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D 7.2– Interim Comparative Environmental Sustainability Assessment

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Nomenclature

AoPs	Areas of protection
CEENE	Cumulative Exergy Extraction from the Natural Environment
CRM	Critical Raw Materials
CTUh	Comparative Toxic Unit for humans
EC	European Commission
EoL	End of life
FU	Functional Unit
IEA	International Energy Agency
IPCC	International Panel of Climate Change
ITO	Indium tin oxide
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
LIBs	Lithium-ion batteries
MG-Si	Metallurgical Grade Silicon
OEF	Organisation Environmental Footprint
PEF	Product Environmental Footprint
PECVD	Plasma Enhanced Chemical Vapor Deposition
PV	Photovoltaic
PVD	Physical Vapor Deposition
RR	Resource Recovery
SALD	Spatial Atomic Layer Deposition
SG-Si	Solar Grade Silicon
SHJ	Silicon Heterojunction
S-LCA	Social Life Cycle Assessment
TCO	Transparent Conductive Oxide
WP	Work Package

Executive Summary

This deliverable has been developed within Work Package 7 (WP7) of RESilEX *(Resilient Enhancement for the Silicon Industry Leveraging the European Matrix)*, entitled "Multi-faceted Impact Assessment & EU Policy Recommendations", under Task 7.2, which focuses on Comparative Environmental Sustainability Assessment. The main objective of RESilEX is to improve the resilience and the sustainability of the EU's silicon value chain. To this end, several innovative technologies are being developed, going from critical raw material's recovery, silicon production, photovoltaic solar cell and module manufacturing to recycling of solar panels or the integration of silicon in battery technology replacing graphite. The main objective of Task 7.2 is to evaluate the environmental performance of various innovative technologies that are being developed and studied in the other work packages of the RESilEX project. To this end, life cycle assessment (LCA) will be used to enable the identification of the hotspots of each innovative technology in order to steer process development towards a lower environmental impact. Subsequently, the LCA results will be compared with conventional processes (reference), indicating the potential benefits of the new technologies. Finally, the contribution to circular economy and potential critical raw material savings will be investigated in this task. The first step towards assessing the environmental sustainability of the innovative technologies is to define the systems under study and create flowsheets for each technology and reference cases. This forms the basis for preparing the life cycle inventory and constructing mass and energy balances. These quantitative data are required for the LCA and circularity and criticality assessment.

According to the project's progress, it has not yet been possible to fully assess the environmental impact of each innovative technology. However, each process has been thoroughly described in this deliverable. A reference case and the scenarios to be studied have been selected for each innovative technology. A functional unit is also selected, needed as the reference for comparison. In other words, the goal and scope of each innovation technology is defined, including the basked of products for many systems, enabling a fair comparison between the innovation technology and the reference case selected.

An overview of the status of data collection is provided with the sources selected in each case, as well as a plan for the next steps. Additionally, a life cycle impact assessment (LCIA) has been conducted for two innovation technologies, the eco-design of both solar cells and modules, providing a detailed illustration of the results obtained. These first results indicate a promising result of the innovations in terms of

environmental impact. However, results might differ among impact categories, highlighting the importance of a broad environmental sustainability assessment.

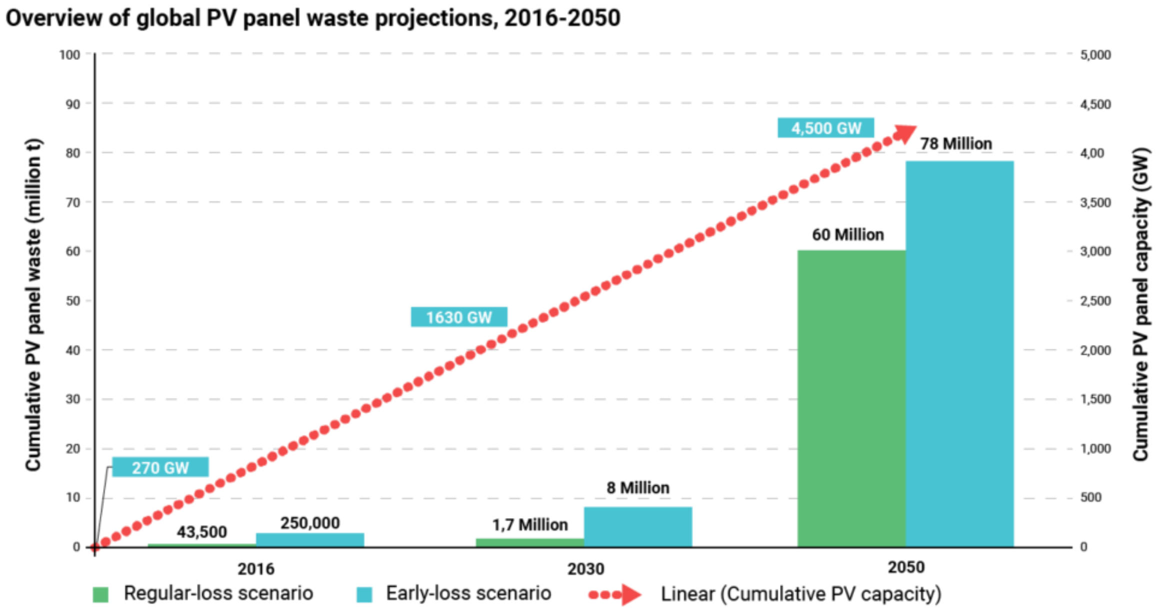
1. Introduction

1.1. General overview

The electricity demand in the world has become a critical challenge for today's society (Preet & Smith, 2024). According to reports from the International Panel of Climate Change (IPCC) and the International Energy Agency (IEA), the global CO_2 emissions increased by 1.1% in 2023 (International Energy Agency, 2023c; IPCC, 2023). The European Commission (EC) aims to reduce CO_2 emissions by 55% by 2030, a goal that requires significant improvements in energy efficiency. To support this transition, the EC has set a target to reduce final energy consumption by at least 11.7% by 2030, compared to projections from the 2020 reference scenario.

However, the production of the photovoltaic (PV) solar cells, as well as the module comprise different processes that require a critical amount of chemicals, energy, and resources that are not always object of study, and it increases the price and the complexity of the manufacturing process (International Energy Agency, 2023b). With the rapid expansion that photovoltaic market has experienced in recent decades, another constraint arises that questions and challenges the sustainability of its implementation in the long-term (International Energy Agency, 2023a). This refers to the implications and impacts on the demand for raw materials used either in the solar cells or the modules. The concentration of certain metals in mines is decreasing, and according to various authors, the energy cost of extracting metals increases exponentially as ore grades decline, along with the associated environmental impacts (Magdalena et al., 2023; Valero & Valero, 2014). With the current installed capacity of 1500 GW and the projected increase to up to 18500 GW by 2050 (according to the IEA's net zero scenario), it is essential to find solutions to reduce these environmental impacts.

One of the solutions could be to focus on recyclability. A substantial amount of PV panels that have been installed for the first time are reaching the end of their useful life. According to the International Renewable Energy Agency, there will be between 1.7 and 8 million tonnes of PV waste in 2030 and between 60 and 78 million tonnes in 2050, as it can be seen in Figure 1. Thus, the recyclability of PV panels and their components arises as a critical solution not only to meet the materials demand in the future, but also to make the production of this technology more sustainable (Maghraby et al., 2025).



Source: International Renewable Energy Agency. (2016). End-of-life Management: Solar Photovoltaic Panels.

Figure 1. Evolution of the PV panel waste until 2050.

However, the current recycling strategy in the PV sector relies on a linear process of take-make-use-dispose, leading to a significant number of PV modules being discarded in landfills. Under the European regulation of recycling 85% in mass of the materials manufactured, only glass, copper, and aluminum is recovered (Al Zaabi & Ghosh, 2024). This practice is not only a waste of valuable materials but also faces considerable environmental challenges, such as the risk of hazardous substances leaching into ecosystems. Recycling PV panels has the potential to recover between 90-95% of the materials used in their manufacturing (Al Zaabi & Ghosh, 2024).

The current recycling technique begins with the dismantling of the PV panel, separating the aluminum frame and the electrical connectors. Then, a process of crushing and grinding convert the panels into very small particles. Next, the material is introduced into a furnace, where high temperatures are applied to remove the embedded polymers. However, at these temperatures, some metals, such as silver and aluminum, may begin to alloy with silicon, making their separation unfeasible. In the case of heterojunction panels, the presence of indium oxide further complicates the recovery of various materials (Kleijn et al., 2024).

Although silicon is the most abundant element in the earth's crust, its production is primarily concentrated in China, which accounts for more than 73% of global output, while Europe only contributes for 4% (according to the Raw Materials Information System of the EC). Furthermore, silicon production is highly energy-intensive, requiring temperatures above 1600°C to concentrate and purify the material for industrial use, a process associated with significant environmental impacts (Moore, 1990).

This project addresses two main challenges. The first is linked to the Critical Raw Materials (CRM) Act developed by the European Commission, which emphasizes reducing dependence on third-party countries. The second challenge relates to sustainability, as the mining industry is among the most polluting sectors globally. To mitigate its environmental impact, reducing waste generation and reusing acid wastewater for metal extraction are key strategies. These approaches not only help minimize pollution but also promote greener processes in the recycling stage, contributing to a more sustainable and resource-efficient industry.

1.2. Introduction to sustainability evaluation of innovations developed within RESiLEX

Several key innovations are assessed. The Resource Recovery (RR) Treatment Train, developed by CETAQUA and THARSIS, focuses on optimizing the recovery of valuable metals from acid wastewater generated by mining processes (WP2). In the field of silicon refining (WP3), while carbothermic reduction is traditionally used, NTNU has introduced an aluminothermic reduction process as an alternative metallurgical route for silicon purification. Additionally, NanoPow has developed a process to purify silicon kerf from wafer residues, producing high-quality silicon nano-powder.

To reduce the reliance on Critical Raw Materials (CRM) in photovoltaic (PV) panels, new solutions have been proposed (WP4). CSEM and CEA have worked on CRM-free, low environmental footprint silicon production cells, aiming to replace and reduce strategic materials in passivated contact solar cells and adapt fabrication processes to reduce environmental impact. Meanwhile, CEA has assessed the quality of eco-designed PV modules, focusing on sustainability improvements.

Given the increasing need for PV panel recycling, efforts have been made to recover valuable materials such as silicon, aluminum, and copper (WP6). COMET has developed a process to extract high-purity silicon from end-of-life PV panels. Additionally, in the field of battery technology, ULIEGE has focused on developing silicon composite materials for high-energy-density Li-ion battery cells, utilizing silicon recovered from mining or recycled solar panels.

This deliverable outlines the goal and scope of the environmental sustainability assessment for each innovation. This is the first step to conduct a life cycle assessment. The limited availability of data, due to the early stages of certain experiments and pilot plant operations, constrains the execution of the impact assessment. Therefore, the analysis will primarily focus on the explanation of the goal and scope of each innovation technology as well as preliminary environmental impact results of the innovations developed within WP4.

Accordingly, this project aims to develop a more sustainable approach to recover metals from secondary sources and producing PV panels with enhanced recyclability. Furthermore, it seeks to establish a closed-loop system for silicon, enabling the recovered metal to be reintroduced into the value chain for manufacturing new PV panels.

Moreover, throughout the project, a comprehensive evaluation will be conducted to assess the environmental, economic, and social impacts of optimized Silicon use in photovoltaic (PV) modules. This will involve a Life Cycle Cost (LCC) analysis to determine the financial viability of PV modules incorporating optimized Silicon, as well as a Life Cycle Assessment (LCA) to compare different strategies for Silicon valorization within the module. In parallel, a social acceptance analysis will be carried out to explore public perception and identify potential barriers to the adoption of these technologies. To further support sustainability, an eco-design approach will be implemented, aiming to establish European recommendations for a Silicon EU label.

Specifically, the main objective of Task 7.2 is to evaluate the environmental performance of various innovative technologies that are being developed and studied in the other work packages of the RESilEX project. To this end, LCA will be used to enable the identification of the hotspots of each innovative technology in order to steer process development towards a lower environmental impact. Subsequently, the LCA results will be compared with conventional processes (reference), indicating the potential benefits of the new technologies. Finally, the contribution to circular economy and potential critical raw material savings will be investigated in this task. The first step towards assessing the environmental sustainability of the innovative technologies is to define the systems under study and create flowsheets for each technology and reference cases. This forms the basis for preparing the life cycle inventory and constructing mass and energy balances. These quantitative data are required for the LCA and circularity and criticality assessment.

Within this framework, the structure of the deliverable is organized as follows. First, a brief overview of each innovative technology is provided, offering the necessary context to understand their development and purpose. Next, after outlining the life cycle assessment methodology, the first results are presented, namely the definition of the goal and scope for each innovation technology. In this section, the eight innovation technologies are categorized by work packages (WPs). It is important to note that while some WPs contain a single innovation technology (e.g., WP2), others include multiple innovations (e.g., WP3 has two). The focus is placed on the goal and scope definition, which serves as the primary outcome for most of these technologies. In addition, this section provides an overview of LCI sources and the status of the LCA. This includes the data collection progress, and outlining the steps taken to ensure a comprehensive assessment of the innovation technologies across the different work packages. Finally, the deliverable concludes with the results of the LCIA for the eco-design of solar cells and modules, illustrating the key findings.

2. Innovation technologies in RESiLEX

Despite silicon is not included in the critical raw materials list developed by the European Commission, it is considered a strategic raw materials and thus, one of the main hotspots to analyse due to its highly energy-intensive production.

Accordingly, within the project framework, eight innovative technologies have been identified as potential solutions to the aforementioned challenges. These technologies address every stage of the PV panel production process, including the sustainable recovery of CRM and production of silicon, the eco-design of PV cells and modules, and the recovery of materials from solar panels at the end-of-life. Table 1 illustrates the various technologies that will be developed during the project, the Work Package (WP) in which they will be studied, and the published deliverable where they are fully explained.

Table 1. Innovation technologies (IT) developed in RESiLEX and published deliverables

Innovation technology		WP	Deliverable
IT1	CRM recovery train	2	D2.2
IT2	Sustainable SG-Si production	3	D3.1
IT3	Crystalline nano-powder production	3	D3.4
IT4	Si wafers production from revalorized Si wastes	4	D4.5
IT5	Eco-designed cells	4	D4.1
IT6	Eco-designed modules	4	D4.2
IT7	Si recycling process	5	D5.2
IT8	Si composite for Li-ion batteries	6	D6.2

2.1. CRM Recovery train

To recover CRMs as efficiently as possible, the RESiLEX treatment train consists of seven different units. The target metals present in the acid wastewater generated from mining operations, are removed in three different units: physico-chemical unit (Fe and Al), sulphide precipitation (Cu and Zn) and evaporator-crystalliser (Co, Ni, Cd). The treatment is conducted in multiple steps due to the different chemical properties and solubilities of the metal ions. Since each metal has a pH-range and a mineral phase to precipitate effectively, sequential selective precipitation ensures a more complete and efficient removal (e.g. Fe precipitates with a pH of 2.5, while Al precipitates with a pH of 5.5). This stepwise approach could prevent issues such as co-precipitation, where mixed and impure sludge forms, and avoid the formation of stable complexes that could hinder precipitation. In addition, it enables the optimised use of precipitating agents, minimising waste and costs. All the information regarding to this innovation technology can be found in the D2.2.

2.2. Sustainable SG-Si production

State-of-the-art production of silicon and solar panels are linear, carbon-intensive processes that produce several low-value by-products and wastes. A transition from carbon emissions and waste generation to a circular economy is essential for building a sustainable industry. The overall objective of this study is to explore one route of sustainable Si production through the utilization of secondary raw materials and a low-carbon process. The specific system investigated was the recycling of silicon kerf through remelting of silicon kerf with a silicon alloy. The silicon alloy used was produced from the sustainable SisAl process, through aluminothermic reduction of SiO_2, a process without direct CO_2 emissions (Vallejo Olivares et al., 2024). After the reduction process, the resulting silicon is in the form of an alloy. By adding quartz and Si-kerf, MG-Si is produced. The material then undergoes a crystal pulling process, obtaining SG-Si. More detailed information regarding to this innovation technology can be found in the D3.1.

