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RECYCLING OF PHOTOVOLTAIC PANELS: PROCESS DEVELOPMENT AND TECHNOLOGY TRANSFER DURING THE LAST TEN YEARS

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ABSTRACT

Research and development in photovoltaic panel (PVP) recycling have evolved to maximize recovery, including less valuable but non-renewable materials. Early recycling relied on low-cost physical processes but failed to produce glass pure enough for the glass industry, except for construction. A process involving crushing, sieving, thermal treatment, fine fraction leaching, and wastewater treatment required 75,000 tons/year capacity to achieve a payback time under 6 years. High-value recovery requires advanced methods to separate glass from the encapsulant, ensuring reintegration into glass production. A solvent-based process, tested at the pilot scale, proved technically and economically feasible. Without metal recovery, it remains viable at 30,000 tons/year, producing high-purity glass. Further developments enabled 82% recycling rates, including polymeric and metallic recovery, potential thermal valorization of EVA, and backsheets recycling. Economic analyses highlight challenges in a complete refining process, particularly for Ag and Si recovery. The Ag content in PVP has declined from 0.2% to 0.02% w/w in two decades. At 0.05-0.2% Ag, a 5-year payback is possible for 43,000-18,000 tons/year. Lower Ag levels require higher recycling volumes or supportive measures (e.g., EoL fees) to remain profitable.

1. INTRODUCTION

Photovoltaic systems have expanded significantly over the last decade as an alternative to fossil fuel-based energy production. Technological maturation and the reduction in production costs have positioned photovoltaic panels (PVP) among the best candidates for generating electricity from renewable sources (Jäger-Waldau, 2020).

Given the expansion, both realized and projected, of photovoltaic panel installations (IRENA, 2024; Oñate et al., 2024; Xu et al., 2024), the European Community has included End-of-Life PVP (EoL PVP) among Wastes of Electrical and Electronic Equipment (WEEE), for which proper separate collection and the development of suitable recycling processes are necessary (Directive 2012/19/EU).

PVPs are composed of glass, polymer sealant, backsheet, photovoltaic cells, and a network of metallic filaments and silver ink for electrical contacts (Isherwood et al., 2022).

Recycling processes for PVPs range from simple mechanical treatments to thermal and hydrometallurgical treatments (Padoan et al., 2019).

Conventional mechanical treatments are the most economic, but cannot ensure the production of market-ready products or materials that can be reintroduced into glass production cycles due to the extreme complexity of the photovoltaic composites. Grounded materials obtained by mechanichal operations can be used in building compartment for low value applications (Goh et al., 2024), otherwise require further refinement by innovative technologies such as optical sorting or electrostatic operations (Dias et al., 2018) to reach high quality products.

Innovative technologies have been applied with the aim of liberating components by size reduction such as high voltage pulse crushing (Zhao et al., 2022), microwaves (Pang et al., 2021), and wire explosion (lim et al., 2021), but none of them still reached large scales.

Thermal treatments aim mainly to degrade or soften the polymer sealant (Ethilen Vynil Acetate, EVA) and separate the various layers that make up the panel. Thermal treatments can be performed by conventional methods such as burning (Fiandra et al., 2019) and pyrolysis (Wang et al., 2019) or by innovative technologies such as halogen lamps (Riech et al., 2021) and hydrothermal treatment (Nekouei et al 2024). These treatments are energy-intensive and generate hazardous gases (Deng et al., 2022).

Chemical methods for encapsulant dissolution or swelling (solvent delamination) include the treatment of

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integer or crushed panels with organic solvents (Lee et al., 24; Dias et al., 2021; Li et al., 2022; Prasad et al., 2022), alkaline alcoholic solution (Cai et al., 2022), and more recently supercritical carbon dioxide (Lovato et al., 2021; Briand et al., 2022).

Hydrometallurgical processes for recovering metals like silver, copper, tin and lead are carried out after mechanical treatments (Sanathi et al., 2024). Silver is the mostly addressed metal generally extracted by nitric acid (Oliveira et al. 2020) followed by solvent extraction (Cho et al., 2019) or by innovative deep eutectic solvents (Lemoine et al., 2024). Other investigated metals are Cu, Sn and Pb extracted by mineral acids and then and separated by solvent extraction and precipitation (Chen et al., 2020; Moon et al 2017).

Metal-targeting hydrometallurgical processes often overlook the recovery of the bulk material, which is glass, thus failing to meet the requirements of EU WEEE regulations (Directive 2012/19/EU) on minimum recycling rate.

