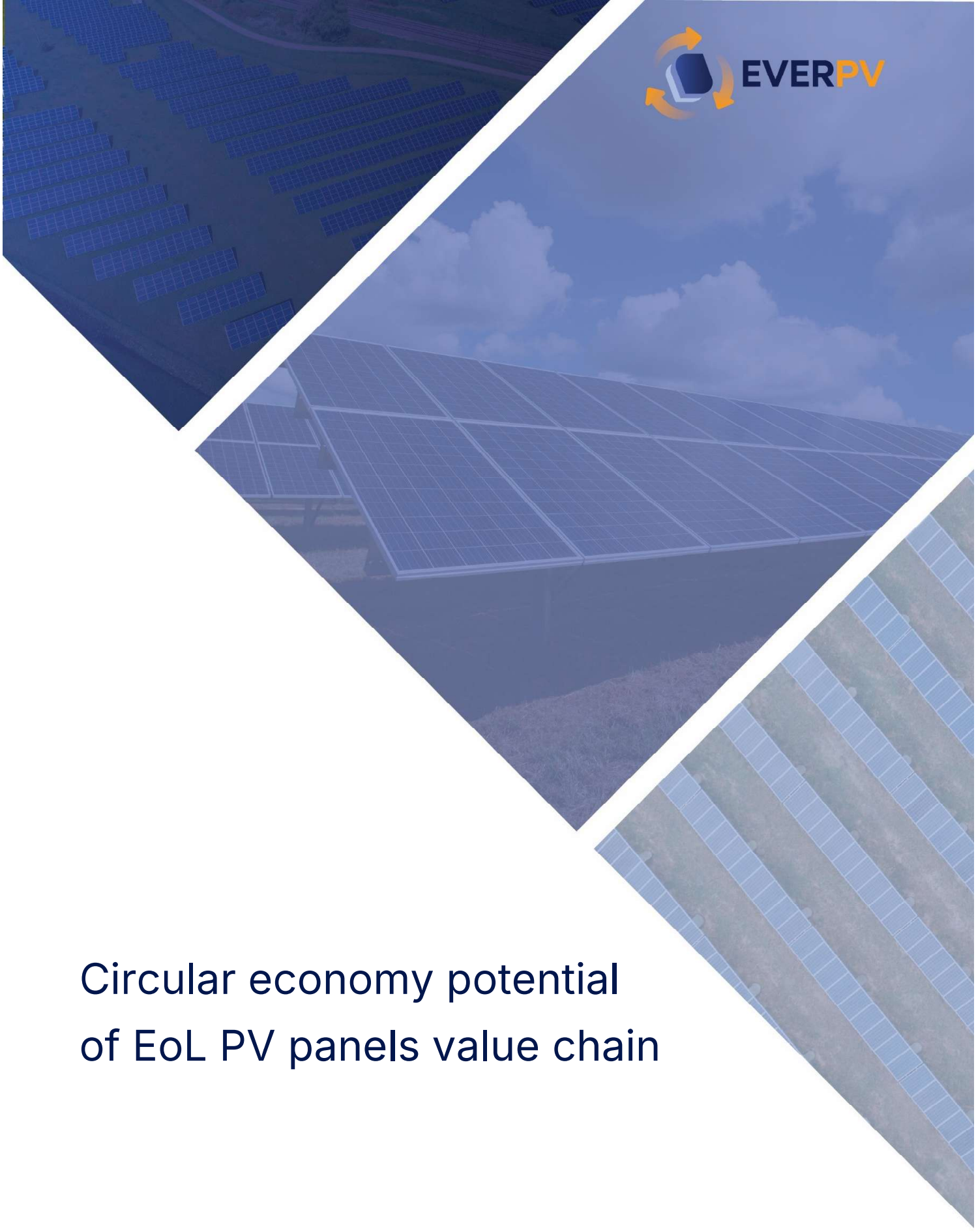

Circular economy potential of EoL PV panels value chain

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ABBREVIATIONS

a-Si	Amorphous silicon	**kW**	Kilowatt
ADEME	French Agency for Ecological Transition	**LCA**	Life cycle assessment
Al-BSF	Aluminium back-surface field	**LCC**	Life cycle costing
BAU	Business-as-usual	**LHV**	Lower heating value
CdTe	Cadmium telluride	**MFA**	Material flow analysis
CEA	French Alternative Energies and Atomic Energy Commission	**mg**	Milligram
CIGS	Copper indium gallium selenide	**Mono-Si**	Monocrystalline silicon
CINEA	European Climate, Infrastructure and Environment Executive Agency	**Multi-Si**	Multicrystalline silicon
CSS	Combustibile solido secondario (secondary solid fuel)	**MW**	Megawatt
DPP	Digital product passport	**PET**	Polyethylene terephthalate
EC	European Commission	**POM**	Placed on the market
EER	Elenco europeo dei rifiuti (European List of Waste)	**PRO**	Producer responsibility organisation
EoL	End-of-life	**PU**	Public dissemination level
EoW	End-of-Waste	**PV**	Photovoltaic
EU	European Union	**PVDF**	Polyvinylidene fluoride
EU-27	27 Member States of the European Union	**PVPS**	Photovoltaic Power Systems Programme
EVA	Ethylene-vinyl acetate	**R1**	Energy-recovery operation under the Waste Framework Directive
EVERPV	Highly efficient delamination technologies to recover and reuse metals, glass and polymers from end-of-life photovoltaic panels	**REC**	Recovery scenario
FUTURAM	Future availability of secondary raw materials	**SCYCLE**	Sustainable Cycles Programme
GA	Grant Agreement	**SCRMs**	Secondary critical raw materials
GW	Gigawatt	**SRF**	Solid recovered fuel
HHV	Higher heating value	**TF**	Thin-film
IEA	International Energy Agency	**TOC**	Total organic carbon
IR	Infrared	**UNITAR**	United Nations Institute for Training and Research
IRENA	International Renewable Energy Agency	**WEEE**	Waste electrical and electronic equipment

kg	Kilogram	**WP**	Work package
kJ	Kilojoule	**XRF**	X-ray fluorescence
kt	Kilotonne		

EXECUTIVE SUMMARY

The rapid expansion of photovoltaic (PV) capacity in the European Union will be accompanied by a substantial increase in end-of-life PV panels. By 2030, cumulative installed PV capacity in the EU is projected to reach approximately 816 GW, while annual PV waste generation could rise to around 326 kt. This emerging waste stream represents a potentially important domestic source of glass, aluminium, silicon, silver, copper and polymers. However, this potential remains constrained by low formal collection, damage occurring during collection and transport, limited specialised treatment capacity, and the absence of established markets for several recovered fractions. In 2022, only approximately 40% of PV waste was estimated to enter formal collection systems, substantially below the collection target established under the Waste Electrical and Electronic Equipment Directive.

Deliverable 6.2 assesses the circular economy potential of end-of-life silicon PV panels in the EU and examines the conditions under which their constituent materials could become reliable secondary raw materials. Building on the PV stock-and-flow model developed in Deliverable 6.1, the assessment integrates harmonised panel-composition data with information on the performance of current and innovative pre-treatment technologies. It further examines collection and reverse logistics through case studies in Italy and France, compares the recycling performance of industrial treatment routes, maps the European PV recycling value chain, assesses technical and economic feasibility, and evaluates the market readiness of the resulting material fractions.

The domestic sourcing assessment demonstrates that the quantity of material entering formal collection remains the first major determinant of recovery potential. Glass and aluminium account for most of the mass of silicon PV panels and can already be directed towards established recycling markets. By contrast, lower-volume but strategically relevant materials, particularly silicon and silver, are embedded within complex panel layers and require selective separation and further refining. The results therefore show that circularity cannot be assessed solely through total mass-recovery rates. The purity, contamination level, legal status, downstream destination and potential value of the resulting fractions are equally important.

The selected pre-treatment route substantially affects the form in which materials become available. Shredding can accept both intact and damaged modules and therefore processes the largest potential input volume. However, it generates comparatively mixed fractions that require further separation and purification. Delamination routes, including hot-knife, sanding, hybrid hot-knife and sanding, and mechanical infrared-assisted processes, produce cleaner glass and more concentrated cell-, silicon- and silver-bearing fractions. Their application is nevertheless dependent on the availability of sufficiently

intact panels. Based on consultations with project partners, the quantitative assessment conservatively assumes that 50% of collected panels arrive intact and are eligible for the investigated delamination routes, while shredding can process the full collected volume[4]. Improving panel integrity during collection and transport could therefore directly increase the volume available for higher-quality treatment without requiring an increase in the overall collection rate.

The Italian and French case studies confirm that collection and reverse logistics are integral parts of recycling performance. Pallet condition, module orientation, packaging, handling and transport influence glass breakage and determine whether panels remain suitable for selective delamination. The French field study showed that breakage can remain below 1% when panels are transported on stable pallets under controlled handling conditions. The findings indicate that relatively simple measures—including minimum pallet-quality requirements, consistent module orientation and appropriately applied strapping—could preserve panel integrity and improve downstream treatment options. The Italian case further illustrates how fragmented collection arrangements and differing financing mechanisms have the potential to affect the organisation and quality of PV waste flows.

The assessment of industrial recycling routes shows that both shredding and delamination can recover the main material streams, but with different qualitative outcomes. Shredding provides high throughput and effective bulk separation, particularly for glass and metals, but the resulting glass may remain legally classified as waste and depend on additional downstream processing. Mechanical delamination can generate End-of-Waste glass and more clearly separated material fractions. Plastics and ethylene-vinyl acetate remain major bottlenecks across the assessed routes, as they are still predominantly directed towards energy recovery rather than material recycling. Silicon- and silver-rich powders are potentially valuable outputs, but their actual contribution to circularity depends on the availability of technically proven refining processes and reliable industrial off-takers.

The mapping of the European recycling value chain shows that current treatment capacity is unevenly distributed and remains dominated by conventional shredding infrastructure. Specialised delamination capacity is smaller and concentrated in a limited number of countries and facilities. The choice of treatment route is also influenced by national governance and procurement arrangements. Producer responsibility organisations and other contracting authorities can support higher-quality recovery by incorporating output quality, material destination and innovation criteria into treatment tenders rather than selecting operators primarily on the basis of cost.

The technical and economic assessment identifies a trade-off between direct treatment cost, throughput and output quality. Under harmonised benchmark assumptions,

[4] Assumption by ENVIE based on expertise estimation, not data driven

shredding has an estimated direct treatment cost of EUR 152.01 per tonne, compared with EUR 224.52 per tonne for mechanical delamination. Shredding also shows higher throughput and lower electricity and labour requirements. These results should not be interpreted as a definitive ranking, as the comparison does not monetise differences in material purity, downstream refining requirements, environmental performance or the potential value of cleaner output fractions. Advanced delamination and sanding routes may become economically competitive where high-quality glass and concentrated silicon- and silver-bearing fractions can access higher-value markets.

Market readiness differs substantially between the recovered fractions. Aluminium, ferrous metals and copper-bearing components can enter mature secondary-material markets, provided that adequate separation and purity are achieved. Glass represents the largest mass-based opportunity, but its value depends on granulometry, contamination levels, End-of-Waste status and compliance with buyer specifications. Silicon- and silver-bearing powders represent the most strategically important high-value fraction, although further refining, industrial-scale recovery validation and off-take agreements are required. Mixed polymer fractions currently have the weakest market prospects and are likely to remain dependent on energy recovery or lower-value applications in the near term.

Overall, the assessment demonstrates that the circular economy potential of end-of-life PV panels is determined by the interaction of collection performance, module condition, treatment technology, output quality, available recycling capacity and downstream demand. Increasing the quantity collected is necessary but insufficient. A more circular European PV value chain also requires the preservation of panel integrity, wider deployment of selective treatment routes, harmonised data on panel composition and recyclability, clearer quality and End-of-Waste criteria, and stable markets for recovered glass, silicon, silver and polymer fractions. The recommendations developed in this deliverable address these interconnected regulatory, organisational, technical and market conditions and aim to support the transition from bulk PV waste treatment towards higher-quality material recovery and domestic secondary raw material supply.

1. INTRODUCTION

1.1. Purpose of the deliverable

The objective of Deliverable 6.2 is to evaluate the circularity potential of the photovoltaic (PV) value chain within the European Union (EU) by assessing the domestic sourcing potential of secondary raw materials from end-of-life (EoL) silicon PV panels. The deliverable examines how improvements in collection systems, pre-treatment technologies, and recycling processes can increase material recovery and contribute to a more circular European PV industry.

Deliverable 6.1 demonstrated that the rapid deployment of photovoltaic systems across the EU is giving rise to an equally rapid increase in end-of-life PV panels. By 2030, the cumulative installed PV capacity is projected to reach approximately 816 GW (±21%), resulting in annual PV waste generation of around 326 kt (±39%)—an almost 180-fold increase compared to 2010. Consequently, what is currently a relatively niche waste stream is expected to become an increasingly important source of secondary raw materials.

However, the development of collection and recycling systems has not kept pace with this growth. Deliverable 6.1 estimated that only 40% of PV waste was formally collected in 2022, substantially below the 85% collection target established by the WEEE Directive. Without improvements in collection, pre-treatment, and recycling, a growing share of valuable materials embedded in end-of-life PV panels will remain unavailable for domestic recovery, limiting the contribution of PV recycling to European resource security and circularity.

Building on these findings, Deliverable 6.2 investigates the opportunity represented by this emerging secondary resource stream while identifying the bottlenecks that currently constrain its utilisation. The deliverable evaluates the European PV recycling value chain, assesses collection systems and reverse logistics, examines the recyclability of current and novel PV technologies, and quantifies the domestic sourcing potential of recovered materials. By combining technical assessments, market analyses, case studies, and stakeholder consultations, Deliverable 6.2 provides a comprehensive evaluation of how advanced recycling solutions can improve material recovery and strengthen the circularity and resilience of the European PV sector.

1.2. Structure of the deliverable

The deliverable is structured around three main chapters that follow the analytical progression of Task 6.2, from the methodological framework to the presentation of results and the formulation of conclusions and recommendations.

Chapter 2 presents the methodological framework used to assess the circularity and domestic sourcing potential of end-of-life photovoltaic panels in the European Union. It first describes how the domestic sourcing potential of secondary raw materials for PV panels was assessed by explaining how the data collected as part of this exercise was combined with the previous findings of the Task 6.1 which examined the stock and flows of PV panels in the European Union. It further lays out the methodology used to estimate potential post collection material flows. Additionally, the approach for the individual desk studies to investigate the PV recycling chain bottlenecks and structural gaps, as well as the field study and sampling activities is given in greater detail. The chapter further presents the structure of the case studies conducted in Italy and France, which examine collection systems, reverse logistics, recycling standards, and the practical feasibility of introducing improved collection and treatment approaches. Finally, it describes how technical, economic, market, and stakeholder information is integrated to assess the domestic sourcing potential and wider applicability of the EVERPV recycling solutions.

Chapter 3 presents and discusses the results obtained through the application of this framework. It brings together the findings on material composition and recyclability, the European recycling value chain, collection and logistics, the case studies, and the estimated availability of secondary raw materials under current and improved conditions. The chapter also considers the technical, economic, and market factors influencing the uptake of the technologies developed within EVERPV.

The concluding chapters summarise the main conclusions of the deliverable and provide recommendations for improving the collection, treatment, and recovery of materials from end-of-life PV panels. It highlights the main opportunities and limitations identified in the assessment and outlines measures to support the wider deployment of circular PV recycling solutions in the EU.

1.3. Relation with other activities in the project

Deliverable 6.2 connects the technological development activities of EVERPV within the work packages 1 to 4 with a market-level perspective obtained as part of the desk studies and field studies conducted in WP6. It places the project's experimental results within the broader context of PV waste generation, collection, recycling, and secondary raw material demand in the European Union.

The deliverable builds on the benchmarking and development of delamination technologies in WP2. Data on the performance of current and innovative pre-treatment processes are used to extend the stock-and-flow model developed in Deliverable 6.1 and to estimate the material fractions that may become available for subsequent recovery. This allows the project's technological results to be considered in relation to the present and projected volumes of end-of-life PV panels in the EU-27.

The estimated pre-treatment outputs also provide a link to the recovery, purification, and characterisation activities undertaken in WP3 and WP4. Deliverable 6.2 places these experimental results in a wider system perspective by assessing the volumes of relevant material fractions that could become available under different collection and treatment conditions. This supports the interpretation of the potential contribution of the project technologies to the domestic supply of secondary raw materials.

A further connection exists with WP5, which investigates the reuse of recovered materials. The assessment of material availability, quality requirements, market demand, and value-chain conditions provides context for evaluating whether recovered glass, silver, encapsulants, backsheets, and other material fractions can be reintroduced into PV manufacturing or related applications.

Stakeholder engagement undertaken under WP9 complements these technical links. Workshops and consultations with producer responsibility organisations, recyclers, industrial actors, and other relevant stakeholders supported the exchange and validation of project findings and helped identify practical conditions for the implementation and wider uptake of the EVERPV solutions.

Within WP6, Deliverable 6.2 bridges the quantification of PV stocks and waste flows in Deliverable 6.1 with the subsequent assessment of environmental, economic, and social impacts in Deliverable 6.3. As illustrated in Figure 1, it provides the market and value-chain perspective needed to contextualise the project's technological developments and modelled PV waste flows into an assessment of their potential implementation and impacts at the EU level.

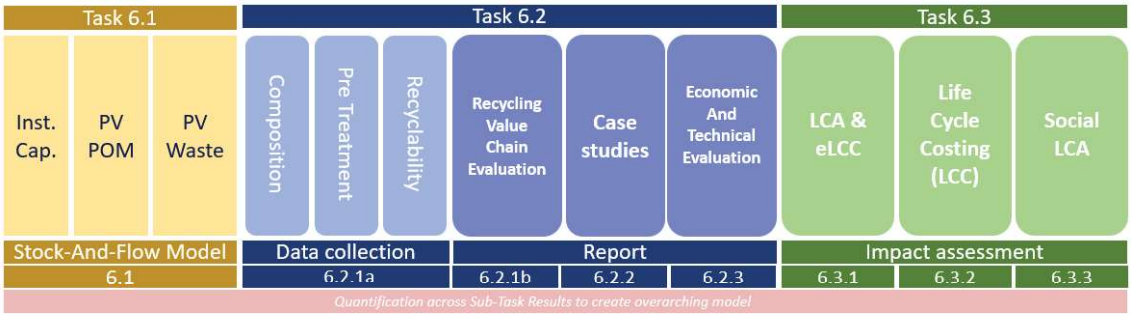


Figure 1 – Work Package 6 structure, tasks and deliverables

2. METHODOLOGICAL FRAMEWORK

2.1. OVERVIEW

The methodological framework applied in Deliverable 6.2 was designed to assess the domestic sourcing potential of end-of-life (EoL) photovoltaic (PV) panels within the European Union and to evaluate the broader circular economy potential of improved PV recycling systems. The approach integrates technical, material-flow, market, and stakeholder perspectives, thereby linking the quantitative waste modelling conducted under Deliverable 6.1 with practical implementation conditions across the PV recycling value chain.

The framework was implemented as an integrated sequence of activities within WP6, building on the stock-and-flow modelling of task 6.1 and generating insights for subsequent environmental, economic, and social assessments in Deliverable 6.3. As illustrated in Figure 2, the work was divided into four main analytical stages: the data gathering stage, the quantification of the results by integrating the stock-and-flow model of the deliverable 6.1, the evaluation of the collection system, and finally a market perspective evaluation. In parallel, a holistic perspective of the PV recycling chain was generated through a desk study assessment of the PV recycling value chain.

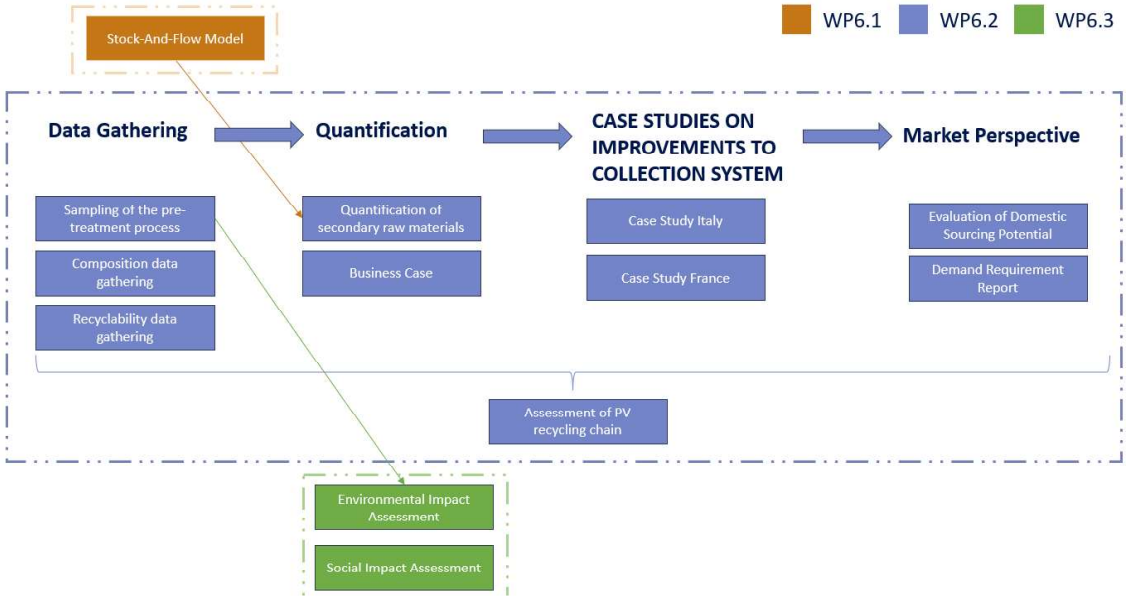


Figure 2 – Task 6.2 activity sequence

Data Gathering

The first stage involved the collection of technical data required for the domestic sourcing assessment. Sampling activities were carried out to characterise both collected PV panels and output fractions from pre-treatment processes. In parallel, composition data and recyclability data were compiled through several channels, including consortium partners, literature research, and project insights, as well as collaboration with relevant external partners.

Quantification

The second stage translates particularly the pre-treatment data into the potential availability of domestic secondary raw material availability. Pre-treatment data gathered from WP2 was connected with the stock-and-flow model developed in Task 6.1.

The analysis focused primarily on the key materials targeted within the EVERPV project, namely silver, glass, encapsulant, and backsheet fractions. Performance comparisons were made between the different technologies within the project to assess the best recycling and recovery solutions.

Collection and Reverse Logistics Examination

The third stage focused on understanding how collection systems and transport logistics influence the efficiency of pre-treatment and recycling operations. Two case studies were conducted in Italy and France. These case studies assessed current collection practices, logistical constraints, recycling standards, and opportunities for introducing innovative collection methods. Particular attention was given to how reverse logistics can affect recyclability, treatment costs, and recovery performance.

Market Perspective

The final stage evaluated the technical and economic feasibility of deploying the demonstrated recycling solutions at wider scale. A business case assessment compared EVERPV innovations with existing treatment technologies, considering operational costs, labour and energy inputs, and the market value of recovered secondary raw materials.

In addition, consultations with industrial stakeholders were undertaken to identify potential users of recovered materials and assess end-user requirements regarding quality, quantity, availability, and price. This provided practical evidence on market readiness and commercialisation pathways for recovered PV materials.

A complementary desk study assessed the current European PV recycling chain, identifying existing actors, structural gaps, and bottlenecks that may limit the development of a closed-loop recycling industry in the EU. This step provided the market and operational context for interpreting the technical recovery potential.

Integration within WP6

As outlined in Chapter 1.3, Figure 1 presents the overall structure of WP6 and illustrates how the individual analytical components contribute to the progression from waste quantification to sustainability impact assessment.

Deliverable 6.2 provides the market and value-chain perspective between the quantification of PV stocks and waste flows in Deliverable 6.1 and the environmental, economic, and social impact assessment undertaken in Deliverable 6.3. The methodological framework operationalises this role by translating modelled PV waste flows into estimates of recoverable material fractions and by examining the practical conditions under which these materials can be collected, treated, and returned to the market.

To this end, the framework combines the analysis of collection systems and reverse logistics with material characterisation, recyclability assessment, secondary raw material quantification, and the evaluation of technical, economic, and market conditions. This integrated approach supports the assessment of the domestic sourcing potential, replicability, and scalability of PV recycling solutions at EU level.

2.2. EVALUATION OF DOMESTIC SOURCING POTENTIAL

2.2.1. Composition data gathering

Overview

The quantitative evaluation of the domestic sourcing potential connects the previously assessed stocks and flows of silicon PV panels in D6.1 to composition data generated within task 6.2 and recyclability data (more specifically pre-treatment data) generated in WP2 and gathered within task 6.2.

Data structure

The required data for this task needs to be highly detailed to allow for a comprehensive evaluation of the recyclability potential. It is, for example, insufficient to merely have information on the elemental composition of PV panels. For subsequent treatment processes, it is highly relevant in which part of the PV panel each element is located and in which quantities, as some parts of the PV panel may be removed during pre-treatment or are not undergoing recovery for certain elements.

To ensure that these insights can be generated, this task followed a data structuring method developed in the FUTURAM project[5], the so-called product-centric approach.[6] In this approach, data is stored in a tree-structure, a hierarchical compositional model in percentage values of total weight.

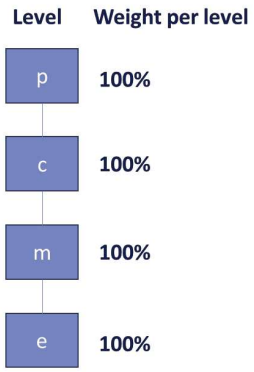


Figure 3 – Data structure of the product-centric approach

Each product is divided into four layers, a product layer (hereafter: p-layer, or "p") that sits at the top, a component layer (hereafter: c-layer, or "c"), a material layer (hereafter: m-layer, or "m"), and an element layer (hereafter: e-layer, or "e") that sits at the bottom. This structure is illustrated in Figure 3. Each level is self-contained, meaning that all individual data points on the same level sum up to 100%. The illustrated product is the simplest form where there is only one value branch, meaning that there is one child-value to each parent-value. The component value has one corresponding material value, and the material value has one corresponding element value. The structure illustrated is linear.

[5] FutuRaM: Future availability of secondary raw materials (Horizon Europe Grant Agreement No. 101058522) [Research project]. (n.d.). https://futuram.eu/

[6] Kippert, K. et al.,Methodology paper—Composition data collection and consolidation (FutuRaM Milestone 23, Version 2) [Project milestone]. Zenodo. https://doi.org/10.5281/zenodo.20392742

In reality, products rarely offer such a simplified composition but are much more complex. As each component can be made up from several materials, and each material can in turn be a compilation of various elements, such branches resemble complex value structures. Therefore, each product tree usually has several value branches, each of which is self-contained, meaning that all child-values of a given branch-segment sum up to the corresponding parent value. This concept is illustrated in Figure 4.

As elaborated above, the data structure uses only relative share values, thus the value of each data point is dependent on the corresponding parent value. In the subsequent example, relative share values are indicated in bold, whereas absolute share values are indicated in italic.

The given product amounts to 100% of total weight and possesses three components (Component 1, Component 2, and Component 3). Together, the components make up 100% of the relative value share (in bold). As the parent value is 100%, the absolute share value, indicated in italic, is the same as the relative share value.

This example gets more illustrative at the material level, in which three materials (Material 2.1, Material 2.2, and Material 2.3) make up Component 2. Together, these materials account for 100% of the relative share value. However, the absolute share value would be the weight of Component 2 itself, indicated in italic.

Similarly, Material 2.2 is divided into three elements (Element 2.2.1, Element 2.2.2, and Element 2.2.3). These elements account for 100% of the relative share value (bold) and amount to the absolute share value (italic) of 20%, the corresponding weight of Material 2.2.

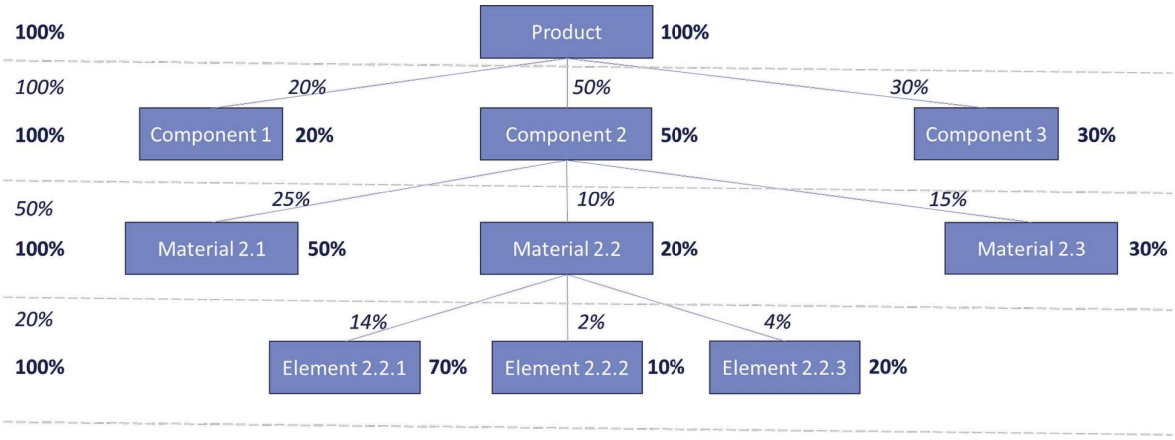


Figure 4 – Data structure of a complex product

To store the data in this structure, the data storing template from the FUTURAM project was adapted to the project and utilised by project partners and the researchers to store the data. The data template used is added to ANNEX I.

Data collection

While data was collected in a variety of ways, literature research formed the bedrock of the data collection. For literature to qualify for consideration, a variety of conditions need to be fulfilled. The papers examined needed to specify the panel technology, as only mono-silicon panels were considered. Furthermore, they needed to be published relatively recently (cut-off year: 2016; maximum age: 10 years) to ensure that the reported

compositions remain representative of a rapidly evolving technology. Lastly, the papers needed to provide an almost completely mass-balanced composition, meaning that the reported composition accounted for more than 90% of the total product weight, if applicable.

From the 12 examined papers that met all the cut-off criteria, a total of 39 product data points were retrieved. Some papers, such as Latunussa et al., 2016[7] would examine a time series or several products, therefore providing several product data points. These data points were subsequently evaluated for the quality and completeness. One important exclusion criterion was the presence of elements commonly found in silicon PV panel, particularly those identified as focus elements within the EVERPV project. For example, if no silicon was contained in the data provided, the paper was discarded.

As the papers examined did not follow the product-centric approach of FUTURAM, some challenges occurred when recording the data into the described structure, and certain information gaps arose. In many cases, the studies did not specify the component or material in which particular elements were present, while in others only material- or component-level information was provided, without a corresponding elemental breakdown.

Therefore, a gap-filling exercise was conducted. In the former case of unknown location of materials, a manual allocation was made for the elements to potential materials and components to the best of the authors' knowledge and with the support of technical partners. In the latter case of gaps in the element breakdown, the missing element composition was essentially ignored. In practice, it was filled with the average element composition of all other eligible data points for the corresponding branch values, having no further impact on subsequent calculations.

After this correction, the data was further pushed into the storing structure and arithmetically averaged across each branch and segment to obtain one single data point per branch segment (or e-m-c-p combination).

The result of the computed composition was then compared with the FUTURAM-generated data and subsequently reviewed by the technical partners of CEA. The values were adjusted, where necessary, based on the expert knowledge, proprietary data in their database, and previously conducted research by CEA.

Data computation

The finished and verified composition data set was then integrated into the stock-and-flow model under 6.1, which converts projected installed capacity into kg of PV panels placed on the market (POM). To develop this stage, those volumes were multiplied by the harmonised composition data, which was calculated as %-shares.

The composition-extended POM in a given year was subsequently paired with a corresponding lifetime assumption for the same year. A Weibull distribution was used to compute the PV waste generated on an annual basis. The stock-driven calculation and

[7] Latunussa, C. E. L., Ardente, F., Blengini, G. A., & Mancini, L. (2016). Life cycle assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Solar Energy Materials and Solar Cells, 156, 101–111. https://doi.org/10.1016/j.solmat.2016.03.020

waste generated computation remained unchanged and was specified in Deliverable 6.1[8], in line with the e-waste guidelines.[9]

As the input to the model is now the composition-extended POM, the output similarly is composition-extended PV waste generated, following the formulas

Furthermore, the composition was associated with the waste flows (collected, exported, other) using the same calculation method. The results for the collected PV waste generated were then ready to be utilised to calculate the domestic sourcing potential by linking the data set to the recyclability assessment (see Chapter 2.2.2). Figure 5 illustrates this process.

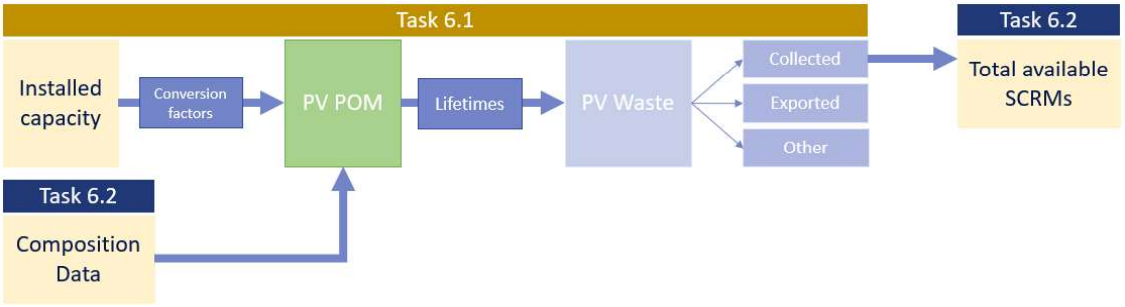


Figure 5 – Schematic data pipeline linking Task 6.1 and Task 6.2

2.2.2. Recyclability assessment

The recyclability assessment focused primarily on the pre-treatment process and the resulting material separation and losses during this process. In particular, the following pre-treatment technologies were examined: (1) Shredding, (2) Hot-knife, (3) Sanding, (4) Infrared+tear off Delamination (IR+tear off Delam), (5) Hybrid Hot-knife Sanding.

[8] Forti, V., Schubert, M., & Vermeersch, E. (2025). *Market assessment of PV and quantification of PV waste and waste streams in EU* (EVERPV Deliverable D6.1) [Project report]. EVERPV. https://everpv.eu/wp-content/uploads/2025/06/EVERPV-Deliverable-6.1-REPORT-Market-assessment-of-PV-and-quantification-of-PV-waste-and-waste-streams-in-EU.pdf

[9] Lysaght, O., et al. (2026). E-waste statistics: Guidelines on classifications, reporting and indicators (3rd ed.). United Nations Institute for Training and Research, Sustainable Cycles Programme. https://doi.org/10.5281/zenodo.18328494

Apart from shredding, which is the current standard practice for PV treatment in EU, all technologies were developed or employed by project partners and applied in WP1 and WP2. This enabled a particularly accurate data gathering process. Hot-knife is employed by ENVIE, Sanding is developed and employed by CEA and employed by ENVIE. IR+tear off Delamination is developed by ENEA and Betatech and set up/employed by 9tech, and the hybrid Hot-knife and Sanding is employed by ENVIE. The pre-treatment methods are laid out in Figure 6Figure 6 with their intermediate and final outputs. These outputs are

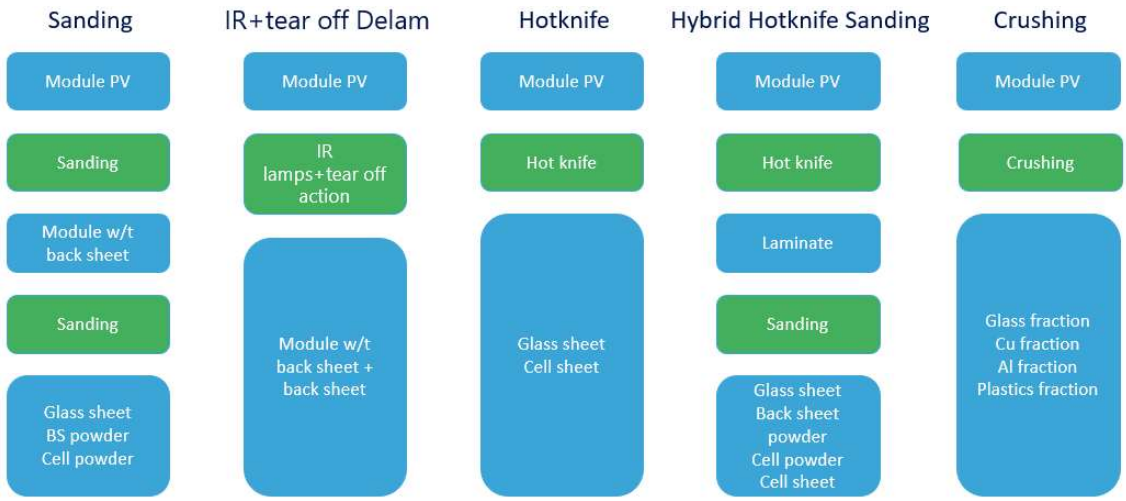


Figure 6 – Pre-treatment technologies and outputs

further explained in Chapter 3.2.2.

Data collection

To accurately capture the data and enable the integration with the previously computed composition-extended waste generated data, a data template was developed as illustrated in Figure 7 and attached in ANNEX II. This data template was distributed among the partners to submit their collected data. Detailed data was available as part of WP2 and the benchmark of the best delamination technologies for PV recycling. With the exception of shredding, for which data was procured from a PRO member of ERION, therefore representing the only external data source used in this process.

Technology: Sanding

Input Component	Input Weight	Output Component	Output Weight	Composition	Composition Weight
Product	1,000	Component 1	700	Material 1	200
Product	1,000	Component 1	700	Material 2	300
Product	1,000	Component 1	700	Material 3	100
Product	1,000	Component 2	300	Material 2	150
Product	1,000	Component 2	300	Material 4	150
				All Materials	1,000

Figure 7 – Data collection template for pre-treatment efficiency data

The data template followed the specific pre-treatment process steps for each technology, wherein input and output materials were tracked along all steps. Each process output entered in the template could subsequently be re-entered as input component, allowing for a seamless tracking of materials throughout the pre-treatment. The provided data was validated through mass balance checks.

