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Original Research Article

RECYCLING OF SILICON-BASED PHOTOVOLTAIC PANELS: BENEFITS, CHALLENGES AND FUTURE DIRECTIONS

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A b s t r a c t

By 2050, the global capacity of photovoltaic (PV) systems is projected to reach approximately 4500 GW, which will lead to an estimated 60–78 million tons of PV waste. This increase presents significant environmental challenges due to hazardous elements like lead and tin in PV modules, necessitating sustainable waste management solutions. This study examines the current technological, economic, and regulatory barriers to recycling c-Si PV modules. Findings indicate that recycling can diminish terrestrial ecotoxicity by 74% and lower greenhouse gas emissions by 24% across the life cycle of PV modules, compared to traditional disposal. Additionally, recycled materials could satisfy over 20% of the PV industry's demand for aluminium, copper, glass, and silicon and nearly 70% for silver between 2040 and 2050. To drive recycling forward, the study proposes a circular economy model for PV waste management, advocating for policy harmonization, industry-led recycling incentives, and technological innovations that improve material recycling and recovery.

Keywords: photovoltaic waste management, crystalline silicon (c-Si) recycling, circular economy, resource recovery, and sustainable development.

1. INTRODUCTION

1.1. Growth of PV panels

The urgent need to combat climate change and reduce greenhouse gas emissions has prompted a global shift toward renewable energy sources. Photovoltaics (PV) has emerged as a vital component of solar energy technology. Projections suggest that global PV capacity will approach 4500 GW by 2050, establishing solar energy as one of the most rapidly expanding sources of electricity (Fig. 1) [1]. Geographically, the distribution of installed PV capacity varies significantly. The Asia-Pacific region leads with 48% of the global total, followed by Europe at 34% and North and South America with a

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combined 15% share (Fig. 2). While the Middle East, Africa, and other regions currently have smaller shares, their contribution is steadily increasing [2]. The increasing adoption of photovoltaics is driven by its capability to produce clean, renewable energy, which is essential for sustainable development. Its main benefits include low carbon emissions, decreased reliance on fossil fuels, and a substantial role in mitigating global warming. It also offers long-term use of solar resources, a short payback period, and contributes to achieving national and international CO_2 reduction targets [3]. While the increasing installation of photovoltaic (PV) systems represents significant progress towards sustainable energy solutions, managing PV modules at the end of their life poses a major future challenge. According to the Institute for Solar Energy Systems (ISE) in Freiburg [5], the average lifetime of a solar module typically ranges between 20 and 30 years, as encapsulated materials and cabling degrade over time. Projected PV waste volumes vary depending on module degradation scenarios (Fig. 3). The regular loss scenario assumes that solar modules operate for their intended lifespan without premature failures, estimating global PV waste at around 1.7 million tons by 2030 and approximately 60 million tons by 2050. The early loss scenario, however, accounts for failures that occur in the initial years, mid-life, or due to wear and tear before reaching the expected lifespan. As illustrated in Fig. 4a, the primary causes of early losses include optical failures (20%), power reductions (19%), and issues with the junction box (J-box) and cabling (19%). Additionally, glass breakage and defective cell connections each contribute 10% of early failures. Other causes include loose frames (6%), unidentified defects (6%), delamination (5%), and transport-related damage (5%). Under this scenario, PV waste could rise significantly, reaching 8 million tons by 2030 and approximately 78 million tons by 2050 [2]. Currently, PV technology is used in more than 100 countries, with China, the United States, Germany, Japan, and India projected to produce the highest PV waste volumes by 2050 (Fig. 4b).

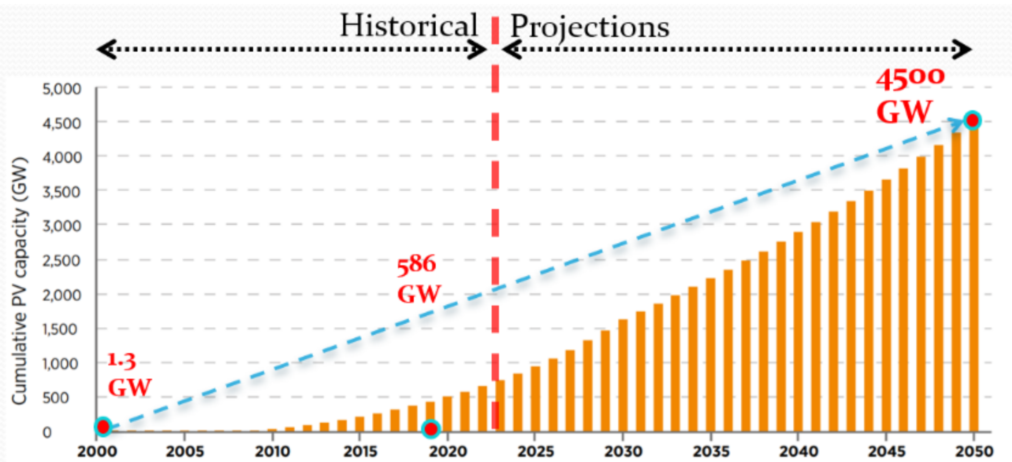

Fig. 1. Anticipated cumulative worldwide photovoltaic capacity [2]

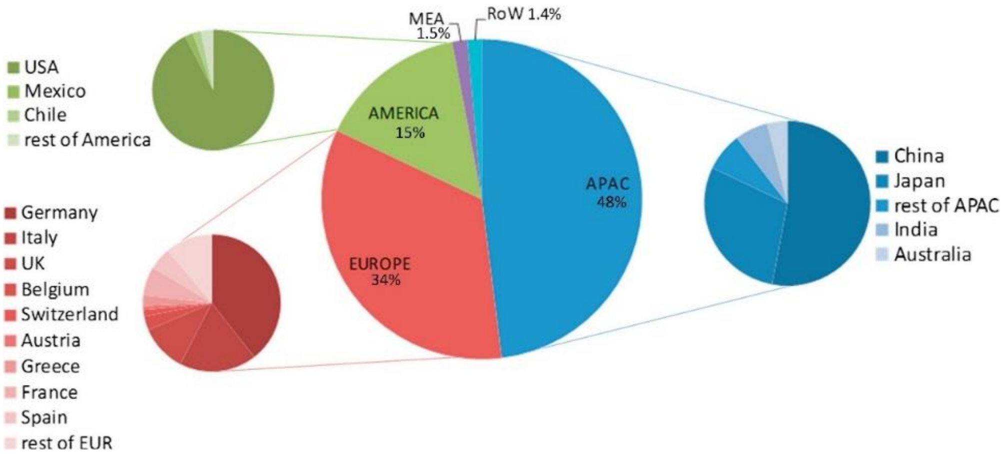

Fig. 2. Installed photovoltaic capacity across different global areas [4]

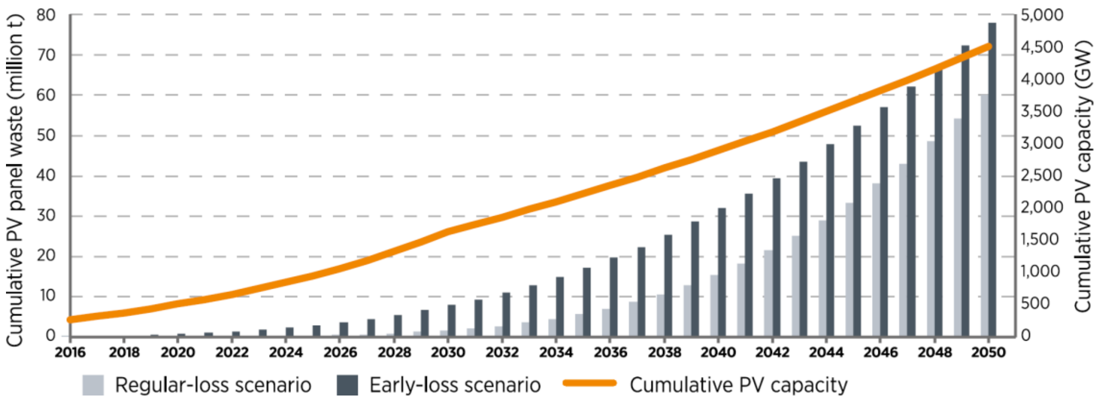

Fig. 3. Predicted cumulative worldwide waste of end-of-life solar modules under the early-loss scenario and the regular-loss scenario [6]

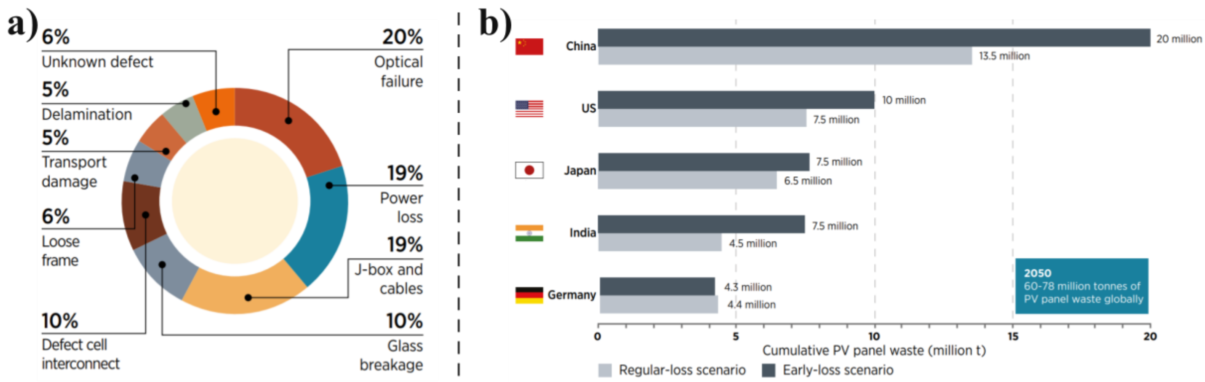

Fig. 4. a) Failure rates based on customer complaints. b) Projected cumulative waste quantities of end-of-life PV panels in the top five countries by 2050 [2]

1.2. Purpose and scope of the study

This study highlights the pressing need to recycle crystalline silicon (c-Si) photovoltaic modules, which account for the largest share of current and future PV waste. Aiming to foster a circular economy in the solar industry, technical challenges, economic barriers, and regulatory frameworks that affect recycling efforts are analysed. The methodology involves a systematic quantitative analysis of the literature, which includes academic research and grey literature reports from governmental and industry sources, including the IEA, EU Commission, and IRENA. The main search terms are "PV module recycling," "c-Si waste management," "circular economy," and "sustainable development goals."