Silicon cells, which were historically the most valuable component of PVPs, have been the focus of various recycling methods, such as manual dismantling and chemical etching to remove coatings. These techniques were prominent but are now largely obsolete due to the collapse in silicon cell prices driven by Chinese overproduction (Lin et al., 2023). Similarly, recycling processes tailored to CdTe and CIGS panels have fallen out of favor as silicon technology dominates the market, primarily due to its reduced cost and superior efficiency, with no reversal of this trend expected (Di Sabatino et al., 2024). In the same view, the initial focus on high-value materials (metals) should give way to the primary goal of maximizing the recovery of non-renewable resources, including materials typically considered low-value, such as glass (Su et al., 2024).

The primary targets of process development at this time are, on the one hand, ensuring high recycling efficiencies and, on the other hand, recovering high-value products. For the first target, it is essential to focus on recovering glass, which is the most significant component by mass. For the second target, glass must again be considered because if it is too small in size (<0.5-1mm) and contains metal contaminants, its value can only be low. Glassworks require large-sized recycled glass to control its purity. Therefore, the process target must be coarse, clean glass (Vieitez et al., 2011). However, glass alone cannot ensure the economic sustainability of a recycling process, so it could be necessary to implement a waste refinery to recover other valuable components such as Ag, Si, as well as Al from the frame, Cu and Sn from the conductive filaments, and finally potentially recyclable polymeric components.

The economic sustainability of PV recycling faces several key challenges, especially due to the high costs involved in establishing and operating recycling facilities. These costs are notably high when more advanced chemical or thermal processes are required, as these techniques demand substantial investment and maintenance expenditures. IRENA and IEA-PVPS Report (2016) highlights the need for robust infrastructure to support recycling efforts, while Dias et al., 2016 point out that the technical complexity of recovering high-purity materials like silicon and silver from PVPs increases costs and limits profitability when operations are small-scale. Another major factor affecting economic feasibility is the fluctuating market value of recycled materials, which makes it difficult for facilities to achieve consistent revenue. Paiano (2015) and Sica et al. (2018) emphasize that when market prices for these materials are low, it often becomes challenging for recycling operations to remain economically viable. Recovered materials, including silicon, glass, and precious metals, do not always fetch prices that can compensate for the intricate separation and purification processes required.

Additionally, the relatively long lifecycle of PVPs limits the volume of end-of-life materials available annually, which can fall short of the mass required to sustain large-scale recycling plants profitably. Kumar and Chatterjee (2021) observe that this low turnover rate constrains recycling capacity, meaning that without significant volumes, even well-designed facilities may struggle to break even.

For recycling processes themselves, mechanical methods like shredding and magnetic separation offer lower-cost options and can operate at a positive margin with smaller volumes of PVPs. However, their efficiency in recovering high-value components such as pure glass is limited. Mechanical recycling methods are thus more feasible on a smaller scale, generally requiring several thousand tons per year to achieve economic viability (Dias et al., 2016). Integration of mechanical methods and advanced electrostatic separations efficiently separates valuable materials from glass and polymers, offering a simpler, lower-cost alternative to full recovery methods including thermal and chemical treatments. While complete recycling provides the greatest environmental benefits, the integration electrostatic separation in mechanical processes is more viable for smaller waste volumes or where glass recycling markets are limited. Economically and environmentally, it offers a feasible interim solution, with further research needed to optimize and scale the process (Dias et al., 2022).

In contrast, chemical treatments, which use reagents to recover materials at a higher purity level, can effectively retrieve valuable components like silver and high-grade silicon. However, the costs associated with reagents and waste management make chemical recycling economically viable only when facilities treat significant amounts of panels (Choi and Fthenakis, 2010; Kumar and Chatterjee, 2021).

Thermal methods, employing high temperatures to separate materials, are similarly effective at retrieving silicon but require significant energy, pushing operational costs higher (IRENA and IEA-PVPS, 2016; Marwede et al., 2013).

Industrial-scale photovoltaic panel recycling is developing globally, with still limited facilities leveraging advanced technologies to recover valuable materials like silicon, silver, and glass.