While the template had the same structure for different technologies, the concrete process steps and process outputs are individual to each technology. For example, while the Hot-knife technology shaves off a so-called *cell sheet* (a combination of the PV panel backsheet and the solar cells), the Sanding technology produces powders from the PV panel backsheet and from the solar cell layer, respectively. The template allowed technology-dependent inputs for accurate material tracking.

Beyond the specific process outputs (which subsequently could be used as process inputs for further processing), the weights of each input and each output were recorded, as well as the associated composition of each output, including weight and material. The materials recorded as final composition output correspond to the material names (or material keys) which were used in the composition-extension of the stock-and-flow model. Additionally, a parameter was recorded to determine if the materials found in the output are target materials, or contaminants.

It should be noted that concrete recovery data beyond the pre-treatment was not available for several reasons. First and foremost, this data is often proprietary and is kept confidential by recyclers due to competitive reasons. No large-scale recycler was part of this project who could share data. Secondly, the Sanding technology is novel and does not yet have established recycling processes that work with the products of this pre-treatment. Therefore, the Sanding technology and the Hybrid Hot-knife Sanding approach are not yet evaluated on an industrial scale.

Data Computation

The data collected in the previous step was then converted into material flows along the pre-treatment processes. The data structure is similar but not equal to what was described under 2.2.1 Data structure of the composition data, following a hierarchical tree-structure. Similarly, each final material can be linked to only one process-component combination. By dividing the final material value by the original input value, a percentage-share of each material along each step can be determined, the treatment coefficient. Thus, based on the masses recorded for each material, a flow-model can be generated and efficiency values calculated, as illustrated in the equations below.

The produced Sankey-diagrams are always mass-balanced. Losses along the processes are shown as specific “loss” flows in order to keep the mass-balance. Losses occur due to improper collection of the output materials in the process, inefficiencies of the process itself (improper separation), or breakdown of the panel (e.g., glass breakage of panel). Additionally, losses of materials may occur due to improper separation and thus contamination of another flow. While these losses do not show as specific loss flows, they contribute to reduced material recovery and thus a reduced treatment coefficient, as shown in the equations above.

The MFA concept is illustrated with a Sankey diagram in Figure 8.

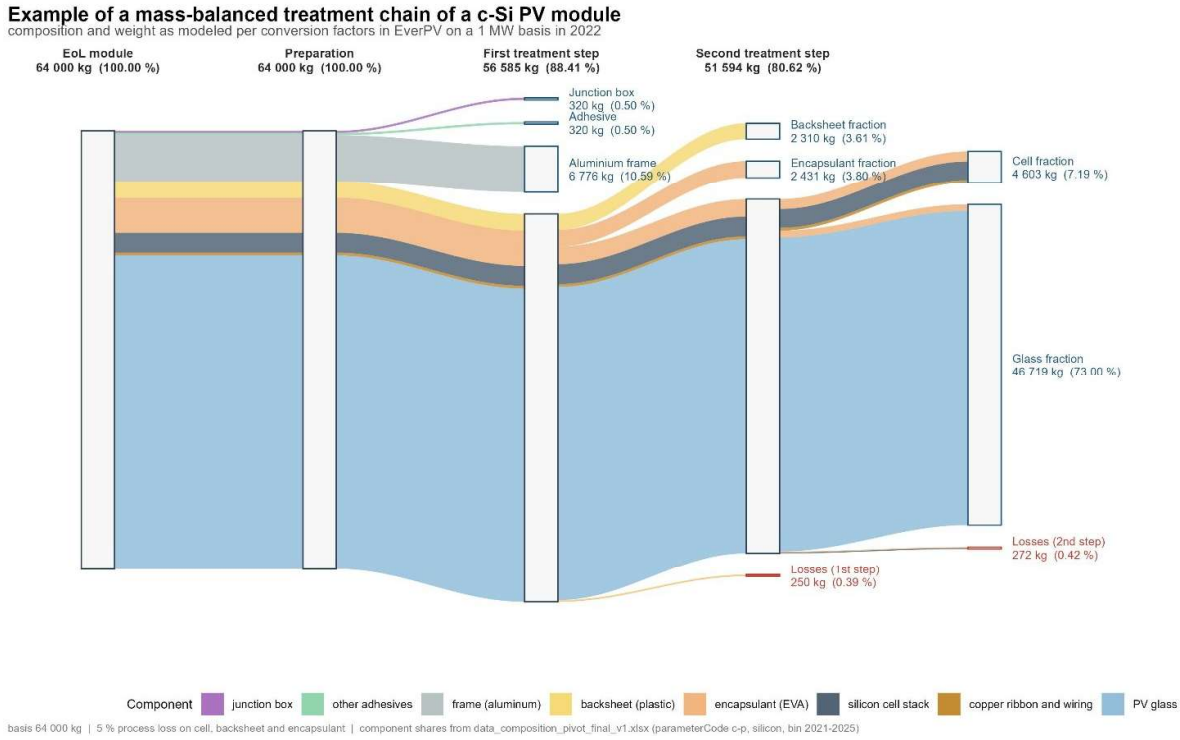


Figure 8 – Example Sankey Diagram

A different methodology was applied for the shredding treatment as this was the only treatment technology not directly used within the project. Therefore, the data procured by ERION and disclosed in 3.4 - Case studies on the recycling efficiencies - Sampling Activities was used to make assumptions about the fraction destination of different materials. Since the evaluated composition of the PV Panels provided by the treatment operator did not entirely overlap to the model composition of the EverPV project, certain inferences were made in order to apply to the modelled composition.

The inferred shredding efficiency values are subsequently applied to the entire flow of crystalline silicon panels, as there is no requirement for structurally intact panels as it is the case for all other treatment routes investigated.

The ferrous fraction reported by ERION is excluded from the balance as this material was not found to be part of the targeted panels in the EverPV project, which assumed mainly aluminium frames with very little iron share. Only screws as contaminants, about 0.02 % as trace Fe in the aluminium alloy and the glass, were modelled.

The chemical analyses of the individual fractions provided in chapter 3.4 are used to determine which panel component ends up in which fraction to which extent. Specifically, as contamination of fractions is an issue in the shredding treatment, this was necessary.

The powder fraction is assumed to be 50.0 % cell-stack material by mass based on the respective mass flows reported, contaminated with 7.9% organic content, based on the chemical residue analysis. The remainder of the mass flow is assumed to be the copper ribbons as part of the cell stack and glass residue as cross-contaminant.

The aluminium fraction is built from the frame at the stated purity. This gives the fraction a flow of 10.83% rather than the reported 11.57%, leading to the assumption of glass and plastic impurities at a 60% to 40% split, respectively.

The junction box is drawn at the modelled mass. The reported cable fraction exceeds the modelled junction box fraction and was therefore assumed to be overstated.

The plastics fraction represents the total remainder of the organics reported and not yet allocated, plus cross-contaminants of glass to reach the share reported.

The glass fraction takes glass plus the cell-stack material that was not allocated to the powder or elsewhere as a residual assumption rather than a measured one.

The loss flow is the sole remainder of all material masses that have not been allocated, which is mostly glass.

2.2.3. Quantification of secondary raw materials

In the final step, the previously computed total potential SCRMs and the efficiency values derived from the collected pre-treatment data are matched up based on the overlapping material keys and simply multiplied.

The model does not assume a share of pre-treatment technologies applied but compares each pre-treatment technology by computing the total available SCRMs for recovery after pre-treatment process if the complete input would be treated with only one technology.

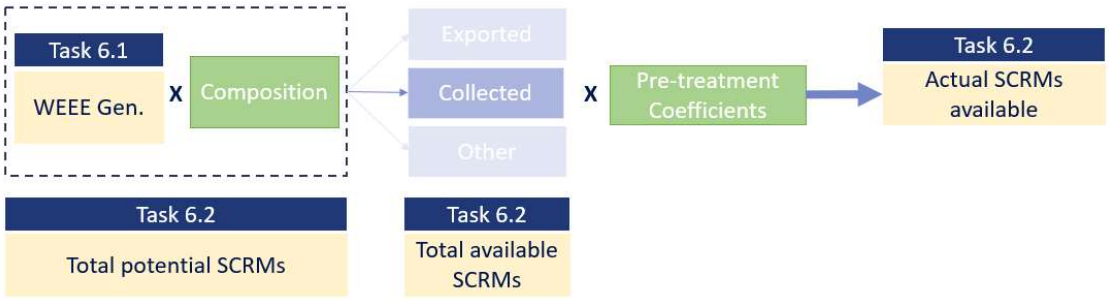


Figure 9 – Framework for the availability of secondary critical raw materials

The overall domestic sourcing potential of materials from end-of-life photovoltaic panels was quantified through a scenario-based material flow assessment. The calculation combines the PV waste flows established in Deliverable 6.1 with the composition assessed as described in 2.2.1, and the pre-treatment as assessed in 2.2.2. The approach follows the material through successive stages of the end-of-life chain, from waste generation and collection to pre-treatment and the recovery of individual material fractions.

Three levels of material availability can be distinguished as highlighted in Figure 9. The first represents the theoretical material potential, defined as the quantity of each material contained in the total PV waste generated. This represents the theoretical ceiling for material availability under lossless collection and recovery conditions, the *total potential SCRMs*. The second represents the collection-constrained potential, which includes only the materials contained in PV panels entering formal collection systems. This represents the theoretical ceiling for material availability within the treatment system, the *total available SCRMs*. The third represents the technically recoverable potential, accounting for material losses and the separation efficiencies associated with the respective pre-treatment and recycling processes, henceforth referred to as the *actual available SCRMs*. This level is the main focus of the subsequent results, as the quantities recovered differ considerably between the applied pre-treatment processes.

However, the technically recoverable potential is also strongly influenced by collection practices. Improving the collection and delivery of physically intact PV panels increases the quantity of material reaching specialised pre-treatment processes and therefore has considerable potential to increase the amount of material available for recovery. Collection performance thus represents another major lever for enhancing domestic sourcing potential and is investigated further in Chapter 2.3.

The calculation begins with the annual PV waste generated, as estimated in Deliverable 6.1 by country, technology, application, and year, specifically using the middle-of-the-road scenario. These results are combined with the material composition of the relevant PV technologies to determine the quantity of each material embedded in the waste stream. For a material (m), the theoretical material potential in year (t) is calculated as:

where:

$Material_{theoretical}$ is the theoretical quantity of material (m) available in year (t); WEEE is the quantity of PV waste generated for silicon PV panels (i) in year (t); and S is the mass share of material (m) within silicon PV panels.

The amount entering the formal recycling chain is subsequently determined by applying the relevant collection rate:

where (C_t) represents the proportion of PV waste formally collected in year (t). The comparison between the theoretical and collection-constrained potential shows the quantity of material that remains unavailable for domestic recycling because the corresponding panels do not enter the formal collection system.

The collected material quantities are then linked to data on the performance of current and innovative pre-treatment technologies. For each treatment route (r), the quantity of material transferred to a separated output fraction is calculated by applying the respective pre-treatment yield:

where $Y^{pre\text{-}treatment}$ describes the share of material (m) transferred into the relevant output fraction under the respective treatment route (r).

The resulting value represents the quantity of material that could potentially become available as a secondary raw material after collection and pre-treatment. The assessment focuses primarily on the fractions addressed within EVERPV, including glass, silver, encapsulants, and backsheet.

Current and future domestic sourcing potential were assessed by varying the main parameters governing the calculation. The current-system assessment reflects existing collection performance and the recovery efficiencies of established treatment routes. Improved conditions are assessed by combining higher collection rates with the performance of the technologies demonstrated within EVERPV. The central PV waste projections from Deliverable 6.1 provide the reference values, while the lower and upper projections define the boundaries associated with future PV deployment and disposal patterns.

The treatment routes are assessed comparatively. Material outputs calculated for different technologies therefore represent alternative processing conditions and are not added together. This avoids double counting the same collected PV waste across multiple treatment routes. At each calculation stage, mass-balance checks are applied to ensure

that the sum of the resulting material fractions does not exceed the mass of the corresponding parent flow.

The results are calculated at the EU-27 as a whole as this is a theoretical exercise. As treatment capacity for various technologies is largely estimated (see Chapter 2.5) and technologies investigated within this project are not broadly available on the market yet, country differences were irrelevant.

2.3. CASE STUDIES ON IMPROVEMENTS TO THE COLLECTION SYSTEM

2.3.1. Scope and target

The collection and logistics stages play a crucial role in shaping the overall performance of photovoltaic panel end-of-life management systems. Beyond determining the efficiency of waste flows, these activities directly influence the quality of the material entering treatment facilities and, consequently, the effectiveness of subsequent recycling processes. Handling practices, packaging methods, palletisation schemes, storage conditions, and transportation arrangements can significantly affect the physical integrity of photovoltaic modules, leading to glass breakage, component damage, contamination, or the mixing of different technologies. Such factors ultimately influence pre-treatment requirements, process stability, material recovery yields, and the quality of secondary raw materials obtained.

The objective of the present case studies is to understand how current collection and logistics practices influence the condition of PV modules before treatment and, ultimately, affect the performance of downstream recycling operations. Particular attention is devoted to packaging and palletisation practices, as these represent critical interfaces between collection, transport, storage and recycling activities.

For this reason, the present studies investigate operational practices adopted along the collection and logistics chain through the analysis of real end-of-life photovoltaic waste streams in Italy and France. The assessment focuses on identifying operational constraints, evaluating current practices and highlighting opportunities for improvement capable of preserving module quality throughout the logistics chain.

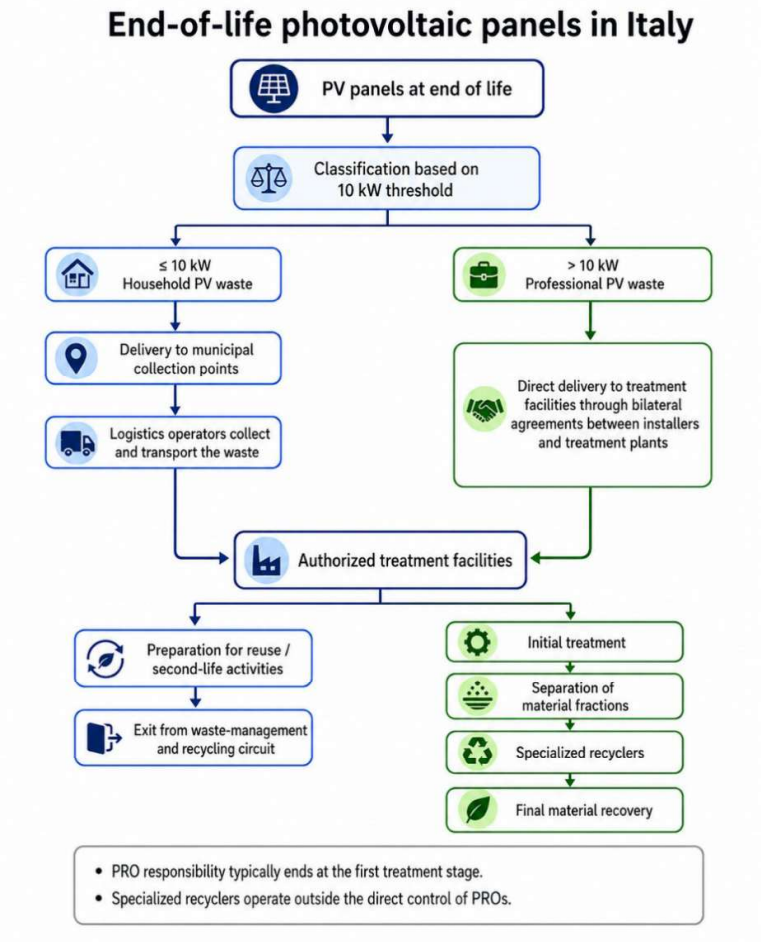
Italy and France were selected as case studies because they represent two mature but structurally different end-of-life PV management systems within Europe. Analysing both contexts makes it possible to identify operational challenges that are common across different organisational models, while also highlighting country-specific factors that may influence collection efficiency, logistics performance and recycling readiness. The comparison therefore provides a broader understanding of how organisational and operational choices can affect the overall circularity of PV waste management systems.

2.3.2 National collection systems and case study context

2.3.2.1 Italy

The end-of-life value chain of photovoltaic panels in Italy is strongly shaped by a regulatory threshold of 10 kW, which determines the classification and subsequent management of the waste. Below this threshold (≤10 kW), photovoltaic waste is considered household waste and, in principle, should be delivered to municipal collection points. From there, it falls under the responsibility of PROs and enters the national WEEE system, where flows are tracked through the Clearing House. The waste is then handled by logistics operators that transport

it to authorized treatment facilities accredited within this system. These facilities perform the initial treatment, separating the different material fractions and directing them toward specialised recyclers. It is important to note that recyclers operate outside the direct control



of PROs, whose responsibility typically ends at the first treatment stage.

Figure 10 – Diagram of Italian collection and logistics process

For photovoltaic waste above the 10 kW threshold (>10 kW), classified as professional waste, the flow differs: delivery to treatment facilities occurs directly through bilateral agreements between professional installers and treatment plants, bypassing municipal collection points and the PRO-managed system. In both cases, however, treatment facilities may also carry out preparation for reuse (second-life activities), extending the lifespan of components before final recycling.

In practice, however, citizens' direct delivery of photovoltaic waste to municipal collection points is often difficult due to the nature of the waste itself and because collection points are frequently not equipped to accept this specific waste stream. As a result, even for panels formally classified as household waste, citizens commonly rely on professional installers for removal and handover. Consequently, a very large share of photovoltaic waste is managed in practice similarly to professional waste, through direct relationships between installers and treatment plants rather than through municipal collection channels. This particular state-

of-affairs place a key role upon figures such as logistics operators, who manage large volume of waste and direct it to treatment operators, installers, who can manage the newly generated waste, and treatment centres. The collection of end-of-life photovoltaic modules is a key step that strongly influences all subsequent treatment stages, especially in such a fragmented market, with multiple operators and managing practice. Panels are usually organised in pallet directly by the installers dismantling the PV plant, then their logistics is handled either directly via agreement with treatment centre or via agreement with large scale logistics operator, especially in the case of large PV fields. Handling, palletisation, packaging, and transport conditions have a direct impact on the physical state of the modules, including component damage or loss, glass breakage, the presence of impurities, and the mixing of different technologies. These issues are often linked to operational constraints encountered on site and later affect pre-treatment options, process stability, and potentially the yields and quality of the recycled fractions.

Another distinctive feature of the Italian system is the coexistence of multiple regulatory provisions governing the end-of-life management of photovoltaic panels. These provisions overlap and differ mainly in terms of the financing mechanisms applied to collection and treatment activities, as well as in the level of the financial contributions required. The key distinction is between photovoltaic panels installed under the Conto Energia[10] built-in tariff scheme and panels not incentivised through this mechanism. For the former, the end-of-life financing system is linked to the incentive framework and relies on specific rules and contribution levels. For the latter, responsibility falls within the usual producer responsibility framework and is currently based on financial guarantees and trust funds associated with the panels placed on the market. This fragmentation creates a complex regulatory landscape, in which similar waste flows may be subject to different financial obligations depending on the date of installation, the incentive status of the panel and the applicable legal regime. As a result, the Italian case is characterised not only by operational complexity, but also by a structurally heterogeneous financing architecture that makes the assessment of long-term cost coverage particularly relevant.

2.3.2.2 France

As previously noted, the end-of-life value chain for photovoltaic panels in Italy is strongly influenced by a regulatory threshold expressed in kilowatts, whereas no such threshold applies in France. In the French context, SOREN acts as the Producer Responsibility Organisation, and the collection system differentiates waste holders according to the volumes they hold, in line with the organisational framework established by SOREN.

An operational threshold of around 40 photovoltaic modules is used to distinguish two main situations: small volumes, mainly coming from residential systems or small installations, and larger volumes, typically generated by ground-mounted solar power plants or rooftop solar

[10] International Energy Agency. (2025, June 25). *Feed-in premium for photovoltaic systems (Conto Energia V).* https://www.iea.org/policies/5210-feed-in-premium-for-photovoltaic-systems-conto-energia-v

power plants. This distinction shapes the overall logistics and directly influences packaging, scaling up collection volumes, and transport practices.

For volumes below 40 panels, collection mainly relies on Voluntary Drop-off Points. Waste holders, such as individuals, small operators, or installers, deliver the PV panels to these dedicated points, where they are temporarily stored before shipment. This system ensures wide territorial coverage but leads to a high diversity of storage and packaging practices, with fragmented volumes and variable storage durations.

After the collection phase, panels are transferred to Collection and Consolidation Centres, which play a key role in the logistics chain. These centres allow the consolidation of flows, intermediate storage, and preparation of batches for transport to treatment facilities. For example, flows collected at Voluntary Drop-off Points are consolidated, operators re-palletise the material when the condition of the pallets is considered unsatisfactory and poses a risk for transport or handling. When pallets contain PV modules of mixed technologies, they are dismantled and re-palletised so that each pallet contains a single technology.

For volumes above 40 PV panels, collection is organised directly at the waste holder's site through on-site pick-up operations. These larger and more homogeneous flows simplify logistics, although they remain highly dependent on dismantling and preparation practices implemented at the project sites.

However, when the collected volumes allow for a full truckload, the modules are transported directly to the Treatment Centre. If a full truckload cannot be achieved, the flows are first routed to a Collection and Consolidation Centre before onward transport. This organisation aims to optimise truck loading rates, reduce transport-related carbon emissions, and improve overall logistical efficiency. It should be noted that a full truckload can hold approximately 14 pallets with average dimension of 180 × 120 × 130 cm.

Treatment Centres represent the final step of upstream logistics, where the modules enter pre-treatment and recycling operations.

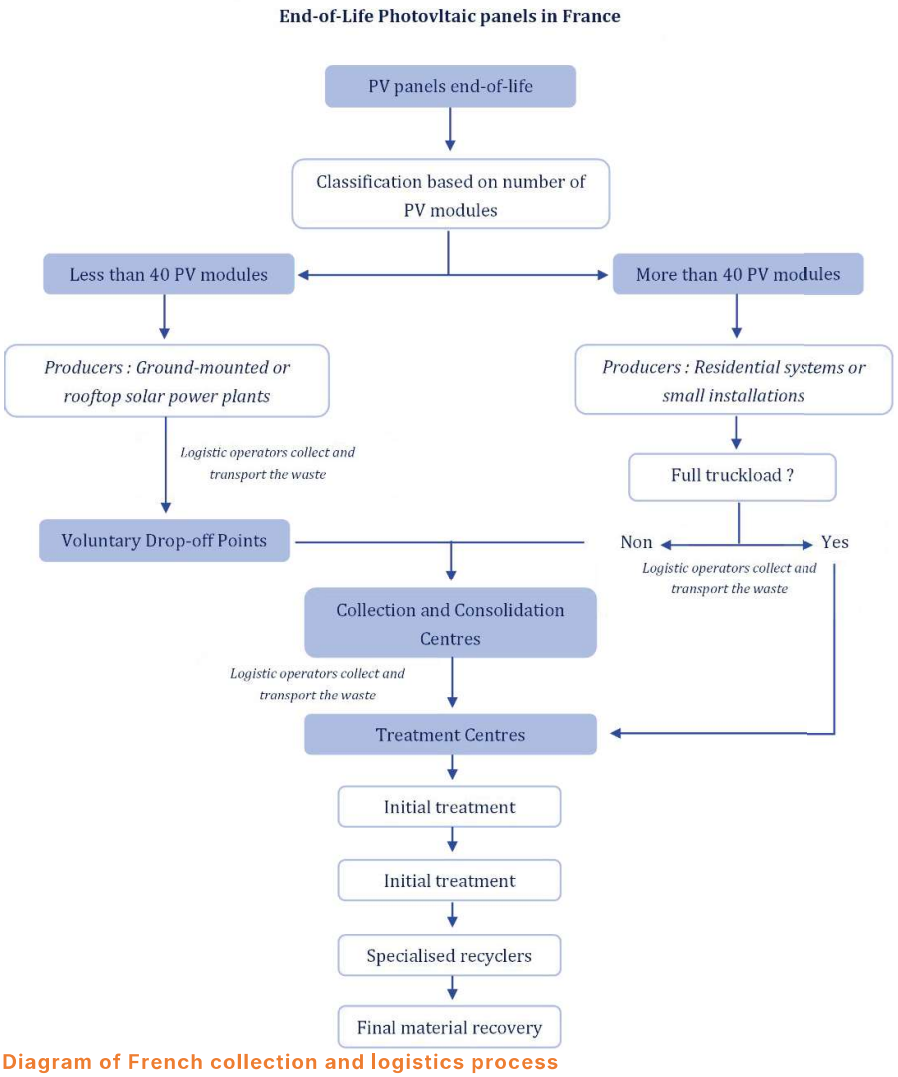


Figure 11 – Diagram of French collection and logistics process

2.3.3 Common methodological framework (ERION and SOREN)

Although the Italian and French case studies differ in their operational implementation, both analyses were developed around a common methodological framework designed to assess how collection and logistics practices influence the quality of photovoltaic modules entering treatment facilities.

The framework was designed to ensure comparability between the two national case studies while accounting for the specific characteristics of each collection system. To achieve this objective, the same analytical categories, stakeholder groups and evaluation criteria were adopted in both countries. The clustering of responses was intended to support a structured comparison between the Italian and French cases. In particular, it allows the analysis to distinguish between issues that are common to both countries and issues that may depend on the specific organisation of the national value chain. The use of common

thematic categories also makes it possible to assess whether improvement opportunities identified in one country may be relevant and transferable to the other. The methodological framework consisted of two complementary activities:

1. Stakeholder consultations;
2. Characterisation of incoming flows at treatment facilities.

Together, these activities provide a comprehensive understanding of current collection practices and their influence on downstream recycling operations.

2.3.3.1 Stakeholder consultations

SOREN and ERION, the two Producer Responsibility Organisations (PROs) involved in the project, conducted interviews with stakeholders directly involved in the management of end-of-life photovoltaic modules, respectively for France and Italy, in order to identify operational issues and constraints across all stages of the value chain.

In France, the analysis focused on providing an overview of the collection and acceptance conditions applied under the SOREN system, including the possibility of feedback from transport providers who carry out palletisation and packaging operations. Building on this approach, the Italian analysis was therefore designed to follow, as far as the different systems allowed, the same logic and thematic structure adopted in France, while adapting the research to the specific organisation of the Italian end-of-life photovoltaic product value chain.

The survey relied on consultations with key operators representing the main functions involved in the management of end-of-life photovoltaic modules and covered complementary operational perspectives, including:

- holders of photovoltaic modules (limited to the French case),
- collection and logistics operators,
- pre-treatment and recycling operators, including those managing both treatment activities and internal logistics between facilities.

The operators consulted were selected based on their direct involvement in the Italian and French end-of-life photovoltaic chains and their practical knowledge of the operational steps under investigation. Taken together, these actors provide a representative view of the system, as they cover significant shares of national flows and a diversity of roles within the value chain.

The diversity of stakeholders consulted enabled cross-checking of operational perspectives and the collection of feedback on current practices, encountered difficulties, and potential areas for improvement. The interviews helped to clarify the specific constraints associated with each stage of the chain and how these constraints influence palletisation, packaging, and handling practices. For confidentiality reasons, individual

operators are not identified, and their contributions are presented in an aggregated and anonymised manner.

The questionnaire was structured to collect information on a common set of parameters, as shown in Table 1.

The details of the questionnaire can be found in ANNEX III .

These included: (i) pallet procurement and availability, (ii) number of pallets per truck, (iii) storage duration and conditions, (iv) strapping and wrapping practices, (v) module orientation on pallets, (vi) pallet dimensions, (vii) maximum pallet height, (viii) loading and unloading operations, (ix) transport securing practices, and (x) possible improvement options.

The questionnaire also included specific questions on cable management, vertical palletisation, reduction of the number of modules per pallet, and measures to limit breakage during handling and transport.

Table 1 – Set of parameters taken into account in the questionnaire

Type of issue	Waste holders	Collection / transport operators	Treatment centres
Technical	Feasibility of palletisation and packaging practices, on-site glass protection	Pallet stability, load securing during transport	Module integrity, glass breakage upon arrival
Operational	palletisation and packaging time, availability of equipment, site constraints	Loading and unloading operations	Unloading efficiency depending on pallet quality
Economic	Time required for palletisation and packaging operations; cost of pallets and consumables	Optimisation of transported volumes	Additional costs linked to degraded flows; re-palletisation when pallets arrive in poor condition
Safety	Risks related to manual handling of PV modules and pallets	Transport stability, loading safety	Safety of operators during unloading

The parameters analysed were defined to cover the entire logistics chain, from the module holder or dismantling site to the treatment centre. This made it possible to consider not only the physical configuration of the pallet, but also the operational conditions in which palletisation and transport take place. Particular attention was given to the interaction

between different stages of the chain, since decisions made during dismantling or pallet preparation can affect transport efficiency, unloading operations and treatment activities.

Additionally, particular attention was given to issues related to glass breakage, which were identified as a critical concern for both the photovoltaic recycling sector and the EVERPV project, notably in France in connection with the sanding process developed within the project.

Finally, the questionnaire was structured to collect information on a common set of parameters aligned across both country case studies, in order to ensure consistency and comparability of the results. Based on the outcomes of the interviews conducted in France, a field case study was subsequently developed, focusing on priority improvement areas identified during the discussions, in particular those related to packaging practices and the reduction of glass breakage.

2.3.3.2 Characterisation of incoming flows

The second phase of the common methodological framework consisted of the characterisation of incoming photovoltaic (PV) module flows at treatment facilities. This activity was implemented in both Italy and France using the same sampling logic and observation parameters.

The objective of this phase was to assess the actual condition of PV modules upon arrival at treatment facilities and to verify the extent to which collection, packaging and transport practices are effectively applied in the field.

This approach makes it possible to establish a direct link between upstream logistics practices and downstream impacts, particularly on treatment operations.

The scope of the study focused primarily on waste streams originating from holders of large volumes of photovoltaic panels. This choice is primarily explained by their relative weight in national collection flows. For example, in France, in 2024, these streams represented a major share (>90%) of the total collected volumes (SYDEREP database, ADEME).

The characterisation activity was designed to measure the concrete impact of palletisation and packaging practices on the quality of photovoltaic panel flows entering Treatment Centres. The analysis aims to understand how collection conditions influence the condition of the modules upon arrival and to identify operational levers that could improve these practices at an industrial scale.

In France, palletisation and packaging practices are generally implemented in accordance with the requirements defined by SOREN, which acts as the only PRO for photovoltaic modules. This common framework results in a high level of harmonisation across sites and operators, thereby facilitating comparative analysis. In the French context, this work also provides a consistent baseline that feeds into the development of the field case study. By contrast, the Italian system is characterised by the presence of multiple actors involved in the collection and management of end-of-life photovoltaic modules, each potentially

applying different operational practices and packaging approaches. As a result, palletisation and handling conditions tend to be more heterogeneous, reflecting the diversity of collection pathways and operational arrangements observed across the national value chain.

To ensure consistency between the two national case studies, a common sampling protocol was implemented in cooperation with two treatment operators in Italy and one in France.

In total, 200 photovoltaic modules per treatment centre were examined.

In both countries, data collection was structured around two complementary levels of analysis: the pallet level, covering palletisation, packaging, and collection conditions, and the module level, focusing on the physical condition and completeness of the panels, as described in Table 2.

Table 2 – Parameters incoming flows

Parameters - Pallet Level	Parameters – PV module level
- **Pallet size compared to panel size:** pallet larger than the panel / same size / smaller - Strapping: pallet strapped (yes/no) - **Number of straps:** count (up to "5 or more") - **Wrapping:** pallet wrapped with plastic film (yes/no) - **Overall pallet condition:** free comments (e.g. stability, deformation, spacing, corner protection, stacking quality, presence of foreign elements)	- **Glass integrity**: glass intact (yes/no) - **Orientation**: glass facing upwards (yes/no) - **Sampling position within the pallet**: top / middle / bottom (to capture potential stacking effects) - **Technology / typology**: monocrystalline, polycrystalline c-Si, bifacial glass-glass, etc. - **Weight:** in kg. - **Other:** distance(km transported)

A common sampling procedure was applied across all sites. Each treatment centre was asked to select 25 photovoltaic modules per day, over two days per week, for a period of four weeks, until the target sample of 200 modules was reached. To improve representativeness, panels were selected from different locations within the storage area rather than from a single stack. This approach was intended to capture the variability typically observed in real end-of-life photovoltaic waste flows, as shown in Figure 12.

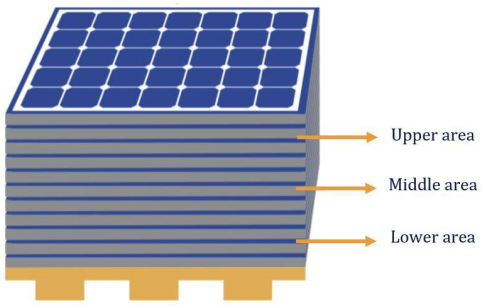


Figure 12 – Sampling area for PV modules on the pallet

These parameters make it possible to assess compliance with collection and acceptance conditions at the pallet level, while simultaneously evaluating the actual condition of photovoltaic modules upon arrival at the treatment centre.

By combining observations related to packaging conditions (pallets) with observations on panel condition (integrity, completeness, and position within the pallet), it is possible to directly link concrete logistics practices to measurable effects on the quality of incoming flows at the Treatment centre. This approach also helps to identify high-risk situations as well as practical levers to reduce glass breakage.

2.3.3.3 Additional field case study - France

This Chapter presents the study conducted exclusively in France and dedicated to the implementation of a field case study. Building on the information collected and analysed through interviews with stakeholders, as well as on the results of the characterisation of incoming flows at treatment centres, it was possible to develop a dedicated field case study for the French context.

SOREN cooperated with a PV waste holder to implement the field study. The objective of this on-site case study was to identify potential improvement pathways in the palletisation and packaging conditions required from operators.

The approach consisted of using only one model of photovoltaic modules for transport and asking the waste holder to palletise the modules in accordance with SOREN's standard requirements (Table 3), as well as according to alternative palletisation configurations selected by SOREN. This made it possible to compare different packaging practices under controlled and comparable conditions.

Table 3 – SOREN's requirements (packaging & palletisation)

Subject	Requirements
PV technologies	• Panels must be sorted by technology (crystalline silicon, CdTe, CIGS, etc.) • No mixing of different technologies on the same pallet
Palletisation	• Use size- and load-adequate pallets adapted to panel dimensions and weight • Panels placed flat and stable (square stacking preferred) • Maximum height: 1.70 m (EU Mainland) / 1.10 m (Overseas)
Panel positioning	• Panels must be placed front glass facing up • Avoid pressure points to prevent glass breakage
Strapping and film	• Minimum 2 straps per side (horizontal securing) • Straps must guarantee load integrity during transport • Pallets must be wrapped with film starting from pallet base • Preferably transparent film for visual inspection

The figure below shows a standard packaging method for photovoltaic panels in France.



Figure 13 – Standard packaging of a PV pallet

The study was designed as a quantitative analysis, with the waste holder's site defined as the starting point and a treatment centre as the final destination. SOREN requested the cooperation of ENVIE, which is also a member of the EVER-PV consortium, to support the implementation of this field study.

Throughout the entire operation, a comprehensive pallet tracking log was maintained to ensure full traceability of the photovoltaic modules from the solar power plant to the treatment centre. This monitoring system was primarily based on systematic photographic records collected at each key stage of the logistics chain.

Finally, the results of the field case study were used to compare the positive or negative impacts of the proposed improvement options against SOREN's standard palletisation conditions. This comparison provides insights into potential future improvements that could be applied within the photovoltaic waste management sector, with the aim of reducing operational risks, improving module condition upon arrival at treatment facilities, and ultimately lowering glass breakage rates.

2.4. CASE STUDIES ON THE RECYCLING EFFICIENCIES - SAMPLING ACTIVITIES

2.4.1 Scope and objectives

Building on the collection and logistics analyses presented in the previous Chapter, the recycling efficiency case studies were developed to establish a benchmark of current industrial photovoltaic recycling practices and to assess how different treatment approaches influence material recovery performance.
The objective of this work is to complement the technology development activities carried out within EVERPV with evidence derived from real industrial operations. While innovative recycling technologies can be evaluated in terms of their theoretical recovery potential, their industrial relevance also depends on how they compare with existing treatment routes currently applied in the photovoltaic recycling sector.

The methodological framework developed within WP6 therefore combines industrial case studies, sampling activities, material characterisation and benchmark data generated within EVERPV in order to assess the recyclability of current and emerging photovoltaic recycling technologies. Particular attention is devoted to the recovery and quality of material fractions identified as strategically relevant within the project, including glass, silver-containing fractions, silicon-containing fractions, encapsulants and backsheet polymers.
The analysis focuses primarily on crystalline silicon photovoltaic modules, which currently dominate the European photovoltaic market and are expected to represent the largest share of future end-of-life photovoltaic waste streams.

To ensure consistency across the national case studies, a common analytical framework was adopted. Although implemented through different operational approaches in Italy and France, both analyses aimed to quantify recycling performance, reconstruct material flows, evaluate the quality of recovered fractions and compare industrial recycling practices with the innovative technologies developed within EVERPV.

To ensure that the assessment reflects current industrial practices, the case studies were designed around treatment routes considered representative of the recycling approaches currently applied in the participating countries. The selection of treatment facilities was therefore not intended to provide a statistically exhaustive representation of the national recycling sector, but rather to capture the most relevant technological configurations currently available and to establish a meaningful benchmark against which the innovative EVERPV technologies could be evaluated.

In Italy, two treatment facilities were selected to represent the two main industrial approaches currently applied to end-of-life photovoltaic panel recycling: shredding-based

treatment and mechanical delamination. The inclusion of both routes made it possible to compare different trade-offs between processing capacity, material selectivity and output quality.

In the French case study, the assessment focused on the industrial hot-knife delamination process currently operated at the facility, which was selected as a representative benchmark of the French recycling context. The choice of ENVIE is also particularly relevant within the EVERPV framework, as the site hosts the sanding technology developed and demonstrated during the project. This configuration makes it possible to establish a direct comparison between the existing industrial treatment route and the innovative EVERPV technologies assessed throughout the project, as evaluated quantitatively in chapter 3.2.