2. SILICON-PV PANEL COMPOSITION AND PRODUCTION PROCESS

2.1. Production process

The production of silicon-based photovoltaic (PV) modules takes place in several critical steps, starting with quartz or sand material and ending with fully assembled PV panels. The steps of the process are shown in Fig. 5.

2.1.1 Silicon purification and metallurgical-grade silicon

Silicon dioxide (SiO_2) in quartz/sand is reduced with carbon in a submerged-arc furnace to produce metallurgical-grade silicon (MG-Si, ~99% purity) [7, 8]. The silicon is melted and crystallized as mono- or multicrystalline ingots (e.g., Czochralski or directional solidification), which are cut into bricks and then sliced into thin wafers (≈180 μm) by wire saws [9]. Wire-saw wafering generates a significant “kerf-loss” solid waste stream (silicon fines/slurry), typically 30–40% of the ingot mass [10].

2.1.2 Solar cell manufacturing (from wafers to solar cells)

Wafers are doped (boron/phosphorus) to form the p–n junction. An anti-reflective coating, typically Si_3N_4, is deposited by plasma-enhanced chemical vapor deposition (PECVD) [11; 12]. Front-side metallization uses silver paste screen-printed into gridlines; the back side is contacted with aluminum paste [13; 14].Texturing/saw-damage removal commonly uses wet-etch baths (e.g., HF/HNO_3 for multi-Si or NaOH for mono-Si), producing spent acid/alkali solutions that are treated by neutralization/precipitation prior to discharge. Some PECVD tools use fluorinated gases (e.g., NF_3/CF_4) for chamber cleaning; emissions are routinely minimized with exhaust abatement [15].

2.1.3 Solar panel assembly (from solar cells to fully assembled modules)

After individual solar cells are created, these cells are assembled into larger panels by arranging several cells in series or parallel configurations. Each cell is connected using copper strips. These strips are generally coated with solder, a blend of tin and lead, at the contact points to form an electrical circuit between cells [16, 17]. The assembled solar cells are then encased between two protective layers. One layer is placed between the cells and the tempered glass front cover, while the other layer is situated at the back of the cells. Ethylene-Vinyl-Acetate (EVA) copolymer is widely used as the encapsulation material for PV cells, as illustrated in Fig. 6a. EVA maintained nearly a 100% share of the PV encapsulant market in 2017 and 2018, demonstrating its extensive adoption and reliability in shielding photovoltaic modules. Projections indicate that EVA will retain a dominant market position until 2028, with a market share close to 70%, due to its proven reliability, cost-effectiveness, and robustness in protecting solar cells against environmental elements [10]. The EVA encapsulant layers on the front and back each have a thickness exceeding 0.4 mm, jointly contributing approximately 6.53% of the panel's weight. A layer of tempered glass is applied over the EVA-encapsulated cells. This glass serves as a protective front barrier, shielding the cells from environmental conditions like wind, rain, and UV rays. This glass layer makes up about 74.16% of the panel's overall weight and is 3.2 mm thick, playing an important role in enabling sunlight to pass through to the cells while adding structural strength [18]. The back surface of the solar panel is protected by a back sheet, which provides mechanical protection and prevents moisture from seeping in. Additionally, the back sheet functions as an electrical insulator for the module, ensuring both safety and durability. This component has an average thickness close to 0.3 mm. The back sheet consists of multiple layers, made from various polymers and adhesives. The main types of back sheet configurations for PV modules are TPT (constructed from Tedlar, PET, and another Tedlar layer), PPE (featuring double PET layers with a central ethylene vinyl acetate layer), and KPK (composed of Kynar, a polyester film (PET), and an additional layer of Kynar). Here, 'Kynar' is a trademark for polyvinylidene fluoride (PVDF), while 'Tedlar' represents polyvinyl fluoride (PVF) [10, 17, 19, 20]. As illustrated in Fig. 6b, TPT (Tedlar-Polyester-Tedlar) is the primary substrate material used in most currently available PV panels. Since 2016, TPT has led the market in share, and while its market dominance may decline by 2027, it remains the primary backsheet material in PV panel manufacturing. This component measures approximately 0.3 mm in thickness, contributing around 3.6% of the total panel mass [10, 21]. An aluminum frame encircles the panel, providing structural support and facilitating installation. The frame comprises about 10.3% of the panel's weight and is 20 mm thick. Its main purpose is to protect the panel's edges and provide structural stability, making installation easier and more secure [22]. Lastly, a junction box is attached to the rear of the panel, housing the electrical connections and bypass diodes. Although the junction box accounts for only 1.93% of the total panel weight, it is essential for connecting the panel to additional panels or to the power grid, ensuring efficient power transfer and system safety [23].

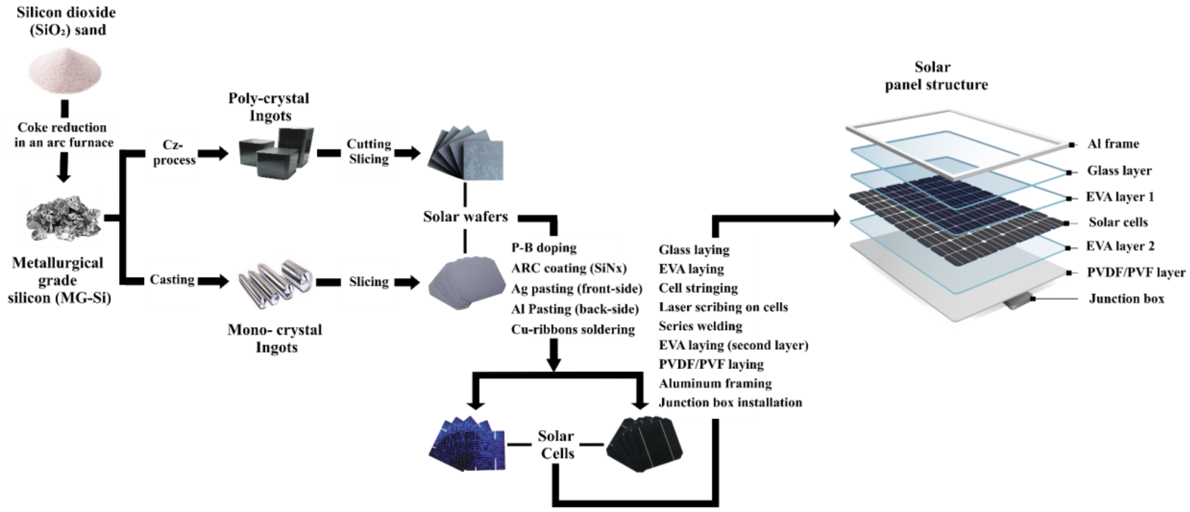

Fig. 5. Manufacturing process of monocrystalline and polycrystalline solar panels (source: own work)

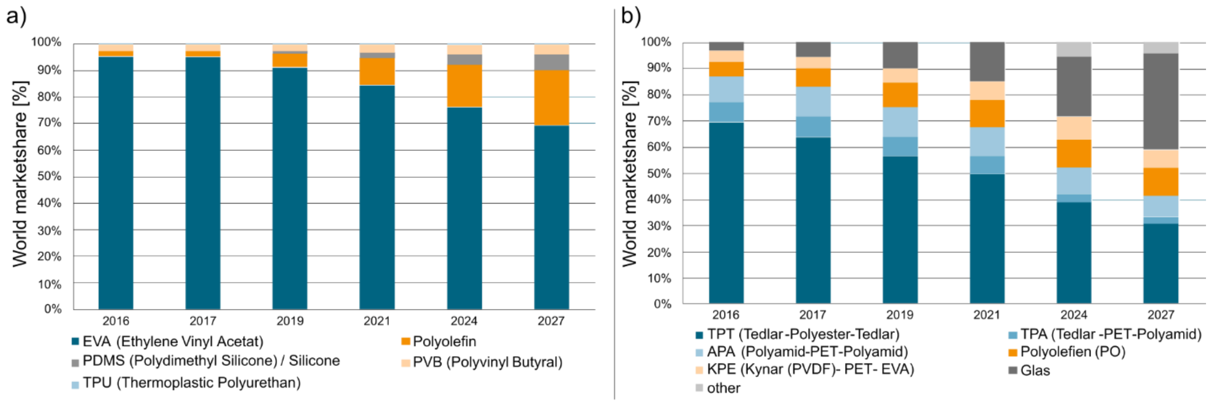

Fig. 6. a) different PV encapsulation materials, b) different PV back sheet materials [10]

2.2. Testing and quality control

Before the PV panels are ready for installation, they must undergo a series of tests to ensure quality, performance, and durability. Electroluminescence (EL) testing uses infrared imaging to detect microcracks or other defects in the cells that are not visible to the naked eye. This ensures that the cells are not damaged before they are installed in the field [24].