2.3. Crystalline nano-powder production

The crystalline nano-powder production is composed of three main steps. The first one is the collection of generated waste when cutting the silicon ingots to produce silicon wafers, resulting in the so-called silicon kerf. This waste stream is collected and through a new developed process, they are treated to eliminate the impurities embedded, producing high-quality silicon nano-powder. The second step is based on the collection of the silicon at the end of life of solar panels. This silicon is integrated into the purification process in an environmentally friendly way, without aircontamination nor pollution, also producing high-quality silicon nano-powder. Finally, to prevent oxidation and ensuring the high-quality product after this innovative process, a thin carbon coating will be added to the nanoparticles produced. This outer thin layer will protect the nanoparticles, assuring that the crystalline nano-powder retains the same properties. For more information regarding this innovation technology, the deliverable D3.4 can be consulted.

2.4. Si wafers production from revalorized Si wastes

This innovation technology starts with the analysis and comparison of silicon wafers, being characterized by oxygen content, defects, resistivity, and uniformity. Accordingly, these wafers will be assessed through different processes to determine which parameters are affecting these properties. First, different and new passivated contact technologies will be developed, comparing low-temperature methods with high-temperature to identify defects related to the temperature. Then, the material quality will be tested using photo-conductance decay, photoluminescence imaging, and IV performance measurement, while the degradation will be evaluated aiming to develop new methods to reduce it. Finally, solar cells will be assembled into modules to test the performance.

2.5. Eco-designed cells

Today, silicon solar cells depend on CRMs. The aim here is to reduce and replace materials with a high supply risk (critical and strategic raw materials) or a high environmental impact with materials with a lower impact or a lower supply risk. The cell technology studied is silicon heterojunction (SHJ) technology, which shows promising trends for future development and improvement. The project focuses on replacing and reducing the most important CRMs used in current SHJ solar cells and on modifying the manufacturing process to reduce the total environmental footprint. The emphasis is on the reduction or replacement of indium tin oxide (ITO) and silver. Various experimental setups have been created to obtain ITO-reduced or even ITO-free SHJ cells, as well as low-silver to silver-free SHJ cell scenarios that are being tested by CSEM, CEA and CNRS.

2.6. Eco-designed modules

The partners CEA and CSEM are looking for solutions to obtain eco-designed PV modules. On the one hand, innovative approaches for the metallization and interconnection scheme are being considered, relying on the solar cells retrieved from the previous innovation. Second, alternatives for the most impactful parts of the PV module are under study. For instance, alternative options to the commonly used aluminium frame and glass front plate are being investigated. Among other things, the partners are investigating the selection of materials, for example materials of biological origin, and testing the performance of each development.

2.7. Si recycling process

The silicon recycling process is carried out by two different partners. Solar PV panels at the end of life are sent to Comet, where through mechanical processes they can separate different materials. The output from Comet consists primarily of glass and silicon, along with moisture, which is sent to the second partner involved in this innovative technology. The University of Liege (GeMMe group) receives this product, where the product is treated to increase the concentration of Si with cleaners and roughers. The information regarding this innovative recycling process can be found in the deliverable D5.2.

2.8. Si composite for Li-ion batteries

The last innovation technology of RESiLEX is the development of a sustainable approach for reviving Si metal reclaimed from EoL PV panels and broken solar cell scraps for high-value energy-efficient Si-based anode active materials for application in Li-ion batteries (LIBs). The production of Si-based composites is carried out at pilot scale by the GREEnMat group, from the University of Liege, that receives high clean Si from the GeMMe group from the same University. The objective is to demonstrate the sustainable pilot-scale production of Si/C composite anode active material powders using the spray drying method, utilizing high-purity solar-grade silicon recovered from end-of-life (EoL) PV solar cells as a cost-effective silicon source. More information on this innovation can be found in Deliverable D6.2.

3. Environmental sustainability

To drive the transition toward a more sustainable metal recovery and production system for photovoltaic (PV) technologies, comprehensive sustainability assessments are essential. As outlined in the Brundtland Report, sustainability is built upon three key pillars: economic, social, and environmental (Elkington, 1997). Economic sustainability seeks to maximize resource efficiency and reduce production costs, while social sustainability ensures the well-being of workers and communities affected by metal extraction, processing, and recycling. Environmental sustainability focuses on minimizing resource depletion, emissions, and ecological damage caused by mining and metallurgical processes. Thus, developing a robust assessment method that integrates these three dimensions is crucial for achieving a circular and responsible metal supply chain for PV applications.

Life Cycle Thinking (LCT) provides a complete approach to evaluate the environmental, economic, and social impacts of metal recovery, refining, and recycling across the entire value chain, from raw material extraction to end-of-life processing, as it is illustrated in Figure 2. Several methodologies operationalize LCT, including LCA, Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA). Additionally, Material Flow Accounting (MFA) and other supply chain assessment tools help quantify resource use and identify intervention points for efficiency improvements (EC Toolbox).

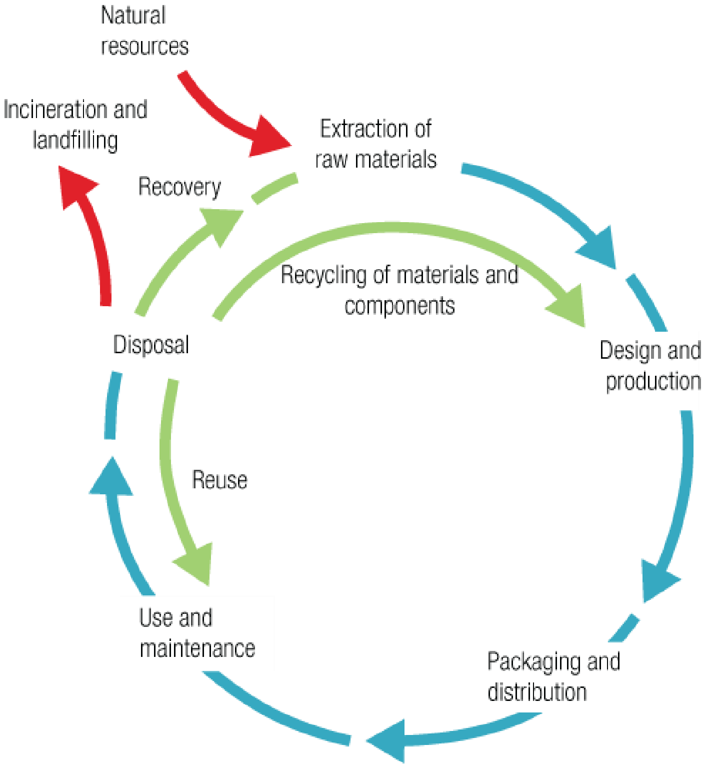


Figure 2. Life cycle thinking concept (Life cycle initiative, 2025).

In its Communication on Integrated Product Policy (COM (2003)302), the European Commission recognized LCA as the most effective framework for assessing the potential environmental impacts of products. This methodology is essential to integrate sustainability into the design, production, and recycling of PV-related materials, guiding policy development and industrial innovation at both EU and global levels.

With environmental sustainability being a key concern in PV metal production and recycling, LCA, complemented by criticality and circularity assessments, plays a crucial role in evaluating the environmental performance of a PV panel's material composition. Accordingly, this deliverable is primarily focused on the LCA, with the collected data also serving as a source for circularity and criticality evaluations. Within the RESiLEX framework, the objective is to assess the environmental impacts of metal recovery from acid wastewater, the newly developed recycling strategies, and an innovative process for cleaner silicon production.

3.1. Life cycle assessment

LCA is a globally recognized methodology for evaluating the potential environmental impacts of product systems. It quantifies these impacts by assessing emissions and resource consumption throughout a product's life cycle, from raw material extraction to end-of-life (Guinée et al., 2002). Policymakers, companies, and business associations rely on LCA as a decision-making tool, as it offers a quantitative assessment of environmental sustainability. LCA considers the entire life cycle and evaluates various environmental factors, allowing the identification of potential shifts in environmental impact across different stages or impact categories.

The LCA methodology follows four key phases: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation, as outlined in the ISO 14040:2006 (ISO, 2006a) and ISO 14044:2006 (ISO, 2006b) standards. This can be seen in Figure 3.

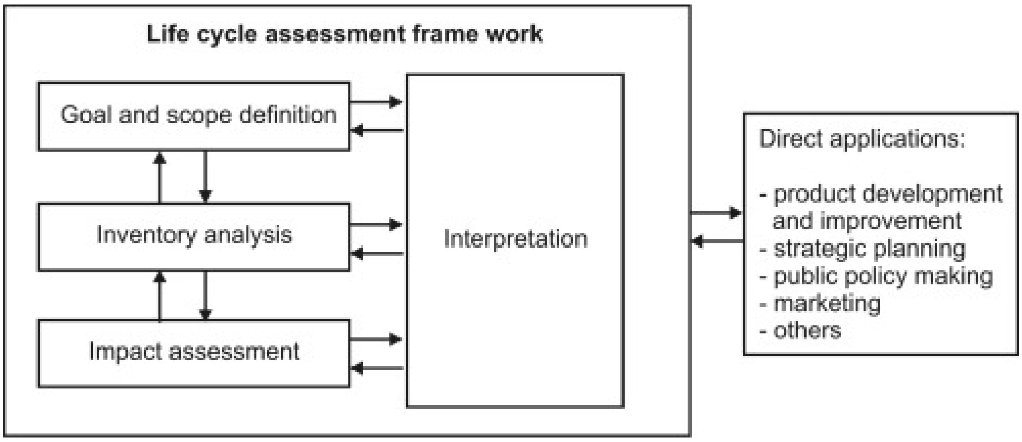


Figure 3. Life cycle assessment methodology

1. The *goal and scope* definition phase implies the formulation of the purpose of the LCA study and additional information such as intended application and target group, description of the product system, definition of functional unit (FU) as a reference of comparison, system boundaries and data requirements, key modelling assumption and limitations.
2. The *inventory analysis* phase covers data collection and/or calculation of the Life Cycle Inventory (LCI) results. It makes use of system analysis to divide the product

systems into unit processes, e.g. PV panel production, electricity production, transportation. Each process converts inputs (e.g. materials and other resources) into outputs (e.g. products or emissions). The emissions and natural resources are the so-called elementary flows of the system.

3. The *Life Cycle Impact Assessment* phase (LCIA) aims to understand and evaluate the magnitude and significance of potential environmental impacts of the product system. LCIA consists of two mandatory steps, i.e. classification and characterisation, possibly followed by normalisation and weighting. During classification, the inventory results are assigned to impact categories to which they contribute on a purely qualitative basis, while in the characterisation step, their contributions to specific impact categories are quantified using substance-specific characterisation factors (e.g. Global Warming Potential, measured in kg of CO_2-eq for the impact category climate change). The contribution of each inventory flow to different impact categories is analysed relying on the cause-effect chain nature of environmental mechanisms. The quantification of indicators by characterisation factors can be at midpoint or endpoint. Midpoint indicators refer to specific environmental impact categories (e.g., global warming, acidification, or eutrophication) that quantify the effects of a process before they translate into broader damages. Endpoint indicators, on the other hand, aggregate these impacts into three main areas of concern—human health, ecosystem quality, and resource depletion—providing a more comprehensive but less detailed evaluation of the overall environmental burden (Finnveden et al., 2009). Results can be normalised, weighted and/or aggregated into the main areas that society wants to protect or sustain, called areas of protection (AoPs), i.e. natural resources, ecosystem quality and human health, and single scores. A variety of impact assessment methods exists with their own methodology to define the characterisation factors for the selected impact categories (Hauschild et al., 2013). The LCIA methods are either emission-based, e.g. Intergovernmental Panel on Climate Change (IPCC), resource-based, e.g. Cumulative Exergy Extraction from the Natural Environment (CEENE) or a combination of the two, e.g. ReCiPe (Dewulf et al., 2007; Huijbregts et al., 2017).
4. The last phase, *interpretation*, requires analysing LCI and LCIA results in relation to the defined goal and scope in order to reach conclusions and recommendations. It is an iterative phase to improve the quality of the study. Among others, this phase can include sensitivity analyses and identification of possible limitations (ISO, 2006a).

LCA is typically carried out with the support of software packages (e.g. SimaPro) and life cycle inventory databases, e.g. ecoinvent or Agrifootprint.

Since 2013, the European Commission has recommended the use of common methods to measure and communicate the life cycle environmental performance of products and organisations (European Commission, 2013). This established a harmonised method for multi-criteria environmental LCAs of products (i.e. Product Environmental Footprint, PEF) (Manfredi et al., 2012) and organisations (i.e. Organisation Environmental Footprint, OEF) (Pelletier et al., 2013).

3.2. Procedure to data collection

Every stream (input and output flows of the system) for each innovative technology is required to conduct an LCA. Therefore, it is essential to gather as much data as possible, particularly at the plant level, also referred to as primary data.

Accordingly, collaboration and communication with consortium partners become critical at this stage, as they are responsible not only for developing the processes but also for collecting the key data needed to calculate the environmental impacts of their processes. Therefore, the approach described below is being followed with each partner developing an innovative technology as a first step in the environmental sustainability assessment.

1. The visualization of the innovation technology assessed and qualitative data collection are carried out by creating a process flow diagram. This diagram outlines the system boundaries, illustrating the included processes and mapping the flows of materials, energy, recovered metals, by-products, waste, and emissions within the whole process.
2. Comprehensive quantitative data collection of all material, energy, product, waste, and emission flows within the production or recovery process is conducted to ensure a detailed and accurate assessment of its environmental and operational performance.
3. Developing a detailed mass and energy balance to validate the collected data, ensuring consistency and accuracy in the assessment of material consumption, energy use, and metal recovery efficiency.
4. Verification and validation of the mass and energy balance by the involved partners, confirming data accuracy, consistency, and reliability of the data obtained for each specific units and flows.

However, it is not always possible to obtain primary data for a specific process stage at either the pilot or large-scale level. Therefore, the following systematic procedure is implemented to gather the necessary information, ensuring a comprehensive and reliable dataset for conducting LCA while maintaining consistency across different process stages:

1. A process flow diagram is designed to define the boundaries of the system under analysis, illustrating the overall process along with all associated inputs and outputs. Instead of dividing the system into its individual sub-processes, this method—known as the black-box approach—addresses the process as a single unit, without assigning specific inputs to particular sub-stages.
2. To gather essential information, data are obtained through discussions with experts, including consortium partners, professionals from industrial companies, and researchers from academic institutions. Additionally, databases and scientific literature are consulted to incorporate established methodologies, best practices, and scaling rules for similar or comparable systems, ensuring a comprehensive data set.
3. A mass and energy balance is meticulously constructed for each process stage. This step is crucial to assess the accuracy of the gathered information, ensuring that material and energy inputs align with expected outputs, thereby providing a quantitative framework for evaluating the process.
4. The accuracy and reliability of the collected data are confirmed through different validation techniques. This includes consulting subject matter experts when data originate from databases or literature, cross-referencing with relevant scientific publications when data are derived from expert experience, and comparing findings with experimental results obtained at the pilot scale to verify consistency and reliability.

4. Results

The following section presents the goal and scope definition for all assessed technologies, providing the basis for the evaluation. A more detailed analysis is then given for the eco-designed cells and modules, both of which are addressed within Work Package 4 (WP4) and are therefore evaluated together to ensure a comprehensive assessment of their innovations.

