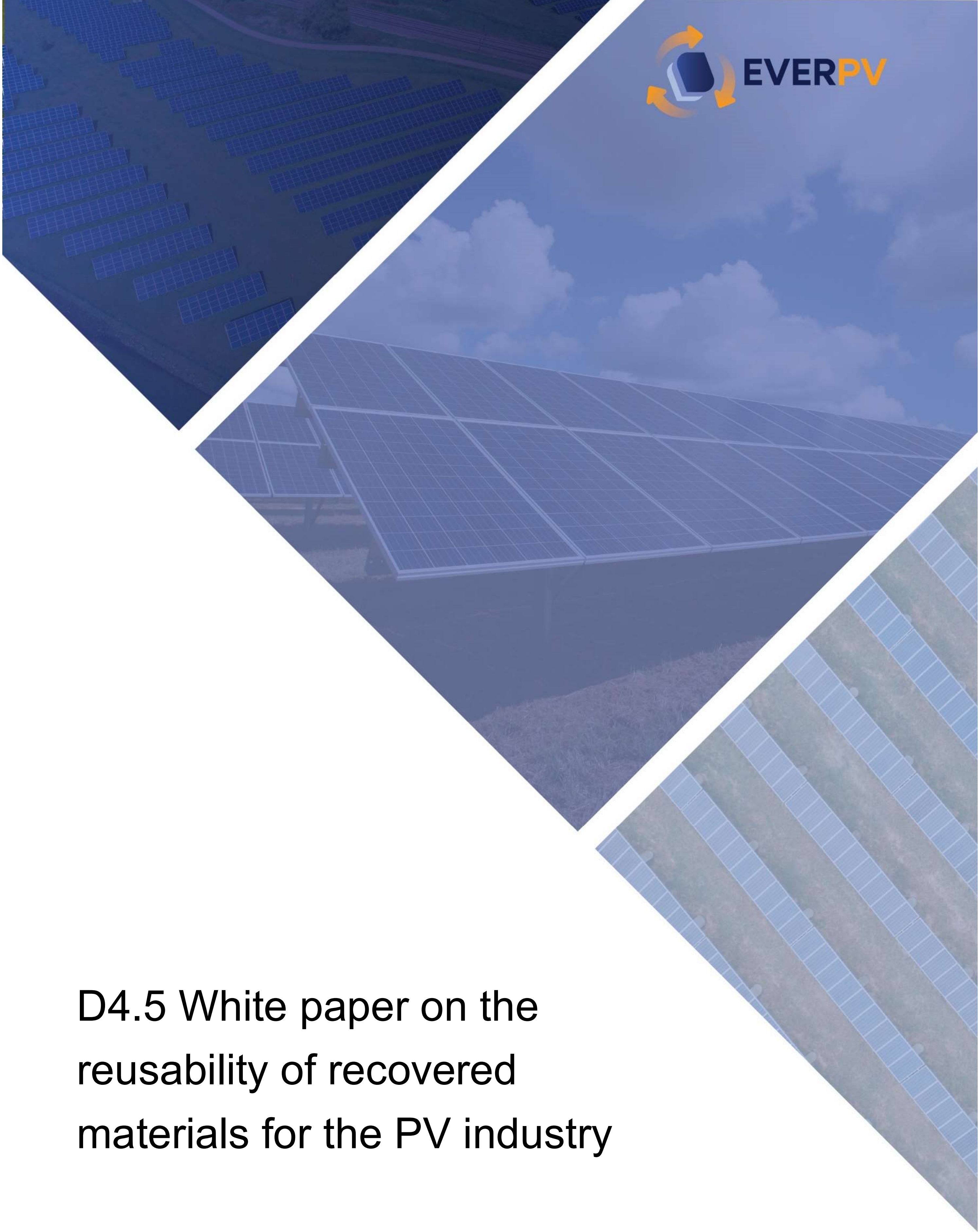

EVERPV

D4.5 White paper on the reusability of recovered materials for the PV industry

Funded by the European Union

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Contents

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[1] Nature of the Deliverable: R = Report, DEM = Demonstrator, pilot, prototype, DMP = Data Management Plan
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Project Details

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Glossary

CAPEX	Capital Expenditure
CRM	Critical Raw Material
EOL	End Of Life
EU	European Union
EVA	Ethylene-Vinyl-Acetate
IR	Infrared
PET	PolyEthylene Terephthalate
PTA	Terephthalic Acid
PV	Photovoltaic
PVDF	PolyVinyliDene Fluoride
PVF	PolyVinyl Fluoride
R-EVA	Recycled-EVA

D4.5 White paper on the reusability of recovered materials for the PV industry

1. Executive summary

The EVERPV project, funded by the European Union under the Horizon Europe programme, addresses the urgent need for sustainable end-of-life management of solar photovoltaic (PV) modules in Europe. With projections indicating that up to 454 000 tons of PV waste could enter the European waste stream by 2030, the sector faces mounting pressure to recover and reuse critical materials, reduce environmental impact and support resource security.

EVERPV delivers a major innovation in solar PV recycling by unlocking the recovery of plastics, specifically EVA encapsulant and backsheet materials, that are usually not recycled. In addition, EVERPV demonstrates a pioneering recycling process based on the sanding of end-of-life solar PV panels, delivering high-purity glass that can be re-used.

This white paper presents an overview of advanced recycling technologies developed within EVERPV, focusing on the reusability of recovered materials (glass, silver, encapsulant and backsheet) from end-of-life solar PV panels. Two innovative processes developed in EVERPV are highlighted: the sanding process from CEA and a thermo-mechanical process from ENEA and 9-TECH.

The paper details the technical and economic challenges associated with recovering and purifying each material. EVERPV's processes achieve high purity for glass and silver, enabling their reintegration into manufacturing and supporting circular economy goals. Notably, the sanding process enables high-purity output for glass, suitable for direct reuse in float glass manufacturing. For polymers, EVERPV has developed a new method for PET recycling and has shown that recycled encapsulant (R-EVA) can be reused in new PV modules. While promising, further validation and cost optimisation are needed for large-scale adoption.