2.4.2 Common methodological framework

The Italian and French case studies were developed within a common analytical framework while focusing on treatment configurations representative of their respective national contexts.

The recycling efficiency assessment builds upon the incoming flow characterisation activities described in chapter 2.3, which provided information on the composition and condition of the photovoltaic modules entering the investigated treatment routes.

The framework was designed to generate comparable information on the performance of industrial photovoltaic recycling routes and consisted of five main analytical steps:

1. Treatment of representative batches in industrial recycling facilities;
2. Reconstruction of process mass balances;
3. Mapping of downstream destinations of output fractions;
4. Characterisation of selected recovered fractions;
5. Assessment of recycling performance indicators.

Together, these activities provide information on the quantity, quality and destination of recovered materials, allowing a comprehensive assessment of recycling performance and material circularity.
The chosen workflow, as outlined in Figure 14 connects input waste characterisation, treatment data, mass balance, downstream destinations and laboratory evidence to support the assessment of recycling performance.

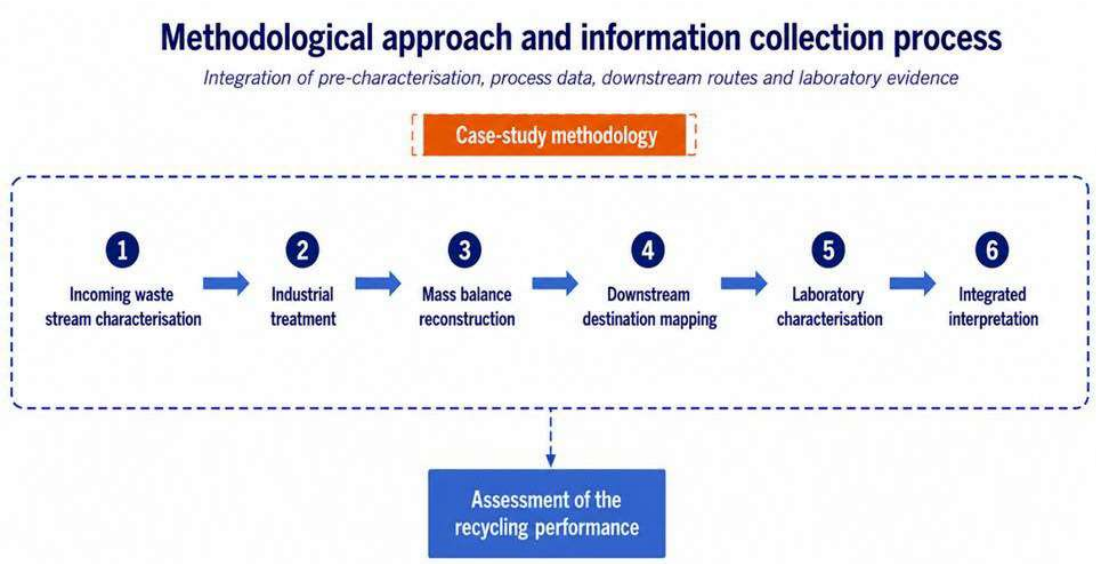


Figure 14 – Methodological approach and information collection process adopted for the industrial PV recycling case studies

The resulting evidence was subsequently compared with the technical benchmark data generated within EVERPV, enabling a direct comparison between currently available industrial recycling practices and the innovative technologies developed within the project.

2.4.2.1 Italy

To establish a representative benchmark of current photovoltaic recycling practices in Italy, two industrial treatment routes currently applied in Italy were selected for detailed investigation. For this reason, the study focused on the collection of operational data from two industrial case studies, selected to represent the most relevant technological approaches currently applied to end-of-life photovoltaic panel treatment in the Italian context.

In Italy, industrial treatment solutions for end-of-life photovoltaic panels are mainly based on two approaches. The first and most widespread approach relies on shredding-based treatment. In this configuration, panels are generally processed after the preliminary manual removal of cables and, depending on the plant, partial or complete removal of the aluminium frame. This route is mainly driven by the need to process large volumes of waste and maximise treatment throughput. The second approach is based on mechanical delamination. Although less widespread, delamination represents a relevant benchmark because it is designed to separate the glass fraction more selectively and to produce a cleaner, higher-value output. Such lines are designed to remove and recover the glass and to allow the subsequent recovery of all the materials present inside the plastic and EVA sandwich (plastics, connections, silicon, etc.). The glass removal process is carried out using a series of special steel tools that gradually remove the glass without contaminating it with other elements present inside the photovoltaic panel. The recovered glass is then sorted by particle size. This improved material quality is generally achieved at the expense of lower processing capacity over the same unit of time.

To reflect these two industrial approaches, two treatment plants were involved in the study and asked to collect and process comparable batches of end-of-life photovoltaic panels under a common methodological framework. The first case study, hereafter referred to as the shredding treatment plant, applies a complete shredding process, with manual cable removal as the only preliminary step. The second case study, hereafter referred to as the delamination treatment plant, applies a mechanical delamination process using commercially available equipment, namely the Compton Solar 4.0 system.

For both treatment routes, representative batches of end-of-life photovoltaic modules were selected and processed under comparable conditions.

The delamination treatment plant processed the full sample, as all selected panels were crystalline silicon modules, including both mono-crystalline and poly-crystalline technologies. By contrast, the shredding treatment plant received a technologically mixed batch. Since the comparative assessment focused on silicon-based photovoltaic panels, only the crystalline silicon sub-stream was included in the treatment test, while the remaining non-target modules were excluded. This difference reflects a relevant feature of real industrial operations: shredding-based plants may receive and treat a broader range of PV technologies, including thin-film and CdTe modules, whereas the delamination route considered in this study is specifically applicable to crystalline silicon panels.

Following the selection and preparation of the representative waste batches, the common methodological framework described in Chapter 2.4.2 Common methodological framework was implemented across both treatment facilities through a structured information collection process:

1. The incoming waste streams were characterised; the characterisation of a batch of 200 EoL panels provided information on weight of modules, their technological composition and the presence of components such as frames, cables and junction boxes. This step was used to understand the composition of real end-of-life flows and to estimate the share of silicon-based modules. In one of the two cases, information on the geographical origins of the waste was included.
2. The selected batches were treated in industrial recycling plants; the treatment phase then generated the process data required to reconstruct the mass balance and quantify the main output fractions, including glass, metals, plastics/EVA, silicon-rich powders and residual dusts.
3. The mass balance of the treatment process was reconstructed.
4. The downstream destinations of the output fractions were mapped; downstream mapping was used to verify whether each output was actually directed to material recovery, End-of-Waste production, energy recovery or disposal. Enabled a comparative assessment of the two case studies and supported the identification of the main drivers and bottlenecks affecting photovoltaic recycling performance.
5. Selected fractions were characterised through laboratory analyses; such analyses were finally used to assess the quality and impurity levels of selected fractions. enabled a comparative assessment of the two case studies and supported the identification of the main drivers and bottlenecks affecting photovoltaic recycling performance.
6. The collected evidence was subsequently integrated to assess recycling performance of the investigated industrial treatment routes.

The industrial benchmark generated through the Italian case studies was finally compared with the technical benchmark data generated within WP2 for the innovative delamination technologies developed within EVERPV, including sanding, infrared-assisted backsheet tear-off, hot-knife delamination, and thermal delamination approaches. This combined assessment enabled a more comprehensive comparison between currently available industrial recycling practices and the innovative technologies demonstrated within the project.

2.4.2.2 France

The analysis carried out in France adopted a specific development and analysis approach, while seeking to align as closely as possible with the common methodology. SOREN also chose to apply the photovoltaic waste characterisation methodology developed within the European PHOTORAMA project [11]. This methodology provides a robust and harmonised framework for characterising end-of-life photovoltaic modules and their material fractions, and complements the approach developed by ERION in Italy.

In the French case study, the selected operator for cooperation was ENVIE. The study was developed based on the benchmark hot-knife process implemented at the ENVIE site and the innovative sanding process in development within EVERPV. This choice is fully consistent with the EVERPV project framework, which enabled the installation and deployment of the sanding process at the same facility. Selecting ENVIE therefore makes it possible to analyse different recycling approaches within a single industrial environment and, in particular, to place the hot-knife process in perspective with the sanding steps developed within EVERPV.

The main difference compared to the Italian case is related to the way the analyses were conducted. In the French study, treatment and characterisation were performed on different batches of PV panels. In the Italian case, the same batches of PV panels were tracked from characterisation through treatment and final output assessment.

Despite these adaptations, the same core analytical steps defined in the common methodology were followed:

1. Treatment of batches in industrial recycling plants, generating the process data required to reconstruct mass balances and quantify the main output fractions.
2. Reconstruction of the mass balance of the treatment process.
3. Mapping of downstream destinations of the output fractions, in order to verify whether each fraction was effectively directed towards material recovery, End-of-Waste production, energy recovery, or disposal.

[11] European Union's Horizon 2020 research and innovation programme, Grant Agreement No 958223

This combined approach ensures a robust and comparable assessment of recycling efficiencies across the Italian and French case studies, while benefiting from established European methodologies and adapting to national industrial practices.

2.5. ASSESSMENT OF PV RECYCLING VALUE CHAIN

2.5.1. Scope

This assessment is structured to provide an overview of the current actors in the European PV recycling chain, identify missing links and bottlenecks, and evaluate barriers to the development of a closed-loop recycling chain in the EU-27.

This analysis is based on a desk study aimed at assessing the current European PV recycling value chain, with a primary focus on identifying and mapping existing recycling actors in the EU with a focus on five selected EU countries with high PV waste volumes. The first step is therefore to establish an overview of recyclers involved in end-of-life PV treatment. This mapping provides the basis for a broader assessment of how recycled materials could be connected to a future closed-loop recycling industry in Europe. In that sense, the recycler overview is a starting point for identifying missing links, potential bottlenecks, and the next steps required to move towards closed-loop recycling. The second step maps relevant PV manufacturing actors in Europe to identify potential demand points for recovered materials as part of a closed-loop end-of-life route.

2.5.2. Step 1: PV waste recyclers mapping in key European countries

Actors were selected if they were found to play a relevant role in the European PV end-of-life value chain. The mapping focused primarily on industrial recycling actors, including facilities carrying out shredding, delamination, or pre-treatment of PV panels. Pre-treatment refers to operations applied to PV modules before final recycling such as removal of frames and junction boxes to prepare modules for more subsequent recycling processes. In addition, selected emerging projects and pilot lines were included where they contribute directly to PV recycling activities or help illustrate missing links in the transition towards closed-loop recycling. The geographical scope focused on European actors, with particular attention to EU countries which concentrate most recycling activity or development.

The source base combined several categories of information. PV-specific technical references, notably IEA PVPS Task 12 materials[12], were used to identify relevant recycling pathways, treatment processes and actors. Scientific publications, industry reports and specialised media[13] were used to complement this information with data on recycling technologies, plant capacities and market developments. Company websites[14], press

[12] https://iea-pvps.org/wp-content/uploads/2025/07/IEA-PVPS-T12-31-2025-REPORT-Status-Module-Recycling.pdf ; https://iea-pvps.org/wp-content/uploads/2026/04/IEA-PVPS-T12-32-2026-REPORT-Recycling-LCI-2026.pdf?

[13] https://www.pv-magazine.it/2026/03/13/riciclo-pannelli-fotovoltaici-al-via-il-primo-impianto-toscano-9-000-t-anno-e-recupero-del-95-dei-materiali/ ; https://www.pv-magazine.es/2024/02/20/retrato-de-empresa-la-hormiga-verde/ ; https://www.pv-magazine.fr/2024/11/14/reportage-lusine-de-recyclage-de-panneaux-rosi-solar-prepare-sa-montee-en-puissance/ ; https://taiyangnews.info/technology/solar-materials-preparing-for-1st-large-wave-of-pv-recycling-in-eu ; https://www.pv-magazine.de/2024/05/13/start-up-des-monats-durch-photovoltaik-modulrecycling-silber-und-silizium-zurueckgewinnen/

[14] https://pvcycle.be/en/annual-reports/2024-annual-report ; https://www.retema.es/actualidad/reciclajes-pozo-canada-lider-en-innovacion-para-el-reciclaje-fotovoltaico ; https://www.greening-group.com/greening-group-inicia-un-proyecto-pionero-a-nivel-mundial-de-economia-circular-con-la-construccion-de-la-primera-planta-de-

releases and project communications were used to identify facilities, reported capacities and process descriptions. Information gathered through stakeholder exchanges at conferences[15] and through project-related interactions was used to complement publicly available data, particularly for emerging actors, pilot projects and less documented facilities. Eurostat data[16] was used as a national-level benchmark for comparison with aggregated facility-level data and to provide an order-of-magnitude reference for the mapped capacity landscape.

Information for each actor was cross-checked across these different source types to confirm its geographical presence, operational status, treatment process, and facility metrics where available. For actors with identifiable recycling activity, available site-level information was collected and harmonised. Treatment capacity was used as the main quantitative indicator for comparison across countries and process types, while treated volume was included where sufficiently documented. Particular attention was given to distinguishing PV-specific recycling capacity from broader WEEE recycling capacities, as these are not always reported separately and, in some cases, may rely on shared equipment or infrastructure. Priority was given to confirmed operational capacity and treatment data. Where discrepancies, gaps or uncertainties remained, values were treated conservatively, flagged, or excluded from quantitative analysis to preserve the robustness of the dataset.

2.5.3. Step 2: PV manufacturers mapping in key European countries

Actors were selected if they had identifiable activities in the European solar PV manufacturing value chain, either through operational production, announced manufacturing projects, pilot-scale activities, or the supply of key module materials. The mapping focuses on manufacturers involved in the four main steps of PV manufacturing: silicon, wafers, cells and modules, as well as selected bill-of-material suppliers where relevant, such as encapsulant and glass manufacturers. The geographical scope is the EU, with a focus on the countries already covered by the recycler mapping.

This step aims to identify potential demand and market entry points for materials recovered from PV recycling and to understand where these materials could, in principle, be reintegrated into the European PV value chain. The mapping therefore provides a first indication of possible links between recycling activities and manufacturing activities in Europe.

The source base is similar to the one used for the recycler mapping and includes company websites[17], press releases, project documentation, industry reports, specialised media[18] and scientific or technical publications[19]. Information gathered through stakeholder exchanges at

recuperacion-de-paneles-solares/

[15] Various stakeholders were consulted at Intersolar 2026, Munich

[16] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_electrical_and_electronic_equipment

[17] https://www.3sun.com/en/search-news/news/2025/05/stephane-sejourne-visits-3sun-gigafactory ; https://www.satinal.it/en/satinal-set-up-innovative-italian-solar-pv-encapsulants-production-hub/

[18] https://www.pv-tech.org/norsun-closes-ingot-and-wafer-manufacturing-plant-in-norway-to-focus-on-us/

[19] https://www.solarpowereurope.org/features/make-solar-eu-wacker-s-role-in-reshoring-solar-manufacturing-to-europe ; IEA, Special Report on Solar PV Global Supply Chains, 2022 ;

conferences[20] was used to complement publicly available data. Where available, information is collected on actor type, location, manufacturing segment, operational status, and production capacity. Particular attention is given to distinguishing operational manufacturing activities from pilot-scale or planned projects as well as from halted or no longer operational ones, given that several actors have faced insolvency in recent years.

IEA-PVPS, Trends in Photovoltaic Applications, 2025

[20] Various stakeholders were consulted at Intersolar 2026, Munich

2.6. TECHNICAL AND ECONOMIC FEASIBILITY OF EVERPV TREATMENT TECHNOLOGIES

2.6.1. Scope

In a project aimed at developing solutions close to market application, techno-economic considerations are essential to assess not only technical feasibility, but also the realistic conditions for future adoption. New treatment technologies need to be evaluated against the industrial context in which they may operate, considering cost structures, revenue opportunities, operational constraints and scalability factors.

This is particularly relevant in the PV waste sector, where different treatment routes involve clear trade-offs between throughput, quality of recovered materials, investment needs and process complexity. A technology that performs well from a technical perspective may still face barriers if its costs, labour requirements, energy demand or logistics needs are not compatible with existing industrial practices. For this reason, the first layer of the analysis integrates economic parameters such as investment costs, maintenance, energy consumption, labour, auxiliary inputs, infrastructure requirements and revenues from recovered materials.

The use of a benchmark is therefore necessary to give meaning to the assessment. However, the choice of benchmark is not neutral: different industrial configurations may lead to different conclusions on competitiveness, profitability or scalability. A comparison based on an unrealistic or marginal benchmark could either overestimate or underestimate the actual potential of the proposed solutions.

For this reason, the exercise adopts a cautious approach and focuses on the technological routes that best represent current market conditions in the countries analysed. These benchmarks are aligned with the case studies already described in the previous characterisation of photovoltaic waste flows, ensuring consistency between the market analysis and the techno-economic assessment. In the Italian case, this means considering both shredding-based processes, which are suited to high-volume treatment, and mechanical delamination processes, which target higher-quality material recovery, particularly for glass, although with lower throughput. This approach strengthens the robustness of the comparison and supports a more realistic understanding of where the proposed technologies may create value.

Hence, the goal of this activity is to compare, from an economic perspective, the technologies developed within the project with the dominant industrial solutions currently operating in Italy and France. The comparison focuses on the main cost and revenue components associated with each process, in order to assess how the proposed technologies perform against the existing market baseline.

The data collection approach therefore follows a bottom-up logic, using the industrial-scale status quo as the reference baseline. Each process is broken down into its individual

operational units, down to the level of single machines and equipment, and the relevant data are associated with each of them. To safeguard comparability, the data collection template was derived directly from the one developed in WP6 task 6.3 for the Life Cycle Thinking (LCT) analyses.

In the Italian case study, both shredding-based and mechanical delamination processes were included, to represent the market coherently and support a robust economic comparison with the project technologies. ERION retrieved the necessary information during workshops (n=2; 3 hours each) with the treatment plants involved in the study.

Unlike the Italian case study, which focuses on the technical and economic assessment of a specific recycling process, the French case study adopts a broader operational and market-oriented perspective. It examines how the French PRO, SOREN, supports the deployment of innovative recycling solutions by establishing the regulatory, contractual and economic conditions required for their integration into the existing value chain.

In this context, SOREN contributes to the development of the sector through tendering procedures, risk-sharing mechanisms and the coordination of stakeholders across the recycling chain. The analysis also includes an assessment of the valorisation potential of the fractions generated by the sanding process in development within EVERPV and the identification of potential downstream markets.

2.6.2. Method for assessing technical and economic feasibility of pre-treatment technologies developed within the project

The methodology covers a set of technical and economic areas that together allow a detailed comparison between current industrial processes and the project technologies. The analysis assumes 1 tonne of incoming PV waste as the functional unit used to estimate treatment costs and potential revenues, and it is consistently used as a common unit to ensure comparability across different treatment approaches.

As a necessary step for ensuring the reliability of the data gathering, each process is broken down at machine level. As a preliminary step, ERION, together with the treatment operators, provided a schematic representation of the industrial processes under investigation.

For the case of shredding, the process has been broken down in seven separate machines operating in line. For the case of mechanical delamination, the process has been broken down in five separate machines.

It should be noted that, depending on the operator, the shredding process can be preceded by a frame dismantling and the separation of the cable and junction box.

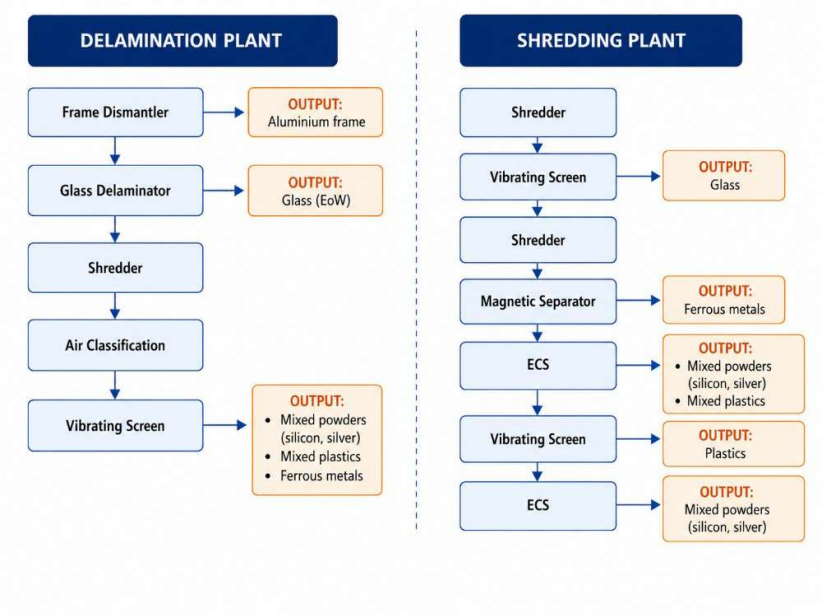


Figure 15 – Structure of the two industrial processes considered

The analysis inquires specifically on the following topics:

- **Investment and machinery-related costs:** considering purchase cost, maintenance, expected lifetime and utilisation rates, so that capital-related costs can be linked to specific process steps.
- **Operational costs:** the inventory includes energy consumption, auxiliary inputs such as water, compressed air, chemicals and consumables, as well as other process-related operating requirements.
- **Labour and skills:** labour needs are taken at mean values if no specialised profile is involved in the day-to-day functioning of the recycling process.
- **Technical and infrastructure requirements:** the analysis considers machinery configuration, treatment capacity, and other technical constraints relevant to industrial implementation.
- **Material outputs and revenues:** recovered fractions such as glass, aluminium, copper cables, plastics and silicon-rich materials containing silver are quantified and associated with potential revenues where valorisation is possible.
- **Residual waste and additional costs:** fractions that cannot be valorised are considered in terms of further treatment or disposal needs, capturing their potentially negative economic impact.
- **Data traceability:** data points are linked, where available, to their source and geographical origin at the level of the province, strengthening the transparency and robustness of the comparison.

The analysis provides an industrial benchmark for the two most common photovoltaic panel treatment technologies currently applied in Italy: shredding and mechanical delamination. To ensure a consistent comparison and isolate the cost effects associated with the treatment processes themselves, both scenarios were assessed under the same operating conditions,

namely three eight-hour shifts per day and 235 operating days per year. The resulting annual treatment volumes therefore represent theoretical benchmark capacities rather than the actual annual throughput of the individual plants.

2.6.3. Source of the information

The technical, economic and market analyses presented in this Chapter are based on a combination of primary and secondary data sources collected throughout the EVERPV project.

The first source of information consisted of direct interactions with industrial stakeholders involved in the photovoltaic recycling value chain. In Italy, ERION organised dedicated interviews with the treatment operators participating in the case studies. These discussions provided detailed information on process configurations, treatment capacities, machinery characteristics, operational requirements, labour needs, maintenance practices, energy consumption and other cost-related parameters. Additional exchanges with actors operating along the recycling value chain contributed to validating assumptions related to material management, downstream destinations and market conditions.

The second source of information was represented by the industrial case studies described in Chapters 2.3 and 2.4. Data collected through treatment campaigns, incoming flow characterisation activities, mass balance reconstruction and downstream mapping exercises provided the empirical basis for assessing both recycling performance and economic feasibility. In addition, laboratory analyses performed on selected output fractions generated by the investigated treatment routes were used to assess material composition, quality and potential valorisation pathways. These datasets made it possible to quantify material flows, evaluate recovered fractions and support both the technical and market-oriented components of the assessment.

The third source of information originated from the technology developers involved in EVERPV. Project partners responsible for the development of innovative recycling technologies provided technical and economic data relating to equipment characteristics, process requirements, treatment capacities, operating conditions and expected material outputs. These data were collected using templates aligned with the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) activities carried out within WP6 task 6.3 in order to ensure consistency across the different evaluation frameworks.

2.7. MARKET DEMAND ANALYSIS

Additionally, a market demand analysis was developed to assess the downstream uptake potential of the output fractions generated by the two PV recycling routes investigated in the Italian case study. The analysis does not only consider the theoretical recyclability or intrinsic value of each recovered material but focuses on its effective marketability. In this context, marketability is understood as the combination of technical quality, availability of potential downstream users, regulatory status, minimum buyer requirements, need for further upgrading or refining, and expected market or recovery value.

The assessment was structured around the main output fractions generated by the two treatment routes. These include (i) aluminium frames, (ii) glass fractions, (iii) mixed silicon and silver powders, (iv) mixed plastics, (v) ferrous metals, (vi) copper-bearing fractions, cables and junction boxes. Since these materials differ significantly in terms of maturity, value and downstream demand, they were not analysed through a single market logic. Aluminium, ferrous metals and copper-based fractions were considered as materials connected to already established secondary raw material markets. Glass was treated as a high-volume but quality-sensitive output, whose market destination depends strongly on chemical composition, granulometry, contamination level and End-of-Waste conditions. Mixed silicon and silver powders were analysed as a strategic but less mature output, whose demand potential depends on the possibility of further refining and on the capacity to meet the specifications required by metallurgical, battery, photovoltaic or precious metal recovery applications. Mixed plastics were assessed separately, as their marketability is generally weaker and often linked to low-grade recycling, energy recovery or alternative recovery routes.

The analysis combined five main sources of information. First, the material output fractions identified in the two case studies were used to define the perimeter of the assessment and to link each fraction to the corresponding treatment route. Second, mass balance data were used to understand the relative weight and relevance of each fraction in the overall process output. Third, laboratory analyses were used to support a preliminary technical characterisation of selected fractions, particularly glass, plastics and silicon/silver powders. These data provide useful information on the physical form, chemical composition, organic content, metal content and other parameters that may influence downstream acceptance. Fourth, the analysis built on stakeholder mapping activities carried out by ERION via direct interviews where potential users of recovered PV glass and silicon were identified and categorised according to their industrial sector, geographic location and level of interest. Finally, the assessment relied on a downstream market logic based on potential buyer requirements, existing recycling routes, possible industrial applications and the distinction between mature, emerging and residual outlets.

Each output fraction was assessed through a five-dimensional framework:

I) Technical quality, including purity, contamination, physical form, granulometry, organic content, metal content and stability of the fraction.
II) Market demand, intended as the existence of industrial sectors or downstream users potentially able to absorb the recovered material.
III) Market readiness, namely the degree to which the output fraction can realistically access an existing market under its current specifications.

IV) Value potential, including both direct market value and avoided disposal or treatment costs.
V) Identification of barriers to uptake, including technical, regulatory, logistic, economic and buyer-specific constraints.

A qualitative market readiness score was then assigned to each fraction. A high score indicates that the material can access an existing and mature market with limited additional treatment, as in the case of aluminium, ferrous metals and copper-bearing fractions. A medium score indicates that demand exists, but further quality validation, additional cleaning, upgrading or buyer-specific testing is required before stable market uptake can be assumed. A low score indicates that the fraction currently has limited marketability, no consolidated downstream route, or only low-value outlets such as energy recovery, disposal or residual recovery options. This scoring system was used to distinguish between immediately marketable fractions and strategic fractions whose value depends on future technological or market development.

The analysis also distinguishes between three possible levels of downstream valorisation. The first level corresponds to mature open-loop recycling routes, where recovered materials are reintroduced into existing secondary raw material markets without necessarily returning to the photovoltaic value chain. This applies mainly to aluminium, copper and ferrous metals, and potentially to some glass applications. The second level corresponds to quality-dependent material recycling, where the recovered fraction may access different outlets depending on its technical specifications. This is especially relevant for PV glass, which may be directed to low-grade construction applications, glass wool, foam glass, ceramics, standard glass recycling or, in more demanding cases, closed-loop PV glass applications. The third level corresponds to strategic high-value recovery, where additional refining or purification is necessary to access advanced applications. This applies mainly to silicon/silver powders, whose potential value depends on the recovery of silver and on the possible upgrading of silicon for metallurgical, battery-related or photovoltaic applications.

The scope of the analysis is preliminary market-oriented. It is intended to identify the most promising downstream routes, the relative maturity of each market outlet and the main barriers that may affect demand for the recovered fractions. It does not replace direct commercial negotiations with buyers, nor does it certify that each output fraction already complies with the technical specifications required by specific industrial users. In particular, glass and silicon/silver powders require direct validation through sample testing, buyer feedback and further quality characterisation before their actual market value can be confirmed. Similarly, for mixed plastics, the analysis should be interpreted as an assessment of possible outlets rather than as evidence of an already established recycling market.

3. RESULTS AND DISCUSSION

3.1. OVERVIEW

This chapter presents the results of the assessment of the circular economy potential of end-of-life silicon photovoltaic panels in the European Union. Building on the methodological framework described in Chapter 2, the analysis considers the full sequence through which PV waste may become a source of secondary raw materials: waste generation and collection, handling and transport, pre-treatment and recycling, available treatment capacity, technical and economic feasibility, and the market uptake of recovered fractions. The purpose of this chapter is therefore not only to quantify material recovery, but also to examine the conditions that determine whether recovered materials can be returned to productive use.

Chapter 3.2 presents the results of the domestic sourcing assessment. It quantifies the material fractions contained in projected PV waste flows and examines how collection rates and the selected pre-treatment route affect their potential availability. The findings show that bulk materials such as glass and aluminium account for most of the recoverable mass, while the recovery of strategically relevant materials such as silicon and silver depends more strongly on selective separation and the quality of the resulting output fractions.

Chapter 3.3 reports the findings of the Italian and French case studies on collection and reverse logistics. The results show that handling, packaging, palletisation, storage and transport influence the physical condition of panels arriving at treatment facilities. These upstream conditions are particularly important for delamination processes, which generally require more intact modules than conventional shredding routes. Collection performance must therefore be considered not only in terms of the quantity collected, but also in terms of the condition and suitability of the collected panels for subsequent treatment.

Chapter 3.4 examines the recycling performance of the treatment routes assessed in the case studies. The results indicate that existing industrial processes can recover the principal material streams, but that the quality, legal status and potential applications of the recovered fractions vary considerably. More selective treatment routes may produce cleaner and more clearly separated outputs, while plastics, encapsulants and some silicon-bearing fractions continue to face limitations in downstream material recovery and market uptake.

Chapter 3.5 presents the assessment of the European PV recycling value chain. It shows that current capacity remains unevenly distributed and is dominated by conventional shredding infrastructure, while specialised delamination capacity is more limited and concentrated in a smaller number of facilities. The findings also illustrate how national collection arrangements, procurement models and relationships between producer

responsibility organisations, treatment operators and recyclers can influence the treatment routes selected and the development of higher-value recycling capacity.

Chapter 3.6 assesses the technical and economic feasibility of the investigated pre-treatment technologies. The results identify a trade-off between treatment cost, operational throughput and the quality of the recovered fractions. Established shredding processes generally benefit from higher throughput and lower direct treatment costs, whereas delamination and sanding approaches may provide cleaner or more concentrated outputs. Their wider deployment therefore depends on whether the additional recovery quality can offset higher processing costs and support reliable downstream recovery pathways.

Chapter 3.7 evaluates the market potential and end-user requirements associated with the recovered material fractions. The findings show that metals connected to established recycling markets are comparatively straightforward to commercialise, while glass, silicon-, silver- and polymer-containing fractions are more dependent on purity, consistency, legal classification, processing requirements and buyer specifications. The marketability of recovered materials therefore depends on closer alignment between treatment outputs and the technical requirements of downstream users.

Taken together, the results show that the management of end-of-life PV panels is a system-wide challenge extending from collection and logistics to pre-treatment, recycling, refining and market uptake. Improving circularity requires more than increasing the total quantity of material recovered: it also requires preserving panel quality during collection, selecting treatment routes suited to the intended outputs, developing sufficient specialised capacity, and establishing viable markets for the resulting secondary materials. The policy recommendations presented in the following chapter build on these findings and address the regulatory, organisational, technical and market conditions needed to support a more circular and resilient PV value chain in the EU.

3.2. EVALUATION OF DOMESTIC SOURCING POTENTIAL

3.2.1. Composition data (1.2)

Figure 16 shows the assumed composition for silicon panels on the component level (c level). The weight of the panel is dominated by the glass and to a smaller extent the frame. The frame, while modelled in the material stream, is removed manually before the pre-treatment routes of the technologies investigated within the project. Therefore, the aluminium flow that is attributable to the frame directly remains unchanged in the subsequent chapters. Other elemental aluminium shown in subsequent flows can be attributed to the aluminium back surface field (Al-BSF)[21].

The third largest component by weight is the encapsulant, mainly made from EVA, which is sandwiched between the glass and the solar cell layer and the solar cell layer and the backsheet. The PV cell itself is the most complex component, as shown in Figure 17, but merely makes up 4.5% of the weight of the overall solar panel. The rest of the weight is distributed between the backsheet and PVDF layer, the junction box, and other rubber and silicon adhesives.

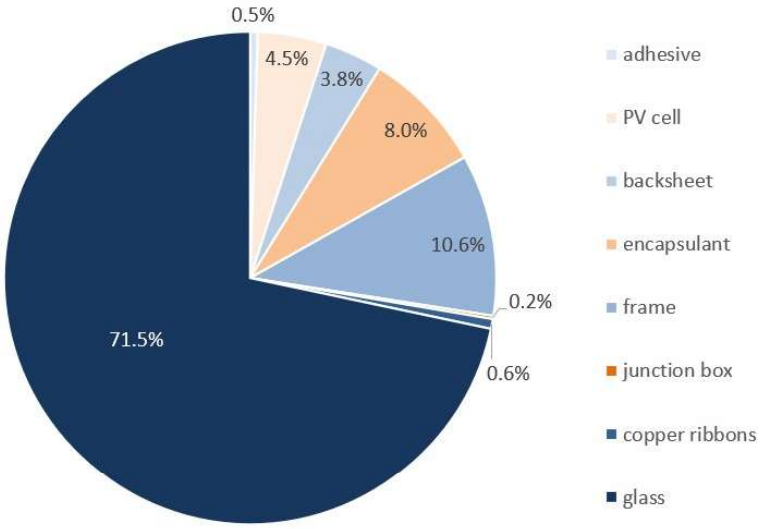


Figure 16 – Assumed silicon PV panel composition

It should be noted that this composition is based on the most common type of monocrystalline silicon PV panel and shows a typical composition. It does omit special cases, such as building-integrated PV panels or specialty modules which may use metal backsheet, as they were out of scope for this project.

[21] Yu, Y., Bai, X., Li, S., Shi, J., Wang, L., Xi, F., & Wang, W. (2023). Review of silicon recovery in the photovoltaic industry. Cleaner Engineering and Technology, 13, 100870.

A closer look at the mono-Si cell stack gives closer insights on further valuable materials that can be subsequently recovered. Although the cell stack may change considerably depending on the Si PV model, generation, and manufacturer, the broad composition and %-weight share in the overall panel remains similar.

The cell layer generally consists of a silicon wafer that accounts for roughly 90% of the weight in the cell, Al rear contacts and Ag front contacts, dopants, such as B, P and Ga, anti-reflective coatings, such as SiN, and Pb and Sn solders.

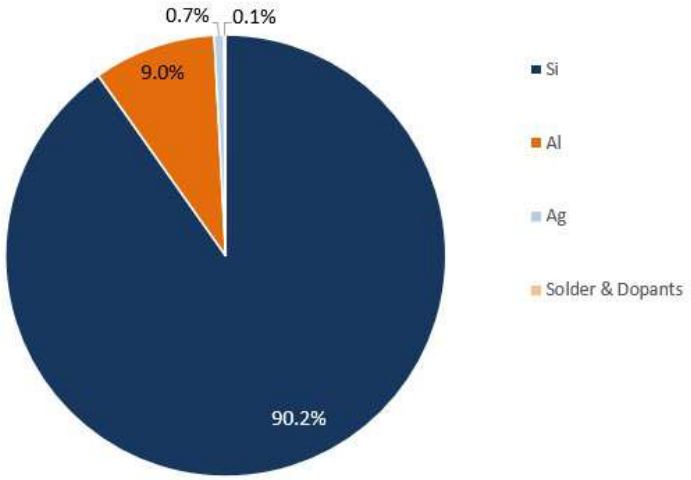


Figure 17 – Assumed composition of silicon PV cell

Depending on what technology was used for the pre-treatment, the components are found in the respectively different unique outputs of each. For example, while the sanding method mainly produces two powders, cell powder and backsheet powder, each containing the same sake component and a mix of encapsulant and contaminant stemming from other components, the Hot-knife output is mainly a single sheet that contains everything except the glass.

An overview of the allocation of each component to the respective outputs is given in Table 4.

Table 4 – Assumed outputs per pre-treatment technology

Component Name	Sanding Output	Hot-knife Output	Sanding/Hot-knife Hybrid	IR + tear off delamination
adhesive	backsheet powder; cell powder	cell sheet; residues on glass	cell sheet, cell sheet powder	available in backsheet-free module sandwich
PV cell	cell powder	cell sheet;	cell sheet, cell	available in

		residues on glass	sheet powder	backsheet-free module sandwich
backsheet	backsheet powder; residues in cell powder	cell sheet; residues on glass	cell sheet, cell sheet powder	Back sheet (intact)
encapsulant	backsheet powder; cell powder; residues on glass	cell sheet; residues on glass	cell sheet, cell sheet powder	available in backsheet-free module sandwich
frame	removed manually	removed manually	removed manually	removed manually
junction box	removed manually	removed manually	removed manually	removed manually
copper ribbons	cell powder	cell sheet	cell sheet, cell sheet powder	available in backsheet-free module sandwich
glass	Glass pane	glass pane	glass pane	available in backsheet-free module sandwich

3.2.2. Recyclability Assessment Results

A direct comparison between the investigated pre-treatment processes is exacerbated by the different nature of outputs the methods produce. As the pre-treatment processes employ mechanical intervention of various kinds, such as cutting, shredding, or friction, the outputs are naturally of different composition and hard to compare.

As outlined in Table 4 above, different components can be found across various outputs. As data collection was restricted to the pre-treatment process and no subsequent material reclamation processes could be investigated, a comparison between recycled material quantities is not possible based on this data but can be inferred from the results.

The following chapter contains Sankey diagrams that quantify the total input as 100%, which refers to the PV Panel with frame, and subsequently displays the material flows along the pre-treatment process steps.

