EMERG, Volume X, Issue 4/2025 ISSN 2668-7003, ISSN-L 2457-5011

GLOBAL PATHWAYS FOR SOLAR PANEL RECYCLING: REGULATORY FRAMEWORKS AND INDUSTRY INNOVATIONS

METODE GLOBALE PENTRU RECICLAREA PANOURILOR SOLARE: CADRE DE REGLEMENTARE ȘI INOVAȚII INDUSTRIALE

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Abstract: *The rapid growth of solar photovoltaic (PV) technology is expected to generate a surge of end-of-life (EoL) panel waste – on the order of 60–78 million tons globally by 2050. Managing this waste is a critical environmental and economic challenge. This article serves as a literature review on recycling silicon-based solar panels, covering mechanical, chemical, and thermal methods, as well as policy frameworks. Policy-wise, the European Union's extended producer responsibility (EPR) requirements under the WEEE Directive have driven the highest recycling rates, while most other regions lack harmonized mandates. Technologically, a combination of mechanical preprocessing (e.g. shredding, delamination) and advanced recovery (thermal or chemical) achieves the best material recovery yields. Innovative processes – such as pyrolysis and novel molten salt etching – can recover over 95% of materials including high-value silver and silicon. However key gaps include insufficient global policy coordination, undeveloped recycling capacity in many regions, and uncertainties in the quality and reuse of recovered materials. Addressing these gaps and enabling the reuse of recycled materials in new panels will be decisive for a sustainable solar PV industry.*

Keywords: photovoltaic waste, solar panel recycling, circular economy

Rezumat: *Se preconizează că, creșterea rapidă a tehnologiei fotovoltaice solare (PV) va genera o creștere bruscă a deșeurilor de panouri solare la*

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sfârșitul duratei de viață - de ordinul a 60-78 de milioane de tone la nivel global până în 2050. Gestionarea acestor deșeuri este o provocare critică de mediu și economică. Acest articol servește drept o analiză a literaturii de specialitate privind reciclarea panourilor solare pe bază de siliciu, acoperind metode mecanice, chimice și termice, precum și cadre de politici. Din punct de vedere politic, cerințele Uniunii Europene privind responsabilitatea extinsă a producătorului în temeiul celei mai stricte Directive DEEE au determinat ratele de reciclare, în timp ce majoritatea celorlalte regiuni nu au mandate armonizate. Din punct de vedere tehnologic, o combinație de preprocesare mecanică (de exemplu, mărunțire, delaminare) și recuperare avansată (termică sau chimică) atinge cele mai bune randamente de recuperare a materialelor. Procesele inovatoare - cum ar fi piroliza și gravarea cu săruri topite noi - pot recupera peste 95% din materiale, inclusiv argintul și siliciul de mare valoare. Cu toate acestea, lacunele cheie includ o coordonare insuficientă a politicilor globale, o capacitate de reciclare nedezvoltată în multe regiuni și incertitudini privind calitatea și reutilizarea materialelor recuperate. Abordarea acestor lacune și permiterea reutilizării materialelor reciclate în panouri noi vor fi decisive pentru o industrie fotovoltaică solară sustenabilă.

Cuvinte cheie: deșeuri fotovoltaice, reciclarea panourilor solare; economie circulară

1. Introduction

A looming waste challenge: The accelerating deployment of solar PV systems will eventually be matched by a wave of retired panels reaching EoL. **By 2030**, cumulative PV waste is projected to reach around 8 million tons, and by **mid-century** this could grow to **60–78 million tons** [1]. To put this in perspective, the value of recoverable materials from PV waste is estimated at **$15 billion** by 2050, suggesting a major opportunity if effective recycling is achieved [2]. However, without intervention, most of these materials may end up in landfills, wasting valuable resources and posing environmental risks (e.g. leaching of lead or other toxicants).

Scope of review: We focus on crystalline silicon PV modules, which dominate global installations, and examine the following aspects:

- **Regulatory and policy frameworks** – with emphasis on Europe, North America, and Asia-Pacific policies shaping PV recycling;
- **Recycling technologies** – including mechanical separation methods, thermal and chemical processes, and hybrid approaches;

Topics such as direct panel reuse, second-hand markets, or broader techno-economic analyses beyond the recycling stage are excluded from our scope, to concentrate on EoL material recovery techniques. The review also identifies future directions, especially the reuse of recycled materials (e.g. reintroducing recovered silicon, glass, or metals into new PV manufacturing), which lies beyond current recycling practices.

2. Regulatory and policy frameworks

Global directives: At international level, policies specific to PV module waste are promising. The **Basel Convention** [3] governs transboundary movement of hazardous and non-hazardous waste, but PV panels are not explicitly classified, leading to inconsistent handling across countries. In practice, whether a discarded solar panel is treated as hazardous e-waste depends on local interpretations (for instance, due to lead solder or cadmium in certain panels). This lack of a unified classification complicates global trade in used or waste panels, as differing rules hinder the efficient shipment of end-of-life panels to specialized recycling facilities. A clear global guideline under Basel or a similar framework may be needed to streamline PV waste shipments, but as of 2025 no such harmonized standard exists. The most influential international directive has been the European WEEE regulation, which other regions are studying as a model.

