

Review

Recent Progress in the Recovery and Recycling of Polymers from End-of-Life Silicon PV Modules

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Abstract: Solar photovoltaic (PV) technology has emerged as the most preferred source of clean energy generation and has been deployed at a large scale. However, end-of-life management of the PV modules is a critical issue that has garnered the recent attention of lawmakers and researchers alike. Consequently, several researchers are actively developing technology to recycle the end-of-life PV modules. Since silicon PV modules account for more than 90% of the modules deployed globally, most of these efforts are focused on recycling crystalline silicon PV modules. Researchers have primarily focused on recovering pure silver from the contacts and pure Si from the solar cells. However, to ensure complete recyclability of such panels, the different polymers used in these modules must also be recycled. This review addresses the issue of recycling the polymers from end-of-life c-Si modules. Scopus and Google Scholar were used to search for the relevant literature. This review presents the current state-of-the-art technology related to polymer recycling found in the PV modules, the challenges encountered in their recycling, and the outlook. While research on the recycling of polymers has progressed in the last few decades, the instances of their applications in the recycling of polymers from PV panels are rarely reported in the literature. In this work, certain technical pathways, which can be employed to recycled polymers obtained from end-of-life PV panels, are presented. Recycling the polymers from the end-of-life silicon PV modules is crucial for improving the sustainability of solar PV technology.

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1. Introduction

Solar photovoltaic (PV) technology has emerged as the most preferred source of generating clean energy due to the unique properties of being scalable, affordable, and having a net negative energy balance over its lifetime [1–4]. The global installed-PV capacity increased to 1.6 TW in 2024 and is expected to rise further to 4.5 TW by 2050 as the efforts to minimize the emission of greenhouse gases continues on a global scale [5,6]. With the increase in the deployment of solar panels, there is a corresponding increase in the discarded solar panels that have reached the end of their useful service life, commonly referred to as end-of-life (EOL) PV panels. Silicon (Si) solar panels occupy almost 95% of the market share of the newly shipped modules [7] and hence are also expected to form a major portion of the discarded panels [8,9]. A typical PV module has a lifetime of 20–25 years. However not all modules remain active for this duration. Damage to the modules can occur during production, transportation, handling, or installation. Due to various faults, some modules will stop functioning after a shorter time [8,10]. Some modules are

discarded even before shipping, during testing at the manufacturing location, and are called factory reject modules. In some cases, large scale PV power plants replace the functioning PV modules of an older technology with modules featuring recent technologies and higher efficiencies. Extreme weather events such as hail, typhoons, and lightning strikes can cause damage to PV modules and cause them to be discarded [11,12]. The global cumulative PV waste is estimated to reach up to 8 Mt by 2030 and 78 Mt by 2050 [6,13,14]. It has also been estimated that the weight of PV panels discarded annually by 2050 (6 Mt) could almost equal the mass of new PV installations (6.7 Mt) [9]. Hence, establishment of a waste management system particularly for handling PV waste is crucial for maintaining the sustainability of energy generation through PV technology and for the protection of the environment from the harmful effects of PV waste. Figure 1 shows the potential value creation through EOL PV waste management as estimated in the IEA PVPS report on the management of EOL PV waste [9]. The value creation shown in Figure 1, USD 450 million in 2030 and USD 15 billion in 2050, only accounts for the direct revenue generated by the recovery of the materials from the PV modules, such as glass, metals, and high-quality silicon. The waste management of EOL PV modules would also have an indirect positive impact on the economy through the creation of new direct and indirect industries which would generate more employment opportunities. For example, the collection and transportation of PV panels itself can be a separate industry. Similarly, industries may focus on extracting only certain materials such as glass and aluminum (Al) frames from the PV panels and discarding the rest. The glass can be sold as raw materials to the industry fabricating new solar glass while Al can be sold to a metal recycling facility. The discarded part of the panels waste could become raw materials for some other industry, which could use specialized processes for recovering the metals and Si. The Si recovered here could be sold to a specialized silicon purification and production unit for the production of Si ingots. The metal extracted from the panels such as Ag, Cu, and Sn can be sold to metal paste manufacturers or to other industries specializing in the downstream application of such metals. Alternatively, all of these processes could be carried out at one location in an integrated recycling facility.

