-designed products.
- 6) **Extending Product Lifespan:** This pillar encourages repair, reuse, and repurposing of products to avoid waste, and supports second-hand markets and product refurbishment.

- 7) **Recycling:** This involves turning waste into new resources to limit the extraction of raw materials, as well as improving sorting and material transformation systems.

Addressing the challenges of the circular economy from the outset of a project requires relying on the pillar of eco-design. Eco-design aims to develop strategies to improve the environmental profile of products while ensuring their compliance with current regulations.

### 3.2.2 Eco-design: Definition and approaches

#### Definition

According to the ISO 14006 standard [Ekva2001], eco-design is defined as: *"A systematic approach that integrates environmental aspects into the design and development of products, with the aim of reducing negative environmental impacts throughout their life cycle."*

Eco-design relies on the combination of technical, economic, and environmental criteria to reduce the ecological impact while ensuring the product's economic viability (Figure 4).

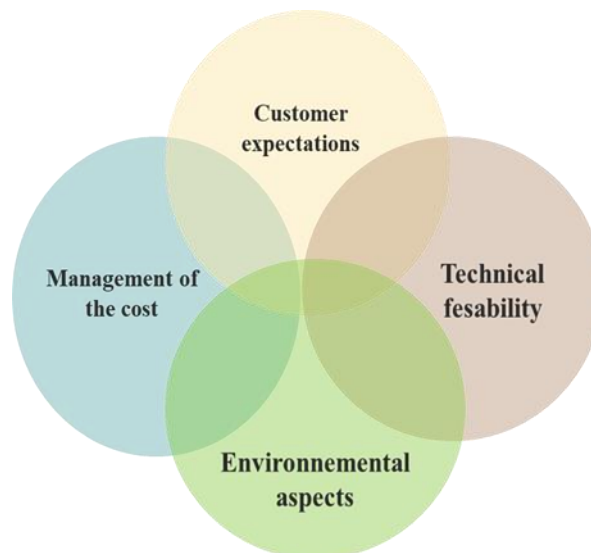


Figure 4: Eco-design criteria

## Eco-design approaches

Among the levers of eco-design, the 3R approach (Reuse, Recycle, Reduce) is a fundamental principle in the eco-design process, aiming to minimize the environmental impact of products while maximizing their added value.

- **Design for Reuse:** This approach involves designing products so that they can be easily reused after their initial use. This can include designing modular or detachable products, where components can be repurposed for other uses or in new products. The goal is to extend the lifespan of materials and avoid the production of new goods, thus reducing the consumption of natural resources.
- **Design for Recycling:** This approach focuses on creating products that can be easily recycled at the end of their life cycle. It involves using recyclable materials and simplifying the design to facilitate disassembly, material separation, and recycling. The aim is to reduce the waste sent to landfills and maximize the reuse of materials in new products, supporting a circular economy.
- **Design for Reduce:** This aims to minimize the consumption of resources, energy, and materials from the design phase. This can include reducing the size and weight of products, optimizing manufacturing processes to limit waste and energy consumption, and using less polluting or more efficient materials. This approach helps to reduce environmental impacts while improving product efficiency and profitability.

Each of these levers contributes to the overarching goal of eco-design: creating products that are more sustainable throughout their life cycle. These approaches will be adopted in this deliverable to define eco-design strategies for PV modules in the context of the RESILEX project.

The different defined strategies will be validated from an environmental point of view using Life Cycle Assessment (LCA). LCA is a common reliable tool used to evaluate the environmental impacts associated with all stages of a photovoltaic system's life cycle, from raw material extraction to production, usage, and end-of-life disposal. LCA helps in identifying key areas where environmental impacts can be minimized [Ekva2001].

## 4. Environmental Directives and Regulations in the Photovoltaic Sector

The photovoltaic industry has undertaken various environmental approaches to reduce its ecological footprint and improve sustainability. These efforts aim to optimize energy efficiency, reduce resource consumption, and enhance the recyclability of photovoltaic systems.

### 4.1. Critical Raw Material Act (CRMA) legislative

Since 2011, the European Commission has evaluated a list of Critical Raw Materials (CRMs) every three years as part of its Raw Materials Initiative. The number of CRMs identified has gradually increased, from 11 in 2011, 20 in 2014, to 34 in 2023.

These materials are primarily used in energy transition technologies, including photovoltaic systems, wind turbines, and electric vehicle batteries, among others. The increasing demand for these materials is driven by the shift toward renewable energy and low-carbon technologies, which rely on certain critical raw materials for their production and efficiency [CRM2020].

#### Main results of the 2023 criticality assessment

The following 34 raw materials are proposed for the CRM list 2023:

2023 Critical Raw Materials ( <i>new CRMs in italics</i> )			
aluminium/bauxite	coking coal	lithium	phosphorus
antimony	<i>feldspar</i>	LREE	scandium
<i>arsenic</i>	fluorspar	magnesium	silicon metal
baryte	gallium	<i>manganese</i>	strontium
beryllium	germanium	natural graphite	tantalum
bismuth	hafnium	niobium	titanium metal
boron/borate	<i>helium</i>	PGM	tungsten
cobalt	HREE	phosphate rock	vanadium
		<i>copper*</i>	<i>nickel*</i>

2023 Critical Raw Materials ( <i>Strategic Raw Materials in italics</i> )			
aluminium/bauxite	coking coal	<i>lithium</i>	phosphorus
antimony	feldspar	LREE	scandium
arsenic	fluorspar	<i>magnesium</i>	<i>silicon metal</i>
baryte	gallium	<i>manganese</i>	strontium
beryllium	germanium	<i>natural graphite</i>	tantalum
<i>bismuth</i>	hafnium	niobium	<i>titanium metal</i>
<i>boron/borate</i>	helium	PGM	tungsten
<i>cobalt</i>	HREE	phosphate rock	vanadium
		<i>copper*</i>	<i>nickel*</i>

\* Copper and nickel do not meet the CRM thresholds, but are included as Strategic Raw Materials.

La liste des matières premières critiques et stratégiques identifiées sur la base du rapport d'étude portant sur les matières premières critiques pour l'UE de 2023.

Figure 5: List of critical material defined by Europe in 2023 [CRM2020]

The European Union is heavily dependent on foreign countries for critical materials essential for green, digital, and industrial technologies. In 2023:

- 98% of the EU's rare earth elements came from China.
- 97% of the lithium required for batteries was imported.
- 93% of the magnesium used in Europe also came from China.

With the rise of electric vehicles, renewable energy technologies, and semiconductors, the demand for critical raw materials has surged. In response, the Critical Raw Materials Act (CRMA) was proposed by the European Commission in March 2023. Its goal is to ensure a secure, diversified, and sustainable supply of critical raw materials (CRMs) for the EU while reducing dependence on imports, particularly from China.

The law was adopted by the European Union in March 2024, and it will be implemented at the member state level [CRM2020]:

- EU should cover at least 10% of its annual consumption of strategic raw materials through domestic extraction.
- EU should ensure that 40% of its annual consumption of these materials is processed within its borders.
- The recycling capacity should cover at least 25% of the EU's annual consumption of critical raw materials. This target was increased from the initial 15% during the legislative process.
- EU aims to diversify its sources of raw materials to ensure that no third country accounts for more than 65% of the EU's annual consumption of any strategic raw material.

## 4.2. Net Zero Industry act (NZIA)

The Net Zero Industry Act (NZIA), adopted by the European Union, sets specific criteria to strengthen the production of clean technologies, particularly in the photovoltaic (PV) sector [NZIA].

The key NZIA criteria for the photovoltaic sector:

- Increase in production capacity: The goal is for the EU to reach a manufacturing capacity for net-zero technologies equivalent to at least 40% of its annual needs by 2030. For photovoltaics, this implies a significant increase in solar module production within the EU.
- Simplification of procedures: The NZIA proposes simplifying regulatory frameworks to facilitate the establishment and expansion of net-zero technology manufacturing facilities, including PV modules. This includes reducing administrative burdens and speeding up permit procedures.
- Sustainability and resilience criteria in public procurement: EU member states are now encouraged to integrate criteria other than price, such as sustainability, carbon footprint, or resilience, into public procurement and certain energy

auctions. This criterion will initially apply to a minimum of 30% of auctions, offering an advantage to European manufacturers adhering to these standards.

- **Support for innovation and competitiveness:** The NZIA aims to attract investments and improve market access conditions for clean technologies in the EU, thus enhancing the competitiveness of the European photovoltaic industry.
- **Development of skills:** The NZIA plans to establish net-zero industrial academies to train a skilled workforce, essential for the development and maintenance of photovoltaic technologies.

These measures aim to strengthen the photovoltaic component supply chain, stimulate innovation, and ensure a sustainable energy transition within the European Union. The European Solar Manufacturing Council (ESMC) has published a recommendation document emphasizing that, while the Net-Zero Industry Act (NZIA) is a positive step, additional measures are needed to restore fair conditions for the European solar industry [ESMC2023].

### 4.3. Eco-design directive

The European Commission is assessing the need for new regulations to govern the environmental impact of photovoltaic products. The 2009/125/EC Framework Directive aims to establish minimum requirements for energy performance and sustainability for PV modules, inverters, and related systems. The goal is to reduce the carbon footprint and improve the recyclability of these products, contributing to a more efficient circular economy.

These initiatives could introduce carbon footprint thresholds for PV modules sold on the European market, eliminating the least environmentally efficient products. The objective is to remove low-quality products from the market by enforcing transparency on two key environmental indicators: Energy Consumption and Carbon Footprint.

The implementation of new criteria for photovoltaic products is set to take effect progressively from 2025, with the introduction of new recyclability and durability requirements for PV modules. This includes strict end-of-life regulations for solar panels, ensuring their recyclability and reuse within the circular economy framework.

### 4.4. EPEAT Ecolabel

The EPEAT (Electronic Product Environmental Assessment Tool) ecolabel is an internationally recognized environmental certification for electronic products [10]. It evaluates and certifies equipment based on its environmental impact throughout its life cycle, considering criteria such as:

- Sustainable design: Use of recyclable materials and reduction of hazardous substances (e.g., lead, mercury).
- Energy efficiency: Compliance with Energy Star standards for reduced power consumption.
- Ease of recycling: Products designed for easy disassembly and end-of-life recycling.
- Manufacturer responsibility: Commitments to e-waste management and corporate social responsibility.

The EPEAT ecolabel classifies products into three levels: Bronze, Silver, and Gold, depending on the number of criteria met. It is commonly used for computers, monitors, servers, and other electronic equipment.

In March 2023, The EPEAT ecolabel has established specific criteria for photovoltaic (PV) modules to promote more sustainable manufacturing practices and reduce their carbon footprint [EPEAT2023]

- "Low Carbon" Level: To obtain EPEAT Bronze certification, a PV module must have an embedded carbon footprint of  $\leq 630$  kg CO<sub>2</sub>e/kWc.
- "Ultra-Low Carbon" Level: PV modules with an embedded carbon footprint of  $\leq 400$  kg CO<sub>2</sub>e/kWc can earn additional points, facilitating access to EPEAT Silver or Gold certification levels.

These criteria are based on a cradle-to-gate life cycle assessment (LCA), covering all production stages from raw material extraction to final module assembly.

## 4.5. Simplified Carbon Evaluation

In France, the carbon footprint assessment of PV panels is part of the tender evaluation process conducted by the French Energy Regulatory Commission (CRE) for PV systems. This assessment follows a simplified evaluation method, excluding the aluminum frame in most cases.

For the evaluation, each eligible and non-rejected application is assigned a score out of 100 points, rounded to the nearest hundredth (0.01). The carbon footprint scoring varies depending on the type of installation [CRE2023].

