Ref. Ares(2025)9943048 - 18/11/2025

D7.1 – Interim report on financial and cost competitiveness analysis solar PV cells with optimized silicon

Co-funded by
the European Union

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°	7
Work package title	Multi-faceted Impact assessment & EU policy recommendations
Work package leader	CEA
Document title	Interim report on financial and cost competitiveness analysis of the Eco-designed solar PV cells
Lead Beneficiary	CEA
Dissemination level	PU
Authors	Nouha GAZBOUR (CEA)
Contributors	
Reviewer(s)	UGENT (Lieselot Boone and Ricardo Magdalena Zarzuel), ISMC (Francisco J. Luque)
Issue date	30/04/2025

Version control table

Version	Date	Main changes
Deliverable 7.1_CEA_VF_	10/04/2025	First version sent to UGent for review
Deliverable 7.1_CEA_VF_UGENT	14/04/2025	UGent review from Lieselot Boone and Ricardo Magdalena Zarzuel
Deliverable D7.1__docx	15/04/2025	New version including review from Ugent sent to ISMC
Deliverable D7.1__docx_V2F	22/04/2025	Modification of the description of the solar cell process by CEA
Deliverable D7.1__docx_V2F_revISMC	23/03/2025	Review from ISMC (Francisco J. Luque)
Deliverable D7.1_Final version_	25/04/2025	Final version including all review
Deliverable D7.1_Final version2_	06/11/2025	Addition of Version control table and reviewers' names

Index

List of figures

List of tables

Executive Summary

The main objective of RESilEX is to enhance both the resilience and sustainability of the European silicon value chain. To achieve this, the project focuses on the development of several innovative technologies covering the entire life cycle—sustainable silicon production, to the eco-design of photovoltaic cells and modules, the recycling of end-of-life solar panels, and the integration of silicon into battery technologies as a substitute for graphite.

This deliverable has been developed within Work Package 7 (WP7) of RESilEX project under Task 7.1, which focuses on the economic evaluation of the sustainable production and the revalorisation of waste silicon in the value chain of a PV module. This task focuses on the economic evaluation and market potential of the developed sustainable PV technologies. It is structured around three main subtasks: The Cost of Ownership (CoO) Analysis aims to estimate the Cost of Ownership for the developed photovoltaic modules, based on data and eco-design strategies provided by WP4. The Cost Assessment of the Silicon Value Chain involves evaluating costs related to waste recovery, sustainable silicon production, and end-of-life silicon recycling, leveraging outputs from WP3 (Sustainable Silicon Production), WP4 (Eco-designed Solar Cells & Modules), and WP5 (Silicon Recycling from PV Modules) and Finally, the Business Plan Development focuses on preparing a comprehensive business plan that incorporates projected costs and revenues, with the goal of identifying the most cost-competitive solutions through key techno-economic indicators such as industrial production costs and revenue per use case.

Due to the project's progress, it has not yet been possible to fully assess the costs of the various innovations. However, data were available for the innovation developed in WP4, focusing on the eco-design of solar cells and modules. This deliverable describes the adopted approach, the different scenarios defined in collaboration with the different project partners and the reference scenario includes the assumptions made for various components of the value chain, including polysilicon, wafers, cells, and modules. Primary results on the Cost of Ownership (CoO) of eco-designed cells integrated into a PV module were assessed in this deliverable.

Initial results indicate a reduction in the cost of PV modules through the eco-design strategies implemented at the cell level by reduced consumption of silver and indium. This reduction is likely to increase with the other scenarios being developed within the project.

1. Introduction

The European energy transition faces a significant challenge: producing resilient photovoltaic modules while reducing reliance on critical materials and maintaining low costs. The increasing demand for renewable energy, combined with sustainability imperatives, requires a rethinking of production chains to minimize the use of rare and costly materials, all while ensuring optimal performance and long module lifespans. Addressing this challenge is essential for enhancing Europe's energy independence and accelerating the adoption of solar energy, in line with environmental objectives.

As a part of the RESILEX project, many innovative and sustainable alternatives have been identified as potential solutions to the challenges outlined above. These technologies cover the entire photovoltaic (PV) panel value chain, from production to end-of-life. They include:

- The sustainable production of silicon, by reintroducing recycled silicon from kerf losses into the ingot manufacturing process (WP3)
- The eco-design of PV cells, by developing alternatives to replace critical raw materials currently used in passivated contact silicon solar cells, specifically Silver and Indium (WP4)
- The eco-design of PV modules, through the use of bio-sourced encapsulation materials to reduce the environmental footprint of the modules (WP4)
- The recovery and reuse of materials at end-of-life, particularly focusing on the extraction and reintegration of silicon as a secondary raw material for future battery applications (WP5 and WP6)

Deliverable D7.1 aims to define the scope of the study related to the innovations developed under Work Package 4 (WP4) at the cell level. It presents an initial cost analysis of the eco-designed solar cells created within the project, with a particular focus on reducing the consumption of critical materials such as silver and indium through various technological approaches. A technological, economic, and market benchmark was conducted in order to understand current trends and dynamics across the various components of the value chain, including polysilicon, wafers, cells, and modules. This comparative analysis helped identify key developments in the sector and supported the definition of the project's reference scenario.

This first cost analysis is intended to support decision-making, guide technological choices, and enhance process optimization for the ongoing and future development phases of the project.

1. Benchmark of the value chain of silicon photovoltaic module

The value chain of a crystalline silicon photovoltaic module begins with the purification of silicon. The purified silicon, called polysilicon, is then melted and crystallized to form an ingot. This ingot is sliced into thin wafers. The wafers undergo chemical treatments to create doped layers that enable the conversion of light into electricity. These resulting photovoltaic cells are then assembled into modules, which are protected by a glass layer and framed to form the final solar panel.

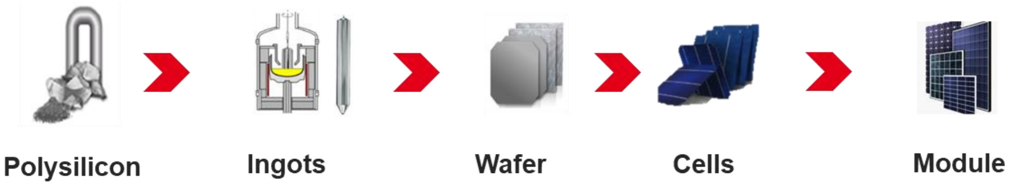


Figure 1 : Value chain of a silicon PV module

1.1.Polysilicon

The production of polysilicon or solar-grade silicon (SOG-Si) involves two purification steps. Initially, quartz is reduced to metallurgical-grade silicon (MG-Si) using an electric arc furnace. MG-Si, with 98–99% purity, is then refined to solar-grade using either the Siemens process—which converts MG-Si into trichlorosilane ($SiHCl_3$), then reduces it at high temperature to produce high-purity silicon rods (9N purity)—or the FBR process, where silicon particles are grown in a reactor by gas-phase deposition, resulting in slightly lower purity (6–7N). The Siemens process accounts for ~95% of the polysilicon market, while FBR covers ~5% in 2024 [1].

The global polysilicon production in 2023 was about 1 608 000 tons, a 61% increase from the previous year. Production of polysilicon for semiconductors was about 38 800 tons. This means that more than 98% of polysilicon production was used for PV applications. The main countries producing polysilicon are China (92%), Germany (4%), the USA (2%), Malaysia (2%), South Korea, Norway and Japan. Chinese production share in 2023 increased to 92% from 86% in 2020 [2].