European Union – extended producer responsibility: The EU integrated PV panels into its **Waste Electrical and Electronic Equipment (WEEE) Directive** [4] in 2012, making PV module producers financially and legally responsible for collection and recycling of EoL panels. Under this EPR scheme, all EU member states have transposed requirements that producers (or importers) must ensure PV waste is properly managed, typically by funding take-back and recycling programs. The directive set ambitious targets – originally, **85% collection and 80% recycling rate** by weight for PV panels – pushing industry-led programs such as PV Cycle [5]. Several EU countries now have dedicated PV recycling facilities. For example, France saw the first large-scale PV recycling plant opened by Veolia in 2018, with capacity to process up to **4000 tons of panels per year [6]**. Early results show high recovery rates (90–95% of materials by mass) are achievable under these programs. Nevertheless, challenges remain: Many member states **struggle to meet WEEE collection targets** for PV waste. Since solar deployments only surged in the last decade, relatively few panels are decommissioned yet – making the current official collection rates (a percentage of recently sold panels) appear very low. Moreover, differences in national implementation exist: some countries classify PV modules as “industrial” waste versus “household” WEEE, affecting how collection is organized. There are calls for greater harmonization in definitions and reporting (e.g. a specific waste code for PV panels) to improve traceability and ensure panels can be shipped to where recycling capacity exists. Overall, the EU’s regulatory approach – mandatory EPR with binding targets – has jump-started a PV recycling industry, but consistent enforcement and fine-tuning (e.g. adjusting targets to realistic end-of-life projections) are needed going forward.

North America – patchwork of state initiatives: In contrast to Europe, North America (especially the US) lacks a federal PV recycling mandate. **United States:** At the federal level, solar panels are generally regulated under existing waste laws (e.g. the Resource Conservation and Recovery Act) depending on whether they test as hazardous waste, but there is *no nationwide requirement* to recycle PV modules. This regulatory gap has led to a state-by-state approach. Pioneering states like Washington passed a solar EPR law in 2017 (effective 2020) requiring PV manufacturers selling in-state to finance EoL recycling programs [7]. California classifies spent solar panels as *universal waste*, easing handling requirements to encourage recycling, and has implemented landfill restrictions (panels must be processed by approved handlers) – effectively pushing panels out of hazardous waste landfills into recycling streams. New Jersey and North Carolina have also introduced rules or task forces for PV module disposal. Despite these efforts, coverage remains incomplete, and enforcement is variable. As a result, only an estimated **<10% of** U.S. PV modules are recycled today, with most EoL panels still landfilled due to lower cost (around \$1–\$5 per panel vs. \$15–\$45 to recycle in the US) [8]. Canada similarly has no national PV recycling law, though provinces like Alberta have included PV modules in electronics recycling programs. The consensus is that federal leadership is lacking – stakeholders have called for national guidelines or incentives to scale up recycling infrastructure. Encouragingly, the U.S. Department of Energy has initiated studies and grants to develop PV recycling technologies, and the 2022 Inflation Reduction Act even provides tax credits for critical material recycling facilities (including PV recycling).

Asia-Pacific initiatives: Several countries in the Asia-Pacific region are recognizing the PV waste issue and formulating responses: **Japan:** Japan is moving toward a stringent PV recycling policy. While as of 2024 there isn’t a PV-specific law, the government has proposed to categorize used solar panels as *industrial waste* requiring proper recycling, analogous to the EU’s approach

[9]. A working group under METI has recommended an EPR-based system where domestic manufacturers (or importers of foreign panels) must bear recycling costs. Japan plans to implement a mandatory recycling scheme by 2025, where certified recyclers will take back panels and a fund is collected from manufacturers (calculated per kilogram of panels produced/imported) to subsidize the recycling when those panels are retired [10]. This effectively acts as a *deposit-refund* or prepaid recycling fee system, ensuring funds are available to handle future waste. The scheme also addresses "orphan" panels (e.g. from bankrupt companies) by having a third-party organization manage the pooled recycling funds. Japan's proactive approach appears likely to yield one of the first comprehensive PV recycling programs in Asia. **China:** China, the world's largest PV producer and installer, is only recently turning attention to end-of-life. By 2025, China plans to establish a nationwide PV recycling mechanism [11]. This includes setting standards for recycling processes and possibly requiring manufacturers to set up take-back programs. Pilot projects in provinces like Jiangsu and companies forming "PV recycling industry alliances" are underway. Notably, at least one Chinese facility has been reported with an annual processing capacity of 110000 modules (~2750 tons), aiming to create a "closed-loop" where recovered glass, silicon and metals re-enter the PV supply chain. Regulatory moves (potential EPR or recycling targets) are expected as China faces a sharp rise in PV waste in the 2030s. **Australia:** Australia has experienced significant solar adoption and is now grappling with waste policy. Some states have announced landfill bans on PV panels, forcing recycling or reuse of pathways. Nationally, PV panels were added to Australia's product stewardship priority list, signaling that a regulated scheme (possibly industry-led voluntary recycling) is being developed. As of 2025, collection programs exist but a uniform law is pending. **Others: India** is in earlier stages – currently PV panels fall under general e-waste rules, but enforcement is minimal; pilot recycling plants are in development. **South Korea** has built a couple of medium-scale recycling plants (capacities in the few thousand tons/year range) and is researching PV recycling technology, but dedicated laws are not yet established. **Taiwan** and **Singapore** have included PV panels in broader electronic waste regulations, requiring proper treatment of scrap panels.