Only installations with a simplified carbon assessment below 550 kg CO<sub>2</sub>e/kWc are eligible [11]. The application of this threshold has been extended to become a mandatory requirement for all installations >100 kWc (outside tenders), as per the tariff decree of October 6, 2021 [AGEC2022]. The tender methodology for building-integrated PV systems was updated in July 2024, introducing a new approach. This revision eliminates life cycle assessments (LCA) for evaluating the carbon footprint of different components in the value chain and instead introduces country-mix values to ensure a

more representative assessment. Additionally, the threshold has been increased from 550 kg CO<sub>2</sub>e/kWp to 740 kg CO<sub>2</sub>e/kWc.

#### 4.6. Extended Producer Responsibility (EPR)

The AGEC Law aims to promote the circular economy and reduce waste by placing Extended Producer Responsibility (EPR) at the core of product sectors. In this context, Soren implements an eco-modulation system for photovoltaic panel producers, based on a bonus-malus (reward-penalty) mechanism [12]. The eco-contribution varies depending on the environmental impact of the panels, encouraging manufacturers to adopt more sustainable practices, such as improved recyclability and a lower carbon footprint. This system perfectly illustrates the application of the AGEC Law, which enforces EPR and eco-modulation, incentivizing stakeholders in the photovoltaic sector to enhance their environmental performance. This system came into effect in France on January 1, 2025 [13].

Eco-design criteria	Threshold
1. Carbon footprint	450 kgCO <sub>2</sub> eq/KWp
2. Quantity of silver in the cell	14 mg/Wp
3. Rate of recycled materials	>3%
4. Rate of lead in the module	< 0.1%

#### 4.7. Conclusion

As a conclusion of part 2 and part 3 of this deliverable, we can say that based on the definition of the circular economy and on the indicators present in various regulations, the eco-design strategies to be defined must necessarily aim to achieve the following key objectives:

- Reduction of CO<sub>2</sub> emissions
- Reduction of critical resource consumption
- Reuse of materials in their second life
- Extension of product lifespan
- Recycling and recovery

## 5. PV technology and eco-design considerations

### 5.1. PV manufacturing value chain

Currently, various solar cell technologies are available on the PV market (see Figure 10, section 4.2.1). For the RESILEX project, the solar cell technology under study is the so-called silicon-heterojunction (SHJ), based on low temperature process layer depositions described in more details the following sub-sections (see Figure 8).

Manufacturing of state-of-the-art efficiency silicon-based solar cells and modules, from raw materials to the final product requires a series of well-controlled and synchronized fabrication steps. A simplified picture of Silicon value chain from raw silica sand to finished photovoltaic modules is depicted in Figure 6. A schematic representation of the fabrication process, depicting the solar cells and modules manufacturing as well as the installation and grid connection is shown in Figure 7 and described throughout this Section.

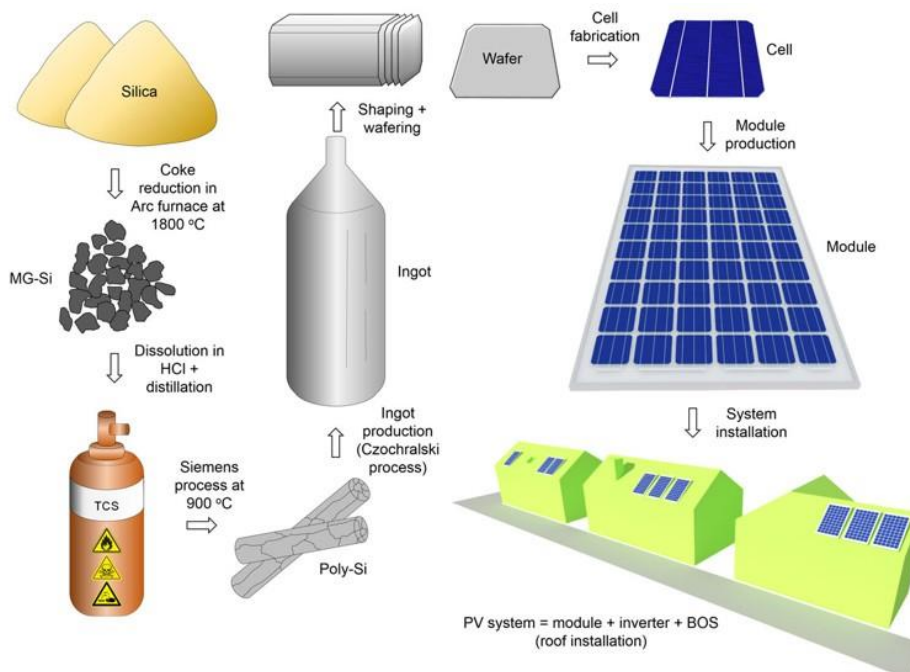


Figure 6 – Schematic of the value chain of silicon PV devices from ingot fabrication to roof installation. Image taken from [OPENPR2020].

According to [Baliff C. 2022], a strong point in the PV sector is the vertical disintegration of fabrication, which has allowed high specialization of stakeholders in the manufacturing side and individual optimization of each processing step both at laboratory and commercial scales. While a great number of promising technologies intended to improve the PV value chain are currently in development, proof-of-concept or early implementation stages as it will be discussed in further sections, in this part a brief description of the industrial processes status is given, following schematics of Figure 7.

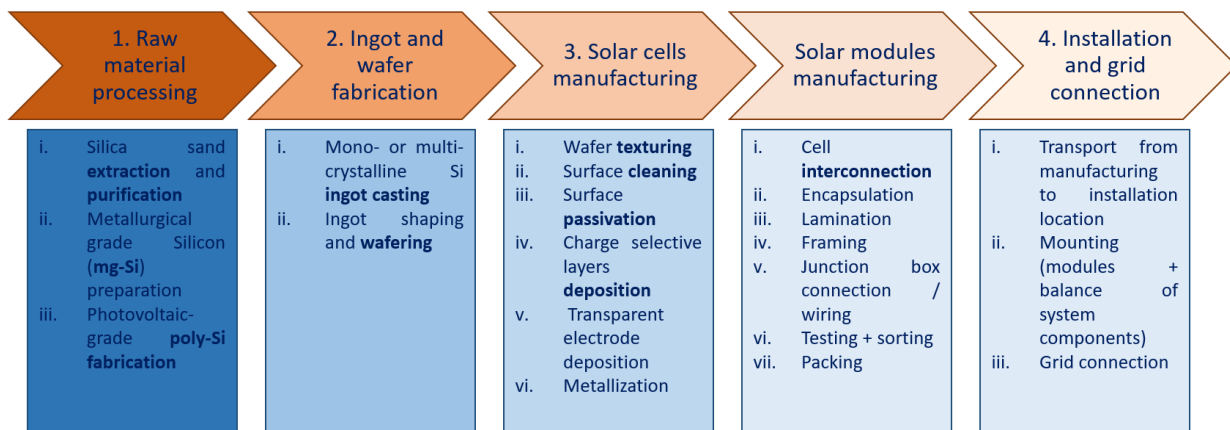


Figure 7: Schematics of the fabrication steps of silicon-based solar modules, from silicon extraction to modules installation.

### Raw material processing

Silica sand ( $\text{SiO}_2$ ) for solar cell applications is the first key raw material in the chain, from which metallurgical grade Silicon (mg-Si) is fabricated through carbothermic reduction of  $\text{SiO}_2$  in electric arc furnaces at temperatures exceeding  $1800^\circ\text{C}$  [Myrhaug E. et al 2021]. These reactions allow formation of Si crystals, generating  $\text{CO}_2$  as a byproduct [Filsinger D. 1990]. After this process step, the purity of mg-Si is roughly 98-99%. For PV industry applications, the lowest acceptable level of Si purity is 99.9999% (6N) to 99.9999999% (9N). This means that, in a Si crystal, only one in one million, to only one in one billion of Si atoms is allowed to be an impurity (a non-Si atom). Therefore, to increase material purity, more treatment is required. The most widely used method for this aim is the Siemens process, in which grounded mg-Si particles are mixed with hydrochloric acid (HCl) inside a closed reactor, in order to form trichlorosilane (TCS) gas. TCS is further transferred and into a Hydrogen-rich reactor containing thin, highly pure U-shaped Silicon rods heated up to  $1150^\circ\text{C}$ . TCS is dissociated and pure Si is deposited around the rods, in the form of polycrystalline Si (poly-Si) while HCl and other byproducts are distilled and recycled. An alternative to Siemens process is the fluidized bed reaction, a potentially competitive method due to the lower operation temperatures resulting in up to 80% less electricity consumption.

Nonetheless, Siemens process is still used due to the higher purity compared to fluidized bed reaction [Jiang L. 2017].

### Ingots and wafer fabrication

The next step in the value chain of Silicon for solar application is the fabrication of mono- or poly-crystalline Si wafers that will serve as photon absorber layer, and substrate for device fabrication. Mono-crystalline Silicon (mono-Si) is casted from poly-Si through the Czochralski process, where molten Si is shaped and pulled in a crucible with a seed crystal dipped in the melt and slowly withdrawn, in order to obtain solid, crystallized Si in the surface of the melt [Zulehner W. 1983]. An alternative method to fabricate mono-Si is Float Zone (FZ), where a rod-shaped seed is located under the ingot, and narrow heater is moved from bottom to top, locally melting it. Together with crystallization, impurities are gathered in the molten zone and brought to the extreme of the ingot, generating highly pure Silicon monocrystal [Muiznieks, A 2015]. Alternatively, the directional solidification (DS) method, where molten silicon is solidified in box-shaped crucibles with multi-crystalline seed layers of varying grain sizes at the bottom [Di Sabatino M. 2024]. Ingot shaping and wafer fabrication are further done in 4 steps: (i) Trimming and squaring, (ii) grinding, (iii) slicing (wafering) and (iv) etching. In step (i) the ends of the ingot are removed usually with an industrial diamond band saw, and shaped in a square. In step (ii), the surface of the ingot is grinded with a diamond cup wheel. In step (iii) the ingot is horizontally sliced in individual wafers of 100 to 200  $\mu\text{m}$  thickness by diamond wire sawing. Finally, in step (iv) contaminants derived from the previous cutting and shaping processes are removed through chemical etching.

### Solar cells fabrication

The first step in solar cells fabrication is silicon wafer texturing. This process allows reducing reflection losses by surface roughening [Kim M. 2020], usually in the form of random pyramids etched in alkaline solutions (generally sodium or potassium hydroxides) [Han S. 2024]. Next, textured wafers are prepared for deposition of passivation layers, charge extraction layers and electrodes. At this stage, avoiding any type of contamination is crucial, therefore, preparation of solar cells is done under cleanroom conditions with controlled temperature and humidity. The aim of surface passivation is to suppress recombination centers at the interface between the Si absorber and subsequent layers. In the case of SHJ technology, surface passivation is done by deposition of a thin (<10 nm) intrinsic (non-doped), hydrogenated amorphous silicon layer ((i)a-Si:H). Hydrogen provides excellent passivation of dangling bonds (Si atoms that lack a bond due to the crystalline network disruption at the surface). Subsequently, charge selective layers in the form of thin n- (phosphorous) and p-

(boron) doped a-Si:H layers are deposited using vacuum chemical vapor phase deposition (CVD) technique. Charge selective layers allow the extraction/blocking of electrons/holes (n-type layer) or holes/electrons (p-type layer) by formation of electrical contacts favorable to each type of carrier. Recent developments using nanocrystalline Si (nc-Si:H) as charge selective layer show promising efficiencies > 26% [Lin H. 2023]. Finally charge extraction is done through the electrodes, which in the SHJ technology are composed of two different types of material: transparent and metallic electrode. The role of the transparent electrode, usually made of doped transparent conductive oxides (TCO) is to provide a lateral path for electrons to move towards the metallic electrodes, given that lateral conductivity of a-Si:H layers is poor. While electrical resistance in TCOs, ranging  $10^{-3}$  to  $10^{-4}$   $\Omega\cdot\text{cm}$  is considered acceptable to find a compromise between transmittance and conduction, metallic electrodes are needed to evacuate electrons to external circuit, with resistances up to  $10^{-6}$   $\Omega\cdot\text{cm}$  [Despeisse M.]. Metallic electrodes, usually made of Silver pastes have good conductivity, but they behave as reflective films in silicon absorption ranges, shadowing the solar cell absorber area and hindering the incoming photons. The most widely used technique for metallic contacts formation in industry is screen printing in the form of narrow strings (< 50  $\mu\text{m}$  width), regularly spaced over the transparent electrode layer [Zeng Y. 2022].