Due to the rapid expansion of manufacturing capacity and persistent imbalances between supply and demand, the price of polysilicon fell significantly, dropping from $22.13 per kilogram at the end of 2022 to around $7 per kilogram by late June 2023. It remained below $10 per kilogram thereafter, reaching $7 per kilogram in January 2024 [1]. However, the price of polysilicon for manufacturers outside of China, particularly in Europe and the United States, remains relatively high (16$/kg and 20 $/kg respectively) [3] (Figure 2)

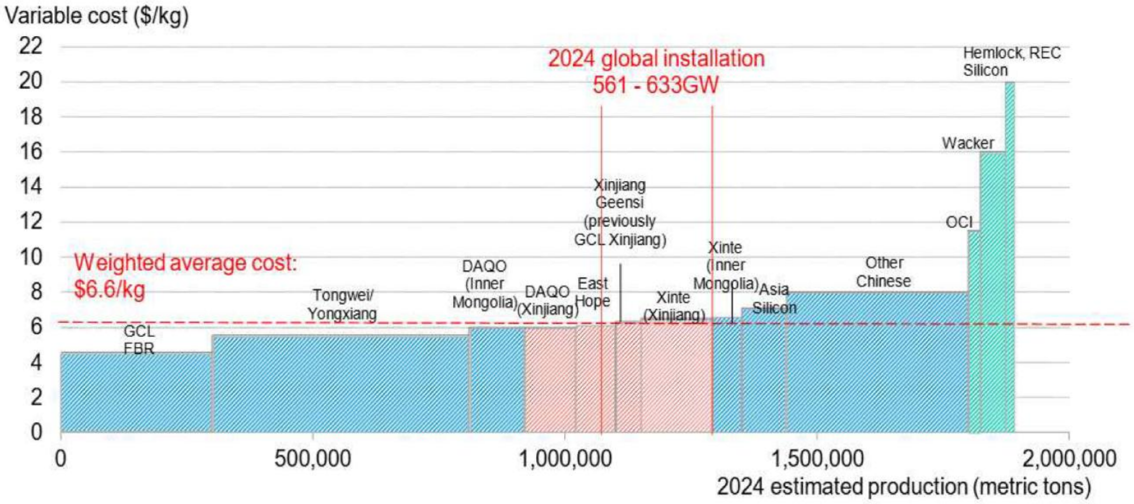


Figure 2 : Cost of the production of polysilicon per manufacturer [2]

Consumption unit of polysilicon per W of solar cells dropped from 2.7 g/W in 2021 to 2.3 g/W in 2022. In 2023, it further dropped to 2.2g /W [1]. Consumption per unit is declining due to the improvement of solar cell efficiency, thinner and larger wafers, and development of slicing technologies.

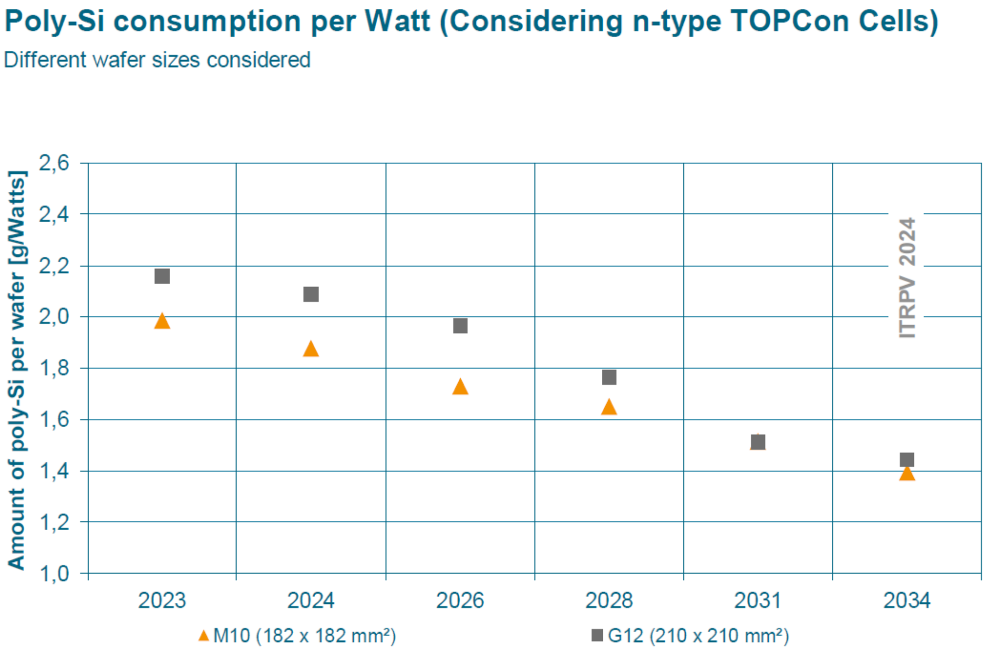


Figure 3 : Evolution of polysilicon consumption

1.2. Ingots and Wafer

Once purified, Polysilicon is solidified through a crystallization process aimed at improving efficiency while maintaining material quality. In the Czochralski (CZ) method, a single crystal (c-Si) is grown from a molten silicon bath using a seed crystal with a known orientation [4]. The seed is slowly pulled upward while rotating, allowing a cylindrical monocrystalline ingot to form. After crystallization, the ingots are cut into bricks, then sliced into thin layers called wafers using diamond wire sawing, a method suitable for cutting hard materials with high precision [4].

The production capacity of mono-Si wafers to 682 GW in 2023, about a 79% increase from 381 GW in 2022. Wafers' production capacity is concentrated in China, accounting for 98% of the global share, indicating an unprecedented level of concentration [3]. Outside of China, wafer manufacturing capacities have been reported in Malaysia, Vietnam, Norway, and Taiwan. In France, CARBON is planning to include a wafer production capacity of 5 GW [5].

The spot price of c-Si wafers generally follows the price of polysilicon. The price of 182 mm c-Si wafers was 50.3 USD cents/ piece in December 2022 and the trend down continued into 2023 to reach a spot price at the end of December 2023 of 34.9 USD cents/ piece and continue to drop to reach 15 USD cents/piece in 2024 [2][6].

From a technological point of view, it is worth noting that larger wafers have been adopted for higher-efficiency PV modules since 2020. As shown in Figure 4, the M6 wafer format is expected to be phased out by the end of 2025, with M10 and G12 becoming the dominant standards moving forward. Rectangular wafer formats are gaining a significant market share, as they offer the best fit for rooftop solar modules due to their efficient use of space and improved performance. Additionally, formats larger than G12 are anticipated in the near future, continuing the trend toward bigger wafers aimed at maximizing module efficiency [1].

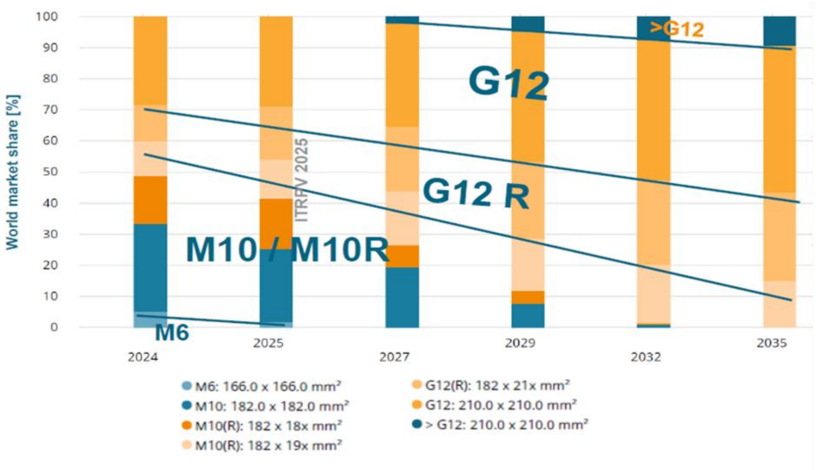


Figure 4 : Trend of the size wafer [1]

Another innovation at the wafer production scale is the optimization of the wire thickness used in the cutting process, which has now reached an average of 40 µm compared to 90 µm in 2019. This optimization helps reduce kerf losses, leading to a significant decrease in both polysilicon consumption and the cost of cutting. Reducing the wafer thickness is one of the alternatives adopted by various manufacturers, along with larger wafers. The thickness is expected to reach 120 µm by 2025 for M10 and M12 wafers. As shown in Figure 5, it is important to note that the wafer thickness varies depending on the cell technology [6].

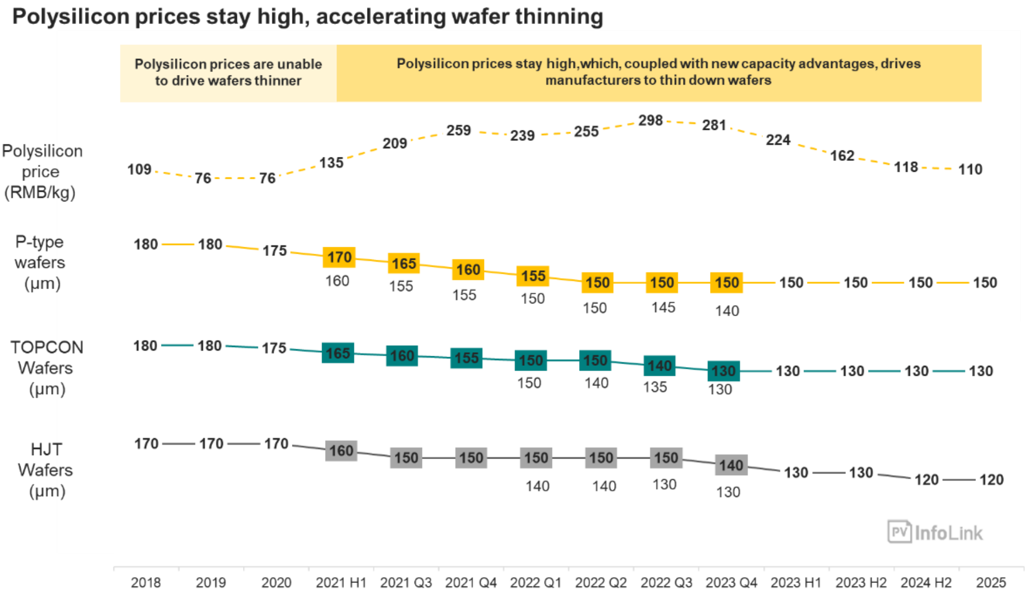


Figure 5: Evolution of the wafer thickness by technology [6]

1.3. Solar Cells

A photovoltaic solar cell can be compared to a photosensitive diode, and its operation is based on the properties of semiconductor materials. Since silicon is made up of atoms with charged electrons, these electrons move randomly when exposed to solar radiation. To generate a direct electric current, where electrons flow in a specific direction, the silicon is doped. This doping process involves creating an excess of electrons on one side and a deficiency of electrons on the other.