4.1.1. Results for Goal & Scope definition for RESiLEX

This section discusses the goal and scope of the LCA for each innovation separately as a different approach is needed to assess the environmental impacts compared to conventional manufacturing or recycling. For all innovations (except for the eco-design of modules and cells), a basket-of-products approach was applied to allow a fair comparison between the scenario including the innovation in the RESiLEX project and the reference. More details about this approach and an example in the chemical sector can be found in previous research performed by Vorst et al. (2010) and Motte et al. (2023). Section 4.1.2 to 4.1.7 illustrate this approach for each innovation in the RESiLEX project together with the selected functional unit.

4.1.2. CRM recovery train in WP2

In WP2, a novel process was developed by Cetaqua and Tharsis to recover metals from acid wastewater produced by mining activities. The goal of the LCA for this innovation is to assess the environmental impacts of metals recovery from mining wastewater via the developed recovery train and the simultaneous valorisation of organic waste (cheese whey) and mine waste. The process developed in the RESiLEX project needs to be compared to a reference case, specifically conventional acid wastewater treatment. However, relying solely on this reference would overlook additional credits of this waste treatment process, leading to an inaccurate analysis. System expansion must be applied, as conventional acid wastewater treatment does not generate useful products. Tharsis, responsible for the acid wastewater used in this process, reports that the acid wastewater is discharged back into the environment, filling ponds and galleries. Accordingly, on one side, the inputs of the innovative technology—including acid wastewater, organic waste, and mine waste—will be compared to the current treatment procedures for each. On the other hand, the output streams, where metals are recovered, will be compared to conventional metal production processes. Currently, zinc sulfide (ZnS) is primarily obtained from sphalerite, the main zinc ore. It undergoes roasting to form zinc oxide (ZnO), followed by reduction or leaching for metal recovery (Sinclair, 2005). Copper sulfide (CuS) is derived from chalcopyrite, processed through flotation, roasting, smelting, and electrorefining (Nayak & Charan Sabat, 2009). Cobalt sulfide (CoS) comes from cobaltite or as a byproduct of nickel and copper ores. It is extracted via flotation, leaching, and precipitation (Crundwell et al., 2011). Finally, it is important to mention that the organic waste introduced in the innovation is currently used for the production of yogurt. If it is noticed during further investigations that the conventional production methods in the reference delivers several co-products, the system of Scenario 1 for innovation technology (IT) 1 must also be expanded with their conventional manufacturing processes. The functional unit for the LCA of this innovation was defined as 1 kg of acid wastewater to be treated, the simultaneous valorisation of a kg organic waste and b kg mine waste and the production of the precipitated metals (x kg Cu, y kg Zn, etc.) and y kg of yogurt. Figure 4 illustrates the goal and scope assessed for this scenario.

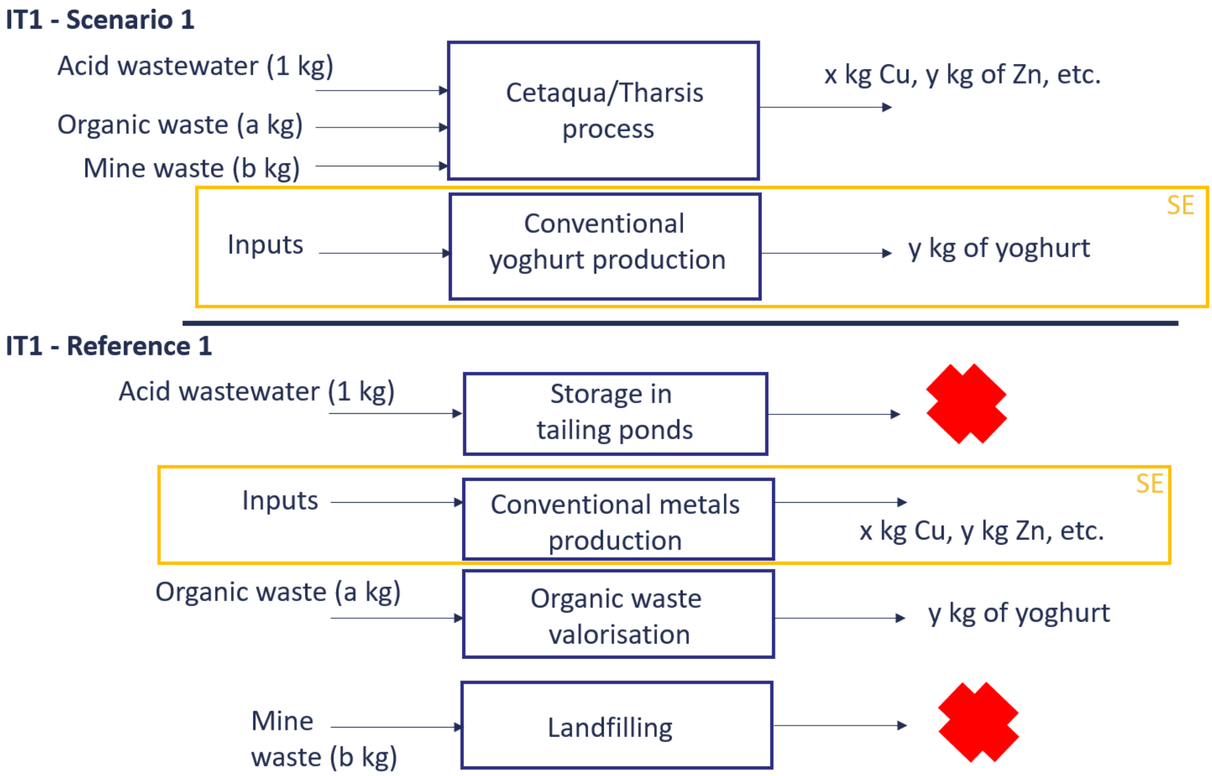


Figure 4. LCA approach for innovation from WP2. The boxes indicated in red and green are only taken into account when the corresponding conditions next to the boxes are met. SE = system expansion.

4.1.3. Sustainable solar production

In WP3, solar grade silicon is produced from silicon kerf using the aluminothermic reduction developed by NTNU. Moreover, Nanopow works on an innovative process to valorise silicon kerf into a crystalline silicon nano-powder. Afterwards, both highly pure silicon streams can be used to manufacture silicon wafers which form the basis for solar panels.

Figure 5a and Figure 5b show the LCA methodology for the innovations in WP3. The LCA of the NTNU process aims to quantify the environmental impacts of solar grade silicon production from silicon kerf and aluminium dross compared to conventional recycling of these two streams and the conventional solar grade silicon production. Since aluminium oxide, aluminium alloy and ammonium sulphate are obtained as co-products during conventional Al-dross recycling, the system of Scenario 1 for IT2 must be expanded with the conventional production of these chemicals to enable a fair comparison (Vallejo Olivares et al., 2024). Moreover, conventional solar grade silicon production must be added to Reference 1 (IT2) when the amount of recovered silicon from Si-kerf through conventional recycling is lower than the obtained amount through the NTNU process. A carbothermic reduction of SiO_2 followed by the Siemens process is considered for this (Méndez et al., 2021). The recycling of 1 kg Si-kerf and a kg Al-dross for the production of x kg of solar grade silicon and the co-production of b kg aluminium alloy, d kg of ammonium sulphate and e kg of aluminium oxide is chosen as functional unit.

The environmental sustainability of the Nanopow process is compared to the Si-kerf recycling combined with the conventional solar grade silicon production. Similar to the LCA for the NTNU process, the system of Reference 1 (IT3) must be expanded with conventional solar grade silicon production when x is greater than y (see Figure 5b). The functional unit for this comparison is defined as the recycling of 1 kg Si-kerf for the production of x kg of solar grade silicon.

The Si-wafer production from the solar grade silicon is not taken into account for both innovations because these production steps are the same for Scenario 1 of IT2 and IT3 and the corresponding references.

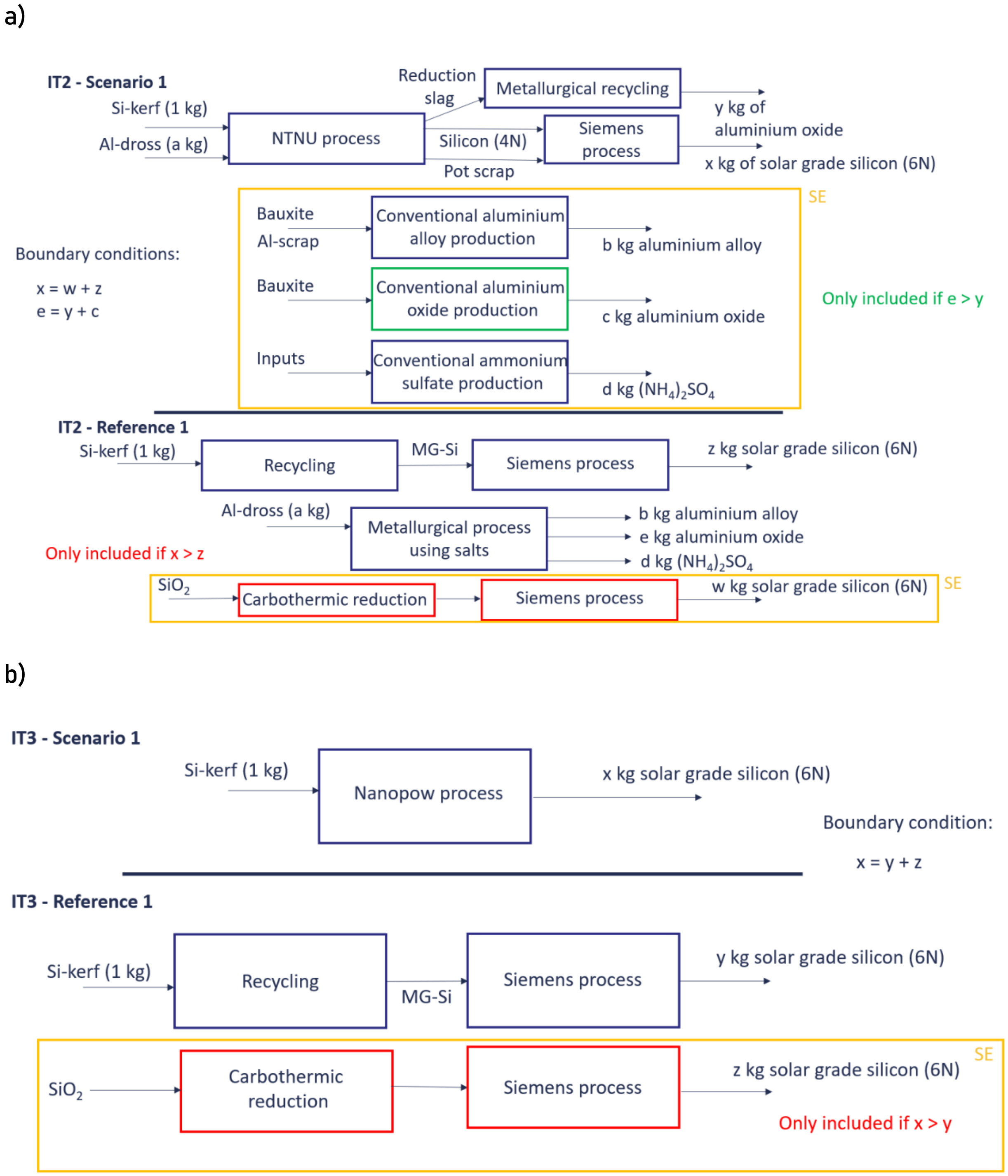


Figure 5. Illustration of LCA methodology for innovations in WP3. A) Solar grade silicon production from Si-kerf and Al-dross through the aluminothermic production process developed by NTNU, B) Crystalline nano-powder production from Si-kerf through process developed by Nanopow. The boxes indicated in red and green are only taken into account when the corresponding conditions next to the boxes are met. SE = system expansion.

4.1.4. Revalorisation of Si-waste obtained from solar panels

The task involving this innovation technology started only in M28. Since this deliverable is aimed for M35 and the preparation of it started months before this deadline, no information regarding to this task has been collected. Thus, the updated deliverable expected at the end of the project will include the goal and scope of this innovation technology as well as the results of the environmental impact assessment.

4.1.5. Eco-designed cells and modules

The aim of the LCA in WP4 is to evaluate the environmental sustainability of the eco-designed SHJ cells and modules. The innovative solutions for cell and module will be compared with the reference case, being the supply chain of SHJ PV modules at the European market. The location differs per process step (see Figure 6) and is defined for each step based on the most or only occurring production location within Europe (CEA, expert knowledge). During the reduction process, SiO_2, which naturally occurs as silica sand, is transformed into high purity silicon by removing oxygen through carbothermic reduction. The resulting metallurgical grade silicon (MG-Si) is further refined to solar-grade silicon (SG-Si) by the Siemens process. For the growth of mono c-Si ingots, the Czochralski process is used, corresponding to step 3 ‘crystallization). Diamond wire sawing is applied to convert the produced ingots into wafers (slicing). These wafers are the basis for the SHJ cells and are utilized to produce modules.

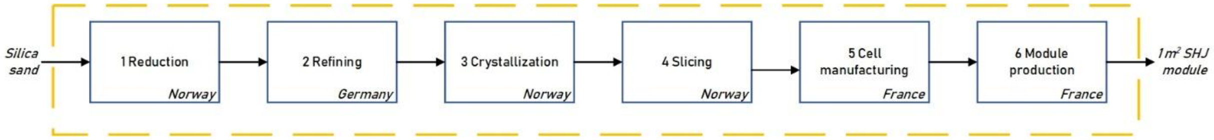


Figure 6: Overview of manufacturing stages of PV modules including location considered in this study

The different steps of manufacturing the reference SHJ cell are presented in (Roffeis et al., 2022). Based on this study, five main steps can be distinguished and are summarized here. First, wafer cleaning and texturing implies the preparation of the wafer to obtain uniformly textured Si surfaces with optimized pyramids size. Second, plasma enhanced chemical vapor deposition (PECVD) of a thin film layer involves ionized plasma that decomposes and deposits gaseous precursors (Yi et al., 2021). Third, a transparent conductive oxide (TCO) layer is sputtered onto both sides of the silicon layers via physical vapor deposition (PVD). Indium tin oxide (ITO) is commonly utilized, as also in the reference, giving a blue color to the cell. Note that steps 1 to 3 need to occur in a controlled atmosphere or clean room due to the risk of contamination. After the TCO deposition, this risk is eliminated. Maintaining this controlled atmosphere is energy intensive and related to substantial auxiliary (e.g. gas consumption such as nitrogen) supply. In the fourth step, screen printing is used as metallization process with a silver-based paste. Finally, curing induces morphology changes, adhesion optimization between the different layers and resistivity changes of the metallization paste.

Within RESilEX, several scenarios for cell manufacturing (IT5) will be considered, each changing step 3 or 4, which might result in the need for additional steps. Reduced use of ITO and partial to complete replacement of ITO are considered. Reduced use of silver by copper substitution in the metallization paste is also investigated. Finally, another technique instead of PVD, namely spatial atomic layer deposition (SALD) is studied. The different scenarios are presented in Figure 7. If the additional steps are the same between the scenarios, they are indicated with the same name.

