HORIZON EUROPE PROGRAMME
HORIZON-CL5-2023-D3-02-11

GA No. 101147275

Silicon solar cells with Low Environmental footprint and Advanced interfaces

SiLEAN - Deliverable report

D6.2 – Initial evaluation of safety of supply

Funded by
the European Union

Deliverable No.	D6.2	
Related WP	WP 6	
Deliverable Title	Initial evaluation of safety of supply	
Deliverable Date	2025-06-30	
Deliverable Type	REPORT	
Dissemination level	Public (PU)	
Author(s)	Mohammad Abdelbaky (TUD) Malte Vogt (TUD), Olindo Isabella (TUD)	2025-05-14
Checked by	Malte Vogt (TUD)	2025-05-14
Reviewed by	Giulia Aprilini (3SUN) Giuliana Giuliano (3SUN)	2025-06-11
Approved by	Karsten Bittkau (FZJ) - Project Coordinator	2025-06-30
Status	Final	2025-06-30

Document History

Version	Date	Editing done by	Remarks
V1.0	2025-05-14		
V1.1	2025-05-15	Karsten Bittkau	Small language changes
V1.2	2025-06-11	Giulia Aprilini; Giuliana Giuliano	Minor clarifications and added supply chain risk and policy context; minor changes and suggestions
V2.0	2025-06-23	Mohammad Abdelbaky; Malte Vogt	
V2.1	2025-06-24	Valerie Depauw; Giuliano Vescovi	Minor changes and suggestions
V3.0	2025-06-26	Mohammad Abdelbaky	
FINAL	2025-06-30	Mohammad Abdelbaky	

Project Scientific Abstract

The SiLEAN project deals with the development of advanced innovations to tackle the major drawbacks of silicon heterojunction solar cell technology, namely the high energy and material demand for Si wafer manufacturing, limited current generation, and the consumption of scarce materials like silver, bismuth and indium. Within the scope of the project, we will directly grow the wafers from the gas phase, apply alternative passivation concepts that show higher optical transparency, develop indium-free contact layers and apply silver and bismuth-free metallization with all-in-one cell interconnection and encapsulation. The project aims to achieve >25.5% solar cell efficiency and >23.5% module efficiency with 50% lower costs for Si wafers and contacting, as well as up to 75% lower carbon footprint. All processes applied allow upscaling to larger sizes as well as high manufacturing throughput. Eventually, the developments of SiLEAN will pave the way for a new, lean, generation of heterojunction solar cell technology that will both increment the energy conversion efficiency and unlock production at terawatt-scale.

Public summary

The SiLEAN project is developing the next generation of silicon heterojunction solar cell technology that is more efficient and contains significantly less critical raw materials. By substituting energy-intensive commercial silicon wafers with NexWafe epitaxially grown ones and eliminating the use of silver and indium in cell manufacturing, the SiLEAN technology will enable a more resilient, supply secure, and sustainable photovoltaic (PV) value chain in Europe.

In this report, TUD assessed the raw materials used in the production of PV modules for potential supply risks and importance to the European economy using a hybrid criticality assessment method. The results of the criticality assessment show that indium, bismuth, and refined silicon metal are among the PV raw materials with high supply risks. These risks are attributed to the concentration in a few geographical regions of mine production, global reserves, and refining operations, increasing Europe's vulnerability to potential trade restrictions and geopolitical uncertainties in these regions. Furthermore, aluminium and indium are among the PV raw materials with high importance to the European economy because of their high demand from key end-use sectors and the sensitivity of their market prices to supply-demand imbalances. Silica sand, in particular, is strategically important to the PV value chain because it is the primary component of solar glass and because of the absence of alternative glass network formers that are both performing and economically appealing.

At the technology level, the resource-use criticality of the SiLEAN technology is benchmarked against other commercial PV technologies by comparing their respective bills of materials, with criticality expressed in kilograms of silicon equivalent per kilowatt-peak. The SiLEAN technology demonstrates a resource-use criticality of 5.2 kilograms of silicon equivalent, which represents a nearly 80% reduction in resource-use criticality when compared to state-of-the-art silicon heterojunction cells. This decrease is primarily caused by the replacement of indium and silver with more abundant performing materials, namely zinc and copper. Moreover, an elasticity-based sensitivity analysis determined improvements in cell efficiency, reductions in wafer thickness, and the use of bismuth-free solder alloys as key parameters to reducing the total resource-use criticality of PV technologies.

Contents

List of Figures

List of Tables

Abbreviations

Abbreviation	Explanation
Al	aluminium
Ag	silver
Bi	bismuth
CF	Characterization factor
Cu	copper
Cz	Czochralski-grown silicon wafer
DTT	Distance-to-target
EoL	end-of-life
EoL RR	End of Life recycling rate
EoL RIR	End of Life recycling input rate
eq.	equivalent
ESP	The Economic resource Scarcity Potential method
EU	European Union
ESSENZ	The criticality assessment for the integrated method to assess resource efficiency
HHI	The Herfindahl-Hirschman Index
IEA	The International Energy Agency
In	indium
ITO	Indium Tin Oxide
ITRPV	International Technology Roadmap for Photovoltaics
MMCD	The Methodology of Metal Criticality Determination
NACE	Classification of economic activities- **N**omenclature statistique des **A**ctivités économiques dans la **C**ommunauté **E**uropéenne
OECD	The Organisation for Economic Co-operation and Development
Pb	lead
PV	Solar photovoltaic
PVPS	Photovoltaic power systems program
RoHS	Restriction of Hazardous Substances
SHJ	Silicon heterojunction
Si metal	metallurgical grade silicon
Sn	tin
TOPCON	Tunnel Oxide Passivated Contact
UK	The United Kingdom
US	The United States
USGS	The United States Geological Survey
WGI	Worldwide Governance Indicators
Zn	zinc

1 Introduction

Solar photovoltaic (PV) technology is widely recognised as a low-cost, low-emission alternative to fossil fuel-based electricity generation. According to the latest assessment by the International Energy Agency (IEA) photovoltaic power systems program (PVPS) Task 12, The average carbon emissions associated with generating 1 kWh of electricity from mono-crystalline PV systems in 2023 were estimated at 35.8 g CO_2 equivalent (eq.), in contrast to 1 kg CO_2 eq. per kWh for fossil fuel-based energy sources [1]. These emission figures consider the full life cycle of PV systems, including raw material extraction, manufacturing, operation, and end-of-life management. Furthermore, 75% of newly commissioned wind and PV power plants deliver electricity at a lower cost than existing fossil fuel-based counterparts [2]. In addition to their deployment in the energy sector, PV is anticipated to play an important role in the electrification of heating systems, including applications such as solar-assisted heat pump systems, and electrification of transportation, including vehicle-to-grid applications [3], [4].

The exponential growth in demand for PV systems will likely contribute to a corresponding increase in manufacturing and installed generation capacity. According to the IEA's Net Zero Emissions by 2050 Scenario and IRENA's 1.5 °C Scenario, global installed PV generation capacity is projected to increase by at least a factor of ten between 2023 and 2050, reaching 20 TWp by 2050 [5], [6]. In contrast, the study by Bogdanov et al. projected 63 TWp of installed capacity by 2050 [3]. This higher projection reflects the assumption that 89% of total primary energy demand will be electrified by 2050, including electricity-based technologies for applications such as water desalination. As a consequence, future annual demand for raw materials may significantly increase by a factor of 2–20 [7].

Beyond the anticipated increase in raw material demand, the criticality of these materials poses an additional challenge to scaling up PV manufacturing and deployment at the terawatt scale. At the cell level, raw materials such as solar-grade silicon, indium, silver, and aluminium are required for wafer production, coating materials and metallization pastes. At the module level, additional raw materials, such as aluminium, silica sand, copper, tin, bismuth and lead, are required for manufacturing components such as the module frame, glass, cell interconnections, and solder joints. Among these materials, silicon and bismuth are classified as critical raw materials in several regions, including the European Union (EU), the United States (US), and the United Kingdom (UK) [8]. The remaining materials are also considered as critical or strategic in several regions/countries, though there is less agreement on their classification.

Given the relatively long operational lifetime of PV installations, closed-loop recycling is projected to meet only 10 to 30% of future raw material demand until 2050 [7], [9]. Therefore, primary production will continue to play an important role in meeting raw material demand for the next two decades. Moreover, supply vulnerability factors such as trade restrictions, and concentration of mine production and geological reserves will remain relevant to the PV industry. In this context, multidimensional resource-use criticality assessments can effectively identify critical raw materials and assist in the optimisation of the bill of materials in emerging technologies by quantifying the benefits of resource efficiency and substitution during the design phase. Such assessments can also help to prioritise technical performance criteria that reduce resource-use criticality prior to large-scale production.