The most applied recycling technique in the current market is shredding. The preparation for this method varies by treatment operator but can include manual labour steps, such as the removal of cables and connectors, the separation of the aluminium frame, and the removal of the junction box. Due to the variability, the following Sankey Figure 18 assumes a mere manual removal of the frame, but a shredding of the junction box.

The aluminium frame is removed manually across all pre-treatment technologies. This is captured by the outflow of the aluminium frame, which is represented by the flow with a mass percentage share of around 7.2%, 0.2% of which are estimated contaminants, such as screws which are usually made from iron. According to a field survey within the project, an estimated 50% of all investigated aluminium frames are corner-key assembled and fastened with screws, while the other 50% are crimped or folded and thus have no contaminants. The frames with screw contamination are sorted differently and likely undergo different treatment-procedures that are either more expensive to remove the contaminants or yield a lower-grade aluminium if contaminants are not properly removed.

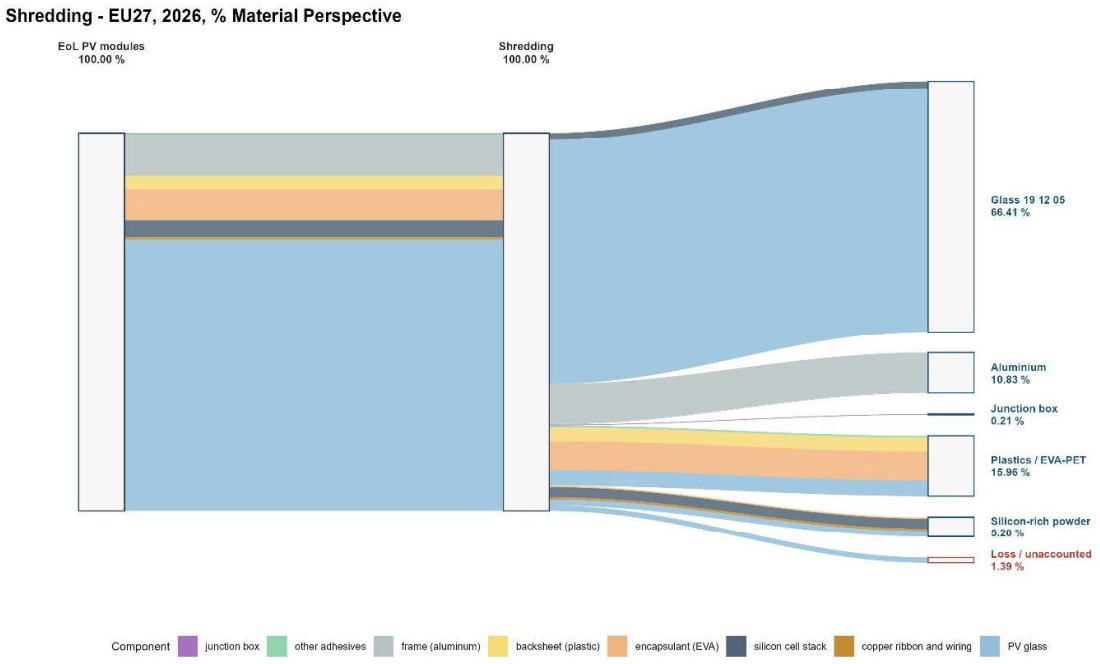


Figure 18 – Shredding material flows

The benchmark method, hot knife, refers to the mechanical separation of the sandwich layers of the PV panel and is shown in Figure 19. The method requires the manual removal of the junction box and of the frame before the cell sheet is separated from the glass, with one or two cuts in a single-lane process. The cell sheet comprises the encapsulant, the solar cells, the backsheet and the copper ribbons that is, the entire laminate other than the glass.

The peel is not always clean. Remnants of the encapsulant and of the solar cell layer, and in some cases the entire cell sheet, may remain on the glass. The cut can also break the glass, in which case further processing is only possible by shredding, which removes the panel from the delamination route. No exact estimate is available for the share of panels broken in this way, so the mass balance in Figure 19 does not account for it.

After hot-knife processing, the glass carries a comparatively low level of contamination residues of the encapsulant and of the PV cells, with very low amounts of backsheet, amounting on average to 0.52 % of the panel weight according to estimates. The recovered glass fraction is accordingly 99.3% glass, with 0.5 % encapsulant and 0.3 % cell material still attached.

The cell sheet, which contains the valuable silicon, copper and silver, is collected separately and sent to treatment facilities. It accounts for 16.4 % of the panel weight in the model, but the valuable materials within it are diluted: approximately 70 % of the fraction is polymer — encapsulant and PET backsheet, equal to 11.5 % of the panel weight — against 30 % of cell stack and copper ribbons, equal to 4.9 % of the panel weight. Recovery of the high value material therefore further processing in a downstream step, which is not modelled here.

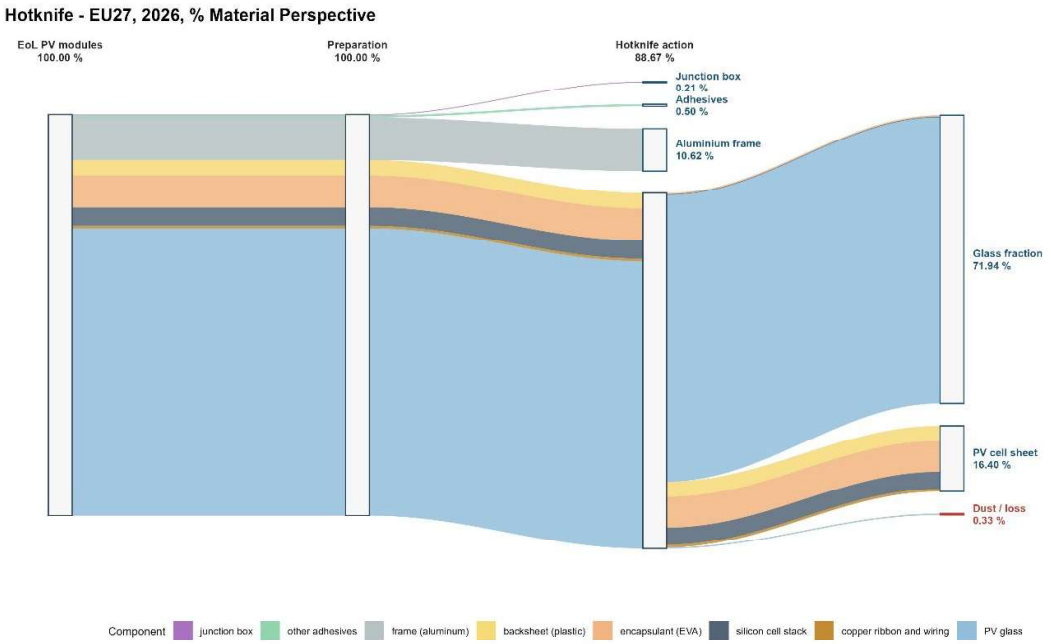


Figure 19 – Hot-knife material flows

The sanding method, shown in Figure 20, requires again the removal of the frame, junction box, and the adhesives. In a subsequent process, the deframed panel is sanded off in a two-stage process, where first the outer layer, the backsheet, and then the inner layer, the PV cells, are removed through a grinding process with sandpaper. The resulting powders are then vacuum sucked into collection stations.

This method results in a very high-purity glass output with little contamination (0.24 % by panel weight, corresponding to a glass purity of 99.76 %), as well as a backsheet powder (5.0 % by panel weight) and an EVA and cell powder (11.6 % by panel weight), the latter also carrying the copper busbars. While there is no clear use for the backsheet powder established just yet, as it consists mostly of a mix of backsheet plastics (e.g., PET),

adhesives (EVA), and potentially hazardous laminations (e.g., PVF), a clean removal enables the theoretically improved processing of the PV cells and the other components. This, however, could not be verified as the cell powder produced with this method is novel and there is no broad market data available. Nonetheless, the lower contamination rates suggest promising results.

The mass balance shown in Figure 20 applies the modelled panel composition rather than the composition of the characterised batch in Section 3.4, so the frame accounts for 10.6 % of panel weight rather than the 14.8 % reported for the sampled panels. The split between the two powder fractions follows the ratio reported in Table 31; the composition within each of them is not measured and is derived from the panel composition and from what the fraction designations state.

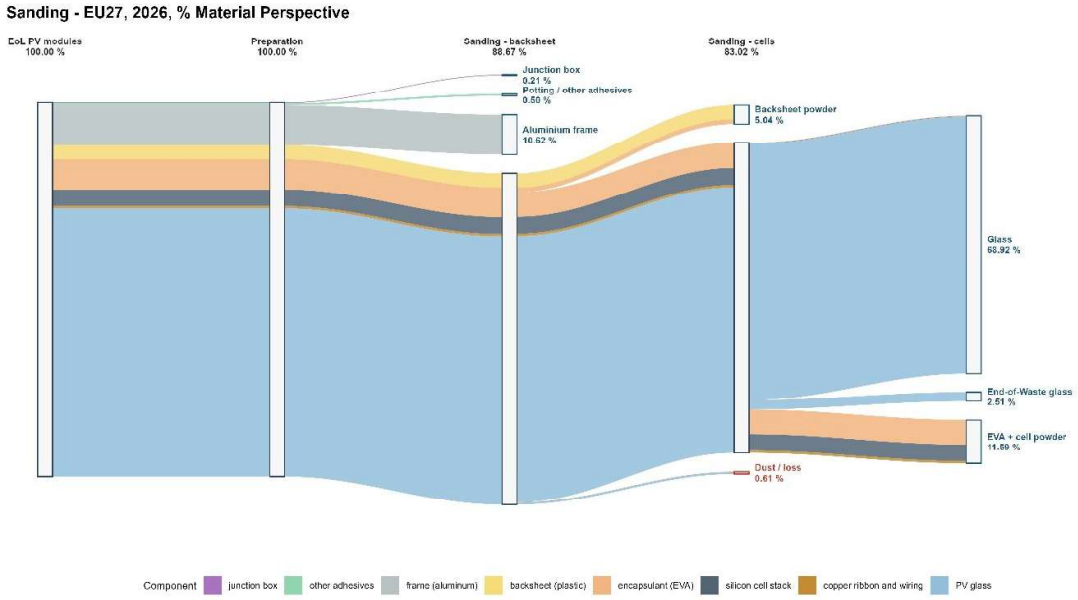


Figure 20 – Sanding material flows

The project further investigated the combination of the previous two methods, namely Hot-knife and Sanding. This aims at combining the advantages of both methods, the throughput speed of the Hot-knife method with the pure outputs of the sanding method. When combined, the panel undergoes the Hot-knife process as illustrated above but the PV glass is post-processed with the sanding method. This way, the resulting glass output is similarly contamination-free as with the sanding method, and cell sheets are obtained in the process. Additionally, previous glass contaminations that are sanded off can be reclaimed from the cell powders and backsheet powders produced, as illustrated in Figure 21.

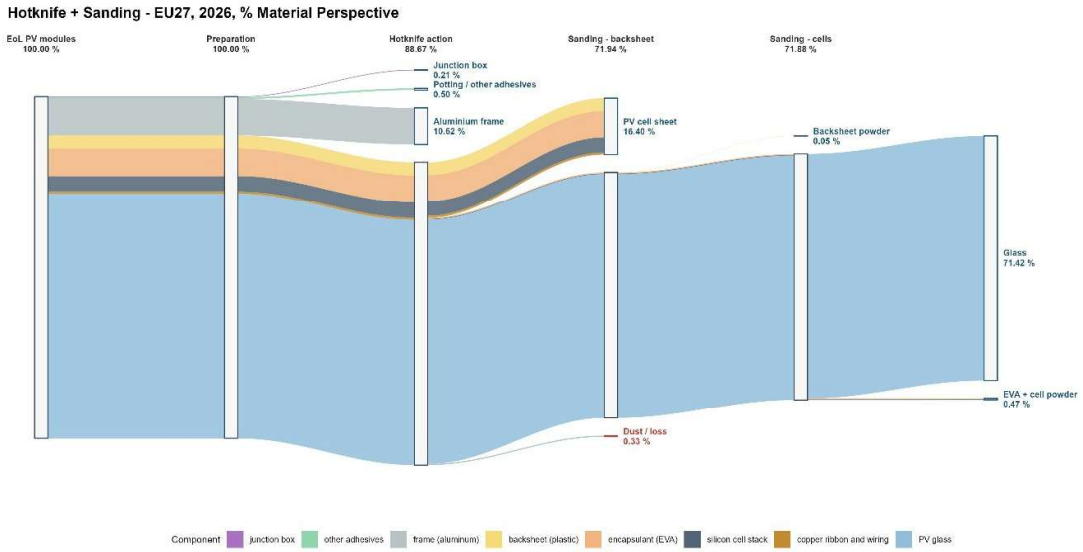


Figure 21 – Hybrid Hot-knife / Sanding material flows

Lastly, the IR+tear off method was scaled up and implemented within the project, which aims to remove the backsheet through a mechanical tear-off action facilitated by infrared lamps. This method has the advantage to peel off the backsheet cleanly, thus removing all contaminants, before undergoing the successive treatment steps.

Assuming that, after IR+tear off delamination, the backsheet-free module sandwich is treated by an incineration process followed by mechanical separation stage, contaminants burn off through the heat and the materials of glass, copper, and the PV cells may be retained fairly contamination-free. For the scope of this model, only the IR-facilitated backsheet tear off was modelled, as shown in Figure 22.

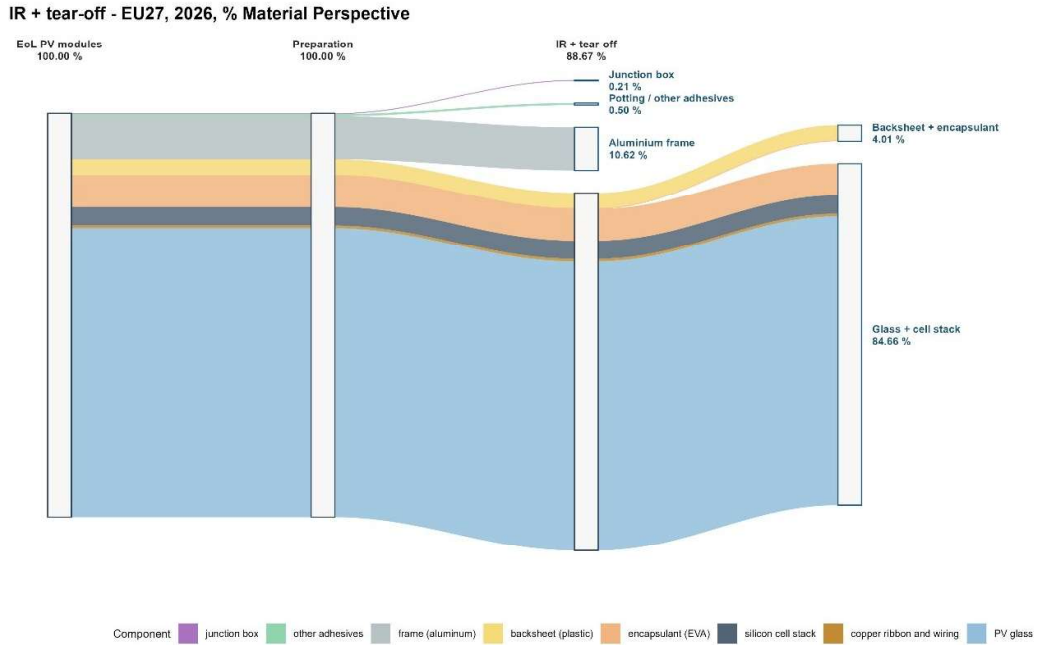


Figure 22 – Hybrid infrared Delamination & Pyrolysis

3.2.3. Quantification Results

Figures 23–27 translate the pre-treatment mass balances presented in Chapter 3.2.2 into annual material quantities for the EU-27. The quantification uses 2026 as its reference year, for which approximately 90.3 kt of end-of-life silicon PV panels are estimated to enter formal collection systems in Europe[22].

An important base assumption concerns the physical condition of the panels upon arrival at pre-treatment facilities. Based on consultations with project partners, the model conservatively assumes that 50 % of the collected panels arrive intact, while the remaining 50 % arrive with broken glass or other damage that prevents their treatment in the investigated delamination lines. This results in approximately 45.2 kt of intact panels being technically eligible for sanding, hot-knife, hybrid hot-knife and sanding, and IR + tear-off delamination. By contrast, shredding can accept both intact and broken modules and is therefore applied to the full collected volume of approximately 90.3 kt. The factors influencing panel breakage and the potential to preserve panel integrity through improved handling, palletisation and transport are examined further in Chapter 3.3.

The treatment scenarios represent alternative processing routes and must not be aggregated. Moreover, their absolute outputs are not directly comparable without considering the different input quantities. Shredding processes twice the mass assigned to each delamination route under the base assumption. Consequently, its higher absolute output quantities reflect both its ability to accept damaged modules and the performance of the process itself.

Under the shredding scenario, all 90.3 kt of collected panels, comprising approximately 45.2 kt of intact and 45.2 kt of broken panels, enter the treatment route. The process produces approximately 60.0 kt of glass fraction, 14.4 kt of plastics fraction, 9.8 kt of aluminium fraction and 4.7 kt of silicon-rich powder, alongside 0.2 kt of junction-box material and 1.3 kt of unaccounted fine material. The glass fraction contains approximately 58.3 kt of glass together with 1.7 kt of PV-cell material. The remaining panel materials are dispersed: the plastics fraction holds approximately 7.0 kt of EVA, 2.6 kt of PET, 0.7 kt of PVDF and 3.7 kt of glass fines, while the silicon-rich powder concentrates a further 2.4 kt of PV-cell material, 0.6 kt of copper and 1.4 kt of glass.

[22] Forti, V., Schubert, M., & Vermeersch, E. (2025). Market assessment of PV and quantification of PV waste and waste streams in EU (Deliverable D6.1). EVERPV. https://everpv.eu/wp-content/uploads/2025/06/EVERPV-Deliverable-6.1-REPORT-Market-assessment-of-PV-and-quantification-of-PV-waste-and-waste-streams-in-EU.pdf

Shredding therefore makes the largest absolute quantity of material available for further processing. This is principally because it can receive the entire collected waste stream, including panels that are already broken. Its main limitation is the heterogeneous nature of the resulting fractions. Glass, polymers, cell materials and metals are distributed across several comparatively mixed outputs, increasing the separation and purification requirements of subsequent recovery processes. Shredding thus provides high operational flexibility and throughput, but less selective liberation of individual material fractions.

For the sanding route, only the estimated 45.2 kt of intact panels are available as input. Removal of the aluminium frame, junction box and potting adhesives produces approximately 4.8 kt of aluminium, 0.1 kt of junction-box material and 0.2 kt of adhesives, leaving around 40.0 kt of deframed panels for mechanical treatment. The principal output is approximately 32.3 kt of glass fraction, of which 1.1 kt is qualified as End-of-Waste glass, around 32.1 kt of reclaimable glass, and only approximately 0.1 kt of residual EVA. Sanding also generates approximately 5.2 kt of EVA and cell powder and 2.3 kt of backsheet powder, with a further 0.3 kt leaving as dust.

The EVA and cell powder concentrates approximately 2.0 kt of PV-cell material, 3.0 kt of encapsulant and 0.3 kt of copper ribbons, while the backsheet powder contains approximately 1.4 kt of PET, 0.3 kt of PVDF and 0.6 kt of EVA. Compared with shredding, sanding therefore produces more clearly differentiated output fractions: a relatively clean glass sheet, a cell-rich powder, and a separate backsheet-rich powder. This reduces the dispersion of PV-cell material across a broad mixed fraction and may facilitate the subsequent recovery of silicon, silver and other cell-associated materials. However, the powders still require downstream separation and purification before their constituents can be considered secondary raw materials.

The hotknife route uses the same input of approximately 45.2 kt of intact panels. Following removal of the frame, junction box and adhesives, approximately 40.0 kt of deframed modules enter the delamination process. The main outputs are approximately 32.5 kt of glass fraction and 7.4 kt of cell sheet. The glass fraction contains around 32.3 kt of glass and comparatively small quantities of EVA, backsheet polymers and PV-cell residues, together amounting to 0.2 kt. The cell sheet concentrates approximately 3.5 kt of EVA, 2.0 kt of PV-cell material, 1.4 kt of PET, 0.3 kt of PVDF and 0.3 kt of copper-bearing material.

The hotknife process therefore separates the principal bulk glass fraction from the polymer- and cell-containing laminate while retaining these materials in a consolidated cell sheet. The resulting glass is considerably less contaminated than the glass-rich output obtained through shredding. Nevertheless, the cell sheet remains a composite fraction and requires further processing to liberate its polymer, silicon, silver and copper constituents.

The hybrid hot-knife and sanding route combines the relatively rapid initial separation provided by hot-knife treatment with a subsequent two-stage sanding step to remove residual cell-sheet material from the glass. From approximately 45.2 kt of intact input, the route produces around 32.2 kt of sanded glass, 7.4 kt of cell sheet, 0.2 kt of EVA and cell powder, and a backsheet-powder fraction of approximately 0.02 kt.

The sanded glass contains approximately 32.2 kt of glass with no residual encapsulant, making it the least contaminated glass output among the assessed mechanical routes. Most of the encapsulant, PV-cell material and backsheet polymers remain concentrated in the cell sheet, which contains approximately 3.5 kt of EVA, 2.0 kt of PV-cell material, 1.4 kt of PET and 0.3 kt of PVDF. Smaller quantities of EVA and PV-cell material are recovered in the powder generated during the additional sanding stage. The hybrid route therefore combines a highly purified glass output with concentrated cell-associated fractions, although this improvement requires an additional processing step and associated operational inputs.

Under the IR + tear-off route, the 45.2 kt of intact input is first deframed and the backsheet is then selectively released by infrared heating and peeled away. This produces approximately 1.8 kt of separately recovered backsheet, consisting of approximately 1.4 kt of PET, 0.3 kt of PVDF and 0.1 kt of adhering encapsulant, and leaves approximately 38.2 kt of glass and cell stack intact. This remaining assembly contains around 32.4 kt of glass, 3.5 kt of encapsulant, 2.0 kt of PV-cell material and 0.3 kt of copper ribbons.

The route does not separate the high-value materials but selectively removes the layer that the benchmark routes valorise least, while preserving the glass, encapsulant, cells and copper together and undamaged for subsequent treatment. Its contribution to domestic sourcing is consequently indirect: it delivers a clean polymer fraction and an intact laminate whose material potential depends entirely on the downstream process applied to it. A subsequent thermal stage would be one such option, and the prior removal of the backsheet is directly relevant to it: the 0.3 kt of PVDF diverted from any downstream furnace corresponds to approximately 0.2 kt of fluorine, so a thermal step applied after tear-off processes an essentially fluorine-free feed and requires correspondingly less acid-gas abatement.

Overall, the results demonstrate that shredding provides the largest absolute quantities of available material under current collection and handling conditions, because it can process both intact and broken panels. The investigated delamination routes are restricted to the 50 % of collected modules assumed to remain intact and therefore begin from a substantially smaller eligible input. Their primary advantage is not higher total output mass, but the production of cleaner and more concentrated material fractions, particularly glass sheets, cell sheets and cell powders.

The comparison also demonstrates that collection quality is an integral component of domestic sourcing potential. Under otherwise unchanged conditions, increasing the proportion of intact panels would directly increase the volume eligible for selective delamination. Improved dismantling, palletisation, storage and transport could therefore expand the application of higher-quality treatment routes without increasing the total quantity collected. Conversely, panels damaged before reaching the treatment facility are effectively restricted to shredding-based treatment, limiting the potential to produce selectively separated output fractions.

Finally, the reported quantities represent materials transferred into specific pre-treatment output fractions, rather than final quantities of market-ready recycled materials. Further separation, refining and purification are required, particularly for the cell sheets, cell powders, backsheets and mixed fractions. The actual contribution to domestic secondary raw material supply will therefore depend on downstream recovery efficiencies, output purity, legal classification and the availability of suitable end markets.

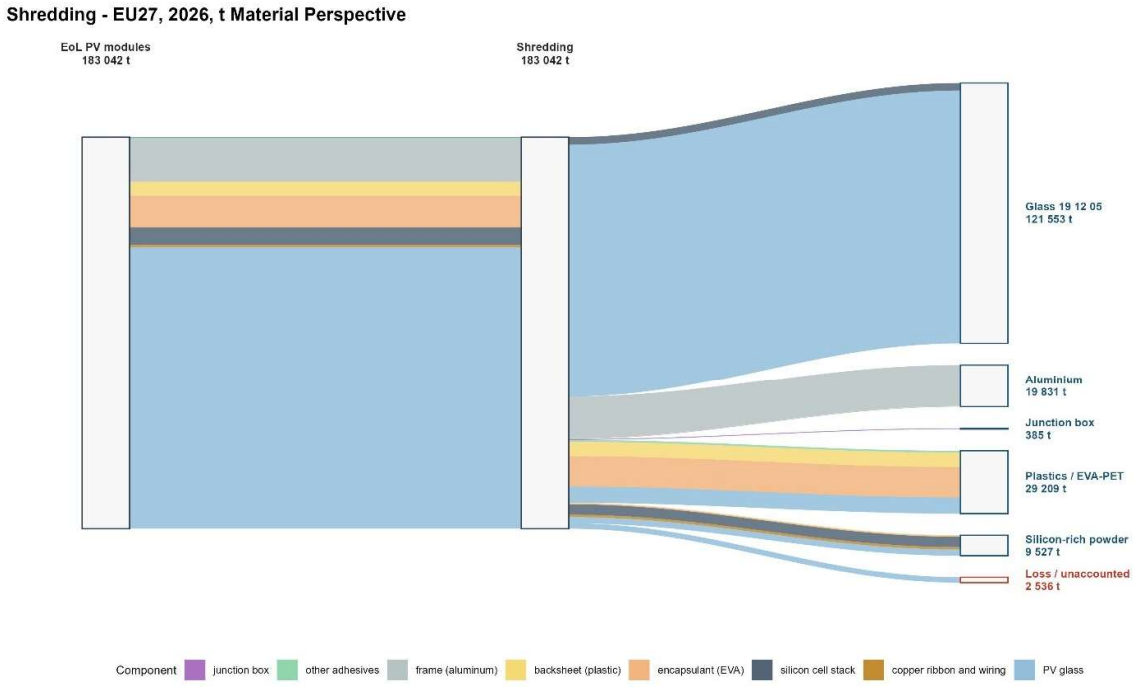


Figure 23 – Quantification of material flows for shredding

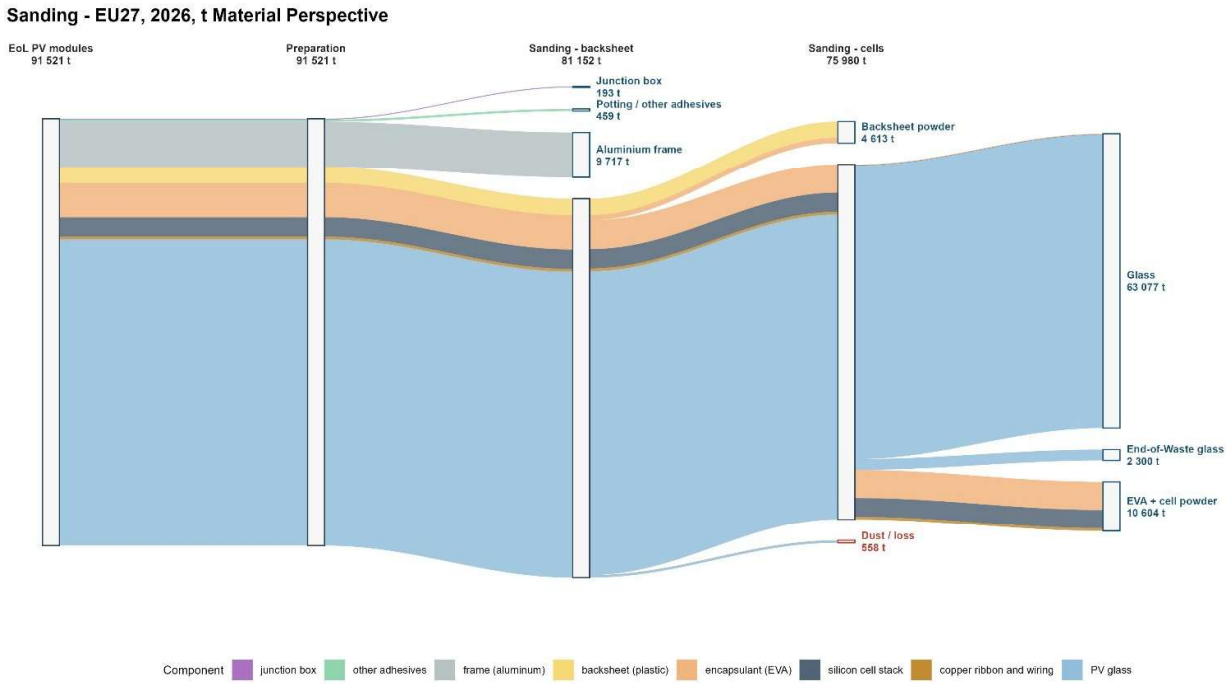


Figure 24 – Quantification of material flows for sanding

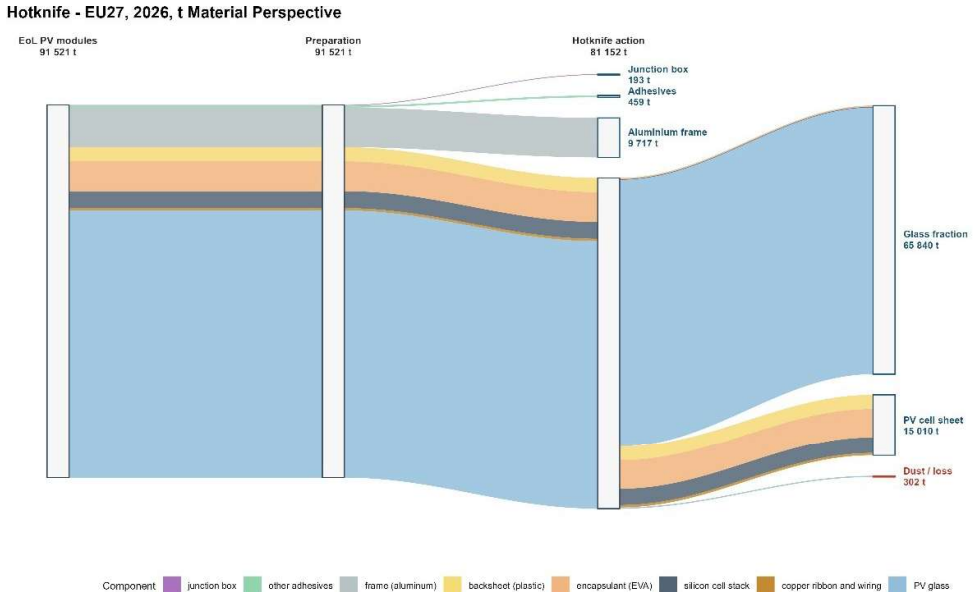


Figure 25 – Quantification of material flows for hot-knife

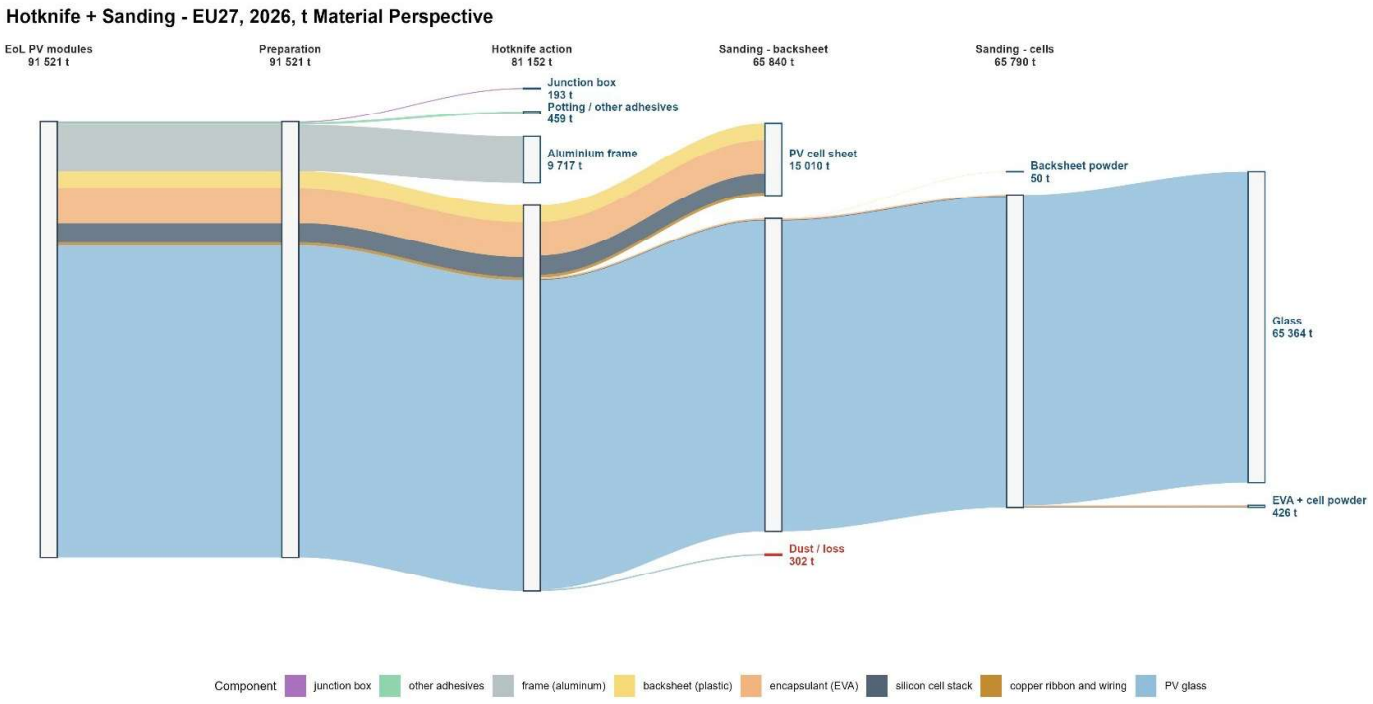


Figure 26 – Quantification of material flows for hot-knife and sanding hybrid

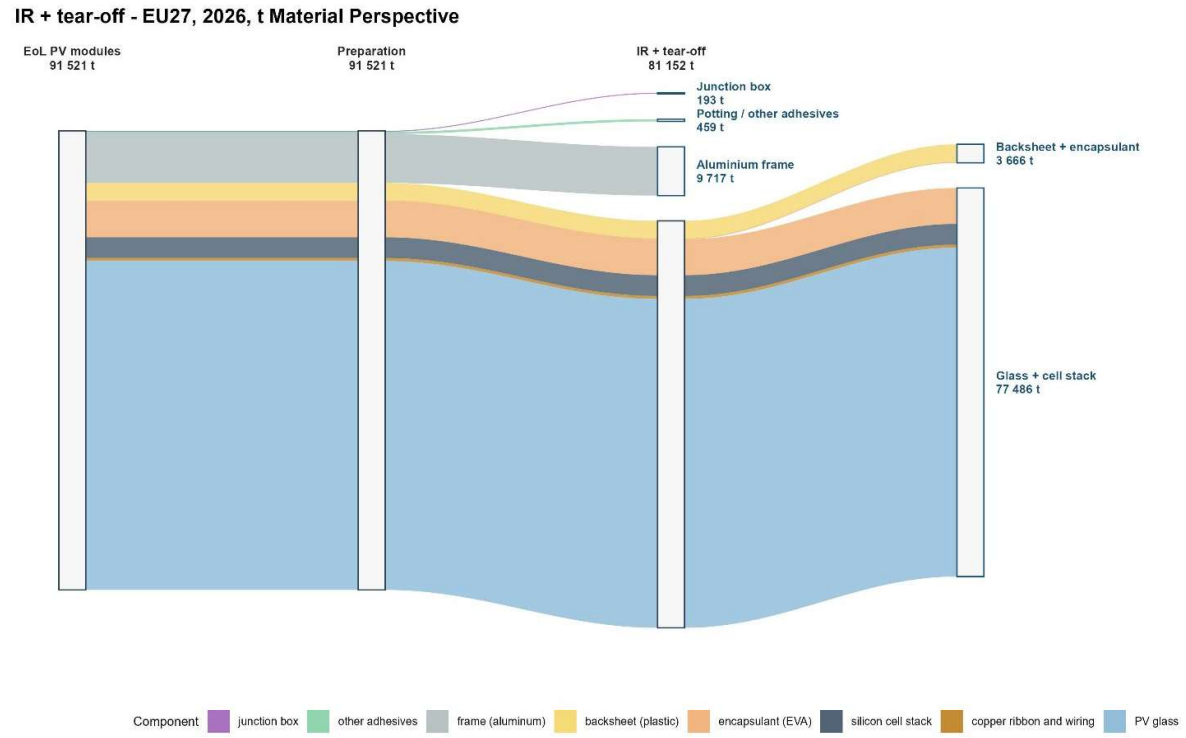


Figure 27 – Quantification of material flows for hybrid IR delamination

3.3. CASE STUDIES ON IMPROVEMENTS TO THE COLLECTION SYSTEM

The results of the analysis of case studies on improvements to the collection system in Italy and France are presented below.

It was decided not to aggregate the results at European level, as each country operates within a distinct operational and organisational framework. Combining the data would therefore risk blur national specificities and creating a disconnect between the observed realities at country level and the overall interpretation of photovoltaic waste management activities in Europe.

In addition, treatment centres apply site-specific admission and acceptance requirements, which further limits the relevance of a collective analysis and reinforces the need to assess results within their respective national and operational contexts.

This separation was also maintained in order to enable a consistent comparison between the two batches developed in Italy, ensuring that differences observed could be attributed to operational conditions rather than to aggregation effects.

3.3.1. Results of the Italian case

The two datasets show very different operational context. The shredding treatment plant provides a differentiated picture of incoming damage: out of 200 modules, 95 were intact, 79 showed scratched glass and 26 had broken glass. This allows actual breakage to be separated from surface damage. By contrast, the delamination treatment plant sample is entirely composed of intact modules. This makes it a useful descriptive case, but it cannot be used to estimate breakage risk. This is not the result of a lower incidence of damage in the collection chain but rather reflects the operational requirements of the delamination process itself. Mechanical delamination systems require modules to maintain their structural integrity in order to ensure proper handling and effective separation of the different material layers. Consequently, damaged or broken modules are generally excluded from this treatment route.