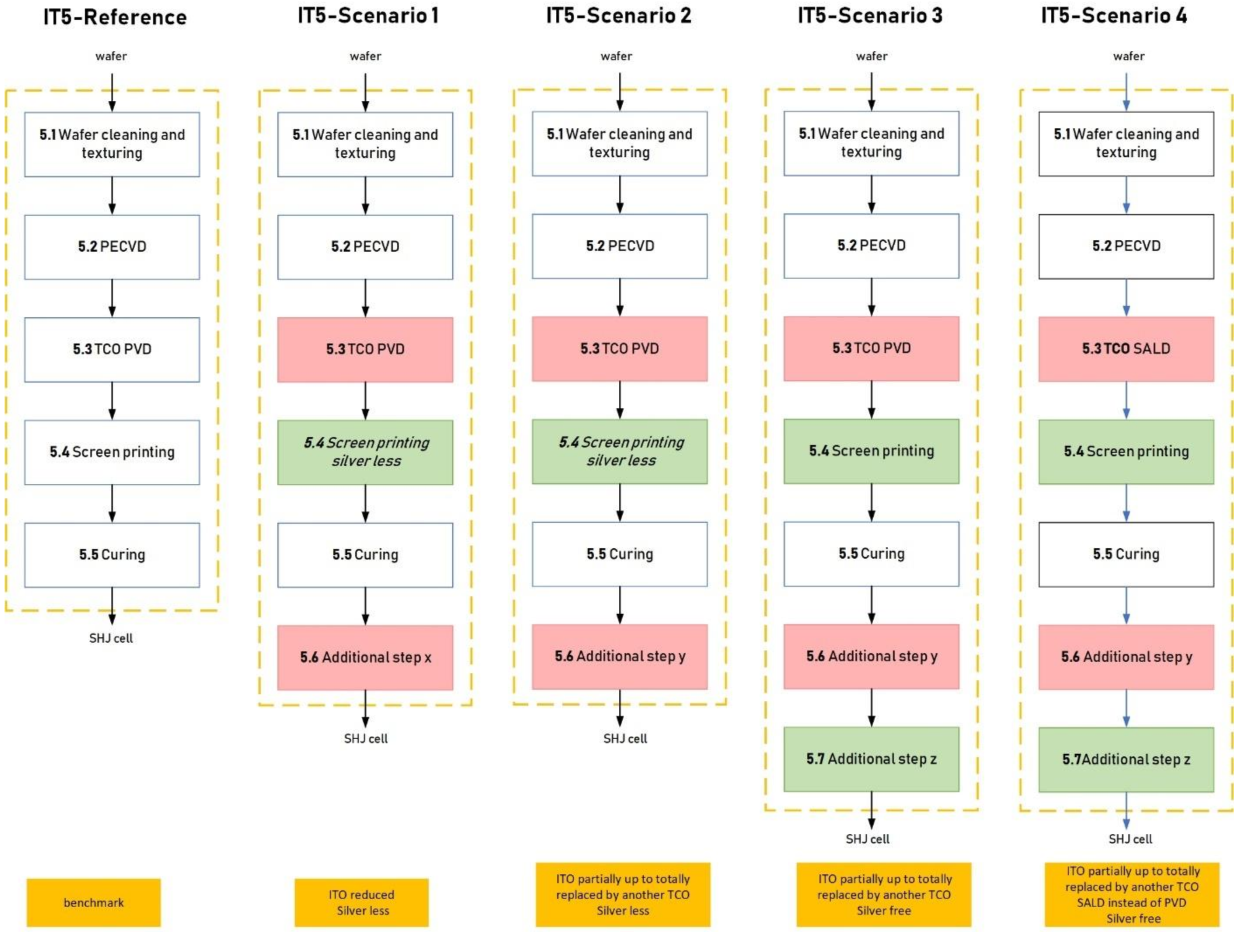


Figure 7: Overview of the considered scenarios for cell manufacturing, corresponding to innovation technology 5 (IT5, eco-designed cells). PECVD = plasma enhanced chemical vapour deposition; TCO = transparent conductive oxide; PVD = physical vapour deposition; SHJ = silicon heterojunction; SALD = spatial atomic layer deposition ; ITO = indium tin oxide

The final step is the production of the module. Encapsulating a PV module is an essential step in guaranteeing the module's long-term operational endurance. Encapsulation films such as ethylene-vinyl acetate (EVA) are used to enclose photovoltaic modules. These films are positioned in between the solar cells and the front and rear sheets, respectively. The interconnections provide electrical, mechanical and thermal contact between the solar cell and electrodes (Zarmai et al., 2015). Interconnections are typically made by soldering or brazing copper and silver, as in the reference case. Lamination is the process of applying pressure and heat to this assembly in order to fuse the encapsulating layer to the solar cells and form a sealed unit. A frame is added around the borders of the laminated module to provide additional protection. The frame, which is made of aluminium, offers mechanical support. Junction boxes provide a connection between the solar panels and the rest of the system, enabling energy to be transferred safely and efficiently.

Within RESilEX, two different alternative modules are investigated (Table 2), called IT6-scenario 1 and IT6-scenario 2 (two eco-designed alternatives for step 6 in the module manufacturing).

Table 2 Overview of the composition of the modules considered in the reference case, scenario 1 and scenario 2 of innovation technology 6 (IT6). ECA = Electrically Conductive Adhesive, TPE = Thermoplastic Elastomer, PET = Polyethylene terephthalate, EVA = Ethylenevinyl Acetate, TPO = Thermoplastic Olefin

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

For reasons of confidentiality, specific quantitative data per scenario cannot be provided at this stage of the project. Several steps are distinguished in this task to get insight into the environmental performance of the PV cell and modules. First, the environmental impact of the entire manufacturing process is evaluated to identify the main contributing process steps to the environmental footprint of a SHJ technology based PV module. Second, the environmental impact of the reference is compared to alternative cell and module manufacturing scenarios where key materials are partially or fully substituted to improve their environmental performance. The functional unit for this assessment is 1 m^2 SHJ-technology based module. However, in literature, next to m^2, also kWh or kWp are often used for comparison of PV technologies. In this case, a surface based functional unit is selected as this can be used to compare the same technology integrating different materials or architectures (International Energy Agency, 2020). At a later stage, when more information of potential efficiency changes due to the modifications in the cell or modules is available, results could be expressed using a different FU as well.

4.1.6. Silicon recycling process

The aim of the LCA for the innovation in WP5 is to evaluate the environmental sustainability of silicon, glass, copper, aluminium and heat recovery from solar panels at their end-of-life compared to conventional solar panel recycling, excluding silicon recovery, and the conventional production of the recovered materials (silicon, copper, aluminium and energy). The solar panel recycling process in RESiLEX is developed by Comet and ULiège (GeMMe). The LCA approach for this innovation is represented in Figure 8. For the reference, it is assumed that the solar panels are first collected, dismantled and shredded. The obtained glass can be used for insulation material or it can be further purified so that it can be valorised again for solar panel production. Afterwards, the copper and aluminium fraction go to a smelter to recover these metals (Thomassen et al., 2022). Finally, it is considered that the removed plastics are incinerated for energy recovery and that the remaining materials from the solar panel are landfilled. In addition to the solar panel recycling, the system of Reference 1 (IT7) must be expanded with the conventional solar grade silicon to enable a fair comparison. Carbothermic reduction of quartz followed by the Siemens process is considered (Méndez et al., 2021). When the amount of glass, copper and aluminium recovered by the innovation process in RESiLEX is higher than in conventional solar panel recycling, the system of this reference must be further expanded with the conventional production of these elements. This means that aluminium production from bauxite, copper extraction from copper ores and glass production from sand must be taken into account as well (Farjana et al., 2019; Hong et al., 2018; Vinci et al., 2019). The purity of all obtained materials in Scenario 1 and Reference 1 for IT7 must be the same. The conventional energy production must be complemented in Scenario 1 (IT7) as energy can be recovered from the combustion of the plastics in the reference. The energy mix for Europe will be assumed for this (European Commission, 2024). The functional unit for this assessment is defined as the recycling of 1 kg of solar panels at their end-of-life for the recovery of silicon (x kg), glass (a kg), copper (b kg), aluminium (c kg) and energy (z MJ) and the conventional production of silicon, glass, copper, aluminium and energy.

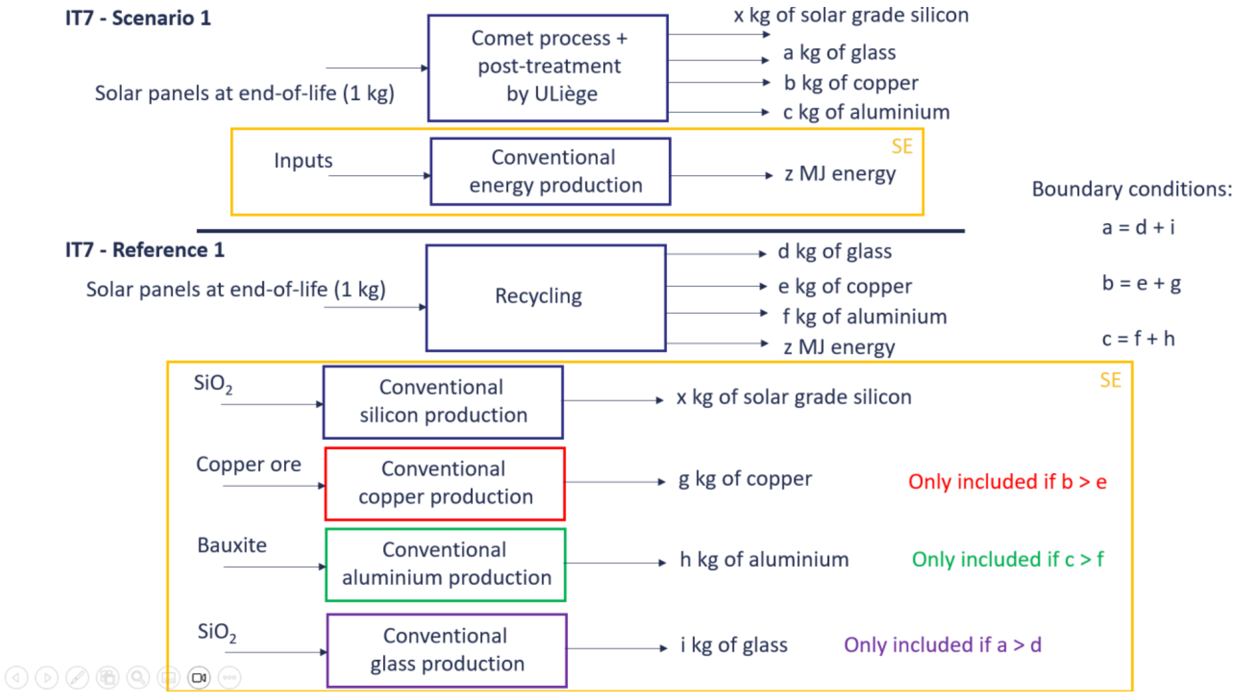


Figure 8. Representation of the LCA approach for the innovation in WP5. The boxes indicated in red, green and purple are only taken into account when the corresponding conditions are met. SE = system expansion.

4.1.7. Li-ion batteries production with recycled silicon in WP6

Finally, silicon is extracted from solar panels by Comet, and impurities such as glass and undesired metals are removed by ULiège (GeMMe) in WP5. This silicon stream is then further processed by another ULiège (GREEnMat) partner in WP6 to ensure its suitability as an anode active material for LIBs. The LCA for these work packages aims to assess the environmental impacts of Si/C composite material production using recycled silicon from EoL PV panels compared to graphite-based anode production and the conventional recycling of solar panels. The system boundaries will be determined by the amount of product obtained from the recycling process. To ensure a fair comparison, the output streams of the innovative technology must be the same that those of the reference case. For example, if more glass is recovered in the innovative recycling process than in conventional recycling, additional conventional glass production must be considered (this would also apply to Cu and Al). Additionally, since polymers are burnt to recover energy in the conventional recovery process, a system expansion must be included in Scenario 1 for IT8, by adding the conventional energy production. For this, the European energy mix will be considered (European Commission, 2024). The functional unit for this assessment is defined as the recycling of 1 kg of solar panels at their end-of-life for the recovery of silicon for the anode production (x kg), glass (a kg), metals (b kg) and energy (z MJ). This is illustrated in Figure 9.

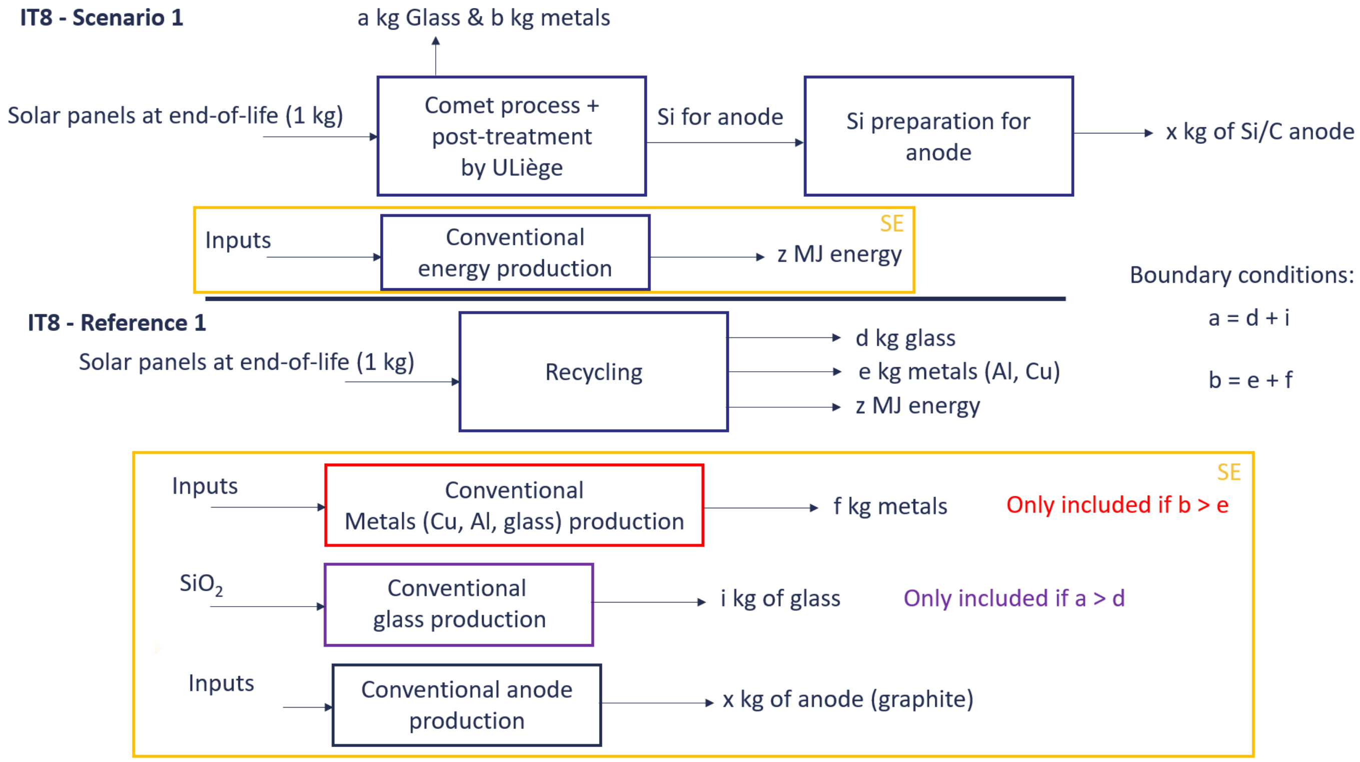


Figure 9. Illustration of LCA approach for innovations in WP6. The boxes indicated in red, green and purple are only taken into account when the corresponding conditions are met. SE = system expansion.

4.2. Results for LCA inventory for RESiLEX

4.2.1. Data collection in RESiLEX

To ensure the accurate and comprehensive collection of data for the LCA, a structured approach is followed when engaging with partner companies and research institutions. Initially, through meetings and a review of the deliverables, a preliminary sketch of the process flow is developed. This serves as a starting point to identify key aspects of the system, including the main inputs, outputs, and intermediate stages. Once this draft is in place, a dedicated meeting is scheduled with the company or research group to refine the flowsheet, addressing any inconsistencies or missing information. In parallel, a standardized data collection template is created and shared with the partner, allowing them to provide structured and relevant information regarding their processes.

A crucial step in this methodology is the on-site visit to the company or research facility. These visits provide valuable insights into the operational details of pilot plants, helping to ensure that all necessary data for the LCA are taken into account. Moreover, face-to-face discussions with partners enhance the understanding of the processes, allowing for the identification of any overlooked variables or system interactions. The visits also facilitate direct clarification of data-related uncertainties, minimizing potential discrepancies in the final assessment. After this stage, the collected information is compiled and used to complete the data collection template. If any gaps remain or discrepancies arise, additional meetings are arranged to finalize the dataset before proceeding with the mass and energy balance calculations. This process is illustrated in Figure 10.