The SiLEAN consortium has strong ambitions to develop the next generation of silicon heterojunction (SHJ) solar cells with low-cost low energy manufacturing process, lower life cycle environmental footprint, and higher efficiency than commercial cells. More importantly, the consortium seeks to achieve these targets with indium-free contact layers, silver-free metallization, and bismuth-free interconnections. As such, assessing the resource-use criticality of SiLEAN solar cells and benchmarking them against other novel and commercial technologies can support efforts to minimise supply risks and position SiLEAN as a key enabler for terawatt-scale PV deployment.

In this deliverable, TUD builds on existing raw material criticality assessment methods by developing a revised method that includes a relevant set of indicators for assessing the supply risk of raw materials used in PV cells. Second, TUD uses this method to assess the resource criticality of SiLEAN solar cells. Third, TUD develops a representative bill of materials for SiLEAN cells based on the modelling work of SiLEAN project partner PVW in Task 6.1. Literature studies are also used to develop representative bills of materials for other commercial and emerging PV cell technologies. Finally, the criticality assessment results will then be used to compare across technologies, with a sensitivity analysis to identify key influencing factors.

The methodology presented in the coming sections of this deliverable and its result address the supply vulnerability factors mentioned in Task 6.2 of the project proposal and can be directly exploited by project partners in the technical work packages to achieve objectives 3 and 5 of this project. For the upcoming deliverable D6.4 on the final valuation of safety of supply, TUD will extend this work by implementing a dynamic criticality assessment that incorporates temporal variations in reserves, mine production, and geopolitical risk, in function of projected developments in mining and processing infrastructure. **Furthermore, accurately quantifying the criticality impacts associated with epitaxially grown wafers requires advanced modelling of the silicon supply chain to distinguish between different grades of refined silicon feedstocks. In particular, the epitaxial wafer production relies on the same purified chlorosilane gas as used in polysilicon production - the feedstock for Czochralski ingots of which the wafers are sawn. These latter feedstocks (polysilicon and ingots/wafers) are associated with higher degrees of production concentration and, consequently, greater supply risks.**

2 Methods and core part of the report

2.1 Background

The study by Ioannidou et al. attributed the emergence of resource-use criticality assessment methods to the ratification of national and international climate change mitigation policies [10]. These policies have accelerated the deployment of low-carbon technologies, which lead to a sharp increase in demand for certain metals classified as "critical," putting significant pressure on their supply chains. Earlier, resource vulnerability was primarily assessed using methods based on the reserves-to-production ratio [11], increased extraction energy due to declining ore grades [12], thermodynamic approaches such as cumulative exergy demand [13], and economic indicators [14]. As Ioannidou et al. pointed out, these earlier methods focused mainly on geological availability, without considering broader geopolitical and market-related risks such as supply concentration or restrictive trade policies [10].

Studies using the supply risk and economic importance two-dimensional approach for evaluating resource-use criticality date back to as early as 2008 [15]. Since then, a growing number of criticality assessment studies have been published, with Schiho and Espinoza identifying at least 23 unique methods in the literature [16]. The main differences among these methods lie in the number of dimensions considered (typically two, supply risk and economic importance, or three, with the third often capturing social or environmental aspects), the geographic scope (national or regional), and the level of analysis (sectoral, product-specific, or company-level).

However, to provide a more balanced perspective, the study by Renner and Wellmer argues that the raw materials market is predominantly a buyers' market, in which price dynamics and volatility are primarily demand-driven, rather than the result of supply-side constraints [17]. According to their analysis, high country concentration or poor governance does not necessarily result in significant or lasting disruptions to market equilibrium. Furthermore, short-term imbalances are neutralized by a dynamic reaction on the demand side via substitution, efficiency gains or technological change. Consequently, they propose the use of price volatility as a key indicator and recommend that policy efforts should prioritise managing demand-side fluctuations over addressing supply risks alone.

2.2 Procedures

This study presents a hybrid criticality assessment method that combines elements from several established methods in the literature, rather than applying a single method in its entirety. The foundation of the criticality assessment follows the Economic Scarcity Potential (ESP) method, particularly its two-dimensional classification of criticality based on supply risk and economic importance [18]. However, the aggregation approach used in ESP is not considered due to its tendency to produce significantly high criticality scores. Indeed, the study's authors chose to aggregate impact factors using multiplication, while recognizing that "*a summation of factors would lead to the same ranking, but the relative differences in results would be smaller*." [18]

Instead, the aggregation and normalization approach from the criticality assessment for the integrated method to assess resource efficiency (ESSENZ) method is adopted, as it calculates the relative distance to targets (DTT) normalized by annual primary production [19]. In addition, the ESSENZ method considers more dimensions of criticality such as societal acceptance and environmental impacts, which, though conceptually relevant, are considered excessive for the scope of this initial study and are thus excluded. Moreover, selected impact categories from the criticality assessment method of the European Commission are incorporated to add European relevance to this study. However, their aggregation formula is not used, as it is rigidly structured around a fixed set of impact categories and cannot be easily adapted to a hybrid approach without substantial revision.

This study considers ten raw materials in the assessment: aluminium (Al), bismuth (Bi), copper (Cu), indium (In), lead (Pb), silica sand, **metallurgical grade silicon** (Si metal), silver (Ag), tin (Sn), and zinc (Zn). **Given the high-level nature of the analysis, the study does not model the precise raw material inputs used in each stage of PV manufacturing. Instead, it relies on publicly available sources, such as the United States Geological Survey (USGS) and the European Commission's critical raw materials reports, to approximate supply characteristics and sector relevance for the analysed raw materials.** Molybdenum is excluded from the current assessment as it is present only in trace amounts, and its limited contribution does not justify the additional effort required for a detailed criticality evaluation. However, it may be included in the final study to ensure completeness of the results. The assessment of supply risk criticality is based on seven of the nine impact categories used in the original ESP study [18], as listed in Table 2.1. Company concentration of mine production is eliminated from the assessment due to the absence of relevant data. Additionally, the human development index is not included in any of the most recent criticality assessment methods, including the successor ESSENZ method, possibly due to its significant overlap with more direct governance-related indicators, and thus it is excluded from this study.

To address end-of-life (EoL) management and the limitations of current recycling technologies, the End-of-Life Recycling Rate (EoL RR) is introduced as an additional supply risk indicator to evaluate the contribution of recycling inefficiencies. Multiple impact categories are also introduced to add European relevance to this study. First, a distinction is made between the supply of raw materials at the extraction stage (mined materials) and at the refining stage (processed materials), in line with the criticality assessment method of the European Commission [20]. Furthermore, the country concentration of both mined and refined materials is evaluated in relation to EU sourcing, and governance stability is also evaluated in terms of the share of the country supply in EU sourcing of mined and processed materials, rather than global averages.

The Herfindahl-Hirschman Index (HHI) is used to evaluate country concentration of production and reserves and is calculated using the formula shown below.

$$HHI = s_1^2 + s_2^2 + s_3^s + \cdots + s_n^2 \quad (1)$$

where s_n is the market share percentage of country n. The aggregated Worldwide Governance Indicators (WGI) developed by the World Bank [21] are used to evaluate the governance stability of countries relevant to raw material i production, as shown in the formula below.

$$Governance\ stability_i = \sum\nolimits_{n\ countries} s_{i,n} \times WGI_n \qquad (2)$$

Table 2.1: Impact categories used in this study and their respective indicators and threshold values. (N) indicates a new impact category to the original ESP method, (A) indicates a category indicator adapted for this study, and (M) indicates a modified threshold value based on the ESSENZ method.

Criticality aspect	Impact category	Impact category indicator	Threshold value
Supply risk	mining capacity *(M)*	reserve-to-annual-production ratio; USGS Mineral Commodity Summaries report [22]	50
	End of Life recycling input rate (EoL RIR) *(M)*	contribution of recycled materials to the total raw materials demand in Europe [23]	25
	End of Life recycling rate (EoL RR) *(N)*	recovery efficiency of a commercial PV recycling process [%]; assumptions from [24]	
	country concentration of global supply of mined materials	HHI index; data from [22]	1500
	country concentration of global reserves	HHI index; data from [22], [25], [26]	
	country concentration of global supply processed material *(N)*	HHI index; data from [20]	
	country concentration of EU supply of mined materials *(N)*	HHI index based on the share of this country in EU sourcing; data from [20]	
	country concentration of EU supply of processed materials *(N)*	EU sourcing HHI index; data from [20]	
	governance stability of EU sourcing, mined materials *(A)*	weighted average WGI; derived by multiplying the share of each country in the EU's sourcing mix by its WGI score [19] and using the WGI provided in the European Commission study [20]	1.9
	governance stability of EU sourcing, processed material *(N)*	weighted average WGI; data from [20]	
	trade barriers mine production *(A)*	percentage of mine production under trade barriers; based on the database provided by the Organisation for Economic Co-operation and Development (OECD) on the export restrictions on critical raw materials [27]	25
	companion metal fraction *(M)*	share of global mine production as a companion metal [%], assumptions from [28], [29], [30]	35