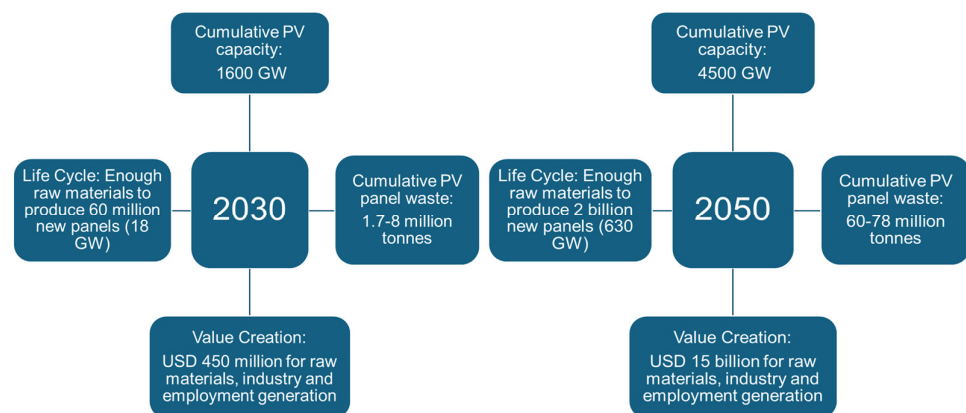


Figure 1. Potential value creation through PV end-of-life management. Adapted from [9].

While the increasing amount of PV waste constitutes a challenging problem, the effective management of such waste could provide several economic and social benefits. It has been estimated that recycling EOL PV panels could generate USD 450 million by 2030 and 15 billion by 2050 [9,15,16]. EOL PV panels can be either repaired and reused, up-cycled for different purposes, and disposed of or recycled using close-loop or open-loop options [17]. An EOL PV panel can be disposed of by incineration, dumping, or landfilling. The incineration of PV panels, while easier, is not an environmentally friendly option as

the incineration of PV panels can require higher temperatures and releases several hazardous gaseous emissions. Disposing the modules in a dump or landfill is also not favorable, especially as the PV modules contain several recyclable and valuable materials such as glass, aluminum, copper, silver, and silicon. Recovering and recycling these materials can not only provide economic opportunities but also reduce the energy consumption resulting from the production of virgin materials [18–20].

The PV recycling process usually comprises four steps—disassembly, delamination, material sorting, and material extraction [21]. These steps may further comprise several individual steps [12,22,23]. The PV recycling process begins with the disassembly of the external aluminum frame, the junction box, and the external copper wiring. This is among the easiest steps of the recycling process and can be performed manually or by using a custom-built machine. They can either be recycled onsite, sent to another facility for recycling, or be reused entirely [24]. It has been reported that in certain instances, the commercial recycling of PV panels could comprise only these steps while the remaining unframed panels or PV laminates, along with the glass and the solar cells, are discarded by dumping or landfilling [25].

Figure 2 shows the varied materials used in a PV panel in terms of their percentage mass and the percentage monetary value [17]. Almost 80% of the mass of the solar panels is concentrated in the glass and aluminum frame which together can contribute about 85% of the mass of the solar panel. However, in terms of the recovered value, they account for $\approx 30\%$ of the value. While the analysis presented here is for a typical glass-backsheet type module, with glass on the front and a polymer backsheet on the rear side, the values for the mass and monetary values can be slightly different for glass-glass modules, frameless modules, and other such variations in module design. However, overall, the proportion of the mass and monetary value is not expected to change much. A Si PV panel may have Al, Ag, Cu, Ni, Pb, and Sn and some extremely small quantities of Cd [21]. Ag, Al, Cu, Cd, Ni, Pb, and Sn are usually found in the metal contacts on the solar cells and in the soldered interconnections between the solar cells [26–31]. Additionally, Al, Cu, and Sn can be found in the metal strips used as end connectors in the module [32,33]. Out of these, Ag is the most valuable metal (albeit not the easiest) that can be recovered from the module and can contribute more than 45% of the value of the materials recovered from a PV module. Several researchers have pointed towards the extraction of Ag to be crucial for the economic viability of the recycling process [34–46]. It is also essential for achieving sustainability at a terawatt scale, since the PV industry is the largest consumer of Ag [47–49]. Al and Cu are among the other valuable metals that can be extracted from the PV modules. In some physical recycling processes, such as those used in Veolia plants, the silicon solar cells along with the metal grid (Ag, Al) are usually considered as the products which are sent to other industries to extract metals from [50]. The materials recovered from the PV panels, in the increasing order of complexity, could be aluminum (frame) < glass < copper conductors < silver < other metals < silicon < polymers [21].