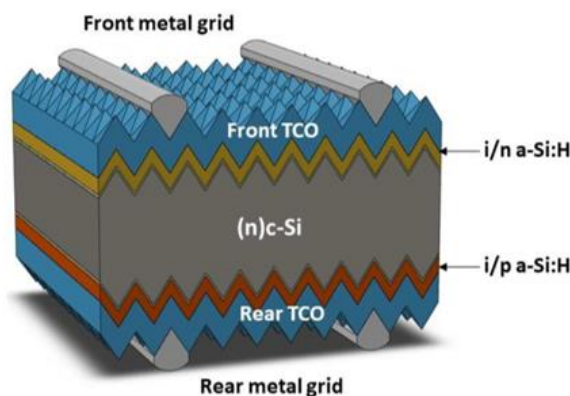


Figure 8: Schematic of a SHJ solar cell developed in the RESILEX project. The various materials layers required to build the solar cells are: the n-type doped silicon bulk, the front and rear intrinsic and n- or p-type doped amorphous silicon layers (i/n/p a-Si:H), the front and rear transparent conductive oxide (TCO) as well as the rear and front metal grid.

### Solar modules fabrication

Finished individual solar cells are then connected in serie to form a string of cells and these strings are connected in parallel to form a module. This connection allows to achieve target voltage/current levels. Usually, solar module voltages ranges within 12-

24 V and currents range within 9–10 A. The most widely used form of interconnection is through metallic ribbons linking the back of one cell to the top of the next one. Another industrially attractive method is shingling, where cell ends are superposed in a tile roof manner, offering several advantages such as increased active area due to the lack of visible metallic interconnection but also new challenges in module design [Klasen N. 2017]. Providing frame, protection from humidity and corrosion as well as mechanical robustness to the modules is done through addition of several layers in top and bottom of the interconnected cells using encapsulant, backsheet, glass and frame (see Figure 9). Status, challenges and eco-design of these components will be detailed in next Sections. Finally, junction box and external wiring is connected to the module and finished modules are cleaned, electrically tested, sorted and packed for transportation.

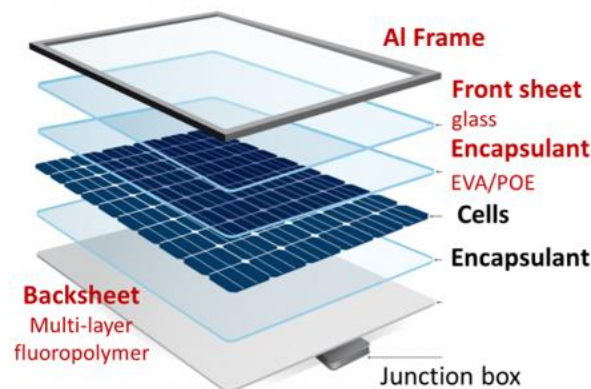


Figure 9: Layered schematics of a PV module. Interconnected PV cells, in the middle of the structure are protected at the front and rear sides by the encapsulant, in order to prevent penetration of humidity and corrosion. The front glass is added in the front and backsheet at the rear side, where the junction box is connected. All layers are bonded together during lamination. The structure is finished with an Al-based frame to give mechanical support and robustness.

### Installation and grid connection

While less controllable than manufacturing steps, transport of modules from manufacturing to installation sites can represent a considerable fraction of the final cost/carbon footprint. In Europe, a relevant potential for the development of a sustainable PV value chain is mostly challenged by policy and regulatory frameworks for enhancing circularity, products traceability and information exchange for further end-of-life treatment [Radavicius T. 2025]. Finally, balance of system (BoS) assets, needed to connect the PV modules to the grid (wiring, inverter, charge controller) or battery in the case of off-grid systems. The type and dimensions of these assets will depend on the dimensions and scope of the PV plants (household, small, medium or utility size).

## 5.2. SHJ solar cells and modules – challenges and considerations

### 5.2.1. Challenges for sustainable PV solar cell production

The main challenge for the photovoltaic solar cell industry is to achieve sustainable multi-terawatt production. Reaching this large production level has become essential when considering the IEA's net-zero CO<sub>2</sub> roadmap, which calls for a massive increase in the electrification of energy consumption, from 20% to 50% of final energy use [NZE2021]. Solar energy is expected to play a major role in this transition, with projections ranging from 14.4 TW to 63.4 TW of installed PV capacity by 2050, depending on the scenario [NZE2021], [ITRPV2024]. The targeted additional capacity per year is therefore expected to range between 600 GW/year and more than 2 TW, including all PV technologies. However, as detailed in specific parts below, the consumption of critical materials such as silver and indium must be significantly reduced to achieve these production levels.

Currently, silicon-based technologies dominate the solar cell market, accounting for more than 95% of production, with an ongoing shift from the PERC to the TOPCon technology. As shown in Figure 10, SHJ technology is expected to increase its market share from less than 10% today to approximately 20%.

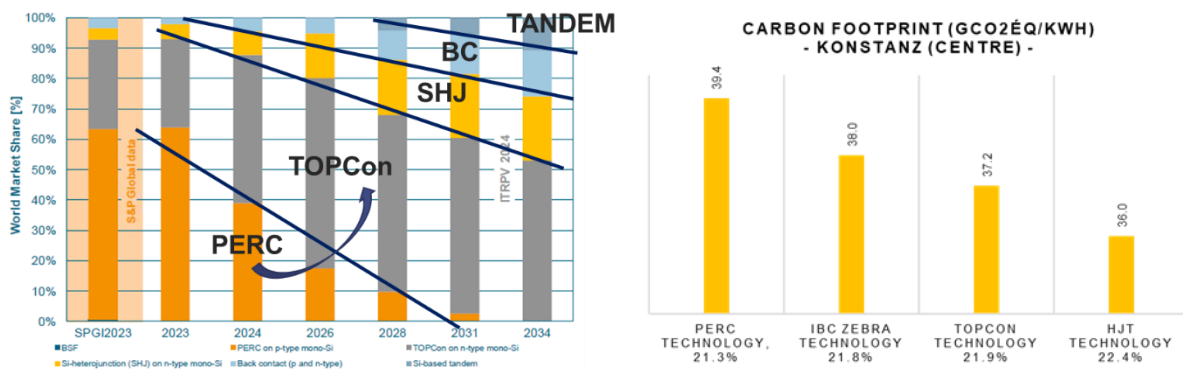


Figure 10 – (left) Photovoltaics world market share per technology [ITRPV2024] and (right) simulated carbon footprint for various solar cells technologies [Libal2024].

SHJ technology presents an attractive option for new industrial production due to several key advantages. Notably, in addition to its high efficiency, it requires low processing temperatures (< 230°C) and a limited number of process steps, while offering a low temperature coefficient (< -0.27 %/°C). This also results in a favourable carbon footprint (gCO<sub>2</sub>eq/kWh) compared to other technologies (see Figure 10), thanks to its high bifaciality factor (> 90%). Additionally, SHJ technology is compatible with

thinner wafers than other solar cell technologies, which can significantly reduce the silicon consumption and further lower its carbon footprint as explained in the silicon challenge below.

Overall, SHJ solar cells are highly appealing for industrial production, and many companies are currently announcing or constructing new SHJ production capacities. The resulting production capacity is expected to exceed 218 GW per year in the near future [TaiyangN]. However, at such high production volumes, SHJ manufacturing may face challenges related to material scarcity. More specifically, if 20% of the global material supply from 2019 were allocated to SHJ cell production, the output would be limited to 171 GW/year due to silver consumption (used in metallization) and 95 GW/year due to indium consumption, based on current material usage per cell [Zang2021].

#### In challenge

Indium was considered a Critical Raw Material (CRM) for the EU at the beginning of the project but has since been removed from the list due to sufficient domestic production. However, in the context of the PV industry, indium remains critical due to the high consumption required for this application compared to the global indium supply.

Indium is almost exclusively obtained as a by-product of zinc ore refining, meaning its primary availability is largely constrained by zinc production levels. Since 2017, global indium production has remained close to 2,000 tons per year, with approximately 900 tons per year originating from primary production and 1,100 tons per year from secondary sources [Sverd2023]. In addition to these supply constraints, the use of indium in photovoltaics competes with other high-value applications, such as LEDs, screens, and other flat-panel displays, which together account for more than 65% of the market. A simultaneous increase in demand across these technologies could lead to price increases and potential supply risks.

In photovoltaics, indium is used in SHJ solar cells as a key component of the transparent conductive oxide (TCO), typically in the form of tin-doped indium oxide (ITO), with a current consumption of 4.23 mg/Watt [Zang2021]. As shown in Figure 11, this consumption level limits the annual SHJ production capacity to a maximum of 95 GW/year when using 20% of the global indium supply. In this context, a reduction of indium consumption by more than 70% appears necessary to maintain a sustainable SHJ cell manufacturing process regarding the planned capacity increases.

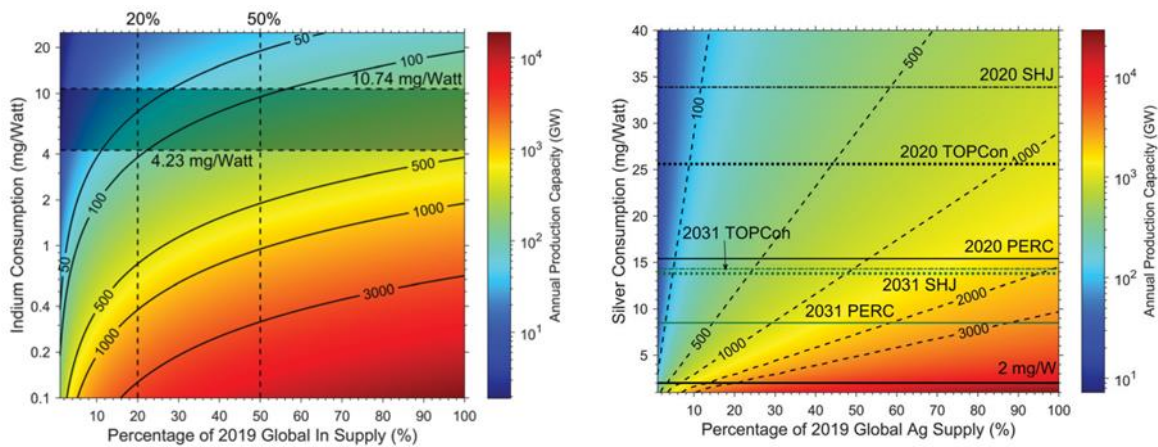


Figure 11 – Allowable annual production capacity as a function of the percentage of 2019 global (left) indium supply and (right) silver supply that can be used in PV manufacturing and of the (left) indium and (right) silver consumption [Zang2021].

### Ag challenge

Silver plays a key role in the metallization of photovoltaic solar cells, serving as the primary component of the front and rear electrodes. It is considered a limiting factor in achieving the production capacity targeted in net-zero emission scenarios. Indeed, to reach a multi-terawatt production scale (>1,000 TW) while limiting silver consumption to no more than 20% of the global silver supply, the consumption must be reduced below 5 mgAg/W [Zang2021]. As shown in Figure 11, there is a significant gap between the consumption levels recorded in 2020 across different technologies and this target.