Criticality aspect	Impact category	Impact category indicator	Threshold value
Economic importance	price volatility *(N)*	the average of a moving standard deviation (1975–2020) with a 7-year window, as described in [17], and based on USGS price data [31]	0.2
	substitute performance *(N)*	performance evaluation scheme [32]	50
	NACE sector value added *(N)*	weighted average of NACE sector value added in million €, using the share of each sector in final demand for the raw material in the EU as weighting factor; and using the data provided in [20]	107

Regarding economic importance, the original ESP method relied on demand growth as the sole metric. However, this approach was criticised by Pell et al. for producing anomalous results, particularly for materials with low annual production volumes [33]. To address this limitation, this study adopts the *price volatility* metric proposed by Renner and Wellmer [17], which captures economic importance through historical price fluctuations driven by shifts in demand, supply disruptions, material substitution, or technological change. This indicator is considered more robust, as it reflects the sensitivity of the raw materials market to external events and can offer predictive insights into potential future price spikes under comparable conditions. The second indicator considered in the evaluation of economic importance is *substitute performance*, as used in the Methodology of Metal Criticality Determination (MMCD) studies [32], [34]. This metric evaluates the extent to which a material can be replaced without performance loss, with materials lacking suitable substitutes being considered more critical due to increased dependency by the PV sector.

Similar to the EU criticality method [20], the third indicator considered is statistical classification of economic activities (*NACE*) *sector value added*, which accounts for the economic relevance of a material based on its end-use in the different EU industrial sectors. For each raw material, the share of final demand attributed to each NACE sector is multiplied by the value added by the sector, and the weighted average is used to reflect the overall economic importance of the material to the EU economy.

To enable a quantitative evaluation of raw material criticality, the ESSENZ method relates each impact category indicator to a predefined threshold value [18]. Therefore, a dimensionless distance-to-target factor *DTT* is calculated, as shown in Equation 3, for each material *i* and supply risk or economic importance criteria *j*, which are listed in Table 2.1. This DTT factor is then normalized (*normDTT*) in function of global production, as shown in Equation 4.

$$DTT_{i,j} = \begin{cases} \left(\dfrac{Indicator_{i,j}}{Threshold_j}\right)^2, & if\, Indicator_{i,j} > Threshold_j \\ 0\,, & otherwise \end{cases} \tag{3}$$

$$normDTT_{i,j} = \frac{DTT_{i,j}}{global\ annual\ production\ volume} \tag{4}$$

For each raw material, a characterization factor (CF) is obtained by summing the normDTT values across all impact categories, as shown in Equation 5.

$$CF_i = \sum_{j=1}^{15} normDTT_{i,j} \tag{5}$$

To ensure comparability across materials and technologies, the total CFs of all raw materials are **normalised relative to Si metal, and based on the bill of materials of the PV technologies**. Based on this normalisation, a resource-use criticality score is calculated for each PV technology, C_{tech}, in kilograms silicon-equivalent per kilowatt-peak (kg Si-eq/kWp).

$$C_{tech} = \sum_{i \in M} \left(\frac{CF_i}{CF_{Si}} \cdot Q_i \right) \qquad [kg\ Si_{eq.}/kWp] \tag{6}$$

where $CF_{total,Si}$ is the total CF for silicon, M is the set of all raw materials used in a given PV technology, Qi is the quantity (in kg) of material i ϵ M used per kWp for a specific PV technology.

In this study, four PV technologies are considered: passivated emitter and rear contact (PERC) cells, tunnel oxide passivated Contact (TOPCON), silicon heterojunction (SHJ), and SiLEAN cells with Czochralski grown wafers (*SiLEAN-Cz*). PERC and TOPCON technologies held a combined market share of around 90% in 2024 [35]. SHJ cells are entering the PV market and are expected to gain a significant market share due to their high module efficiency [36]. This technology also serves as the foundation for the advanced SiLEAN technology under development.

The bill of materials and cell efficiencies assumed for these technologies, based on bifacial modules, are presented in the table below. Additionally, the quantities of raw materials used in the modules, including silica sand for solar glass, and Al for frames, are calculated based on fixed additional content values per solar cell power output (kWp), as derived from the research of Xu et al. and Müller et al [7], [37]. The study by Müller et al. provides a life cycle inventory for PERC modules based on a wafer thickness of 170 µm, which was adapted to 138.5 µm based on the latest estimate from the 2025 International Technology Roadmap for Photovoltaics (ITRPV) report [35].

For the advanced technologies, a wafer thickness of 124 µm is assumed for SHJ cells, based on the estimate from the 2025 ITRPV report [35], and 100 µm for SiLEAN-Cz, based on the targeted project results. The bill of materials for the SiLEAN technology is assumed to contain Bi because, at the time of writing, SiLEAN cells with Bi-free Cu contacts could not be derived from modelling work of PV Works or the other technical work packages. In addition, the use of graphene-based pastes, can be evaluated later in the project depending on the progress of the technical work packages as the second deliverable to provide a final evaluation of safety of supply (D6.4). Nevertheless, an initial estimation of the potential of Bi-free SiLEAN modules is conducted at the end of this report.

*Table 2: Bill of Materials of the PV technologies considered in this study based on the work of Müller et al. [37] *, Xu et al. [7] §, ITRPV 2025 [35] ^, PV Works modelling ζ, and estimates from project proposal #.*

	Material intensity [kg/m^2]			
	PERC	**TOPCON**	**SHJ**	**SiLEAN-Cz**
Si metal (wafer)	4.41E-01^	4.41E-01^	4.08E-01^	3.52E-01#
Al (metallization)	1.70E-03*	2.08E-03§	-	-
Ag (metallization)^	2.12E-03	3.44E-03	4.34E-03	-
Cu (cell fingers)#	-	-	-	6.38E-03
Indium Tin Oxide (ITO) layer#	-	-	1.41E-03	-
Zinc Oxide layer ζ	-	-	-	1.13E-03
Amorphous Si layers (39 nm in total)ζ	-	-	8.79E-05	8.79E-05
Aluminium oxide (10 nm) §	3.97E-05	-	-	-

	Material intensity [kg/m²]			
	PERC	TOPCON	SHJ	SiLEAN-Cz
Silicon nitride (75 nm) §	2.38E-04	-	-	-
Silicon oxide (1.5 nm) §	-	5.47E-05	-	-
Polysilicon (140 nm) §	-	2.0E-03	-	-
Bi (in solder alloy $Sn_{42}Bi_{58}$) #	-	-	3.38E-03	1.79E-03
Sn (solder alloy)	1.04E-02*	1.04E-02*	1.39E-03#	7.34E-04#
Pb (solder alloy)*	1.10E-02	1.10E-02	-	-
Cu (cell interconnection)	2.07E-02^	2.07E-02^	2.07E-02^	1.56E-02#
Panel glass (2.5.mm front & 2.5 mm rear)*	12.55	12.55	12.55	12.55
Frame (AlMg3 alloy) *	1.51	1.51	1.51	1.51
Cell efficiency [%]	**23.5^**	**25.5^**	**26.0^**	**25.50#**
Wafer thickness [µm]	**138.5**	**138.5**	**124**	**100**

To quantify the influence of input parameters on the resource use criticality of PV technologies, an elasticity-based sensitivity index is computed for each technology-parameter combination. This index is defined as the ratio of the relative change in output (technology resource-use criticality) to the relative change in the input parameter, as presented in Equation 5.

$$S_{tech,x} = \frac{C_{tech,x,max} - C_{tech,x,min} / C_{tech,x,min}}{X_{max} - X_{min} / X_{min}} \tag{5}$$

where X_{max} and X_{min} are the maximum and minimum values of parameter X, respectively. The sensitivity analysis examines the influence of three parameters on technology resource-use criticality: wafer thickness, cell efficiency, and solar glass thickness. To enable a comparative assessment across parameters and technologies, each calculated sensitivity index is normalized by dividing it by the maximum observed sensitivity value across all cases, as shown in Equation 6. This normalization allows for the identification of the most influential parameters, where higher normalized values indicate greater effectiveness in reducing material criticality per kWp.

$$S_{tech,x}^{norm} = \frac{S_{tech,x}}{max(S_{tech,x})} \tag{6}$$

An important assumption in the sensitivity analysis is that the area of the solar glass is assumed to scale linearly with cell area, and thus with cell efficiency, since glass directly covers the active cell surface and increases proportionally with it. For the remainder of the module-level materials, such as the aluminium frame and interconnection materials, the relationship to cell efficiency is less direct. These components are more closely associated with the module's perimeter or layout rather than its surface area. To reflect this, a square root dependency on cell efficiency is assumed as a simplified approximation, based on the geometric relationship between area and perimeter for rectangular modules. This approach avoids overestimating material savings for components whose demand does not scale directly with the active cell area.