EVERPV's innovations align with major European policy initiatives, including the EU Green Deal and the Critical Raw Materials Act, reinforcing the importance of sustainable resource management in the clean energy transition. The recycling of end-of-life PV modules is essential to secure critical materials and support Europe's circular economy. Silver, glass, aluminium and copper offer the greatest market value, but recovery remains complex and profitability is currently low. Policy support and partnerships will be key to scaling operations and ensuring safe handling of hazardous substances. Developing recycling activities will strengthen Europe's supply chain and aligns with the Critical Raw Materials Act. With PV waste volumes set to rise sharply, the next three years will be decisive. EVERPV technologies provide efficient solutions to complement existing tools, and early investment and innovation are vital to prepare for large-scale recycling by 2050.

In conclusion, EVERPV demonstrates that advanced recycling technologies can deliver high-quality recovered materials, support circularity, and contribute to Europe's climate and resource objectives. Continued research, policy support, and industrial validation will be essential to fully realise the potential of these innovations for the PV industry.

2. Introduction

The rapid expansion of solar photovoltaic (PV) deployment across Europe has brought with it significant opportunities for clean energy generation. However, it also presents considerable end-of-life management challenges. As solar PV installations reach the end of their operational lifespans, the sector faces increasing pressure to address the environmental and economic impacts of waste, resource scarcity and the responsible stewardship of critical materials. By 2030, the EVERPV project estimates that between 207 000 and 454 000 tons of end-of-life solar PV modules could reach the waste stream.[3] In this context, circularity has become strategically important, emphasising the need to design, recover and reuse solar PV materials in a sustainable manner.

The R-ladder framework, as outlined in the ETIP PV Strategic Research and Innovation Agenda (SRIA), provides a hierarchy of strategies for resource efficiency, ranging from reuse and refurbishment to recycling and recovery. This approach underpins the transition towards a more circular solar PV industry, where material loops are closed and value is retained for as long as possible.

The EVERPV project, funded by the EU, is at the forefront of this transition, advancing innovative recycling technologies and processes that enhance the reusability of recovered materials from end-of-life PV modules. By focusing on high-purity material streams and efficient separation techniques, EVERPV contributes directly to the circular economy ambitions of the sector.

EVERPV stands out as the first project to successfully address the recycling of plastics within solar PV modules, specifically targeting both EVA encapsulant and backsheets, components that have long been overlooked due to their complex composition and low economic value. The project's focus is particularly significant, as fluorinated backsheets are both environmentally problematic and not recycled. In addition, EVERPV demonstrates a pioneering recycling process based on the sanding of end-of-life solar PV panels, delivering high-purity glass that can be re-used.

This work aligns closely with major European policy initiatives, including the EU Green Deal and the Critical Raw Materials Act, both of which prioritise resource security, reduced environmental impact, and the sustainable management of materials vital to Europe's clean energy future. By driving progress in circularity within the PV sector, EVERPV supports these strategic objectives and reinforces the importance of sustainable innovation in achieving Europe's climate and resource goals.

The paper first decribes the two innovative recycling technologies developed in EVERPV, the sanding process from CEA and a thermo-mechanical process from ENEA and 9-TECH. Then, the paper details the technical and economic challenges associated with recovering and purifying each material recovered from end-of-life solar PV panels, that is to say, glass, silver, encapsulant and backsheet. Finally, the paper outlines future prespectives for solar PV recycling.

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[3] By 2030, EVERPV projects 207 kt in the Low Scenario, 454 kt in the High Scenario, and 326 kt in the Mid Scenario. EVERPV, *Market assessment of PV and quantification of PV waste and waste streams in EU*, April 2025. 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

3. What's inside a solar PV panel

From the perspective of the recycling industry, a PV panel is an assembly of solid materials designed specifically for electricity generation. Figure 1 provides an overview of the components that make a solar PV panel. PV panels are large, flat devices that convert solar photons into a continuous flow of electrons, a process based on the photoelectric effect occurring in semiconductor material. Pure crystalline silicon is typically used as the active material in solar PV panels.

Even if silicon is the core material, a lot of other components are used to connect, encapsulate and protect the fragile and thin wafers of silicon. Silicon solar cells are generating electricity collected by a various set of metallic compounds, such as silver, copper, lead, tin. The global mass of metals used in PV panels is rather low, but some of these metals are of great interest. Some are toxic, some are precious. Toxic and heavy metals have to be isolated to avoid pollution of the environment. Precious metals have to be recovered as they may represent a great economic value on the market.

Insulating materials are implemented in solar PV panels to confine the electrical current and prevent leakage or electrical shock. Solar cells are laminated between two insulating sheets of materials, generally transparent glass for the front side and polymer multilayer structure for the back side (referred as the backsheet). The backsheet and the glass sheet show several functions: moisture and oxygen ingress, electrical insulation, transparency for sunlight, at least for the front side.

To obtain a stable and durable assembly, the three layers of glass, silicon cells and backsheet are laminated in a single layered device with encapsulation polymers. This PV component is supposed to be highly durable and resistant to outdoor environment all over the world for 25 years or more. The PV modules from the last decades mainly incorporate Ethylene-Vinyl-Acetate (EVA) as the encapsulant, which is cross-linked during the lamination process, under high temperature and pressure.

The stiffness and mechanical stability of the module are obtained with a peripheric aluminium frame. The module is finally completed with a junction box from which wires are drawn to connect the module to a power electronic device.

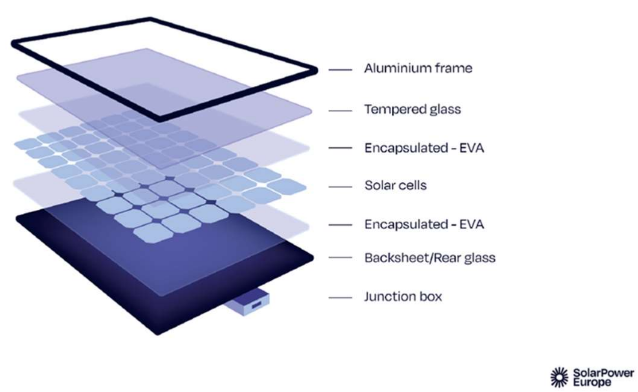

Figure 1: Solar module components for assembly (Source: SolarPower Europe)

The recycling of solar PV modules is increasingly vital as resource scarcity intensifies and the volume of end-of-life solar PV panels grows.