Economic instruments: Alongside regulations, economic incentives are vital to make recycling preferable to disposal. Europe's EPR effectively internalizes recycling costs into the product price, but additional tools are discussed: landfill fees or bans (to increase the cost of dumping panels), subsidies or tax credits for recyclers (to improve profitability of recycling operations), and deposit–refund systems. This may encourage panel owners to return modules rather than abandon them. Another idea is a deposit on PV modules at sale, refundable upon return for recycling – although not yet implemented, it could directly incentivize end-users. Some U.S. states have considered classifying panels as hazardous waste if not recycled, effectively imposing high disposal costs that nudge companies toward recycling. Moreover, *market creation* for recycled materials can act as an indirect economic driver: e.g. if manufacturers agree to buy back refined silicon or glass collet from recyclers, it guarantees revenue for recycling businesses. Currently, however, the economics remain challenging – recycling a panel can cost $20–30, while the material value recovered is only $3–10, absent any policy support. Therefore, a combination of penalties for landfilling and financial support for recycling is likely needed, at least until scale and technology improvements bring costs down.

Policy gaps and challenges: Across the board, a prominent gap is the lack of harmonization. Where the EU has a unified framework, other countries have patchy or voluntary regimes; this fragmented landscape makes it difficult to develop global recycling supply chains or economies of scale. Even within the EU, inconsistencies in classifying and reporting PV waste have emerged, pointing to a need for clear definitions (e.g. what counts as "recycled" content, how to account for reused panels, etc.). Enforcement is another concern – rules on paper do not always translate to action. For instance, illegal dumping of used panels or export to countries with weaker standards can occur if oversight is weak. Ensuring that manufacturers comply (especially if they cease business decades later) and that sufficient recycling capacity will exist when large volumes hit end-of-life require long-term planning. Lastly, current policies often do not address quality standards for recycled materials; there is an implicit assumption that recovered glass, aluminum, or silicon will find markets, but without standards or incentives for using recycled PV materials in new products, demand may lag. In summary, while the EU's WEEE/EPR approach leads the way, a more globally coordinated effort – akin to how global solar deployment was pushed by common targets – appears necessary. Emerging policies in Asia and state-level experiments in the US are steps in the right direction, but significant gaps remain in creating a *level playing field* for PV recycling worldwide.

3. Mechanical recycling techniques

Mechanical recycling methods [12-14] form the backbone of most current PV recycling operations, as they are often the first step in processing solar panels. These techniques rely on physical processes—cutting, crushing, shredding, and sorting—to break down a PV module into its component materials (glass, metals, plastics, etc.) with minimal chemical alteration. Below we discuss the main mechanical methods and their characteristics.

- **Shredding and crushing:** EoL solar panels are typically first dismantled to remove the aluminum frame and junction box. This is often done manually or with simple cutting tools, as frames are bolted or clamped in various ways depending on manufacturer. After deframing, what remains is a laminated sandwich of glass/ethylene vinyl acetate (EVA) encapsulant/silicon cells/backsheet. Mechanical recyclers commonly feed these modules into shredders or crushers, which break the panel into smaller fragments. The rationale is that shredding liberates materials: glass is released from the encapsulant, and metals (like copper ribbons or solder pieces) detach from the cells. In practice, however, this approach has limitations. The EVA encapsulant holding the layers together is extremely tough and tends to keep glass shards and silicon pieces bound in chunks. It is difficult to completely tease the glass away from the solar cells, so recyclers often resort to shredding everything together and obtaining a mixed output. The result is contaminated glass cullet — glass pieces still coated with bits of plastic and silicon — which are low value (usually suitable only for low-grade applications like construction aggregate). One industry observer notes that because delicate separation is hard, many recyclers simply shred the entire panel and end up selling the glass “contaminated with other materials” for minimal revenue. Another issue is dust generation: crushing panels releases fine particulate (silica dust, polymer dust) that can be hazardous if inhaled and can contaminate nearby soil/water if not contained. Modern shredding systems therefore include dust extraction and filtration units.

Despite these issues, shredding remains popular due to its throughput and simplicity. Commercial e-waste recycling lines adapted for PV can process hundreds of kilograms per hour through automated conveyors and rotating shear blades. This scale is expected to rise as waste volumes grow. But purely mechanical processing rarely recovers the high-value fraction (silver, silicon) effectively. It primarily yields bulk materials: ~70–75% glass and ~10% aluminum (from frames), plus copper from cables, all of which are relatively low-value per mass. The valuable silver (typically <0.1% of a panel’s mass) ends up dispersed in shredded silicon cell pieces. Thus, mechanical shredding alone tends to have poor economic return unless fees or subsidies are in place. In summary, shredding is an essential preparatory step but not sufficient for high-value recovery.