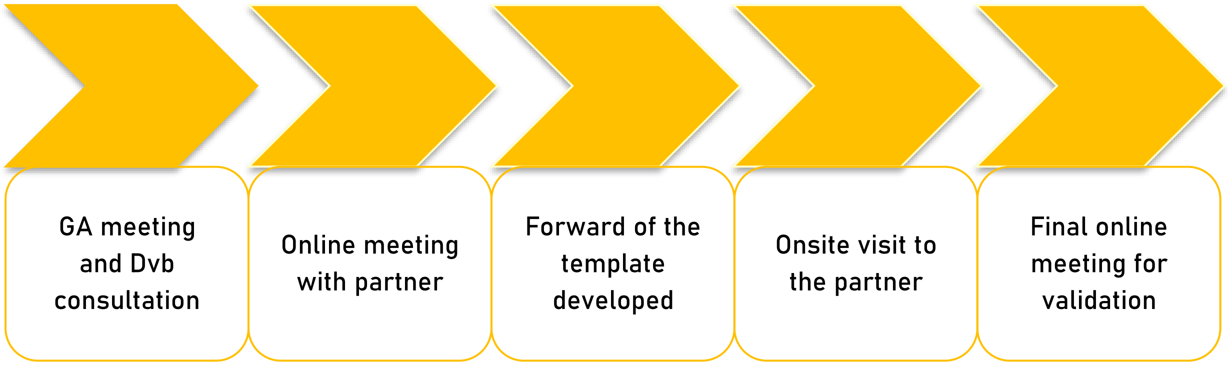


Figure 10. Process carried out for data collection in RESiLEX.

Several key partners have been engaged in this process so far. A visit to Cetaqua in Barcelona provided essential insights into the recovery treatment train, where data from the first unit of their pilot plant was collected. Additionally, at CEA, significant progress was made in obtaining information regarding the eco-design of photovoltaic modules and cells, a task that is nearly complete. NTNU in Trondheim was also visited to know the scale and processes that they were developing in the research center. On the other hand, the recycling of the PV panels is carried out by COMET, partner that was visited to learn the process from the collection of the PV panels to the further treatment to recover different materials and provide to another partner. During the general assembly (GA) in Neuchatel, we visited the pilot plant that CSEM has developed, seeing in live the manufacturing and testing of solar PV panels. Another visit was conducted at the University of Liège, specifically the GeMMe group, responsible for eliminating impurities from the silicon stream. The collaboration with this team has been key for obtaining the refining the dataset for this process. Furthermore, another unit at the University of Liège, the GreenMat group, was visited as well. Their role in WP6 involves developing a pouch cell battery that incorporates silicon as a replacement for graphite in the anode. During this visit, most of the required information was obtained, ensuring that the data collection for this part is nearly finalized.

4.2.2. Results of the data collection

Table 3 shows the plan for the data collection of all LCAs that will be performed in this project. The mass and energy balances for all innovations will be constructed by UGENT based on quantitative data obtained from the respective partners in the RESiLEX project. For the references, this information will be retrieved from literature and LCA databases such as ecoinvent and Agribalyse.

Table 3. Illustration of data collection for different innovations and their respective references.

Innovation technology		Data source for innovation	Considered production methods in scenarios and references	Data source for reference	Year
1	CRM recovery train	Cetaqua and Tharsis	Conventional yogurt/lactose production (IT 1)	Ecoinvent 3.10	2020
			Yogurt/lactose production from organic waste (IT 1)	Agribalyse 3	2020
			Not treatment (IT 1)	Not applicable	
			Conventional metal production (IT 1)	ZnS-Ecoinvent 3.10 CuS (Bibliography, pending)	2023
			Landfilling of mine waste (IT 1)	Ecoinvent 3.10	2023
2	Sustainable SG-Si production	NTNU	AlO production (IT 2)	Ecoinvent 3.10	2019
			Ammonium sulfate production (IT. 2)	Ecoinvent 3.10	2020
			Aluminium alloy production (IT. 2)	Ecoinvent 3.10	2014
			Solar grade silicon production (IT 2)	Ecoinvent 3.10	2023
			Conventional Si-kerf recycling (IT 2)	Blömeke et al. (2023)	2023
			Al-dross recycling (IT 2)	Vallejo Olivares et al. (2024)	2024
3	Crystalline nano-powder production	Nanopow	Conventional Si-kerf recycling (IT 3)	Blömeke et al. (2023)	2023
			Solar grade silicon production (IT 3)	Ecoinvent 3.10	2023
4	Si wafer production from revalorized Si wastes	CEA	To be confirmed	To be confirmed	
5	Eco-designed cells	CEA and CSEM	Reduction	Vallés, 2021	2021
			Refining	IEA PVPS report (Frischknecht, Stolz, Krebs, et al., 2020)	2020
			Cristallization	IEA PVPS report (Frischknecht, Stolz, Krebs, et al., 2020)	2020
			Slicing	IEA PVPS report (Frischknecht, Stolz, Krebs, et al., 2020)	2020
			Cell manufacturing	Roffeis et al., 2022 complemented with expert knowledge from CEA	2022

6	Eco-designed modules	CEA	Module production (reference and scenario a and b)	Expert knowledge from CEA, based on Roffeis et al. 2022	2022
7	Si recycling process	Comet and ULiège (GeMMe)	Conventional energy production (IT. 7)	European energy mix as specified in European Commission + Corresponding data sets from Ecoinvent 3.10	2024
			Conventional glass production (IT 7)	Ecoinvent 3.10	2010
			Solar panel recycling (IT 7)	Ansanelli et al. (2021)	2021
			Solar grade silicon production (IT 7)	Ecoinvent 3.10	2023
			Conventional copper production. Primary copper production (IT 7)	Ecoinvent 3.10	1994
			Conventional aluminium production (IT 7)	Ecoinvent 3.10	2018
8	Si composite for Li-ion batteries	ULiège (GREEnMat)	Conventional energy production (IT. 8)	European energy mix as specified in European Commission + Corresponding data sets from Ecoinvent 3.10	2024
			Conventional glass production (IT 8)	Ecoinvent 3.10	2010
			Solar panel recycling (IT 8)	Ansanelli et al. (2021)	2021
			Solar grade silicon production (IT 8)	Ecoinvent 3.10	2023
			Conventional copper production. Primary copper production (IT 8)	Ecoinvent 3.10	1994
			Conventional aluminium production (IT 8)	Ecoinvent 3.10	2018
			Conventional anode production (IT 8)	Econinvent 3.10	2021

4.3. Plan for impact assessment for RESiLEX

The environmental footprint method 3.1 is chosen being the recommended impact assessment method by the European Union (European Commission, 2021). Results for all impact categories will be calculated, however the main categories will be discussed in detail. The identification of the most relevant impact categories will be based on the standardised and weighted results (single score) of the environmental footprint. The ones that contribute the most to this aggregated score will be analysed more in detail at midpoint level. If necessary, additional impact categories are added to the discussion, looking at insights from literature.

4.4. Plan for interpretation for RESiLEX

A contribution analysis will be conducted for all innovations to identify the main hotspots in the production processes. Next, a sensitivity analysis can be performed if the uncertainty on some parameters in the LCA model is high.

5. Status of LCA for different innovations

Table 4 shows the status of the progress to perform to life cycle assessment for each innovative technology, from the selection of the reference case to the validation of results after the environmental assessment.

Table 4. Status of the innovation technologies in RESiLEX

Innovation technology		WP	Selection of reference case	Selection of Scenarios	Flowsheet developed	Flowsheet validated	Inventory	LCIA	Validated results
1	CRM recovery train	2	X	X	X	X			
2	Sustainable SG-Si production	3	X	X	X	X	X		
3	Crystalline nano-powder production	3	X	X					
4	Si wafers production	4							

	from revalorized Si wastes								
5	Eco-designed cells	4	X	X	X	X	X	(X)	
6	Eco-designed modules	4	X	X	X	X	(X)	(X)	
7	Si recycling process	5	X	X	X	X			
8	Si composite for Li-ion batteries	6	X	X	X	X			

Note: X marked between brackets indicates that part of the scenarios are analysed.

Considering the progressed status of the eco-designed cells and modules, first results are presented in this deliverable in the following section.

6. Life cycle assessment of the eco-designed cells and modules

The intermediate results for eco-designed cells and modules are presented in this section. The calculations are based on the data retrieved so far, while updates and further scenario assessment will be performed when experiments are in the next phase. In this deliverable, only the first scenario for the cell manufacturing is considered. Both module scenarios are analysed. The used data sources are mentioned in section 4.2.1. The data are coupled to ecoinvent 3.9 and the assessment is performed using the software SimaPro v9.5.

6.1. Environmental impact of the reference PV panel production

In this section, the impact of the production of one square meter SHJ module is discussed. In work package 4, the goal is not to evaluate the environmental impact of the entire value chain of PV modules in detail, but the focus is on cell and module. However, it does provide an idea of the contribution of cell production and module production to the total impact per FU. The reference production is taking place in Europe, according to the locations indicated in Figure 6.

6.1.1. Environmental footprint of the reference PV panel production

In Figure 11, the relative contribution of wafer production (including reduction, refining, crystallization and slicing), cell manufacturing and module production are presented. Using the approach of section 4.3, six impact categories are considered. The contribution of cell manufacturing to climate change is rather small (8%). The impact is relatively evenly distributed between wafer production (steps 1-4) and module production (step 6), with the latter contributing slightly more, i.e. 46% for both. This finding contrasts with the prevailing view in the literature, where wafer fabrication is generally reported as the most significant contributor to climate change impacts, rather than module production (Müller et al., 2021; Roffeis et al., 2022; Smith et al., 2024) However, several aspects should be taken into account. In this study, data for wafer production are based on (Pastor-Vallés, 2021) in which recent data is reported for the Norwegian solar-grade silicon production. Second, primary data for module production was obtained from the partners in the consortium. However, the smaller scale of module manufacturing compared to wafer fabrication can lead to inconsistencies compared to literature that typically uses more uniform data sets or focuses on a single scale throughout the study. For instance, Roffeis et al., (2022) based their assessment on process data from a high volume manufacturing line in Germany for cell and module manufacturing, while wafer data came from industrial sources in China. In contrast, Muller et al. (2021) analyzed locations in the EU, Germany, and China, with data on the electricity mix from China (2012) and Europe (2017). Their inventory is based on the (International Energy Agency, 2015) which represents large-scale industrial operations. Another factor to consider is that the studies may focus on a different location. This study considers wafer production in Europe, which has a much lower climate change impact than Chinese production, for instance (see next section).

The share of wafer production ranges between 73 up to 92% for the categories freshwater ecotoxicity and human toxicity, mainly due to the wastewater treatment, while it is only 35% for the category fossil resource use and even neglectable in resource use, minerals and metals. Conversely, 69% of the impact in the latter category can be attributed to cell manufacturing. Cell manufacturing is also responsible for a significant portion of the impact in the freshwater ecotoxicity and fossil resource use categories, namely 15 and 21%, respectively. In the human toxicity categories, the share of cell manufacturing is really small. Finally, module production is the main contributor, not only to climate change, but also to fossil resource use (44%), while this production also plays an important role in mineral and metal resource use (30%). The impact results of the module production are thoroughly discussed in section 6.3. The change in proportion shows the importance of taking into account different impact categories in the impact assessment and indicates as well the relevance to look for alternative developments to reduce the impact of cell and module production.

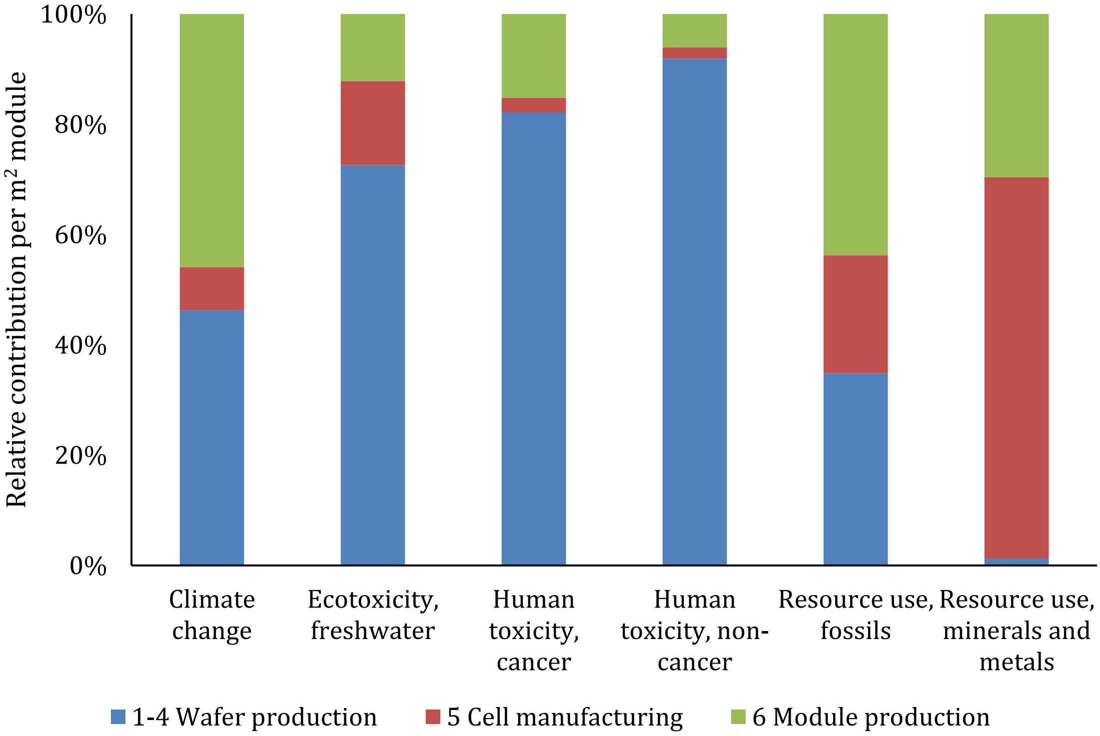


Figure 11 Relative contribution of the steps wafer production, cell manufacturing and module production to the environmental impacts of 1 m² SHJ module.

6.1.2. Carbon footprint of the reference PV panel production

Figure 12 presents the climate change impact of the different steps, i.e. reduction, refining, crystallization, slicing, cell manufacturing and module production, expressed in kg CO_2-eq per m² SHJ module. The total impact corresponds to 65.7 kg CO_2-eq per FU. Almost half of the impact is due to module production (46%). The second most contributing step is refining (28.0%), followed by cell manufacturing, crystallization and reduction with a share of 7.9, 7.3 and 6.5%, respectively. Slicing has only a minor impact of 2.9 kg CO_2-eq per FU (4.4%).