4. EVERPV recycling processes overview

Deframing is the first step of the solar PV recycling process. It involves removing the aluminium frame, the junction box and cables from the solar PV panel. Deframing is typically performed using a machine to separate the frame from the laminated module without damaging the underlying materials. The extracted aluminium is highly recyclable and can be directly reintroduced into manufacturing streams, contributing to resource efficiency. Deframing allows to facilitate access to the internal components of the solar PV module, enabling subsequent recycling steps.

The EVERPV project is improving two recycling technologies for end-of-life solar PV panels, the sanding process from CEA and a thermo-mechanical process from 9-TECH with ENEA's IR technology. Both are described in this section and compared to state of the art technology, highlighting the added value of EVERPV.

4.1. Sanding process

The sanding process, developed by CEA and installed at ENVIE 2E's facility in France, is a novel mechanical method for recycling solar PV panels. CEA and EVERPV are the first to develop and sanding process for solar PV recylcing. It enables the recovery of clean glass and other materials in powder form.[4] The sanding process focuses on the delamination of glass/backsheet solar PV panels with intact glass.

This method involves sanding the solar PV panel from the rear side using abrasive belts, performed in two successive steps. The first step separates the backsheet, which mainly consist of plastics, including potentially fluorinated polymers. The second step targets the cells, metallisation and encapsulant. Upon completion, the process results in a clean glass sheet and two distinct powders, all of which are separated and ready for further treatment. Figure 2 provides an overview of the process and Figure 3 shows the machine developed during the EVERPV project.

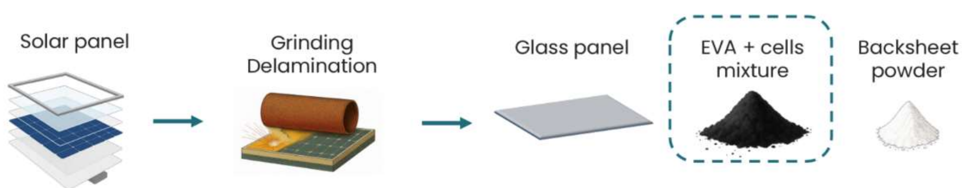

Figure 2: Overview of the sanding process developed by CEA in the EVERPV project (source: CEA[5])

Among the principal advantages of the sanding process is its high throughput, already capable of processing one panel in two minutes and having shown the potential to achieve rates of up to one

[4] Coustier, Fabrice, et al. "Mechanical Glass-Backsheet Photovoltaic Modules Delamination: Toward Materials Recycling." *Advanced Energy and Sustainability Research*, Nov. 2025, p. e202500276, https://doi.org/10.1002/aesr.202500276

[5] Romain Duwald, Youcef Karar, Fabrice Coustier, Roland Riva, Xavier Mackré-Delannoy, *Efficient method for separation and valorization of materials from End of Life PV panel*, Poster, EUPVSEC 2025. https://everpv.eu/wp-content/uploads/2025/10/Poster-EUPVSEC-2025-CEA.pdf

panel per minute. This technique facilitates the recovery of polymers and enables effective separation of the backsheet, which is particularly valuable for isolating fluorinated polymers and their titanium dioxide fillers. Another notable benefit is the high purity of the output glass, which is sufficiently clean to be sent directly to float glass recycling without requiring further treatment. The process also offers significant hybridisation potential, as backsheet removal can serve as a beneficial pre-treatment for pyrolysis or combustion processes and glass rectification following hotknife operations can be efficiently accomplished using this method.

The sanding process is also very versatile and adaptable. In case of panels showing a more complex multilayer structure, the sanding process can be adpated to extract specific layered materials with additional sanding steps. The technique can be adapted to thin film panels for example.

However, there are a few limitations to the sanding process. While materials recovered in powder form are easy to process chemically, they are less cost-effective compared to mechanical sorting, which remains the mainstream approach in the industry. Although the powder generated is not nanometric and thus poses limited risk, concerns persist regarding its ease of adoption. A new network of industrial players is needed for the treatment of these powders. Some industrials have been identified for the further use of some specific materials obtained with sanding (silver seems to be of interest in a general way, polymer powders show an interesting calorific value).

Nonetheless, the sanding process is a fonctional innovative and novel delamination method for solar PV recycling. It stands out for its high throughput and robust, industry-ready design. Its ability to produce exceptionally clean glass makes it suitable for high-end applications, while the recovery of polymers adds further value. These characteristics position the sanding technique as a compelling option for solar PV recycling, offering unique advantages in terms of efficiency, product quality and integration potential with other recycling methods.[6]

Figure 3: EVERPV pilot line installed at ENVIE 2E in France, using the sanding process

[6] Mechanical Glass-Backsheet Photovoltaic Modules Delamination: Toward Materials Recycling, Coustier, Mackré-Delannoy, Riva, Aimé, Duwald, Karar, 21 November 2025 https://doi.org/10.1002/aesr.202500276

4.2. Thermo-mechanical IR process

The second solar PV recycling technology improved by EVERPV is a thermo-mechanical technique combining ENEA's "Tear-off and Infrared (IR) technology" and 9-TECH's process (see Figure 6). The former approach utilises infrared lamps to soften the encapsulant holding the backsheet at the rear of the panel. Simultaneously, the delamination equipment tears off the backsheet, which is cleanly extracted as an intact, high-purity polymeric foil (see Figure 4). This leaves the remaining panel, consisting of EVA, ribbons, cells, and glass, ready for further treatment.