2.3 Data gaps and assumptions

Regarding the assessment of supply risk in the impact categories of *mining capacity and country concentration of reserves*, reserve data for silica sand, and quartz, the precursor of Si metal, are not quantified. This is because silica sand deposits are relatively abundant and widely distributed, they may be evaluated as uneconomic due to exogenous factors such as environmental restrictions and stringent quality requirements for specific applications [22]. For quartz, no quantitative data are available regarding global mine production or reserve estimates [22]. However, qualitative indications suggest that the United States is the leading global producer, followed by several other countries, including Australia, Brazil, and Canada [22]. As such, silica sand and quartz, represented by Si metal in this study, are assigned high reserve availability and low values for country concentration of reserves. For Bi, and In, which are directly produced as refined materials, a value of zero is assigned to the extraction stage when calculating the country concentration of global mine production, EU sourcing, and political stability. In contrast, silica sand is treated exclusively as a mined material in both the USGS and European Commission studies [20], [22]. Therefore, a value of zero is assigned to the refining stage for the corresponding impact categories. For Ag, due to the unavailability of data on the refining stage, a value of zero is likewise assigned to the relevant indicators [22].

Regarding the assessment of economic importance, in the impact category of *NACE sector value added*, a value added of zero is assigned to the share of raw material end-use classified as “others” in the European Commission report [20]. The threshold value for this category is derived from the same study, calculated as the average NACE sector value added across all 60 raw materials assessed [20]. The threshold value was determined to be 107 million Euros. Based on this threshold, 27 raw materials have a higher average NACE sector value added, including Al, Bi, and Cu, which are examined in this study. For the *substitute performance* category, PV-technology based scores are derived from literature and SCRREEN project reports, following the performance evaluation scheme used in the MMCD methodology [25], [26], [38], [39], [40], [41], [42], [43], [44]. These values are illustrated in Figure 1.

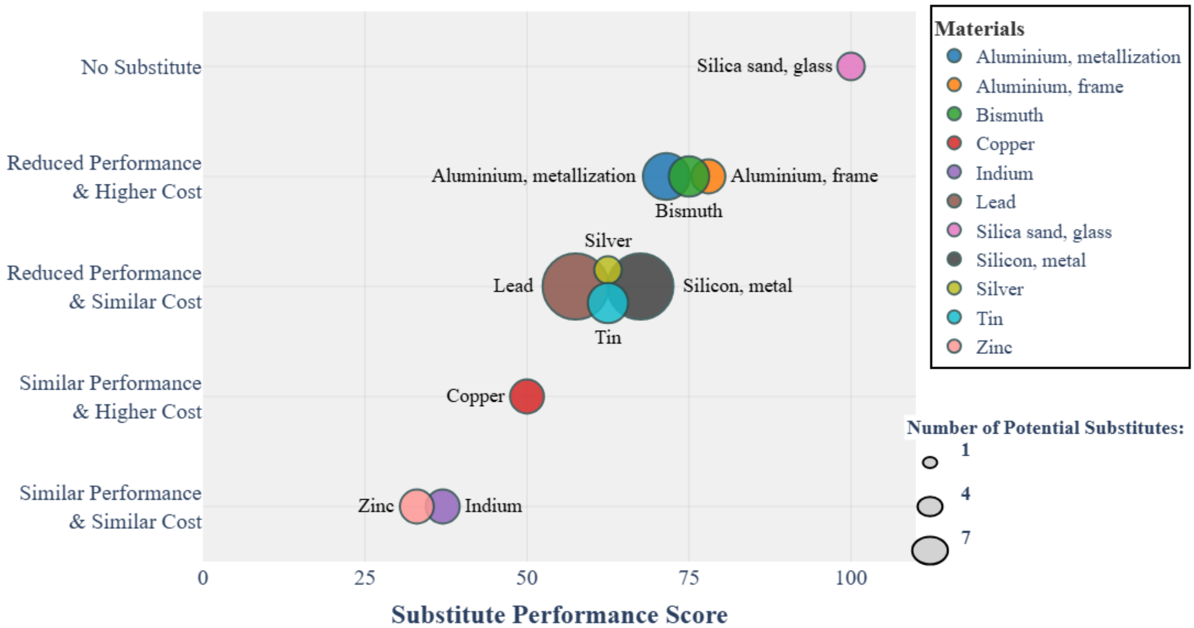

Figure 1: The assumed PV-based substitute performance scores for the raw materials investigated in this study.

3 Results & Discussion

3.1 Raw materials

The criticality results for the 10 raw materials are illustrated in Figure 2.

At the raw material level, the results identify In as potentially the most critical PV raw material. This high criticality is largely driven by its low annual production volume relative to the other assessed materials. This has a significant influence on both its normalized DTT values and the resulting CF. First, the highest normDTT values are observed in the categories related to *reserves availability* and *country concentration of processed material production*, primarily due to limited available reserves and the contribution of China and South Korea alone to around 87% of global supply [22]. Second, global In production occurs entirely as a companion metal [25], mainly with Zn minerals, which restricts the potential to scale up/down production independently in response to change in demand. Third, the enforcement of export taxes on In by China introduces an additional supply risk by constraining free trade.

The assessment also identified Bi, Ag, and Sn with potentially higher criticality than Si metal. For Bi, the main supply risk aspect relates to the significant concentration of its global production, with over 80% supplied by China. For Ag, the high criticality score is due the concentration of 78% of EU sourcing from Poland and Sweden. However, this concentration does not necessarily indicate a vulnerability, as both countries are EU Member States with aligned trade policies. The supply risk of Ag is further driven by its limited global reserves and the occurrence of approximately 71% of global production as a companion metal. For Sn, the main driver of potential supply risks is the limited mining capacity, estimated at 14 years only based on 2024 production data and USGS reserve figures [22]. Another notable contributor to Sn supply risks is the relatively low governance stability of Indonesia and Turkey, which together supply around half of the EU's processed Sn.

The potential supply risks of Si metal are mainly driven by the high concentration of global refining activities in China. China dominates multiple stages of the Si value chain – from metallurgical-grade silicon production to polysilicon refinement and ingot production– which significantly increases geopolitical and supply risks. **As highlighted earlier, the estimates for country concentration of global silicon production used in this study can be considered conservative, as higher concentration levels are typically observed in the value chains of higher-purity forms such as polysilicon and silicon ingots. Thus, supply risks may be even more pronounced in the downstream refining activities of the silicon value chain.** In addition to the export taxes imposed on certain Si metal and silicon-containing products, photovoltaics also fall under China's export tax rebate system, further distorting international trade flows and contributing to a high impact factor in the *trade barriers* category [45]. Moreover, the EoL-RR emerges as a low performing category across multiple raw materials. Bi, In, Pb, Sn, and Zn all suffer from low recovery rates in state-of-the-art recycling technologies, often resulting from technical limitations, economic non-viability, or dissipative end-uses [24]. This limits the potential for circularity and increases dependence on primary extraction.

Pb, Zn, Cu, and Al all have lower CFs than Si metal due to lower DTT factors across most impact categories and higher annual production volumes, which result in comparatively low normalized DTT scores. For Pb and Zn, the primary supply risk is linked to their limited mining capacity. In the case of Cu, approximately 60% of global mine production is subject to restrictive trade measures, including fiscal taxes on Chilean exports and export prohibitions or surcharges imposed by the Democratic Republic of Congo. For Al, supply risks are associated with the heavy dependence on Guinea, which provides 62% of the EU's mined aluminium, despite exhibiting very low governance stability.