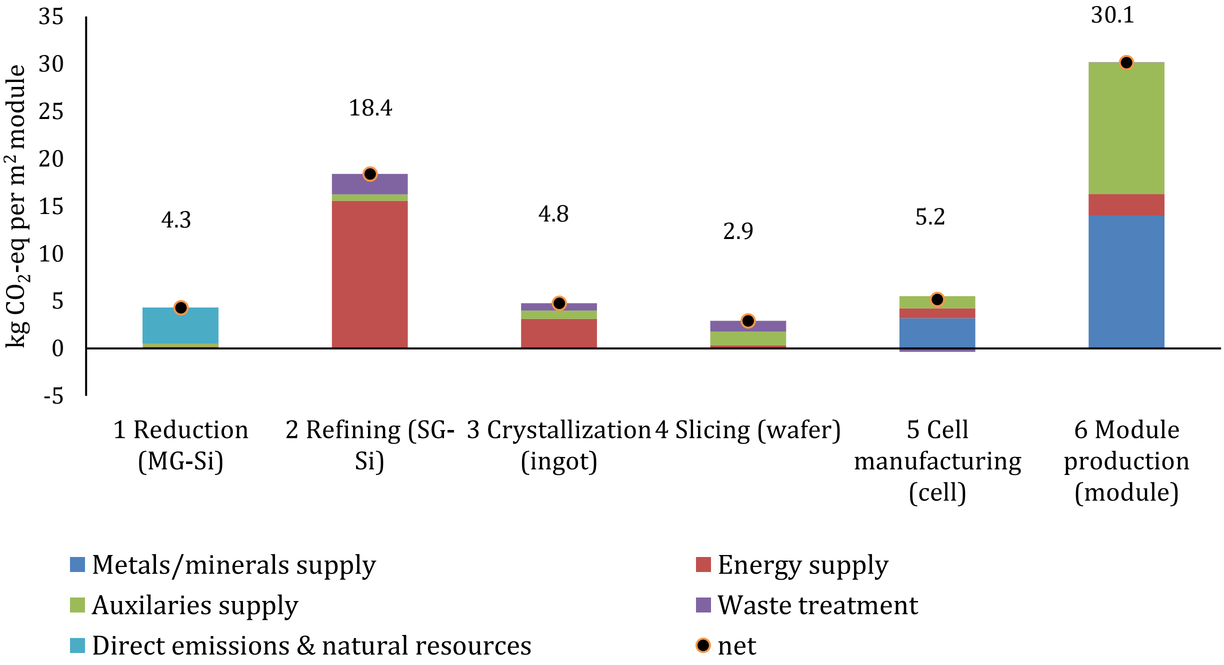


Figure 12 Climate change impact in kg CO_2-eq per step (step 1 - 4: reduction, refining, crystallization, slicing, cell manufacturing and module production) for 1 m² SHJ module.

In step 1 (reduction), the climate change impact is primarily due to direct greenhouse gas emissions. The reduction process, in which silica sand is converted into MG-Si, requires substantial use of carbon sources like hard coal and wood chips, which is unavoidable in a carbothermic process. The production of 1 kg of MG-Si generates 5.9 kg of CO_2-eq. These results are in line with those reported by (Nøstvold et al., 2025) which also considered the Norwegian production, while Chinese manufacturing would result in an approximately three times higher carbon footprint.

The climate change impact of step 2 (refining) is primarily due to the high energy requirements of this process, i.e. 91.8 MJ to produce 1 kg of solar grade silicon. Therefore, energy supply corresponds to a share of 85% of the impact. The waste treatment of used chemicals has a share of 12%, while the impact of the other groups is minimal. Also in step 3 (crystallization), the impact can be mainly attributed to energy supply. However, although energy use is also high (183.4 MJ per kg ingot), the Norwegian energy mix contributes less to climate change than the German market mix (i.e. 0.02 compared to 0.46 kg CO_2-eq per kWh) used for step 2 (see Figure 6) due to a higher share of renewable energy in Norway, so the absolute impact for step 3 is lower. Step 4 (slicing) exhibits the lowest climate change impact among the six steps. The impact is mainly due to the minimal contribution of auxiliary supplies, such as nitric acid consumption, compared to the energy-intensive processes of refining and crystallization or the direct emissions of reduction.

Cell manufacturing and module production will be discussed in detail in the following sections.

6.2. Comparison of the reference cell with an eco-designed alternative

6.2.1. Relative comparison of a reference and alternative cell manufacturing (step 5)

In this section, we are zooming in on step 5, cell manufacturing. Figure 13 displays the environmental impacts per m^2 SHJ module, i.e. the FU applied within the LCA of IT5 and IT6. Results are non-cumulative (so the wafer impact is not included) and shown for five The impact of scenario 1 (IT5) is expressed relative to the impact of the reference in each impact category. Results indicate a clear preference for scenario 1 over all considered impact categories. The largest percentage difference is found for mineral and metal resource use, namely 44%. Scenario 1 shows a reduction of 36% compared to the reference for human toxicity non-cancer. For climate change, freshwater ecotoxicity and fossil resource use, a decrease of approximately 30% is obtained. Finally, the smallest difference between both cases equals 19% for human toxicity, cancer. The reasons for the differences are discussed in the following sections.

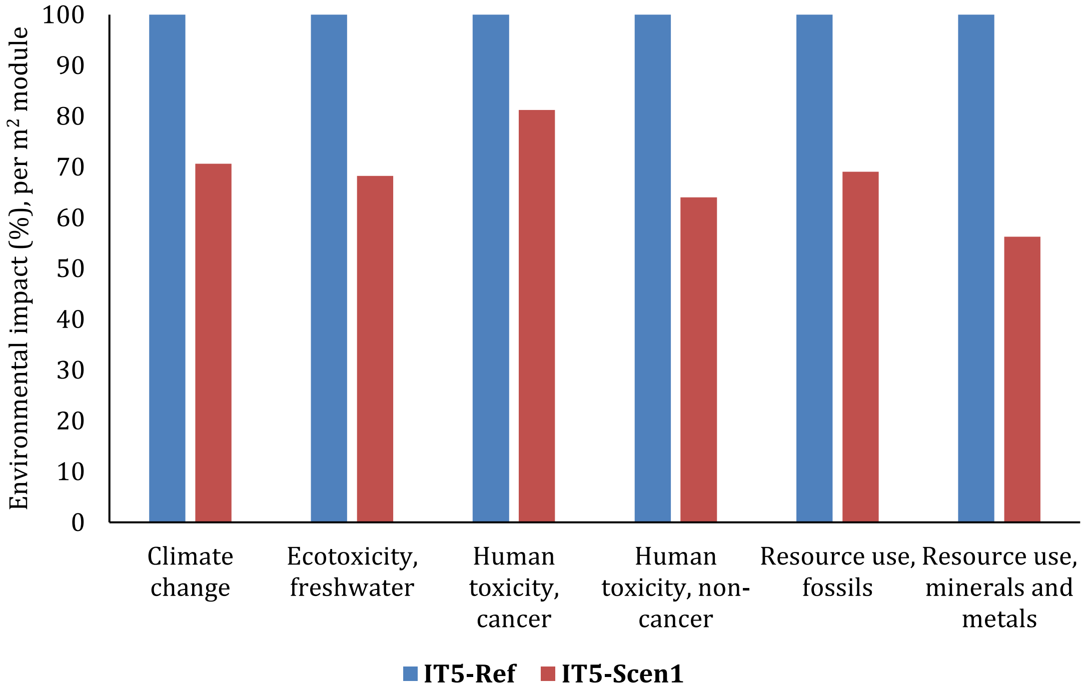


Figure 13 Environmental impact of the reference (IT5-Ref) and alternative cell manufacturing ((IT5-Scen1) for innovation technology 5 (IT5), expressed per 1 m² SHJ module. The impact of scenario IT5-Scen1 is expressed relative to the impact of the reference for each impact category.

6.2.2. Environmental impact of cell manufacturing (step 5) per impact category

Figure 14 provide a detailed view of the climate change impacts associated with the production of a 1 m² SHJ module, comparing the reference with the alternative scenario (IT5-Scenario 1) for cell manufacturing, in which less ITO and silver are used, requiring an additional step. The figures offer insights into the distribution of this impact across different groups and production steps. The total impact equals 5.2 and 3.6 kg CO_2-eq per FU for the reference and scenario 1, respectively. The main contributors to the reference are metal supply (62%), auxiliary supply (24%) and energy supply (20%). Regarding the manufacturing steps, step 3 is significant due to the extensive energy and auxiliary (66 and 30% contribution to the impact of TCO deposition, respectively). The former is due to high energy requirements for maintaining the deposition environment. The auxiliary supply involves substantial quantities of gases needed for deposition and maintaining a controlled atmosphere in the deposition chamber. Adopting alternative scenarios that can reduce the impact of those steps is therefore relevant.

The primary improvements are found in the metal and energy supply, related to manufacturing steps 3 and 4, as these are the only steps that changed between the reference and scenario 1. Replacing copper with silver leads to a considerable decrease in climate change impacts. Regarding TCO PVD, the use of reduced amounts of ITO results in a lower energy consumption, and to minor extent also a reduced impact of auxiliary supply (e.g. gas consumption of nitrogen etc.). While the contribution of the additional step to the overall climate change impact is not negligible, it is relatively minor when compared to the initial processes. Combining the insights of both figures, it is clear that silver reduction is responsible for the main reduction in impact of metal supply.

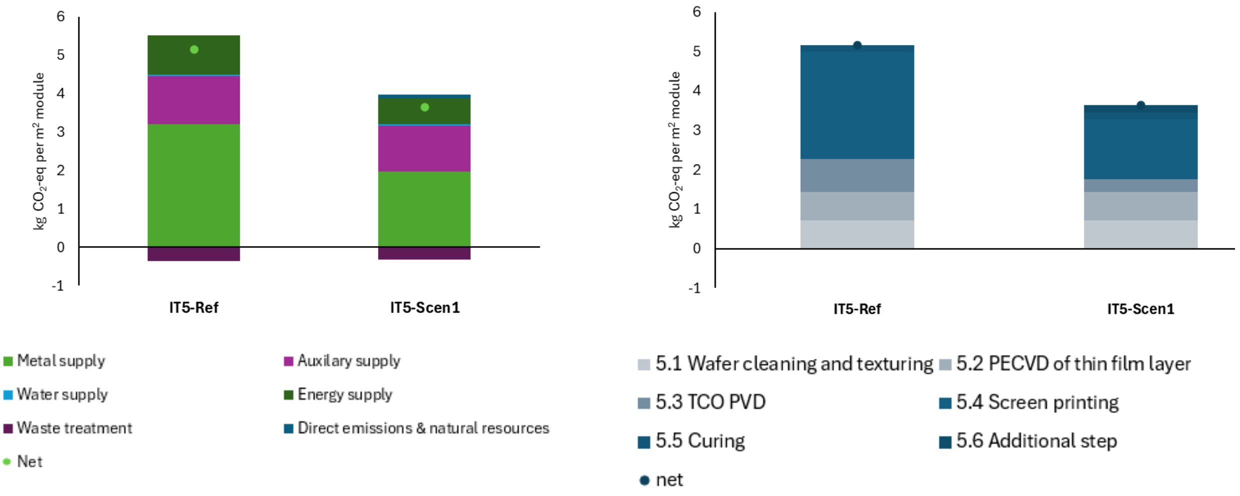


Figure 14. Impact on climate change of the manufacturing of the reference (IT5-reference) and scenario 1 (IT5-scenario 1) for innovation technology 5 (IT5), expressed per 1 m² SHJ module.

The impact on freshwater ecotoxicity is presented in Error! Reference source not found. and is equal to 322.5 and 220.1 CTUe for IT5-reference and IT5-scenario 1, respectively. The main contributions to the impact for cell processing come from metal supply (77% for the reference), waste treatment (13%), and from auxiliary supply (8%). The latter does not change significantly, while a strong reduction in impact of metal supply can be noticed for IT5-scenario 1. Clearly the impact primarily originate from step 4 (screen printing) and to a minor extent step 1 (wafer cleaning and texturing). Combining those insights shows that the reduction is mainly due to the substitution of part of the silver by copper. The increased impact of waste treatment in scenario 1 is caused by the additional step which implies an additional PV wastewater treatment, which has a high impact on freshwater ecotoxicity.

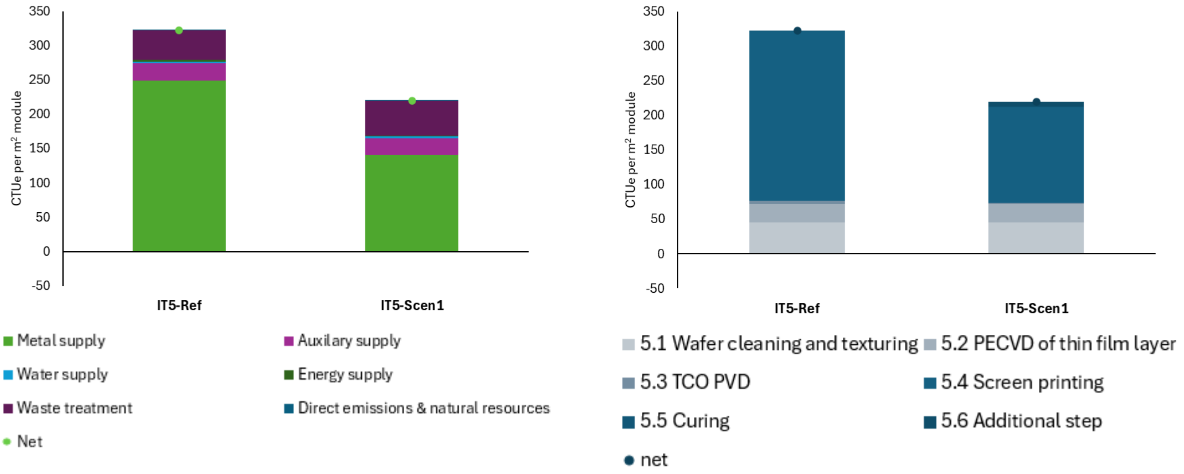


Figure 15. Impact on freshwater ecotoxicity of the manufacturing of the reference (IT5-reference) and scenario 1 (IT5-scenario 1) for innovation technology 5 (IT5), expressed per 1 m² SHJ module.

Figure 16 provides a detailed analysis of the human toxicity, cancer and non-cancer, impacts associated with the production of a 1 m² SHJ module for the reference cell and IT5-scenario 1, measured in Comparative Toxic Unit for humans (CTUh). Regarding both impact categories, the contribution of metal supply is predominant, linked to step 4 (screen printing). The reduction is therefore also linked to the reduction in silver consumption in the screen printing paste.

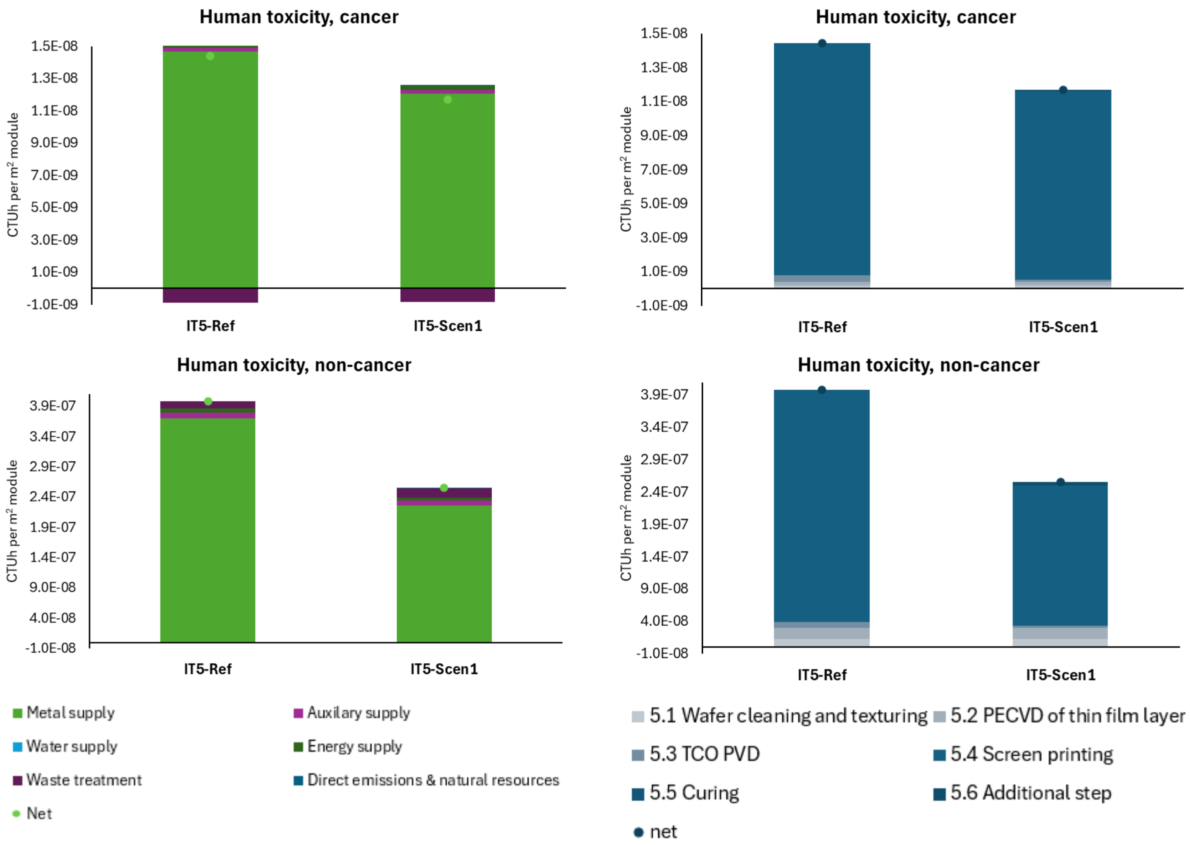


Figure 16. Impact on human toxicity, cancer and human toxicity, non-cancer of the manufacturing of the reference (IT5-reference) and scenario 1 (IT5-scenario 1) for innovation technology 5 (IT5), expressed per 1 m² SHJ module.