Table 5 – Incoming module condition in the Italian case studies

Case study	Intact	Scratched glass	Broken glass	Total
Shredding treatment plant	95	79	26	200
Delamination treatment plant	200	-	0	200

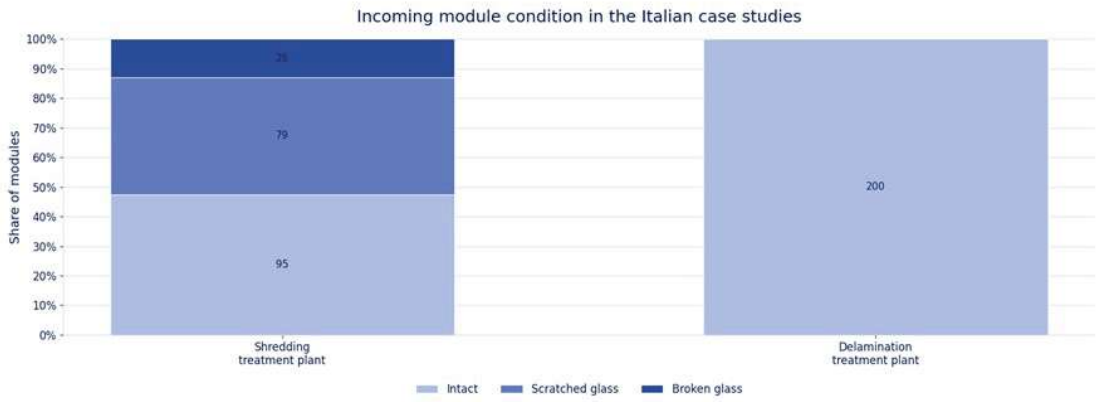


Figure 28 – Incoming module condition in the Italian case studies

The shredding treatment plant is the Italian case best fits the analysis of logistics-related damage, because it contains module condition, pallet condition, glass-face orientation, technology and weight. The relationship between pallet condition (intact, damaged – if partly broken or rotten, broken) and glass condition should be interpreted cautiously: broken pallets show the highest proportion of broken glass, but damaged pallets do not automatically correspond to higher breakage. This suggests that pallet condition alone does not fully explain damage occurrence and should be read together with orientation, product characteristics and handling conditions.

Table 6 – Shredding treatment plant - pallet condition and glass condition

Pallet condition	Intact glass	Scratched glass	Broken glass	Total	Broken glass rate
Intact	43	34	17	94	18.1%
Damaged	40	39	3	82	3.7%
Broken	12	6	6	24	25.0%



Figure 29 – Shredding treatment plant - glass condition by pallet condition

Orientation is one of the most promising variables for assessing logistics-related damage. In the shredding treatment plant sample, modules with the glass side facing upwards show a higher incidence of broken glass than those facing downwards. This result should not be interpreted as a standalone causal effect, but it highlights the need to further investigate how module stacking and handling practices interact with glass orientation.

Table 7 – Shredding treatment plant - glass-face orientation and glass condition

Orientation	Intact glass	Scratched glass	Broken glass	Total	Broken glass rate
Glass side down	77	60	9	146	6.2%
Glass side up	18	19	17	54	31.5%

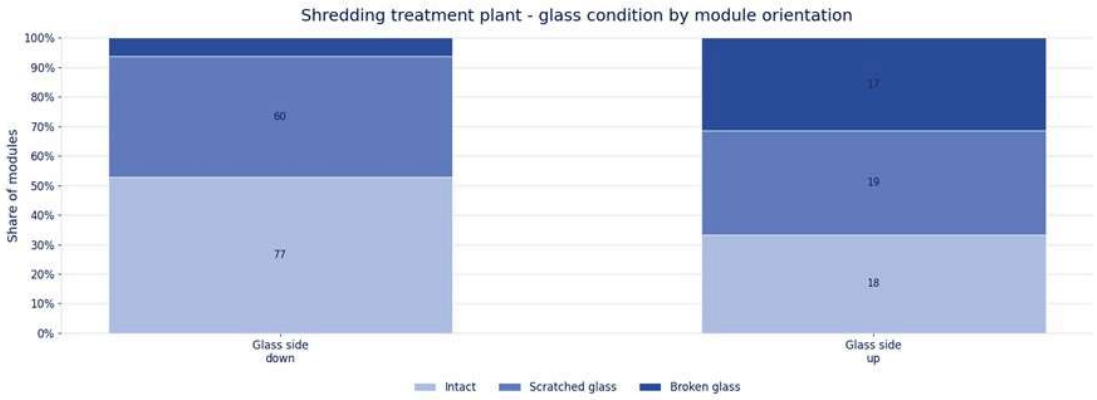


Figure 30 – Shredding treatment plant - glass condition by module orientation

The Italian datasets also make it possible to add a product-related layer. In the shredding treatment plant sample, module technology appears to influence the observed damage pattern: mono modules account for most broken glass cases, whereas glass-glass modules are more frequently scratched but rarely broken. On average, mono modules, usually made of a glass layer and a plastic backsheet, are older than their counterparts, hence more subject to breakages.

Table 8 – Shredding treatment plant - technology and glass condition

Technology	Intact	Scratched glass	Broken glass	Total	Broken glass rate
Silicon Mono	66	30	24	120	20.0%
Glass-glass	29	49	2	80	2.5%

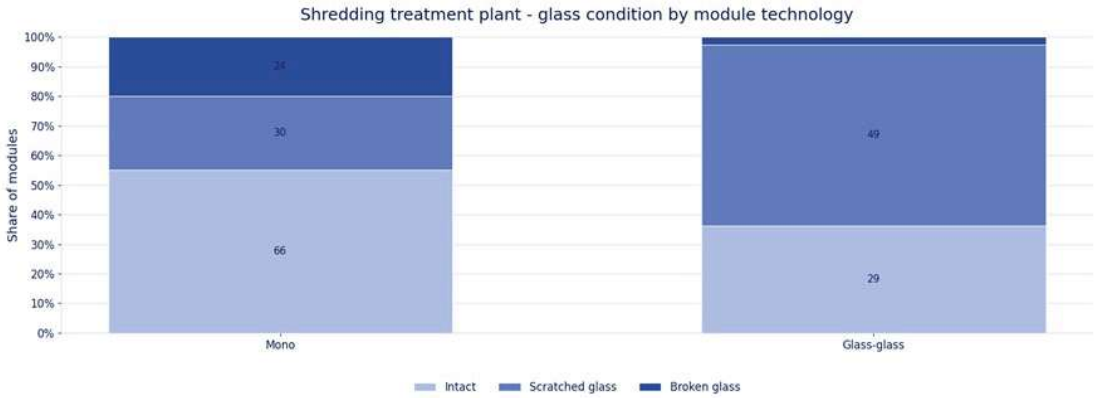


Figure 31 – Shredding treatment plant - glass condition by module technology

Table 9 – Shredding treatment plant - module weight class and glass condition

Weight class	Intact	Scratched glass	Broken glass	Total
15-20 kg	90	79	26	195
20-25 kg	3	0	0	3
>25 kg	2	0	0	2

Weight should be interpreted with caution. Almost all modules from the shredding treatment plant fall in the 15-20 kg class, which prevents a robust weight-class analysis. Weight remains useful for descriptive work by model, production year or technology, but not for estimating a strong relationship with breakage in the current sample.

In the delamination treatment plant dataset, technology is available, but all sampled modules are intact. The variable therefore describes the composition of the sample rather than explaining damage. The sample includes 75 silicon mono modules and 125 silicon poly modules.

Table 10 – Delamination treatment plant - technology composition of the sampled modules

Technology	Modules	Condition
Silicon Mono	75	All intact
Silicon poly	125	All intact

The delamination treatment plant cannot be used to estimate the effect of logistics variables on breakage because no damaged modules are observed in the sample. Nevertheless, it provides several useful descriptive variables. The sample covers upper, middle and lower pallet areas in a balanced way, supporting the representativeness of the sampling strategy. Orientation is also recorded, with 150 modules facing up and 50 modules facing down.

Table 11 – Delamination treatment plant - module condition by pallet position

Pallet position	Modules	Observed condition
Upper area	68	All intact

Middle area	63	All intact
Lower area	69	All intact

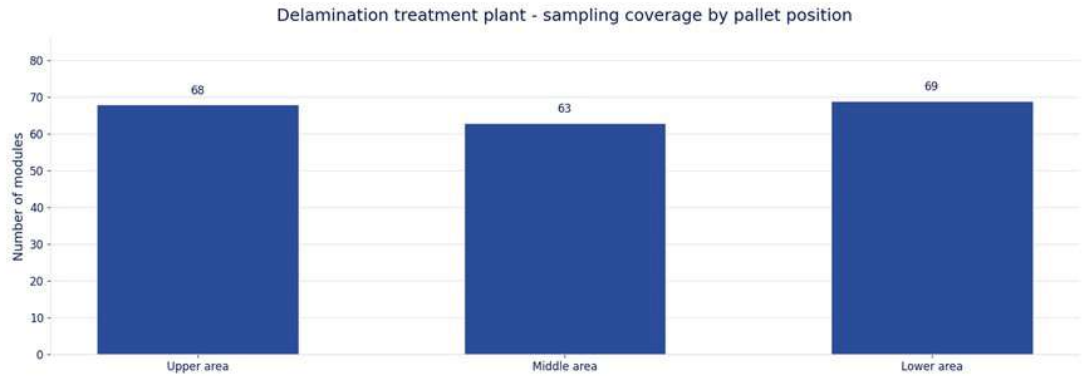


Figure 32 – Delamination treatment plant - sampling coverage by pallet position

Table 12 – Delamination treatment plant - module condition by orientation

Orientation	Modules	Observed condition
Face up	150	All intact
Face down	50	All intact

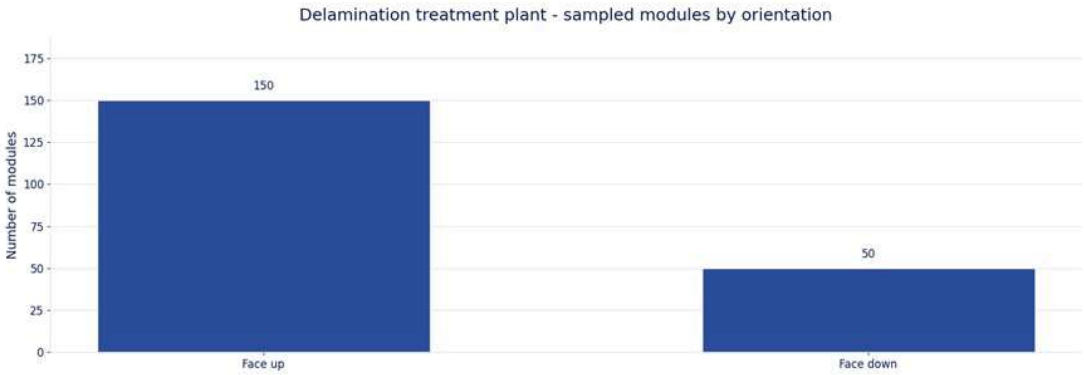


Figure 33 – Delamination treatment plant - sampled modules by orientation

Packaging configuration is homogeneous in the delamination treatment plant dataset: the sampled modules are recorded as coming from pallets that were strapped and without plastic film. The dataset does not include multiple packaging configurations, so it is not possible to test the independent effect of film or different numbers of straps. The absence of damage under this observed configuration should therefore be treated as a case-specific finding, not as a general causal conclusion.

Both Italian datasets include information on the presence of components that are relevant for pre-treatment and material recovery. This layer strengthens the Italian case by linking incoming module characteristics to the practical feasibility of removing or recovering aluminium frames, junction boxes and cables before or during treatment.

Table 13 – Component presence in the Italian samples

Case study	Component	Modules with component	Share of sample
Shredding treatment plant	Aluminium Frame	199	99.5%
Shredding treatment plant	Junction box	200	100.0%
Shredding treatment plant	Cables	128	64.0%
Delamination treatment plant	Aluminium frame	200	100.0%
Delamination treatment plant	Junction box	200	100.0%
Delamination treatment plant	Cables	150	75.0%

The overall integrity of the modules, where only the cable component is missing in a significant number of cases, reflects the system's ability to protect the waste without it being 'scavenged,' losing value along the value chain.

3.3.2. Results of the analysis — France

The analysis conducted in France is based on a database built from PV modules sent to the ENVIE treatment centre. The dataset includes 201 PV modules, reflecting a range of dismantling situations encountered in practice.

At the French level, the causes leading to the dismantling of PV modules can be identified and classified. The resulting typology highlights a variety of technical and operational situations. This stage is currently only applied in France; in Italy, due to differences in the collection operation, it is not possible to trace the information regarding the reason for dismantling.

Causes related to external events are among the most frequently reported. In particular, hail impacts are commonly observed and are typically associated with visible damage to the front glass, also breakage during installation can compromise the mechanical integrity of the glass and justify its dismantling.

Other cases are linked to performance losses and manufacturing defects which account for a smaller number of modules. Finally, category labelled “other causes” includes a variety of less well-documented situations, for which the available information does not allow a clear identification of the underlying dismantling reason.

The table below shows the different reasons for dismantling and the number of modules that arrived at the treatment centre intact and broken.

Table 14 – Dismantling causes in relation to glass condition

Dismantling reason	Broken glass	Intact glass	Broken glass rate
Breakage during installation	14	7	66,7%
Hail Damage	27	12	69,2%
Decrease of efficiency	9	36	20,0%
Manufacturing defects	0	9	0,0%
Other reason	35	52	40,2%
Total	85	116	

Some dismantling causes involve uncertainty regarding the origin of the damage, particularly when it is difficult to distinguish between degradation occurring during operation and damage caused during collection operations. This mainly concerns modules affected by breakage during installation or hail damage.

To address this uncertainty, in the French scenario a refinement step was applied to retain only modules for which the dismantling cause could be reliably attributed to the operational phase. As a result, **141 modules were included in the final analysis, while 60 modules were excluded** due to insufficient traceability or ambiguity regarding damage origin. This methodological choice reduces the risk of misclassification and improves the robustness and consistency of the analysis, despite a smaller dataset.

As shown in Figure 34, cases involving broken glass upon arrival at the treatment centre are not uncommon, but they are not the rule either. As shown in Figure 35, 31 % of the modules exhibit broken glass, while 69 % have intact glass, corresponding to 44 damaged modules and 97 intact modules, respectively.

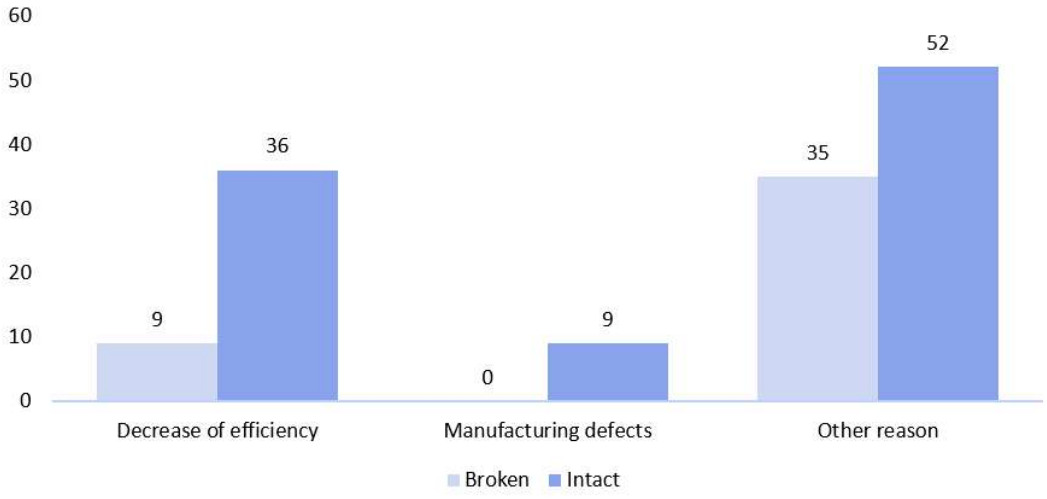


Figure 34 – Dismantling causes in relation to glass condition

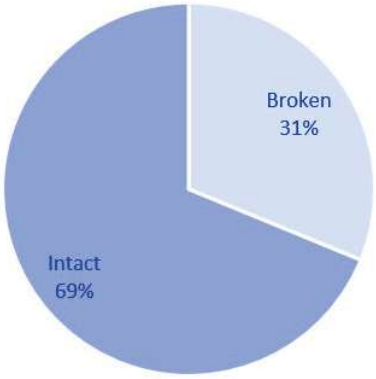


Figure 35 – Rate of broken modules upon arrival at the treatment centre

The table below presents the number of PV modules classified according to pallet condition and glass integrity. It provides a quantitative overview of the dataset, highlighting the distribution of intact and broken modules across the different pallet quality categories. This illustrates the extent to which pallet quality can play a significant role in preventing damage to PV modules, particularly by limiting mechanical stress and impacts during transport.

Table 15 – Pallet condition and glass breakage

Pallet condition	Broken glass	Intact glass	Broken glass rate
Good condition	14	67	17,3%
Average condition	17	16	51,5%
Poor condition	13	14	48,1%
Total	44	97	31,2%

The figure below shows that in the majority of cases, PV modules transported on pallets in good condition arrive with intact glass, indicating a lower risk of mechanical damage during collection operations. Conversely, when pallets are in average or poor condition, the probability of receiving modules with the glass intact decreases significantly. This highlights the role of pallet quality as a key factor influencing glass breakage, with degraded pallets increasing the risk of damage during logistics operations.

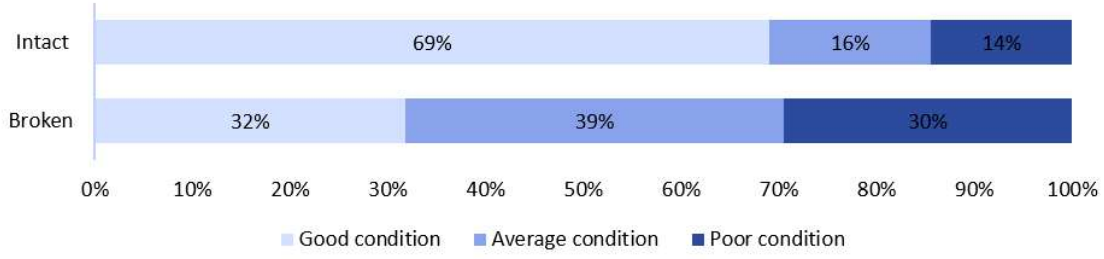


Figure 36 – Glass breakage rate by pallet condition (%-deviation due to rounding)

Another requirement for producers is to place the module with the glass side facing up, a procedure that is not always followed. The table below indicates the number of broken modules based on the pallet configuration and the orientation of the module's glass side.

Table 16 – Module orientation and glass breakage

Pallet condition	Broken glass	Intact glass	Broken glass rate
Front-glass facing up			
Good condition	13	58	18,3%
Average condition	8	6	57,1%
Poor condition	5	4	55,6%
Front-glass facing down			
Good condition	1	9	10,0%
Average condition	9	10	47,4%
Poor condition	8	10	44,4%

37Table 16 shows that both configurations involving pallets in good condition, whether modules are transported with the glass side facing up or down, appear to be the most favourable. This observation suggests that pallet quality remains the dominant factor influencing glass integrity during transport. Module orientation (glass face) plays a secondary role, potentially modulating the risk of damage, but its effect is less pronounced when pallet condition is adequate.

Still, this table seems to suggest a correlation between the front glass facing up and a higher glass breakage rate. It should be interesting to look at the global condition of PV in relation to the glass' orientation. The reason why Soren ask to palletize with glass above is to avoid water stagnation into the PV which can decrease the laminated integrity.

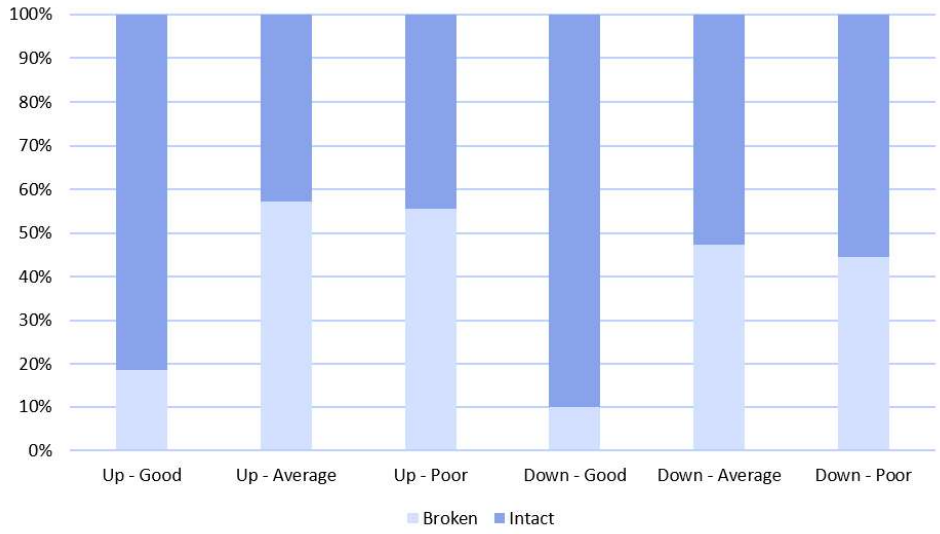


Figure 37 – Glass breakage rate by pallet condition and glass-face orientation

Information below focuses on the level of compliance with the different requirements defined for palletisation and packaging practices, namely the use of pallets in good condition, as well as the strapping and wrapping of pallets containing PV modules. In addition to these criteria, the sampling was carried out by pallet area, distinguishing between the upper, middle, and lower area. This approach makes it possible to assess how a complete packaging practice and module positioning influence the condition of PV modules upon reception.

Due to the lack of sufficient data to assess all factors simultaneously, the analysis focuses on the pallet in good condition under several configurations (number of straps), as well as on the three pallets conditions using two straps.

Data corresponding to pallets in good condition includes a total of 81 PV modules, distributed across different numbers of straps and the presence or absence of plastic film. Overall, configurations using plastic film are more frequently represented (54 PV modules) than those without plastic film (27 PV modules), indicating either a more common operational practice or a partial coverage of the tested configurations.

Table 17 – Packaging practices and glass breakage

Pallet condition	Broken	Intact	Broken	Intact
Good condition				
Number of straps	Plastic film - Yes		Plastic film - No	
2	7	23	1	8
3	0	0	1	17
4	1	8	0	0
>5	4	11	0	0
Total	12	42	2	25

Higher levels of glass breakage are mainly observed in configurations where plastic film is present, particularly for pallets secured with two straps and more than five straps. This pattern leaves a clear determination of the added usefulness of plastic film for stabilization ambiguous. It may provide limited additional support to the load. However, the data also show that in the absence of plastic film, glass breakage does not increase significantly, indicating that the protective effect of the film remains moderate under these conditions.

Regarding the number of straps, the current dataset seems to show that, for pallets in good condition, 3 or 4 straps involve less breakage than 2 or more than 5.

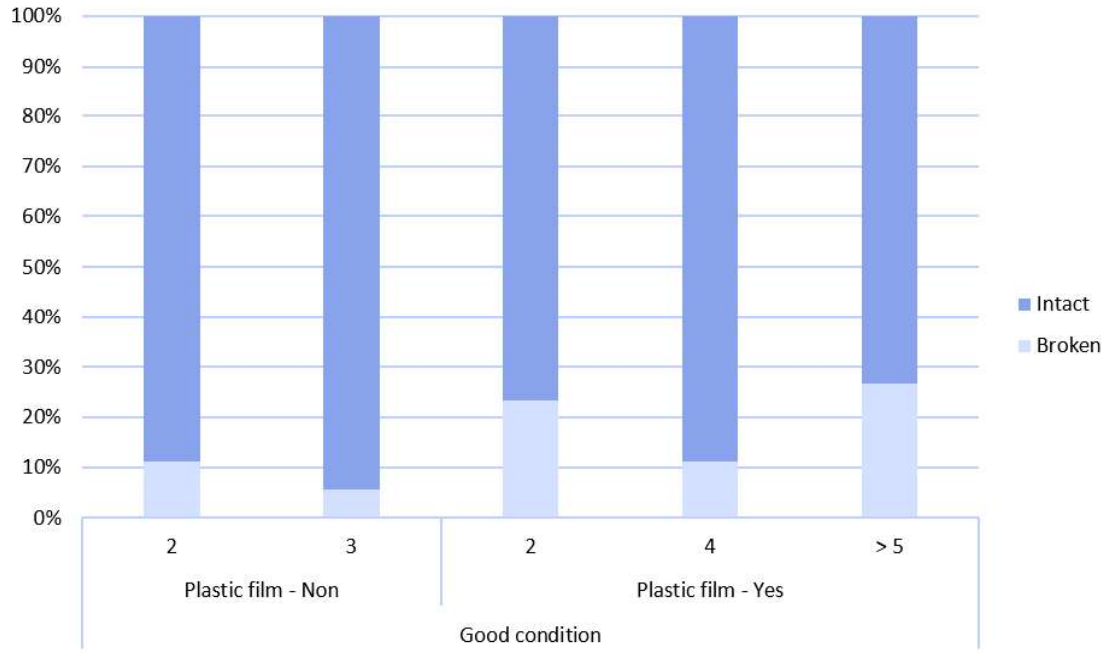


Figure 38 – Glass breakage rate by packaging practices - pallet in good condition

The second analysis is based on a total of 84 PV modules, evaluated under a two-strap configuration and distributed across three pallet conditions (good, average, and poor), with and without plastic film.

Table 18 – Packaging practices and pallets conditions – 2 straps

Number of straps - 2	Broken	Intact	Broken	Intact
	Plastic film - Yes		Plastic film - Non	
Good condition	7	23	1	8
Average condition	4	5	2	7
Poor condition	5	4	8	10
Total	16	32	11	25

In pallets in good condition, the majority of PV modules remain intact, particularly with plastic film.

For pallets in average condition, there is a higher number of broken PV modules than the pallets in good condition, however, in poor condition, breakage becomes more frequent regardless of the presence of plastic film, this suggests that pallet condition is the primary factor influencing breakage, while the presence or absence of plastic film has little apparent impact.

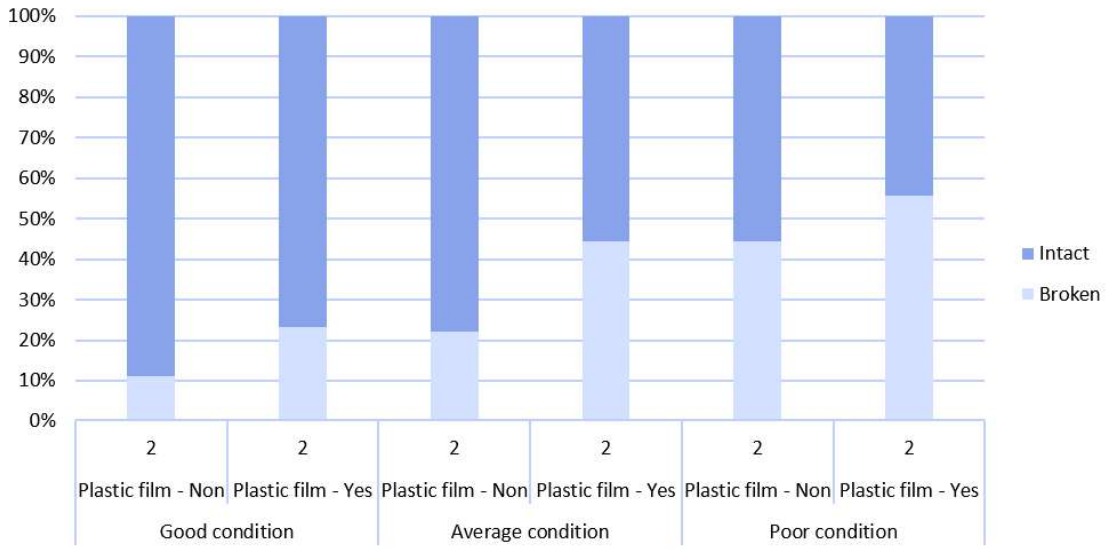


Figure 39 – Glass breakage rate by packaging practices and pallets conditions – 2 straps

The analysis of PV module weight across different pallet quality levels is a key element in understanding breakage mechanisms during handling and transport. Module weight directly influences load distribution on the pallet and the mechanical stresses transmitted to both the pallet structure and the glass surface.

The relevance of this analysis is reinforced by the ongoing trend toward larger and heavier PV modules, which increases loads per pallet and mechanical stress on packaging components.

The analysis covers a total of 81 PV modules placed on good-conditioned pallets, distributed across three sampling areas (upper, middle, and lower) and three weight classes.

Table 19 – Module breakage by weight and sampling area – Pallet good condition

Pallet condition	Broken	Intact	Broken	Intact	Broken	Intact
Good condition	Upper area		Middle area		Lower area	
≤15 kg	0	3	0	3	0	3
15-20 kg	3	14	4	13	3	14
20→25 kg	2	5	1	6	1	6
Total	5	22	5	22	4	23

Overall, the results show an observational relationship between module weight and the occurrence of glass breakage, while no significant influence of the vertical position on the pallet is observed when the pallet is well conditioned. Low-weight modules remain intact across all areas, whereas breakage appears progressively as module weight increases. This trend is consistent across upper, middle, and lower sampling areas, indicating that module weight is the main driver of breakage, even when pallets are in good condition, while the sampling area plays a secondary role.

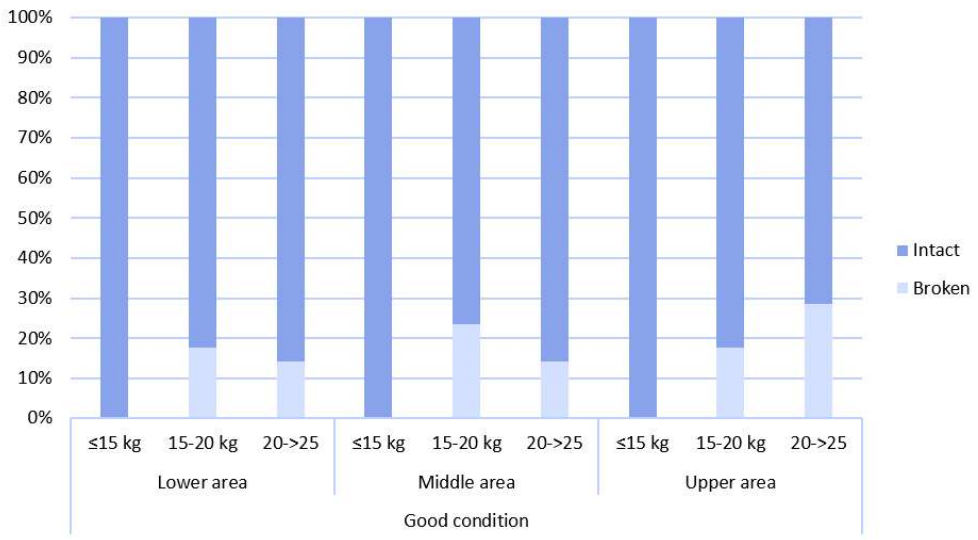


Figure 40 – Glass breakage rate by weight and sampling area – Pallet good condition

Due to the limited available data, a comparative analysis of pallet quality can only be performed for modules in the 15–20 kg weight range, as other weight classes do not provide sufficient information across all pallet conditions.

The analysis covers a total of 102 PV modules in the 15–20 kg weight range, distributed across three pallet quality levels (good, average, and poor) and three sampling areas (upper, middle, and lower).

Table 20 – Module breakage by pallet quality and sampling area - range 15–20 kg

Weight 15-20 kg	Broken	Intact	Broken	Intact	Broken	Intact
	Upper area		Middle area		Lower area	
Good condition	3	14	4	13	3	14
Average condition	3	5	3	5	6	2
Poor condition	2	7	6	3	5	4
Total	8	26	13	21	14	20

On good condition pallets, breakage rates are consistently low across all areas, ranging from 18% to 24%, with more than three-quarters of the modules remaining intact in every position. This indicates a stable and homogeneous load support when pallet quality is high.

For average condition pallets, breakage rates increase. The upper and middle areas show similar breakage levels, while the lower area exhibits a markedly higher breakage rate. This suggests that as pallet quality degrades, the lower part of the pallet becomes more sensitive to mechanical stress.

On poor condition pallets, breakage rates remain high and unevenly distributed. While the upper area shows a relatively moderate breakage rate, the middle and lower areas experience substantially higher levels of damage, confirming a reduced capacity to uniformly support module weight.

Overall, for 15–20 kg PV modules, the results highlight a clear interaction between module weight and pallet quality. While pallets in good condition are able to consistently support this weight range with low and uniform breakage rates, degradation in pallet quality leads to a reduced capacity to manage mechanical loads. As pallet condition worsens, the same module weight results in higher and more uneven glass breakage, particularly in the middle and lower areas. This confirms that increasing module weight amplifies the impact of pallet quality on damage occurrence, making pallet condition a critical factor for heavier modules.

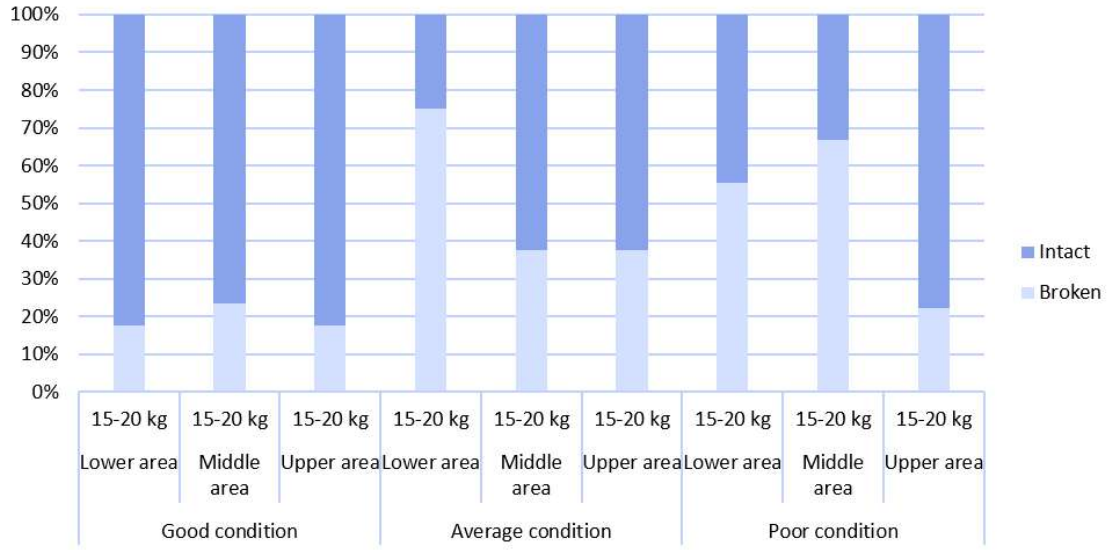


Figure 41 – Glass breakage rate by pallet quality and sampling area - range 15–20 kg

The analysis of covered distance during transport provides additional insight into potential damage mechanisms affecting PV modules. This parameter reflects the cumulative mechanical stresses experienced along the operational chain, including handling, loading, unloading, and road transport.

It should be noted that distance covered data are only available for the French case, due to the specific structure and traceability of the operational chain in the country. As a result, this analysis cannot be directly extended or compared to Italy case.

The analysis covers a total of 114 PV modules, distributed across three distance levels and is limited to pallets in good and average condition, as insufficient information is available for poor condition pallets.

Table 21 – Module breakage by pallet quality and covered distance

Covered distance	Broken	Intact	Broken	Intact
Good condition				
0-150 km	1	17	5.6%	94.4%
150-300 km	10	41	19.6%	80.4%
300→450 km	3	9	25.0%	75.0%
Average condition				

0-150 km	0	0	–	–
150-300 km	15	9	62.5%	37.5%
300→450 km	2	7	22.2%	77.8%

For pallets in good condition, glass breakage remains low and does not show a clear dependency on the distance covered. This suggests that pallet integrity is sufficient to withstand transport-related stresses across the observed distance ranges.

In contrast, for pallets in average condition, breakage decreases as transport distance increases. Even if no data has been obtained for short distances (less than 150km), it's visible that there is significantly less breakage for distances above 450km than underneath. It could indicate that the transport distance is not the main reason of breakage of average conditioned pallets.

Overall, this analysis does not provide conclusive evidence on the impact of transport distance on glass breakage. Although distance may contribute to cumulative mechanical stresses during transport, the results are inconsistent between pallets in good and average condition. This suggests that any effect of transport distance is likely influenced by pallet condition, making it difficult to isolate distance as a standalone factor.