From an economic importance perspective, Al, Bi, and Cu exhibit the highest NACE sector value added among the assessed materials. For Al, this is largely due to strong end-use demand in construction, packaging, and the automotive industry (together accounting for 55% of the total end-use sector

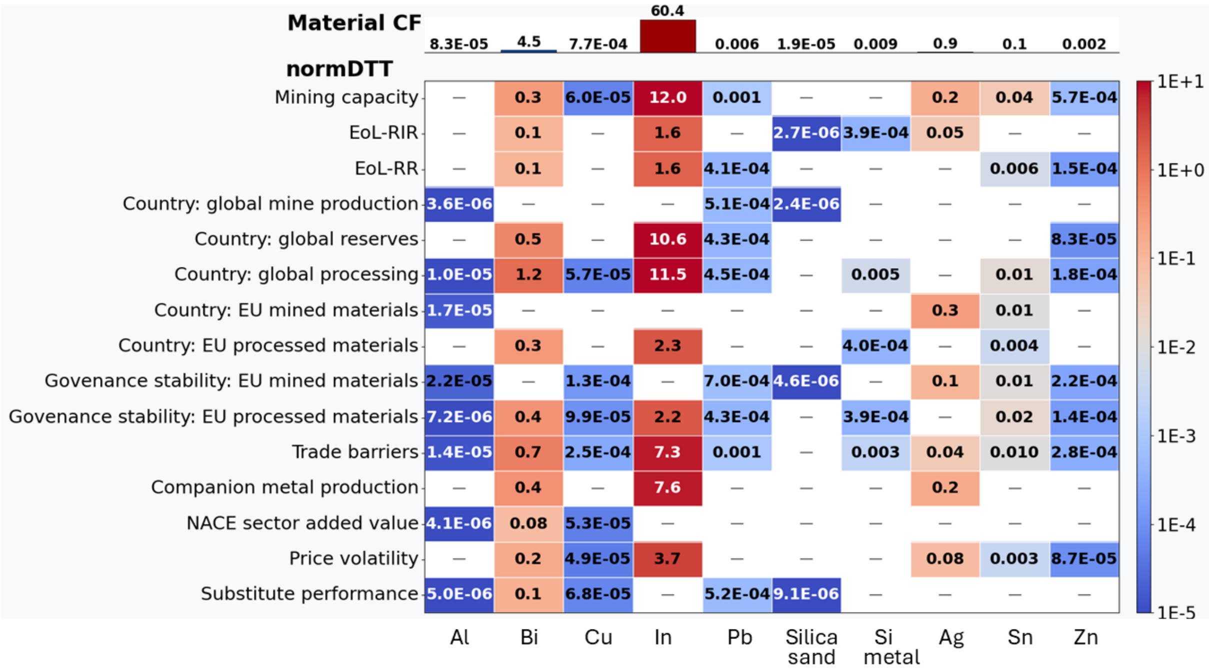

Figure 2: The normalized DTT values and CFs computed for the assessed PV raw materials

demand). Hence, securing sufficient Al supply for an exponentially growing PV sector may prove increasingly challenging, as these materials are already heavily relied upon by well-established and economically influential sectors. Bi and In also demonstrate relatively high normDTT values in the *price volatility* category. For Bi, this is primarily supply-driven, attributed to China's imposition of an export license pricing mechanism, which led to a 92% price surge in 2007 [46]. For In, this is primarily demand-driven, attributed to historical rise in demand for transparent conductive ITO in display panel applications [17]. Finally, unlike other assessed raw materials that have potential substitutes with varying performance trade-offs (as summarized in Figure 1), silica sand has no viable substitute for use in glass manufacturing, which is essential for PV module encapsulation. The strategic importance of high-purity silica sand is likely to increase further due to the rising adoption of glass-glass PV modules, which require an additional layer of tempered or patterned glass compared to traditional glass-backsheet configurations [37]. As such, future PV deployment trends are likely to drive up demand for high-quality silica sand resources.

3.2 PV technologies

At the product level, **the SHJ technology emerges as the most resource-intensive among the technologies assessed** with a criticality score of 38 kg-Si equivalent per kWp, as illustrated in Figure 3. Remarkably, cell criticality accounts for more than 80% of total impacts, despite being more efficient than the other assessed technologies. This is primarily due to the use of In in the ITO transparent conductive oxide layer, which accounts for approximately 90% of the critical resource use. Si and Ag contribute significantly less to the remaining impacts, despite accounting for the majority of the cell's mass. At the module level, Bi in the solder alloy is the dominant contributor, accounting for approximately 97% of criticality impacts, followed by marginal contributions of Sn in the solder alloy and silica sand in the solar panel glass (1% for each).

Commercial PERC and TOPCON technologies have 90% lower resource-use criticality impacts per kWp than SHJ, mainly due to the absence of In and Bi in their bill of materials. Despite assuming a higher cell efficiency for the SHJ technology based on the most recent ITRPV estimates [35], 2.5% higher than PERC and 0.5% higher than TOPCON this efficiency gain comes at the cost of a significantly increased reliance on critical raw materials. This trade-off raises concerns regarding the long-term resilience of raw material supply chains in the European PV sector. For the commercial technologies, Ag is a main

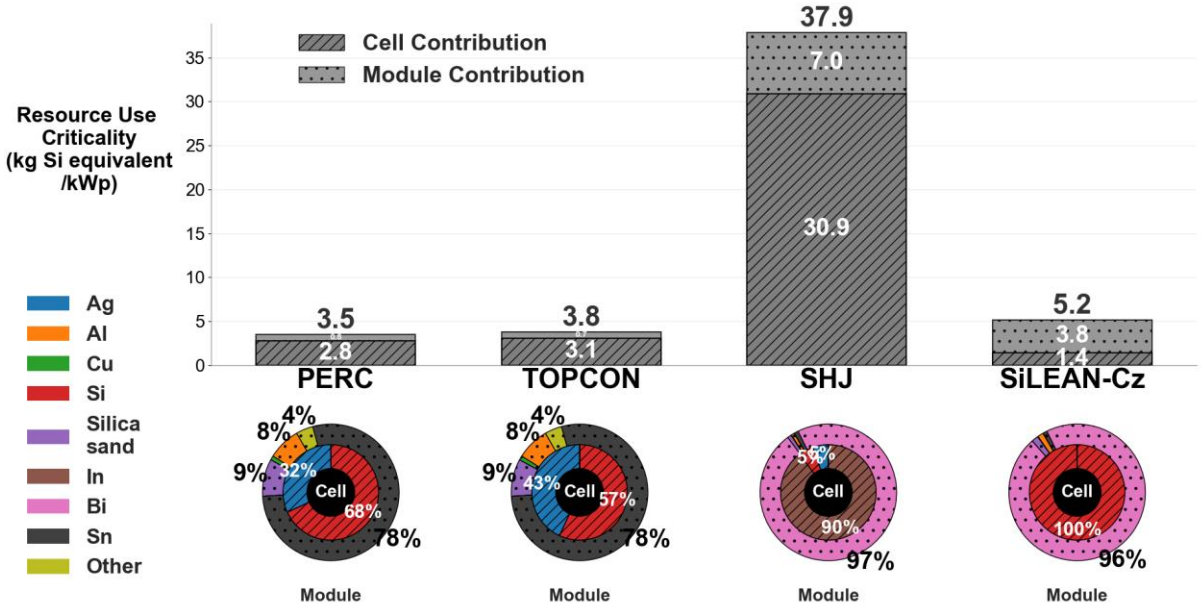

Figure 3: Resource-use criticality of the PV technologies considered in this study. The inner pie chart represents the contribution of materials to criticality at the cell level, while the outer pie chart represents the contributions at the module level.

driver of criticality impacts at the cell level. At the module level, the soldering alloy (Sn + Pb) accounts for 82% of the criticality, followed by silica sand for solar glass and Al for frame, which together contribute an additional 17%.

The SiLEAN-Cz technology, which replace Ag metallization with Cu and In in the ITO layer with Zn, demonstrate at least an 85% reduction in resource-use criticality compared to conventional SHJ technology. The targeted cell efficiency and reduced wafer thickness together contribute to a 23% reduction in Si metal demand per kWp compared to PERC and TOPCON. However, **the overall criticality of the SiLEAN-Cz cells remain higher due to Bi content in the cell interconnect solder alloy (that has been assumed in this variant),** which contributes to 96% of module criticality and 70% of the overall criticality.

Although the solder alloy composed of Sn and Pb, with composition data taken from the life cycle inventory in the study by Müller et al. [37] and detailed in Table 2, has a reduced impact on the resource-use of PERC and TOPCON cells, the presence of Pb remains a concern. Pb poses significant health and environmental risks during end-of-life treatment, as highlighted by the Restriction of Hazardous Substances (RoHS) directive [47]. Although PV panels are currently exempt from the European Union’s Restriction of Hazardous Substances (RoHS) Directive, which limits lead to 0.1% by weight in homogeneous materials, this exemption may be subject to future revision. According to the most recent ITRPV report, lead-free soldering held a 3% market share in 2024, but is expected to increase to 15% by 2035 [35].