- A critical challenge in PV recycling is **delamination** [15]– separating the layers of the module, especially freeing the glass and silicon cells from the encapsulant. If this can be done effectively, one can recover clean glass and intact silicon pieces *before* they are ground to dust. Several methods have been explored:
  - **Mechanical delamination:** This includes methods like **ultrasonic wave** treatment and **knife peeling**. Ultrasonic delamination uses high-frequency vibrations to break the bond between the EVA encapsulant and glass/cells. Laboratory trials have shown ultrasonication can detach solar cell slices from glass in a liquid medium, albeit slowly and usually on small samples. Manual or mechanical **scraping/heated knives** can also remove backsheet and cut away the EVA encapsulant, but this is labor-intensive and not feasible at scale. Robotic arms with precision knives or wires heated to slice through the encapsulant have been proposed to automate this task. A technique called hot knife or hot wire cutting moves a heated blade across the module to separate layers – effective on some thin-film modules and being tested on silicon panels. However, these methods are currently too slow for high throughput and can struggle if the panel is damaged or warped.
  - **Thermal delamination:** Heating the panel to soften or decompose the encapsulant. Approaches include fluidized bed reactors, where crushed panel pieces are suspended in hot sand or air at ~450–600 °C to burn off plastics, and **conventional pyrolysis furnaces** (oxygen-free ovens) that break down the EVA encapsulant into char and gases. Another variant is **electro-thermal heating**, applying electric current to heat the panel (often via resistive heating of the semiconductor). Thermal methods can effectively separate glass and metal from cells because the encapsulant either combusts or vaporizes. For instance, in a fluidized bed at ~500 °C, EVA is completely burned off, leaving behind loose glass and silicon fragments. A key advantage of thermal delamination is the purity of outputs: after pyrolysis, glass cullet and copper ribbons are liberated

without polymer contamination, and these can be mechanically separated from the remaining cell fragments. The downside is energy consumption and emissions – heating to high temperatures is energy-intensive, and burning EVA releases organic pollutants (unless controlled with afterburners and scrubbers). Some systems recover thermal energy by combusting gaseous decomposition products to fuel the process. Industrial pilot plants have demonstrated thermal delamination that yields clean glass and metals, simplifying subsequent recycling.

In practice, thermal methods have gained more traction for silicon panels due to their reliability. For instance, a European project (FRELP) [16] combined initial mechanical shredding with a subsequent thermal treatment to break laminates. An advantage of thermal delamination is that it deals with encapsulant and backsheet in one step, whereas a purely mechanical approach leaves one with sticky, shredded material that still contains bits of plastic. The choice of method also influences downstream purity: a panel that is delaminated yields cleaner glass (suitable for high-quality glass reuse) versus direct shredding, which, as noted, yields contaminated glass that often must be downcycled. On the other hand, thermal processes must ensure that valuable metals (e.g. silver) are not lost (e.g. silver can oxidize or volatilize if not careful with atmosphere control). Successful delamination is key to improving recovery rates of high-value materials. If done well, the glass from panels can achieve ~95% recovery with minimal impurities (meeting standards to be remelted into new glass). Similarly, intact silicon cell fragments could potentially be refined and reused in new solar cells, but only if separated without heavy contamination. Mechanical-only processes currently tend to smash the silicon into mixed glass fines, making silicon recovery infeasible. Delamination by contrast can produce larger silicon pieces or whole cells. Some recyclers are experimenting with robotic disassembly to carefully remove cells and bypass shredding altogether – though this is not yet common. In summary, the strength of mechanical processes lies in handling large volumes cheaply (especially for glass and metal recovery), but their weakness is the lower recovery of critical materials (silver, high-purity silicon) and the contamination of outputs. This has motivated the integration of mechanical pretreatment with more sophisticated thermal or chemical steps to boost overall recovery.

- **Separation and sorting technologies:** After initial breakage and delamination steps, recycling facilities employ various **separation techniques** [17] to sort the mixture of materials obtained. Key technologies include:

- **Screening and sieving:** Given that crushed panel output is a mix of particle sizes, vibrating screens can separate bulk glass pieces (typically 2–5 mm particles) from finer fractions. The fine fraction often contains concentrated cell pieces (silicon and attached metals) since cells tend to shatter into small bits. Sieving thus helps isolate the “fines” that are then sent to chemical processing (for metal extraction), while larger glass pieces can be cleaned and recycled as cullet.
- **Air classification:** Differences in density and aerodynamic properties allow separation via air flow. Light materials like plastic films, backsheet fragments, and very small dust can be blown out or sucked away from heavier glass and metal chunks. Some recycling lines use an air classifier or simple suction to remove the light fluff of encapsulant/backsheet after shredding. This reduces contamination in the glass stream.
- **Magnetic and eddy-current separation:** magnetic separators pull out ferrous metals (screws, steel mounting clips) from the mix. While PV modules have mostly non-ferrous materials, there may be small steel pieces from junction boxes or mounting hardware. Eddy-current separators, which induce currents in metals to eject them, are used to capture non-ferrous metals like aluminum and copper. For instance, shredded PV material passing under an eddy-current separator will throw out aluminum frame pieces and copper wires into a separate bin, away from the glass. This is a common step to recover the ~8% metal content of a panel (mostly aluminum by weight).
- **Density separation (gravity tables):** Shaking tables or dense media separators can exploit slight density differences – e.g. silicon (density ~2.3 g/cm^3) vs glass (~2.5 g/ cm^3) vs plastic (~1 g/ cm^3). In practice, because glass and silicon densities are similar, this is not a very effective separation for those. But density methods might separate pieces of solar cells (which include metals and silicon, making them heavier) from pure glass fragments. Research has shown some promise using liquids or slurries of intermediate density to float glass while sinking cell fragments, achieving partial separation of the high-silver fraction.