3. PV WASTE CLASSIFICATION

The classification and management of photovoltaic (PV) waste differs significantly across various countries, resulting in diverse environmental and economic impacts. Fig. 7 illustrates the main components of crystalline silicon (C-Si) panels, along with their environmental impacts, commercial values, and recyclability. Many regions classify discarded PV panels as general or industrial waste, resulting in disposal methods like landfills or incineration [2, 25]. These disposal practices are environmentally questionable, as hazardous substances like lead and tin found in cell interconnections and solar cell coatings can leach out, contaminating soil and groundwater. Furthermore, incinerating panels containing fluorinated polymers can release toxic gases, including dioxins and furans, which contribute to air pollution and pose health risks [26]. Economically, PV panels contain valuable and recyclable materials like silver, aluminum, and copper, as shown in Fig. 7. Disposal methods that fail to recover these materials lead to a loss of limited resources and miss out on opportunities for resource recovery that could support advancements in technology. In some countries, such as Japan and the USA, PV module waste is tested for hazardous substances. Panels may be classified as hazardous if they exceed certain thresholds for metals like lead and cadmium, requiring stricter disposal or recycling measures. For instance, the allowable leachate concentration for lead is 5 mg/l in the USA and 0.3 mg/l in Japan. Cadmium limits are set at 1 mg/l in the USA, 0.3 mg/l in Japan, and 0.1 mg/l in Germany [2]. These variations in hazardous substance limits reflect regional differences in waste classification, complicating global efforts in waste management. The European Union (EU) distinguishes itself by classifying PV panel waste as electronic waste under Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE) [27, 28]. This classification establishes specific targets for the collection, recycling, and recovery of PV waste. Since 2018, the directive has mandated that 85% of PV waste must be recovered, with 80% prepared for reuse or recycling. This regulatory framework aims to ensure that valuable materials, such as glass, aluminum, silver, and indium, are effectively recovered while also managing the disposal of hazardous substances to minimize environmental harm [29]. In 2024, the

WEEE Directive (Directive (EU) 2024/884) was updated to increase the responsibility of manufacturers in handling end-of-life PV modules and to enhance the recovery of valuable resources while ensuring safer disposal of hazardous substances [30].

4. PV PANEL WASTE RECYCLING

4.1. Benefits

Solar panel recycling is important for mitigating environmental and economic challenges while promoting industrial sustainability in the renewable energy sector. For silicon-based PV panels, this process prevents hazardous substances such as lead, tin, and fluorinated polymers from entering ecosystems. By avoiding landfill disposal or incineration, recycling substantially reduces the environmental footprint of PV modules. It leads to a 74% decrease in terrestrial ecotoxicity, a 26% reduction in human toxicity, a 24% drop in global warming potential, and a 37% decline in acidification throughout the modules' lifecycle [31, 32]. From an economic perspective, the advantages are significant. The surging demand for solar energy is expected to greatly increase the consumption of valuable resources like silicon, silver, copper, and aluminum, along with essential materials such as glass and polymers. For instance, silver demand could multiply by a factor of 4 to 27 by 2050 [33], and copper demand is projected to peak at 2,062 kilotons by 2035 [34]. Recycling emerges as a practical solution to meet this growing demand. The International Energy Agency's roadmap to achieve net-zero emissions by 2050 suggests that recycling could supply over 20% of the solar industry's needs for aluminum, copper, glass, and silicon and nearly 70% for silver between 2040 and 2050 (Fig. 8a) [35]. Projections indicate that by 2030, under a regular loss scenario, recycling could recover approximately 965,100 tons of glass, 101,300 tons of polymers, 75,000 tons of aluminum, 29,500 tons of silicon, and 7,200 tons of copper from decommissioned PV modules (Fig. 8b). Based on 2016 market values, these materials could be worth around 450 million USD. This volume is sufficient to manufacture about 60 million solar modules, translating to a generation capacity of 18 GW. Looking ahead to 2050, the value of recovered materials could exceed 15 billion USD, supporting the production of 2 billion solar cells or approximately 630 GW of energy. By integrating recycled PV materials back into the economy, either through the production of new solar modules or by trading them on global material markets, the long-term availability of critical raw materials can be secured [**2**].

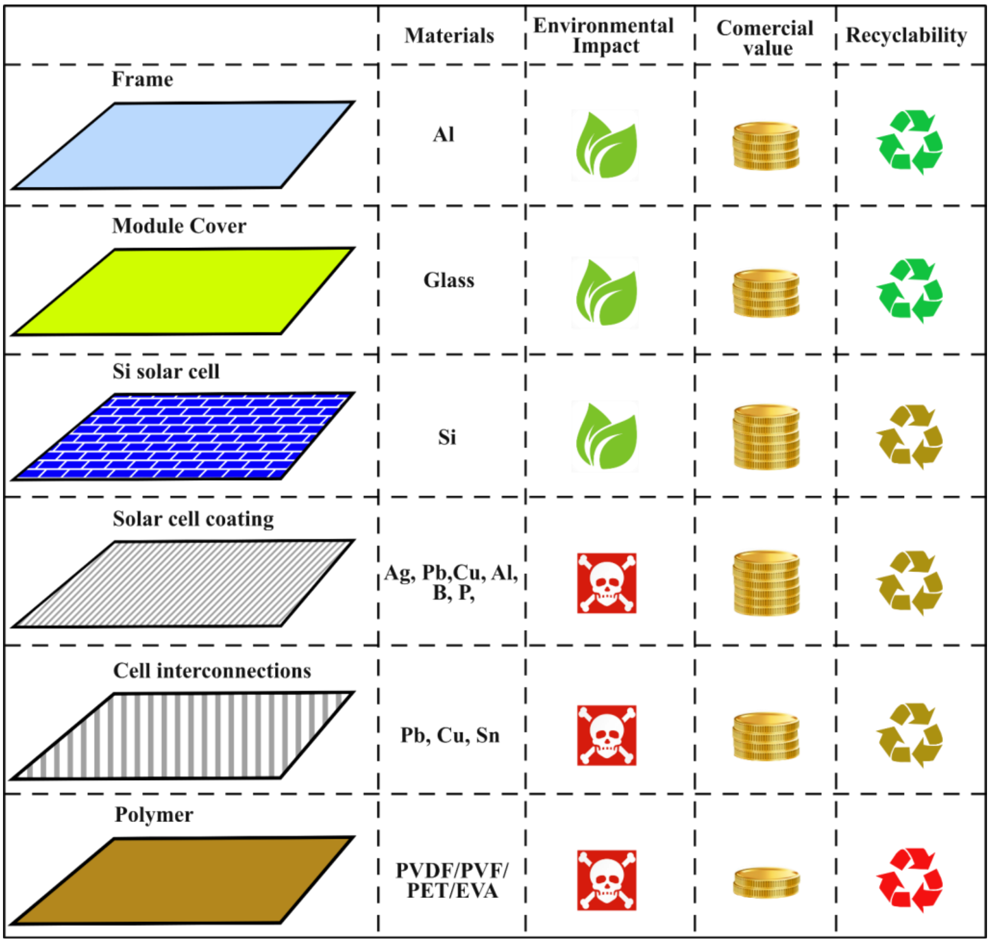

Fig. 7. The main components of crystalline silicon (C-Si) panels, along with their materials, environmental impacts, commercial values, and recyclability. Green leaf: low environmental impact; Red skull: hazardous impact; Gold coins: Commercial value (number of stacks reflects relative value); Green recycling symbol: easy to recycle; Brown recycling symbol: moderately recyclable; Brown recycling symbol: difficult recyclable

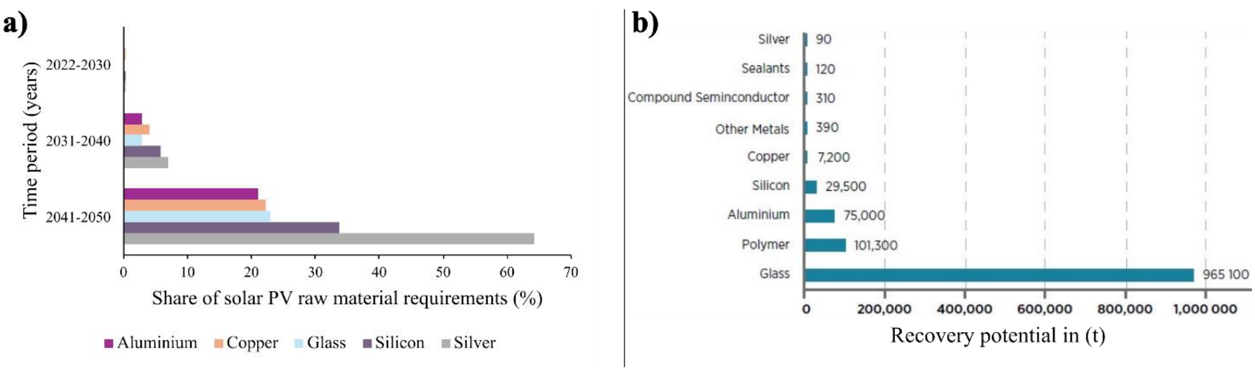

Fig 8. a) The extent to which the recycling of PV modules can meet the demand for selected materials from 2022 to 2050 under a net zero emissions scenario. b) The capacity to recover materials at the end of their life cycle under a typical loss scenario by 2030 (measured in tons) [2]

In addition, recycling plays a crucial role in improving the environmental and economic outcomes of solar cell manufacturing, in particular by conserving energy and reducing the environmental impact. In solar cell manufacturing, the most energy-intensive and greenhouse gas-emitting step is silicon refining, where raw silicon, typically extracted from quartz, is purified into high-purity polysilicon (see Fig. 9) [36]. By recovering silicon from recycled photovoltaic panels instead of extracting it from quartz, we can bypass these energy-intensive mining and purification stages, resulting in energy savings of up to 70% and significantly lowering emissions [25, 37]. The advantages of recycling extend to aluminum. Recycling aluminum conserves up to 95% of the energy required for producing it from raw materials and can cut CO2 emissions by up to 92% compared to primary production. Recycling a single ton of aluminum can save around 8 tons of bauxite and 14,000 kilowatt hours of energy and reduce landfill consumption by 7.6 cubic meters [38, 39]. Similarly, glass production gains substantial energy efficiencies when using recycled materials. The production of glass from cullets consumes around 30% less energy than that from new raw materials [40]. By incorporating recycled glass into their processes, manufacturers can decrease their carbon footprint and promote sustainability initiatives. Every ton of recycled glass used in place of raw materials prevents the emission of 580 kilograms of CO_2 [2].