To maximize photon absorption, specific treatments are applied, which define the cell's manufacturing process. These treatments are commonly referred to as the process flow. This process flow varies depending on the technology used (Figure 6) [7]. In fact, there are several technologies available on the market today, all aiming to achieve the highest efficiency at the lowest cost [1].

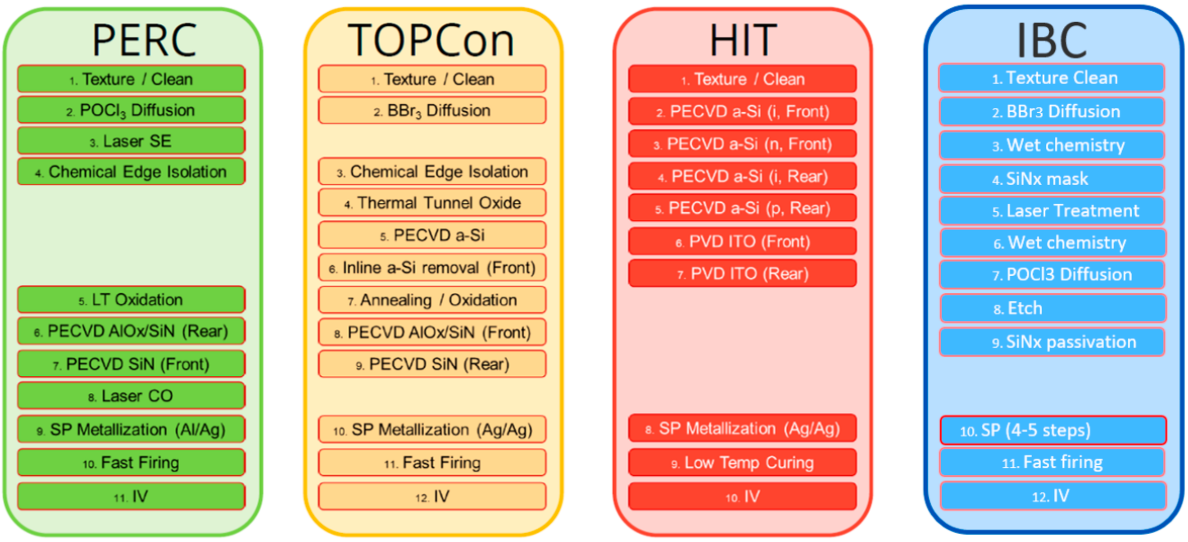


Figure 6 : Variability of the process flow by technology [7]

As shown in Figure 6, Passivated Emitter and Rear Contact (PERC) technology has replaced the Al-BSF structure and has become the dominant technology in the market. However, PERC is expected to gradually be phased out, giving way to Tunnel Oxide Passivated Contact (TOPCon) and Heterojunction (HJT) technologies. These next-generation technologies offer improved performance and higher efficiency, making them the most likely successors to PERC in the coming years [1]

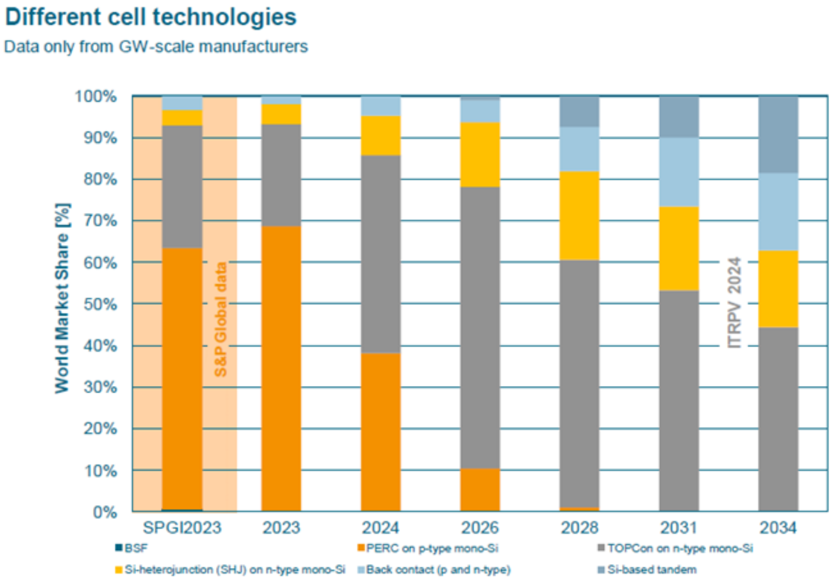


Figure 7 : Different cell technologies [1]

In this section, we will focus specifically on the HJT cell, as it is the technology studied in the RESILEX project and partners aims to improve it.

- Process flow of HJT solar cells

HJT solar cells are produced from silicon wafers in a low temperature process that does not exceed 200 °C. High temperature diffusion of the p-n junction is replaced with a low temperature deposition of a p-doped amorphous silicon layer on an n-type monocrystalline silicon wafer. The process flow of a standard HJT solar cell is detailed below:

1. *Chemical Wet (Chemical Cleaning and Texturing)*

This step involves the use of chemical solutions to clean and texture the wafer surfaces, improving the adhesion of subsequent layers and optimizing light reflection to enhance the cell's efficiency. The associated costs are primarily linked to the chemicals (such as acids or cleaning solutions), the maintenance of cleaning equipment, and the energy consumption required for the process. The CAPEX costs are mainly related to the purchase of specialized cleaning and texturing equipment, as well as their maintenance.

2. *PECVD (Plasma-Enhanced Chemical Vapor Deposition)*

PECVD is used to deposit amorphous silicon and passivation layers on the wafers. This process is crucial for enhancing the cell's efficiency by reducing charge losses and improving charge carrier collection. The costs are primarily related to the reactive gases (such as silane, methane, or dopant gases), energy consumption (as PECVD equipment operates under high temperature and pressure conditions), and the purchase and maintenance of the PECVD reactors. CAPEX expenditures primarily involve the installation and maintenance of the equipment, with recurring costs for the gases used.

3. *PVD ITO (Physical Vapor Deposition for Indium Tin Oxide)*

PVD is used to deposit a transparent conductive oxide (ITO) layer, which serves as a transparent conductive film on the cell. The costs for this step include the purchase of ITO material and the consumables used in the PVD process. CAPEX is primarily related to the purchase of PVD deposition systems and their maintenance. The equipment requires regular maintenance and adjustments to ensure high-quality deposition, leading to additional costs.

4. *Metallization*

Metallization involves applying silver paste to form the electrical contacts on the cell. This is typically done using screen printing, where metallic layers are deposited onto the cell surface. The costs are dominated by the price of silver paste, which can be expensive, as well as the equipment needed for printing and drying (screen printing presses and curing ovens). CAPEX expenditures include the acquisition of printing presses and drying equipment, along with maintenance costs for these machines.

5. *Curing*

Curing is the final metallization step, where the metal contacts are fixed and hardened by passing the cells through a high-temperature furnace. Costs for this step are primarily linked to energy consumption for operating the curing furnaces, as well as the materials used in flux and other process aids. CAPEX includes the purchase and installation of the curing furnaces, as well as ongoing maintenance costs.

For confidentiality reasons, instead of expressing the cost of each step in the process flow, it is more appropriate to express the share of each process in the total cost of the cell.

- Economic and technological evolution

The global capacity for HJT is estimated to be 49 GW, with an additional 95 GW of capacity under construction [3] (Figure 8). This significant increase in capacity reflects the growing adoption and investment in HJT technology, driven by its high efficiency and potential for future market dominance.