After these processes, the output streams are typically: **clean glass** (which can be sent to glass recyclers), **metal concentrate** (a mix of copper wiring, solder, and silver-bearing cell bits, usually destined for smelting or leaching), **aluminum** (frames go to metal recycling), and **residual plastic** (often sent to energy recovery or landfill as it has little value). Recovery rates for glass and aluminum in mechanical processes can exceed 80–90%, whereas recovery of silicon and precious metals by mechanical means alone is very low. This is why mechanical recycling is usually coupled with the chemical processes described next, if the goal is to maximize material circularity.

Mechanical recycling techniques are **straightforward, scalable, and relatively low-cost**. Thus, even simple recycling can yield net energy and emissions savings by displacing raw material production. On the other hand, the weaknesses are: mechanical methods struggle to *fully separate composite materials*; encapsulants and other polymers cause fouling and contamination; valuable metals like silver are not recovered in usable form as they end up diluted in the outputs (e.g. tiny silver bits adhering to glass cullet). Moreover, fine silica/silicon dust lost during processing can amount to a few percent of the material that is not recovered, contributing to waste. Finally, from an economic view, the revenues from selling basic recovered materials (glass, scrap metal) often do not cover the operational costs of mechanical processing without a recycling fee. These limitations have driven the development of **chemical and thermal processes** that can target high-value fractions and improve purity, as discussed in the next section.

4. Chemical and thermal processes

To achieve higher recovery of valuable materials (and to deal with the tightly bonded composites in PV modules), researchers and industry specialists have developed a range of chemical and thermal recycling processes [12-13]. These methods go beyond physical separation, employing heat or reactive chemicals to extract metals, remove encapsulants, or purify the recovered components. They can be used standalone or in combination with mechanical preprocessing. Below we review major categories:

- **Acid and base leaching** [18]**:** One common approach to recover metals (like silver, tin, lead, copper) from shredded solar cell pieces is chemical leaching. In this process, crushed PV cell fragments (often after removing glass) are treated with acidic or basic solutions that dissolve the target metals into a solution, from which they can be recovered. For example, nitric acid (HNO_3) is frequently used to leach silver and base metals from silicon cells. Silver, which exists as fine lines of Ag paste on cell surfaces (~10 grams Ag per panel), readily dissolves into nitric acid, forming silver nitrate in solution. Studies report silver recovery efficiencies above 95–99% using nitric acid leaching. Copper (from ribbons) and lead (from solder) can also dissolve in nitric or other strong acids. Another approach uses hydrochloric acid (HCl) possibly with oxidizing agents to target solder metals (Sn, Pb). The acidic solutions after leaching are processed (e.g. via precipitation or electrolysis) to extract pure metals (like silver precipitated as AgCl or reduced to metallic silver powder). On the alkaline side, strong bases like sodium hydroxide (NaOH) can attack certain components – for instance, NaOH can dissolve the anti-reflective silicon nitride layer and etch away metallic contacts on silicon, which might help free up the silicon surface. However, alkali leaching is more often applied to specific materials (like dissolving aluminum frames or removing silicone potting materials). Generally, acid leaching is more aggressive and faster for metal recovery from PV cells.

Acid leaching comes with the issue of handling **hazardous reagents and waste**. Concentrated nitric or hydrochloric acid is dangerous, and once it has dissolved metals, the resulting solution is a toxic waste if not properly managed. The process can generate fumes (e.g. NOx from nitric acid) that must be captured. Researchers have worked on minimizing these impacts, for example by recycling the acids through distillation or using weaker organic acids. But there is often a trade-off: milder acids yield lower metal recovery or require heating and longer time. After leaching, the waste acid must be neutralized and heavy metals captured, often producing sludge that needs disposal as hazardous waste. Despite these issues, from a *life-cycle perspective* the environmental footprint of recovering silver via chemical means can be beneficial if the recovered silver displaces primary silver mining (which itself is quite impactful). The key is to ensure emissions (acid fumes, wastewater) are well-controlled with scrubbers and treatment systems.

➢ **Solvent extraction processes [19]:** Instead of dissolving metals, some recycling methods use organic solvents to selectively dissolve polymers or separate layers. One target is the EVA encapsulant – if it can be dissolved or sufficiently softened, the glass and cells can be separated intact. Solvents like trichloroethylene, dichloromethane, toluene, and NMP have been tested. Another solvent approach is aimed at extracting specific metals: for instance, solvent extraction techniques from hydrometallurgy can be applied to a leachate solution to selectively pull-out metals like tellurium (for CdTe thin-film panels) or gallium/indium (for CIGS panels) by using organic extractants that bind those metals. However, for silicon panels, such solvent extraction is less common; it's more straightforward to precipitate or electrodeposit the metals from solution.