SHJ technology faces a disadvantage in this regard due to its higher silver consumption compared to other solar cell structures (24.6 mgAg/W at the beginning of the project [ITRPV2023]). This is primarily due to the lower processing temperatures used in SHJ manufacturing, which require specially designed, low-temperature silver pastes with higher silver content. Currently, the constrained silver supply makes the photovoltaic (PV) industry particularly vulnerable to silver price fluctuations. Moreover, silver remains one of the most expensive materials in solar cell manufacturing, making its reduction a priority for the SHJ solar cell industry.

### Silicon challenge

Silicon is a critical raw material for EU and is the main scope of the RESILEX project, which aims to cover the full silicon value chain to contribute to improving the resilience and sustainability of this critical raw material value chain in Europe. Silicon is a

strategic component for EU competitiveness, and it has a significant quantitative importance being the main element used in the PV sector, which is absolutely needed to help Europe reach its climate's targets. Currently, only 32% of the Silicon used in Europe is produced within the EU and this element is of the utmost importance to maintain the competitiveness of the European industry [EUSI2020]. In particular, silicon is one of the few critical raw materials used in most of the strategic renewable energy applications, and together with copper it is the only CRM used in all strategic applications for the e-mobility sector (from battery to traction motors) [EUCRM2020].

In terms of environmental impact, the processes involved in purifying silicon as well as producing ingots and wafers consume a significant amount of energy. These processes often depend on non-renewable energy sources, leading to substantial greenhouse gas emissions, resulting in a high environmental impact contribution of silicon based solar cells compared to the others building blocks of the PV module (see section 4.2.2 Figure 12) [Müller2021].

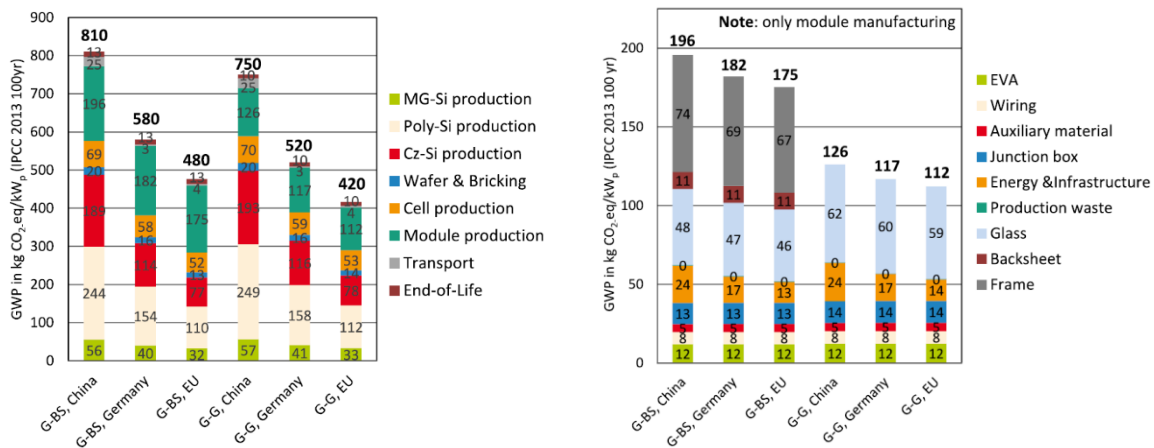


Figure 12 - Global Warming Potential (GWP) of Glass-Glass (G-G) and Glass-Backsheet (G-BS) modules manufactured at several locations. GWP of full value chain (left) and module manufacturing (right) [Müller2021].

### 5.2.2. Challenges for sustainable PV module production

Despite its low-carbon emissions compared to other non-renewable counterparts, PV cannot be considered as a net zero-emission technology. The environmental impact of a PV module is not limited to its operational phase but extends across its entire life cycle including the production of solar cells and modules [Müller2021], when most

emissions take place, and its disposal [Mao2024]. Figure 12 presents the global warming potential (GWP) of glass-glass and glass-backsheet PV modules manufactured at several locations, for the case of the full value chain (left) and the PV module manufacturing (right).

### Glass and aluminium frame challenges

At the module level, the aluminium (Al) frame and the glass are the highest contributors to CO<sub>2</sub> footprint for module manufacturing as shown in Figure 12 right. It corresponds to respectively to 9% and 6% of the total GWP of module manufacturing. The use of Al frame has a major impact on full module's LCA as it requires huge amount of energy during its manufacturing. For this reason, the reduction of Al quantity in PV module is under investigation by various institutes and companies.

Glass is used as the front cover in PV modules. In addition of its CO<sub>2</sub> footprint, solar grade glass can contain antimony (Sb) to increase its light transmission (in patterned solar glass). Its presence currently poses a problem for the recycling of solar glass by smelters, as it contaminates the furnaces [ESIA2023].

Glass in PV module is a very suitable material to reach high efficiency module as it presents high transmittance, serves as an effective barrier against moisture and oxygen, is inert, and provides mechanical rigidity to protect cells from impact. Alternative materials and solutions are under investigation to replace the PV module glass; however, finding suitable materials with similar properties is challenging.

### Encapsulant challenges

The most widespread encapsulants of PV modules is made of ethylene-vinyl acetate (EVA). This polymer is the traditional cross-linking encapsulant which ensure a good adhesion between module components (frontsheet, backsheet, solar cells, etc.) for several decades without creep. This material is also crucial for good module reliability and to ensure necessary lifetime. EVA has a minimal impact at module production level (contribution lower than 2.8 % of the GWP cf. Figure 12 right) however, their chemical nature may have a more important impact at the end of life of the PV module or before as harmful byproducts appear during EVA's degradation.

Indeed, their high adhesion is a challenge for recycling as it makes the separation of the EVA from other PV components complex. Moreover, their cross-linking is irreversible so they cannot be recycled with current economically feasible technologies. The same issues occur with polyolefin encapsulants, such as polyolefin

elastomers (POE), which are cross-linking encapsulants too. To improve the recyclability of EVA and PV components, few ways can be considered such as mechanical, chemical or thermal treatment with energy recovery [Lunardi2018]. In addition, 30% of newly manufactured modules contain 3 layers encapsulants EVA/POE/EVA known as EPE [ITRPV2024]. This configuration could further complicate the separation of materials during the recycling process. Recycling of EVA is particularly challenging, and this topic is treated in the EU project EVERPV.

#### Interconnection challenges

Interconnection in PV modules relies on the ability to connect the solar cells in series to create strings and to connect the different strings in parallel. The PV module interconnection depends on the metallic grid design of solar cells as well on the technology of solar cells wiring. Silver is still largely used to create these different interconnections. Like the concerns of solar cell production concerning silver detailed in the previous section, the silver consumption of PV module interconnection needs to be decrease.

#### Backsheets & frontsheet challenges

Despite the low carbon impact of PV module backsheets compared to other module components at the manufacturing phase (see Figure 12 right), backsheets can be challenging when it comes to the end of life (EoL). The backsheet components can contain a layer of polyvinyl fluoride (PVF) or polyvinylidene fluoride (PVDF). These elements contain fluorine-carbon bond which classes them in the category of PFAS (perfluoroalkyl substances, including fluoropolymers) elements. Due to their toxicity, actions are underway within the EU to modify regulations and completely ban PFAS from PV modules.

These fluorinated materials necessitate additional processes and equipment to manage waste and fluorinated emissions at EoL. When they are recycled using a thermal process, specialized facilities must be used due to the highly corrosive nature of hydrofluoric acid exhaust gases during the recycling process, resulting in a higher cost of the process compared to process for non-fluorinated module. Importantly, modules components containing fluor cannot currently be disposed in landfills and must be treated in costly incineration plants.

### 5.2.3 Eco-design trade-offs: environmental impact and PV module lifetime

The trade-offs involved in material selection for photovoltaic (PV) systems are well-documented, as highlighted by Heath et al. in their comprehensive review on the circular economy for PV systems [Heath2022]. For instance, while the elimination of toxic and critical materials can yield environmental benefits during certain life cycle phases (e.g., end-of-life) and enhance sustainability rankings, it may also compromise the PV module durability and performance during the use phase. Indeed, a long lifetime is essential to reduce the global warming potential (GWP) of solar electricity per kWh. This is not accounted for when considering the GWP per kWp during the module production phase [Müller2022]. Therefore, it is important to explore the potential of substituting or reducing traditional PV module components with lower-impact materials and to determine if these changes can significantly affect the module's lifetime.

Specific trade-offs considered in the RESILEX project are:

- Substituting indium tin oxide (ITO) with aluminium-doped zinc oxide (AZO) might affect the durability and conductivity and reflectivity of these layers.
- Replacing silver with copper for the metallization and interconnection could negatively influence both durability and performance.
- Fluorine-free backsheets may exhibit reduced durability.
- Frame-free designs could undermine the economic feasibility of downstream PV recycling.

## 5.3. General strategies for eco-design PV

In this section, we will propose strategies across the entire value chain aimed at meeting sustainable development goals while ensuring alignment with current regulations.

### 5.3.1 Strategies for Solar cells

Polysilicon: Relocation of production in Europe

For polysilicon, eco-design strategies are largely based on relocalizing production in Europe, which significantly reduces the carbon footprint associated with the manufacturing of photovoltaic modules and the consumption of fossil resources. By

transferring polysilicon production from China to Germany, which is the leading producer of polysilicon in Europe, the global carbon footprint (GCF) of the PV module can be reduced by 12% [GAZB2023].

### Silicon wafer: Reduction of the thickness

For the silicon wafer cutting step, a key criterion is the reduction in wafer thickness. By optimizing this step, it is possible to reduce the amount of material used, which in turn lowers resource consumption and waste production. This approach also helps to reduce the carbon footprint by decreasing the energy required to produce thinner wafers and minimizing material losses.

As shown in Figure 13, a reduction of the total carbon footprint by approximately 20 kg CO<sub>2</sub>e/kWp can be achieved by reducing the wafer thickness by 10 μm.

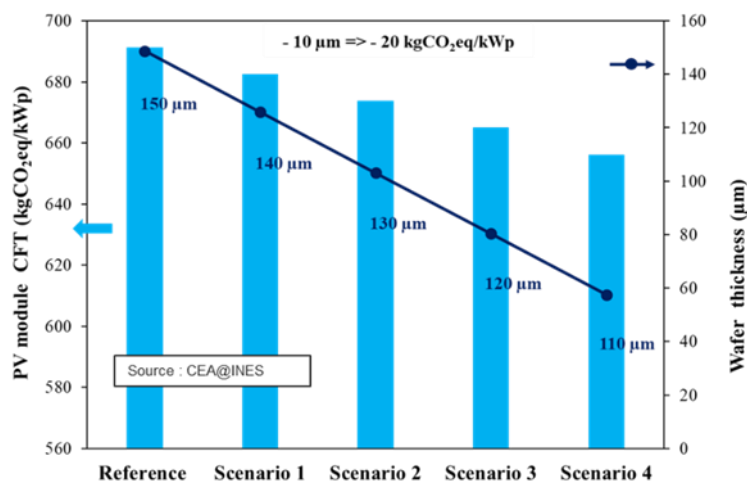


Figure 13 - Impact of the wafer thickness on the carbon footprint.

### Silicon wafer: Reuse of kerf

In addition, as nearly 40% of silicon feedstock used to prepare silicon cells is lost during wafering step in micrometric powder form (kerf loss), the reuse of kerf silicon is another possible eco-designed approach. Many works, focused on process development for silicon-kerf recovery and purification, pave the way on kerf recycling. A recent environmental assessment study demonstrated that kerf recycling to produce secondary MG-silicon should allow to reduce up to 77% of GHG emission [Blom2023].

### Solar cells: Reduction of critical materials consumption

Replacing silver with copper in the production of photovoltaic panels helps optimize costs while protecting the environment. Copper, being more abundant and less

expensive than silver, reduces material expenses while maintaining good electrical performance. By decreasing dependence on a precious and limited metal, this approach makes solar panel production more cost-effective. Additionally, it contributes to reducing the environmental impact by minimizing the extraction and processing of silver, thus lowering the carbon footprint of the manufacturing process. This change supports both the economic efficiency and ecological sustainability of the photovoltaic industry.