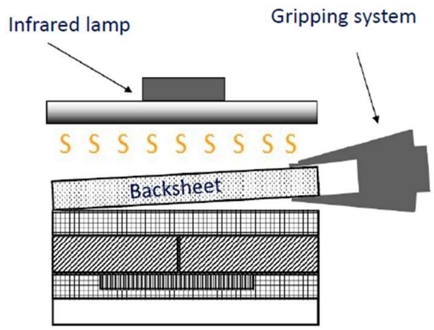

Figure 4: Illustration of ENEA's process with Tear-off and Infrared (IR) technology

Once the backsheet had been removed, the solar PV panels are cut into strips 33 centimetres wide and put through the 9-TECH "9PV" recycling system (see Figure 5). The process involves two steps: heating and sorting. First, the solar PV panels are heated in a specialised furnace that uses a heat exchanger and filters to clean the air. The solar PV panels are exposed to a heating process with temperatures higher than 450°C, which burn away the plastic layers and other non-metal parts. Next, the materials left are mechanically separated in stages. Copper is removed first and then two rounds of sieving sort out the remaining elements. In the end, four main types of material are recovered: glass, the solar cells, copper strips and a fine powder made up of tiny pieces of glass and cell fragments.

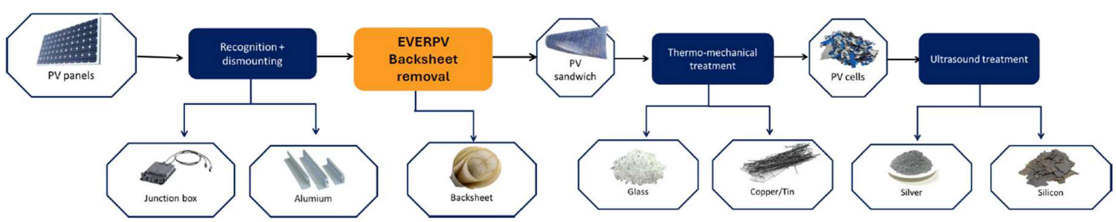

Figure 6: Overview of thecombination of ENEA's "Tear-off and Infrared (IR) technology" and 9-TECH's thermo-mechanical recycling process (source: 9-TECH)

The process showcases several advantages. The material separation is carried out using mechanical means, so there is no need for chemical reagents or burning, eliminating the use of additional chemicals or fuels. As a result, the process does not generate any waste by-products. One of the main advantages of the process is that the recovered plastic material is kept as a single, pure sheet. Because the material stays solid, it does not create dust, which makes working conditions safer and helps protect the environment. This also simplifies both the handling of the material within the facility and its transport to further destinations. Furthermore, removing the backsheet at the start means that the rest of the solar PV panel, which consists of several layers bonded together, can be sent on for further recycling using other methods if required. Handling this backsheet separately improves the environmental sustainability of the subsequent recycling stages, since it avoids having to process certain plastics that can release harmful substances if burned.

However, there are currently some drawbacks. The process is not yet fully operational and project partners will continue to improve it. Automating the cutting and gripping of the backsheet before it is pulled away presents technical challenges and can slow down the process. This method only works for solar PV panels that have unbroken glass at the front.

Overall, compared to other technologies, this approach stands out because it enables the recovery of the backsheet in a single clean piece, which reduces dust and makes the process both safer and easier to manage. Furthermore, the use of controlled infrared heating means that the emission of smoke or fumes can be avoided, so the method has lower environmental impact than others.

4.3. Process hybridisation

The sanding process and the ifrared-assisted tear-off technique can be intergated with other recycling methods to enhance the overall efficiency of solar PV module recycling. Both approaches offer controlled and selective operations, enabling the separation of materials at the earliest stage of the recycling process, with a high level of purity. This early segregation reduces complexity in subsequent steps, making post-treatment more effective and lowering potential costs at industrial scale.

Hybridisation of these technologies with other processes is both feasible and advantageous. When a critical or specific material is identified within a PV module, it can be isolated during sanding or tear-off. For example:

- If fluorinated polymers are present in the backsheet, the tear-off process will separate the backsheet before delamination. Then the fluor is treated separately in a specific process dedicated to toxic components and the PV recycler can focus on material of interest as glass or silver.
- If encapsulant residues remain on the glass sheet after the delamination process, a post-tratment based on sanding can remove the residues. This step provides a final cleaning of the intact glass sheet.

The technologies developped in EVERPV can then be implemented in different ways, either as targeted operations within a complete recycling line or as core processes complemented by additional steps for material isolation and purification.

5. Recovered materials: purification and re-use

After providing details on the delamination technologies developed in EVERPV, this section looks at the materials that can be recovered from end-of-life solar PV panels, that is to say glass, silver and polymers from the encapsulant and backsheet. For each materials, technical and economic challenges are highlighted, as well as EVERPV's methods for recovery, purification and re-use pathways.

The material breakdown of solar PV panels can be assessed by weight and value of the materials (see Figure 7). Glass represents 70% of the weight of a solar PV panel, aluminium 15%, plastics 9%, silicon 5%, copper 1% and silver 0.07%. In terms of value, silver represents 47% of the value of a solar PV panels (market and technology-dependant), while glass represent 7% of the value.

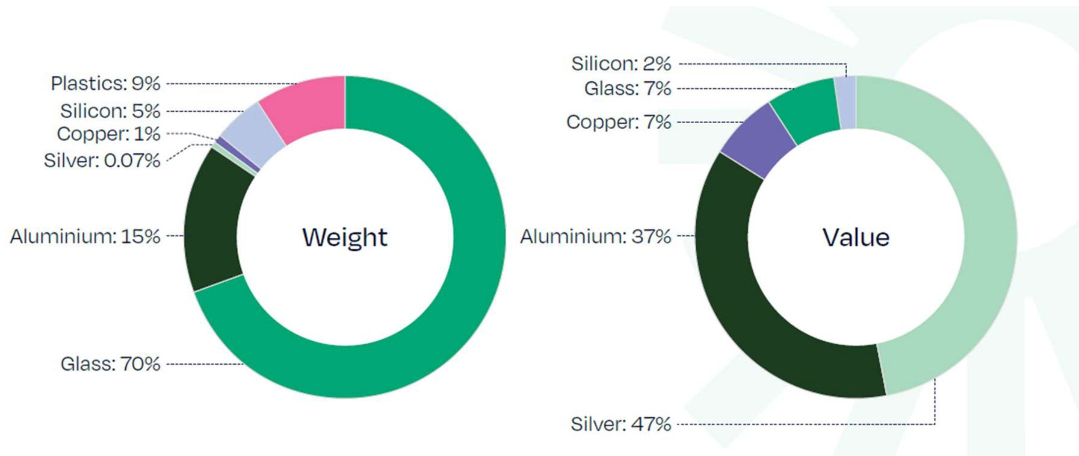

Figure 7: Weight and value of materials from solar PV modules (sources: Solar Materials and SolarPower Europe - 2024)[7]

5.1. Glass

With the current state of the art crushing technique, recovered glass tends to be contaminated with metallic impurities and polymers. Hence, such glass is usually downcycled. Metal impurities are a major challenges as glass makers have extremely stringent criteria for float glass. Metal impurities as low as 0.1% may compromise a batch, while polymers may be tolerated in higher quantities. Achieving high levels of glass purity with recycling process is therefore crucial.