Concerns with solvent processes include flammability, toxicity, and generating a secondary waste stream (dirty solvent). Most solvents used are volatile organic compounds (VOCs) that require careful handling to avoid worker exposure and emissions. Many are petroleum-derived, so using large quantities has environmental downsides. Researchers are investigating greener solvent alternatives – e.g. bio-based solvents or ionic liquids – but these can be expensive. Additionally, after a solvent has dissolved the EVA encapsulant, a mixture of polymer in solvent remains that must be distilled or otherwise processed to possibly recover the solvent for reuse. This re-distillation consumes energy, reducing the overall environmental benefit. As such, purely solvent-based PV recycling is not yet commercial; it may find a place as part of a hybrid process (for instance, after mechanical removal of the frame, apply solvent to remove encapsulant, then proceed with acid leaching for metals).

- **Pyrolysis and thermal processing:** Pyrolysis involves heating organic materials in the absence of oxygen to decompose them. In PV recycling, pyrolysis is used to decompose the encapsulant and backsheet polymers that encapsulate the cells, thereby freeing the glass and cell materials. A typical pyrolysis process for PV modules might heat panel pieces to ~500°C under inert gas (e.g. nitrogen). The EVA, which is ~28–30% of a module by weight (if including backsheet), breaks down into hydrocarbon gases (like ethylene, acetic acid fumes from the vinyl acetate, etc.) and carbon char. These gases can be combusted in a secondary chamber to recover energy and to avoid releasing harmful substances directly. Pyrolysis effectively achieves what mechanical methods cannot: complete separation of glass and silicon without physical force. After pyrolysis, one is left with **clean glass shards, copper ribbon pieces, and silicon cell remnants** with most of the plastic gone. The cell remnants still have the metallic contacts (silver and solder) attached, but now those are accessible for chemical leaching because the encapsulating plastic is gone.

- A variant of pyrolysis is using a **molten salt [20] or molten metal bath** to heat and delaminate modules. In some experiments, panels (or cell strips) are dipped in a molten salt like **molten carbonate or nitrate** at a few hundred degrees Celsius. The molten salt conducts heat very well and can decompose the EVA encapsulant quickly. Additionally, certain salts may help to chemically break the bond between glass and silicon or even participate in removing the anti-reflective coating and metal contacts. A recent breakthrough in 2024 demonstrated a molten alkali hydroxide bath (a mix of NaOH–KOH) at ~200 °C that could completely separate and recover both **silver and silicon in under 3 minutes**. In that process, the molten NaOH–KOH is highly corrosive to the silicon nitride and glass at the cell surface, effectively lifting off the silver grid and simultaneously etching away a very thin layer of silicon, yielding >99% Ag recovery and ~98% silicon recovery in a very short time. The authors noted this did not produce the secondary acid waste that typical leaching would, since the molten hydroxide could be reused. Such molten salt or base treatments are at lab scale, but they highlight an important point: thermal/chemical processes can be extremely efficient at resource recovery. For example, in the molten salt-etching case, not only were Ag and Si recovered, but subsequent steps recovered Cu, Pb, Sn, and Al as well via oxidation and electrorefining, achieving essentially full recovery of all metals.

Conventional pyrolysis, while effective for delamination, must manage its emissions carefully. EVA contains about 33% vinyl acetate, which produces acetic acid upon decomposition – corrosive vapors that need neutralization. Backsheets often contain fluoropolymers (PVF or PVDF), which can release hydrogen fluoride (HF) gas when heated. Recycling plants like ROSI address this by having scrubbers with basic solutions to capture acid gases (HF, HCl, etc.). The scrubber produces a neutralized salt solution and ultimately a sludge that contains the captured pollutants. This sludge (fluoride salts, heavy metal traces) is a hazardous waste requiring safe disposal (often in specialized landfills). Still, the volume of such waste is relatively small (e.g. a few kg of sludge per ton of panels processed). Energy-wise, pyrolysis can be significant – heating to 500 °C for each batch of material. But if the organic content of the panel (the EVA/backsheet, ~10–15% of mass) is used as fuel (their combustion energy recaptured), the net energy input can be lowered. Some LCA studies indicate that using the panel's own polymer as energy reduces the need for external fuel by a substantial fraction.

- **Hybrid and advanced processes:** In practice, the most promising recycling flows are **hybrid**, combining mechanical, thermal, and chemical steps to maximize recovery. A representative example is the **FRELP process** (an EU-funded project around 2016):
  - a. Remove frame and junction box (mechanical).
  - b. Shred panel and use thermal treatment to separate glass (the EVA is burned off in a controlled reactor).
  - c. Recover glass cullet (reported >90% glass recovery).
  - d. Leach the remaining shredded cell concentrate with nitric acid to dissolve silver and lead. Recover silver by precipitation or cementation (yield ~95% of silver).
  - e. Treat the leachate for lead removal and dispose of or recycle the acid.
  - f. The leftover silicon from cells (now free of metals) can be refined further (in FRELP they explored melting it to produce metallurgical-grade silicon for reuse).

This multi-step approach achieved high recovery rates: nearly 95% of glass, >90% of metals like Al and Cu, ~97% of silver, and a significant fraction of silicon was retrieved (though in lower purity form). The trade-off is process **complexity** – multiple stages and different technologies in one line. Many newer startups adopt similar combined flows, often described as "physical + chemical" recycling.