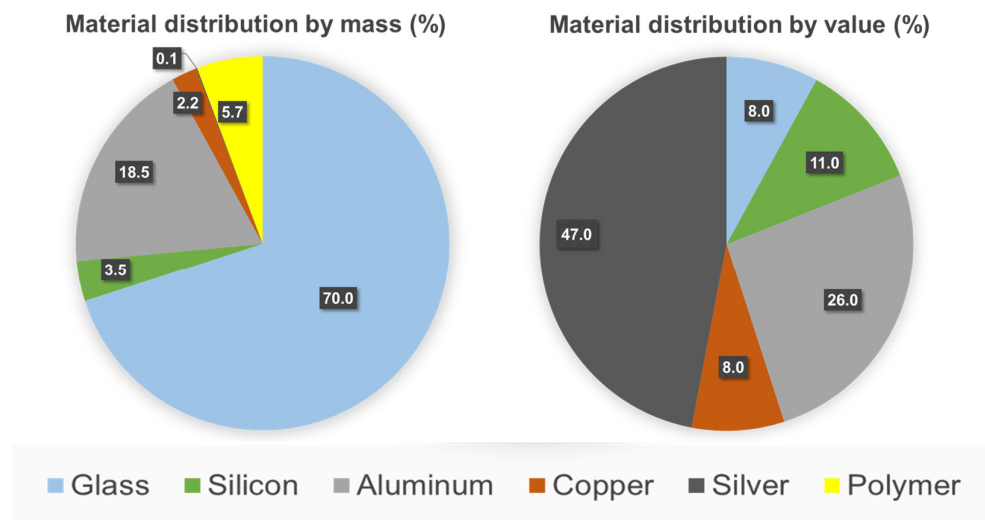


Figure 2. Mass (left) and value (right) of materials recoverable from a c-Si PV module [17].

Several researchers have reviewed the technical aspects of the recycling of EOL PV panels in recent years [12,22,23,25,51–58]. Researchers have also analyzed the recycling of the EOL Si PV panels using life cycle assessments [16,59–67]. While in all these reviews, the necessity of recycling EOL PV modules has been clearly outlined, most of these have only focused on the recovery of glass metals and silicon from the PV modules. The recycling of polymers had been mostly overlooked due to the complex process and the low value of the recovered material. The polymers are mostly burned or pyrolyzed to obtain more expensive materials. However, the recycling of polymers is a crucial step in improving the sustainability of the PV modules and further reducing their impact on the environment [61,68–72].

The objective of this review is to understand the progress made and existing technological barriers in the recycling of polymers from EOL PV modules. Databases such as Google Scholar, Web of Science, and ScienceDirect were primarily used to obtain the literature. Several reports from various organizations and press releases from industries were also used in this review. In this work, the introduction (Section 1) provides an overview of the research efforts in recycling EOL c-Si PV modules, followed by a short description of the health hazards caused by PV modules discarded by landfilling (Section 2) to highlight the necessity of recycling polymers from EOL PV modules. Section 3 describes the different polymers used in c-Si PV modules while in Section 4, the different processes used for separating these polymers from the EOL PV modules are described. Section 5 describes the different technological pathways of recycling the different polymers found in EOL PV modules. Section 6 briefly discusses the policies and commercial efforts in recycling PV panels. Section 7 present the challenges in recycling polymers, the techno-economical assessment of the recycling process, and the outlook for recycling polymers from EOL PV panels. This review aims to present the possible pathways of recycling polymers from EOL PV modules and tries to provide research direction, based on the assessment of the published literature, to improve the total circularity of Si PV modules. While the policies and economic feasibility of these processes has been briefly discussed, a detailed analysis of such factors on the recycling process of polymers from EOL PV modules is beyond the scope of this work.