Furthermore, detecting and quantifying impurities is a challenge. In addition, the presence of antimony in the glass, used as dopant, makes glassmakers reluctant to accept glass cullet (shredded glass) from solar PV panels, as it represents an added risks for them. One concern for PV is the specificity of the extraclear glass used in PV modules. A too high concentration of antinomy in the glass is unacceptable for glass manufacturers. Information on the amount of antinomy in solar PV glass and on the acceptable threshold for glass manufacturers would be a first step to solve this challenge.

Beyond technical issues, glass recycling is also economically challenging. While recovered glass cullet allow to save materials and heat compared to raw materials (sand), the process presently remains cheaper with raw materials, leading to low cullet price and acceptance.

Both EVERPV technologies, thermo-mechanical and sanding processes yield very clean glass in the form of shard and panes respectively. The sanding process allows to recover 100% of the

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[7] SolarPower Europe (2024): *Sustainable Solar. Environmental, social, and governance actions along the value chain.*

glass from the end-of-life solar PV panel as clean, usable panes/cullet, which is unique among solar recycling technologies and a clear advantage of the process. Regarding the grinding process, no contamination by metals was detected, except for a very low silicon fraction (>0.01%) and a slightly higher polymer contamination, both are not an issue for glass recycling.

Figure 8: Glass pallet after the sanding process (source: CEA[8])

The EVERPV sanding technology will be able to provide more than 100 tons of cullet for float glass in the frame of the project, demonstrating the re-use of recycled glass in high-end float glass fabrication. Sheddred glass can also be re-used in down-cycling approaches as aggregates for building construction, embankments or backfills. As the solar PV glass can show specific additives that may not be suitable for float glass furnaces (as antimony), mixing or specific treatment would be needed.

5.2. Silver

Silver is found within the solar cells as fine conductive lines, it carries the electrical current generated by the photovoltaic effect. Because silver is valuable and used in many industries, finding ways to recover it from old solar panels is a key goal for recycling projects like EVERPV.

In the EVERPV project, a special process was developed by ENEA to separate silver (and copper) from the other parts of the solar cells, once the panels reach the end of their life. This process was first tested in the lab using small samples, and then tried out on larger batches that had gone through more industrial recycling steps. The fact that the process works on both small and larger samples shows that it could be used in industrial recycling plants. The silver recovery processes were patented during the project.

The flexibility of the EVERPV approach is key. It can handle different types of material mixes, sometimes just the cells, sometimes just the electrical contacts, or a combination of both. This is

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[8] Coustier, Fabrice, et al. "Mechanical Glass-Backsheet Photovoltaic Modules Delamination: Toward Materials Recycling." *Advanced Energy and Sustainability Research*, Nov. 2025, p. e202500276, https://doi.org/10.1002/aesr.202500276

helpful for recycling companies, as the mix of materials they receive can vary. The process also helps recyclers complying with rules regarding safely handling old electronics, especially when older panels might contain hazardous substances.

The results from EVERPV show that the recovered silver is very pure (over 98%) which means it can be used again in new products. Copper is also recovered at a high level of purity. This high-quality recovery is important as it means the materials can go back into manufacturing, supporting a more circular economy.

Recovering silver from end-of-life solar PV panels not only makes recycling more worthwhile financially, but it also helps reduce waste and supports the supply of critical materials needed for clean energy technologies. The recovered silver can be used again in the manufacturing of new solar PV panels or in other industries. Silver recovery is an important value brought by the project. Silver remains the most used material for silicon PV cells showing a high value of power conversion efficiency. Silver price presents a high variability on the market and the consumption of this precious metal by the PV industry add a stress on its availability.

5.3. Backsheet

The backsheet is a multilayered plastic sheet that protects the back of solar PV panels, providing insulation and shielding the module from environmental damage. It is typically made from several different polymers, such as PET and fluoropolymers, and is glued tightly to the rest of the panel with encapsulant. Backsheets can also include other materials like aluminium foil or various plastics, and their structure often consists of three layers, such as PVDF/PET/PVDF or PVF/PET/PVF. This structure has varied over production period and EoL panels globally present important variability.

Recycling backsheets is challenging for several reasons. First, separating the the backsheet is a difficult operation as it is firmly attached to the panel to garanty its durability. Once removed, the different polymer layers of the backsheet will need proper separation before further treatments. As many backsheets contain fluorinated polymers that can release harmful substances in the environment, the recycler has to handled the issued materials properly. The wide variety of backsheet types and compositions makes sorting and recycling even more complex, and the low value of plastics discourages recyclers from investing in these processes.

In the actual situation, backsheets are not recycled but are instead burned to recover energy, either during the panel’s destruction or as a separate step after mechanical separation. This approach does not recover materials for reuse and can create environmental risks due to the presence of fluoropolymers and toxic fumes when burning the materials. Though some research exist, recovery of these fluorinated polymers is hard, and no industrial process currently achieves it. As such, it is crucial to recycle and revalorise backsheets.

For the first time, EVERPV has developed a method to enable backsheet recycling. For PET recovery, the project has created a straightforward process that can make high-purity recycled PET powder. However, further research is still needed to assess if the cost of recovered PET is reasonable compared to the value of the recovered material.

With the thermo-mechanical process removing the backsheet as a whole sheet, the sheet might be reused as it is. With the sanding process, chemical recycling is used to extract PET from the powder, sometimes with a pre-treatment to remove EVA. The leftover fluoropolymers can also be recovered and recycled, helping to avoid toxic emissions. EVERPV's sanding method produces a backsheet powder, which is easier and faster to purify than traditional methods. EVERPV's process for making pure PET powder is simpler and can be used to make new materials, and the project is also testing the use of recovered fluoropolymers as protective coatings for lightweight solar modules.