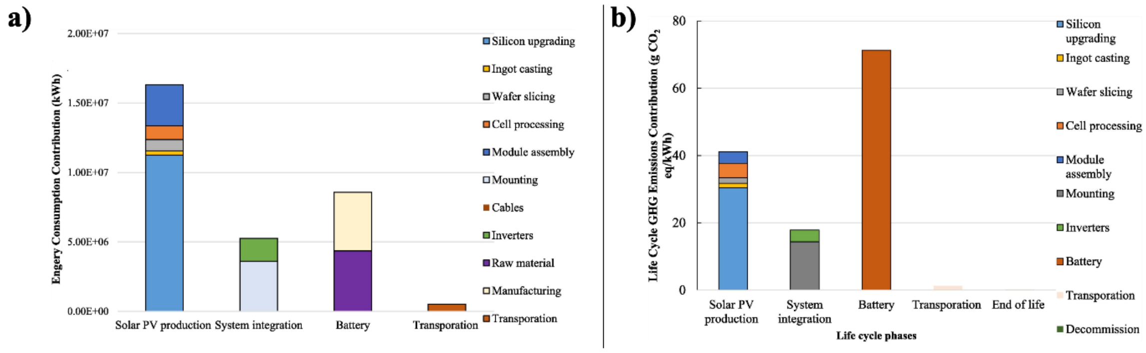

Fig. 9. a) the energy consumption pattern of a utility-scale solar farm with a capacity of 5 MWp, (b) the distribution of life cycle greenhouse gas (GHG) emissions by each phase [36]

4.2. Current recycling methods

The recycling of c-Si (PV) waste begins with the delamination phase, in which the aluminum frame is dismantled, the cables and junction box are pulled out, and the glass and polymer layers are separated. This step allows access to valuable materials within the silicon solar cells, including metals such as silicon, silver, copper, and aluminum, which are then available for subsequent extraction and purification. Various techniques for this process are documented in the literature, typically categorized into mechanical, thermal, and chemical methods [27, 41]. These methods are employed individually or in combination.

4.2.1 Physical treatment

Physical separation processes such as grinding, crushing, and screening are often used to break down photovoltaic modules and release their components. These physical processes offer a cost-effective approach for the rapid recovery of materials such as silicon, glass, and copper ribbons. Several studies have investigated different aspects of these methods. Granata et al. (2014) focused on physical separation methods, including hammer crushers [42]. Paiano et al. (2015) investigated the manual disassembly of silicon-based PV components [43]. Tokoro et al. (2021) improved glass separation by 88 by selective crushing with an eccentric agitator mill [44]. A comminution and screening method that efficiently separates metals and polymers into various size ranges was presented by Ying Sim et al. (2023) [45]. Wahman and Surowiak (2022) optimized fragmentation and screening methods to maximize material recovery from solar panels. They used a hammer mill with a mesh size of 5 mm and performed several comminution stages to achieve a specific particle distribution. The sieve analysis over six mesh sizes showed that the process predominantly yielded particles in the size intervals of 2.0–5.0 mm and 0.5–1.6 mm. EVA films and back sheet materials were mainly observed in the size category above 5.0 mm and, mixed with glass, in the smaller size fractions (Fig. 10). Consequently, about 81.5% of the sample weight was recovered as glass after heat treatment [46].

4.2.2 Thermal treatment

Thermal treatments play a key role in unlocking materials from decommissioned PV modules. This method targets the breakdown of polymer encapsulants like EVA at elevated temperatures, which enables the release of glass, copper ribbons, and silicon solar cells containing critical materials mainly silver, aluminum, and cooper, etc. Wang et al. (2012) employed a dual-stage heating approach. In the initial stage, the PV back sheet (PVF) of the module is detached by heating to 330 °C for 30 minutes. In a subsequent stage, EVA and remaining back sheet elements are combusted at 400 °C for a duration of 120 minutes [47]. Park et al. (2016) examined the removal of polymers from crystalline silicon (c-Si) modules in ambient settings, also assessing how heating rate and peak temperature impact the modules. Their findings revealed that complete polymer removal was achieved at a peak temperature of 480 °C [48]. Dias et al. (2017) studied the pyrolytic decomposition of polymers in PV modules, finding through thermogravimetric analysis that 75% of the mass broke down at 500 °C within a nitrogen environment [19]. Lee et al. (2018) effectively separated module layers by heating samples to 550 °C over 2 hours in ambient conditions using a muffle furnace with a steady increase of 5 °C per minute [49]. Wahman and Surowiak (2022) subjected PV panels to 300°C in an oven for 60 minutes to fully eliminate polymer layers. Samples were positioned glass side down and back side up in ceramic crucibles to aid in layer separation, including both front and back EVA layers situated among the glass, solar cells, and back layers. Their findings, shown in Fig. 11, suggest that the majority of the glass was retained in the larger particle fractions, with size intervals of 1.6–2.0 mm, 2.0–5.0 mm, and above 5.0 mm (Figs. 11a, 11b, and 11c). Smaller glass fragments were identified in fractions below 1.6 mm, alongside metal and silicon particles (Figs. 11d, 11e, and 11f). Metal components, including bus bars and PV strips, were magnetically extracted from the fraction below 1.6 mm. This approach achieved a direct glass recovery rate of 90.22% per weight [46].

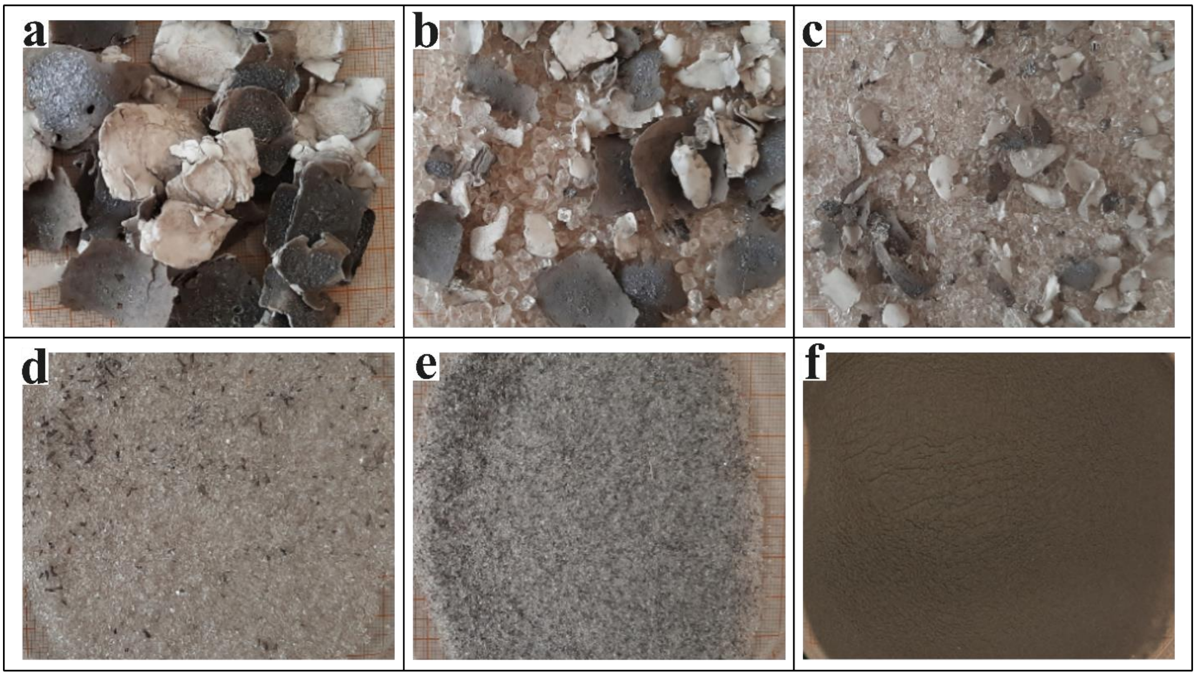

Fig. 10. Particle size fractions obtained after hammer milling and screening. (a) particles greater than 5.0 mm; (b) 2.0–5.0 mm; (c) 1.6–2.0 mm; (d) 0.5–1.6 mm; (e) 0.05–0.5 mm; and (f) particles smaller than 0.05 mm [46]