2. Health, Safety, and Environmental Aspects of EOL PV Modules

The EOL PV modules can be managed in one of the following three ways—landfilling, reusing, and recycling [17,73,74]. Landfilling is the most common practice for disposing EOL PV modules. In some instances, the aluminum frame and the external wires are removed and the remaining modules, including the glass and the solar cells, are sent to landfills [25]. If the landfills are not properly isolated from the underlying soil, toxic runoff from the decomposing modules under the action of water and sunlight can seep into the earth, polluting the underlying soil and, in some cases, the groundwater [60,75]. Furthermore, these leachates can mix with rainwater and become washed off into the local streams, polluting rivers and irrigation water supplies. This can cause serious damage to aquatic plants and animals and further contribute to irreversible river water pollution [18,76]. The toxic metals from PV leachate can include lead, cadmium, arsenic, indium, molybdenum, and gallium [57,75,77,78]. When ingested, these metals can cause a range of health problems in humans, animals, and plants. If water contaminated with such leachate is used for irrigation, these metals can be absorbed by the plants and transferred to the produce (grains, vegetables, fruits). If the disposed modules catch fire, it can lead to the catastrophic emission of harmful and poisonous gases [79–82]. Most of these gases result from the burning of fluoride polymers used in the PV modules. These emissions could be carried away by winds and reach far distances, causing air pollution over large areas. The polymers used in PV modules are non-biodegradable and can remain in the ecosystem for thousands of years, while their further breakdown can create microplastics that can cause further pollution of the soil and water sources [83–87].

3. Polymer Materials Used in c-Si PV Panels

The polymers used in Si PV modules play two major roles: they are either used as encapsulants or as a backsheet in monofacial modules. Figure 3 shows the different layers in a typical silicon PV module using a polymer backsheet. Such modules are also called glass–backsheet modules.

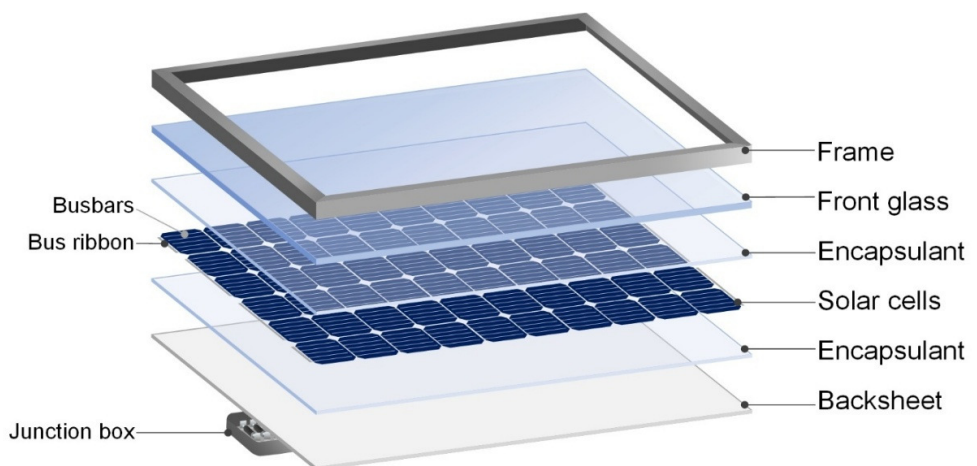


Figure 3. Figure showing the different layers in a typical glass–backsheet Si PV module. Image Source: [88].

3.1. Encapsulants

The encapsulation of solar cells provides protection against air and moisture ingress while allowing maximum light to reach the solar cells. Hence, the main characteristics of encapsulant materials should be optical transparency, chemical and thermal stability, electrical insulation, and mechanical strength. Encapsulation material has the most

prominent impact on the time-related performance decay of the PV modules. Therefore, a suitable material to be used as encapsulant must satisfy a number of criteria [89,90].