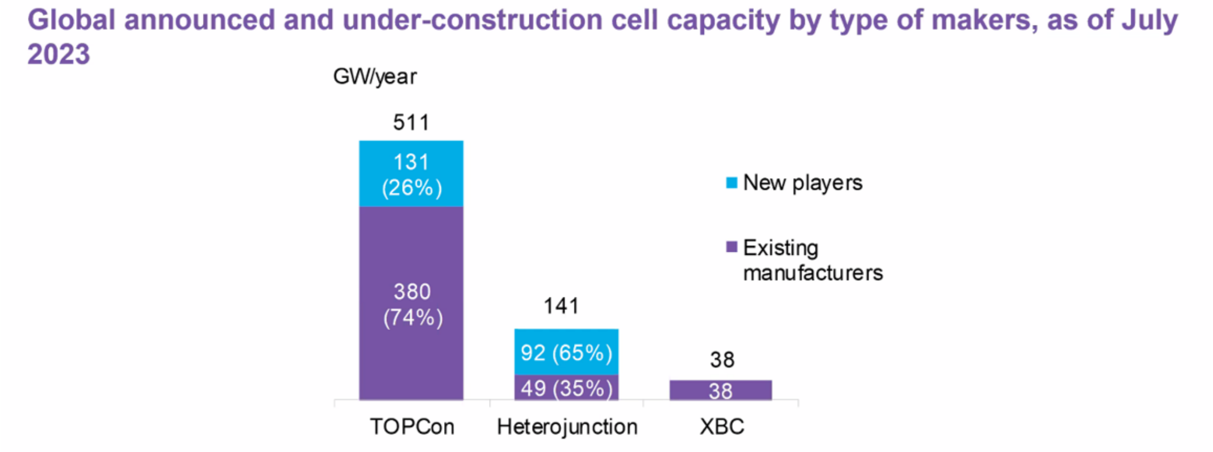
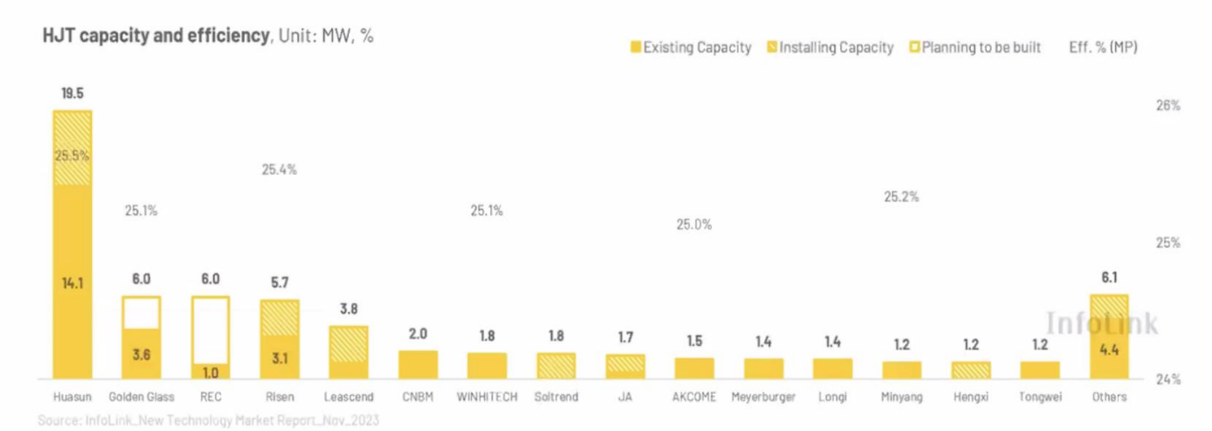


Figure 8 : Capacity of production by technology [3]

As shown in Figure 9, Production of HJT is dominated by Asian manufacturers, but there are European producers also positioning themselves with this technology, including companies like Mayer Burger, ENEL 3 SUN, and MCPV [8] [6].



Source: InfoLink_New Technology Market Report_Nov_2023

Figure 9: HJT Developpement status [6]

The cost of an HJT cell produced in Europe ranges between 6.5 to 8.5 USD cents/Wp while the cost of a TOPCon cell produced in Europe is between 5 and 6.6 USD cents/Wp [9] (Figure 9). This price difference is mainly due to the more complex production process of HJT cells, which involves additional materials and specialized equipment, compared to the relatively simpler manufacturing process of TOPCon cells and the the use of critical materials such as silver and ITO (Indium Tin Oxide). Silver is used for the metal contacts and has excellent conductivity, but it is expensive, which increases the overall cost of the cell. ITO, used as a transparent conductive oxide for the front contact, is also costly due to the material itself and the complex deposition process required [7].

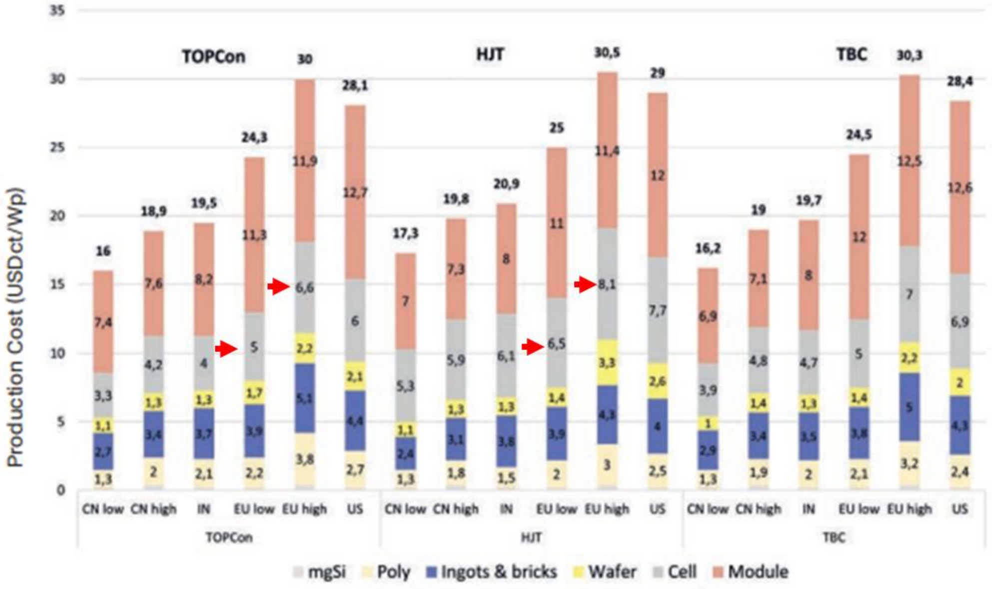


Figure 10 : Variability of the cost by technology and by region with a breakdown by component in the value chain _Focus cell level [8]

One of the main objectives in the WP4 of the RESILEX project is to reduce the cost and environmental impact by proposition new processes flow to optimize the consumption of silver and ITO in the cell.
The different proposed scenarios studied in RESILEX will be detailed later with an initial cost analysis compared to the standard HJT cell.

1.4. Module assembly

The main role of a PV module is to protect the solar cells from external environmental factors such as humidity and mechanical stress. This stage involves interconnecting the cells and encapsulating them in a transparent polymer, such as EVA (Ethylene Vinyl Acetate) or POE (Polyolefins), with tempered glass on the front side and a protective backsheet on the rear side. The backsheet is typically made from polymer-based materials like Polyvinyl Fluoride (PVF) or Polyethylene Terephthalate (PET). Figure 11 shows the standard structure of a module (glass – encapsulant – cells – backsheet) is pressed and heated under vacuum in a laminator. A junction box is then placed on the back of the laminated structure, enabling the connection of the module's electrical outputs. Finally, an aluminum frame is added to complete the module's assembly. In bifacial modules, the backsheet is replaced with glass, and the resulting rigidity allows the module to be used without an aluminum frame.