In Europe, PV Cycle operates a network of facilities that comply with the WEEE directive (www.pvcycle.org). These facilities combine mechanical and chemical processes to manage several thousand tonnes of panels annually, promoting material recovery while adhering to stringent regulations. Veolia's ReProSolar project in France represents a significant initiative, utilizing thermal and chemical delamination processes to recycle silicon-based panels (www.veolia.com). The plant has a capacity of 5,000 tonnes annually, aiming to recover high-purity materials such as silicon and silver without relying on mechanical shredding. ROSI Solar (www.rosi-solar.com) another French initiative, focuses on the chemical recovery of high-value materials like silicon and silver from EoL-PVP, with an estimated capacity of 3,000 tonnes annually.

Other EU initiatives at pilot scale include Flaxres in Germany (using high intensity light pulse heating the Si wafer for delamination)(https://www.flaxres.com), 9-Tech in Italy using thermo-mechanical treatment (https://www.9tech.it) and addressing silicon valorization (Cerchier et al., 2024), Geltz-Umwelt Technologie in Germany using advanced pyrolysis (https://cordis.europa.eu/article/id/238592-stateoftheart-solar-panel-recycling-plant).

Outside EU the most important initiative is First Solar in the United States and Malaysia for thin-film modules including chemical and thermal treatments that achieve a recycling rate of 90% (semiconductor materials and glass) with 25,000 ton/y potentiality (www.firstsolar.com).

The main obstacles to scaling up end-of-life panel treatment lie in intermediate pilot-scale technology transfer activities, which are essential for assessing the technical feasibility of processes and the quality of products, thus enabling reliable economic analyses to guide scaling decisions.

Below are the main steps of the research activities made in the last 10 years by the research group on Theory of the development of chemical process of the Department of Chemistry of Sapienza University in collaboration with the Sapienza Spin off company Eco Recycling. Research and technology transfer activities addressed the need for further scaling, including pilot demonstrations and economic feasibility assessments.

2. MATERIALS AND METHODS

2.1 Physical treatments

The input waste material were samples from different types of PV devices of different types Monocrystalline, Polycrystalline, and Amorphous Silicon-based panels. Samples were obtained by manually removing external aluminum frames (if present) and cutting a 40 × 40 cm section using a diamond blade and a hammer. Crushing operations were carried out in a two blade rotors crusher (DR120/360, Slovakia) without any controlling sieve and in a hammer crusher (SK 600, Slovakia) using a 5 mm sieve. Thermal treatment experiments were carried out on the coarse fraction (d > 1 mm) in a silite resistance furnace under an air flux of 30 l/h. The samples were placed in ceramic crucibles, heated at a rate of 10°C/min up to 650°C, and maintained at this temperature for 1 hour. After cooling, the samples were sieved, and particle size distribution was analysed (Pagnanelli et al., 2017).

2.2 Solvent treatment

EoL-PVPs were initially disassembled manually to extract aluminum frames. They were then crushed at a pilot scale using a single-shaft shredder (Guidetti Ltd) and classified into three size fractions through sieving: coarse fraction (>3 mm), intermediate fraction (0.5–3 mm), and fine fraction (<0.5 mm). Solvent treatment tests were conducted with a solid-to-liquid ratio of 1:8 at a temperature of 70°C. In the Photolife process, after treatment, the solvent was recovered through filtration and distillation, while solid fractions were separated via gravimetric separation by adding water. This process resulted in glass and metallic filaments settling in the underflow, whereas polymers (EVA and Tedlar) along with cell residues floated in the overflow (Pagnanelli et al., 2019).

The enhanced polymer separation process included sieving after solvent treatment, with a 7 mm cut-off to remove Tedlar from the oversized fraction. This was followed by gravimetric separation, where water was added to the remaining solids suspended in the solvent, creating a biphasic system (water-cyclohexane), leading to the separation of glass and metallic filaments in the underflow (Rubino et al., 2021).

3. RESULTS AND DISCUSSION

3.1 Physical treatments

First activities on photovoltaic recycling focused on simple physical processes. Starting with different types of panels, alternative mechanical treatments and thermal methods were tested with the primary aim of freeing glass and metals from the sealant (Granata et al., 2014; Pagnanelli et al., 2017).