EVERPV has studied the composition of these powders and purified materials at different stages, as well as how new coatings made from recovered fluoropolymers hold up over time. Recovered PET can be used to make new PET products, such as packaging or textiles, while recovered fluoropolymers can be used as coatings to improve the durability of solar modules or other surfaces. Despite these advances, challenges remain, such as the cost of recycling, the diversity of backsheet materials, and whether the recovered plastics will be accepted by mainstream recyclers.

5.4. Encapsulant

The encapsulant plays a key role in solar PV modules, surrounding and bonding the solar cells between the glass front and the backsheet. Its primary function is to "cushion" the cells. In combination with the front and back sheets, it prevents the ingress of moisture and other degrading agents, thereby ensuring the long-term durability and performance of the module. The role of the encapsulant is particularly critical in the lateral diffusion of water vapor and chemical species. Typically, the encapsulant is made from crosslinked polymers such as ethylene-vinyl acetate (EVA). While this material provides excellent protection and stability during the operational life of the module, its crosslinked structure presents significant challenges at end-of-life, as it is not recyclable by conventional means.

Although the encapsulant (in this case, EVA) has relatively low economic value, it constitutes a significant fraction of the PV module by weight, accounting for nearly 10% (see Figure 1). It is therefore essential to separate the encapsulant from other components to ensure high purity and, consequently, greater value of the recovered materials. EVERPV's ability to recycle the encapsulant represents a first in the field and is particularly important in a context where resources are becoming increasingly scarce.

Recovering the encapsulant from end-of-life solar PV modules is particularly challenging. The crosslinked polymer is not only inherently non-recyclable, but it also remains tightly bonded to the metallic contacts and silicon cells after dismantling. This strong adhesion requires chemical assistance to separate the encapsulant from the valuable metals and semiconductor materials. Furthermore, the encapsulant itself has a low commercial value, which necessitates the development of low-cost recovery processes to make recycling economically viable.

To date, there are no established industrial processes for recycling encapsulant materials from PV modules. Most reported methods are limited to laboratory scale, where separation of metals and encapsulant is achieved by swelling the polymer with organic solvents. Another approach involves pyrolysing the EVA, which allows for the separation of encapsulant from metals and cells but does not enable the recovered material to be reused. As a result, EVA from end-of-life solar PV modules is rarely, if ever, valorised as a material for new applications.

The EVERPV project addresses these challenges by developing a novel mechanochemical delamination process. With the sanding technology, a powder mixture is produced containing both encapsulant and solar cell fragments, from which the encapsulant can be isolated under mild chemical conditions. The process has been demonstrated at the kilogram scale, showing that it is feasible and can be scaled up for industrial application. This represents a significant advancement over the state of the art, offering a potentially cost-effective and scalable solution for encapsulant recovery.

Regarding reuse, intial tests show that recycled encapsulant (R-EVA) can be reused in new PV modules, with 10% R-EVA blends performing well in terms of physicochemical properties, though optical performance was slightly lower than standard encapasulants. Picture of a reference module and a module containing 10% of R-EVA are shown in Figure 9. Early durability tests indicate promising results, but further validation is needed before large-scale adoption of R-EVA in new solar PV modules.

a) b)

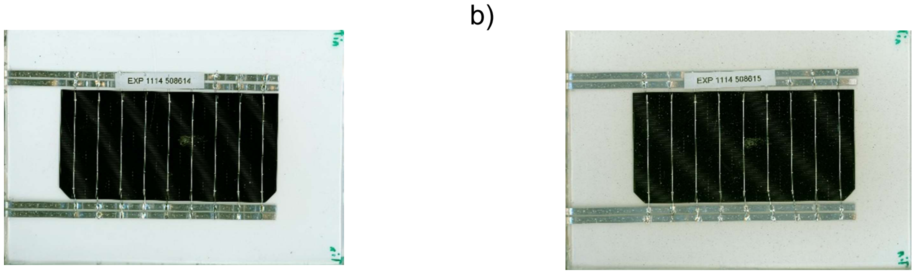

Figure 9: Picture of a) a reference module b) a module containing 10% of recycled EVA

Beyond PV applications, recovered encapsulant has also been tried as an additive in composite materials and adhesives. While the capabilitity of processing the recovered polymers with usual shaping processes remains with regard to composites made with virgin EVA, mechanical properties declined. This highlights the need for improved compatibility with other polymers in the global view of the re-use of recycled cross-linked EVA[9]. In addition to mechanical and chemical reuse, EVERPV has developed a chemical recycling route capable of depolymerising EVA under mild conditions. This process produces smaller molecules and useful compounds. Work will continue to optimise this process and better understand the resulting materials.

Despite these advances, several technical challenges remain. Maintaining the same level of purity at larger scales is essential for industrial adoption. It is also necessary to validate that recycled EVA can be reused in new encapsulant formulations without compromising performance or reliability. Achieving good compatibility between recovered EVA and polymer matrices is crucial

[9] Beatriz Pereza, Maialen Chaparteguia, Olatz Olloa, Sonia Garcíaa, Raquel Rodriguez, *Recycling strategies to valorize EVA recovered from PV panels*, Poster, EUPVSEC 2025. https://everpv.eu/wp-content/uploads/2025/09/EUPVSEC2025_POSTER_Raquel-Rodriguez_TECNALIA.pdf

for reinforcing effects in composites. Continued assessment of the hydrothermal depolymerisation process will be required to ensure efficient recycling and high-quality end products.

6. Outlook for solar PV recycling

6.1. Business models and market opportunities

Materials with established market value include silver, glass, aluminium and copper, as these can be sold through existing industrial networks. However, the ease of recovery and the ability to secure buyers varies significantly between materials.

First, **aluminium** from the frame is easily recovered. Several deframing systems are commercially available and aluminium profiles can be sold to established recyclers or scrap dealers. Coatings, brackets and screws made from mixed materials may require additional treatment, and market price will depend on purity.