Reducing the consumption of indium specific Heterojunction (SHJ) technology is also an eco-design strategy. Indium, a rare and expensive material, is used in small quantities in SHJ solar cells for its excellent conductive properties. By minimizing its usage, the environmental impact associated with its extraction and processing can be significantly reduced. This strategy helps to lower material costs and decrease resource depletion, making the production of SHJ solar cells more sustainable while still maintaining their high efficiency and performance.

### 5.3.2 Strategies for PV modules

#### Aluminium frame

Frame design belongs entirely to module manufacturers and is optimized for each module configuration. Efforts to reduce Al quantities are mainly driven by economical and not ecological purposes. Al replacement arrives on the market, for example by the use of steel frames, which is cheaper but requires heavier manufacturing machines than aluminum. A natural way to keep strength and reduce environmental and economic impact is to use bio-based frames. Wood or wood-based composites offer an interesting alternative but brings new challenges such as fire resistance to improve.

#### Glass removal

To reduce the negative environmental impact of glass in PV modules, an alternative approach involves manufacturing glass-free PV modules. This can be achieved by using a polymer as the front cover and a rigid backsheets or by using a rigid polymer as frontsheet. However, due to their higher cost and the superior mechanical stability of glass, polymeric frontsheet are only adopted in special products such as “lightweight” PV modules. For environmental concerns, the use of fluorine-free polymers should be prioritized.

### Encapsulant - adaptability

Within this project, we focused on non-cross-linking encapsulants to ease recycling such as thermoplastic olefin (TPO) encapsulants. They need some more reliability testing to enhance their long-lasting performance notably against moisture ingress. Delamination and recycling are simplified by using a TPO instead of EVA. Their non-cross-linking feature allows TPOs to be reshaped and recycled without compromising their physical properties. It should be noted that, to our knowledge, there is currently no generalized and public recycling process for the encapsulant. However, Borealis claims that its thermoplastic (poly)olefin (TPO) encapsulants are fully recyclable.

### Metallization: silver reduction

It is possible to reduce the silver consumption to module level by using a OBB interconnection technology, without busbar. This interconnection scheme brings more advantages regarding performance and reliability compared to standard multi-busbar brazing interconnection. OBB interconnection is a successful solution as it allow a direct reduction of silver consumption in addition to enhance the performance of the module thanks to lower ohmic losses, reduced cell cracking as well as thanks to a decrease of thermo-mechanical stress as the soldering happens during lamination [Faes2018].

Finally, lead-free interconnections are also under investigation, by replacing conventional lead-based solders [ITRPV2024] with alternative lead-free solutions. Adhesive bonding or lead-free OBB interconnection, helps reduce the environmental and health risks associated with lead. Moreover, these alternatives enable lower process temperatures.

### Backsheet: fluorine-free and bio-based materials

The EoL life cycle assessment for fluorine-free backsheets demonstrates a lower environmental impact compared to fluorinated in 11 out of 12 impact categories (excluding GWP) for the incineration scenario, and in 8 out of 12 categories for pyrolysis [Aryan2018]. In addition, avoiding such materials reduces the economic cost of photovoltaic (PV) module recycling [Heath2022]. Similar reasoning can be made for polymeric frontsheets that can substitute glass in lightweight module configurations. In this case, fluoropolymers should be avoided for frontsheets.

Backsheet without fluoropolymer, such as pure polyethylene terephthalate (PET) or polypropylene (PP), are more environmentally friendly and easier to recycle but are less durable than backsheets containing also PVF and PVDF layers. Indeed these

fluoropolymers are excellent UV protectors for the backsheet's PET core layer thus they prevent its embrittlement under UV light. Today's challenge is to find new substitute layers to prevent UV degradation without fluorine-carbon bound containing materials (PFAS). Alternatives to fluorinated backsheets such as full PET and bio-based materials are recommended [Aryan2018].

## 6. RESILEX solutions and Scenarios

This section introduces and details the eco-design solutions and scenarios of solar cells and PV modules which are under investigation in the RESILEX project.

### 6.1. Solar cells

#### Solar cells solution

##### a) Silicon reduction:

In the RESILEX project, two approaches are investigated for silicon reduction:

- The use of silicon made from revalorized waste produced by NTNU with a carbon-free and sustainable, aluminothermic reduction process. The growth of a CZ ingot using this revalorized silicon will be realized and the wafers coming from this ingot will be assessed for high efficiency solar cells fabrication.
- The use of thinner wafer. For this approach the impact of the wafer thickness reduction will be assessed for the eco-designed solar cell process developed in RESILEX.

##### b) Indium reduction:

For Indium reduction several approaches are investigated in the RESILEX project to easier reduce the use of indium by more than 70% or completely remove indium from SHJ solar cells.

- The first approach developed at CEA, called "In-less SHJ", is to strongly reduce the ITO layer thickness, by developing highly conductive thin layers and by compensating other losses by adding a dielectric layer made of silicon nitride (SiN) [Cruz2022]. The SiN will be deposited after the metallization step which may induce reliability issues for interconnection. The module reliability of this

approach will be assessed under humidity and UV and the process optimized in consequence. Thanks to this solution a reduction of indium by 70% is expected. The maturity of this technology will be increased from TRL6 to TRL8.

- The second approach developed both at CSEM and CEA is to develop Indium-free transparent conductive oxide that will fulfill all the TCO requirements (a low contact resistance with the active layers and the metal grids, a low sheet resistance to provide a high lateral transport toward the electrode, but also a high transmittance and an efficient antireflective layer). From literature results, the solution chosen for the project will be focused on Aluminum doped zinc oxide (AZO) layer deposited by plasma vapor deposition (PVD) [Sena2022]. As this solution may face stability issues under humidity, module reliability under humidity exposure will be assessed during the development.

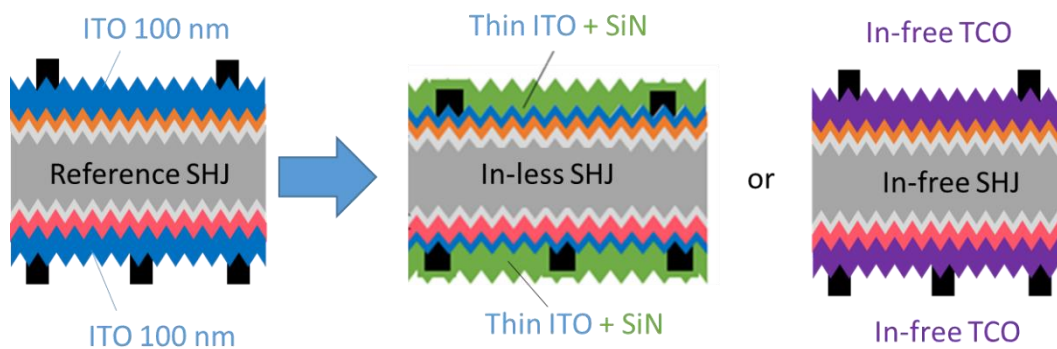


Figure 14: SHJ solar cell structure with Indium reduction solutions “In-less” and “In-free” developed in RESILEX.

- The third approach is the development of In-free TCO deposited using a non-vacuum technique instead of standard PVD at LMGP:

A promising alternative to PVD is the spatial atomic layer deposition (SALD) technique which is a modified version of traditional atomic layer deposition (ALD). In contrast to the latter, where pulses of gas-phase precursors are alternated with time intervals for film growth, in SALD precursors are continuously injected, with the substrate moving under each gas channel. In this way, when the substrate is placed very close to the channels, separated by inert gas walls each point of the substrate is exposed to each precursor alternatively, reproducing the pulse/purge scheme of ALD.

Two main advantages of this approach can be highlighted: 1. Film growth can occur up to 2 orders of magnitude faster than in traditional ALD, therefore, SALD is a much more promising alternative than ALD from the industry application point of view. 2. SALD can be performed without any vacuum chamber, therefore, the costs associated to vacuum pumps found in most industry-size PVD reactors are avoided, and the electricity consumption is significantly lower.

c) Silver reduction:

For silver reduction many approaches are currently under investigation in the photovoltaics community. Among them two approaches have been chosen in the RESILEX project:

- Screen-printing of copper-based pastes

This first approach is investigated by CEA. It is based on the well-established industrial screen-printing technique and consists in replacing the standard silver paste by silver-coated copper pastes. Indeed, printable copper-based pastes are under active development with the aim to replace partly or completely the silver particles with copper ones. As copper tends to oxidize at low temperatures, one promising solution consists of using copper particles coated by a thin silver layer. By developing SHJ with electrodes deposited with these new pastes on the front and rear side a drastic reduction of the silver content is expected in this project.

- Copper electroplating based on the simple CSEM process

The second approach aims at demonstrating industrial silver-free SHJ solar cells by using copper electroplating deposition using the simple process developed by CSEM presented on Figure 15. The solution is based on a screen-printing copper-based seed-grid, which is similar to the previous approach but without silver and followed by the electrodeposition of copper performed after protecting the TCO thanks to the deposition of a dielectric layer on the full cell area. The maturity of this process will be increased in the RESILEX project with precursor optimization on CEA pilot line for the seed-grid and dielectric steps.

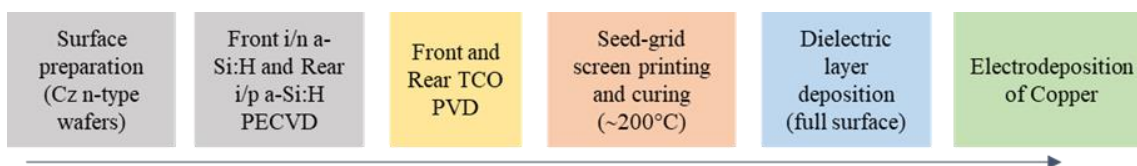


Figure 15: Ag-free SHJ solar cell process by copper electroplating on a screen-printing seed-grid.

### Solar cells scenarios :

Based on the eco-design considerations and investigations detailed in this report, we propose three main scenarios for processing solar cells, aiming to reduce their environmental impact and to decrease their content of critical raw materials. The three scenarios are detailed in Figure 16. 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 in-free and silver-free solar cells. The reference scenario considers 100 nm thick front and back indium thin oxide (ITO) as well as standard silver screen print paste for the front and back metallic grids. Scenario 1 replaces the standard 100 nm ITO with thinner ITO and a combination of thin ITO and aluminum zinc oxide (AZO), an indium free TCO. Additionally, it uses silver-copper paste for the metallic grids on both sides. Finally, an additional dielectric layer (step 6) needs to be deposited on both sides of the solar cells to complete the thin TCOs thickness and achieve optimized anti-reflective coating (ARC). Note that in the standard scenario, the thick ITO layer already has the appropriate thickness to serve as ARC as well. Scenario 2 again considers using thin ITO as well as AZO layers, but this time AZO is used alone deposited by PVD or SALD, allowing fully remove the use of indium. Additionally, it uses full copper paste to screen print the thin seed metallic grid on both sides, along with an additional copper plating process (step 7) to complete the copper seed grid, thereby completely eliminating the use of silver. To complete this description, Figure 17 details the process steps for the SHJ solar cell processing of scenario 2.

These three scenarios detailed in Figure 16 were shared with the RESILEX WP7 team for a complete assessment of their economic, environmental, and societal impacts.