In particular, different combination of mechanical treatment followed by thermal treatment of coarse fraction for EVA removal were compared. Single crushing followed by thermal treatment resulted in an overall glass recovery ranging from 50% to 70%, depending on the type of panel. Introducing hammer crushing after single crushing improved glass recovery to 80–85%, although the recovered products had a significant presence of fine fractions (40–45% by weight, depending on the type of panels). To address the formation of fines, a triple crushing operation was tested, which allowed for a reduction of waste to be thermally treated (only 62% compared to 85% after single crushing). Comparing triple crushing with single crushing plus hammer crushing, the obvious advantage is the use of a single piece of equipment instead of two different ones, thus reducing investment costs. Additionally, glass recovered through triple crushing contained lower amounts of fine fractions compared to the scheme including hammer crushing. As a result, after triple crushing a fraction of pure glass (0.4-1 mm) can be directly recovered by sieving, while coarse fractions can be fed to the furnace for sealant distruction and glass liberation giving coarse glass >1 mm. Thermal treatment resulted in a weight loss of 5-10% due to EVA decomposition. This phase releases various gases and suggests the need for a condensation unit in the recycling plant. The separation of glass from EVA is crucial for the glass's value; it must be free of polymeric materials to be used as cullet in soda-lime glass production. Thermogravimetric analysis confirmed that the recovered glass fractions are clean enough for reuse in manufacturing.

In Figure 1 the scheme of operations and the size distribution of crushed materials and thermally treated materias are reported according to triple crushing and thermal treatment combination.

The minimisation of fine fractions during mechanical operations is advantageous considering that, according to their metal content (Pagnanelli et al., 2017), a metallurgical/hydrometallurgical treatment is necessary to recover these fractions as pure glass. At the same time, it is possible to attempt the recovery of metals present in the panels, which are of different types: metallic contacts (busbars) recovered after thermal treatment of the coarse fraction, and as powder in the fine fraction subjected to leaching.

Metallic contacts containing aluminum (Al), copper (Cu), and silver (Ag) can be directly recovered after thermal treatment and sold as scrap. In the fine waste fractions (<0.08 mm and 0.08–0.4 mm), the most abundant metals are iron (Fe), zinc (Zn), and aluminum (Al), with concentrations below 5 mg/g. The low content and market value of these metals, and low potentiality of photovoltaic panel recycling plants make it less advantageous to include a specific metal recovery section in these plants.

The goal of leaching the 0.08–0.4 mm fractions is to clean the glass to enhance the overall mass recovery of the process. The leach liquor containing Fe, Zn, and Al can be treated in the wastewater section using primary treatments like precipitation and secondary treatments with ion exchange resins, following conventional routes for metal-bearing wastewaters.

For the finest fraction, which represents less than 5% of the total weight of treated panels, higher concentrations of metals are found, with silver (Ag) being of greatest interest due to its higher market value (0.5 €/g) and concentrations in the finest fractions ranging from 0.3 to 2 mg/g. This Ag-bearing fraction could be directly treated in the photovoltaic recycling plant or sold to refiners, improving the overall economic feasibility of the recycling process as further discussed in the following dedicated section.

A preliminary economic analysis, which includes crushing, sieving, thermal treatment of the coarse fraction, leaching of the fine fractions for glass cleaning (not metal recovery), and wastewater treatment, indicates that the process is economically feasible (with a payback time of less than 6 years) with a capacity of 75,000 tons per year. It should be noted that the estimate is conservative and does not account for the costs associated with managing waste panels (recycling fee, that is fee for collection and treatment paied to the smelters by consortia) (Pagnanelli et al., 2017).

3.2 Solvent treatment

The process development triggered by the preliminary data from physical treatment, which highlighted in the laboratory the possibility of using a method different from thermal treatment for the liberation of glass from the sealant (EVA) in the coarse fraction: the use of an organic solvent for swelling the sealant and thereby making it lose adhesion to the glass without dissolving the sealant (Figure 2).

The process, initially optimized in the laboratory, was patented (Toro et al., 2013) and subsequently validated on a pilot scale as part of the Photolife project's demonstration activities (Photolife project). During this project, 3 tons of panels of various types were processed using the same method (referred to as the Photolife process), demonstrating its effectiveness from an environmental and economic point of view (Pagnanelli et al., 2019) and flexibility for different panel types (dos Santos Martin Padoan et al., 2021). The use of the solvent meant that it was not necessary to reduce the initial sizes too much. Therefore, a single crusher, specifically designed to adequately reduce the size of