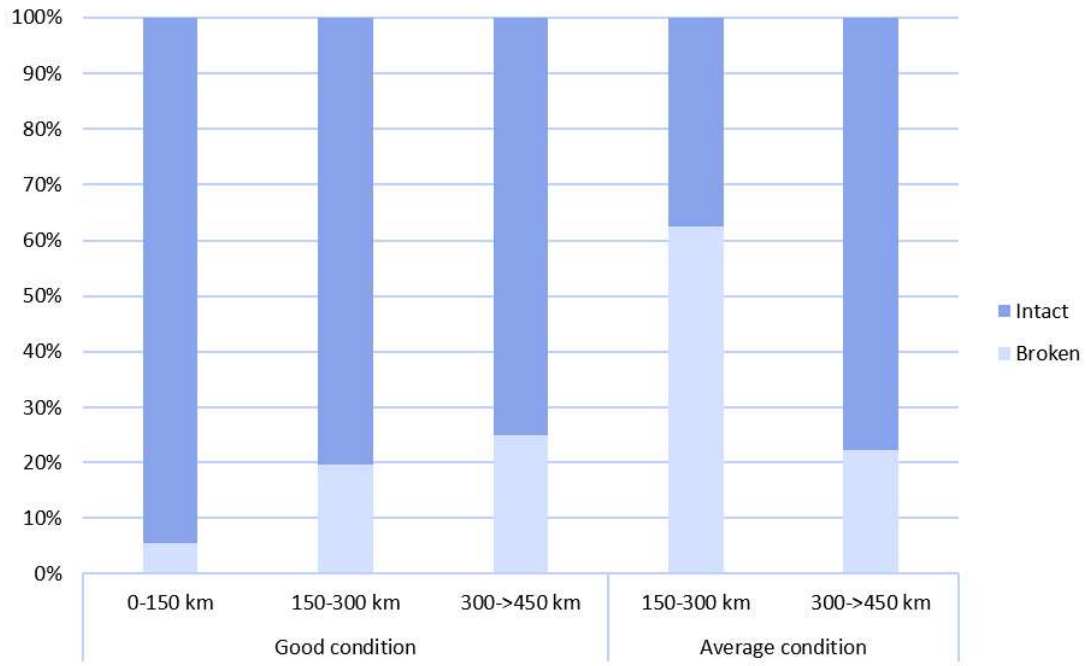


Figure 42 – Glass breakage rate by pallet quality and covered distance

A specific analysis was conducted for long transport distances (300 to >450 km). This distance range is of particular interest as it reflects extended exposure to handling operations, vibrations, and cumulative mechanical stresses. The analysis compares glass

breakage across the three pallet quality levels in order to better understand how pallet condition influences module integrity over long transport distances.

The analysis covers a total of 48 PV modules transported over distances of 300 to >450 km, distributed across three pallets condition.

Table 22 – Module breakage by pallet quality and covered distance 300 to >450 km

300→450 km	Broken	Intact
Good condition	3	9
Average condition	2	7
Poor condition	13	14
Total	18	30

For transport distances of 300–450 km, breakage rates are clearly higher when pallet is poorly conditioned. Moreover, breakage is slightly higher for pallets in good condition compared to the average ones. Thus, with so few samples, the difference could be due to uncertainty related to the practical case. As a consequence, it is relevant to assume that pallets in good and average condition show similar and relatively low breakage levels, with most PV modules remaining intact. In contrast, poor-condition pallets exhibit a substantially higher breakage rate, indicating a reduced ability to withstand cumulative transport-related stresses over long distances.

Overall, these results confirm that, for long transport distances, pallet quality is a key determinant of module integrity, while distance alone is not sufficient to explain breakage when pallets are in good or average condition.

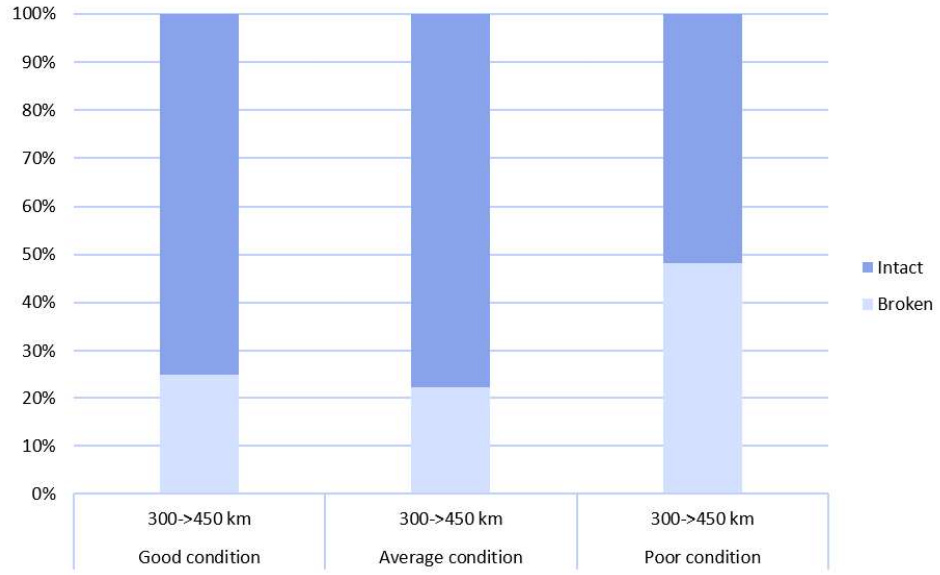


Figure 43 – Glass breakage rate by pallet quality and covered distance 300 to >450 km

3.3.3.Field case study FRANCE

In total, 12 pallets were assembled and monitored for the field study, representing a stock of 427 photovoltaic modules. The selected pallets covered all palletisation and packaging configurations tested within the scope of the field case study, including variations in strapping, use of stretch film, mixed securing systems, and alternative stacking arrangements. A total distance of 373 km was covered between the solar power plant site and the treatment centre.

Each pallet was treated as an individual observation unit. The combination of quantitative data (number of modules, handling times, number of broken modules) and qualitative observations (photographic evidence, operator feedback, visual assessment of pallet condition) formed a robust dataset for comparative analysis.

Photographs were taken prior to any handling operations, allowing the initial condition of the pallets and PV modules to be documented (figure 44). These images provided clear evidence of the original palletisation layouts, configuration of palletisation (figure 45), the type and number of securing elements used (straps, stretch film, tape), and the overall integrity of the pallets before departure from the site.



Figure 44 – Pallet quality before collection operation



2 straps and plastic film



4 straps



4 panels on the side



6 straps

Figure 45 – Palletisation configuration

Additional photographic records were collected during transport and upon arrival of the truck at the treatment centre. These photographs made it possible to assess the global condition of the load after road transport, to identify any visible pallet deformation, displacement of modules, or damage to packaging elements, and to verify load stability at the moment of unloading.



Figure 46 – Arrival of the loaded truck

Finally, a third set of photographs was taken during unloading of pallets, and temporary storage of the modules at the treatment centre. This stage was essential to document handling conditions, the behaviour of the different palletisation configurations during dismantling, and any damage observed at this step. These images also supported the identification of potential critical moments, such as strap cutting, removal of stretch film, re-palletisation operations, or module repositioning.



Figure 47 – Unloading and storage of the pallets



Figure 48 – Handling operation at treatment centre

Table 23 summarises the results regarding the number of modules per pallet, the broken modules, and the time required to assemble the pallet and remove the packaging components.

The measured palletisation and packaging times before logistic operation correspond to the phase during which the producer places the PV modules on the pallet and installs the associated safety and securing elements (such as straps, plastic film, or protective materials).

The measured handling times correspond to the phase at the treatment centre, when treatment operators remove these securing elements. This moment directly precedes the pickup of the modules for feeding into the processing line and therefore reflects the effective operational handling time downstream.

Table 23 – Data of palletisation methods, handling times and PV module integrity

Reference	Packaging configuration	Total PV modules	Broken PV modules	Palletisation and packaging time (min) - before logistic operation	Handling time (min) - after logistic operation
1/12	4 panels on the side	39	0	43,0	0,8
2/12	6 straps	35	0	39,0	0,2
3/12	4 panels on the side	39	0	43,0	0,8
4/12	4 straps	35	2	35,5	0,3
5/12	4 straps	35	0	35,5	0,3
6/12	6 straps	35	0	39,0	0,6
7/12	2 straps and	35	0	39,0	0,5

	plastic film				
8/12	4 straps	35	0	35,5	0,4
9/12	4 straps	34	0	35,5	0,6
10/12	2 straps and plastic film	35	0	39,0	0,7
11/12	2 straps and plastic film	35	0	39,0	1,1
12/12	6 straps	35	0	39,0	0,7

The field case showed a very low level of module breakage, with only 2 broken photovoltaic modules out of 427, corresponding to less than 1% of the total volume. This result is consistent with the conclusions previously drawn during the characterisation of incoming flows at the treatment centre, where low breakage rates were observed for pallets arriving in good condition.

The limited number of damaged modules can be explained by the overall quality of the pallets, the care taken by operators during palletisation, and the controlled handling practices applied during transport and unloading. Photographic records confirm that pallets remained structurally stable throughout the logistics chain and that unloading operations were carried out with appropriate caution.

Overall, these observations confirm that the condition of the pallet is the primary factor determining the condition of the modules upon arrival at the treatment centre. When pallet integrity and handling quality are maintained, module breakage remains marginal, even under representative transport conditions.

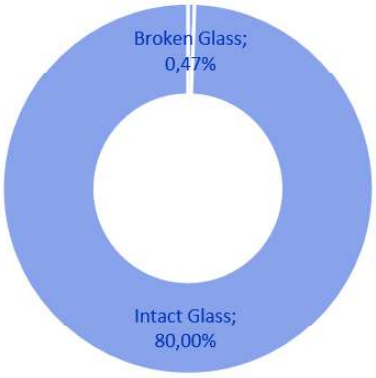


Figure 49 – Glass breakage rate

Regarding operational times, clear differences are observed between packaging configurations. The 4-strap configuration shows the best overall performance, with the shortest palletisation time and the lowest handling time after logistics. Configurations using 6 straps or 2 straps combined with plastic film require longer preparation times and slightly higher handling times, reflecting additional securing and removal steps.

The 4 side-panel configuration is the most time-consuming, both during palletisation and handling, due to increased positioning and stability constraints. Overall, the results indicate

that simpler strap-based configurations are the most time-efficient, both before and after the logistics operation.

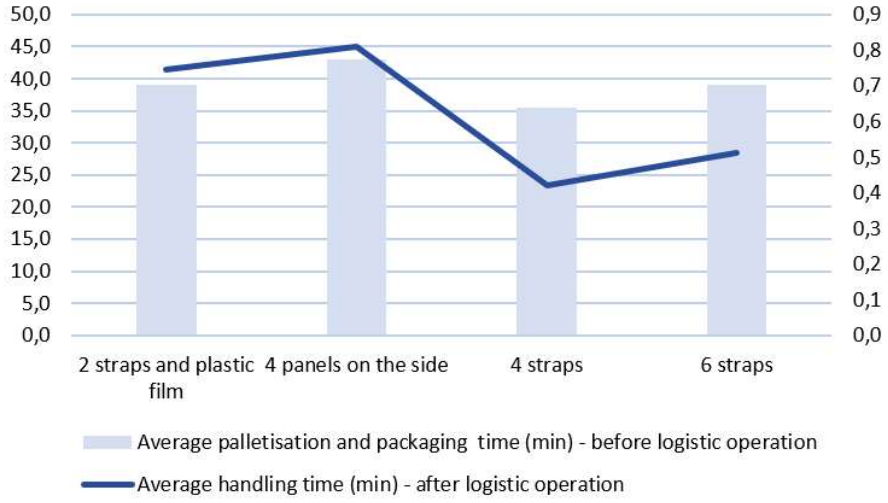


Figure 50 – Operational times by packaging configurations

3.4. CASE STUDIES ON THE RECYCLING EFFICIENCIES - SAMPLING ACTIVITIES

The results of the analysis on the recycling efficiencies in Italy and France are presented below.

As in the previous analysis, the results were not aggregated at European level, as each country operates within a distinct operational and organisational framework.

In Italy, the analysis focused on treatment centres applying two competing approaches, by providing a common format for data gathering, hence enabling a robust and consistent comparison of performance.

This approach was subsequently leveraged for the French study, where a single treatment centre operates both treatment technologies. In addition, the photovoltaic waste characterisation methodology was not identical in both countries, even if, in the case of France, the aim was to follow Italy's approach.

3.4.1. Results of the Italian sampling activities

The two Italian case studies differ mainly in the share of silicon-based panels available for treatment. In the shredding treatment plant, the initial batch was technologically mixed and only 120 out of 200 panels were processed, corresponding to the mono-crystalline silicon-based sub-stream. In the delamination treatment plant, the entire batch was treated because all 200 panels were crystalline silicon modules, including both mono- and poly-crystalline technologies. This difference is relevant because the delamination route is specifically applicable to c-Si panels. Despite this difference, the two cases are comparable in methodological terms, as both are based on real batches of 200 end-of-life PV panels and both include pre-treatment characterisation of mass, technology and key removable components.

Table 24 – Comparison of incoming samples and treated panels in the Italian case studies

Indicator	Shredding treatment plant	Delamination treatment plant
Total panels characterised	200	200
Total sample weight	3,860.2 kg	3,873 kg
Mono-crystalline technology	120 panels	75 panels
Poly-crystalline technology	—	125 panels
Glass-glass technology	80 panels	—
Silicon-based panels	120 panels	200 panels
Share of silicon-based panels	60% by number; 58% by mass	100%
Panels actually treated	120 panels	200 panels
Weight of treated panels	2,228.2 kg	3,873 kg



Figure 51 – Panels extracted from the pile and set aside for controlled treatment at the delamination treatment plant

Mass balances and recovery destinations

The comparison of the mass balances shows that the two treatment routes generate broadly similar material categories, but with different distributions and, more importantly, different levels of output qualification. Both processes recover the main material streams typically associated with crystalline silicon photovoltaic panels, namely glass, aluminium, plastics/EVA, cables and silicon-rich fractions. However, the way these fractions are separated, classified and subsequently valorised differs significant

y between the two industrial approaches.

Output fractions generated by the two treatment routes

Table 25 – Comparison of output fractions generated by shredding and delamination

Output fraction	Shredding treatment plant – % of treated mass	Shredding treatment plant – estimated kg	Delamination treatment plant – % of treated mass	Delamination treatment plant – estimated kg	Interpretation
Glass, EER 19 12 05	65.71%	1,464.2 kg	2.45%	95 kg	In the shredding route, the whole recovered glass fraction remains classified as waste. In the delamination route, only a minor residual glass fraction remains classified as EER 19 12 05.
End-of-Waste	—	—	50.09%	1,940 kg	Specific output of the

glass					delamination route and the main qualitative difference between the two cases.
Total glass fraction	65.71%	1,464.2 kg	52.54%	2,035 kg	Glass is the dominant mass fraction in both cases, but with a substantially different legal and material status.
Plastics / EVA-PET, EER 19 12 04	15.79%	351.8 kg	14.43%	559 kg	Similar share in both cases; this remains the main critical fraction because it is mainly directed to energy recovery.
Aluminium , EER 19 12 03	11.45%	255.1 kg	14.02%	543 kg	Consolidated material recovery stream in both cases, with a slightly higher share in the delamination route.
Powder / silicon-rich fraction, EER 19 12 03	5.15%	114.8 kg	15.72%	609 kg	Strategic fraction in both cases; much higher mass share in the delamination route.
Iron / ferrous metals, EER 19 12 02	1.05%	23.4 kg	—	—	Separately identified only in the shredding route.
Copper, EER 19 12 03	—	—	0.39%	15 kg	Separately identified only in the delamination route.
Cables, EER 16 02 16	0.85%	18.9 kg	0.67%	26 kg	Present in both mass balances, with a similar relative order

					of magnitude.
Junction boxes, EER 16 02 16	—	—	0.72%	28 kg	Separately reported only in the delamination route.
Dust from aspiration system, EER 19 12 11*	—	—	1.50%	58 kg	Residual hazardous-coded dust fraction reported only in the delamination route.
Total treated mass	100%	2,228.2 kg	100%	3,873 kg	The delamination route treated the full 200-panel batch, while the shredding route treated only the selected silicon-based sub-stream.







The first common element is that glass is the dominant output stream in both treatment routes. In the shredding treatment plant, glass accounts for 65.71% of the treated mass, whereas in the delamination treatment plant the total glass fraction accounts for 52.54%. However, this difference should not be interpreted only in quantitative terms. The shredding route generates a larger glass fraction by mass, but this output remains classified as glass waste, EER 19 12 05. By contrast, the delamination route generates a slightly lower total glass share, but most of this fraction — 50.09% of the treated mass — is qualified as End-of-Waste glass. This represents a higher level of output quality, market readiness and regulatory qualification.

A second key difference concerns the powder / silicon-rich fraction. In the shredding treatment plant, this fraction represents 5.15% of the treated mass, while in the delamination treatment plant it reaches 15.72%. This suggests that the delamination process transfers a

larger share of fine, cell-related and mineral material into a dedicated fraction. This fraction is strategically relevant because it may contain silicon and valuable metals, but its actual valorisation depends on the availability of further downstream refining or concentration steps.

The plastic fraction is very similar in the two cases: 15.79% in the shredding treatment plant and 14.43% in the delamination treatment plant. This is a key cross-case result, because it shows that plastics/EVA remain a structurally relevant output stream regardless of the treatment route. Since this fraction is mainly directed to energy recovery rather than material recycling, it represents a common bottleneck for full circularity in industrial PV panel recycling.

The comparison also confirms that aluminium is a stable and relevant recovery stream in both cases. Aluminium accounts for 11.45% of the treated mass in the shredding route and 14.02% in the delamination route. This confirms that aluminium frames are among the most easily valorisable fractions in PV recycling, with consolidated downstream recovery routes.

Finally, the delamination treatment plant provides a more detailed separation of minor fractions, including copper, cables, junction boxes and aspiration dusts, while the shredding treatment plant presents a more aggregated output structure. This may reflect both the process configuration and the way the mass balance was reported. From an analytical perspective, the more granular breakdown of the delamination route makes it easier to assess the recovery potential, destination and economic value of individual output streams.

Overall, the mass balance comparison shows that the two treatment routes should not be assessed only on the basis of total recovered mass. The shredding treatment plant performs strongly in terms of glass separation by mass, while the delamination treatment plant provides stronger evidence of qualitative recovery, particularly through the production of End-of-Waste glass and the more detailed separation of output fractions. In both cases, plastics remain the main limitation, while glass, aluminium and silicon-rich powders represent the most relevant fractions for material recovery and future valorisation.

Recovery routes and downstream destinations

The downstream destination of each output fraction was also assessed in order to distinguish between theoretical recyclability and actual recovery routes. This distinction is essential because a fraction may be technically recoverable but still classified as waste or may be separated during treatment but ultimately directed to energy recovery or disposal.

Table 26 – Comparison of recovery routes and downstream destinations

Recovery route	Shredding treatment plant	Delaminatio n treatment plant	Interpretation
Material recovery	1,740 kg, equal to 78.1% of treated mass	3,256 kg, equal to 84.1% of treated mass	The delamination route shows a higher material recovery share, mainly due to End-of-Waste glass, aluminium, silicon-rich powders and metals.
Energy recovery	334 kg, equal to 15.0% of	559 kg, equal to 14.4% of	In both cases, energy recovery is almost entirely driven by the plastic/EVA fraction.

	treated mass	treated mass	
Disposal / incineration / residual treatment	Approx. 154 kg, equal to 6.9% of treated mass	58 kg, equal to 1.5% of treated mass	The shredding route has a higher residual/non-material recovery share, partly due to the corrected plastic destination.
Total treated mass	2,228.2 kg	3,873 kg	The delamination route treated the full 200-panel batch, while the shredding route treated only the selected silicon-based sub-stream.

The aggregated recovery data confirm that both treatment routes achieve a high level of material recovery, but through different output profiles. The shredding treatment plant reaches approximately 78.1% material recovery when the glass fraction classified as EER 19 12 05 is considered as being sent to an authorised material recovery route. The delamination treatment plant reaches approximately 84.1% material recovery, with a stronger qualitative profile because a major share of the recovered glass is already qualified as End of Waste.

The key difference, therefore, is not only the percentage of material recovery, but the quality and status of the recovered material. In the shredding route, the glass fraction can be considered as material recovery only insofar as it is actually sent to an authorised recovery process, while it remains legally classified as waste. In the delamination route, the main glass fraction is already an End-of-Waste output, which indicates a higher level of marketability and downstream usability.

Energy recovery is similar in relative terms in the two cases: approximately 15.0% in the shredding route and 14.4% in the delamination route. In both cases, this share is driven almost entirely by the plastics/EVA fraction. This confirms that plastics are the common bottleneck across the two treatment approaches. Even when they are separated as an output fraction, they are not currently valorised through material recycling at significant scale.

The residual share directed to disposal, incineration or dedicated residual treatment is higher in the shredding route, at approximately 6.9%, compared with 1.5% in the delamination route. This difference is partly linked to the corrected allocation of the plastic fraction in the shredding route, where a small share is directed to incineration/disposal, and partly to the different level of fraction separation and reporting between the two plants.

Overall, the downstream analysis reinforces the need to assess PV recycling performance through a combined reading of mass balance, material status and final destination. A high mass recovery rate alone is not sufficient to describe the quality of recycling. The delamination route shows a stronger qualitative recovery profile due to End-of-Waste glass production, while the shredding route remains highly dependent on the effective recovery destination of its glass fraction. In both cases, the improvement of plastic/EVA recovery remains the main unresolved challenge.

Chemical and material quality analyses

The chemical and material quality analyses were used to complement the mass balance results and to assess whether the output fractions were suitable for effective material

recovery. This step is particularly important because recycling performance cannot be evaluated only through the quantity of material separated by the treatment process. The quality, purity, impurity profile and downstream usability of each fraction are equally relevant.

The comparison focused on the three most relevant output streams: glass, plastics/EVA and aluminium. These fractions play different roles in the recycling performance of the two treatment routes. Glass is the main differentiating output between the two approaches; plastics/EVA represent the main common bottleneck; aluminium is one of the most robust and consolidated recovery streams.

Glass fraction

The glass fraction represents the most important qualitative difference between the two treatment routes. Both plants are able to separate a glass-rich stream with low levels of contamination, but the level of output qualification differs substantially. The shredding treatment plant generates a glass fraction still classified as waste, while the delamination treatment plant produces a major End-of-Waste glass output.

Table 27 – Overview of glass fraction

Parameter	Shredding treatment plant – glass 19 12 05	Delamination treatment plant – EoW glass	Interpretation
Fraction status	Glass waste, EER 19 12 05	End-of-Waste glass	Substantial difference in qualitative and documentary level.
TOC / organic content	TOC <0.050%	Silicones/ plastics <0.01%	The delamination treatment plant documents an even lower and more specific organic content.
Lead	1.23 mg/kg	<1 mg/kg	Low in both cases; slightly lower in the delamination treatment plant output.
Copper	1.38 mg/kg	1.00 mg/kg	Low in both cases; slightly lower in the delamination treatment plant output.
Aluminium	Not identified as a critical parameter in the shredding treatment plant glass	36 mg/kg	The delamination treatment plant quantifies residual aluminium content.
Plastic/EVA/ silicone impurities	Not measured through a dedicated material composition analysis of the glass	<0.02 kg in the analysed sample	The delamination treatment plant provides stronger evidence of material composition purity.

Non-glass impurities	Not measured as a dedicated parameter	<0.1%	The delamination treatment plant demonstrates material/EoW-grade output quality.
Particle size distribution	Not available	<0.5 mm: 24.9%; 0.5–1 mm: 18.8%; >1 mm: 56%	Only the delamination treatment plant allows an assessment of granulometric suitability.

The comparison shows that both treatment routes can recover a low-contamination glass stream, but they differ significantly in the level of output qualification achieved. In the shredding treatment plant, the glass fraction is classified as EER 19 12 05. The available chemical data confirm that this is a clean mineral fraction, with low organic content and low concentrations of metals such as lead and copper. This supports its recoverability, provided that it is sent to an authorised material recovery route.

However, the shredding route does not currently demonstrate the production of a market-ready secondary raw material, because the glass remains legally classified as waste and is not supported by dedicated material composition or granulometric evidence. By contrast, the delamination treatment plant produces a major End-of-Waste glass fraction. This output is supported not only by chemical analyses, but also by material composition and granulometric data, which provide stronger evidence of material quality, residual impurity levels and suitability for downstream use. The main comparative result is therefore not simply that one process produces more glass than the other. The shredding route produces a higher relative amount of glass by mass, but the delamination route produces a better qualified glass output. Glass is therefore the main differentiating fraction between the two industrial approaches: the shredding treatment plant demonstrates glass recoverability, while the delamination treatment plant demonstrates EoW glass production and market readiness.

Plastic / EVA fraction

The plastic/EVA fraction shows a different pattern from the glass fraction. In this case, the comparison does not highlight a clear qualitative advantage of one route over the other. Rather, it confirms that plastics remain a structurally critical output stream in both treatment approaches.

Table 28 – Overview of plastic fraction

Parameter	Shredding treatment plant – plastics 19 12 04	Delamination treatment plant – EVA/PET plastics	Interpretation
Fraction status	Plastic and rubber waste, EER 19 12 04	EVA/PET plastic fraction, EER 19 12 04	Both fractions remain waste streams, unlike the EoW glass in the delamination case.
Share of treated mass	15.79%	14.43%	Plastics represent a very similar share in both processes, around 14–16% of the treated input.

Estimated mass	351.8 kg	559 kg	The delamination treatment plant generates a larger absolute quantity because it processed a larger batch.
Physical description	Mixed solid plastic/rubber fraction, non-pulverulent	EVA/PET plastic fraction, mainly mat-like material	Both are polymer-rich fractions resulting from PV panel treatment.
TOC / organic content	TOC 43%	TOC approx. 56%	Both fractions are strongly organic/polymeric; the delamination fraction appears richer in organic carbon.
Calorific value	HHV 25,200 kJ/kg; LHV 24,100 kJ/kg	Not used here as primary indicator	The shredded plastic has a high calorific value, coherent with energy recovery.
Ash / inorganic residue	Residue at 600 °C: 21.0%	Ash content approx. 12.9%	Both contain inorganic residues, probably linked to glass, silicon, metals or treatment contamination.
Lead	69 mg/kg	113 mg/kg	Lead is present in both; higher in the delamination plastic fraction.
Copper	1,060 mg/kg	172 mg/kg	Copper is much higher in the shredding plastic fraction, suggesting stronger contamination from conductive components or mixed material residues.
Tin	282 mg/kg	221 mg/kg	Similar order of magnitude in both cases.
Hydrocarbons	Total hydrocarbons: 368 mg/kg	Total hydrocarbons: approx. 1,170 mg/kg	Hydrocarbons are present in both; higher in the delamination plastic fraction.
Hazard classification	Non-hazardous special waste	Non-hazardous special waste	Neither fraction is classified as hazardous on the basis of the analysed parameters.
Downstream route	95% energy recovery, 3% material recycling, 2% incineration/disposal	R1 energy recovery: waste-to-energy, CSS/SRF or cement kiln depending on availability	Plastics are the common bottleneck: they are mainly or entirely directed to energy recovery rather than material recycling.

The comparison confirms that the plastic/EVA fraction is a relevant output stream in both cases, representing approximately 14–16% of the treated mass. The analytical data show that both fractions are strongly organic and polymer-rich, although they also contain inorganic residues and traces of metals. This mixed composition is consistent with the physical nature of the fraction, which may include EVA, backsheet material, residual glass, silicon particles and metal contamination.

The most important result is not the difference in chemical composition, but the downstream destination. In the shredding treatment plant, the corrected downstream information indicates that the plastic fraction is mainly sent to energy recovery, with only a marginal share directed to material recycling. In the delamination treatment plant, the EVA/PET fraction is sent to energy recovery, potentially through waste-to-energy treatment, CSS/SRF production or cement kiln use, depending on outlet availability. Therefore, unlike glass and aluminium, plastics do not currently represent a robust material recovery stream in either case. They are classified as non-hazardous, but their recovery remains primarily energetic rather than material. This confirms that plastics/EVA are the main common bottleneck for the full circularity of industrial PV panel recycling. High recycling performance in PV treatment depends not only on the recovery of glass and metals, but also on the development of more effective downstream solutions for polymeric fractions.

Silicon powders fraction

Table 29 – Overview of silicon powders

Parameter	Shredding treatment plant – silicon-rich powder	Delamination treatment plant – silicon-rich powder	Comparative reading
Fraction status	EER 19 12 03, non-hazardous special waste	EER 19 12 03, non-hazardous special waste	In both cases, the fraction remains a waste stream requiring further treatment or valorisation.
Share of treated mass	5.15%	4.5%	The powder fractions are similar in size.
Estimated mass	114.8 kg	609 kg	The delamination plant produces a higher absolute quantity due to both larger input mass and higher powder generation.
Physical nature	Pulverulent grey powder	Silicon-rich / fine mineral fraction	Both are fine fractions generated during treatment, but they may not be compositionally equivalent.
Mineral/ inorganic content	Residue at 600 °C: 92.1%	Ash content: approx. 98%	Both fractions are predominantly inorganic/mineral.
Silicon indicator	SiO_2: 64%; Si by XRF: 29.9%	Silicon-rich fraction; direct Si% to be confirmed from available data	The shredding route provides a clearer quantitative silicon indicator in the available analysis.
Silver concentration – analysed sample	Ag by XRF: 0.36%, equivalent to approx. 3,600 mg/kg; Ag_2O: 0.39%	168 mg/kg in the analysed sample	The analysed delamination sample shows much lower Ag, but this value is considered anomalous.
Silver concentration – expected / normal range	Around 3,600 mg/kg in the analysed sample		The low Ag value in the delamination sample is likely not representative of normal process performance.

Possible reason for anomalous Ag value	Not applicable based on current data	Possible laboratory precipitation issue or accidental selection of an Ag-poor sample	The delamination Ag result should be treated with caution and not used alone to infer lower process performance.
Recovery interpretation	Smaller but highly enriched fraction	Larger fraction, normally expected to contain relevant Ag levels	Both fractions are strategic, but require further refining/concentration to recover silicon and silver.

The silicon-rich powder fraction is a strategic intermediate output in both treatment routes. In the shredding treatment plant, it represents 5.15% of the treated mass and shows high concentrations of silicon and silver in the analysed sample, with Ag around 0.36% by XRF. In the delamination treatment plant, the powder fraction is much larger, equal to 15.72% of the treated mass. Although the analysed sample reported a low silver concentration of 168 mg/kg, this value is considered non-representative, likely due to a laboratory precipitation issue or to the accidental selection of an Ag-poor sample. For the shredding route, the analysed mixed silicon/silver-bearing powder shows a silver concentration of 0.36 ± 0.11% Ag, corresponding to approximately 3,600 ± 1,100 mg/kg. For the delamination route, no directly comparable certified Ag concentration is currently available for the full mixed powder stream. Therefore, the silver content of the delamination powder should be treated as a data gap and validated through representative sampling and chemical analysis before drawing conclusions on marketability or recovery performance. Therefore, silicon-rich powders should be interpreted as a potentially valuable but non-final output stream, requiring further downstream treatment to recover silicon and silver effectively.

Aluminium fraction

The aluminium fraction shows a more favourable and stable recovery profile. In both treatment routes, aluminium mainly derives from the PV module frames and represents one of the most easily valorisable material streams. The available information indicates high purity in both cases, although the type and variability of impurities differ.

Table 30 – Overview of aluminium

Parameter	Shredding treatment plant	Delamination treatment plant	Comparative reading
Aluminium fraction over treated mass	**11.45 wt.%**	**14.0 wt.%**	The delamination route generates a higher aluminium output share, mainly because the frame is removed as a dedicated early fraction. The shredding route recovers aluminium after mechanical separation, with possible distribution of small Al residues in other fractions
Estimated aluminium purity	Generally variable; approximately 97–99%	Average 98% ± 1.5%	Both plants recover a high-purity aluminium fraction, although the shredding route reports more variable quality.
Estimated	Approximately	Approximately	The impurity level is broadly

impurity range	1–3%	0.5–3.5%, based on the ±1.5% variability around 98% Al	comparable between the two plants.
Main impurity types	Mainly glass and plastics	Mainly silicone residues and occasional mat-like material fragments	The type of impurity differs: the shredding route shows more mineral/polymeric cross-contamination, while the delamination route shows residues linked to sealing or encapsulant materials.
Quality stability	More variable quality according to operator feedback	More stable average purity based on internal material composition assessment	The delamination route appears more consistent in aluminium quality, while the shredding route may depend more on batch composition and separation efficiency.
Recovery interpretation	Consolidated material recovery stream, with some variability in cleanliness	Consolidated material recovery stream with high documented purity	In both cases, aluminium remains one of the most robust and marketable material recovery fractions.

The aluminium fraction can be considered a consolidated recovery stream in both treatment routes. In the shredding treatment plant, the operator reports a variable but generally good quality, with impurities typically ranging between 1% and 3%. These impurities mainly consist of glass and plastic residues, suggesting some degree of cross-contamination from the mechanical treatment and downstream separation process.

In the delamination treatment plant, internal material composition assessment indicates an average aluminium content of 98% ± 1.5%. The main impurities are silicone residues and occasional fragments of mat-like material. This suggests that the impurity profile is more closely linked to sealing, encapsulant or residual panel-layer materials rather than to broad cross-contamination with glass and plastics.

Overall, aluminium differs from plastics/EVA because it already has a consolidated material recovery route and a relatively high marketability. The main difference between the two cases is not the recovery route, which is robust in both plants, but the type and stability of impurities. The shredding route shows more variable quality and impurities mainly linked to glass and plastic contamination, while the delamination route shows a more stable purity profile with impurities mainly related to silicone and occasional mat residues.

3.4.2. Results of the French sampling activities

The comparative evaluation between the hot-knife process and the sanding process made it possible to identify clear differences in terms of quality output fractions.

In the hot-knife process, the primary objective is to mechanically separate the glass from the rest of the photovoltaic module components. This first step isolates the glass fraction from a mixed fraction composed of encapsulant, photovoltaic cells, and backsheet. Subsequently, this mixed fraction is subjected to additional downstream processes aimed at recovering the different constituent materials.

In contrast, the sanding process follows a different operational practice. One of its most notable advantages is that it produces a significantly cleaner glass fraction as shown in Figure 52, resulting in a higher final quality at the end of the treatment chain. This improved glass quality increases its potential for direct recycling and downstream recovery. However, the sanding process also generates a powder fraction rich in EVA, which contains concentrated amounts of silicon and silver. As previously mentioned, this fraction is still under investigation, and research activities are ongoing to identify a validated recycling outlet capable of recovering this specific stream.

A characterisation campaign was conducted to identify the remaining fractions and the differences between the processes.

Table 31 – Mass balance hot-knife and sanding processes

Output fraction	Hot-knife process – estimated kg	Hot-knife process – % of treated mass	Sanding process – estimated kg	Sanding process – % of treated mass
Glass	1007,00	65,63%	960,00	65,40%
End-of-Waste glass	74,00	4,82%	35,00	2,38%
Total glass fraction	1081,00	70,48%	995,00	67,78%
Plastics / encapsulant + cells	217,00	14,15%	NA	NA
Backsheet powder	NA	NA	67,00	4,56%
Encapsulant + cells	NA	NA	112,00	7,63%
Aluminium	207,00	13,50%	217,00	14,78%
Busbars + encapsulant and cell	NA	NA	42,00	2,86%

powder				
Cables & Junction boxes	23,72	1,55%	26,00	1,77%
Dust / mixed waste	5,00	0,33%	9,00	0,61%
Total treated mass	1 534 kg	100,00%	1 468 kg	100,00%

The comparison between the Hot-knife process and the sanding process highlights a trade-off between overall yield and material quality.

The glass fraction remains at a similar level for both processes (around 65%), while the total glass fraction is slightly higher for the Hot-knife process. However, the sanding and hot-knife process significantly reduces the proportion of end-of-waste glass (2.38% compared to 4.82%), indicating lower contamination levels and improved glass quality. In this respect, the sanding process produces cleaner glass despite a slightly lower overall yield.

The silver fraction has not been separated from the several cell powders of the sanding process. Most of this fraction should be present in the “encapsulant + cells” fraction which represents approximately 7,63% of total fractions.

With some technical development, copper from busbars could potentially be easier to extract with an industrial pace by using the sanding process. This element is present in the fraction “Busbars + encapsulant and cell powder” which reaches 2,86% of total sanding fractions.

For polymer fractions (EVA/PET), the hot-knife process achieves higher recovery: 14.15% vs 12.19% (7,63 + 4,56%).

However, this improved separation comes with a slight increase in residual waste. Dust and mixed waste nearly double (0.61% vs 0.33%), indicating higher material fragmentation during sanding operations.

It should also be noted that, for the sanding process, no downstream buyers have yet been identified for mixed powder output fractions. As a precautionary assumption in the characterisation analysis, a default 100% removal rate has therefore been applied to these fractions. This introduces uncertainty in the current performance assessment, particularly regarding the actual valorisation potential.

Table 32 – Recovery ratio balance hot-knife and sanding processes

Recovery route	Hot-knife process	Sanding process
Material recovery	Data not disclosed due to confidentiality reasons	1 030,76kg, equal to 70,22% of treated mass
Energy recovery	Data not disclosed due to confidentiality reasons	153,60kg, equal to 10,46 % of treated mass
Disposal / incineration / residual treatment	Data not disclosed due to confidentiality reasons	283,64kg, equal to 19,32 % of treated mass
Total treated mass	Data not disclosed due to confidentiality reasons	1 468 kg

The analysis of recovery routes shows that both treatment processes achieve high overall recovery levels, while relying on clearly differentiated valorisation pathways. When expressed as a share of the treated mass, the hot-knife process reaches a higher material recovery rate than the sanding process for which the unmarketable powder involve final elimination, indicating a stronger orientation toward material recycling rather than downstream elimination or energy valorisation. A key factor influencing the applicability and performance of both recycling processes is the integrity of the glass. The presence of intact glass significantly enhances recycling potential.

Overall, the comparison demonstrates that the difference between the two processes is not limited to the level of recovery achieved but lies primarily in the quality and orientation of the recovery routes.

52The comparison shows that the difference between the two processes is not limited to the level of recovery achieved but primarily relates to the structure and orientation of the recovery routes. The hot-knife process currently favours higher material recovery, while the sanding process, although still under development, demonstrates a strong potential for improvement. Despite being a newer process, its performance is already approaching that of the hot-knife process. A key challenge remains the identification of downstream outlets, which could significantly enhance its material recovery performance and alignment with circular economy objectives.



Hot-knife process



Sanding process

Figure 52 – Hot-knife vs. sanding process – Glass fraction

3.4.3. Contribution of EVERPV pre-treatment technologies to overcoming limitations identified in current industrial recycling practices

The benchmark case studies carried out in Italy and France provided an overview of representative industrial photovoltaic recycling routes currently adopted in Europe. The Italian assessment considered two industrial pre-treatment approaches based on mechanical shredding and mechanical delamination, while the French case study evaluated an industrial hot-knife delamination process. These benchmark technologies were compared with the innovative pre-treatment technologies developed within EVERPV, namely the sanding process and the IR + tear-off delamination process, in order to assess how they address the technical limitations identified in current industrial recycling practices. The comparison focuses on the intermediate fractions generated during pre-treatment, their degree of material selectivity, and their potential suitability for subsequent material recovery. The sanding technology is designed to improve the separation and cleanliness of material fractions, whereas the IR + tear-off technology selectively removes the backsheet while preserving the remaining laminate for subsequent processing. Their contributions should therefore be interpreted according to the different intermediate fractions they generate rather than as alternative solutions providing identical outputs.