Reference SHJ	Scenario 1 « In-less & Ag-less SHJ »	Scenario 2 « In-free or less & Ag-free SHJ »
1) WET chemicals	1) WET chemicals	1) WET chemicals
2) PECVD a-Si	2) PECVD a-Si	2) PECVD a-Si
3) PVD ITO 100 nm Front & Rear	3a) PVD thin ITO 3b) PVD thin ITO + AZO	3a) PVD thin ITO 3b) PVD AZO 3c) SALD AZO
4) Screen-printing Ag paste	4) Screen-printing of <b>Ag-Cu</b> <b>paste</b>	4) Screen-printing <b>Cu</b> <b>paste</b>
5) Curing	5) Curing	5) Curing
	6) PECVD SiN or SiON (front side)	6) PECVD SiN or SiON (front & back sides)
		7) Cu plating

Figure 16: Description of the three solar cells scenarios under study.

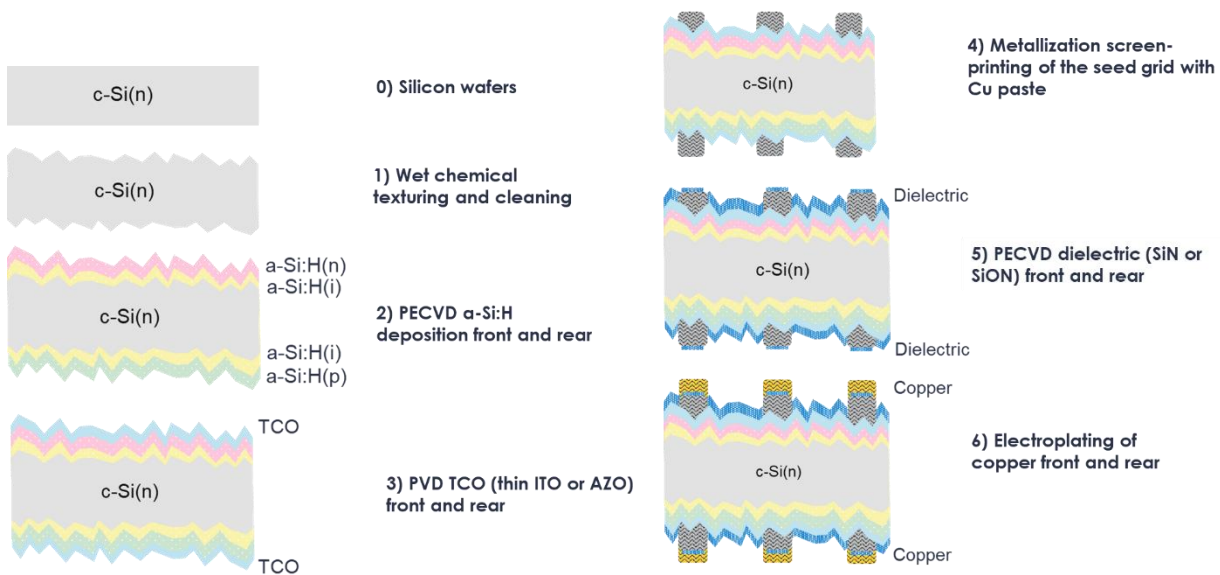


Figure 17: Details of the process steps to process the SHJ solar cell of scenario 2.

## 6.2. PV modules

PV modules solutions:

Bio-based materials:

One of the approaches we evaluate in this study is the substitution of PV components with bio-based materials. Bio-based materials are fully or partially derived from the biomass, they have the potential to reduce the fossil fuel dependence and lower the greenhouse gases emissions. Our main objective is to provide a comprehensive overview of the subject, by first a literature search and then introducing bio-based materials into modules and testing their performances in terms of efficiency, reliability, and environmental impact.

Aluminum-free PV modules:

In this work we study a solution which consists in substitution of aluminium by bio-based materials for frameing. In this case we investigate available materials, which are currently not on the PV market, in order to pass IEC normes. The first suggested

material is wood which needs to be adapted for this application to be able to pass fire certification (societal challenge) in addition to mechanical tests.

**Glass-free PV modules:**

In this work we introduce polymeric front sheets (preferably non fluorinated) that can substitute glass to reduce the module global warming potential.

**Fluorine-free materials:**

- Fluorine-free backsheet:

In this work we screened the backsheet market and selected a PET based, fluorine-free backsheet. The first version contains a thin (7µm) aluminium layer in order to increase moisture ingress resistance of the polymer. In further investigation we adopted an aluminium-less PET backsheet to further decrease its environmental impact.

- Fluor-free rigid backsheet:

Non fluorinated backsheets can also be rigid to bring mechanical stability making it possible to remove the front glass by replacing it with polymer frontsheet. For this purpose, bio-based materials made of fibre reinforced polymer composite materials are investigated in this work. In particular, bio-based backsheets made either of wood planks or with a polypropylene/flax fibre composite are processed and characterized. In addition, the challenges regarding the recyclability of PV module integrating these new bio-based backsheets are considered.

- Fluor-free frontsheet

In this work we investigated and developed a custom fluorine-free frontsheet formulated at CSEM that allows the removal of the front glass. In addition, these developments are performed considering that the base resin of the formulation can be bio-based.

**Lead-free interconnection:**

- OBB

Regarding PV module interconnection, we are investigating a lead-free OBB interconnection that allows for low-temperature processing. In addition to removing the lead content, this method also allows for a strong reduction of silver consumption for solar cell metallization.

- ECA

A 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 as it is also a low-temperature interconnection technology, it offers low stresses paving the way to the use of tandem cells or thin cells. ECAs are used either for shingle interconnection or for ribbons attachment on SHJ cells with proven extended reliability in accelerated tests and in outdoor conditions [Harrison2021]. 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. 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.

New encapsulants:

- TPO

New TPO encapsulant in UV through and UV cut versions had been developed within the project. CEA had integrated several versions of these materials (TPOs) into mini modules to test their reliability compared to market available conventional encapsulants (POE). We also integrated TPOs from the market into mini-modules to expand comparison.

- Improved reliability

Encapsulant itself has a low global warming potential compared to other module components, but it is a key component for module reliability and lifetime. Our aim is to develop an encapsulant that enhance the reliability of the developed eco-design PV modules. In this work, a custom formulation of PO-based encapsulant is under development, which can be fine-tuned to provide good reliability for eco-designed module components. In addition, these developments are performed considering that the base resin of the formulation can be bio-based.

PV modules scenarios:

As for cell scenarios, we took into consideration eco-design approach detailed in this report, and propose three main scenarios for module manufacturing as showed in Figure 18. The first scenario describes the reference module using SHJ solar cells interconnected by brazing, in glass/backsheet configuration. The encapsulant is EVA as 80% of the modules manufactured actually. The framing is in aluminium and the

backsheet contains fluorine. The second scenario describes module making with SHJ solar cells interconnected by ECA technology, using thin front glass and fluorine free polymer backsheet which contains aluminium moisture barrier. The module has wood frame and made with TPO encapsulant. The third scenario covers several combination of studied eco-design solutions such as ECA or 0 BB interconnection, the use of different solutions of front or rear side layers.

Figure 19 details the assembly steps of the modules according to the scenarios.

These three scenarios detailed in Figure 18 were shared with the RESILEX WP7 team for a complete assessment of their economic, environmental and societal impacts.

	Reference	Scenario1	RESILEX other Scenarios
Interconnection	Copper based multiwire brazing	ECA	a) ECA b) OBB
Front sheet	Glass 3.2 mm	glass 2 mm	a) glass 2 mm b) Polymer
Backsheet	TPE	Fluor-free PET-Al	a) Glass 2 mm b) No-fluor, no-Al, PET c) Wood d) Flax/PP composite
Encapsulant	EVA	TPO	a) PO b) POE c) TPO
Frame	Aluminium	Wood	Wood

Figure 18: Details of PV module bill of materials for the three scenarios under study.

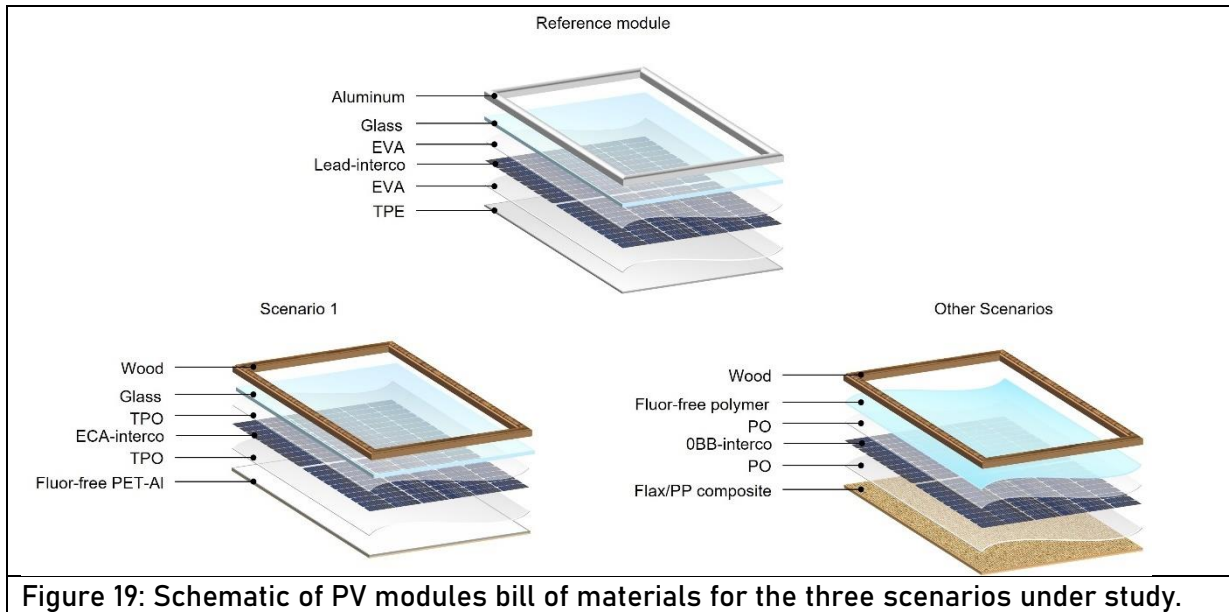


Figure 19: Schematic of PV modules bill of materials for the three scenarios under study.

## 7. Milestone M11: Proof-of-principle eco-designed mini-module

### 7.1. Modules with eco-designed backsheet (CSEM)

One of the main developments and investigations of this WP4 is the substitution of the conventional backsheet with a rigid bio-based composite backsheet made of flax fibres and polypropylene. The rigidity of the composite backsheet allows for the removal of the front glass and its replacement with a polymer frontsheat. In these developments, a non-fluorinated frontsheat formulated at CSEM was used. In addition, the PO based encapsulants developed at CSEM was used with the aim to improve the reliability. Regarding the solar cells, three different technologies were introduced for module implementation which are (i) Passivated-Emitter-Rear-Cell (PERC), (ii) Silicon Heterojunction (SHJ) and (iii) Interdigitated-Back-Contact (IBC). In particular, the SHJ technology was interconnected thanks to 0BB scheme, allowing for silver reduction in the screen printing of the solar cell.

As shown in Figure 20 a et b, the implementation of the different cell technologies with this developed eco-design bill-of-material (BoM) was demonstrated to be successful. Visual inspection and electroluminescence (EL) imaging showed intact cells with no

breaking, indicating that the eco-design materials are compatible with the optimized lamination process.

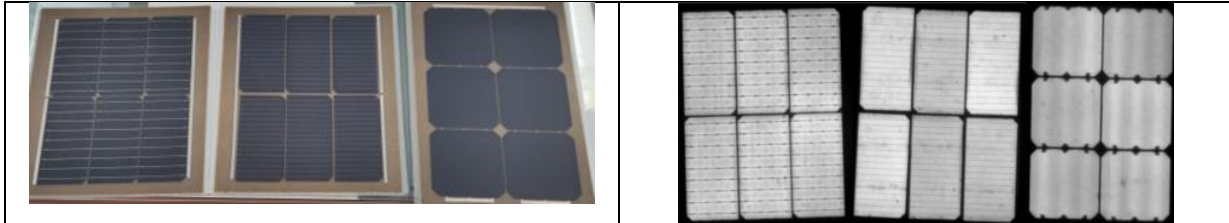


Figure 20: a) visual inspection and b) EL imaging of eco-designed modules incorporating a flax fibre based composite backsheets, a non-fluorinated polymer frontsheet and a PO encapsulant for improved reliability. The cell technologies are from left to right: PERC, SHJ with OBB interconnection and IBC.