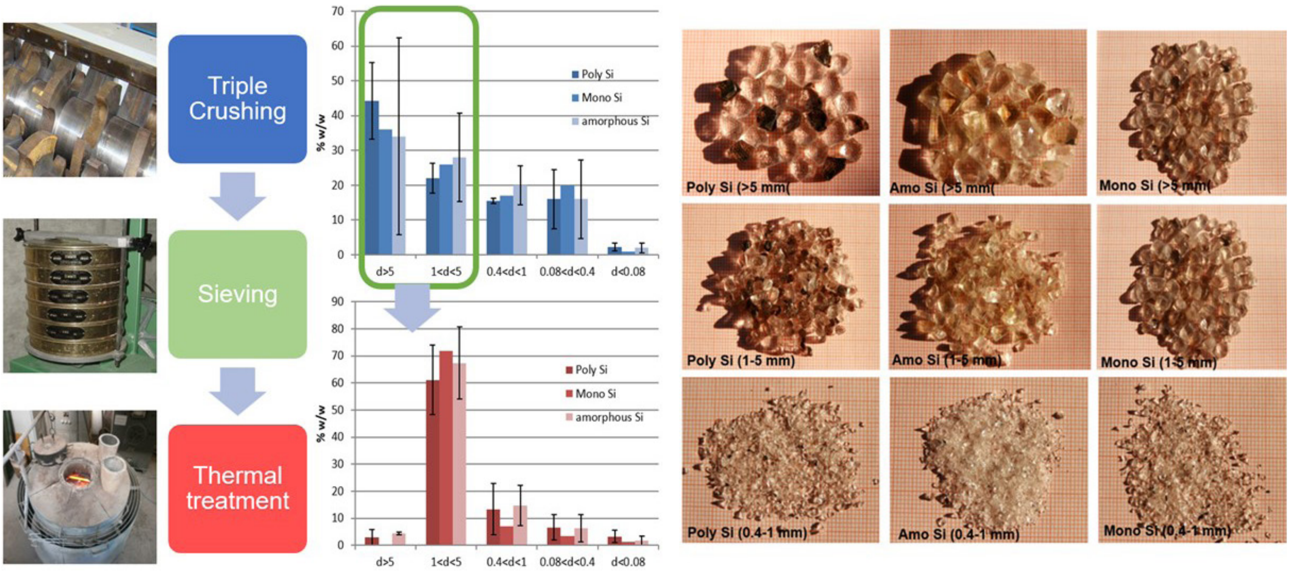

FIGURE 1: Schematic block diagram for optimised physical treatment of EoL PVP including triple crushing, sieving and thermal treatment in a furnace of fractions larger than 1 mm. Size distribution of crushed materials (blue bar graph) and of thermally treated materials (red bar graph). Photos of materials collected after thermal treatment for different kinds of photovoltaic panels (Poly Si: Polycrystalline Silicon; Amo Si: Amorphous Silicon; Mono Si: Monocrystalline Silicon).

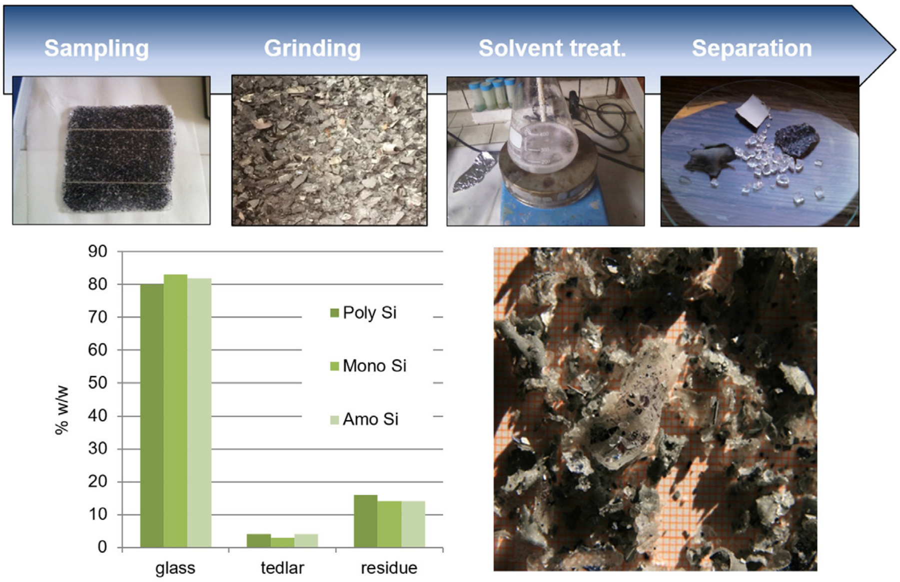

FIGURE 2: Schematic representation of the laboratory scale phase for solvent-base delamination process of EoL PVP fragments; green bar graph reports the weight distribution after solvent treatment of separated components for different types of panels (Poly Si: Polycrystalline Silicon; Amo Si: Amorphous Silicon; Mono Si: Monocrystalline Silicon).

the glass while minimizing the production of low-value fine fractions, was used for the mechanical part.