Recycled aluminium offers strong environmental benefits, as producing aluminium from mining activities is highly energy intensive. Using recycled aluminium can save up to 95% of energy compared to primary production. However, depollution steps, such as removing coatings or mixed metals, often require thermal treatment and can increase costs. Despite these challenges, market trends for recycled aluminium remain positive, supported by its widespread use in sectors such as automotive and aerospace. Furthermore, geopolitics consideration shows a strong impact on aluminium market and material fluxes over the world, making aluminium recovery beneficial.

Glass is also relatively easy to separate and can enter existing recycling streams. The chosen delamination technique strongly influences its end-use. Sanding provides a unique advantage by delivering high-purity glass suitable for float glass applications, which represents the highest-value market segment.

Glass recycling networks are well established in many countries, but solar PV glass presents specific challenges. Glass has been used in packaging for several decades and proven industrials players have organised collection, transportation and transformation. The main challenge of PV glass is that it has been optimised for its use as a highly transparent material with antimony, which can disrupt conventional recycling processes. A dedicated control step will likely be required to ensure compatibility with industrial standards.

Silver is by far the most valuable material in solar PV modules, accounting for nearly half of the total material value. However, silver concentration is very low and melted on the cells and ribbons with other metals. All these materials can be extracted with the processes developed within EVERPV. Current modules entering the recycling process contain significant silver content, making extraction economically relevant. Market grades range from 99.9% purity for investment-grade silver to lower grades used in jewellery and industrial applications. Some other standard composition exists as, Britannia silver (95,8%), solid silver (or sterling silver which is used in high-value jewellery with 92,5%). The lowest grade silver reaches 80% purity. Below 80%, the metal alloy is not denominated silver anymore. In a general way, copper is used as the complementary element in Britannia, Sterling or other degraded silver, bringing mechanical stiffness. Recycling metals from PV is interesting from this point of view as copper is present as a built-in component in the PV modules.

Silver grade	Price on the market (11/2025)
Silver 999 (99,9% purity)	1610 €/kg
Silver 925 (92,5%)	1490 €/kg
Silver 900 (90%)	1450 €/kg
Silver 800 (80%)	~1200-1300 €/kg (higher market dependence)

Table 1: Overview of silver grade and price on the market as of November 2025

Table 1 shows the status of silver prices, showing that the prices are not highly correlated with the chemical content of silver. Hence, it appears that the purification level does not have a great impact on the market price. Probably the industry of precious metals has a long tradition of purification and equipment cost is already amortised. We can conclude that for a new-comer recycler, purifying silver may be too expensive and brings relatively low added incomes. If the silver content is too low, then the price will strongly depend on the market. A good target would be to obtain 90% refined silver to guaranty incomes attached to silver official market price. 80% is a minimum target value.

The price of silver on the market was rather stable since 2020, in the range 800-1000 €/kg. It increased exponentially in 2025 up to 3000 €/kg to finally drop. Looking to silver market history, we can state that the silver price is strongly depending on monetary policy of highly developed countries.

The question of open or close-loop for silver is critical, as it is a speculative material. Silver is one of the most critical material identified for the PV manufacturing with a great consumption of the solar PV industry. The actual tendency is providing PV modules with less and less silver, that reduce progressively the available reservoir.

Oher metals such as **copper**, tin and lead (in older modules) can also be recovered from end-of-life solar PV panels. Copper is embedded in the plastic layers and soldered to other metallic parts. However, once separated, the copper recycling industry is well established and is hence it is easy to recover, purify and re-use in open-loop markets.

Other materials such as **plastics** (with the notable exception of PET) or **silicon** are not very valuable but may have to be treated to avoid contamination of the environment depending on legislation (lead and fluoropolymers mainly). Silicon recovery at high purity could offer future opportunities, although most current processes achieve only metallurgical grade.

In conclusion, industrial recyclers must take into account external competition across both upstream and downstream markets. When identifying potential buyers for recycled materials, it is essential to assess alternative sources of similar materials that may offer higher yields and profitability. For example, PET from packaging can be easier and more cost-effective to recover than PET from PV backsheets. Likewise, sourcing waste streams such as automotive components may provide greater market stability and volume compared to PV modules. Regulatory frameworks will also play a decisive role, as they can either support or hinder the viability of recycling business models.

6.2. Role of recyclers, manufacturers and policymakers

The recycling of end-of-life PV modules and other waste operates within a regulatory framework that aims to promote circularity, reduces landfill and prevents harmful emissions. Policymakers play a critical role in shaping this framework, ensuring that recycling activities contribute to sustainable resource use and environmental protection. Legal requirements and financial incentives are key levers to accelerate the development of the sector and foster collaboration across industries such as energy, materials and transport.

Solar PV panels contain a certain amount of toxic and/or not so environmentally friendly compounds, such as fluorides in the backsheet (PVF/PVFD) and titanium dioxide (TiO2), lead (Pb) on the copper ribbons and welds, and finally antimony (Sb) in the glass sheets. As of today, no strict regulation exists on encouraging or imposing the recovery of these elements, neither incentive for the potential recyclers. This lack of regulatory pressure limits the uptake of advanced recycling solutions, although some actors are already investing in innovative approaches.

Recyclers occupy a central position for material and products transformation in the global process of PV lifecycle. Transforming a PV panel in its original materials is complex: some of the materials are incorporated in very small quantities, at micro or even nano-scale inside the PV module. But these elements show a fundamental role in the operation of the PV panel (as silver metal for the electrical connections, or boron doping of the silicon cell to generate the fundamental photoelectric effect). Determining the appropriate depth of recycling and the level of purity required to achieve market value is therefore essential. EVERPV has addressed this question for silver, providing data to guide investment decisions. For other materials such as EVA or PET, information on reuse pathways remains limited, making long-term strategies more challenging.

Current practice often considers energy recovery as the default option for polymers, thus downcycling. EVERPV promotes a more ambitious vision, exploring chemical and mechanical routes for true material reuse, including PET extraction and depolymerisation. Even with very low value of polymers, despite the fact that plastics are basically manufactured from oil. The project has investigated several possibilities with this question of depth of recycling or number of processes to re-obtain raw materials (extracting PET in PV backsheet, depolymerize PET to form the original component PTA). While these processes are not yet economically viable, they represent important steps towards closing the loop and reducing reliance on raw materials.