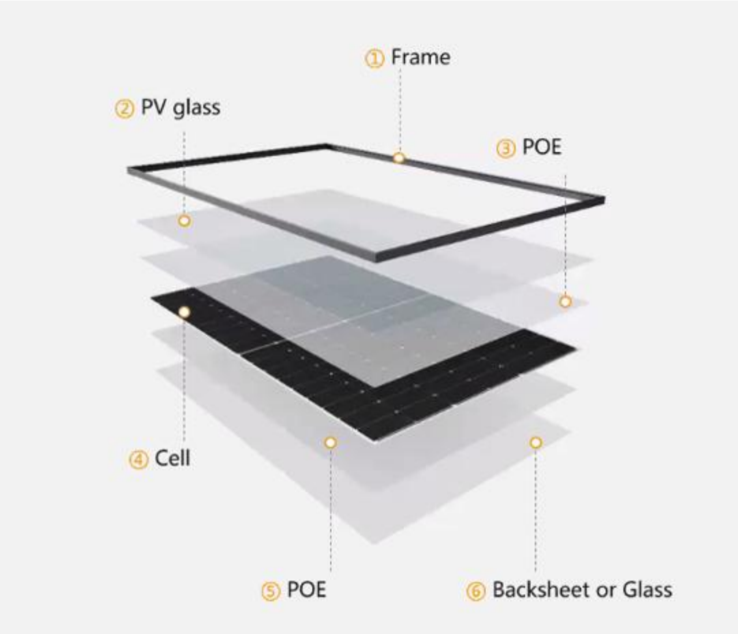
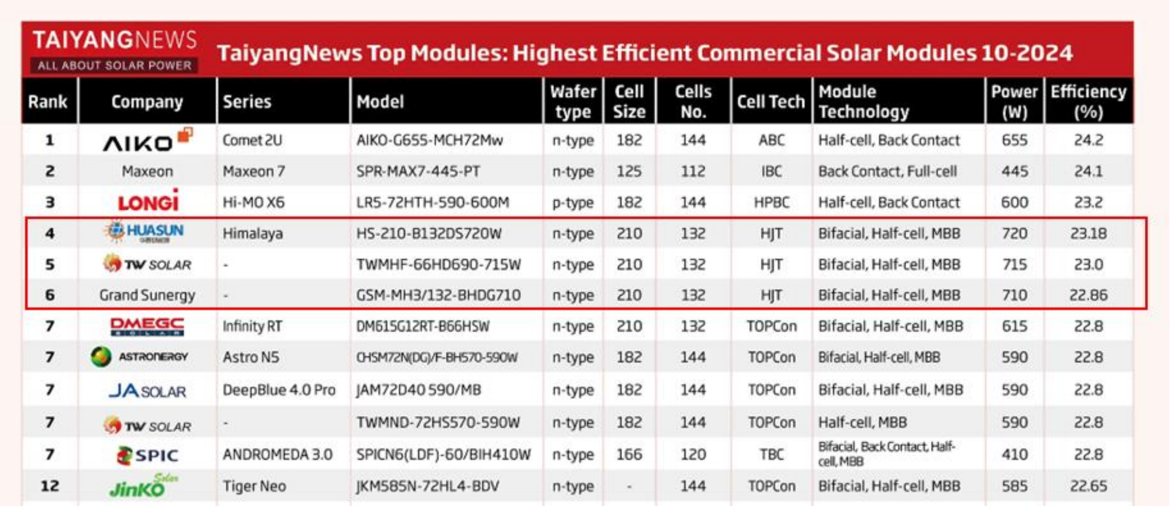


Figure 11 : Structure of a PV module [1]

Global PV module manufacturing capacity exceeded 1 TW per year for the first time in 2023, reaching 1,032 GW per year thanks to the addition of 419 GW of new capacity [1] Module efficiency is a key parameter for manufacturers today. Their goal is to increase module efficiency to reduce production costs (€/Wp). Efficiency has significantly improved since 2014, rising from 16% efficiency modules in 2014 to 24% efficiency modules in 2023 [1]. Figure 12 shows the highest efficient commercial module in October 2024. Modules using HJT technologies rank among the top 5 in efficiency and performance [10].



TAIYANGNEWS
ALL ABOUT SOLAR POWER

TaiyangNews Top Modules: Highest Efficient Commercial Solar Modules 10-2024

Rank	Company	Series	Model	Wafer type	Cell Size	Cells No.	Cell Tech	Module Technology	Power (W)	Efficiency (%)
1	AIKO	Comet 2U	AIKO-G655-MCH72Mw	n-type	182	144	ABC	Half-cell, Back Contact	655	24.2
2	Maxeon	Maxeon 7	SPR-MAX7-445-PT	n-type	125	112	IBC	Back Contact, Full-cell	445	24.1
3	LONGi	Hi-MO X6	LR5-72HTH-590-600M	p-type	182	144	HPBC	Half-cell, Back Contact	600	23.2
4	HUASUN	Himalaya	HS-210-B132DS720W	n-type	210	132	HJT	Bifacial, Half-cell, MBB	720	23.18
5	TW SOLAR	-	TWMHF-66HD690-715W	n-type	210	132	HJT	Bifacial, Half-cell, MBB	715	23.0
6	Grand Sunergy	-	GSM-MH3/132-BHDG710	n-type	210	132	HJT	Bifacial, Half-cell, MBB	710	22.86
7	DMEGC	Infinity RT	DM615G12RT-B66HSW	n-type	210	132	TOPCon	Bifacial, Half-cell, MBB	615	22.8
7	ASTRONERGY	Astro N5	CHSM72N(DG)/F-BH570-590W	n-type	182	144	TOPCon	Bifacial, Half-cell, MBB	590	22.8
7	JA SOLAR	DeepBlue 4.0 Pro	JAM72D40 590/MB	n-type	182	144	TOPCon	Bifacial, Half-cell, MBB	590	22.8
7	TW SOLAR	-	TWMND-72HS570-590W	n-type	182	144	TOPCon	Half-cell, MBB	590	22.8
7	SPIC	ANDROMEDA 3.0	SPICN6(LDF)-60/BIH410W	n-type	166	120	TBC	Bifacial, Back Contact, Half-cell, MBB	410	22.8
12	JinKO Solar	Tiger Neo	JKM585N-72HL4-BDV	n-type	-	144	TOPCon	Bifacial, Half-cell, MBB	585	22.65

Figure 12 : Highest commercial solar module 10-2024 [10]

The price of PV modules was influenced by the supply-demand imbalance and the growing inventories in the market. In January 2023, the average spot price of 182 mm PERC PV modules with a nominal power of 550 W to 595 W was 22.3 USD cent/W. By June, the price had dropped to 18.7 USD cent/W and continued to fall, reaching 11.5 USD cent/W by the end of the year [1].

The production cost of a PV module varies depending on both the location and the technology used. For HJT PV modules, manufacturing costs in Europe range between 11 and 11.4 USD cents/W, compared to approximately 7 USD cents/W in China (Figure 13) [9]. This difference is primarily attributed to the higher labor costs in Europe [9].

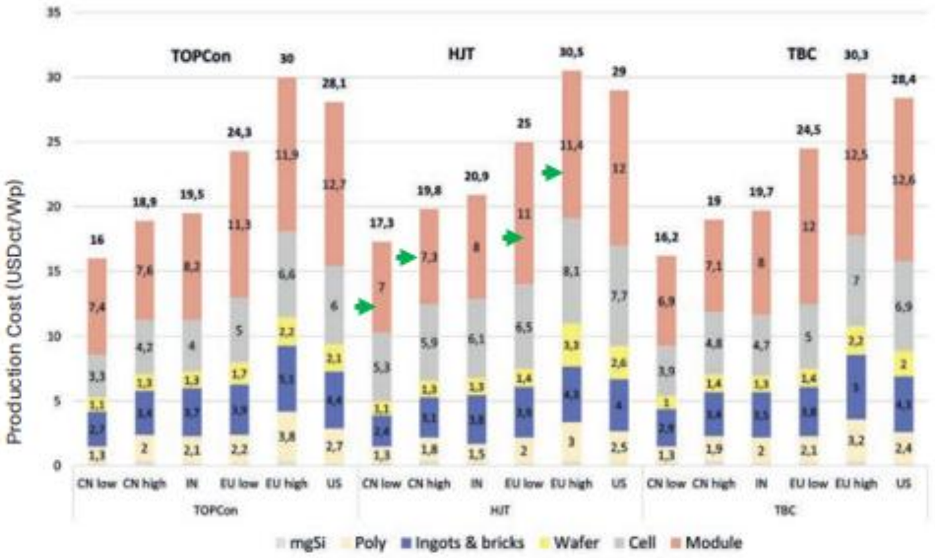


Figure 13 : Variability of the cost of the PV module by technology and region - Focus HJT, module level [9]

Within this module cost, the majority is attributed to processing and manufacturing operations (more than 50%) [3]. In contrast, depreciation and selling, general, and administrative (SG&A) expenses represent only a small portion of the overall cost.

One of the main objectives in the WP4 of the RESILEX project is to reduce the cost and environmental impact at the module level by proposing new eco-designed material for the structure of the PV module.
The different proposed scenarios studied in RESILEX were studied with the partners and will not be analyzed in this deliverable because of the lack of certain data.

2. Innovations in the RESILEX project

As a part of the RESILEX project, many innovative and sustainable alternatives have been identified as potential solutions to the challenges outlined above. These technologies cover the entire photovoltaic (PV) panel value chain, from production to end-of-life. They include:

- The sustainable production of silicon, by reintroducing recycled silicon from kerf losses into the ingot manufacturing process (WP3)
- The eco-design of PV cells, by developing alternatives to replace critical raw materials currently used in passivated contact silicon solar cells, specifically Silver and Indium (WP4)

- The eco-design of PV modules, through the use of bio-sourced encapsulation materials to reduce the environmental footprint of the modules (WP4)
- The recovery and reuse of materials at end-of-life, particularly focusing on the extraction and reintegration of silicon as a secondary raw material for future battery applications (WP5 and WP6)

As mentioned earlier, due to the lack of available data, this deliverable will focus on innovations at the cell level.