The integrated mechanical and chemical Photolife process combines automatic panel crushing, solvent treatment of the coarse fraction, and leaching of the fine fractions for glass cleaning from metal impurities. The main products of this process are high-quality glass (>1 mm) obtained from solvent treatment of the coarse fraction and low-quality glass from the fine fractions. The automatic crushing stage was optimized to minimize the production of fine fractions, which ensures the maximum yield of high-quality glass while reducing the amount of low-quality fine glass (<1 mm). The solvent treatment of the coarse fraction allowed for the complete separation of various components within just 1 hour at 50°C with continuous agitation (Pagnanelli et al., 2019). This efficiency in the kinetics of detachment is notably higher than that reported in the literature, where solvents are typically used for cell recovery and often require several days for complete detachment.

The glass recovered through solvent treatment exhibited superior quality standards compared to the glass obtained from thermal treatment. Specific tests designed to assess the quality of recycled glass from solvent treatment confirmed that these samples are suitable as raw materials for producing new PVP. In contrast, glass obtained from thermal treatment had a superficial metal residue, rendering it unsuitable for direct use in foundries.

A preliminary economic analysis of the solvent process, excluding metal recovery, indicated that solvent treatment is economically viable for a processing capacity of 30,000 tons per year. For lower capacities, the End-of-Life (EoL) fee is essential for making the photovoltaic panel treatment economically sustainable. When using the same inputs, solvent treatment presents a lower Payback Time (PBT) compared to thermal treatment. Additionally, a Life Cycle Assessment reveals that the solvent process has positive environmental impacts compared to thermal treatment, largely due to the higher value of the recycled glass (Pagnanelli et al., 2019).

An additional improvement to the process was achieved within the ORiFo project, co-funded by the Italian Ministry of the Environment and Sea Protection. In this project, a laboratory-scale optimization of the solvent treatment operation of the basic Photolife process (already demonstrated on a pilot scale) was proposed, focusing on polymer separation and metal recovery (Rubino et al., 2021), and then a patent application was made (Toro et al., 2020).

Analyzing the Photolife process sequence, the main issue was the lack of separation between polymers: after gravimetric separation, Tedlar (the backsheet) and EVA (the sigillant) residues remained glued together in the light fraction (due to the adhesive properties of EVA), with no possibility of separation through subsequent operations. In response to this need for polymer separation, four different operational sequences were tested. Specifically, the selectivity of the filtration operation (following the solvent treatment) on the degree of polymer separation was evaluated, demonstrating that Tedlar can be effectively separated from EVA residues. Furthermore, compared to the basic Photolife process, an additional thermal treatment of EVA residues (containing the photovoltaic cell and silver from the electrical connections) was introduced. The metal extraction yields highlighted the effectiveness of this strategy compared to direct extraction from uncombusted EVA residues.

By processing 100 kg of crushed material, it is possible to recover 0.03 kg of Ag, 45.5 kg of high-quality glass, 10 kg of Al scraps, and 1.2 kg of metallic filaments.

The Sankey diagram of the process is reported in Figure 3.

Thanks to the optimization, the recycling rate of the implemented process has increased to 82%, while the recov-