The impact on mineral and metal resource use is entirely linked to the metal supply, more specifically to the use of metals in step 4 (screen printing). The reduced use of silver results in a reduction of 44%. There are more aspects that contribute to the difference in the use of fossil resources between the reference (241.9 MJ) and IT5-scenario 1 (167.0 MJ). Energy supply (electricity and heat) now makes the greatest contribution to the impact of resource use (71 and 68% for reference and scenario 1, respectively). Metal supply is responsible for 17% of the impact for the reference and 15% for scenario 1. Auxiliary supply is the third main contributor, mainly due to the use of chemicals and gas, while the contribution of other groups is negligible. In the reference scenario, in descending order of contribution, there is step 3 (41%), step 4 (21%), step 1 (19%); step 2 (16%) while step 5 contributes only 3%. The different contributions of each step to the total impact more or less align with the energy consumption per step, when expressed per 1 m² SHJ module. However, the variations are due to the metal supply of silver. This explains why step 4, although not as energy intensive, still has a high impact. The lower impact of scenario 1 is also explained by the lower energy use in step 3 due to a thinner ITO layer and a lower silver consumption in step 4.

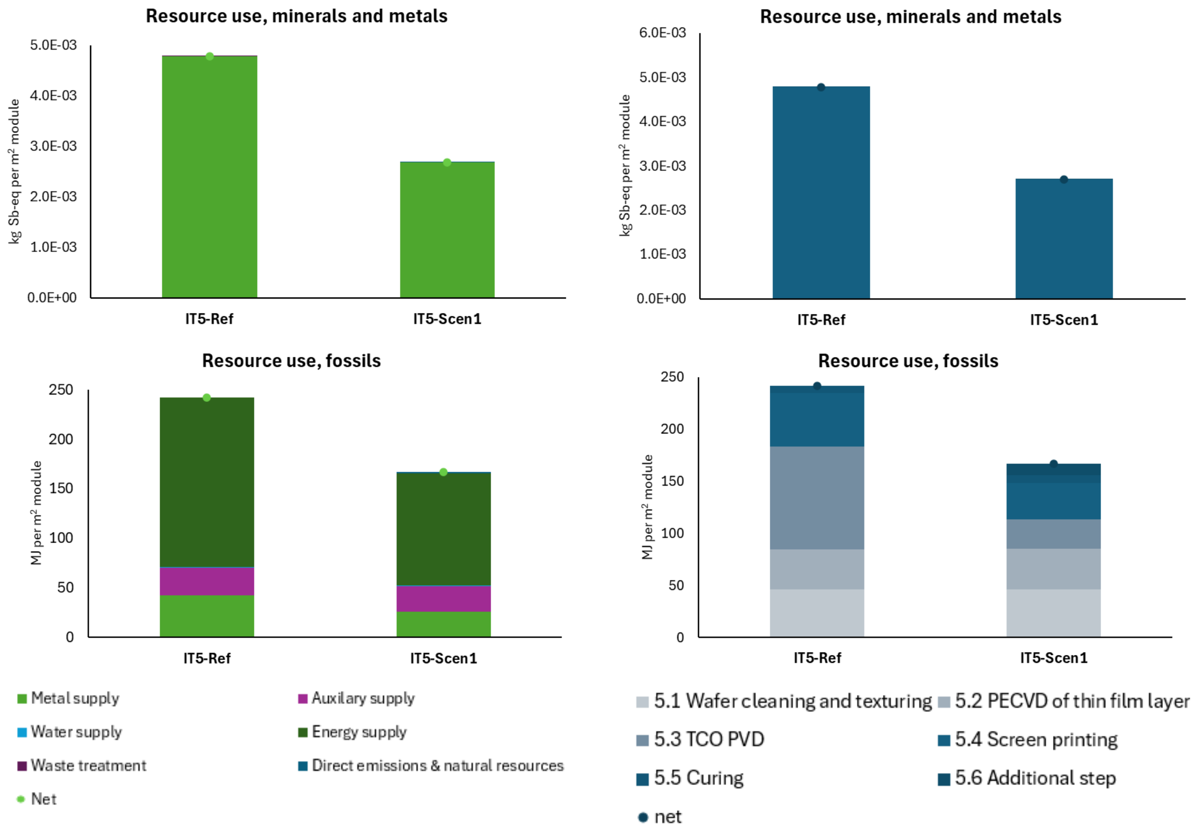


Figure 17. Impact on resource use, minerals and metals and resource use, fossils of the manufacturing of the reference (IT5-reference) and scenario 1 (IT5-scenario 1) for innovation technology 5 (IT5), expressed per 1 m² SHJ module

Reviewing the six considered impact categories reveals a consistent trend: opting for the alternative scenario reduces impacts compared to the reference. It is clear that the composition of the metallization paste plays a critical role, whereas reduction in TCO material has a smaller effect, although it still reduces energy and auxiliary supply.

6.3. Comparison of the reference module production step with two alternatives

The reference module step (IT6-reference) is compared with two alternatives. IT6-Scenario 1 contains copper wire and electrically conductive adhesive interconnections, a thin glass front- and backsheet, a thermoplastic polyolefin encapsulant and an aluminium frame. Scenario B includes copper wire and electrically conductive adhesive interconnections, a glass frontsheet, a fluorine-free PET backsheet, a thermoplastic polyolefin encapsulant, and a wood frame. Figure 18 shows the environmental impact for an SHJ module made in France (Figure 6). The impacts are expressed again relative to the reference scenario. Compared to the previous LCIA results, land use impacts are also included in the assessment, taking into account the effect of choosing a wood alternative for the frame.

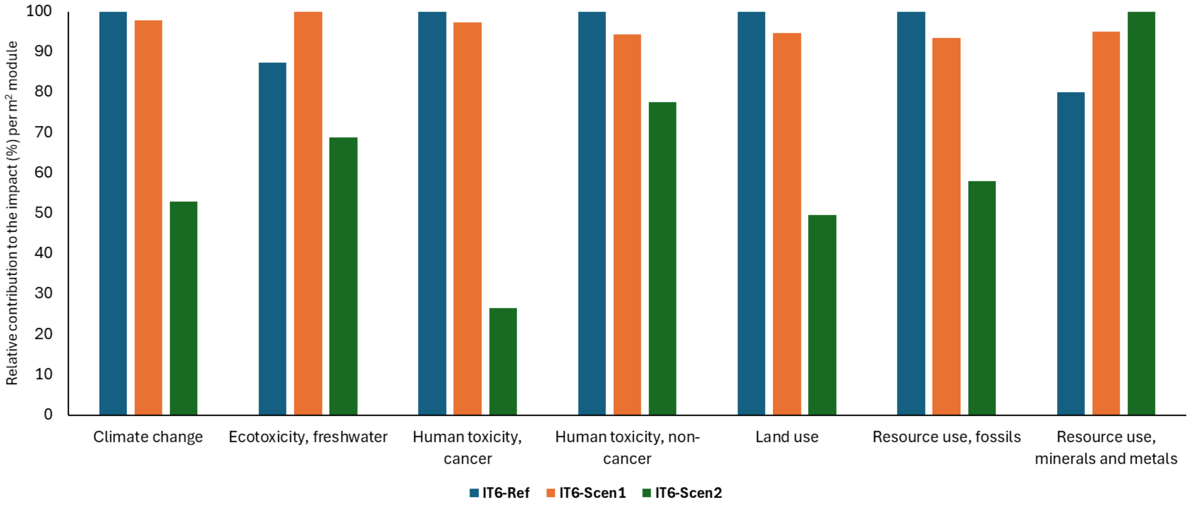


Figure 18: Environmental impact of the reference (IT6-Ref) and alternative scenarios for module (IT6-Scen1 and IT6-Scen2) for innovation technology 6 (IT6), expressed per 1 m² SHJ module. Impact is expressed in percentage relative to the maximum impact in each impact category.

A clear trend can be observed for climate change, human toxicity cancer and non-cancer, land use and fossil resource use, for which the base case always has the highest impact, followed by a slightly lower impact for IT6-Scenario 1 (94-98%). The lowest impact is for those categories noted for scenario 2. For freshwater ecotoxicity, IT6-Scenario 1 has the highest impact, while for resource use, minerals and metals, Scenario 2 is the least favorable. Results will explained per impact category by relying on Figure 19. In this figure, the results are combined according to the main components of a module along with lamination (energy use) and waste treatment of defective cells. However, the last two items are considered constant over the scenarios.

Figure 19 shows the key aspects that cause the change in climate change impacts between the scenarios. The reference scenario has the largest total impact (30.1 kg CO_2-eq), followed by IT6-Scenario 1 (29.5 kg CO_2-eq) and finally IT6-Scenario 2 with an impact of only 16.1 kg CO_2-eq, corresponding to a reduction of 2 and 46 % respectively compared to the reference. The frame has the highest impact for the reference and IT6-Scenario 1 (i.e. 44 and 45%). The sum of the impact of the front- and backsheet is similar in the two scenarios (around 40%), while the reduced amount of plastics used for the encapsulant is the main reason for the difference between these two cases. The other aspects (waste treatment, interconnections, junction boxes and lamination) have only a minor contribution to the total climate change impact.

With respect to IT6-Scenario 2, the frame is the main reason for the strong decline in impact, with a small contribution of 0.2 instead of 13.3 kg CO_2-eq. While the frontsheet is the same, aluminum is used in IT6-Scenario 2 for the backsheet, inducing a higher impact compared to the reference. Similar to scenario 1, scenario 2 uses less plastics for the encapsulant, which explains the lower impact compared to the reference. Although the share of interconnections to the total impact is minimal, there is a strong difference between the reference and scenario 2 due to the use of silver in the latter.

The differences in freshwater ecotoxicity impacts across the scenarios are less pronounced compared to other categories. Frontsheet and backsheet together have an impact of 93.2, 109.4 and 92.5 CTUe for the reference, IT6-Scenario 1 and 2, respectively, which indicates that these changes do not cause major differences in freshwater ecotoxicity impacts. The difference between the reference and IT6-Scenario 1 can mainly be attributed to the interconnections, more specifically to the use of silver. This is also reflected in the higher number of silver consumption and thus consequently higher impact of the interconnections in IT6-Scenario 2. Finally, the use of a wooden frame is clearly beneficial with respect to freshwater ecotoxicity.

Regarding human toxicity, cancer and non-cancer, the main reduction in impact for IT6-Scenario 2 is thanks to the wooden instead of aluminum frame. For human toxicity, cancer, the preference for IT6-Scenario 1 over the reference is mainly due to the encapsulant (reduced amount) and frontsheet (less glass), but impact reductions are very minimal. Considering IT6-Scenario 2, it is mainly the encapsulant, in addition to the frame, that are responsible for the reduced impact, while the backsheet (using some aluminum) counteracts this effect. With regard to human toxicity, non-cancer interconnections, mainly the copper use, are responsible for 75% of the impact of the reference and IT6-Scenario 1 and even up to 93% of the impact of IT6-Scenario 2. The contribution of the changes in the other components are minimal.

Similar trends for climate change and fossil resource use can be observed. However, lamination has a clear contribution in this impact category. Up to now, a similar energy consumption is assumed across the scenarios. The change in frame is the most remarkable change in impact. The sum of the impact of the front- and backsheet does not differentiate a lot across the cases, i.e. 147.8, 133.6 and 143.3 MJ for reference, IT6-Scenario 1 and 2, respectively. The avoidance of ethylvinylacetate explains the lower impact for the encapsulants in the scenarios. Finally, the contribution of junction boxes, interconnections and waste treatment is minimal.

Figure 19 shows that the impact of resource use (minerals and metals) is mainly driven by the interconnections. In the reference, copper consumption is responsible for 83% of the impact. The increasing amounts of silver throughout the scenarios used in the interconnections contribute considerably to the increase in impact for IT6-Scenarios 1 and 2 and do not compensate for the reduced use of solder bars and copper. Although the interconnections only make up about 1% of the total module weight compared to the aluminum frame (13% of the total weight in the reference and IT6-Scenario 1), the interconnections have a much greater impact. This emphasizes the significant environmental impact associated with the use of copper and silver.

Using wood instead of aluminium clearly affects the land use impacts. The wooden frame even accounts for 83% to the impacts on land use. This results in an almost three times higher impact for IT6-Scenario 2 compared to the reference. The production of wood plays a dominant role in the land use impacts, far greater than the contributions of other components. Although the use of solar glass in the frontsheet and copper in the interconnections also contribute to the land use impacts, these contributions are relatively small compared to the others. Similarly, the frame is the most important influencing component in the reference scenario and IT6-Scenario 1, namely 44 and 46%. The total impact on land use for these two cases is similar. This is because the reduction in the impact for the encapsulant and the frontsheet is counteracted by the increase in the impact of the backsheet in IT6-Scenario 1 compared to the reference.