2.1. Innovations at the cell level

Within WP4, several eco-designed innovations were carried out at both the cell and module levels. However, due to data availability, the focus of this deliverable will be on the approaches adopted at the cell level to reduce or replace critical raw materials in a HJT solar cell, specifically silver (used in metallization) and indium (used for passivation). In collaboration with the project partners CEA and CSEM, several alternative process routes were defined, leading to the identification of four new scenarios, as illustrated in Figure 13.

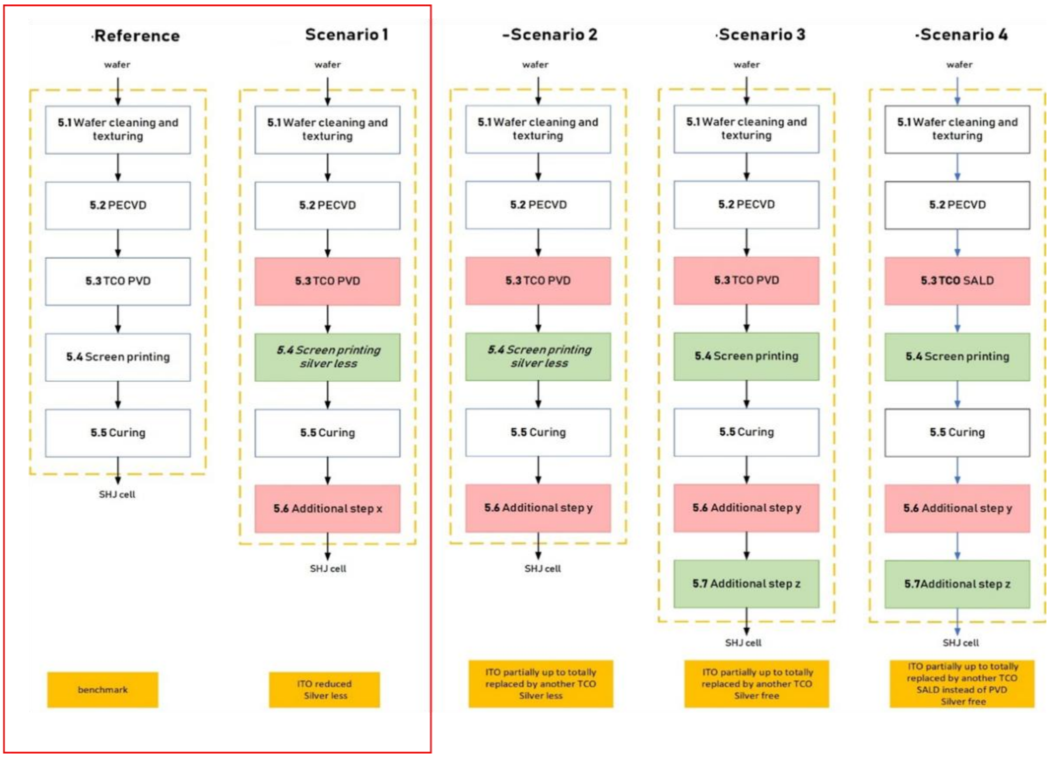
- Scenario 1 (S1) consists of reducing the thickness of the ITO layer and decreasing silver consumption. The reduction of silver is provided by the introduction of copper for the metallization. And the reduction of the ITO layer requires the addition of a PECVD SiNx (silicon nitride) layer. This step is essential to act as a good anti-reflective layer, and protection against humidity to ensure long-term stability and performance.

- Scenario 2 (S2) involves further reducing the ITO layer, possibly replacing it entirely with Aluminum-doped Zinc Oxide (AZO), and reducing silver usage by partially replacing it with copper. The use of AZO instead of ITO also requires the addition of a PECVD SiNx (silicon nitride) layer on the front side for its anti-reflective and humidity protection properties.

- Scenario 3 (S3) involves further reducing the ITO layer, possibly replacing it entirely with AZO, and completely replacing silver with copper. The complete replacement of silver with copper in the metallization process requires the implementation of copper plating. This technique involves depositing a thin layer of copper onto the solar cell surface through an electroplating or light-induced plating (LIP) process

- Scenario 4 (S4) also involves further reducing the ITO layer, possibly replacing it entirely with AZO or SALD, and fully replacing silver with copper. The complete replacement of silver with copper in the metallization process requires the implementation of copper plating

Due to data availability constraints, only Scenario 1, compared to the reference case, will be analysed from a production cost perspective.



Focus on this deliverable

Figure 14 : Process flow of the eco-designed cell in the RESILEX project

2.2. Innovations at the module level

The consortium partners are engaged in the development and evaluation of novel materials characterized by a reduced environmental footprint, recyclability, and long-term durability, while maintaining high photovoltaic performance. The various material scenarios under consideration are summarized in the table below.

A detailed techno-economic analysis of these alternative materials will be conducted in the subsequent deliverable.

Table 1 details the various defined structures that will be the subject of a comprehensive economic assessment in a subsequent phase of the study.

Table 1 : Overview of the composition of the modules considered in the reference case, scenario 1 and scenario 2 of innovation in WP4 .

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

ECA = Electrically Conductive Adhesive, TPE = Thermoplastic Elastomer, PET = Polyethylene terephthalate, EVA = Ethylenevinyl Acetate, TPO = Thermoplastic Olefin

3. Methodology

3.1. Definition of the methodology

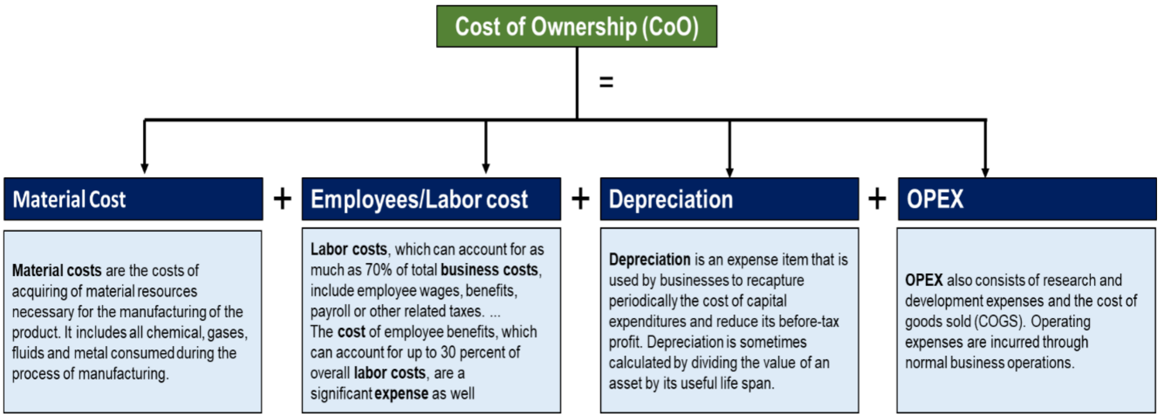
The production cost or Cost Of Ownership (CoO) includes several key factors, each contributing to the overall expense of manufacturing (Figure 14). These components are:

- Material Cost: This refers to the cost of raw materials used in the production process, such as polysilicon, glass, aluminium frames, copper wiring, and other essential materials. The price of these materials can vary depending on market conditions, location, and availability.

- CAPEX (Capital Expenditure): This includes the costs associated with setting up production facilities, such as the purchase of equipment, machinery, and infrastructure. It also covers the installation and setup of factories and other facilities required for manufacturing. These costs are typically spread over several years.

- OPEX (Operating Expenditure): This refers to the ongoing costs of running the production facility, including maintenance, utilities (electricity, water), insurance, and other operational expenses. OPEX is incurred on a regular basis and can fluctuate depending on the scale of production and efficiency of operations.

- Labor Cost: This includes the wages and benefits of workers involved in the production process, from machine operators to engineers, and administrative staff. Labor costs can vary depending on the region and the level of expertise required.



Material costs are the costs of acquiring of material resources necessary for the manufacturing of the product. It includes all chemical, gases, fluids and metal consumed during the process of manufacturing.

Labor costs, which can account for as much as 70% of total **business costs**, include employee wages, benefits, payroll or other related taxes. ... The **cost** of employee benefits, which can account for up to 30 percent of overall **labor costs**, are a significant **expense** as well

Depreciation is an expense item that is used by businesses to recapture periodically the cost of capital expenditures and reduce its before-tax profit. Depreciation is sometimes calculated by dividing the value of an asset by its useful life span.