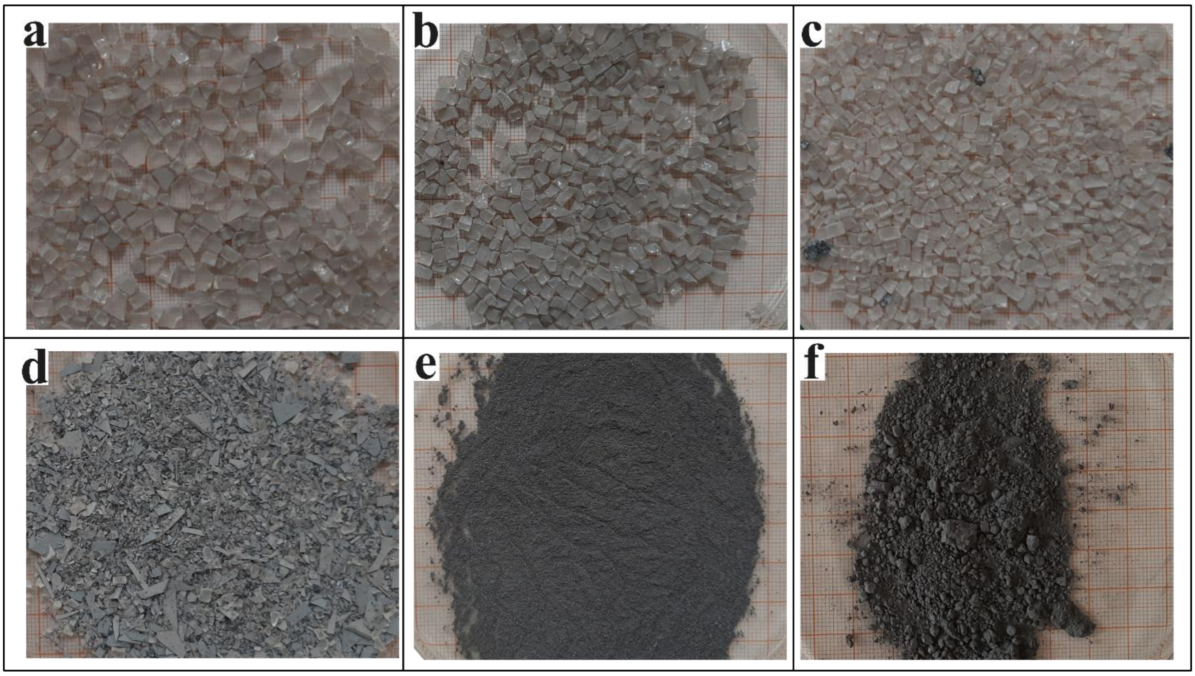

Fig. 11. Particle size fractions obtained after thermal treatment and screening: a) 5.0 mm and above; b) 2.0–5.0 mm; c) 1.6–2.0 mm; d) 0.5–1.6 mm; e) 0.05–0.5 mm; f) below 0.05 mm [46]

4.2.3 Chemical processes

Chemical approaches are used to dissolve encapsulants and other polymeric substances by the application of solvents or specific reagents. Doi et al. (2001) were the first to report the effective dissolution of EVA in trichloroethylene [50]. This method was later improved by Kim et al. (2012), who refined the dissolution technique by using ortho-dichlorobenzene (O-DCB) to dissolve EVA at 70 °C, with ultrasound assisting the reaction [12]. Azeumo et al. (2019) presented a new technique using toluene to dissolve EVA at 60 °C, assisted by 200 W ultrasound [51]. Vanek et al. (2023) investigated several solvents for chemical layer separation and found that toluene dissolved EVA most effectively, although strong swelling led to cracks on the silicon wafer [52]. Min et al. (2024) achieved complete separation of the glass and backsheet from the EVA while preserving the silicon cells by utilizing limonene-induced EVA expansion in an ultrasonic environment [53].

4.2.4 Combination process

In some studies, the recycling of PV panels has been improved by combining several treatments. Kamano et al. (2022) focused on glass separation processes for the recycling of solar modules by combining mechanical separation and microwave heating. According to their results, microwave heating accelerates the delamination of photovoltaic modules and reduces the force required to separate the glass from the EVA layer by about 50–60% [54]. Królikowski et al. (2024) combined a mechanical-thermal treatment with chemical delamination to effectively obtain and characterize EVA, polyvinylidene fluoride (PVDF), and polyethylene terephthalate (PET) polymers. By subjecting only 11 wt% of the original PV mass to chemical delamination, they reduced solvent consumption [55]. Wahman et al. (2023, 2024a, 2024b) proposed a method that combines mechanical and thermal processes in a sequential and controlled manner. Their approach focuses on the careful separation of each individual layer of the PV module with minimal material loss. The separation and recovery steps for each layer are shown in Fig. 12. The procedure starts with the manual removal of the junction box, cables, and aluminum frame, which are not bonded components of the PV module [56]. The back sheet is then separated from the rest of the module with a hot knife and recovered (Fig. 13a). A knife warmed to 200 °C selectively softens the adhesives that bond the layers, making it easier to separate the layers without damaging the materials. This method has proven to be very effective, as the recovered back sheet looks intact and uniform with no visible damage (Fig. 14a) and achieves a recovery rate of 99.42% [57]. Once the back sheet is removed, the flexible ethylene vinyl acetate (EVA) on the back can be pulled out directly by mechanical pulling (Fig. 13b). Once the EVA on the back is separated, the copper tape on the back can also be removed, leaving only the glass, the EVA on the front, the copper tape on the front, and the silicon solar cell. The separated EVA is shown in Fig. 14b. A hot wire process is used to separate the glass from the remaining layers (Fig. 13c). A wire heated to 200 °C is passed through the interface between the glass and the encapsulation, allowing precise and controlled detachment of the glass sheet. This step is completed in less than a minute and results in a glass recovery success rate of over 99% without material degradation or gas leakage. The detached glass layer is shown in Fig. 14c. The final stage consists of a 5-minute heat process in a furnace set to 400 °C to remove the residual polymers from the glass layer and breakdown the remaining encapsulations to release the silicon solar cells, containing valuable metals such as silver (Ag), aluminum (Al), and silicon (Si). The released glass, copper ribbons, and silicon cells after thermal treatment are shown in Figs. 14d, e, and f, respectively [58].

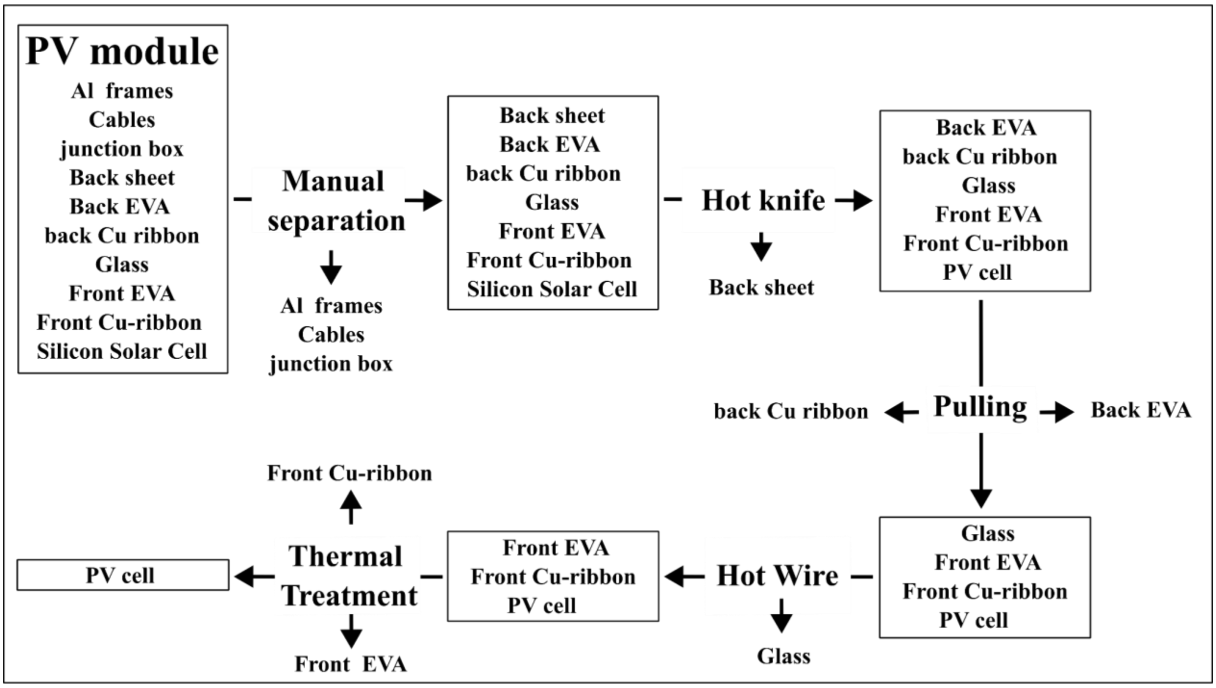

Fig. 12. Sequential steps for the separation and recovery of c-Si panel main elements (source: own work)

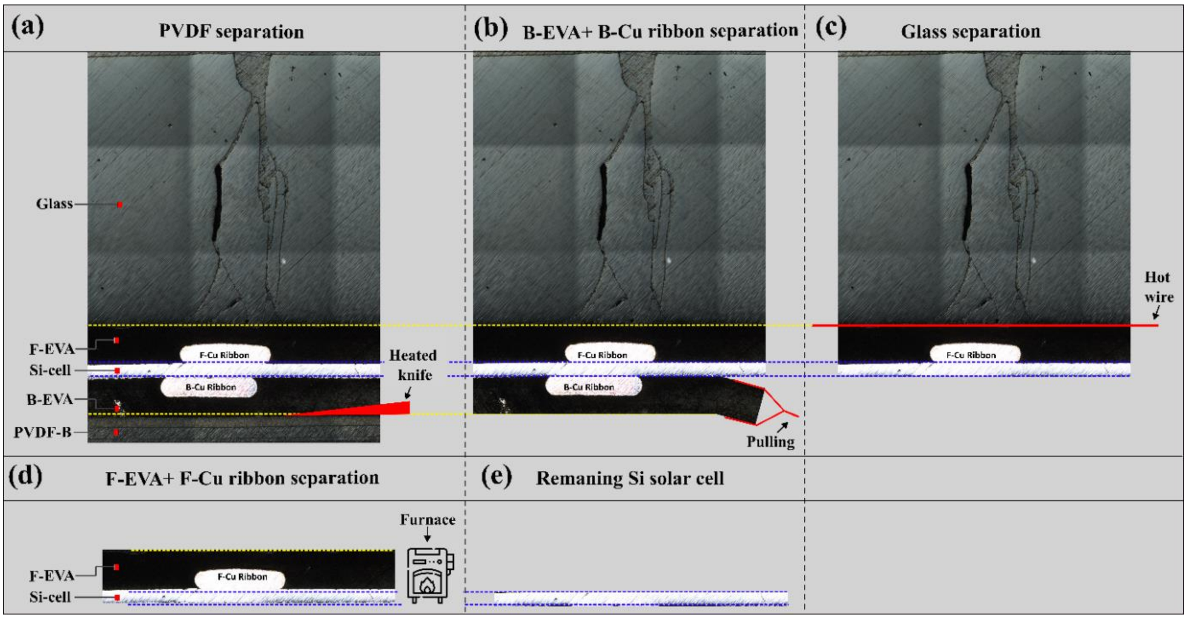

Fig. 13. Evaluation of samples subjected to the sequential steps for the separation process. a) PVDF back sheet, b) back EVA encapsulant and copper ribbon, c) tempered glass, d) front EVA encapsulant and copper ribbon after thermal treatment, e) silicon solar cell [56,57,58]