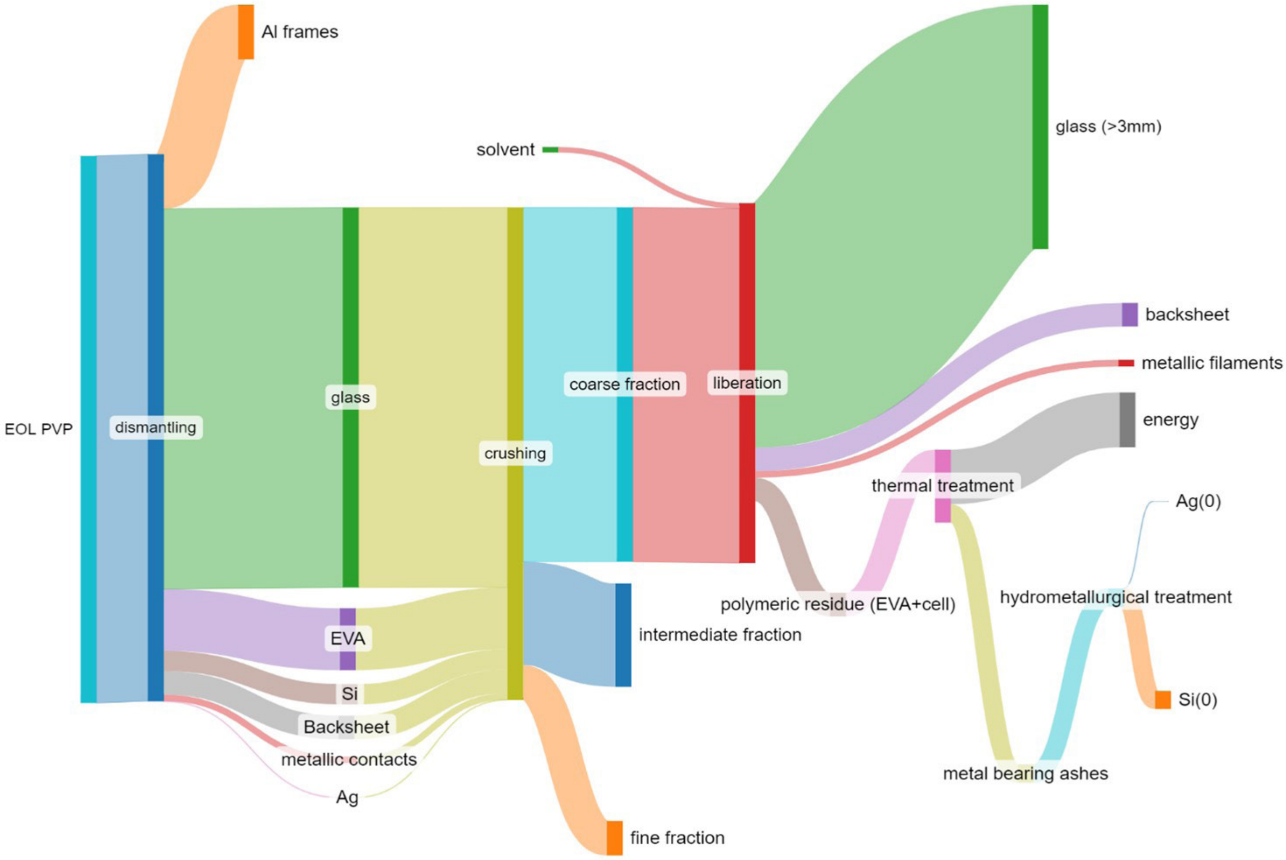

FIGURE 3: Sankey diagram of the process including frame dismantling, panel crushing, sieving, solvent lamination of coarse fraction, thermal treatment of the polymeric residue, and hydrometallurgical treatment for Ag and Si recovery.

ery was estimated at 94%. Remarkably, these figures exceed the EU Directive, which since August 2018 has raised the minimum rates for recovery and reuse and recycling rates to 85% and 80%, respectively.

In addition to improving recycling and recovery rates, the recoverable value of the implemented process has also increased. The total value of EoL-PVP was estimated by considering the composition of the input waste and the market price of the recycled fractions according to scrap prices (https://www.dailymetalprice.com) and metal quotations (https://www.dailymetalprice.com), specific quotations received for high-quality glass recycled by the Photolife process, and literature values. Market prices were fixed at: 0.7 €/kg for Al scraps; 2 €/kg for metallic filaments; 0.2 €/kg for high-quality glass; 0.001 €/kg for recycled Tedlar; 600 €/kg for Ag (https://www.capitalscrapmetal.com/prices/); and 0.5 €/kg for Si. Considering these inputs, it is possible to distribute the value among the different components of EoL-PVP (at this stage, no value was assigned to intermediate glass). According to this analysis, the intrinsic total value of 100 kg of EoL-PVP is 54 €, with Ag representing 53% of this value, high-quality glass 26%, Al scraps 13%, metallic filaments 4.5%, and Si 3.5%. The basic Photolife process, which did not include the metal recycling section, allowed for a recovery of 34% of this intrinsic value. The implemented process, allowing for the recovery of Ag and Si, increases the recoverable value to 73%. Further improvements up to 80% are also possible by optimizing the Ag recovery section.

Additionally, to further increase the recoverable value, the same optimization can be applied to the Si recovery section as residue after Ag leaching from residue ashes.