OPEX also consists of research and development expenses and the cost of goods sold (COGS). Operating expenses are incurred through normal business operations.

Figure 15 : Composition of the CoO

The CoO of a PV module is the sum of the production cost of the different components in the value chain (Polysilicon, Ingots& Wafer, cell and module)

3.2. Scope and System boundary

The objective of this study is to conduct a Life Cycle Cost (LCC) analysis of a PV module incorporating eco-designed HJT solar cells (Scenario 1), and to compare it with a standard HJT PV module with a standard HJT solar cell. The analysis covers the entire value chain, from polysilicon production to ingots, wafers, cells, and module assembly, all within the context of a European gigawatt-scale manufacturing facility (Figure 15).

The definition of the production location is based on a market benchmark (Section 2), reflecting the distribution of production volumes by component. For polysilicon, Wacker in Germany is considered the main producer in Europe, supplying high-purity material. For ingots and monocrystalline silicon wafers, Norsun in Norway has been identified as a key European manufacturer. Regarding cells and modules, since the developments within the project are being carried out at CEA in France and in light of recent announcements of giga factories in France, we have assumed that cell and module production takes place in France [5]

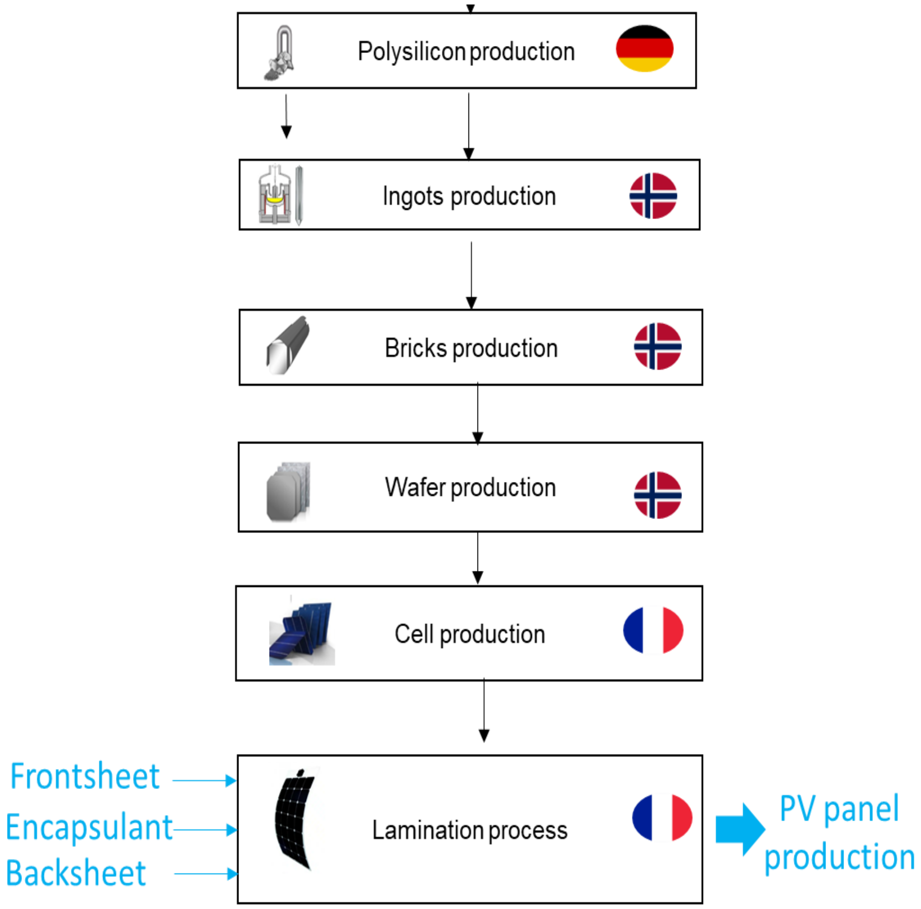


Figure 16 : System boundary and location production

3.3. Scenarios and assumptions of the analysis

The reference considered in this analysis is a HJT module manufactured in Europe using a standard HJT cell. This module will be compared to an alternative module A1 produced with the innovative cell developed in Scenario 1 (Figure 17). For both modules, the wafer cost—which includes polysilicon, ingot, and wafering is assumed to be identical, as well as the module assembly step cost.

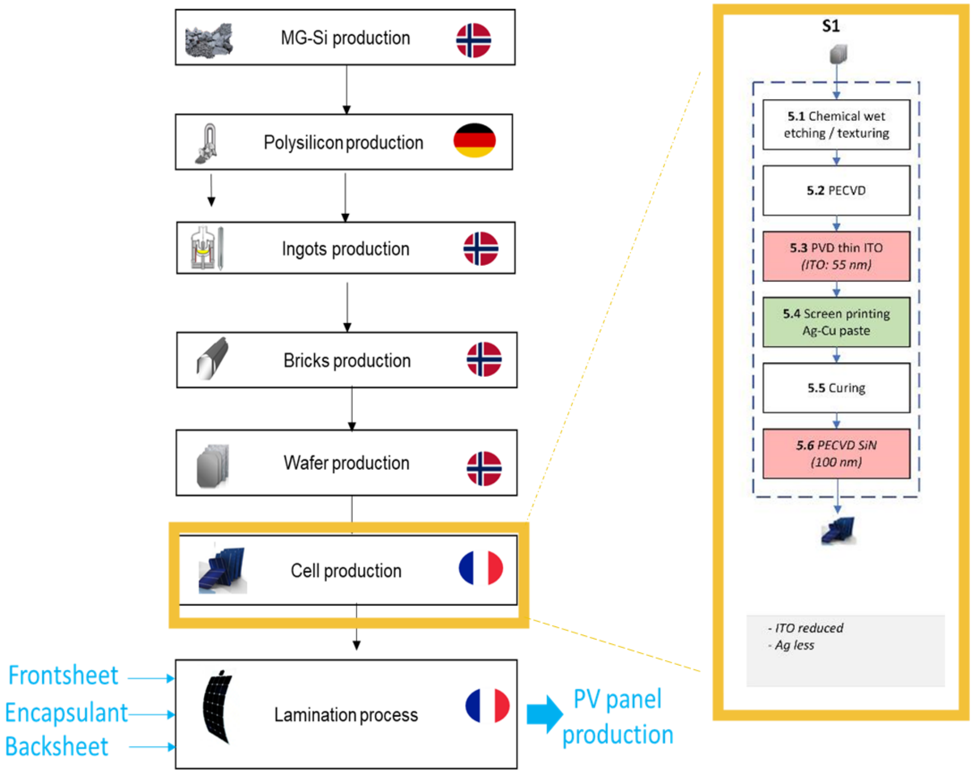


Figure 17 : Structure of the alternative module A1

3.4. Data cost assumption: Wafer

According to [9] , the cost of a wafer produced in Europe ranges between 7.3 and 10.6 USD cent/W (Figure 18). An average value of 8.95 USD cent/W has been defined for both the reference module and the alternative module A1.

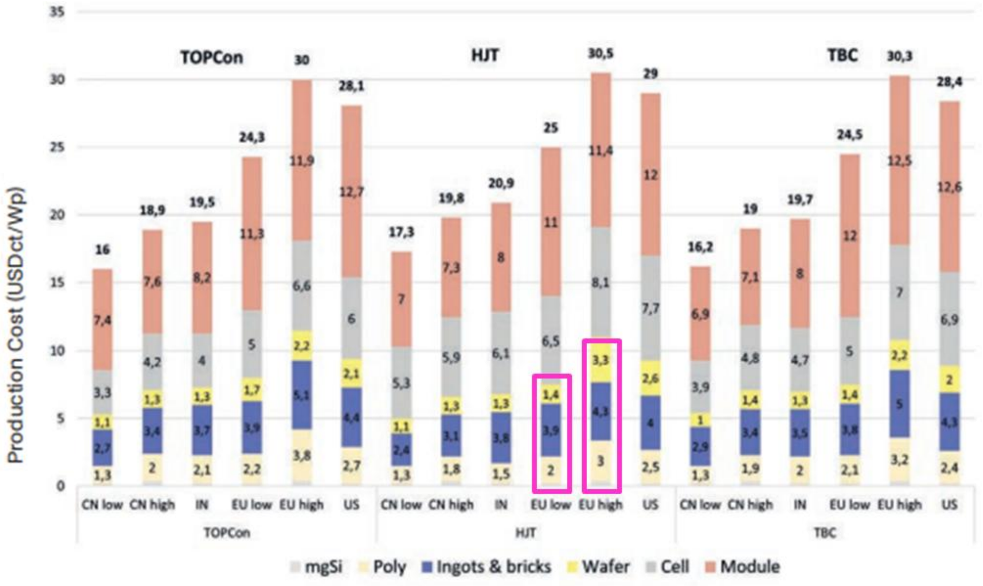


Figure 18 : Cost by technology and region_Focus wafer [9]

3.5. Data cost assumption: Cell

Data collection was carried out according to each step of the process flow (wet, PECVD, PVD, metallization, and curing) (Figure 14=. The data consists of primary inputs, complemented by findings from the state of the art. For confidentiality reasons, only the Cost of Ownership (CoO) is provided per step, expressed in USD/W. To estimate the results in USD/W, a wafer size of 182 mm × 182 mm and a cell efficiency of 25% were assumed. It is considered that both the reference cell and the innovative cell share the same dimensions and efficiency. For the various process steps, identical costs are assumed for both configurations in steps that remain unchanged. Cost variations are only accounted for in the processing steps that are modified between the reference and innovative steps in scenario 1.