To **compare performance** of different approaches, we consider a few metrics: *material recovery yields, energy input, and emissions/effluents.* A mechanical-only process might recover ~80% of a panel's mass (mostly glass, aluminum) with low energy input (50 kWh/ton) and minimal direct emissions but leaves valuable fractions unrecovered. A full thermal + chemical process could push recovery to >95% of mass (including nearly all metals and semiconductor material), but at a cost of higher energy use (perhaps 200–300 kWh/ton combined) and the need to manage chemical wastes.

- **Mechanical shredding:** ~75% mass recovered, energy ~50 kWh/ton.
- **Thermal + mech:** ~85–90% recovered (adds glass purity, some metal recovery), energy ~150 kWh/ton plus thermal energy from polymer;

- **Thermal + chemical (full recovery):** 95%+ recovered, energy ~200+ kWh/ton, plus chemical consumption leading to some emissions (CO_2 from energy, acid waste).

Notably, a high-yield process often implies **more steps and higher energy** – one survey found that achieving better recovery yields "seems to require more process steps and greater energy inputs". Recent innovations are trying to break that trade-off. The molten salt-etching method described is a good example: it achieves extraordinary recovery rates (>98% Si, >99% Ag) in a short time, potentially keeping energy low, but it's yet to be proven on large scales. Similarly, some researchers are exploring **electrochemical processes** (using electricity to dissolve and recover metals from panels directly) which could be more selective and generate less chemical waste. **Biotechnological approaches** (like using bacteria to leach metals) have even been mooted, though PV panels may not be the easiest target for bioleaching given their composition.

In conclusion, chemical and thermal processes greatly enhance the recovery of valuable PV panel components. **Acid leaching** is effective for metals but must be managed to avoid shifting pollution to air or water. **Thermal treatments** like pyrolysis cleanly separate materials but need emissions control and energy input. The best strategies combine these methods, using mechanical steps for bulk separation and targeted thermal/chemical steps for the rest. The yields from such integrated approaches are high – multiple sources agree that well-designed recycling systems can recover on the order of 80–90% of material by mass, and in some cases up to **83% or more of the entire panel can be recycled into useful products**. The remaining fraction (often the encapsulant or certain by-products) may end up as waste or energy recovery. As research continues, the goal is to push recovery closer to 100%, reduce the energy and chemical use per unit, and simplify the process to be economically viable at scale.

5. Emerging innovations and future directions

As the PV recycling industry evolves from infancy to industrial scale, a wave of innovations is emerging to overcome current limitations. Researchers and startups around the world are experimenting with advanced technologies to improve efficiency, reduce costs, and handle the coming influx of solar panel waste. In this section, we outline several promising innovations and future directions:

- **Automation and AI in PV recycling:** One major trend is the push toward **automated disassembly and sorting** of solar panels using robotics and artificial intelligence. Manual dismantling (for frames, junction boxes, etc.) is labor-intensive and costly. Automating these steps can significantly increase throughput and lower costs. For instance, advanced recycling facilities are incorporating robotic arms that can identify and unscrew or cut the aluminum frame from a panel, or pop off the junction box, within seconds. **Vision systems** (cameras with AI algorithms) can recognize different panel models or conditions and adjust the disassembly accordingly. Beyond dismantling, robots are being developed to perform precise delamination – e.g. using automated suction cups and heated blades to peel back the backsheet or even separate cells from glass. While challenging, such systems could recover components with minimal damage. **Computer vision and machine learning** also have a role in sorting materials after crushing: AI-driven sorters could distinguish between silicon fragments and glass, or detect circuit board pieces, improving purity of output streams. Additionally, **AI optimization** can help in process control – for example, dynamically adjusting shredder speed or furnace temperature based on input composition to maximize efficiency. A futuristic concept is a fully **smart recycling plant** where incoming panels are scanned (perhaps via QR code or database lookup to get their composition), then a series of robots and machines tailor the recycling method to that panel type – maybe gently disassembling newer modules for reuse of cells or aggressively shredding older ones for material recovery. Preliminary steps in this direction are being taken. One report suggests that using AI-driven robots could *significantly increase material recovery rates and improve worker safety* by taking over dangerous tasks. By eliminating human error and fatigue, automation ensures more consistent separation of materials. Moreover, **autonomous quality control** (AI checking the cleanliness of recovered glass, for example) can help guarantee that recycled output meet standards for reuse.

- ➢ **Pilot-scale and demonstration projects:** Over the last few years, several pilot projects and dedicated recycling facilities have come online, serving as proof-of-concept for different technologies:
  - In Europe, aside from the Veolia plant in France, there are pilots in Germany, Italy, and Belgium focusing on advanced techniques. For example, a German pilot plant tested a combination of **electrical discharges** (high-voltage pulse fragmentation) to crack panels and then mechanical separation

– reporting very low energy cost per panel (on the order of \$0.002 per W). Italy’s ENEA research agency ran a demo that uses **microwave heating** to delaminate panels, following on the idea that targeted microwave can heat the EVA internally and loosen the bond. In Belgium, the company SOLARCYCLE demonstrated an automated dismantling line integrated with chemical leaching for silver.