Glass Recovery

The benchmark case studies confirmed that glass represents the largest recoverable material fraction in crystalline silicon PV modules. However, the quality of the recovered glass strongly depends on the pre-treatment technology adopted.

The Italian shredding process generated large glass-containing output fractions, but these fractions were highly contaminated by polymers, silicon particles and metallic residues. Consequently, the reported mass of the recovered glass fraction should not be interpreted as clean glass recovery, since part of the recovered mass is associated with contaminants that reduce its suitability for high-value applications.

Both the Italian mechanical delamination process and the French hot-knife process better preserved the integrity of the glass sheets compared with shredding. Nevertheless, residual polymer contamination remained attached to the glass surface, meaning that further cleaning steps may still be required before reuse.

The sanding technology developed within EVERPV addresses these limitations by selectively removing the backsheet through controlled abrasion while preserving the integrity of the glass and significantly reducing surface contamination. In addition, the process generates separate backsheet-derived and cell-containing powder fractions, reducing cross-contamination between material streams. Compared with the benchmark industrial routes, the principal contribution of sanding is therefore the improvement of glass quality rather than simply increasing the quantity of recovered material, thereby enhancing its potential suitability for higher-value recycling applications. The direct characterisation reported in D3.3 showed that improvements to the sanding process reduced large metallic residues on the recovered glass and, after process adjustment and systematic cleaning, enabled glass purity above 99%.

The IR + tear-off technology contributes differently by selectively removing the backsheet while preserving the glass-laminate assembly intact for subsequent processing. Rather than directly improving glass cleanliness, its main contribution is maintaining the integrity of the remaining laminate for downstream recovery operations.

Silver and Silicon-Rich Fractions

The benchmark case studies showed that conventional industrial recycling processes recover silicon- and silver-containing materials mainly through mechanical size reduction, generating heterogeneous mixtures that require complex downstream separation. Material losses and contamination reduce the efficiency of recovering high-value secondary raw materials.

The EVERPV pre-treatment technologies do not directly recover purified silicon or silver but generate intermediate fractions with characteristics that are more suitable for subsequent recovery processes. In particular, sanding produces concentrated cell-containing powder fractions that can be used for downstream physical and hydrometallurgical treatments,

while the IR + tear-off process selectively removes the backsheet and preserves the remaining laminate for further processing.

The downstream recovery routes developed in WP3/WP4 demonstrated the technical feasibility of recovering valuable materials from these intermediate fractions, including silver purities approaching 90%. These results demonstrate the potential of the overall recycling strategy but should be interpreted as downstream recovery achievements rather than direct outputs of the pre-treatment technologies themselves.

Encapsulant and Backsheet Fractions

The benchmark case studies confirmed that polymer-containing fractions remain among the least valorised outputs of current industrial PV recycling systems, with most materials currently directed towards energy recovery or other low-value applications.

The industrial hot-knife benchmark produces a laminate in which the EVA remains strongly attached to the PET backsheet and the cell layer. Consequently, additional separation steps are required before polymer recovery can be attempted. Similarly, conventional shredding generates mixed polymer fractions with significant contamination, limiting opportunities for high-value recycling.

The sanding technology developed within EVERPV generates separate backsheet-derived and cell-containing powder fractions, providing feedstocks for downstream polymer purification. The IR + tear-off technology follows a different approach by selectively removing the backsheet from the remaining laminate, producing two distinct fractions while preserving the integrity of the laminate for subsequent treatment. Although this process does not directly recover purified polymers, it improves the selectivity of the pre-treatment stage and facilitates subsequent recovery operations.

WP4 investigated several feedstocks originating from different pre-treatment routes, including hot-knife laminates and grinding-derived fractions. The most promising results were obtained from the densimetric separation of the EVA/cell powder generated by the grinding process, which achieved EVA purities of up to 98%. These results therefore demonstrate the downstream potential of specific grinding-derived fractions. By contrast, the hot-knife route produced a heterogeneous recovered material that was considered unsuitable for reuse.

Aluminium Recovery

The benchmark case studies confirmed that aluminium frame recovery is already a well-established operation in current industrial PV recycling. In all investigated recycling routes, aluminium frames are manually removed during the preliminary dismantling stage before the application of the main pre-treatment technology.

Consequently, aluminium recovery is not a direct contribution of the EVERPV pre-treatment technologies. Rather, the sanding and IR + tear-off processes are fully compatible with the existing dismantling sequence, allowing the aluminium fraction to remain clean and suitable for conventional recycling without introducing additional contamination.

Overall Contribution of EVERPV Technologies

The comparison between industrial benchmark practices and EVERPV technologies demonstrates that the principal innovation of the project does not lie solely in increasing recycling rates, but rather in shifting the focus from mass-oriented recovery to material-oriented recovery. Current industrial systems are generally effective in recovering bulk material fractions such as glass and aluminium, but they still face significant limitations regarding the recovery and valorisation of strategic materials including silver, silicon-rich fractions, encapsulants, and backsheet polymers.

The innovative pre-treatment technologies developed within EVERPV address these limitations by improving the selectivity of material separation before downstream recovery. Rather than replacing existing industrial recycling routes, the sanding and IR + tear-off technologies complement them by generating intermediate fractions with different characteristics and levels of selectivity, which can support dedicated downstream recovery processes. The downstream developments achieved within WP3 and WP4 further demonstrate the potential for recovering high-value secondary raw materials from these improved fractions, supporting more circular and higher-value recycling pathways for crystalline silicon photovoltaic modules.

Table 33 - Comparison of industrial benchmark limitations and EVERPV contributions

Material	Limitation identified in benchmark case studies	EVERPV contribution	Circularity implication
Glass	Contamination and downcycling	Cleaner fractions and preserved integrity through selective pre-treatment	Higher potential for closed-loop recycling
Silver	Dilution and difficult recovery	Generation of suitable intermediate fractions for downstream recovery	Reduced dependence on primary silver
EVA	Mainly directed to energy recovery	Grinding-derived fractions successfully upgraded through	Increased material

		downstream purification (EVA purity up to ~98%)	recycling opportunities
Backsheet polymers	Low valorisation	Selective separation of backsheet or backsheet-derived fractions	Improved resource efficiency
Aluminium	Already mature recovery route	Compatible with existing dismantling practices	Support of existing recycling markets

3.5. ASSESSMENT OF PV RECYCLING VALUE CHAIN

3.5.1. Data uncertainty

There are several aspects to be considered with regards to data reliability. Firstly, if all actors active in the EU PV recycling industry have been covered. For countries with a single Producer Responsibility Organisation (PRO), such as Belgium and France, certainty with regards to exhaustivity is higher compared to countries with multiple PRO's where contractual arrangement between each PRO and recyclers are not necessarily disclosed. Secondly, the different types of sources used (primary from recycler, primary from PRO, secondary from specialised literature) for identified actors impact their reliability. The third aspect is if the reported and obtained value relates to PV waste specifically. For delamination actors our confidence is high because these specialised actors dedicate all their recycling line capacity to solar PV waste. For shredding actors, PV waste is used on the same infrastructure and equipment as other WEEE. Insights shared by large shredding facilities indicate that 5-10% of treatment capacity is allocated for PV (compared to WEEE in general) and that it can be considered that this number could be brought up to 20-30% to accommodate increased PV waste feedstock. These orders of magnitude were used to estimate capacity for other shredders if only the total WEEE treatment capacity was known.

Overall, however, the confidence level for the data obtained can be considered high, as the estimates are generally supported by multiple primary data points. In addition, where recent data were available, treatment-capacity figures were cross-checked and compared against nationally recycled PV waste volumes, providing another verification on the results' order of magnitude.

Lastly, while the latest available data was used, the actual treated volumes fluctuate heavily between actors. Therefore, it is important to note that the focus is on PV recycling treatment capacity rather than treated volumes. Such analysis implies that year-on-year changes are less significant. For Figure 54, the uncertainty is reflected in error bars.

3.5.2. PV recycling treatment capacity per process

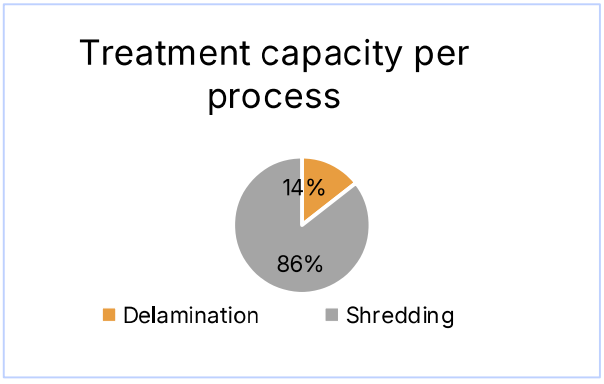


Figure 53 – Share of pre-treatment process

Figure 53 focuses on the process distinction between shredding and delamination.

Figure 53 highlights that for PV waste recycling, shredding accounts for the largest share of identified capacity with around 200kt/y, while delamination is already present in the market with around 40kt/y. Shredding is currently the main scaled treatment route among the identified actors and forms the backbone of PV recycling capacity in all five selected EU countries with high PV waste volumes.

As illustrated in the actor mapping in Figure 55, larger-capacity facilities are mostly associated with shredding. Specifically, established actors with long lasting experience in waste recycling (metals, glass, WEEE in general) are positioned on shredding, while delamination offers an entry point for newer and more specialised actors. Hence, the two routes are not only different technical options, but also reflect different actor typologies and stages of market maturity.

Even in case of delamination remaining more limited in total capacity, its presence is nonetheless important because it enables more specialised or advanced treatment routes. In general, delamination processes aim to separate the layers of a PV module more selectively than shredding (typically associated with lower recycled material purity and quality output), usually by separating the front glass panel from the rest of the laminate. Different approaches rely on heat, chemical, mechanical separation or a combination of these steps, such as demonstrated in EVERPV. Their common objective is to recover cleaner material fractions, reduce contamination, and preserve higher-value components, but they are generally more complex and less established at scale than conventional shredding.

3.5.3. Treatment capacity per country

Recycling capacity is unevenly distributed within selected countries. Concentration can largely, but not only, be explained by industrial clustering and proximity to off-takers (metal smelters, plastic-based energy recovery units, ...).

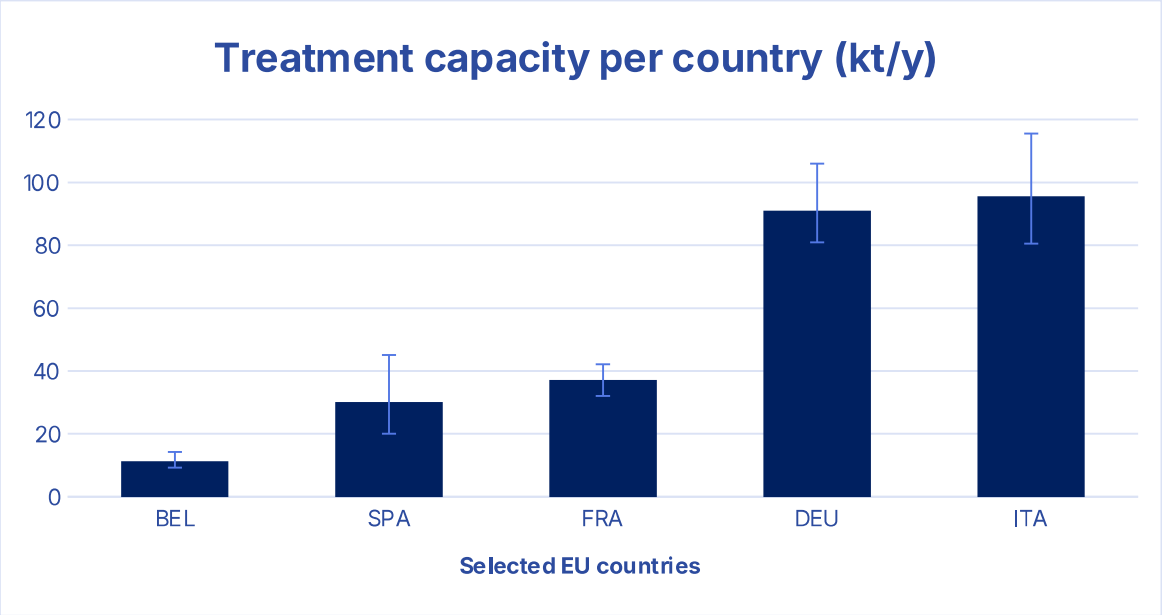


Figure 54 – Treatment capacity per selected EU countries in kt/y

Figure 54 shows a chart with the total capacity for identified PV treatment facilities with latest available data for selected EU countries.

As explained in Chapter Data uncertainty, uncertainty of exact treatment capacity for solar PV waste in each country is reflected through error bars. Underestimation stems from a variety of sources but is mainly linked to non-identified recycling actors. Especially local and small-scale recyclers positioned on WEEE in general could be not properly assessed, but their contribution to total treatment capacity is expected to be small in comparison to identified actors. Overestimation may result from the misallocation of existing treatment capacity for PV waste specifically as opposed to WEEE in general. It is expected, however, that such estimation errors to be small to moderate, as estimations were based on insights shared by large shredding facilities.

The five selected EU countries have different operating systems when it comes to PV waste collection and recycling. In Belgium and France, the take-back scheme is centralized with a unique entity in charge as the Producer Responsibility Organisation (PRO). This allows non-cost criteria to influence the selection of recyclers and their recycling process through tendering. In the other countries, i.e. Germany, Spain and Italy, multiple PROs operate in a distributed take-back scheme, meaning that there is no single organisation managing the return and recycling of end-of-life PV modules; instead, several PROs organise these flows in parallel.

This creates a system where cost is the main criteria for the selection of PV recyclers in tendering processes, thus favouring the most cost-effective processes, which in turn has led to shredding leading the recycling market in those countries. Nevertheless, recently

opened delamination facilities with treatment capacity in the range of 10 kt/y indicate that for these advanced recycling processes, cost-competitiveness can also potentially be reached under a set of favourable conditions, such as adequate scale of recycling activities and off-take, as well as positive associated revenue perspectives).

The flexibility to accommodate varying PV waste input feedstock quantities of existing treatment capacity depends strongly on the type of recycling process considered. For shredding-based routes, some additional flexibility may exist because many facilities are not dedicated exclusively to PV modules but treat WEEE or other waste streams more broadly. This can allow operators to accommodate moderate increases in PV waste volumes by reallocating capacity, adjusting throughput, or adapting operational planning. By contrast, delamination-based routes are specialised and have less flexibility to absorb strong growth in treated volumes without additional investment. Some short-term increase may be possible through additional shifts or improved line utilisation, but substantial volume growth would require dedicated new capacity to become available.

Moreover, the comparison between identified treatment capacity and actual nation-wide PV waste volumes can only be partially conducted, as the most recent official PV waste treatment data from Eurostat is for the year 2023, with only Belgium and France having detailed PV waste collection and treatment data for 2024. This limits the ability to draw firm conclusions on most recently available data for potential over- or under- capacity and further hindering verifying any treated volume data. The interpretation is further complicated by the rapid growth of PV waste flows, which can increase very substantially over only a few years. Annual increases of 50% to 250% are not uncommon in emerging PV waste markets, meaning that capacity databased on older waste data can quickly become outdated.

3.5.4. Geographical distribution of PV recycling actors

Figure 55 shows the identified PV recycling actors. The colour code indicates the process, either categorised as delamination or shredding. The dot size indicates the treatment capacity in each recycling plant. The size of the dots is merely an indicator of available recycling infrastructure, not as a measure of current recycling activity. This distinction is important because capacity reflects the potential annual throughput of identified recycling actors, whereas collected or treated volumes reflect the quantity of PV waste entering the system. Moreover, especially for shredding actors, PV recycling capacity should be viewed with caution as explained in 3.5.1, as they generally do not have a dedicated PV waste line but rather use generic WEEE lines also for PV waste. The potential capacity can therefore be theoretically quite high, while actual volume might be significantly lower. Values shown account for PV specific waste, to the best of our knowledge.

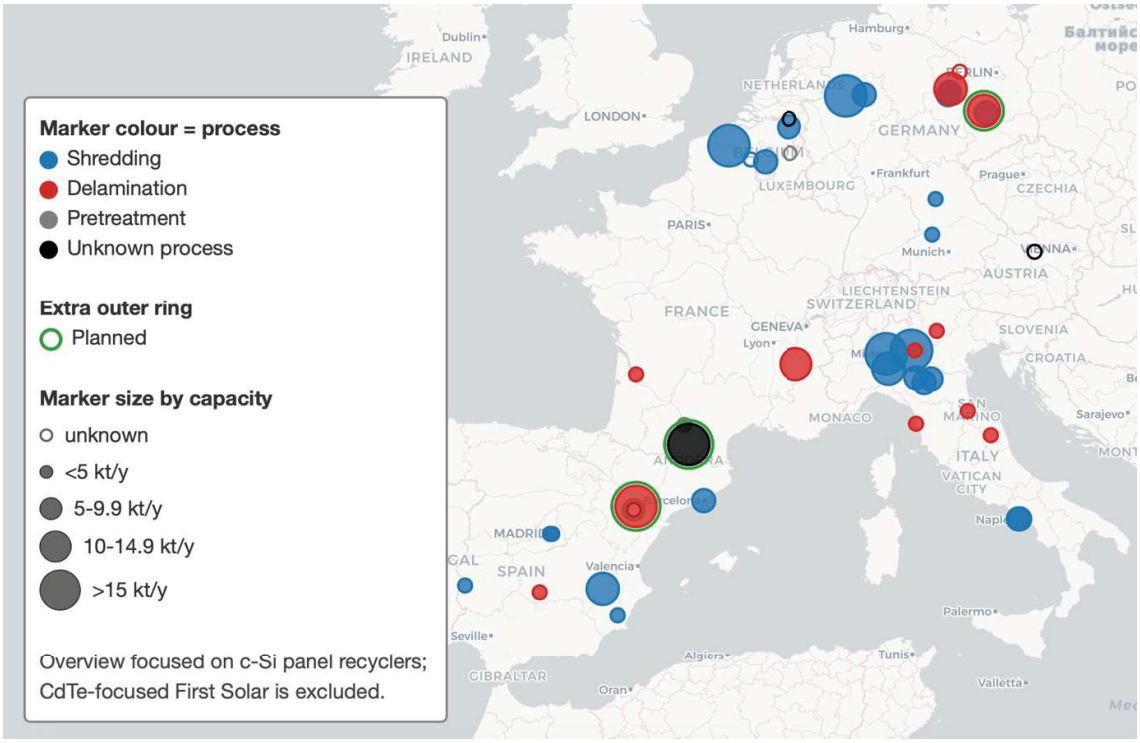


Figure 55 – Geographical distribution of EU PV recycling actors in 5 selected countries

The largest identified actors are mainly associated with shredding, while delamination actors are present, but generally associated with smaller treatment capacity with some important exceptions. Overall, the map suggests that the European PV recycling landscape is unevenly distributed, with a few hubs concentrated in some countries. Italy stands out for its density and diversity of actors, while Germany and France stand out for fewer but larger facilities.

More concretely, a strong concentration in Italy and specifically around Milan can be observed. Italy combines a relatively high number of sites, with both shredding and delamination actors. Germany and France point to a different pattern, with one actor (*Reiling* and *Galloo*) concentrating most of the shredding treatment capacity and one or two actors (respectively *Solar Materials* and *ENVIE/ROSI*, respectively) concentrating the delamination treatment capacity.

The presence of several planned sites indicates an evolving landscape, especially for more advanced treatment routes. This is particularly relevant for the transition towards closed-loop recycling, as higher capacity for delamination actors is planned to become operational.

Delamination actors are bound to become more relevant in the coming years if the processes become more commercially attractive. For instance, if the demand for high purity recycled materials from the material off-taker side becomes stronger, this will further incentivize advanced recycling. Simultaneously, with growing PV waste volumes, this will allow to reach economies of scale and reduce the cost of delamination per module.

3.5.5. Status of EU PV industry for closed-loop end-of-life route

Polysilicon is the stage where Europe's nameplate figures look strongest on paper: around 10 GW of capacity is still in operation, all of it at a single German site. The ingot and wafer stage, by contrast, no longer has any active European production at all: the two producers that had kept this segment alive, both exited in 2025, leaving this part of the chain without a domestic manufacturing base. Cell production shows a similar pattern of concentration around a single site: one facility in Italy has scaled up to 1.8 GW as of 2025 and stands as the only industrial-scale operation left. Beyond it, activity is confined to R&D activity and a handful of pilot-scale projects exploring perovskite and thin-film routes.

The encapsulant film manufacturers landscape is fragmented and small in scale next to the Asian producers that dominate the PV encapsulant industry globally. Europe's underlying strength in polymer science, compounding, and specialty materials has not translated into many dedicated PV-film producers; one company stands out as a clearly PV-focused encapsulant manufacturer, while a small number of others operate more at the margins, in specialised, innovation-led, or niche segments of the market.

Today's European flat-glass industry is built almost entirely around general float-glass production, with no identified facility dedicated to rolled solar glass for PV applications even if rolled solar-glass production once existed. What remains is a set of float-glass lines run mainly by a large international glass groups, with only very few of them positioned on glass for solar applications.

On the module manufacturers' side, a small number of larger players running annual capacities in the several-hundred-MWp range exist, sitting alongside a much longer tail of smaller producers. Alongside these are manufacturers pursuing PV market segments with specific technical needs (including lightweight-module, BIPV modules, tailor-made PV modules for revamping and repowering, ...).

Read together, these stages describe a value chain heavily weighted toward its downstream end: module assembly is the only one with a broad base of active European manufacturers, while the stages that would need to reabsorb PV-specific recycled materials, polysilicon at scale, ingots and wafers, rolled solar glass, dedicated encapsulant film, are each marginal or absent. Even where high-quality recovered materials could be recovered domestically, little European capacity currently exists to reabsorb it into new modules.

Within the module stage itself, a nuance stands out. The presence of smaller, specialised manufacturers, notably in BIPV, in tailor-made modules and other differentiated segments, tend to be more receptive to circularity as a product attribute, since differentiation and sustainability positioning matter more to their proposition than to volume-driven producers. Their cost structure may also make them somewhat less sensitive to higher prices on certain

input materials, for instance where recycled content is integrated, since such a premium is more easily absorbed within a differentiated, higher-margin offering than in a volume-driven one.

Two points are worth flagging. First, a pipeline of announced projects spanning these same stages, from polysilicon to modules, could still reshape this picture; its materialisation, however, remains uncertain and tied to how the Net-Zero Industry Act and the IAA are implemented across member states. Second, this assessment is drawn purely from a value-chain perspective, the technical and economic considerations addressed elsewhere in this work remain separate factors in whether closed-loop recycling is ultimately achievable.

3.6. TECHNICAL AND ECONOMIC FEASIBILITY OF EVERPV TREATMENT TECHNOLOGIES

3.6.1. Presentation of the first results

This Chapter presents indicative industrial benchmark costs for the two photovoltaic panel treatment routes applied in Italy: shredding and mechanical delamination. The two reference cases are anonymised as the Shredding treatment plant and the Delamination treatment plant. The estimates describe established industrial practice and are intended to provide a reference against which the EVERPV project technologies can be assessed.

To isolate the cost effects associated with the treatment processes themselves, the two scenarios were compared on a ceteris paribus basis (i.e. with all other variables kept equal). Both were assessed assuming three eight-hour shifts per day and 235 operating days per year. Annual maintenance was fixed at 10% of the original equipment CAPEX in both cases, regardless of previous or actual utilisation. The resulting annual treatment volumes therefore represent theoretical benchmark capacities under harmonised operating conditions, rather than the actual annual throughput of the individual plants.

3.6.2. Reference characteristics of the industrial benchmark plants

The two benchmark plants require a similar initial investment, but differ in nominal treatment capacity, electricity demand and staffing. The Delamination treatment plant has a lower nominal throughput and a higher estimated average power demand, while its staffing requirement includes one additional technician.

Table 34 – Characteristics of benchmarks categories

Parameter	Shredding treatment plant	Delamination treatment plant
CAPEX	€932,550	€1,000,000
Nominal throughput	56 modules/hour	44 modules/hour
Average electrical power	40 kW	95 kW (estimated)
Staffing requirement	3.5 operators	4 operators + 1 technician

3.6.3. Annual operating results

Under the common operating schedule, the Shredding treatment plant reaches an estimated annual output of approximately 281,916 modules, corresponding to 5,638 tonnes. The Delamination treatment plant processes approximately 219,854 modules, or 4,397 tonnes. These figures are annualised reference capacities used to normalise the economic results and should not be interpreted as the plants' actual operating volumes.

The difference in electricity consumption is more pronounced. The Delamination treatment plant consumes approximately 477 MWh/year, compared with 201 MWh/year for the

Shredding treatment plant, and its annual labour expenditure is also higher. The shredding benchmark therefore combines a higher annual throughput with lower electricity demand and lower labour cost under the harmonised assumptions.

Table 35 – Performance characteristics of benchmark plants

Metric	Shredding treatment plant	Delamination treatment plant
Standard operating hours	5,640.00 h	5,640.00 h
Effective runtime	5,025.24 h	5,025.24 h
Electricity consumption	201,009.60 kWh	477,397.80 kWh
Annual electricity cost	€38,191.82	€90,705.58
Annual labour cost	€539,117.65	€596,538.46
Net annual output	281,915.96 modules	219,854.25 modules
Net annual output	5,638.32 t	4,397.09 t

3.6.4. Cost comparison

The annualised benchmark includes utilities, labour, maintenance and depreciation. Total annual cost is estimated at EUR 857,074 for the Shredding treatment plant and EUR 987,244 for the Delamination treatment plant. When normalised by annual output, the estimated treatment cost is EUR 152.01/t for shredding and EUR 224.52/t for delamination, corresponding to a difference of approximately EUR 72.51/t.

Labour is the largest cost component in both cases, reaching EUR 95.62/t for shredding and EUR 135.67/t for delamination. Utilities amount to EUR 6.77/t and EUR 20.63/t, respectively. Maintenance and depreciation are also higher per tonne for the Delamination treatment plant because the fixed annual costs are distributed over a lower benchmark throughput. Overall, all four cost categories considered in the model are higher on a per-tonne basis for delamination.

Table 36 – Cost overview for module pre-treatment

Cost item	Shredding total (€)	Shredding €/module	Shredding €/t	Delamination total (€)	Delamination €/module	Delamination €/t
Utilities	38,191.82	0.14	6.77	90,705.58	0.41	20.63
Labour	539,117.65	1.91	95.62	596,538.46	2.71	135.67
Maintenance	93,255.00	0.33	16.54	100,000.00	0.45	22.74
Depreciation	186,510.00	0.66	33.08	200,000.00	0.91	45.48
Total	857,074.47	3.04	152.01	987,244.04	4.49	224.52

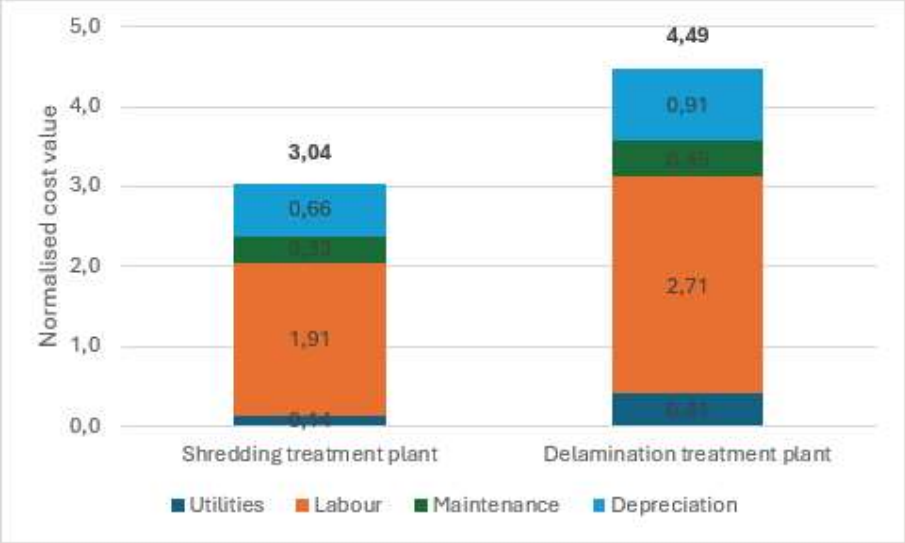


Figure 56 – Normalised cost breakdown of the two industrial benchmark plants

The chart provides a comparative view of the cost structure of the two industrial benchmark configurations. The values should be read together with the tables above, which report the corresponding annual, per-module and per-tonne costs.

3.6.5. Interpretation of the results

The results indicate that shredding is the lower-cost industrial route under the common assumptions applied in this benchmark. This should not be interpreted as a definitive ranking of the two technologies, since the analysis does not capture differences in material recovery performance, output purity, downstream refining requirements, environmental impacts or the potential market value of the recovered fractions. A process with a higher direct treatment cost may still provide advantages through improved material quality or reduced downstream processing needs.

For a complete assessment, these industrial benchmark results should be considered together with Deliverable 6.3, which will present the Life Cycle Assessment and Life Cycle Costing of the EVERPV project technologies. The combined reading of the industrial benchmark and Deliverable 6.3 will make it possible to compare the economic and environmental performance of the project solutions with established Italian treatment practice, while accounting for differences in system boundaries, treatment capacity, recovery yields and output quality.

3.7. DEMAND AND MARKET REQUIREMENTS

3.7.1. Market demand by material flows

The market demand analysis confirms that the recovered PV output fractions differ significantly in terms of technical quality, market demand, market readiness, value potential and barriers to uptake. The assessment therefore distinguishes between mature material streams, quality-dependent recycling routes and strategic high-value recovery routes. Aluminium, ferrous metals and copper-bearing fractions show the highest market readiness, as they are already connected to established secondary raw material markets. Glass represents the main mass-based opportunity, but its final market destination depends on the quality of the recovered fraction and on its compliance with downstream technical requirements. Mixed silicon/silver powders represent the most strategic fraction from a value creation perspective, although their uptake depends on further refining and buyer-specific validation. Mixed plastics remain the weakest fraction in terms of market readiness, with potential outlets mostly linked to low-grade recovery, energy recovery or residual management.

The chemical analyses performed on selected output fractions provide a useful technical benchmark for assessing their marketability. They do not replace direct buyer validation, but they make it possible to move beyond a generic assessment of recyclability and to evaluate whether the recovered fractions are close to the quality thresholds required by downstream markets. In this sense, the laboratory results support the identification of marketability gaps: for each fraction, they help determine whether the material can be considered directly marketable, marketable after additional treatment, or currently limited to low-value or residual outlets.

Mature material streams: aluminium, ferrous metals and copper-bearing fractions

From a technical quality perspective, aluminium, ferrous metals and copper-bearing fractions are the least problematic outputs, provided that separation is effective. Their marketability depends mainly on the degree of purity, the absence of excessive non-metallic contamination, and the ability to generate homogeneous lots. These fractions do not require the creation of new downstream markets, since they can rely on mature scrap and non-ferrous metal recycling routes.

From a demand perspective, secondary aluminium, steel scrap and copper-bearing materials already have established industrial outlets, well documented both in the literature and in the case studies. Aluminium frames can be directed to secondary aluminium producers or scrap operators, ferrous metals to steel recycling routes, and copper-bearing fractions such as cables and junction boxes to non-ferrous metal recyclers. In these cases, market readiness is high because buyers, pricing mechanisms and quality requirements are already well established.

The main barrier is therefore not the absence of demand, but the efficiency of separation and the quality of the recovered material. Aluminium recovered before destructive treatment, as in the delamination route, is expected to have higher market readiness because early frame removal reduces the risk of contamination. However, marketability stays high also in the case of shredding. Copper-bearing fractions can also have high value potential, but only if they are sufficiently separated from plastics and mixed components.

Table 37 – Marketability of the Aluminium fraction

Output fraction	Technical quality requirement	Market demand	Market readiness	Main barrier	Suggested outlet
Aluminium frame	Clean metal fraction, limited screws or mixed metals	High	High	Impurities and mixed metals	Secondary aluminium
Ferrous metals	Clean ferrous fraction	High	High	Purity of separated fraction	Steel scrap recycling
Copper, cables and junction boxes	Separation from plastics and mixed components	High	High	Additional separatio n	Copper and non-ferrous recycling

Overall, these fractions can be considered mature open-loop recycling streams. They contribute positively to the economic balance of PV recycling, but they are not the main strategic bottleneck of market demand.

Glass: high volume output with quality-dependent demand

From a technical quality perspective, glass is the most relevant recovered fraction in mass terms, but its marketability depends strongly on its composition and contamination profile. The laboratory analysis of the glass fraction describes it as a solid inorganic material, non-pulverulent and white-transparent, with a very high residue at 600 °C. These characteristics indicate a predominantly mineral fraction and support its potential suitability for material recovery routes, although further parameters such as granulometry, polymer residues, metallic impurities and specific contaminants remain essential for defining the most appropriate outlet. The chemical analysis can therefore be used as a first marketability benchmark, but not as a final qualification for high-grade applications.

From a demand perspective, several potential markets exist for recovered PV glass. Lower-grade outlets may include construction materials, aggregates or other open-loop applications. Medium-grade outlets may include ceramics, foam glass or glass wool, depending on particle size and contamination levels. Higher-value outlets, such as standard glass recycling, glass furnace applications or closed-loop PV glass applications, require much stricter specifications. Mapping activities highlighted that PV glass may face specific barriers compared with standard recycled glass, particularly due to chemical composition and the possible presence of elements such as antimony, which can affect compatibility with some of the most common European flat glass production routes.

Market readiness is therefore medium and strongly dependent on the specific output quality. Clean glass recovered through a delamination process is expected to be more aligned with higher-value outlets, especially if the process preserves material quality and limits contamination. Glass recovered after shredding may still be marketable, but it is

significantly more likely to require additional cleaning, sorting or validation before being accepted by demanding downstream users.

Table 38 – Marketability of the Glass fraction

Potential glass outlet	Technical requirement	Market readiness	Value potential	Main barrier
Construction materials / aggregates	Basic contamination control	Medium-high	Low-medium	Low value, local demand
Foam glass, ceramics, glass wool	Granulometry and impurity control	Medium	Medium	Material consistency
Standard glass recycling / furnace input	Strict impurity and composition limits	Medium-low	Medium-high	Chemical composition, contaminants
Closed-loop PV glass	High purity and stable specifications	Low-medium	High	Direct buyer validation required

The main marketability gap for glass is therefore the distance between “recoverable glass” and “buyer-ready glass”. The chemical analysis supports the identification of the material as a potentially recoverable mineral fraction, but market uptake at higher value requires additional evidence on impurities, organic residues, granulometry and compliance with buyer specifications. Glass should therefore be considered a high-potential but quality-sensitive fraction, which can easily turn from a source of revenue for the recycler to a disposal cost.

Mixed silicon/silver powders: strategic value and refining-dependent demand

From a technical quality perspective, mixed silicon/silver powders are one of the most strategic but complex output fractions. The laboratory analysis describes the silicon powder as a solid pulverulent grey material and identifies relevant silicon and silver contents. In particular, the XRF analysis reports silicon and silver as measurable components of the fraction, confirming that the material contains potentially valuable elements but is not a purified silicon or silver product. This is crucial for marketability: the fraction cannot be treated as a directly marketable high-purity raw material, but rather as a candidate input for refining or further concentration.

From a demand perspective, the potential markets for this fraction are significantly different from those of aluminium, copper or ferrous metals. Possible downstream routes include precious metal refining, metallurgical applications, battery-related applications and, in more ambitious scenarios, PV-grade or polysilicon-related applications. However, these markets have very different quality thresholds. Metallurgical applications may tolerate lower purity, provided that the composition is compatible with alloy requirements. Silver-focused refining may be attractive if the silver concentration and recovery yield justify treatment costs. Battery anode or PV-grade applications offer higher value potential, but require much more advanced refining and direct validation by downstream users.

The analysis already highlighted that the value of silicon-based outputs changes significantly depending on the level of refining and final application, ranging from lower-

value metallurgical uses to higher-value applications such as battery anodes or PV-related uses. This logic remains valid here: the market demand for mixed silicon/silver powders should be interpreted as refining demand, not as direct demand for an immediately usable secondary raw material.

Table 39 – Marketability of mixed powders: Silver

Potential market route	Technical requirement	Demand potential	Market readiness	Main barrier
Low-value recovery / disposal avoidance	No dedicated refining	Low	High feasibility	Low or negative value
Metallurgical silicon route	Composition control, impurity tolerance	Medium-high	Medium	Buyer-specific specifications
Silver-focused refining	Sufficient Ag concentration and recoverability	High	Medium	Refining cost and yield
Battery anode applications	High purity, controlled contaminants	High	Low-medium	Advanced refining and testing
PV-grade or polysilicon applications	Very high purity	Very high	Low	Very demanding specifications

The main marketability gap is the need to transform a mixed powder into a buyer-ready material. The chemical analysis is highly valuable because it provides a first benchmark of recoverable elements and contaminant profile, but potential buyers would still require more detailed characterisation, minimum volumes, consistency over time and pilot-scale validation. This fraction should therefore be treated as a strategic priority for future market development.

The chemical analysis of the mixed silicon/silver powder provides a first technical benchmark for assessing the marketability of this fraction. The sample shows a significant silicon content, confirming that the fraction is strongly silicon-bearing but not directly comparable to purified silicon raw materials. More importantly, the presence of silver confirms that the powder should also be assessed as a potential precious-metal-bearing fraction.