As shown in Figure 4, cell efficiency is the most influential parameter affecting resource-use criticality across all evaluated PV technologies, followed by the thickness of cell wafer and solar glass, although to a lesser extent. The results for the SHJ technology are presented separately in Figure 6 in Appendix A of this report due to its high resource-use criticality score, which minimizes the nuance in the sensitivity analysis results. Despite having the largest mass fraction in the whole PV module, the influence of solar glass thickness exhibits limited influence on technology resource-use criticality due to abundance of silica sand, and the limited influence of DTT factors in relation to annual production volume. In contrast to SiLEAN cells, cell materials are the main drivers of overall criticality impacts in PERC and TOPCON cells. As such, PERC and TOPCON cells are more sensitive to cell efficiency and wafer thickness, as demonstrated in Figure 4. The SiLEAN technology is significantly sensitive to cell efficiency

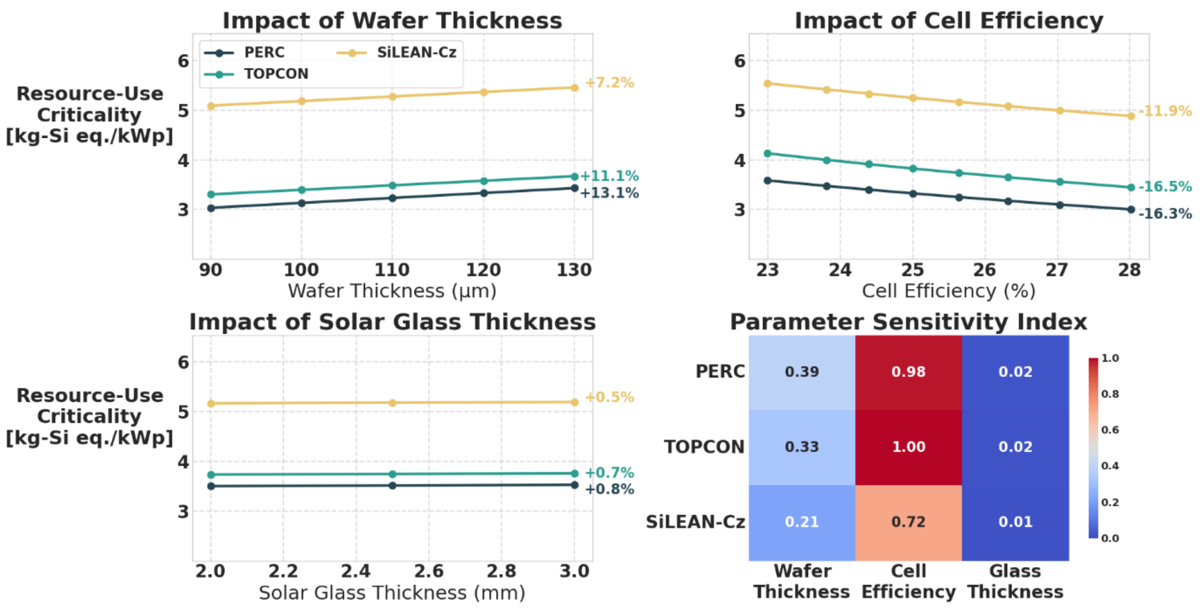

Figure 4: Sensitivity analysis results for the influence of wafer thickness, cell efficiency, and solar glass thickness on the resource-use criticality of the studied PV technologies. Note that the efficiency variation is entirely theoretical and it is not realistic for mass-produced PERC cells to reach efficiency >25%.

and wafer thickness as Si-metal contributes to more than 99% and 27% of cell and overall criticality impacts, respectively.

To evaluate the influence of solder alloy composition on criticality, an alternative scenario is introduced in which the $Sn_{42}Bi_{58}$ alloy was replaced with a lead- and bismuth-free $Si_{99.5}Cu_{0.5}$ alloy in the SiLEAN cell configurations. The results, illustrated in Figure 5, indicate a 95% reduction in module criticality, and as such the SiLEAN technology may even have even a lower overall criticality than PERC and TOPCON technologies. In the absence of Bi, Sn becomes the major driver of module criticality at 53%, followed by the bulk materials used in the frame and solar panel glass. Cu contribution remains limited to 2% and is attributed to the cell interconnects rather than the solder alloy content.

The results of this study are in line with findings from prior research by Müller et al. which has shown that both efficiency and Si metal consumption are key contributors to the life-cycle environmental impacts of crystalline silicon PV systems [37]. Similarly, Xu et al. emphasized that improving efficiency is essential for keeping cumulative global material demand within the limits of known reserves [7]. Furthermore, Xu et al. forecast cumulative PV-related demand for Ag and In between 2022 and 2050 to exceed current global reserves [7]. These concerns are reflected in the results of the present study, particularly in the large differences in criticality scores between SHJ and SILEAN cell technologies. The substitution of critical materials such as In and Ag in PV cells not only mitigates supply risks, but also enables high deployment of PV in the coming years.

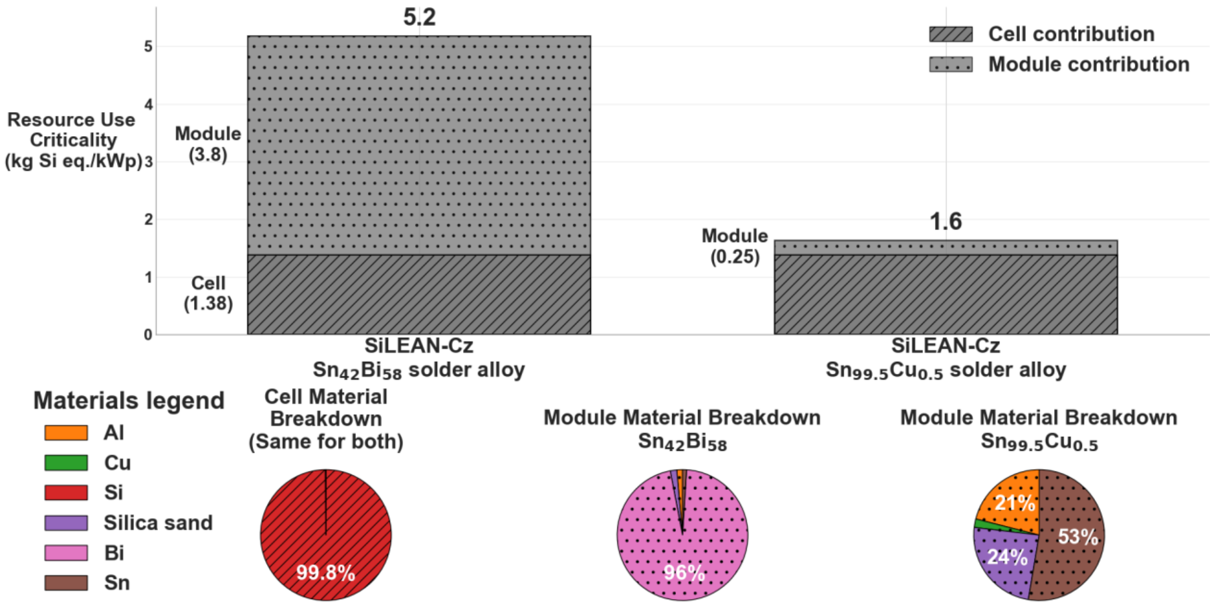

Figure 5: Sensitivity analysis results for the resource-use criticality of the SiLEAN-Cz technology in function of cell interconnect solder alloy material composition

3.3 Contribution to project objectives

As demonstrated in the previous sections, the results presented in this deliverable directly contribute to Objectives 3 (Demonstration of novel contacts for thin SHJ solar cells with a strong reduction of scarce materials), and 5 (Assessment and demonstration of reduced environmental impact of the production process and materials and increased circularity for the SiLEAN products) of the project. Specifically, the application of criticality assessment at the technology level demonstrates that the SiLEAN technology has a significantly lower content of critical raw materials per kWp than SHJ, and comparable performance with PERC and TOPCON technologies. It has also been demonstrated that the substitution of indium and silver has the potential to significantly reduce cell criticality impacts relative to state-of-the-art SHJ cells. At the module level, bismuth-free cell interconnections have the potential to reduce resource-use criticality by more than 90%.

In relation to the targets established by the EU Critical Raw Materials Act [48], Al (bauxite) is, on the one hand, the raw material in the SiLEAN technology that most closely approaches the 65% threshold for import dependency from a single non-EU country [20]. On the other hand, for Si metal, the EU share of global refined Si metal production only accounts for 4.1%, with an import reliance of 64% [49], which is significantly higher than the Act's target of 40% for processing within the EU. Furthermore, copper appears to be a more favourable choice for cell metallization as it has an EoL RIR of 30% [23], which exceeds the 25% threshold set by the EU Critical Raw Materials Act. In contrast, silver has a significantly lower EoL RIR of just 19% [44], highlighting its limited contribution to secondary raw material supply. Therefore, material substitution strategies, increased cell efficiency and reduced wafer thickness may effectively contribute to lowering exposure to critical raw material supply risks and supports the advancement of a more resilient PV value chain in Europe.

4 Conclusion and Recommendation

In this deliverable, a hybrid criticality assessment method was presented and applied to ten PV raw materials to estimate the resource-use scarcity potential of five PV technologies based on their respective bill of materials. An elasticity-based sensitivity analysis was then conducted to assess the influence of wafer thickness, cell efficiency, and solar glass thickness on the resource-use criticality of these technologies. **The criticality method results determine In and Bi as the most critical PV raw materials, mainly due to the high concentration of production and refining activities in China and their high share of global mine production as a companion metal**. Si metal encounters similar supply risks as Bi and In, as well as export taxes on silicon-containing products. Furthermore, the main criticality of silica sand is due to the absence of performing substitutes for solar glass manufacturing.