Economic analysis of the improvement proposed was specifically assessed (Rubino et al., 2020). Simulations indicate that the advanced PhotoLife process is economically feasible at a high recycling volume of 30,000 tons per year. This is largely due to economies of scale, which reduce the plant cost per unit with increased size. However, the hydrometallurgical section's size and cost are critical factors. For smaller volumes, it may be more cost-effective to exclude this section and sell the Ag-Si-EVA material to external processors. Operating costs analysis reveals that labor costs, particularly for manual dismantling of aluminum frames, are a significant constraint. Manual dismantling of frames is time-consuming and costly, and scaling up the process will significantly increase labor hours. Automating this step could improve economic feasibility and scalability. Energy balances show that the thermal treatment of EVA provides significant energy savings. At 30,000 tons per year, the exothermic degradation of EVA could produce about 12.5 MWh per batch, which can be used to heat other parts of the process, such as the leaching reactor and cyclohexane evaporator. This energy credit reduces overall energy consumption and helps meet recovery targets.

3.3 Economic feasibility of metal recovery by hydrometallurgical treatment

Feasibility of recycling process including hydrometallurgical section for metal recovery (Ag, Si) was further investigated (Granata et al., 2022) considering the decreasing concentration of precious metals in PVP due to technology improvements.

In fact, the economic sustainability of photovoltaic (PV) recycling hinges on balancing process costs with revenues from recovered materials, which depends on recycling volumes, recovery rates, and the commercial value of these materials. Silver (Ag), copper (Cu), silicon (Si), and tin (Sn) are the most valuable materials to target, with Ag being particularly significant due to its high value compared to Sn and Cu. Despite Ag's low concentration in PV waste, it often provides higher revenues than Cu and Sn. Thus, investing in Ag recovery is crucial for profitability, especially when Ag concentration is at least 0.1%. For lower concentrations, investments are less impactful at low recycling volumes but become significant at higher volumes.

Selling an Ag-Si rich fraction could be more profitable both short- and long-term, potentially reducing capital and operational expenses. For Ag concentrations around 0.2%, selling the Ag-Si fraction at about 50% of its actual value may be financially advantageous. At lower concentrations (0.05%), hydrometallurgical recovery may offer higher returns but with lower profit margins, unless the material is sold for a significant portion of its value.

The recycling fee also affects profitability. Lower Ag concentrations and PV throughputs may necessitate a recycling fee to make the process economically viable. For concentrations between 0.05% and 0.2%, suitable returns on investment (ROIs) (>20%) can be achieved without a PV fee if recycling volumes are substantial (43,000–18,000 tons/year). With decreasing Ag concentrations, the timing of investments becomes crucial; higher recycling volumes and fees are needed to maintain profitability. For instance, investing in 2025 with current Ag prices may result in positive net present values (NPVs) if recycling volumes are at least 30,000 tons/year.

All these estimates have been done with Ag price ranging from 600 to 750 $/kg (range observed during 2014-2022 period), then they are all conservative considering the current price of Ag which is over 1100 $/kg (https://stonexbullion.com/it/grafici/prezzo-argento/).

4. CONCLUSIONS

EoL-PVP are complex wastes with low intrinsic values, and both of these characteristics hinder the development of economically sustainable recycling processes with respect to other WEEE. While the primary focus in the past might have been on recovering metals (primarily silver), current recycling regulations now highlight an additional need to recover glass, which is the main component of these wastes. The low intrinsic value underscores the necessity for low treatment costs, which are generally associated with physical treatments. However, current technology does not provide products suitable for reintroduction into the glass manufacturing sector. Therefore, it is necessary to support the feasibility of recycling operations with fees for recyclers, who could then invest in dedicated lines for not only high-grade glass recovery but also for recovering valuable (Ag) and critical (Si) metal components. Economic analysis depends on various technical inputs but is also affected by the uncertainty related to the level of support that policy will provide to establish a virtuous cycle of secondary raw material recovery through the introduction of recycling fees, which need to be adjusted over time. In past activities different process options have been developed according to these trends. Solvent lamination seems to be a sustainable solution for effectively recovering high-value materials. In addition process optimisation can also allow for polymer separation improving recycling rates and recovered value significantly. The process is economically feasible at high volumes and could benefit from automation and further optimization to enhance economic viability. Overall, the process shows promise as a more efficient and higher-quality alternative to conventional physical treatments, aligning with both the recycling targets of Directive 2012/19/EU and promoting high-value recycling in accordance with CENELEC EN50625-2-4 guidelines.

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