After the lamination processes, the reliability and the LCA of these eco-design modules were investigated.

The reliability under damp heat (DH) at 85°C with 85% RH and thermal cycling (TC) (from -40 to +85°C) of such modules is evaluated following the IEC61215 standards. DH is critical for cells that are sensitive to humidity, such as SHJ, and TC can be critical especially if the thermal coefficients of expansion of the materials are different. Figure 21 shows the reliability results of the modules in DH (a) and TC (b). First it is observed that all the modules passed two times the IEC standard in TC with no cell cracking. This demonstrates that the differences in thermal coefficient of all the eco-design materials used of this new BoM are compatible. Secondly, the three solar cell technologies passed the IEC standard once, validating the reliability of the BoM for these technologies. However, only the PV module integrating the IBC technology passes two times the standard, with critical failure of PERC and slow performance loss of SHJ after passing one time the standard. These results demonstrate that moisture ingress through the module materials can be critical and could be reduced to protect the solar cells and interconnections. Overall, these preliminary results are promising and quite impressive as we demonstrated that the PV modules integrating non-fluorinated frontsheet, PO-based encapsulant and flax backsheets pass the standard in TC and DH.

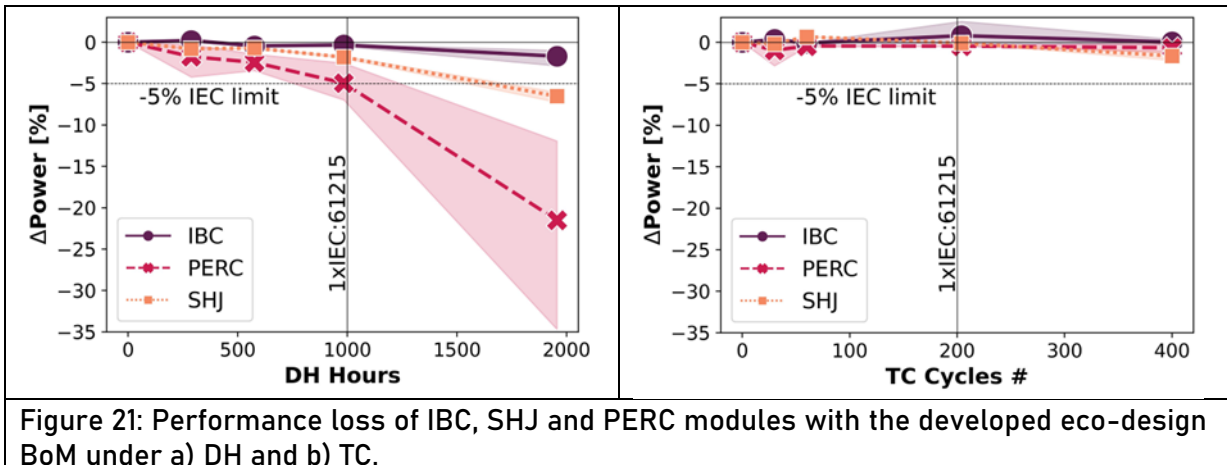


Figure 21: Performance loss of IBC, SHJ and PERC modules with the developed eco-design BoM under a) DH and b) TC.

To complete the reliability study, a preliminary LCA was performed to investigate the potential of this eco-design BoM to reduce the environmental impact of PV module. Figure 22 shows the global warming potential of the developed eco-design PV module integrating the flax composite backsheets, the PO encapsulant as well as the non-fluorinated polymer frontsheet along with conventional PV module BoM in the two glass/glass and glass/backsheets configurations. The double glass PV module presents the highest impact due to the glass contribution and the eco-design PV module the lowest global warming potential impact. Importantly it is observed that the flax backsheets presents a higher impact in term of CO<sub>2</sub> equivalent than the conventional backsheets. However, it provides the mechanical stability allowing to remove the glass and thus significantly reducing the total PV module global warming potential. In addition, it allows to remove the fluor content reducing the negative impact at recycling stage. To complete and continue further this LCA study, in depth investigations of the different LCA impact categories will be performed in collaboration with WP7 to discuss and compare more precisely the environmental impact of conventional and eco-design PV modules.

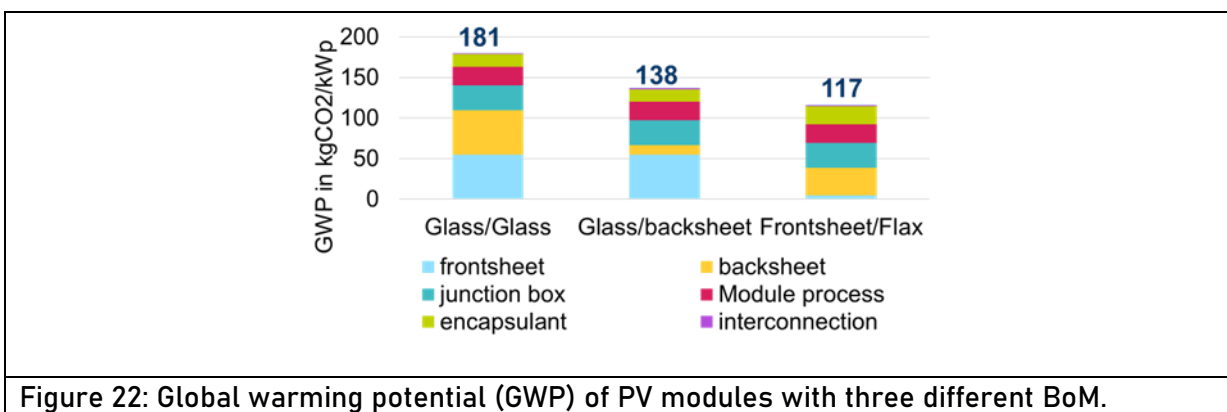


Figure 22: Global warming potential (GWP) of PV modules with three different BoM.

### First proof of principle outcomes:

- Eco-design PV module demonstrated promising results:
  - Successful lamination process integrating all eco-design components
  - Passed the IEC norm in DH and TC
  - Non-fluorinated flax composite backsheets with polypropylene which could be bio-sourced
  - Non-fluorinated frontsheet
  - Adaptable PO encapsulant for high reliability
- Substitution of glass with non-fluorinated polymeric front sheet is efficient to reduce the module GWP/kWp.
- Depending on the cell technology used, the eco-design BoM reliability may be lower than conventional BoM. This highlights the need to enhance the humidity resistance of eco-design PV modules.
- The use of non-rigid backsheets that have a lower or similar GWP compared to conventional backsheets could be used for an overall improved module GWP.
- The environmental impact in GWP/kWp of bio-based materials is not necessarily lower than that of conventional materials. A comprehensive study comparing all the different LCA impact categories is needed to accurately assess the environmental impact reduction, including the use phase and the end-of-life phase.

## 7.2. Second proof of concept of eco-designed module with low In and low Ag containing cells (CEA)

The idea of this proof of concept (POC) module making was to put together several findings of the project. On one hand side, we had encapsulant from the project which contains bio-based components and on the other hand we had solar cells with less indium or less silver content. In this POC we combined these eco-design options to decrease the module's overall LCA target values and decrease environmental impact.

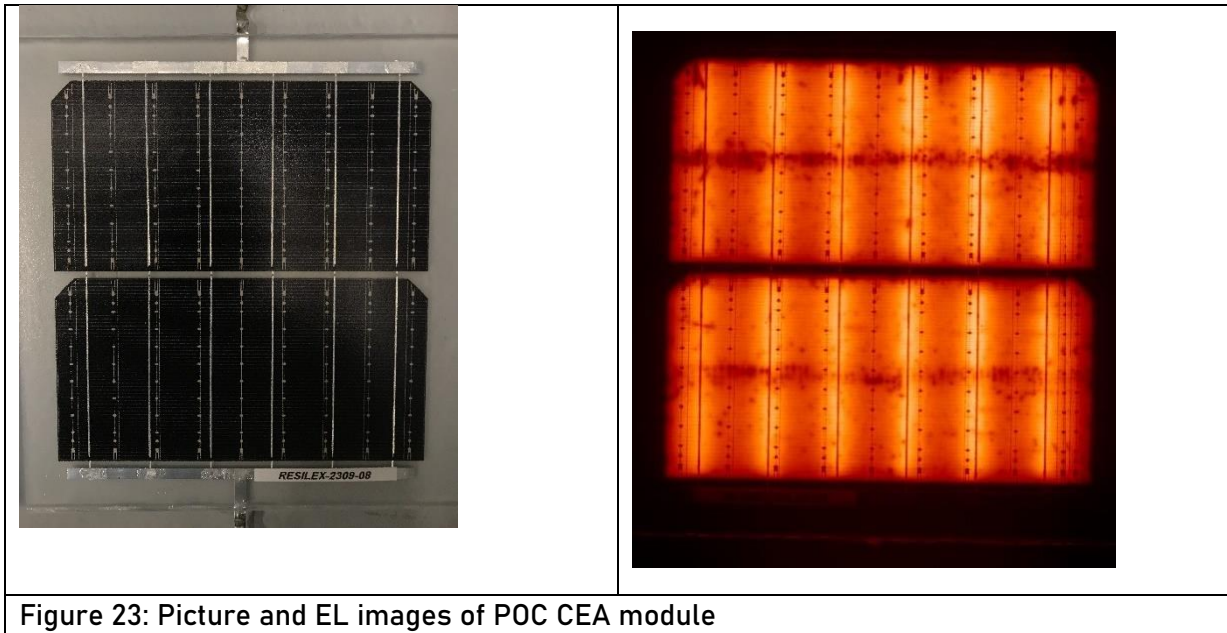


Figure 23: Picture and EL images of POC CEA module

In this study, we have incorporated two versions of a European encapsulant, supplied by project partner CSEM, into silicon heterojunction cell (SHJ) technology modules. This first experiment enabled us to validate the two encapsulants (one that cuts UV radiation and one that lets it through), using solar cells with reduced amount of Silver and Indium, and for two module configurations: glass / glass (cf. Figure 23) and glass / backsheets (size 20 cm \* 20 cm). Initial aging tests have been very encouraging, with all modules passing the standard IEC norm requirement (less than 5 % Pmax loss after 1000 h in damp heat at 85 °C and 85 % relative humidity) 1,5 times and 70 % of modules passing the standard twice (2000 h DH).

More details about these results and milestone will be presented in the next deliverables D4.2 and D4.3.

## 8. Conclusions

1. **Reduction of Environmental Impact:** The eco-design strategies developed in the RESILEX project aim to reduce CO<sub>2</sub> emissions, minimize the consumption of critical resources, and promote the reuse and recycling of materials.
2. **Regulatory Compliance:** Adhering to regulations like the CRMA and NZIA is crucial for the PV industry to enhance sustainability and competitiveness.
3. **Technological Advancements:** Innovations in SHJ solar cells and the use of alternative materials, as explored in the RESILEX project, are essential for achieving sustainable multi-terawatt production.
4. **Future Directions:** Continued research and development in eco-design, coupled with regulatory support, will drive the PV industry towards a more sustainable and resilient future, as demonstrated by the RESILEX project.