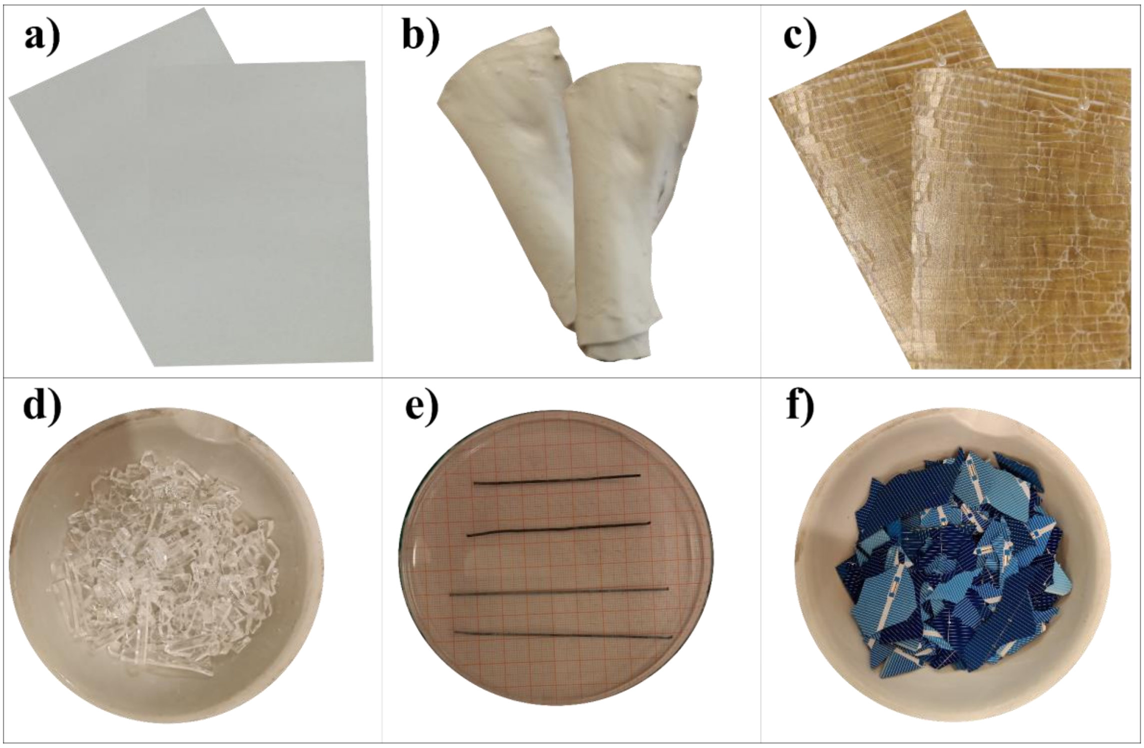

Fig. 14. Separated and recovered materials. a) PVDF back sheet, b) back EVA Encapsulant, c) tempered glass, d) tempered glass after thermal treatment, e) copper ribbon, f) silicon solar cell [56,57,58]

5. PV WASTE RECYCLING CHALLENGES

The recycling of photovoltaic (PV) waste faces numerous obstacles that prevent efficient recycling and sustainability. Technologically, current methods are inefficient in key areas, especially in the separation phase (delamination), where different layers of a PV module are detached [59]. The structure of PV modules, which are designed to withstand harsh environmental conditions, makes disassembly and material recovery difficult. While the proposed mechanical or physical methods for this purpose are effective, they often result in a heterogeneous mixture of materials that requires complex separation processes, usually yielding low purity and limited recovery of materials. Furthermore, these methods consume substantial energy and generate dust, which poses additional environmental and health risks. Thermal treatments, which require high temperatures to break down the encapsulation materials, can lead to the release of harmful by-products. These emissions include volatile organic compounds (VOCs), carbon monoxide (CO), and halogenated hydrocarbons, which poses a serious risk to the environment due to their corrosive and toxic nature [21, 60, 61, 62]. Chemical approaches, e.g., with solvents such as toluene, allow lower processing temperatures and are promising for layer separation. However, these chemicals are often associated with environmental risks due to their toxicity, longevity, and potential health risks [60]. In addition to technological hurdles, the recycling of PV waste is also hindered by market dynamics, logistical problems, and legal restrictions. The current limited waste volumes, often below 10000 tons, undermine economic feasibility by preventing economies of scale. Furthermore, inadequate waste collection networks create additional market barriers and complicate the logistics of gathering end-of-life PV modules from various regions, especially those with limited infrastructure [63, 64]. The absence of specific regulations makes standardized handling and disposal difficult. Without a comprehensive framework, the varied recycling methods lead to complexity and uncertainty. Collectively, these challenges significantly hinder the global adoption of crystalline silicon (c-Si) recycling and delay progress towards an environmentally sustainable infrastructure. Addressing these issues requires coordinated international policies, improved collection and recycling systems, and technological innovation for effective separation and recovery of materials from end-of-life PV modules.

6. FUTURE OUTLOOK AND RECOMMENDATIONS

The recycling of photovoltaic (PV) waste is important for sustainable economic and environmental practices, as it enables the recovery of valuable resources and reduces the environmental impact. To create an efficient recycling process and a sustainable life cycle for PV modules, a circular economy approach is required that encompasses all stages of the PV life cycle—manufacturing, use, and end-of-life"—and focuses on minimizing material losses and maximizing resource recovery [2]. Fig. 15 illustrates this framework: Green arrows indicate best pathways, red arrows indicate worst pathways, and blue and brown arrows represent upcycling and downcycling options, respectively. In the manufacturing phase, it is important to increase production efficiency to minimize material waste and develop durable PV panels. This can mean selecting materials that facilitate recycling and reuse and promoting modular designs for simple disassembly and repair. For example, using dissolvable sealants that do not damage other components or layer materials for easier separation, which can simplify disassembly and improve resource recovery, Extending the lifetime of PV modules by 2–3 years could reduce the amount of waste by an estimated 2–3 million tons by 2050 [65] and thus improve the economic feasibility of recycling through efficient material recovery [1, 2]. In addition, the recovery of production waste helps to maintain a closed loop and ensure that the recovered materials are reintegrated into new PV modules. In the usage phase, the focus shifts to extending the longevity of PV modules through repair and reuse. Repairing and reusing worn or defective modules reduces disposal and conserves resources. By introducing systems to repair and resell used modules, these are brought back onto the market, reducing the demand for new materials. Addressing common causes of premature failure, such as weather-related damage, can further extend the life of solar modules. Extending the lifespan strengthens recycling initiatives and contributes to a sustainable PV sector [1]. In the end-of-life phase, efficient recycling methods for irreparable components are essential. The use of cost-effective techniques to separate all materials for recycling is crucial. Care must be taken during dismantling, collection, and transportation to ensure that the integrity of the components is maintained. Disassembly and preliminary recycling close to the point of use can improve economic feasibility by reducing logistics costs, maintaining component quality, and improving recycling efficiency. For these strategies to succeed, collaboration between governments and industry is essential to incentivize a circular economy across the PV lifecycle. Such partnerships can lead to robust regulatory frameworks that enforce global recycling standards and thus promote the widespread adoption of PV recycling [2]. Although low PV waste volumes currently pose an economic challenge for recycling facilities, this hurdle will decrease as PV waste volumes are expected to reach 8 million tons by 2030. This growth will increase economic feasibility as economies of scale make recycling more cost-effective and sustainable. Through a coordinated approach that includes regulatory support and economic incentives, the PV industry can achieve better recyclability, promote environmental sustainability, and drive a resource-efficient future for PV that conserves resources, minimizes waste, and significantly reduces the environmental impact of solar technology [66, 67].

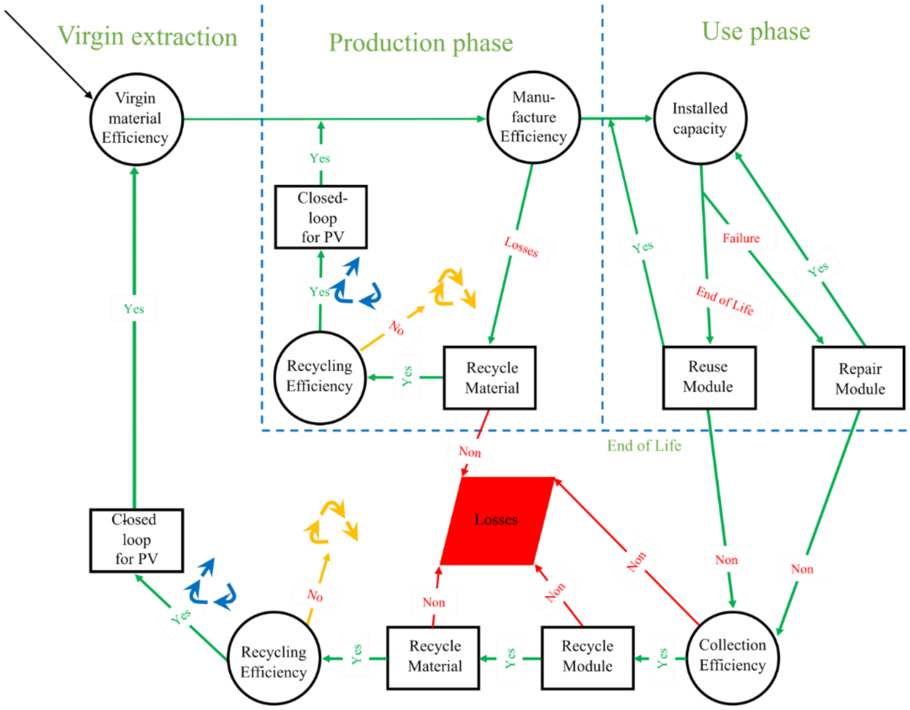

Fig. 15. Diagram illustrating the life cycle of photovoltaic (PV) panels and proposed waste management strategies. Green arrows indicate best pathways, red arrows indicate worst pathways, and blue and brown arrows represent upcycling and downcycling options, respectively