- In North America, startup companies have emerged, such as Recycle PV and SolarCycle (USA), which have pilot operations using proprietary methods (often a mix of mechanical and thermal). One facility in Nevada uses a conveyorized system to remove glass in large pieces before shredding the remainder, claiming higher glass purity. First Solar, which recycles its own CdTe thin-film panels, operates a fully scaled recycling program – their process (which involves crushing and chemical baths to recover cadmium and tellurium) achieves over 90% recovery of semiconductor material and glass. This is often cited as a success story, although it’s specific to thin-film technology. For silicon panels, a promising demonstration is the Solar Circular Recovery plant in Texas (opened 2022) which aims to process several thousand tons/year using mostly mechanical methods initially, but with plans to incorporate metallurgical recovery for silicon and silver. –
- In **Asia**, we see companies like NPC in Japan (which traditionally made PV manufacturing equipment) now offering a PV recycling machine that uses a robotic cutter to separate glass from cells with no glass breakage. They claim to leave “no metal residue and no breakage on the glass,” effectively producing clean glass sheets and a stack of cells, albeit damaged. This suggests some panels could even be refurbished or their cells reused. Meanwhile, China’s scale-up is mostly at larger facilities trying out different methods regionally – e.g. a plant in Jiangsu uses a fluidized bed for thermal treatment, whereas one in Sichuan is testing chemical etching. These demonstration projects are essential for ironing out practical issues like continuous operation, handling panel variability, and meeting safety and environmental regulations in real-life conditions.

The lessons from pilots so far indicate that no one-size-fits-all solution exists yet. Each technology has had to adapt: some early processes had trouble with newer panels that have tougher encapsulants or frameless designs. But incremental improvements are building a toolkit of methods that can be deployed.

6. Conclusions

This review highlights that recycling solar photovoltaic panels is not only technically feasible but also essential for the sustainable growth of solar photovoltaic industry. The main conclusions and takeaways are:

Surging PV waste requires proactive management: The volume of end-of-life solar panels will increase dramatically in coming decades (tens of millions of tons by 2050). Without recycling, this could pose an environmental burden and squander valuable materials. Proactive policies (like the EU's WEEE Directive) and early investment in recycling infrastructure are crucial to avoid a PV waste crisis and instead turn it into a resource opportunity.

Policy frameworks drive recycling but need harmonization: Extended producer responsibility schemes, landfill restrictions, and economic incentives are proving effective at jump-starting PV recycling where they are implemented (e.g. Europe, certain U.S. states, Japan's forthcoming rules). However, there is a clear need for more harmonized and enforced policies globally. Gaps in regulation (especially at the federal level in countries like the U.S.) currently allow many panels to end up in landfills simply because it's the cheapest route. Strengthening and aligning policies – making sure producers everywhere are responsible for end-of-life – is likely to be the most important factor in scaling up recycling worldwide.

Combination of mechanical and advanced processes achieves high recovery: Mechanically, we can already recover bulk materials (glass, aluminum) from PV modules with established techniques, but these alone leave a lot of value on the table (particularly silver and silicon). The latest research and pilot projects demonstrate that combining **mechanical pre-treatment** (for disassembly and size reduction) with **thermal and/or chemical processes** can push recovery rates above 90% for most materials. Innovations like controlled pyrolysis and molten salt baths show that even the notoriously hard-to-recycle components (like encapsulant-bonded cells) can be separated and refined. Continued innovation is expected to further improve efficiency and reduce cost – for instance, through automation and novel chemistries – making recycling technologically and economically more attractive. In short, there is no fundamental technical barrier to achieving near-complete recycling of silicon PV modules; it is a matter of optimizing and industrializing these processes.

In closing, it is evident that a **harmonized policy framework combined with scalable, efficient recycling technologies is fundamental** to handling the solar PV waste challenge. Solar energy's green credentials can only be fully realized if we address the end-of-life stage responsibly. Immediate next steps should include accelerating pilot projects, establishing producer responsibility programs in lagging regions, and encouraging design for recyclability in the next generation of PV modules. The timeline is pressing – the earliest large waves of PV waste will hit in the 2030s – but with collaborative effort from engineers, policymakers, and industry, we are likely to meet this challenge and ensure that today's renewable energy solutions do not become tomorrow's waste problems but rather feed into a sustainable circular loop for decades to come.

7. Future research

Future research directions include better integration of recycled materials for reuse and primary design of solar panels for recycling. One gap is understanding how well recycled materials perform when put back into new products, especially new solar panels. Testing over time is needed: e.g. modules made with some recycled content should be field-tested to see if they last as long as new solar panels. This is an area where very few data are published, and it's crucial for a true circular economy. The lack of data perhaps reflects that not enough recycled material has been produced yet to try manufacturing at scale. Bridging this gap will likely require collaboration between recyclers and panel manufacturers – perhaps pilot projects where a batch of new panels is produced using recycled glass or silicon and then evaluated. On the other hand, reuse of whole panels (using still-working used panels in secondary markets) can delay waste generation and is often more energy-efficient than tearing down a panel. Some researchers have proposed that automated grading of used panels (using AI to inspect for cracks, output testing) could divert a portion of panels to reuse markets and the rest to recycle. Design for Recycling involves making new PV modules in ways that simplify their end-of-life disassembly – for example, using encapsulants that can be softened at lower temperatures, or using mechanical fasteners for frames instead of glues, or avoiding toxic additives.

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