## References

### Section 1:

[CRE2023] La CRE publie les cahiers des charges des nouvelles périodes des appels d'offres dit "PPE2 Eolien", "PPE2 PV Bâtiment" et "PPE2 PVSol" et accompagne les porteurs de projets. Accessed Jun 19, 2023. [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 | CRE](#)

[ETIPV2023] Expert input paper – Eco-design & energy labelling for photovoltaics modules, inverters and system in the EU - ETIP PV. Accessed Jun. 26, 2023

[QCells2019] Q CELLS' Q.PEAK DUO modules earn further low-carbon certification for French tenders - Q CELLS South East Asia. January, 2019. [Qcells Q.PEAK DUO modules earn further low-carbon certification for French tenders | Qcells](#)

[REC2022] 'Le panneau solaire REC Alpha Pure sans plomb obtient la certification CERTISOLIS bas carbone', L'Echo du Solaire. Februray, 2022. [Le panneau solaire REC Alpha Pure sans plomb obtient la certification CERTISOLIS bas carbone - L'Echo du Solaire](#)

[Voltec] Voltec Solar, Aspects environnementaux. [Un Fabricant de Panneaux Solaires Engagé - Voltec Solar](#)

### Section 2:

[ADEME2021] « [PHOTOVOLTAÏQUE] une feuille de route pour mener la filière vers l'excellence environnementale », ADEME Presse.

[Agenda2030] L'Agenda 2030 en France, « 17 Objectifs de développement durable », <https://www.agenda-2030.fr/17-objectifs-de-developpement-durable/>

[Brundtland] S. D. Myttenaere, « Rapport Brundtland : la naissance du développement durable », Bioxegyproject.

[Circ2023] « Circular economy: definition, importance and benefits », Topics | European Parliament. <https://www.europarl.europa.eu/topics/en/article/20151201STO05603/circular-economy-definition-importance-and-benefits>

[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](https://doi.org/10.1016/S0959-6526(00)00052-4)

[Kirch2017] J. Kirchherr et al. "Conceptualizing the circular economy: An analysis of 114 definitions". Volume 127, December 2017, Pages 221-232  
<https://doi.org/10.1016/j.resconrec.2017.09.005>

### Section 3:

[AGEC2022] P. Cieplik, « Décret AGEC 2022-748 : la réglementation française en matière d'étiquetage environnemental », Scantrust. <https://www.scantrust.fr/agec-decret-2022-748-france-reglement-sur-letiquetage-environnemental/>

[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>

[CRM2020] « The 2020 EU Critical Raw Materials List – Policies », IEA.  
<https://www.iea.org/policies/15274-the-2020-eu-critical-raw-materials-list>

[EPEAT2023] EPEAT Registry. Accessed Jun. 26, 2023. [EPEAT Registry](#)

[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/>

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

### Section 4.1:

[Ballif C. 2022] Ballif, C., Haug, F. J., Boccard, M., Verlinden, P. J., & Hahn, G. (2022). Status and perspectives of crystalline silicon photovoltaics in research and industry. *Nature Reviews Materials*, 7(8), 597-616.

[Despeisse M.] Despeisse, M., Ballif, C., Faes, A. & Lachowicz, A. (2015). Metallization and interconnection for silicon heterojunction solar cells and modules. *Photovoltaics International*. 30. <https://www.pv-tech.org/wp-content/uploads/legacy-publication->

[pdfs/b40c4315ce-metallization-and-interconnection-for-silicon-heterojunction-solar-cells-and-modules.pdf](#)

- [Di Sabatino M. 2024] Di Sabatino, M., & Hendawi, R. (2024). Crystallization processes for photovoltaic silicon ingots: Status and perspectives. *Journal of Crystal Growth*, 127772.
- [Filsinger D. 1990] Filsinger, D. H., & Bourrie, D. B. (1990). Silica to silicon: key carbothermic reactions and kinetics. *Journal of the American Ceramic Society*, 73(6), 1726-1732.
- [Han S. 2024]. Han, S., Chu, M., Pham, D. P., Dhungel, S. K., & Yi, J. (2024). Comparison of different approaches to texturing monocrystalline silicon wafers for solar cell applications. *Surface Science*, 748, 122540.
- [Jiang L. 2017] Jiang, L., Fieselmann, B.F., Chen, L., Mixon, D. (2017). Fluidized Bed Process with Silane. In: Yang, D. (eds) *Handbook of Photovoltaic Silicon*. Springer, Berlin, Heidelberg. [https://doi.org/10.1007/978-3-662-52735-1\\_5-1](https://doi.org/10.1007/978-3-662-52735-1_5-1)
- [Kim M. 2020] Kim, M. S., Lee, J. H., & Kwak, M. K. (2020). Surface texturing methods for solar cell efficiency enhancement. *International Journal of Precision Engineering and Manufacturing*, 21(7), 1389-1398.
- [Klasen N. 2017] Klasen, N., Mondon, A., Kraft, A., & Eitner, U. (2017, April). Shingled cell interconnection: a new generation of bifacial PV-modules. In *7th Workshop on Metallization and Interconnection for Crystalline Silicon Solar Cells*.
- [Lin H. 2023] Lin, H., Yang, M., Ru, X., Wang, G., Yin, S., Peng, F., ... & Xu, X. (2023). Silicon heterojunction solar cells with up to 26.81% efficiency achieved by electrically optimized nanocrystalline-silicon hole contact layers. *Nature Energy*, 8(8), 789-799.
- [Muiznieks, A 2015] Muiznieks, A., Virbulis, J., Lüdge, A., Riemann, H., & Werner, N. (2015). Floating zone growth of silicon. In *Handbook of Crystal Growth* (pp. 241-279). Elsevier.
- [Myrhaug E. 2021] Myrhaug, E., Tuset, J., & Tveit, H. (2004, February). Reaction mechanisms of charcoal and coke in the silicon process. In *Proceedings: tenth international ferroalloys congress* (Vol. 1, p. 4).
- [OPENPR2020] Global Silicon-Based Ingots for Solar Market to Witness a Pronounce Growth During 2025, <https://www.openpr.com/news/2077439/global-silicon-based-ingots-for-solar-market-to-witness>
- [Radavicius T. 2025] Radavičius, T., Groesser, S. N., & Tvaronavičienė, M. (2025). Assessment of constraints in the European Union photovoltaics circular supply chain for enhanced circularity. *Journal of Cleaner Production*, 489, 144682.
- [Zeng Y. 2022] Zeng, Y., Peng, C. W., Hong, W., Wang, S., Yu, C., Zou, S., & Su, X. (2022). Review on metallization approaches for high-efficiency silicon heterojunction solar cells. *Transactions of Tianjin University*, 28(5), 358-373.
- [Zulehner W. 1983] Zulehner, W. (1983). Czochralski growth of silicon. *Journal of Crystal Growth*, 65(1-3), 189-213.

## Section 4.2 et 4.3

[Aryan2018] Aryan V, Font-Brucart M, Maga D. A comparative life cycle assessment of end-of-life treatment pathways for photovoltaic backsheets. Prog Photovolt Res Appl. 2018; 26: 443–459. <https://doi.org/10.1002/pip.3003>

[Blom2023] S.Blömekea et al., Procedia CIRP 116 (2023) 179–184; 30th CIRP Conference on Life Cycle Engineering, DOI 10.1016/j.procir.2023.02.031

[ESIA2023] EUROPEAN SOLAR PV INDUSTRY ALLIANCE RECOMMENDATIONS PAPER SERIES II, <https://solaralliance.eu/wp-content/uploads/2023/10/Recommendation-on-Addressing-uncertain-antimony-content-in-solar-glass-for-recycling.pdf>

[EUCRM2020] European Commission, Critical materials for strategic technologies and sectors in the EU - a foresight study, 2020

[EUSI2020] European Commission, Study on the EU's list of Critical Raw Materials (2020), Factsheets on Critical Raw Materials

[Faes2018] A. Faes et al., "Direct Contact to TCO with SmartWire Connection Technology," 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), Waikoloa, HI, USA, 2018, pp. 1998–2001, doi: 10.1109/PVSC.2018.8547406.

[GAZB2023] N. GAZBOUR « Solaire photovoltaïque : quel impact sur l'environnement ? », Encyclopédie de l'énergie. <https://www.encyclopedie-energie.org/solaire-photovoltaique-impact-environnement/>

[Heath2022] G. A. Heath, D. Ravikumar, B. Hansen, and E. Kupets, "A critical review of the circular economy for lithium-ion batteries and photovoltaic modules – status, challenges, and opportunities," Journal of the Air & Waste Management Association, vol. 72, no. 6, Art. no. 6, Jun. 2022, doi: 10.1080/10962247.2022.2068878

[ITRPV2023] 14th edition International Technology Roadmap for PV on 2022 results (2023)

[ITRPV2024] 15th edition International Technology Roadmap for PV on 2023 results (2024)

[ITRPV2024] M. Fischer, M. Woodhouse, and P. Baliozian, "International Technology Roadmap for Photovoltaics (ITRPV) 2023 results," VDMA e. V. Photovoltaic Equipments, Frankfurt, 2024

[Libal2024] Libal, J., Gazbour, N., n.d. "Cost of ownership of n-type silicon solar cells and modules and life cycle analysis". N-Type Cryst. Silicon Photovolt., Books 253–280, Chapter 6.

[Lunardi2018] Lunardi, M.M.; Alvarez-Gaitan, J.P.; Bilbao, J.I.; Corkish, R. Comparative Life Cycle Assessment of End-of-Life Silicon Solar Photovoltaic Modules. *Appl. Sci.* 2018, 8, 1396. <https://doi.org/10.3390/app808139>

[Mao2024] Dan Mao, Shengqiang Yang, Lin Ma, Wenhui Ma, Zhiqiang Yu, Fengshuo Xi, Jie Yu, “Overview of life cycle assessment of recycling end-of-life photovoltaic panels: A case study of crystalline silicon photovoltaic panels”, *Journal of Cleaner Production*, Volume 434, 2024, <https://doi.org/10.1016/j.jclepro.2023.140320>.

[Müller2021] A. Müller, L. Friedrich, C. Reichel, S. Herceg, M. Mittag, and D. H. Neuhaus, “A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory,” *Solar Energy Materials and Solar Cells*, vol. 230, p. 111277, Sep. 2021, doi: 10.1016/j.solmat.2021.111277

[NZE2021] Net Zero by 2050 – A Roadmap for the Global Energy Sector – IEA (revised 2021)

[Sverd2023] Sverdrup, H.U., van Allen, O. & Haraldsson, H.V. Modeling Indium Extraction, Supply, Price, Use and Recycling 1930–2200 Using the WORLD7 Model: Implication for the Imaginaries of Sustainable Europe 2050. *Nat Resour Res* 33, 539–570 (2024). <https://doi.org/10.1007/s11053-023-10296-z>

[TaiyangN] « Day 2: TaiyangNews High Efficiency Solar Technologies Conference | TaiyangNews ». <https://taiyangnews.info/technology/day-2-taiyangnews-high-efficiency-solar-technologies-conference>

[Zang2021] Y. Zhang, M. Kim, L. Wang, P. Verlinden, et al. “Design considerations for multi-terawatt scale manufacturing of existing and future photovoltaic technologies: challenges and opportunities related to silver, indium and bismuth consumption” *Energy Environ. Sci.* 14 (11) (2021) 5587–5610, <https://doi.org/10.1039/D1EE01814K>

## Section 5

[Cruz2022] A. Cruz et al., *Sol. Energy Mater. & Sol. Cells*, vol. 236 (2022) 111493. doi:10.1016/j.solmat.2021.111493.

[Harrison2021] S. Harrison, C. Carriere, V. Barth, A. Bettinelli, P. Bertrand, and B. Portaluppi, ‘400W in Shingle SHJ configuration: promising optimization path for high power modules’, in 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), Jun. 2021, pp. 0331–0334. doi: 10.1109/PVSC43889.2021.9518854.

[Sena2022] L.-L. Senaud et al., *IEEE J. Photovolt.*, vol. 12 (2022) 906–914. doi:10.1109/JPHOTOV.2022.3176983.



**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.