7. CONCLUSION

The expanding deployment of photovoltaics (PV) underscores solar energy's critical role in sustainable electricity generation. However, as first-generation PV modules approach the end of their lifespan, the industry is faced with a significant increase in PV-related waste, which is expected to rise to 78 million tons by 2050. Managing this incoming waste effectively is important to reduce environmental hazards and achieve economic benefits through the recovery of materials. The path to efficient PV waste recycling is hindered by notable challenges, including technological limitations, logistical barriers, and legal challenges. From a technological standpoint, current recycling methods struggle with the complex, multi-layered structure of PV modules, which complicates the delamination process and diminishes material quality, lowering recycling efficiency. On the economic front, limited PV waste volumes and fragmented collection systems drive up logistics costs and hinder scalability. With solar module waste projected to reach approximately 8 million tons by 2030, the economic feasibility of recycling is anticipated to increase substantially. Insufficient waste collection systems pose additional market challenges, making it difficult for recyclers to gather end-of-life PV modules from various regions. Inconsistent legislation in different regions further complicates matters. Although the European Union has issued directives such as the Waste Electrical and Electronic Equipment Directive that require the recycling of photovoltaic systems, many countries do not have specific guidelines, which leads to inconsistent handling and disposal practices. This regulatory gap hinders the global adoption of effective recycling strategies and results in valuable materials ending up in landfills or incinerators. A circular economy framework is key to overcoming these barriers. Waste reduction strategies should focus on efficient production practices, durable materials, and modular designs to facilitate disassembly and minimize disposal. Reuse programs must incorporate repair and refurbishment systems that extend the life of modules and reduce the need for raw materials. Recycling initiatives require cost-effective, high-yield processes and local facilities to reduce transportation costs and keep materials intact. Cooperation between government and industry is essential to developing coherent regulatory standards and support mechanisms that enable recycling throughout the life cycle of PV modules. By proactively addressing technological and economic constraints alongside regulatory support, the PV industry can turn the challenge of PV waste into an opportunity for innovation and sustainable growth.

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REFERENCES

1. IRENA 2019. Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper). International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/publications/2019/Nov/Future-of-Solar-Photovoltaic
2. IRENA and IEA-PVPS 2016. End-of-Life Management: Solar Photovoltaic Panels. International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems. https://www.irena.org/publications/2016/Jun/End-of-life-management-Solar-Photovoltaic-Panels
3. BIO Intelligence Service on European Commission, DG ENV 2011. Study on photovoltaic panels supplementing the impact assessment for a recast of the WEEE Directive. A project under the Framework contract ENV.G.4/FRA/2007/0067, FINAL REPORT, 14 April 2011. https://ec.europa.eu/environment/pdf/waste/weee/Study%20on%20PVs%20Bio%20final.pdf
4. Padoan, FC, Altimari, P and Pagnanelli, F 2019. Recycling of end of life photovoltaic panels: a chemical prospective on process development. Solar Energy 177, 746–761. https://doi.org/10.1016/j.solener.2018.12.003
5. Fraunhofer Institute for Solar Energy Systems ISE 2024. Recent Facts about Photovoltaics in Germany. Fraunhofer ISE, April 2024. https://www.ise.fraunhofer.de
6. IEA PVPS 2022. Status of PV Module Recycling in Selected IEA PVPS Task 12 Countries. IEA-PVPS T12-24:2022. https://iea-pvps.org/key-topics/status-of-pv-module-recycling-in-selected-iea-pvps-task12-countries/
7. Pizzini, S 2010. Towards solar grade silicon: challenges and benefits for low cost photovoltaics. Solar Energy Materials and Solar Cells 94(9), 1528–1533. https://doi.org/10.1016/j.solmat.2010.01.016
8. Hoover, H, Bell, R and Rippy, K 2024. Emerging technologies for decarbonizing silicon production. Journal of Sustainable Metallurgy. https://doi.org/10.1007/s40831-024-00913-3
9. Niclas 2015. Solar Cell Production: From silicon wafer to cell. Sinovoltaics (Hong Kong Office), 15 October 2015. https://sinovoltaics.com/solar-basics/solar-cell-production-from-silicon-wafer-to-cell/
10. Søiland, A, Meatza, Id, Muguruza, A, Xu, Y and Bellmann, M 2024. Silicon kerf loss as a potential anode material for lithium-ion batteries. Frontiers in Photonics 5. https://doi.org/10.3389/fphot.2024.1332830

11. American Chemical Society 2014. How a Solar Cell Works. ChemMatters, American Chemical Society. https://www.acs.org/education/chemmatters/past-issues/archive-2013-2014/how-a-solar-cell-works.html
12. Kim, J, Park, J, Hong, JH, Choi, SJ, Kang, G, Yu, G and Song, H 2012. Double antireflection coating layer with silicon nitride and silicon oxide for crystalline silicon solar cell. Journal of Electroceramics 30(1-2), 41–45. https://doi.org/10.1007/s10832-012-9710-y
13. Ma, S, Zhang, M, Feng, L, Wang, H and Bai, J 2017. Effects of screen printing and sintering processing of front side silver grid line on the electrical performances of multi-crystalline silicon solar cells. Journal of Materials Science: Materials in Electronics 28(16), 11934–11949. https://doi.org/10.1007/s10854-017-7003-6
14. Guo, G, Gan, W, Feng, X, Jin-ling, Z, Zhou, H, Liu, H, … and Luo, J 2010. Effect of dispersibility of silver powders in conductive paste on microstructure of screen-printed front contacts and electrical performance of crystalline silicon solar cells. Journal of Materials Science: Materials in Electronics 22(5), 527–530. https://doi.org/10.1007/s10854-010-0172-1
15. Grohe, A, Preu, R, Glunz, SW and Willeke, G 2006. Laser applications in crystalline silicon solar cell production. SPIE Proceedings. https://doi.org/10.1117/12.663225
16. Oh, C, Kim, A, Kim, J, Bang, J, Ha, J and Hong, WS 2015. Bonding copper ribbons on crystalline photovoltaic modules using various lead-free solders. Journal of Materials Science: Materials in Electronics 26(12), 9721–9726. https://doi.org/10.1007/s10854-015-3640-9
17. Huang, WH, Shin, W, Wang, L, Sun, W and Tao, M 2017. Strategy and technology to recycle wafer-silicon solar modules. Solar Energy 144, 22–31. https://doi.org/10.1016/j.solener.2017.01.001
18. Maani, T, Celik, I, Heben, MJ, Ellingson, RJ and Defne, A 2020. Environmental impacts of recycling crystalline silicon (c-SI) and cadmium telluride (CDTE) solar panels. Science of The Total Environment 735. https://doi.org/10.1016/j.scitotenv.2020.138827
19. Dias, PR, Javimczik, S, Benevit, M and Veit, H 2017. Recycling WEEE: Polymer characterization and pyrolysis study for waste of crystalline silicon photovoltaic modules. Waste Management 60, 716–722. https://doi.org/10.1016/j.wasman.2016.08.036
20. Camargo, PSS, Domingues, A.da-S, Palomero, JPG, Kasper, AC, Dias, PR and Veit, HM 2021. Photovoltaic module recycling: thermal treatment to degrade polymers and concentrate valuable metals. Journal of Sustainable Metallurgy 16, 48–62. https://doi.org/10.31025/2611-4135/2021.15119
21. Danz, P, Aryan, V, Möhle, E & and Nowara, N 2019. Experimental study on fluorine release from photovoltaic backsheet materials containing PVF and PVDF during pyrolysis and incineration in a technical lab-scale reactor at various temperatures. Toxics 7(3), 47. https://doi.org/10.3390/toxics7030047
22. Domínguez, A and Geyer, R 2017. Photovoltaic waste assessment in Mexico. Resources, Conservation & Recycling 127(C), 29–41. https://doi.org/10.1016/j.resconrec.2017.08.013
23. Grandell, L and Thorenz, A 2014. Silver supply risk analysis for the solar sector. Renewable Energy 69, 157–165. https://doi.org/10.1016/j.renene.2014.03.032
24. Brian 2023. Processes for the assembly and production of solar panels. Professional Distributed PV Module Manufacturer, 26 July. https://www.maysunsolar.com/blog-processes-for-the-assembly-and-production-of-solar-panels/
25. Deng, R, Chang, NL, Ouyang, Z and Chong, CM 2019. A techno-economic review of silicon photovoltaic module recycling. Renewable and Sustainable Energy Reviews 109, 532–550. https://doi.org/10.1016/j.rser.2019.04.020