The results also highlighted a substantial reduction in raw material supply risks associated with the SiLEAN cell bill of materials. In particular, the substitution of indium for TCO layers and silver for metallization with Zn and Cu and the use of bismuth-free solder alloys for cell interconnects. For all PV technologies considered, the results showed the strong influence of solder alloy material composition on the module criticality. Cell materials, such as In, Ag, and Si, are strong drivers of criticality at the cell-level. The results also indicated the strong influence of cell efficiency in reducing resource-use efficiency, due to its impact in reducing the required material input per functional unit of solar power generation. Overall, the SiLEAN technology can bring the criticality of the SHJ technology more than 85% lower, and eventually on par with that of TOPCON. By suppressing the use of Bi in cell interconnection, an even more resilient technology may be achieved.

While criticality assessment provides essential insights into raw material supply security and economic importance, the detailed nuances revealed in this study in terms of material composition, cell architecture, and electrochemical performance should also be examined from an environmental perspective. To this end, these results will serve as a key input to the ongoing work under Task 6.3 on the environmental impact analysis of the SiLEAN technology. **One important limitation of this study is that it adopts a high-level assessment of raw material use and does not model the exact level of refining that is applicable for PV manufacturing.** The analysis is based on the commodity form of each raw material, using open-source data such as those provided by the USGS and the European Commission. As such, it does not capture variations in material forms, purity grades, or process-specific inputs that may influence actual supply risks. This simplification applies to all assessed materials, including silicon, silver, copper, and indium. These limitations could be better addressed in the upcoming tasks on detailed criticality assessment and life cycle assessment, which allows for process-level modelling of material flows, energy supply, and emissions.

5 References

[1] M. Stucki, M. Götz, M. de Wild-Scholten, and R. Frischknecht, “FACT SHEET: Environmental Life Cycle Assessment of Electricity from PV Systems 2023 DATA UPDATE,” 2024. Accessed: Jun. 26, 2025. [Online]. Available: https://iea-pvps.org/wp-content/uploads/2024/05/Task-12-Fact-Sheet-v2-1.pdf

[2] IEA, “Renewables 2023,” Paris, 2024. Accessed: Apr. 16, 2025. [Online]. Available: https://www.iea.org/reports/renewables-2023/executive-summary

[3] D. Bogdanov *et al.*, “Low-cost renewable electricity as the key driver of the global energy transition towards sustainability,” *Energy*, vol. 227, p. 120467, Jul. 2021, doi: 10.1016/J.ENERGY.2021.120467.

[4] T. Boström, B. Babar, J. B. Hansen, and C. Good, “The pure PV-EV energy system – A conceptual study of a nationwide energy system based solely on photovoltaics and electric vehicles,” *Smart Energy*, vol. 1, p. 100001, Feb. 2021, doi: 10.1016/J.SEGY.2021.100001.

[5] IEA, “World Energy Outlook 2024,” Paris, 2024. Accessed: Apr. 16, 2025. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2024

[6] IRENA, “World Energy Transitions Outlook 2023: 1.5°C Pathway,” Abu Dhabi, 2023. Accessed: Apr. 16, 2025. [Online]. Available: https://www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023

[7] C. Xu, O. Isabella, and M. R. Vogt, “Future material demand for global silicon-based PV modules under net-zero emissions target until 2050,” *Resour Conserv Recycl*, vol. 210, p. 107824, Nov. 2024, doi: 10.1016/J.RESCONREC.2024.107824.

[8] HCSS, “HCSS Critical Raw Materials Dashboard.” Accessed: Apr. 16, 2025. [Online]. Available: https://hcss.nl/critical-minerals/

[9] V. Tan, P. R. Dias, N. Chang, and R. Deng, “Estimating the Lifetime of Solar Photovoltaic Modules in Australia,” *Sustainability 2022, Vol. 14, Page 5336*, vol. 14, no. 9, p. 5336, Apr. 2022, doi: 10.3390/SU14095336.

[10] D. Ioannidou, N. Heeren, G. Sonnemann, and G. Habert, “The future in and of criticality assessments,” *J Ind Ecol*, vol. 23, no. 4, pp. 751–766, Aug. 2019, doi: 10.1111/JIEC.12834.

[11] L. van Oers, J. B. Guinée, and R. Heijungs, “Abiotic resource depletion potentials (ADPs) for elements revisited—updating ultimate reserve estimates and introducing time series for production data,” *International Journal of Life Cycle Assessment*, vol. 25, no. 2, pp. 294–308, Feb. 2020, doi: 10.1007/S11367-019-01683-X/FIGURES/5.

[12] M. Goedkoop and R. Spriensma, “The Eco-indicator 99 A damage oriented method for Life Cycle Impact Assessment Methodology Report,” Amersfoort, 2001. Accessed: Apr. 17, 2025. [Online]. Available: www.pre.nl

[13] M. E. Bösch, S. Hellweg, M. A. J. Huijbregts, and R. Frischknecht, “Applying Cumulative Exergy Demand (CExD) indicators to the ecoinvent database,” *International Journal of Life Cycle Assessment*, vol. 12, no. 3, pp. 181–190, Nov. 2007, doi: 10.1065/LCA2006.11.282/METRICS.

[14] R. B. Norgaard, “Economic indicators of resource scarcity: A critical essay,” *J Environ Econ Manage*, vol. 19, no. 1, pp. 19–25, Jul. 1990, doi: 10.1016/0095-0696(90)90057-6.

[15] National Research Council, “Minerals, Critical Minerals, and the U.S. Economy,” National Academies Press, Washington, DC, 2008. doi: 10.17226/12034.

[16] M. Schicho and L. Tercero Espinoza, “Criticality assessment for raw materials: perspectives and focuses,” *Mineral Economics*, pp. 1–18, Oct. 2024, doi: 10.1007/S13563-024-00474-7/TABLES/2.

[17] S. Renner and F. W. Wellmer, “Volatility drivers on the metal market and exposure of producing countries,” *Mineral Economics*, vol. 33, no. 3, pp. 311–340, Oct. 2020, doi: 10.1007/S13563-019-00200-8/FIGURES/31.

[18] L. Schneider *et al.*, “The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment,” *International Journal of Life Cycle Assessment*, vol. 19, no. 3, pp. 601–610, Mar. 2014, doi: 10.1007/S11367-013-0666-1/FIGURES/3.

[19] V. Bach *et al.*, “Integrated method to assess resource efficiency – ESSENZ,” *J Clean Prod*, vol. 137, pp. 118–130, Nov. 2016, doi: 10.1016/J.JCLEPRO.2016.07.077.

[20] European Commission: Directorate-General for Internal Market Industry Entrepreneurship and SMEs, M. Grohol, and C. Veeh, “Study on the critical raw materials for the EU 2023 – Final report,” 2023. Accessed: Apr. 17, 2025. [Online]. Available: https://data.europa.eu/doi/10.2873/725585

[21] World Bank, “Worldwide Governance Indicators.” Accessed: Jun. 16, 2025. [Online]. Available: https://www.worldbank.org/en/publication/worldwide-governance-indicators

[22] U.S. Geological Survey, “Mineral commodity summaries 2025 (ver. 1.2, March 2025),” Virginia, 2025. doi: 10.3133/MCS2025.

[23] Eurostat, “Contribution of recycled materials to raw materials demand - end-of-life recycling input rates (EOL-RIR).” Accessed: Jun. 13, 2025. [Online]. Available: https://ec.europa.eu/eurostat/databrowser/view/cei_srm010/default/table?lang=en&category=cei.cei_srm

[24] G. A. Heath *et al.*, “Research and development priorities for silicon photovoltaic module recycling to support a circular economy,” *Nature Energy 2020 5:7*, vol. 5, no. 7, pp. 502–510, Jul. 2020, doi: 10.1038/s41560-020-0645-2.

[25] SCRREEN, “FACTSHEETS UPDATES BASED ON THE EU FACTSHEETS 2020-INDIUM.” Accessed: Apr. 30, 2025. [Online]. Available: https://scrreen.eu/wp-content/uploads/2023/12/SCRREEN2_factsheets_INDIUM-update-.pdf

[26] SCRREEN, “FACTSHEETS UPDATES BASED ON THE EU FACTSHEETS 2020-BISMUTH.” Accessed: Apr. 30, 2025. [Online]. Available: https://scrreen.eu/wp-content/uploads/2023/12/SCRREEN2_factsheets_BISMUTH_V1.pdf

[27] OECD, “OECD Inventory of Export Restrictions on Industrial Raw Materials.” Accessed: Apr. 17, 2025. [Online]. Available: https://www.oecd.org/en/topics/export-restrictions-on-critical-raw-materials.html

[28] N. T. Nassar, T. E. Graedel, and E. M. Harper, “By-product metals are technologically essential but have problematic supply,” *Sci Adv*, vol. 1, no. 3, Apr. 2015, doi: 10.1126/SCIADV.1400180/SUPPL_FILE/1400180_SM.PDF.