3.6. Dara cost assumption: Module

According to [9] , the cost of the module assembly step produced in Europe ranges between 11 and 11.4 USD cent/W (Figure 18). An average value of 11.2 USD cent/W has been defined for both the reference module and the alternative module A1.

4. Results of the analysis

This section begins with a cost analysis of the innovation at the cell level, compared to a reference cell. In a second step, the impact of this innovation is evaluated within the overall PV module.

4.1. Results at the cell level

This section presents the results of the impact of reduced ITO and silver consumption in Scenario 1, compared to a reference HJT cell.

For the Wet processing, which includes cleaning, oxide removal, and texturing, has a total cost-of-ownership (CoO) of 1.006 USD cent/W, mainly driven by chemical consumables, CAPEX and waste treatment. PECVD, used for intrinsic and doped a-Si:H layers, incurs 1.047 USD cent/W, with a higher CAPEX influenced by tool cost and throughput. PVD, used for the deposition of ITO as a transparent conductive oxide, has a CoO of 1.167 USDcent/W, of which 31% is attributed to ITO material cost [11]. For metallization, using low-temperature silver paste leads to the highest materials cost, around 3 USDcent/W.

The reduction of ITO in Scenario 1 enables a cost decrease, bringing the PVD step down to 0.9 USD cent/W. Additionally, the reduction of silver usage and its replacement with copper allows for a 42% cost reduction, lowering the metallization cost to 1.74 USD cent/W.

The cost reduction achieved through the innovation in Scenario 1, compared to a standard HJT cell, is estimated at 10%.

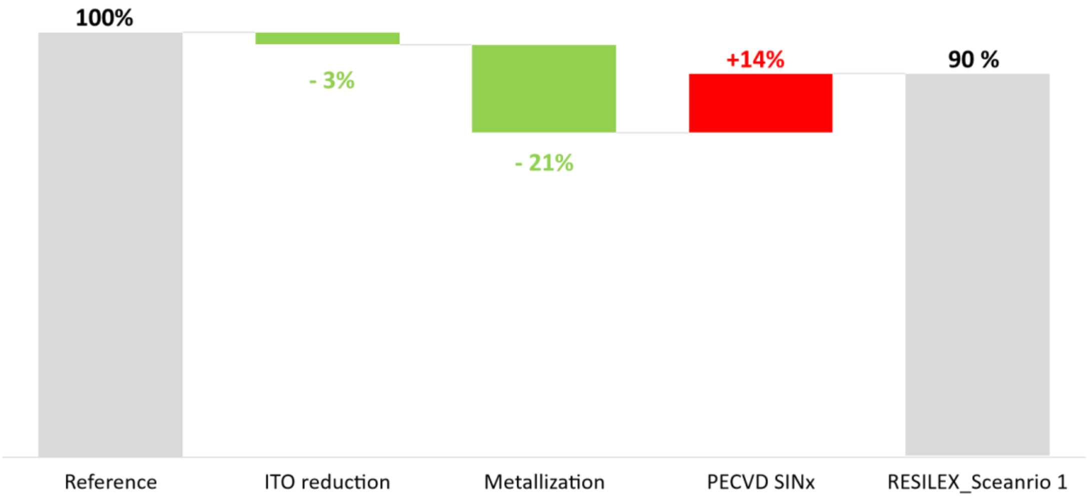


Figure 19 : Cost reduction comparison between the reference and Scenario 1

4.2. Results at the module level

Based on the data defined in Sections 4.3 and 5.1, the Figure below illustrates the cost reduction at the global module when integrating the Scenario 1 cell. A reduction of approximately 3% is estimated compared to the reference module.

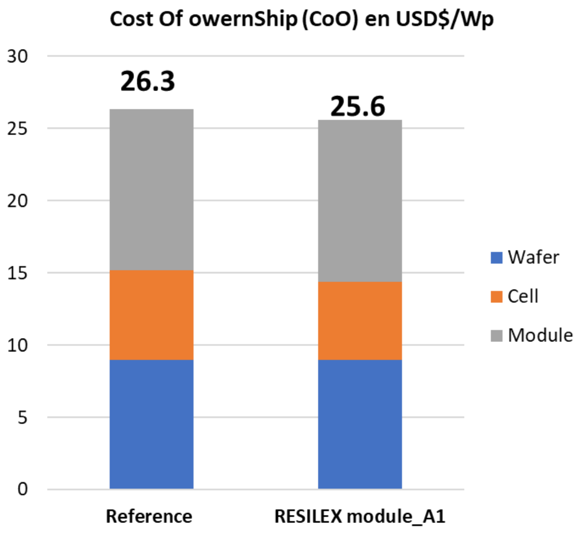


Figure 20 : CoO comparaison in USD cent/W

This cost could be further reduced by exploring additional cell scenarios and the use of eco-designed materials at the module level, which will be addressed in future phases of the project. Given that the module stage accounts for 61% of the total module cost, it represents a significant lever for cost optimization [9].

5. Conclusion

This deliverable provides a comprehensive overview of the innovations developed under Work Package 4 (WP4), with a primary focus on eco-designed solar cells and the reduction of critical materials such as silver and indium. A technological, economic, and market benchmark was conducted to assess the current trends across the photovoltaic value chain — from polysilicon to modules — and to define the project's reference scenario.

An initial Life Cycle Cost (LCC) analysis was carried out to evaluate the economic performance of the innovations, particularly at the cell level. While several innovative scenarios were identified, only Scenario 1 was evaluated in this deliverable due to limited data availability. This scenario demonstrates a cost reduction potential of approximately 10% at the cell level, and a 3% reduction at the module level when the new cell is integrated into the final product.

The analysis not only guides technological choices and supports process optimization, but also informs strategic decision-making for future project phases. At this stage, the economic assessment primarily focuses on defining the goal and scope of WP4 innovations, laying the groundwork for deeper evaluations in upcoming deliverables. Given that the module stage accounts for 61% of the total cost, it represents a major opportunity for further cost optimization. Upcoming evaluations will integrate additional data, including recycled silicon and eco-designed modules using alternative, more sustainable materials. These scenarios will be subjected to more detailed economic assessments to identify the most cost-effective and sustainable pathways for next-generation photovoltaic technologies.

6. Reference

[1] « International Technology Roadmap for Photovoltaic (ITRPV) - vdma.org - VDMA ». https://www.vdma.org/international-technology-roadmap-photovoltaic

[2] « Trends in PV Applications 2024 », IEA-PVPS. https://iea-pvps.org/trends_reports/trends-2022/

[3] « New Energy Outlook 2024 | BloombergNEF | Bloomberg Finance LP », BloombergNEF. https://about.bnef.com/new-energy-outlook/

[4] « Czochralski Process - an overview | ScienceDirect Topics ». https://www.sciencedirect.com/topics/chemistry/czochralski-process

[5] International Energy Agency, *Special Report on Solar PV Global Supply Chains*. OECD, 2022. doi: 10.1787/9e8b0121-en.

[6] « InfoLink Consulting: Global management consulting firm ». ttps://www.infolink-group.com/

[7] « Interdigitated Back Contact Technology as Final Evolution for Industrial Crystalline Single-Junction Silicon Solar Cell ». Disponible sur: https://www.mdpi.com/2673-9941/3/1/1

[8] « Technologie 3Sun: le choix le plus novateur est entièrement européen ».

[9] « ETIP PV publications - ETIP PV ». https://etip-pv.eu/publications/etip-pv-publications/

[10] « TOP SOLAR MODULES H1/2023 | TaiyangNews ». Disponible sur: https://taiyangnews.info/reports/top-solar-modules-h1-2023/

[11] A. Louwen, W. van Sark, R. Schropp, et A. Faaij, « A cost roadmap for silicon heterojunction solar cells », *Sol. Energy Mater. Sol. Cells*, vol. 147, p. 295-314, avr. 2016, doi: 10.1016/j.solmat.2015.12.026.