26. Berger, W, Simon, F, Weimann, K and Alsema, EA 2010. A novel approach for the recycling of thin-film photovoltaic modules. Resources, Conservation and Recycling 54, 711–718. https://doi.org/10.1016/j.resconrec.2009.12.001
27. Lunardi, MM, Alvarez-Gaitan, JP, Bilbao, JI and Corkish, R 2018. A review of recycling processes for photovoltaic modules. Solar Panels and Photovoltaic Materials. https://doi.org/10.5772/intechopen.74390
28. Yu, H, Hasanuzzaman, M, Rahim, NA, Amin, N and Adzman, NN 2022. Global challenges and prospects of photovoltaic materials disposal and recycling: a comprehensive review. Sustainability 14(14), 8567. https://doi.org/10.3390/su14148567
29. Council of the European Union & European Parliament 2012. Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). Official Journal of the European Union, 24 July. https://eur-lex.europa.eu/eli/dir/2012/19/oj
30. Council of the European Union & European Parliament 2024. Directive (EU) 2024/884 amending Directive 2012/19/EU on waste electrical and electronic equipment (WEEE). Official Journal of the European Union, 19 March. https://eur-lex.europa.eu/eli/dir/2024/884/oj
31. Jung, B, Park, J, Seo, D and Park, N 2016. Sustainable system for raw-metal recovery from crystalline silicon solar panels: from noble-metal extraction to lead removal. ACS Sustainable Chemistry & Engineering 4, 4079–4083. https://doi.org/10.1021/acssuschemeng.6b00894
32. Vellini, M, Gambini, M and Prattella, V 2017. Environmental impacts of PV technology throughout the life cycle: importance of the end-of-life management for Si-panels and CdTe-panels. Energy 138, 1099–1111. https://doi.org/10.1016/j.energy.2017.07.031
33. Xu, C, Isabella, O and Vogt, MR 2024. Future material demand for global silicon-based PV modules under net-zero emissions target until 2050. Resources, Conservation and Recycling 210, 107824. https://doi.org/10.1016/j.resconrec.2024.107824
34. IEA 2023. Critical Minerals Market Review 2023. International Energy Agency, Paris. https://www.iea.org/reports/critical-minerals-market-review-2023
35. IEA 2022. Potential contribution of module recycling to solar PV material demand under the Net Zero Scenario for selected materials, 2022–2050. International Energy Agency, Paris. https://www.iea.org/data-and-statistics/charts/potential-contribution-of-module-recycling-to-solar-pv-material-demand-under-the-net-zero-scenario-for-selected-materials-2022-2050
36. Mehedi, T, Gemechu, E and Kumar, A 2022. Life cycle greenhouse gas emissions and energy footprints of utility-scale solar energy systems. Applied Energy 314, 118918. https://doi.org/10.1016/j.apenergy.2022.118918
37. Müller, A, Wambach, K and Alsema, E 2005. Life cycle analysis of solar module recycling process. MRS Proceedings 895. https://doi.org/10.1557/proc-0895-g03-07
38. Aluminum Association 2023. Recycling and Sustainability in the Aluminum Industry. Aluminum Association. Available at https://www.aluminum.org/Recycling
39. Circular Economy European Union Platform 2023. Environmental and Economic Benefits of Aluminum Recycling. European Circular Economy Stakeholder Platform. Available at https://circulareconomy.europa.eu/platform/sites/default/files/euric_metal_recycling_factsheet.pdf
40. Glass Futures 2024. Recycling and the Glass Industry: A Match Made in Heaven. Available at https://www.glass-futures.org/article/?p=CNlIJhQ0QJmugmzbF56Fo4aKAxGlolLFjbdHMgoeqOLevKl8A2zQE01
41. Xu, C, Li, B, Yuan, X, Liu, C, Shen, C and Dai, G 2019. Separation of backsheets from waste photovoltaic (PV) modules by ultrasonic irradiation. IOP Conference Series: Earth and Environmental Science 242, 032046. https://doi.org/10.1088/1755-1315/242/3/032046

42. Granata, G, Pagnanelli, F, Moscardini, E, Havlik, T and Toro, L 2014. Recycling of photovoltaic panels by physical operations. Solar Energy Materials and Solar Cells 123, 239–248. https://doi.org/10.1016/j.solmat.2014.01.012
43. Paiano, A 2015. Photovoltaic waste assessment in Italy. Renewable and Sustainable Energy Reviews 41, 99–112. https://doi.org/10.1016/j.rser.2014.07.208
44. Tokoro, C, Nishi, M and Tsunazawa, Y 2021. Selective grinding of glass to remove resin for silicon-based photovoltaic panel recycling. Advanced Powder Technology 32(3), 841–849. https://doi.org/10.1016/j.apt.2021.01.030
45. Sim, Y, Tay, YB, Pham, HK and Mathews, N 2023. A facile crush-and-sieve treatment for recycling end-of-life photovoltaics. Waste Management 156, 97–106. https://doi.org/10.1016/j.wasman.2022.11.023
46. Wahman, M and Surowiak, A 2022. Recycling of discarded photovoltaic modules using mechanical and thermal methods. Inżynieria Mineralna 1, 107–116. https://doi.org/10.29227/im-2022-01-13
47. Wang, TY, Hsiao, JC and Du, JH 2012. Recycling of materials from silicon base solar cell module. Conference Record of the IEEE Photovoltaic Specialists Conference 2355–2358. https://doi.org/10.1109/PVSC.2012.6318071
48. Park, J, Kim, W and Cho, N 2016. An eco-friendly method for reclaimed silicon wafers from a photovoltaic module: from separation to cell fabrication. Green Chemistry 18, 1706–1714. https://doi.org/10.1039/C5GC01819F
49. Lee, JK, Lee, JS and Ahn, YS 2018. Efficient recovery of silver from crystalline silicon solar cells by controlling the viscosity of electrolyte solvent in an electrochemical process. Applied Sciences 8, 2131. https://doi.org/10.3390/app8112131
50. Doi, T, Tsuda, I, Unagida, H, Murata, A, Sakuta, K and Kurokawa, K 2001. Experimental study on PV module recycling with organic solvent method. Solar Energy Materials and Solar Cells 67(1–4), 397–403. https://doi.org/10.1016/S0927-0248(00)00308-1
51. Azeumo, MF, Germana, C, Ippolito, NM, Medici, F, Piga, L and Settimio, S 2019. Photovoltaic module recycling, a physical and a chemical recovery process. Solar Energy Materials and Solar Cells 193, 314–319. https://doi.org/10.1016/j.solmat.2019.01.035
52. Vaněk, J, Jandova, K, Vanýsek, P and Maule, P 2023. Chemical delamination applicable to a low-energy recycling process of photovoltaic modules. Processes 11(11), 3078. https://doi.org/10.3390/pr11113078
53. Min, R, Deng, W, Wang, Z, Qi, T, Zhang, Z, Xiao, W, … and Wang, D 2024. Effective decapsulation method for photovoltaic modules: limonene-induced EVA controlled swelling under sonication and debonding mechanism analysis. Journal of Cleaner Production 450, 141917. https://doi.org/10.1016/j.jclepro.2024.141917
54. Kamano, K, Jaroenkhasemmeesuk, C, Chaisartra, C, Thoopkaew, T and Tippayawong, N 2022. Glass separation process for recycling of solar photovoltaic panels by microwave heating. AIP Conference Proceedings. https://doi.org/10.1063/5.0115199
55. Królkowski, M, Fotek, M, Żach, P and Michałowski, M 2024. Development of a recycling process and characterization of EVA, PVDF, and PET polymers from end-of-life PV modules. Materials 17(4), 821. https://doi.org/10.3390/ma17040821
56. Wahman, M, Surowiak, A, Berent, K and Szymczak, P 2023. Eco-efficient removal of polymer back sheet fraction and material separation from solar cell waste. Solar Energy 264, 112085. https://doi.org/10.1016/j.solener.2023.112085
57. Wahman, M, Surowiak, A and Ebin, B 2024. PV back sheet recovery from c-Si modules using hot knife technique. Solar Energy Materials and Solar Cells 276, 113067. https://doi.org/10.1016/j.solmat.2024.113067

58. Surowiak, A and Wahman, M 2024. Thermal–mechanical delamination for recovery of tempered glass from photovoltaic panels. Energies 17, 4444. https://doi.org/10.3390/en17174444
59. Kuczyńska-Łażewska, A and Klugmann-Radziemska, E 2018. Key issues of the recycling process of used photovoltaic modules of the 1st and 2nd generation. Scientific Papers of the Institute of Mineral and Energy Economy, Polish Academy of Sciences 102, 329–342. https://9lib.org/document/yr3k66oy-key-issues-recycling-process-generation-life-photovoltaic-modules.html
60. Brenes, GH, Riech, I, Giácoman-Vallejos, G, González-Sánchez, A and Rejón, V 2023. Chemical method for ethyl vinyl acetate removal in crystalline silicon photovoltaic modules. Solar Energy 263, 111778. https://doi.org/10.1016/j.solener.2023.05.055
61. Ellis, D, Mabury, SA, Martin, JW and Muir, DC 2001. Thermolysis of fluoropolymers as a potential source of halogenated organic acids in the environment. Nature 412(6844), 321–324. https://doi.org/10.1038/35085548
62. Fiandra, V, Sannino, L, Andreozzi, C, Corcelli, F and Graditi, G 2019. Silicon photovoltaic modules at end-of-life: removal of polymeric layers and separation of materials. Waste Management 87, 97–107. https://doi.org/10.1016/j.wasman.2019.02.004
63. Faircloth, CC, Wagner, KH, Woodward, K, Rakkwamsuk, P and Gheewala, SH 2019. The environmental and economic impacts of photovoltaic waste management in Thailand. Resources, Conservation and Recycling 143, 260–272. https://doi.org/10.1016/j.resconrec.2019.01.008
64. Peplow, M 2022. Solar panels face recycling challenge. ACS Central Science 8(3), 299–302. https://doi.org/10.1021/acscentsci.2c00214
65. U.S. Department of Energy. Beyond Recycling: Reducing Waste from Solar Modules Before They're Even Made. Office of Energy Efficiency and Renewable Energy, n.d. https://www.energy.gov/eere/solar/articles/beyond-recycling-reducing-waste-solar-modules-theyre-even-made
66. Saidani, M, Yannou, B, Leroy, Y, Cluzel, F and Kendall, A 2019. A taxonomy of circular economy indicators. Journal of Cleaner Production 207, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014
67. Silvana, O, Mirletz, H and Sridhar, S 2022. PV in the circular economy, a dynamic framework analyzing technology evolution and reliability impacts. iScience 25(1), 103488. https://doi.org/10.1016/j.isci.2021.103488