[29] SCRREEN, “FACTSHEETS UPDATES BASED ON THE EU FACTSHEETS 2020-SILICA SAND.” Accessed: Apr. 17, 2025. [Online]. Available: https://scrreen.eu/wp-content/uploads/2023/08/SCRREEN2-factsheets_SILICA-SAND.pdf

[30] SCRREEN, “FACTSHEETS UPDATES BASED ON THE EU FACTSHEETS 2020-SILICON METAL.” Accessed: Apr. 17, 2025. [Online]. Available: https://scrreen.eu/wp-content/uploads/2023/12/SCRREEN2_factsheets_SILICON_METAL-update.pdf

[31] U.S. Geological Survey, “Historical Statistics for Mineral and Material Commodities in the United States.” Accessed: Apr. 20, 2025. [Online]. Available: https://www.usgs.gov/centers/national-minerals-information-center/historical-statistics-mineral-and-material-commodities

[32] L. Bongartz, S. Shammugam, E. Gervais, and T. Schlegl, “Multidimensional criticality assessment of metal requirements for lithium-ion batteries in electric vehicles and stationary storage applications in Germany by 2050,” *J Clean Prod*, vol. 292, p. 126056, Apr. 2021, doi: 10.1016/J.JCLEPRO.2021.126056.

[33] R. S. Pell, F. Wall, X. Yan, and G. Bailey, “Applying and advancing the economic resource scarcity potential (ESP) method for rare earth elements,” *Resources Policy*, vol. 62, pp. 472–481, Aug. 2019, doi: 10.1016/J.RESOURPOL.2018.10.003.

[34] T. E. Graedel *et al.*, “Methodology of metal criticality determination,” *Environ Sci Technol*, vol. 46, no. 2, pp. 1063–1070, Jan. 2012, doi: 10.1021/es203534z.

[35] M. Fischer, M. Woodhouse, T. Brammer, and P. Baliozian, “International Technology Roadmap for Photovoltaics (ITRPV)- 2024 Results,” 2025. Accessed: Jun. 16, 2025. [Online]. Available: https://www.vdma.org/international-technology-roadmap-photovoltaic

[36] M. Fischer, M. Woodhouse, and P. Baliozian, “International Technology Roadmap for Photovoltaics (ITRPV)- 2023 Results,” Frankfurt am Main, 2024. Accessed: Apr. 28, 2025. [Online]. Available: https://www.qualenergia.it/wp-content/uploads/2024/06/ITRPV-15th-Edition-2024-2.pdf

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

[38] B. Cao *et al.*, “Active learning accelerates the discovery of high strength and high ductility lead-free solder alloys,” *Mater Des*, vol. 241, p. 112921, May 2024, doi: 10.1016/J.MATDES.2024.112921.

[39] A. Virtuani, “Solar module technology,” *Springer Series in Materials Science*, vol. 301, pp. 219–247, 2020, doi: 10.1007/978-3-030-46487-5_9/TABLES/3.

[40] Y. Zeng *et al.*, “Review on Metallization Approaches for High-Efficiency Silicon Heterojunction Solar Cells,” *Transactions of Tianjin University*, vol. 28, no. 5, pp. 358–373, Oct. 2022, doi: 10.1007/S12209-022-00336-9/TABLES/1.

[41] SCRREEN, “FACTSHEETS UPDATES BASED ON THE EU FACTSHEETS 2020-COPPER.” Accessed: Apr. 30, 2025. [Online]. Available: https://scrreen.eu/wp-content/uploads/2024/01/SCRREEN2_factsheets_COPPER-update.pdf

[42] SCRREEN, “FACTSHEETS UPDATES BASED ON THE EU FACTSHEETS 2020-LEAD.” Accessed: Apr. 30, 2025. [Online]. Available: https://scrreen.eu/wp-content/uploads/2023/08/SCRREEN2-factsheets_LEAD.pdf

[43] SCRREEN, “FACTSHEETS UPDATES BASED ON THE EU FACTSHEETS 2020-TIN.” Accessed: Apr. 30, 2025. [Online]. Available: https://scrreen.eu/wp-content/uploads/2023/08/SCRREEN2_factsheets_TIN.pdf

[44] SCRREEN, “FACTSHEETS UPDATES BASED ON THE EU FACTSHEETS 2020-SILVER.” Accessed: Apr. 30, 2025. [Online]. Available: https://scrreen.eu/wp-content/uploads/2023/08/SCRREEN2_factsheets_SILVER.pdf

[45] T. Xiao, “Navigating China’s Latest Export Tax Rebate Adjustments: What Are the Implications?” Accessed: Apr. 30, 2025. [Online]. Available: https://www.china-briefing.com/news/navigating-chinas-latest-export-tax-rebate-adjustments-implications/

[46] Asian Metal Ltd., “2007 Annual Report on Chinese Bismuth Market.” Accessed: May 01, 2025. [Online]. Available: https://www.asianmetal.com/report/en/2007Bi_en.pdf

[47] European Parliament and Council of the European Union, *Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast)*. Directorate-General for Environment, 2011. Accessed: Jun. 19, 2025. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011L0065

[48] *Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020* . Official Journal of the European Union: Luxembourg, 2024. Accessed: May 07, 2025. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02024R1252-20240503

[49] European Commission, “RMIS - Raw materials’ profiles-Silicon metal.” Accessed: May 07, 2025. [Online]. Available: https://rmis.jrc.ec.europa.eu/rmp/Silicon%20metal

6 Acknowledgement

The authors would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project partners:

#	Partner short name	Partner Full Name
1	FZJ	FORSCHUNGSZENTRUM JULICH GMBH
2	IMEC	INTERUNIVERSITAIR MICRO-ELECTRONICA CENTRUM
3	TUD	TECHNISCHE UNIVERSITEIT DELFT
4	UNR	UNIRESEARCH BV
5	NXW	NEXWAFE GMBH
6	PVW	PV Works B.V.
7	GET	GraphEnergyTech
8	3SUN	3SUN S.R.L.
9	ODTÜ-GÜNAM	The Center for Solar Energy Research and Applications

Disclaimer/ Acknowledgment

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101147275. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

7 Appendix A – Sensitivity analysis results with SHJ cells

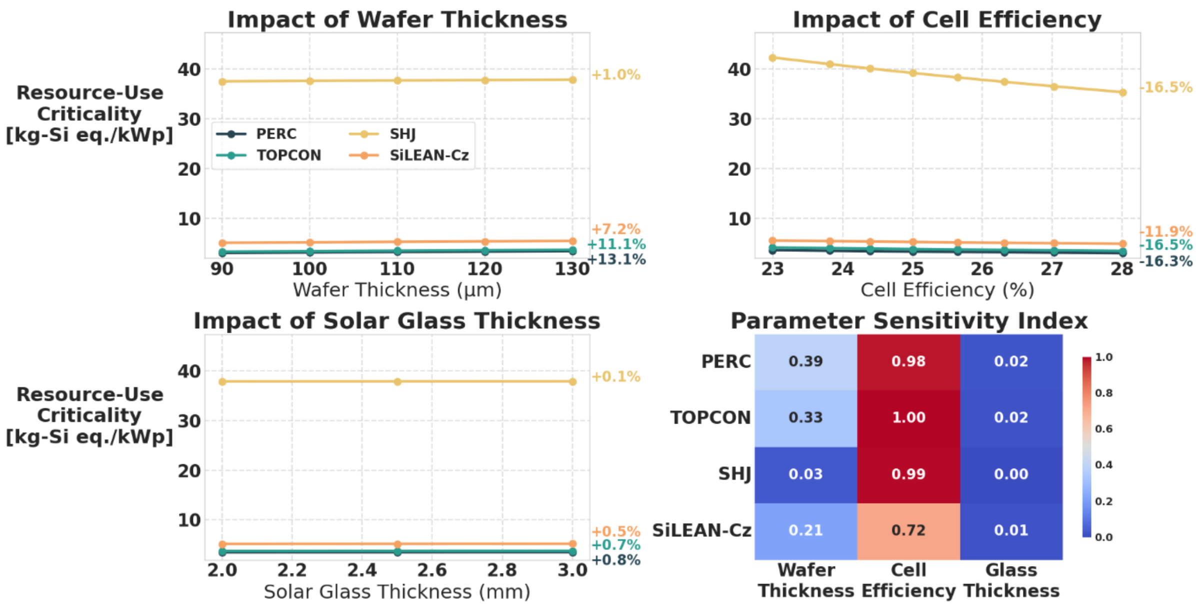

Figure 6: Sensitivity analysis results for the influence of wafer thickness, cell efficiency, and solar glass thickness on the resource-use criticality of the studied PV technologies, including SHJ technology