The economic reality of PV recycling is complex. The total material value in an end-of-life module rarely exceeds €10, and operations are typically split between different companies for frame removal, delamination and metal recovery. This fragmentation, combined with modest market value, makes the solar PV recycling business model extremely difficult with low profitability. Building partnerships across the value chain is therefore critical to share risks and optimise resources. Examples include collaborations for module collection, hazardous waste treatment and advanced purification.

Recyclers encounter a high level of constraints. Several risks arise from the handling of harmful materials which comes with constraints and regulation in the area of transportation, personal safety and other non-technical aspects. In this area, the local authority can propose some valuable help. The CAPEX for one company that would integrate many of these operations (removal of the frame of the PV modules to pure silver 999 recovery for example) makes the return on investment risky without proper legislation and organisation guarantying volumes over numerous years through long-term contracts. Policymakers at local and European levels have a decisive role in structuring the sector, ensuring stable volumes and creating conditions for sustainable growth.

The development of recycling activities for EOL solar PV modules will secure a reliable flow of domestically sourced secondary raw materials, reducing dependence on imported resources and strengthening Europe's supply chain resilience. However, to ensure these recovered materials find consistent buyers, it is essential to establish a comprehensive solar PV manufacturing value chain within Europe. At present, the secondary market for such materials remains limited, making the creation of a robust domestic manufacturing ecosystem a strategic priority. This approach not only supports the circular economy but also aligns with the objectives of the Critical Raw Materials Act (CRM Act), which aims to enhance the EU's resource security and competitiveness in strategic sectors. The CRM Act also emphasises the importance of domestic sourcing and the integration of recycled materials into strategic sectors.

6.3. Perspective after the project

EVERPV anticipates a sharp increase in end-of-life PV modules over the coming years, requiring a rapid expansion of industrial capacity. The next three years will be decisive for the sector. Profitability is expected to remain modest due to high investment needs and the relatively low market value of recovered materials. In addition, recycling equipment may not yet be fully mature, necessitating frequent upgrades to improve efficiency and yield. The technologies developed within EVERPV offer promising solutions to complement existing tools and enhance performance.

As volumes of PV waste grow and metal prices continue to rise, the strategic importance of this urban mine will increase. This may attract investors and encourage EU incentives to accelerate deployment. However, a key risk for the next decade is the progressive reduction of silver content in PV modules. Silver remains a critical material for PV manufacturing, and maintaining a balance between mining, recycling and consumption will be essential. In the longer term, if silver use declines significantly, similar concerns may emerge for other metals such as copper.

By 2050, PV waste will reach very high volumes, making large-scale recycling unavoidable. Europe must prepare now, leveraging its leadership through the WEEE directive to turn this challenge into an opportunity for recycling operations and equipment manufacturing. Silver recovery can provide an initial source of value, but alternative pathways must be explored through continued research and development.

7. Conclusion

The EVERPV project has delivered significant innovations that contribute to the accelerate the recycling and circularity of end-of-life solar PV modules. By developing and demonstrating novel mechanical and thermo-mechanical processes, EVERPV enables the recovery of high-purity materials (glass, silver, encapsulant and backsheet). These technologies stand out for their efficiency, safety and ability to produce outputs suitable for direct reuse in manufacturing, notably float glass and high-grade metals.

Key added values of EVERPV include:

- High-purity material recovery: Both the sanding and thermo-mechanical processes achieve exceptional purity levels for glass and silver, overcoming longstanding barriers to their reintegration into new products and supporting the circular economy.
- Plastic recycling: for the first time, EVERPV has demonstrated that plastics, EVA and backsheet can be recycled. EVERPV introduces new methods for separating and purifying PET and fluoropolymers from backsheets, as well as scalable approaches for recovering and reusing encapsulant materials. These advances open new pathways for valorising plastics that were previously destined for energy recovery or disposal.
- Industrial scalability: The project's technologies are designed for robust, high-throughput operation, with minimal environmental impact. In addition, EVERPV demonstrates a pioneering recycling process based on the sanding of end-of-life solar PV panels, delivering high-purity glass that can be re-used.
- Alignment with EU policy: EVERPV's work directly supports the EU Green Deal and Critical Raw Materials Act, reinforcing Europe's leadership in resource security and sustainable innovation for clean energy.
- Market and employment impact: By enabling the recovery and reuse of valuable materials, EVERPV strengthens the economic case for PV recycling and contributes to job creation in the fast-growing decommissioning and recycling sector.

To accelerate the transition towards large-scale PV recycling, the next strategic step should be the financing of a fully integrated pilot line by the EU. This facility should cover the entire process chain, starting from deframing and continuing through advanced delamination and material recovery for silver, PET, PVDF, silicon and copper. Such a demonstration line would serve multiple purposes: validating the technical feasibility of combined processes, optimising operational efficiency, and generating reliable data to assess economic viability. It would also provide a platform for testing hybrid approaches, refining purity targets and evaluating environmental performance under real industrial conditions.

Beyond technical validation, this initiative would enable a comprehensive business case analysis, identifying cost drivers, market opportunities and scalability challenges. Coupled with supportive policy measures, such as incentives for recycled content, harmonised standards and long-term contracts, this approach would create the conditions for investment and industrial uptake. In parallel, research should continue on eco-design for recyclability, advanced polymer recovery and digital traceability systems to strengthen material flows and compliance.

Looking ahead, the rapid growth of end-of-life solar PV modules will require a significant scale-up of recycling capacity within the next three years. While profitability remains modest and equipment maturity is still evolving, EVERPV technologies offer practical solutions to improve efficiency and complement existing tools. Policy support and partnerships will be critical to secure domestic supply chains and meet the objectives of the EU Critical Raw Materials Act. With solar PV waste volumes expected to surge by 2050, early investment and innovation are essential to transform this challenge into an opportunity for Europe's circular economy.

In summary, EVERPV demonstrates that advanced recycling technologies can deliver both environmental and economic benefits. Continued research, industrial validation, and supportive policy frameworks will be essential to fully realise the potential of these solutions and accelerate the transition to a circular solar PV sector.

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