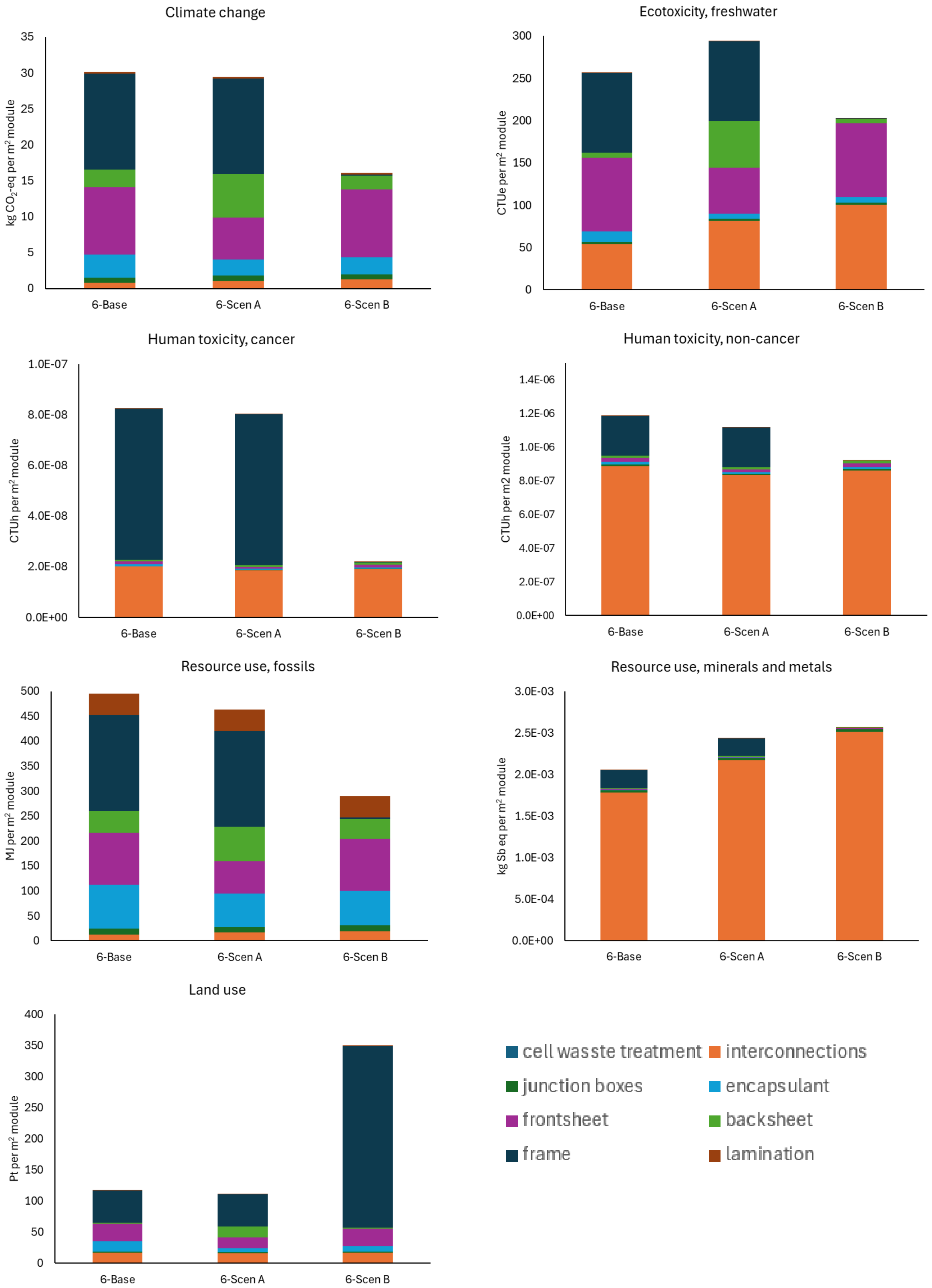


Figure 19. Environmental impact of module production for reference (IT6-Ref) and alternative scenarios (IT6-Scen1 and IT6-Scen2) for innovation technology 6 (IT6), expressed per 1 m² module production

For the impact categories climate change, fossil resource use, ecotoxicity, human toxicity-cancer and land use, the frame contributes significantly to the total impact of module assembly. This is primarily due to the use of aluminum. When aluminum is substituted with wood, the frame's contribution to the total impact becomes almost negligible across all categories except for land use. The wooden alternative thus emerges as a better option than aluminum for most impact categories, except for land use. For human toxicity, non-cancer and mineral and metal resource use, interconnections dominate the impact. Here, the use of silver does not appear to be favorable. The impact of front-and backsheets is particularly visible in the impact categories climate change, freshwater ecotoxicity and fossil resource use.

6.4. Next steps regarding environmental impact of eco-designed cells and modules

For future research, more scenarios for the cell will be considered. Updated information on the ongoing experiments may lead to small changes in the life cycle inventory and consequently affects the impact results for cell and module. However, this analysis already provides the researcher with some initial insights. A critical aspect is the fact that a cradle-to-gate analysis is used; the processing of PV module components at the end of the life cycle is not yet taken into account. The expansion of the system boundaries is needed for a complete picture. Furthermore, results are expressed per square meter of module, while often kWp is used in literature. When insights into efficiency across the scenarios is obtained, results will be expressed in this alternative functional unit. In addition, these impact categories contributing up to 80% of the impact at single score are considered at midpoint. However, it would be relevant to analyse the remaining impact categories as well. Finally, a criticality analysis can provide more insight into the effect of the use of critical raw materials. Combining the insights from the LCA and the criticality analysis will provide a broader picture of the environmental performance of the different cell and module scenarios.

7. Conclusions

This deliverable presents an interim comparative environmental sustainability assessment of the innovative technologies developed within the RESilEX project. The study highlights the importance of circularity in the silicon and PV industry, addressing critical challenges related to resource scarcity, energy consumption, and environmental impact.

Key innovations analyzed include the CRM recovery train, sustainable silicon production, crystalline nano-powder synthesis, eco-designed PV cells and modules, silicon recycling processes, and the integration of recovered silicon in Li-ion batteries. These technologies aim to reduce dependence on critical raw materials, improve resource efficiency, and lower environmental footprints across different stages of the value chain.

The LCA methodology has been applied to evaluate the environmental performance of these innovations. However, due to the early development stage of some technologies, the current analysis focuses primarily on the identification of the goal and scope of each innovation technology, as well as the WP4 innovations, specifically the eco-design of modules and cells.

The innovations evaluated seem promising, however, more scenarios must still be considered. The gained insights can be used to steer further experiments. Furthermore, it is important to note that the environmental performance of scenarios differ across impact categories. This indicates the need for a broad environmental sustainability assessment.

Future assessments will integrate additional data from ongoing pilot-scale experiments to refine impact evaluations and enhance the reliability of sustainability projections.

The project potentially emphasizes the need for sustainable production and recycling strategies to mitigate the environmental burden of silicon-based technologies. Establishing a closed-loop system for silicon recovery and reuse is crucial for increasing circularity in the PV sector. Additionally, improving the efficiency of metal extraction and refining processes can further contribute to resource conservation and emission reductions.

8. References

Al Zaabi, B., & Ghosh, A. (2024). Managing photovoltaic Waste: Sustainable solutions and global challenges. *Solar Energy*, *283*(May), 112985. https://doi.org/10.1016/j.solener.2024.112985

Ansanelli, G., Fiorentino, G., Tammaro, M., & Zucaro, A. (2021). A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels. *Applied Energy*, *290*(March), 116727. https://doi.org/10.1016/j.apenergy.2021.116727

Blömeke, S., Arafat, R., Yang, J., Mai, J., & Cerdas, F. (2023). ScienceDirect Environmental assessment of silicon kerf recycling and its benefits for applications in solar cells and Li-ion batteries. *Procedia CIRP*, *116*, 179–184. https://doi.org/10.1016/j.procir.2023.02.031

Crundwell, F. K., Moats, M. S., Robinson, T. G., Ramachandran, V., & Davenport, W. G. (2011). *Extractive Metallurgy of Nickel, Cobalt and Platinum-Group Metals*. Elsevier Ltd.

Dewulf, J., Bösch, M. E., De Meester, B., Van Der Vorst, G., Van Langenhove, H., Hellweg, S., & Huijbregts, M. A. J. (2007). Cumulative exergy extraction from the natural environment (CEENE): A comprehensive life cycle impact assessment method for resource accounting. *Environmental Science and Technology*, *41*(24), 8477–8483. https://doi.org/10.1021/es0711415

Elkington, J. M. (1997). *Brundtland Report*.

European Commission. (2013). Recommendation 2013/179/EU on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. *Official Journal of European Union*, *L 124*, 210.

European Commission. (2024). *EU enegy in Figures*. https://doi.org/10.2833/870216

Farjana, S. H., Huda, N., & Mahmud, M. A. P. (2019). Science of the Total Environment Impacts of aluminum production : A cradle to gate investigation using life-cycle assessment. *Science of the Total Environment*, *663*, 958–970. https://doi.org/10.1016/j.scitotenv.2019.01.400

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, *91*(1), 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Guinée, J. B., M, G., R., H., G, H., R, K., Oers, K. van de, Sleeswijk, W., S, S., H.A., U. de H., H., D. B., R., V. D., & M.A.J., H. (2002). Handbook on Life Cycle Assessment Operational Guide to the ISO Standards. In *Environmental Impact Assessment Review* (Vol. 7). https://doi.org/10.1016/s0195-9255(02)00101-4

Hauschild, M. Z., Goedkoop, M., Guinée, J., Heijungs, R., Huijbregts, M., Jolliet, O., Margni, M., De Schryver, A., Humbert, S., Laurent, A., Sala, S., & Pant, R. (2013). Identifying best existing practice for characterization modeling in life cycle impact assessment. *International Journal of Life Cycle Assessment*, *18*(3), 683–697. https://doi.org/10.1007/s11367-012-0489-5

Hong, J., Chen, Y., Liu, J., Ma, X., Qi, C., & Ye, L. (2018). *Life cycle assessment of copper* *production : a case study in China* (Vol. 23). The International Journal of Life Cycle Assessment.

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *International Journal of Life Cycle Assessment*, *22*(2), 138–147. https://doi.org/10.1007/s11367-016-1246-y

International Energy Agency. (2015). *Photovoltaic power systems programme*.

International Energy Agency. (2020). *Methodology Guidelines on Life Cycle Assessment of Photovoltaic 2020*.

International Energy Agency. (2023a). International Energy Agency (IEA) World Energy Outlook 2022. *Https://Www.Iea.Org/Reports/World-Energy-Outlook-2022/Executive-Summary*, 524. https://www.iea.org/reports/world-energy-outlook-2022

International Energy Agency. (2023b). Snapshot of Global PV Markets 2023 Task 1 Strategic PV Analysis and Outreach. *International Energy Agency Photovoltaic Power Systems Programme Iea*, 1–21. www.iea-pvps.org

International Energy Agency. (2023c). *World Energy Outlook 2023*. https://www.iea.org/news/the-energy-world-is-set-to-change-significantly-by-2030-based-on-today-s-policy-settings-alone

IPCC. (2023). Climate Change 2023. Synthesis Report. In *Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Vol. 13, Issue 3). https://doi.org/10.3390/atmos13030405

Kleijn, R., Peck, D., Sprecher, B., Nem Singh, J., Van der Voet, E., Isabella, O., & Huisman, R. (2024). Critical materials, green energy and geopolitics: a complex mix. In *Leiden Delft Erasmus Universities* (pp. 39–43). https://doi.org/10.59490/mg.92

Magdalena, R., Valero, A., & Calvo, G. (2023). Limit of recovery: How future evolution of ore grades could influence energy consumption and prices for Nickel, Cobalt, and PGMs. *Minerals Engineering*, *200*(May), 1–11. https://doi.org/10.1016/j.mineng.2023.108150

Maghraby, Y. R., Ibrahim, A. H., Tayel, A., Mohamed El-Said Azzazy, H., & Shoeib, T. (2025). Towards sustainability via recycling solar photovoltaic Panels, A review. *Solar Energy*, *285*(October 2024), 113085. https://doi.org/10.1016/j.solener.2024.113085

Méndez, L., Forniés, E., Garrain, D., Pérez, A., Souto, A., & Vlasenko, T. (2021). Science of the Total Environment Upgraded metallurgical grade silicon and polysilicon for solar electricity production : A comparative life cycle assessment. *Science of the Total Environment Journal*, *789*(147969), 1–12. https://doi.org/10.1016/j.scitotenv.2021.147969

Moore, J. J. (1990). Chemical Metallurgy (Second Edition). In *Butterworth & Co. Ltd.* (Issue June).

Motte, J., Nachtergaele, P., Mahmoud, M., Vleeming, H., Thybaut, J. W., Poissonnier, J., & Dewulf, J. (2023). Towards alternative solutions for flaring: Life cycle assessment and carbon substance flow analysis of associated gas conversion into

C3 chemicals. *Journal of Cleaner Production*, *414*(March), 137742. https://doi.org/10.1016/j.jclepro.2023.137742

Müller, A., Friedrich, L., Reichel, C., Herceg, S., Mittag, M., & Neuhaus, D. H. (2021). Solar Energy Materials and Solar Cells A comparative life cycle assessment of silicon PV modules : Impact of module design , manufacturing location and inventory. *Solar Energy Materials and Solar Cells*, *230*(July), 111277. https://doi.org/10.1016/j.solmat.2021.111277

Nayak, S., & Charan Sabat, K. (2009). Principles of extractive metallurgy. *Department of Metallurgical and Materials Engineering. Parala Maharaja Engineerin College, Berhampur, 3rd semest*(Lectures note), 98. https://doi.org/10.1201/9780203742112

Nøstvold, C., Pastor, E., Vegar, V., Gabriella, A., Johan, T., & Pettersen, B. (2025). Life Cycle Assessment of Metallurgical Grade Silicon Comparing Charge Mixtures and Yields. *Journal of Sustainable Metallurgy*, *11*(1), 436–455. https://doi.org/10.1007/s40831-024-00941-z

Pastor-Vallés, E. (2021). *Life Cycle Assessment of silicon metal by aluminothermic reduction : an industrial symbiosis approach* (Issue June).

Pelletier, N., Allacker, K., Manfredi, S., Chomkhamsri, K., & Souza, D. M. da. (2013). Organisation Environmental Footprint Guide. *European Commission-Joint Research Centre-Institute for Environment and Sustainability*, *56*, 216. http://ec.europa.eu/environment/eussd/pdf/footprint/OEF Guide_final_July 2012_clean version.pdf

Preet, S., & Smith, S. T. (2024). A comprehensive review on the recycling technology of silicon based photovoltaic solar panels: Challenges and future outlook. *Journal of Cleaner Production*, *448*(March), 141661. https://doi.org/10.1016/j.jclepro.2024.141661

Roffeis, M., Kirner, S., Goldschmidt, J., Stannowski, B., Miranda, L., Case, C., & Fnkbeiner, M. (2022). New insights into the environmental performance of perovskite-on-silicon tandem solar cells – a life cycle assessment of industrially manufactured modules. *Sustainable Energy & Fuels*, *6*, 2924–2940. https://doi.org/10.1039/d2se00096b

Sinclair, R. J. (2005). The Extractive Metallurgy of Zinc. *The Australasian Institute of Mining and Metallurgy*, *13*, 297.

Smith, B. L., Sekar, A., Mirletz, H., Heath, G., Margolis, R., Smith, B. L., Sekar, A., Mirletz, H., Heath, G., & Margolis, R. (2024). *An Updated Life Cycle Assessment of Utility-Scale Solar Photovoltaic Systems Installed in the United States An Updated Life Cycle Assessment of Utility-Scale Solar Photovoltaic Systems Installed in the United States* (Issue March).

Thomassen, G., Dewulf, J., & Passel, S. Van. (2022). Resources , Conservation & Recycling Prospective material and substance flow analysis of the end-of-life phase of crystalline silicon-based PV modules. *Resources, Conservation & Recycling*, *176*(October 2021), 105917. https://doi.org/10.1016/j.resconrec.2021.105917

Valero, A., & Valero, A. (2014). *Thanatia: the destiny of the Earth's mineral resources*. World Scientific Publishing.

Vallejo Olivares, A., Pastor-Vallés, E., Pettersen, J. B., & Tranell, G. (2024). LCA of recycling aluminium incineration bottom ash, dross and shavings in a rotary furnace and environmental benefits of salt-slag valorisation. *Waste Management*, *182*(March), 11–20. https://doi.org/10.1016/j.wasman.2024.04.023

Vinci, G., Ascenzo, F. D., Esposito, A., Musarra, M., Rapa, M., & Rocchi, A. (2019). A sustainable innovation in the Italian glass production : LCA and Eco- Care matrix evaluation. *Journal of Cleaner Production*, *223*, 587–595. https://doi.org/10.1016/j.jclepro.2019.03.124

Vorst, G. Van Der, Swart, P., Aelterman, W., Brecht, A. Van, Graauwmans, E., Langenhove, H. Van, & Dewulf, J. (2010). Resource consumption of pharmaceutical waste solvent valorization alternatives. *Resources, Conservation and Recycling*, *54*(12), 1386–1392. https://doi.org/10.1016/j.resconrec.2010.05.014

Yi, K., Liu, D., Chen, X., Yang, J., Wei, D., Liu, Y., & Wei, D. (2021). Plasma-Enhanced Chemical Vapor Deposition of Two-Dimensional Materials for Applications. *Actions of Chemical Research*, *54*, 1011–1022. https://doi.org/10.1021/acs.accounts.0c00757

Zarmai, M. T., Ekere, N. N., Oduoza, C. F., & Amalu, E. H. (2015). A review of interconnection technologies for improved crystalline silicon solar cell photovoltaic module assembly. *Applied Energy*, *154*, 173–182. https://doi.org/10.1016/j.apenergy.2015.04.120

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