Table 40 – Marketability of mixed powders: Silicon

Parameter	Analytical result	Marketability interpretation
Silicon, XRF	29.9 ± 9.0%	The fraction is strongly silicon-bearing, but not purified silicon
Silver, XRF	0.36 ± 0.11%	Corresponds to approximately 3,600 mg/kg Ag; potentially relevant for precious metal refining

Ag_2O	0.39 ± 0.12%	Confirms the presence of silver also as an oxide form
SiO_2	64 ± 19%	Indicates a relevant oxidised/mineral component, requiring refining or pre-concentration

The silver concentration measured in the sample is particularly relevant because it provides a minimum benchmark for downstream discussions with precious metal refiners. Although the value does not by itself prove commercial viability, it indicates that silver is not present only as a negligible trace element. Its recovery may therefore represent a more immediately actionable valorisation route than high-purity silicon recovery, provided that recovery yields, refining costs, contaminant profile, available volumes and consistency of the fraction over time are compatible with buyer requirements.

Mixed plastics: limited marketability and residual recovery routes

From a technical quality perspective, mixed plastics are the weakest output fraction. The laboratory analysis describes the plastic fraction as a mixed solid material, non-pulverulent and variegated. It also reports a high organic carbon content and a significant calorific value, which suggests that the material may be more suitable for energy-related recovery routes than for high-quality mechanical recycling, unless additional separation and cleaning are performed.

From a demand perspective, the potential outlets for mixed plastics are limited. Mechanical recycling would require clean, homogeneous and well-characterised polymer fractions, which are difficult to obtain from PV module layers without dedicated separation processes. Low-grade applications as fillers or mixed compounds may be possible only after further characterisation and buyer validation. In the short term, the most realistic outlets are likely to be energy recovery, use as alternative fuel, cement kiln applications, or other residual recovery routes, subject to regulatory and technical constraints.

Market readiness is therefore low. Unlike aluminium or copper, the plastic fraction does not correspond to a mature and high-value secondary raw material stream. Its value potential is also limited and may be mainly linked to avoided disposal costs rather than positive market revenues. The main barriers are heterogeneity, contamination, polymer complexity, and limited demand for mixed PV-derived plastics.

Table 41 – Marketability of mixed plastics

Potential outlet	Technical requirement	Market readiness	Value potential	Main barrier
Mechanical recycling	Clean and homogeneous polymer fraction	Low	Medium, if feasible	Heterogeneity and contamination
Low-grade compound or filler	Further characterisation	Low-medium	Low-medium	Buyer validation required
Energy recovery / alternative	Calorific value, compliance with limits	Medium	Low	Regulatory and acceptance conditions

fuel				
Disposal	No market requirement	High feasibility	Negative value	Not aligned with circularity goals

The chemical analysis is particularly useful here because it helps define a realistic market positioning. The plastic fraction should not be presented as automatically recyclable into new plastic products. Rather, its current marketability appears closer to residual or energy recovery routes, unless further technological improvements allow cleaner polymer separation.

3.7.2. Value Chain Organisation and Market Conditions for PV Recycling in French context

- EPR framework and structuring French' photovoltaic recycling value chain

Extended Producer Responsibility (EPR) is a key pillar of waste management policy in France, as defined in the French Environmental Code. By assigning both financial and operational responsibility for end-of-life management to producers, this framework establishes a structured and stable foundation for waste collection and treatment systems.

Strengthened over time, notably through the 2015 Energy Transition Law and the 2020 Anti-Waste and Circular Economy Law (AGEC), the EPR system now represents a major driver of the circular economy. It encourages improvements in waste management performance while promoting eco-design practices among producers.

A key finding is that, in practice, these responsibilities are largely implemented through state-approved Producer Responsibility Organisations. These not-for-profit entities play a central operational role by managing:

- waste collection,
- treatment (recycling and recovery),
- and the monitoring and traceability of material flows.

PV modules fall under the WEEE category in France. The rapid growth of installed capacity is expected to lead to a significant increase in end-of-life volumes in the coming years, making their management a key challenge.

PV modules present a strong potential for recycling due to the presence of valuable materials such as glass, aluminium, silver and silicon. However, the required treatment processes remain technologically complex and continue to evolve, reinforcing the importance of supporting innovation in recycling technologies.

Within this context, SOREN plays a central role by structuring the entire operational chain. The analysis shows that its activities, ranging from the organisation of collection networks to the contractualisation of treatment operators, ensure both the continuity and the coherence of the system at a national scale.

- Central role of a PRO in structuring the value chain

The organisation of the PV recycling sector in France relies on the PRO SOREN, which ensures the operational implementation of EPR.

Its main activities include:

- the development and management of a national collection network,
- the organisation of logistics and on-site collection for large volumes,
- and the contractualisation of specialised treatment operators.

Beyond these operational functions, SOREN structures the entire value chain, from collection to recycling through a network of industrial partners. Its governance, led by producers, defines strategic orientations and ensures compliance with regulatory objectives such as collection, recycling and traceability targets.

In the French context, SOREN applies tendering procedures as a key mechanism for structuring the market and ensuring the selection of efficient recycling solutions.

These calls for tenders are designed to guarantee transparency, competition and overall system performance. Operators are required to submit comprehensive technical, economic and organisational proposals demonstrating compliance with regulatory and operational requirements.

Selection is based on a multi-criteria framework including:

Table 42 – Framework of selection criteria applied to evaluate treatment process viability

Criterion	Description
Technical	Quality of the treatment process, recycling performance, traceability, and adequacy of technical resources
Economic	Competitiveness of the pricing offer (treatment costs)
Proximity	Distance between collection points and the treatment facility (logistical and environmental optimisation)
Quality / Safety / Environment (QSE)	Risk management, organisation, traceability, and environmental performance
Social	Commitment to social inclusion and employment (societal criterion)

The proximity criterion plays a particularly structuring role. It directly influences transport distances between collection points and treatment facilities, while also affecting downstream logistics by determining the location of material outlets. This contributes to reducing overall costs and environmental impacts across the value chain.

- Integration of innovation and risk-sharing mechanisms

A pragmatic approach to innovation enables the integration of new recycling technologies, including those developed within the EVERPV project, despite inherent uncertainties.

Several constraints are associated with the deployment of innovative processes:

- industrial ramp-up challenges,
- regulatory approval timelines,
- variability in input materials,
- and uncertainties related to performance and costs.

To address these challenges, SOREN implements risk-sharing mechanisms with operators. These mechanisms combine:

- remuneration of treatment activities (fixed and variable components),
- sharing of revenues from material recovery (glass, aluminium, silicon, etc.).

These revenues may either be shared between parties, this model helps balance risks, particularly in contexts of uncertain performance or volatile commodity markets.

It contributes to:

- securing operators against market fluctuations,
- stabilising the economic framework of the sector,
- and aligning incentives with recycling performance.

The use of indexed pricing mechanisms further reflects market conditions and reinforces the dynamic balance between stakeholders.

However, the performance of the system depends not only on treatment efficiency but also on the efficiency of recovered materials.

Operators must demonstrate their ability to secure reliable downstream buyers by:

- identifying industrial off-takers,
- ensuring regulatory compliance,
- and guaranteeing full traceability of material flows.

The value of materials, such as glass, aluminium, silver and silicon, is highly dependent on both quality and market conditions. Reliable and well-structured outlets are therefore essential to ensure economic viability.

The location of downstream actors also plays an important role. Proximity between treatment facilities and final outlets reduces transport distances, lowers costs and limits environmental impacts, thereby improving overall system efficiency.

- Estimated costs of output fractions

In this context, within the French scope, ENVIE has been selected as the treatment operator for the new SOREN operational cycle, with the integration of the sanding process demonstrated within EVERPV, applied to photovoltaic panels. This process generates a specific powder fraction concentrating several high-value elements.

The work carried out under Task 6.2 provides the following mass-based characterisation of this powder:

Table 43 – Mass composition of the sanding powder

Component	Share (%)
Silicon (Si)	83%
Aluminium (Al)	7%
Copper (Cu)	5%
Silver (Ag)	2%
Residual fines	3%

From a technical perspective, this composition confirms the presence of valuable materials. However, the actual recovery potential depends on the ability to separate these elements at industrial scale and at sufficient purity levels.

At this stage, no fully operational downstream outlet has yet been secured for this powder fraction. Current assumptions therefore remain indicative and subject to validation. One identified player is *Mob-E-Scrap*, which is developing a hydrometallurgical process targeting the recovery of silver, copper, tin, and silicon, with an expected industrial deployment by 2027.

For the other fractions, existing classic downstream buyers are already in place

Table 44 – Existing downstream outlets for recovered fractions

Fraction	Downstream outlet	Application
Glass	Saint-Gobain (France)	Flat glass industry
Aluminium	European recyclers	Automotive / aerospace
Silicon	European markets	Metallurgy / energy
Copper	European markets	Electrical networks
Silver	Specialised recovery	Electronics

An indicative valuation of the sanding powder has been established based on observed industrial purchase prices:

Table 45 – Indicative market prices and value contribution of powder components

Material	Average price (€/kg)	Average price since 2020 (€/kg)
Silicon (Si)	1,315	1,696
Aluminium (Al)	1,318	1,008
Copper (Cu)	8,446	5,751
Silver (Ag)	2059,25	1081,23

The economic performance of the process is largely driven by the recovery of silver. Without a stable and efficient recovery route for this element, the overall value of the powder decreases significantly.

From an operational perspective, the main constraint is not the generation of the fraction itself, but the lack of validated downstream buyers. While the process already shows promising results, its economic viability will depend on securing industrial partners capable of recovering high-value metals, especially silver, and on confirming recovery performance at an industrial scale.

4.CONCLUSIONS

This deliverable shows that the circular-economy potential of end-of-life photovoltaic panels is determined by the interaction of collection performance, treatment technology, output quality and downstream market demand. The projected growth of PV waste creates a substantial future source of secondary materials, but this potential cannot be realised while a large share of panels remains outside formal collection systems or arrives at treatment facilities in a condition that limits advanced delamination and recovery routes.

At material level, glass and aluminium dominate the mass of silicon PV panels and can already be directed to established recycling markets. The principal strategic challenge concerns lower-volume materials, particularly silver and silicon, whose recovery depends on selective pre-treatment and sufficiently pure output fractions. The comparison of shredding, hot-knife, sanding and hybrid processes demonstrates that mass-recovery rates alone are an incomplete measure of circularity: material separation, contamination levels, legal status and suitability for further refining determine whether an output becomes a usable secondary raw material.

The Italian and French case studies confirm that collection and logistics are integral parts of recycling performance. Pallet quality, packaging, module orientation and handling influence glass breakage and therefore the proportion of panels suitable for higher-quality treatment. Maintaining intact modules through clear acceptance requirements, appropriate pallets and simple, consistently applied packaging standards is a practical and comparatively low-cost means of improving downstream recovery.

The European value chain remains dominated by shredding capacity, while delamination capacity is smaller and geographically concentrated. The techno-economic benchmark reflects this maturity gap: shredding achieved a lower estimated direct treatment cost under harmonised assumptions, whereas mechanical delamination had higher energy, labour and per-tonne costs. This comparison must be interpreted together with output quality and revenue potential. Advanced routes may become competitive where cleaner glass and concentrated silver- and silicon-bearing fractions reduce downstream processing requirements or command higher prices, but this requires industrial-scale validation and reliable off-take agreements.

Overall, the transition from high-volume waste treatment to genuinely circular PV recycling requires coordinated action across the value chain. Priority should be given to increasing formal collection, preserving module integrity, harmonising composition and recyclability data, defining quality and End-of-Waste criteria for recovered fractions, and developing stable markets for glass, silicon/silver powders and polymer outputs. Under these conditions, the technologies assessed in EVERPV can complement established treatment routes and strengthen the contribution of PV recycling to European resource security.

5. RECOMMENDATIONS

The results demonstrate that improving the circularity of end-of-life photovoltaic panels requires coordinated intervention across the full value chain. Increasing collection alone will not ensure circular outcomes if panels are damaged during handling, treatment routes generate contaminated fractions, specialised capacity remains unavailable, or recovered materials cannot meet downstream market requirements. Policy measures should therefore address the quantity of PV waste entering formal systems, the condition in which panels reach treatment facilities, the quality and destination of recovered fractions, and the economic conditions needed to develop higher-value recycling routes.

5.1. POLICY RECOMMENDATIONS

5.1.1. Strengthen formal collection and preserve panel integrity

Measures to increase the formal collection of end-of-life PV panels should remain a central priority, as uncollected panels and materials cannot contribute to domestic secondary raw material supply. Collection performance should, however, be assessed not only according to the quantity collected but also according to the physical condition of the panels delivered for treatment.

Minimum requirements should be established for pallet quality, panel orientation, strapping, storage, loading and transport. These requirements could be integrated into operational guidance for installers, collection points, logistics operators and treatment facilities, supported by training and periodic compliance checks. The Italian and French case studies indicate that relatively simple handling measures can substantially reduce breakage and preserve access to selective pre-treatment routes.

Collection systems should also support the early identification and separation of panels according to their condition and technology. Intact panels suitable for reuse or delamination should be kept separate from heavily damaged panels that are more appropriately directed to shredding. This would reduce unnecessary breakage, improve process efficiency and allow treatment routes to be matched more closely to the characteristics of the incoming waste.

5.1.2. Evaluate recycling performance beyond mass recovery rates

Current assessment and reporting frameworks should move beyond aggregate mass-recovery rates. High mass recovery may largely reflect the recovery of glass and aluminium while providing limited information on output purity, final destination or the recovery of strategically relevant materials.

Recycling performance indicators should therefore include:

- the share directed to material recycling rather than energy recovery or disposal;
- the treatment type of EoL panels (with preference to higher quality mechanical delamination lines);

- the quantity and purity of individual output fractions;
- contamination levels and additional refining requirements for output fractions; and
- the recovery of strategically important materials, such as silicon, copper, and silver

These indicators would provide a more accurate picture of whether treatment contributes to genuine circularity or primarily produces low-value intermediate waste fractions.

5.1.3. Introduce harmonised quality and characterisation requirements

The development of stable downstream markets requires recovered fractions to be consistently characterised and comparable across treatment facilities. Common European or sector-level protocols should be developed for sampling, testing and reporting the composition of recovered PV glass, silicon/silver powders and polymer fractions. Such protocols should cover, where relevant, chemical composition, granulometry, metal contamination, and the physical form and variability of the outputs.

Greater harmonisation of End-of-Waste criteria should also be considered, particularly for recovered glass. Differences in legal classification can determine whether a technically similar fraction is treated as a marketable secondary raw material or remains subject to waste-management requirements. Clearer criteria would reduce uncertainty for recyclers and potential off-takers, and can directly contribute to the development of an established circularity market.

5.1.4. Use producer responsibility and procurement to reward higher-quality treatment

Producer responsibility organisations and public authorities can influence treatment outcomes through the criteria used to select logistics and recycling operators. Tendering and contracting decisions should not be based on direct economic factors only but should also consider:

- if applicable, the preservation of panel integrity during collection and transport;
- the capacity to treat adequate volumes of materials and their subsequent downstream recycling routes / destination;
- the quality and purity of recovered fractions;
- the recovery of strategically important materials, such as silicon and silver;
- traceability and data reporting; and
- environmental performance

Where appropriate, contracts could include performance bonuses for verified high-quality recovery or penalties where recyclable fractions are unnecessarily directed to energy recovery or disposal. Longer-term contracts may also provide treatment operators with sufficient certainty to invest in specialised equipment and develop downstream partnerships.

5.1.5. Support complementary rather than uniform treatment routes

Nonetheless, while mechanical delamination has shown the highest potential for subsequent material recovery, policy should not prescribe a single treatment technology for all end-of-life PV panels. Shredding and delamination provide different advantages and are suited to different input conditions and output objectives. Shredding offers higher throughput and can accept damaged panels, whereas delamination and sanding can produce cleaner glass and more concentrated silicon- and silver-bearing fractions from suitable input material.

Treatment strategies should therefore recognise the complementary role of these processes. Policy and investment support should encourage facilities to select or combine routes according to panel condition, material composition, available downstream markets and the intended quality of the recovered outputs.

Support for innovative technologies should be conditional on evidence of complete downstream pathways. This requires a holistic policy intervention. The demand and market requirements have shown that funding technologies that produce output fractions is insufficient where no technically and economically viable refining or market route exists for that fraction.

5.1.6. Develop specialised treatment and refining capacity

The European PV recycling landscape remains dominated by conventional shredding infrastructure, while specialised delamination and refining capacity is more limited and geographically concentrated. Capacity planning should anticipate increasing PV waste volumes and identify regions where insufficient treatment infrastructure could lead to long-distance transport, capacity bottlenecks or reliance on lower-quality treatment routes. Additionally, a holistic perspective needs to be applied when supporting the development of new capacity. Pre-treatment represents one of many steps in the recycling value chain and may benefit strongly from established partnerships or value chains for existing and new output fractions.

Targeted support may be justified for:

- industrial-scale delamination and sanding technologies which produce high quality output fractions;
- shredding technologies with a verified recycling downstream path for produced fractions;
- upgrading equipment for high-quality material separation;
- pilot lines for polymer separation and treatment;
- shared refining facilities for silicon- and silver-bearing powders;
- industrial validation campaigns with prospective material users; and
- partnerships between recyclers, refiners, PV manufacturers and material-consuming industries.

Investment decisions should anticipate the rapidly rising waste volumes which will, based on existing capacity, necessarily be diverted mainly into shredding facilities. Thus, it is

paramount to support the development of high-quality fraction producing pre-treatment technologies and support the development of a subsequent market for recovered PV materials.

5.1.7. Develop markets for recovered PV materials

The results show that the economic and industrial relevance of PV recycling cannot be assessed only through mass recovery rates. Aluminium, copper and ferrous metals provide access to stable and mature markets, but they do not represent the main strategic challenge. Glass is the dominant mass fraction and offers several potential outlets, but its value depends on quality and compliance with downstream requirements. Silicon and silver represent the most strategic opportunity for value creation, although their uptake depends primarily on the specific output fraction and purity, as well as the need for further refining and a subsequent direct validation by potential users. Mixed plastics remain the weakest outlet and are likely to require further technological development or low-value recovery routes.

Overall, the market demand analysis suggests that future efforts should focus on three priorities. First, improving the quality and consistency of glass outputs in order to access higher-value markets. Second, developing and validating refining pathways for silicon and silver outputs, with particular attention to silver recovery and possible silicon applications in metallurgy, batteries or PV-related uses. Third, identifying realistic and economically sustainable outlets for mixed plastics, while reducing their contamination and residual disposal burden. The successful market uptake of recovered PV fractions will therefore depend not only on recycling efficiency, but also on the ability to generate stable, well-characterised and buyer-ready material streams.

5.1.8. Improve traceability and information exchange

Reliable information should accompany PV panels and recovered fractions throughout the value chain. Digital systems, including future digital product passport applications, could provide information on panel technology, composition, installation date, ownership, dismantling, collection, treatment and final material destination.

Treatment operators should report material outputs using harmonised categories and distinguish between fractions that are:

- directly marketed as secondary raw materials;
- sent for further refining;
- recycled into lower-value applications;
- used for energy recovery; or
- disposed of.

Improved traceability can support enforcement, strengthen the evidence base for policy decisions and allow producers and producer responsibility organisations to evaluate the actual outcomes of contracted treatment operations.

5.1.9. Align economic support with full value-chain performance

The technical and economic assessment shows that direct treatment cost alone does not provide an adequate basis for comparing recycling technologies. Lower-cost shredding may be economically preferable under a narrow plant-level comparison, while more selective processes may reduce downstream refining needs or generate cleaner and potentially more valuable outputs.

Future economic assessments and support mechanisms should therefore account for a variety of cost and price factors, ranging from treatment and logistics costs over the revenues from recovered materials to the costs of further separation and refining and residual waste and disposal costs. Additionally, non-traditional factors that have indirect economic impact could be considered to fully assess the value chain. Particularly the output quality and marketability, environmental impacts, avoided primary material use, and the recovery of strategically relevant materials are such relevant factors.

Public funding, investment aid or innovation incentives should be linked to measurable improvements in these wider outcomes rather than to equipment installation alone. The findings should also be considered together with the Life Cycle Assessment and Life Cycle Costing results of Deliverable 6.3 before drawing final conclusions on the relative performance of the EVERPV technologies.

5.1.10. Integrate recycling considerations into PV product design

This study has shown the high potential of pre-treatment technologies and collection practices to improve material recovery. Nonetheless, these interventions are limited by challenging product designs that are optimized for cost and performance, rather than for recycling.

Long-term improvements in recycling should begin at the design stage. Manufacturers should be encouraged to reduce material combinations and adhesives that impede separation, provide reliable composition data, facilitate the removal of frames and junction boxes, and consider the recyclability of encapsulants and backsheets.

Eco-design requirements should be linked to practical evidence from treatment operators. Design changes should be evaluated not only according to whether a panel is theoretically recyclable, but also according to whether its components can be separated at industrial scale into fractions that meet downstream material specifications.

5.2. OVERALL POLICY DIRECTION

The central policy implication is that end-of-life PV management should be treated as an integrated material-supply system rather than only as a waste-treatment obligation. Collection targets remain important, but they must be accompanied by measures that preserve module integrity, differentiate treatment according to input condition, reward high-quality outputs, develop specialised refining capacity and create reliable markets for recovered materials.

A successful policy framework should therefore align the incentives of manufacturers, producers, collection organisations, logistics providers, treatment operators, refiners and material users. Without such alignment, increasing PV waste volumes may primarily expand conventional bulk treatment. With appropriate collection standards, quality-based performance indicators, targeted innovation support and stronger downstream market integration, the same waste stream could provide a more reliable source of glass, silicon, silver, aluminium, copper and other secondary raw materials for the European economy.

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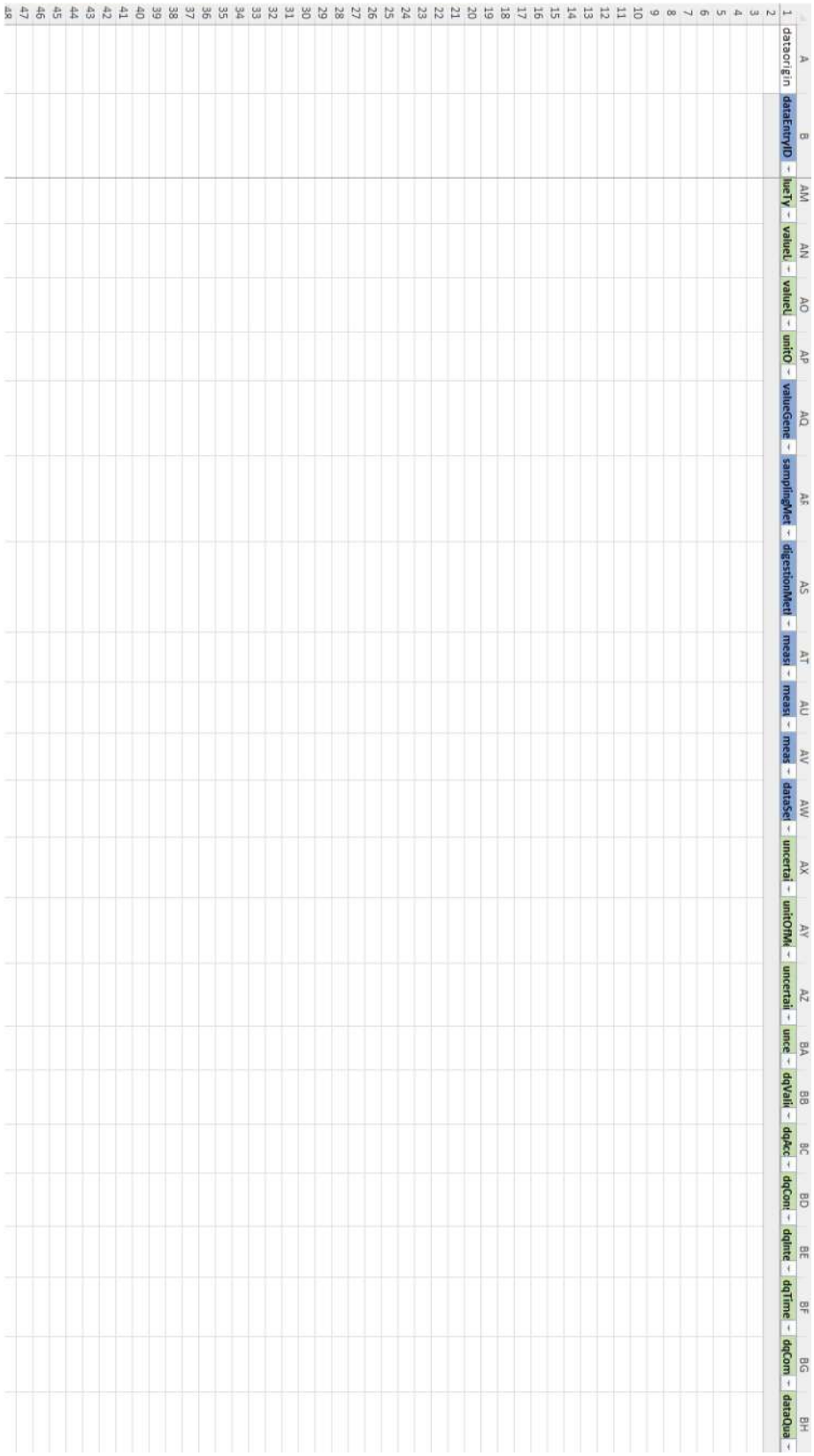
ANNEX

ANNEX I

FUTURAM Project Data Collection Template – Overview of Columns

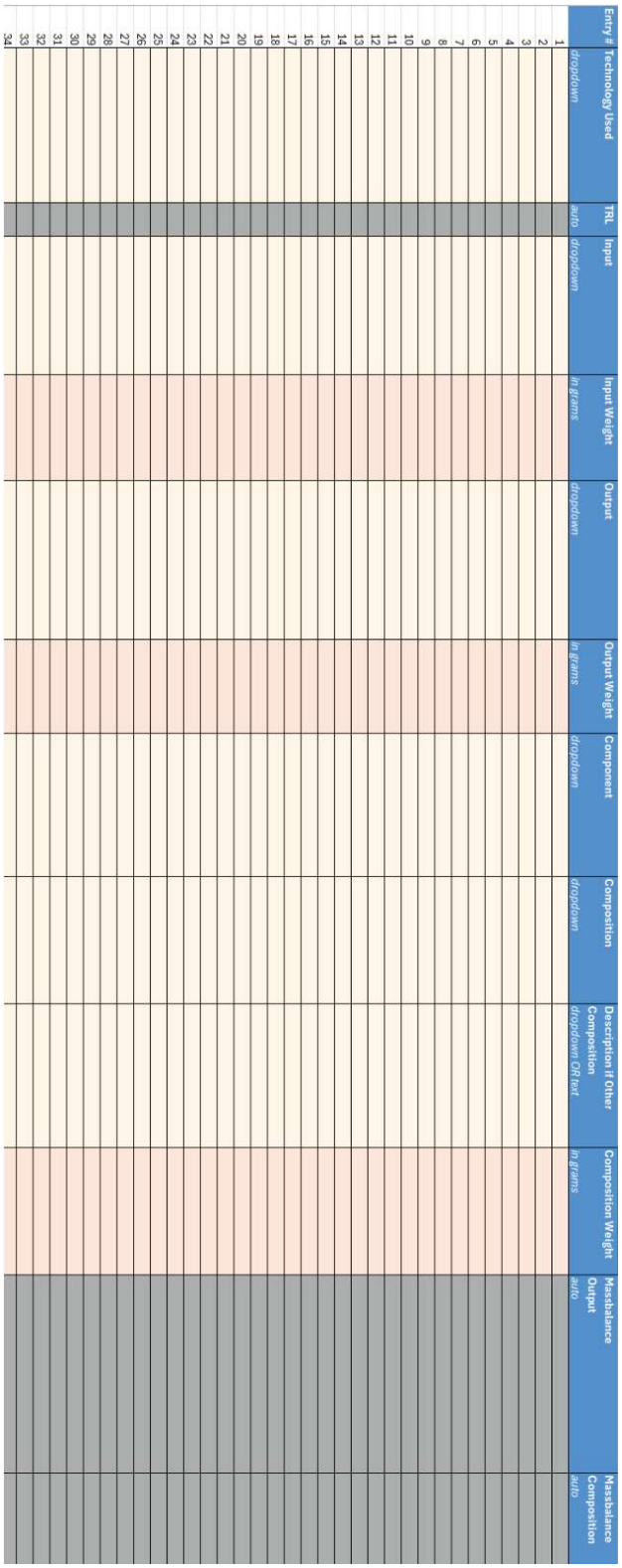
description	entryType	
unique identifier for data entry	number	number
designation of data entry to FutuRaM WS	codelist relatedFutuRaM-WS	FutuRaM_codelists_repository.xlsx
data entry refers to use phase or EoL phase	codelist use_EoL	FutuRaM_codelists_repository.xlsx
unique stock or flow name, as depicted in WS-specific flow chart	codelist_flowCharts	FutuRaM_codelists_repository.xlsx
chapter in the list of waste, described in Commission Decision 2001/118/EC	codelist LoWchapter	FutuRaM_codelists_repository.xlsx
sub-chapter in the list of waste, described in Commission Decision 2001/118/EC	codelist LoWsubChapter	FutuRaM_codelists_repository.xlsx
list of waste code, described in Commission Decision 2001/118/EC	codelist LoWkey	FutuRaM_codelists_repository.xlsx
scrap specification codes from the Institute of Scrap Recycling Industries (ISRI)	codelist ISRI	FutuRaM_codelists_repository.xlsx
Harmonized System Codes	codelist HS	FutuRaM_codelists_repository.xlsx
categories used for the collection of waste	codelist collectionCategory	FutuRaM_codelists_repository.xlsx
unique identifier for each characterised product	number	number
product key to describe the product; allocation table designates the product key name	codelist EEEkey, BATTkey, VEHICLEkey, builtenvironmentCategor	FutuRaM_codelists_repository.xlsx
product sub-key to describe the product; allocation table designates the product key name	codelist EEESubKey, BATTSubKey, builtEnvironmentSubCategory	FutuRaM_codelists_repository.xlsx
product sub-sub-key to describe the product; allocation table designates the product key name	codelist EEESubSubKey, builtEnvironmentArchetype	FutuRaM_codelists_repository.xlsx
product description used in data source	free text	free text
similarity between description for product in original data source and in product key	codelist similarity	FutuRaM_codelists_repository.xlsx
year in which the product was produced/manufactured	free text	free text
year when the product entered the end-of-life phase	free text	free text
unique identifier for characterised component	number	number
description of the component from code list componentKeyLevel0	codelist componentKeyLevel0	FutuRaM_codelists_repository.xlsx
description of the component from code list componentKeyLevel1	codelist componentKeyLevel1	FutuRaM_codelists_repository.xlsx
description of the component from code list componentKeyLevel2	codelist componentKeyLevel2	FutuRaM_codelists_repository.xlsx
component description used in data source	free text	free text
similarity between description for component in original data source and in component code list	codelist similarity	FutuRaM_codelists_repository.xlsx
designation to other FutuRaM WS for embedded components (e.g. battery in electric vehicle)	codelist embeddedComponent	FutuRaM_codelists_repository.xlsx
designation of material to metals, organics, minerals, and mixed/unspecified	codelist materialKeyLevel0	FutuRaM_codelists_repository.xlsx
designation of material to main material groups within m0	codelist materialKeyLevel1	FutuRaM_codelists_repository.xlsx
designation of material to subgroups within the material groups m1	codelist materialKeyLevel2	FutuRaM_codelists_repository.xlsx
designation of material to alloy and other subgroups within the material groups m2	codelist materialKeyLevel3	FutuRaM_codelists_repository.xlsx
description of the material from code list materialKeyLevel4	codelist materialKeyLevel4	FutuRaM_codelists_repository.xlsx
material description used in data source	free text	free text
similarity between description for material in original data source and in material code list	codelist similarity	FutuRaM_codelists_repository.xlsx
designation of chemical element, if the data entry refers to an element mass fraction	codelist element	FutuRaM_codelists_repository.xlsx
designation of what the parameter refers to (e.g. e-m for the mass fraction of an element in a material)	codelist parameterCode	FutuRaM_codelists_repository.xlsx
designation of what the parameter describes (e.g. mass, mass fraction, volume, etc.)	codelist parameter	FutuRaM_codelists_repository.xlsx
country where sample originates	codelist locationNUTS-0	FutuRaM_codelists_repository.xlsx
numeric (measurement) value	codelist	number
designation of the value type (e.g. single value, mean value, median, etc.)	number	FutuRaM_codelists_repository.xlsx
minimum value, if a range is given, in addition to/instead of a single or mean value)	number	number
maximum value, if a range is given, in addition to/instead of a single or mean value)	number	number
unit of measurement assigned to the value (e.g. ppm, mg/kg, Mg, etc.)	codelist UoM	FutuRaM_codelists_repository.xlsx
designation of how the value was generated (e.g. measured, estimated, calculated)	codelist valueGeneration	FutuRaM_codelists_repository.xlsx
designation of sampling method	codelist samplingMethod	FutuRaM_codelists_repository.xlsx
designation of digestion method, if measurement includes wet digestion	codelist digestionMethod	FutuRaM_codelists_repository.xlsx
designation of measurement method, if value is the result of a measurement	codelist measurementMethod	FutuRaM_codelists_repository.xlsx
year in which the measurement was executed	number	number
country where the measurement was executed	codelist locationNUTS-0	FutuRaM_codelists_repository.xlsx
designation to what the value refers to, i.e. if it is product-specific/site-specific or generic	codelist dataSetType	FutuRaM_codelists_repository.xlsx
uncertainty as given in the original data source	number	number (+/-)
unit of measurement assigned to the uncertainty from the original data source	codelist UoM	FutuRaM_codelists_repository.xlsx
uncertainty from original data source divided by the value, given in percent	automatic	automatic
type of uncertainty given in the original data source	codelist uncertaintyType	FutuRaM_codelists_repository.xlsx
FutuRaM data quality code for the DQ dimension validity	codelist dataQualitycategory	FutuRaM_codelists_repository.xlsx
FutuRaM data quality code for the DQ dimension accuracy	codelist dataQualitycategory	FutuRaM_codelists_repository.xlsx
FutuRaM data quality code for the DQ dimension consistency	codelist dataQualitycategory	FutuRaM_codelists_repository.xlsx
FutuRaM data quality code for the DQ dimension integrity	codelist dataQualitycategory	FutuRaM_codelists_repository.xlsx
FutuRaM data quality code for the DQ dimension timeliness	codelist dataQualitycategory	FutuRaM_codelists_repository.xlsx
FutuRaM data quality code for the DQ dimension completeness	codelist dataQualitycategory	FutuRaM_codelists_repository.xlsx
mean value of all six FutuRaM DQ dimensions	automatic	automatic
resulting FutuRaM DQ category	automatic	automatic
designation, if element was assessed as critical in the EU criticality list in 2023	automatic	automatic
designation, if element was assessed as critical in the EU criticality list in 2020	automatic	automatic
designation, if element was assessed as critical in the EU criticality list in 2017	automatic	automatic
designation, if element was assessed as critical in the EU criticality list in 2014	automatic	automatic
designation, if element was assessed as critical in the EU criticality list in 2011	automatic	automatic
original data source, given as [author, year]	free text	free text
rights assigned to the data from the original data source	codelist rights	FutuRaM_codelists_repository.xlsx
notes and comments regarding the data, original data source, or data entry	free text	free text
reference URL (permanent URL, if available)	free text	free text
person who entered the data entry	free text	free text
institution of data processor	free text	free text
date of data entry	date	date

Data Recording Template



ANNEX II

Data Collection Template – Pre-Treatment Efficiency



Entry #	Technology Used	TRL	Input	Input Weight	Output	Output Weight	Component	Composition	Description if Other Composition	Composition Weight	Massbalance Output	Massbalance Composition
	dropdown	*auto*	*dropdown*	*in grams*	*dropdown*	*in grams*	*dropdown*	*dropdown*	*dropdown OR text*	*in grams*	*auto*	*auto*
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ANNEX III

QUESTIONNAIRE - CASE STUDIES ON IMPROVEMENTS TO THE COLLECTION SYSTEM (FRENCH EXAMPLE)

I - Information and context :

Palletisation operation

1. How do you source the pallets for dismantling operations? If you buy them, at what price?
2. How do you source the pallets for deliveries of new panels? If you buy them, at what price?
3. How many pallets per truck?
4. What is the palletising format for pallets of new panels arriving on site?
5. How long can palletised panels be stored while awaiting intervention? Under what conditions?

Strapping operation

6. How do you strap the pallets (manually or with a strapping machine)?
7. If you use a strapping machine, do you own it? If so, did you buy it specifically for palletising panels?
8. Do you have any comments to add regarding the previous questions?

II - Thoughts on current palletisation methods :

PV modules

9. In your opinion, what would be the optimal way to store palletised panels?
10. Are you encountering any difficulties during the dismantling of the panels?

Pallets

11. Do you think it is useful to palletize with plastic film?
12. Do you think it's useful to strap the pallets? If so, do you think two straps per side are sufficient? If not, how many straps per side?
13. Is it appropriate for you to place the panels with the glass facing upwards?
14. Is it difficult to find pallets that are at least the same size as the panels?
15. Do you think the maximum palletising height (1.70m) is suitable? If not, what would be the optimal height (or how many panels per pallet)?
16. Do you think SOREN's current take-back conditions are adequate to limit glass breakage during transport operations?
17. Do you have any ideas for limiting glass breakage?
18. Are you experiencing any difficulties when palletising the panels?

19. Are you experiencing any difficulties when loading palletised panels onto trucks?
20. Are you experiencing any difficulties unloading palletised panels into trucks?

Logistic operation

21. Are the truck's straps always used to secure the pallets? If so, in your opinion, are they used appropriately (or are they too loose/not tight enough)?
22. In your opinion, is it common for strapping to be the cause of breakage of pallets and/or panels?
23. Do you have any comments to add regarding current panel management methods?

III - Area for improvement:

Cables

1. Do you think cables play a positive/negative role during palletising? Would removing them beforehand and putting them back in a big bag be more practical for you?
2. Would you be willing to remove the cables from the panels if it reduced breakage during transport (and then return the cables to SOREN in a big bag)?

Pallets

3. Would palletising the panels vertically be relevant, in your opinion? What are the implications for you?
4. Do you think there is more optimal way to palletize, in comparison to the current way?
5. Would you be willing to reduce the number of panels per pallet if it reduces breakage during transport?
6. Do you have any comments to add regarding areas for improvement?



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