Ethyl vinyl acetate (EVA) is the most used encapsulation material in commercial Si PV modules, occupying 70% of the market share in 2023 [7,90]. Polyolefin-based encapsulants (elastomers and thermoplastics) are upcoming materials which are especially used for glass–glass modules. Since they soften at lower temperatures, they are used for the encapsulation of temperature sensitive solar cells technologies such as heterojunction solar cells [7,91]. Recently, researchers have also developed silicon as an alternative to the EVA and polyolefin-based polymers [92,93]. Other suggested alternatives to EVA include polyvinyl butyral, polyurethane, and polyacrylate-based materials [90,94,95]. Silicone-based encapsulants have also been suggested and used as encapsulants [90,93,96–99]. Recently these materials have also been evaluated for long-term outdoor exposure, proving to be a promising material to replace EVA [92,93]. Silicones, especially polydimethylsiloxane (PDMS), have been used as encapsulants [93] and can be recycled using chemical processes [100–104]. A recent initiative to recycle silicone on a commercial scale was announced by Dow and Circuil [105]. However, since EVA is the most widely used encapsulant with more than 60% of the market share [7], the recyclability of EVA is analyzed in this work.

During the encapsulation process, the layers of encapsulation material are placed above and below the stringed solar cells and heated to a certain temperature (300–500 °C) under vacuum conditions. The EVA melts partially and as the temperature decreases, the molten EVA resolidifies, encasing the solar cells in an air-tight lamination and concurrently fusing to the front (glass) and rear (glass/polymer) layers of the module. This process is usually carried out with equipment called laminator. The process could be understood as an advanced and complicated version of the lamination process of paper documents.

The commercially available EVA has a VA content of between 30–40% [89,106]. The VA content is responsible for most of the properties of the EVA (without the additives and stabilizers), which includes optical transparency, density, mechanical stability (flexibility), resistance to weather elements, and radiation increases with increases in VA content. On the other hand, the mechanical hardness, melting temperature, and resistance to chemicals decreases with an increasing VA content [107–111]. Several additives are added to EVA to improve its properties. These include glass adhesive promoters, rheology modifiers, thermal stabilizers, antioxidants, UV stabilizers, and an initiator that helps with initiating the crosslinking of the EVA at the desired temperature [94,106,112–115].

3.2. Backsheets

In glass–backsheet modules, the polymeric backsheet laminate is used at the rear side of the module to provide mechanical stability and protection from natural elements. The backsheets are usually opaque and can be white or black in color [116]. The backsheet laminates are usually composed of polymer layers of different materials and often include additives, modifiers, and fillers [117]. The incorporation of multiple layers allows for designing the appropriate backsheet layer with the desired chemical, electrical, mechanical, optical, and thermal properties depending on the requirements of the module.

There are different ways to classify the backsheet layer, depending on the material, the number of layers, properties, appearance, and lifetime among others. However, classifying the backsheet layer depending on the material also helps in identifying the EOL recycling options. Hence, in this work, the backsheets are classified based on the type of polymers used to manufacture them. Broadly, backsheets can be classified as fluoropolymers (FP) or non-fluoropolymers (nFP). Fluoropolymer backsheets usually include some fluoride in the polymers, the most prominent examples being polyvinyl fluoride (PVF)

and polyvinylidene difluoride (PVDF). They can be applied as multi-layered sheets of a single material or as composite layers of different materials, where at least one layer is made from a fluoropolymer. Commercially, these are the most widely used backsheets [7]. The most widely available fluoropolymer backsheet material is Tedlar® by DuPont™ [118]. Several industries purchase Tedlar® as a raw material and prepare the composite backsheet as an end product. Backsheets made from other fluoropolymers such as PVF and PVDF (without using Tedlar®) are also available. Non-fluoropolymer backsheets are usually made from polyamides (PA), polyethylene terephthalate (PET), or polyolefins (PO). The side of the backsheet that remains exposed to the environment is usually called the outer later/exposed layer while the layer that is adjacent to the encapsulation layer is referred to as the inner layer. Almost all commercially available backsheets are composite layers incorporating an outer layer, a core layer, and an inner layer [116,117,119]. Commonly available FP backsheets have PVF or PVDF layers on the outer and inner layer, while the core is mostly made from a PET layer. The commercially available backsheets based on nFPs also have a triple layer configuration, where PET forms the core layer and is usually the thickest layer [117]. The outer and the inner layers could be made of either PA, PET, or PO.

4. Separation and Recovery of the Polymers

The separation of the different polymer layers such as the backsheet and encapsulant occurs during the delamination in a c-Si PV module. In this section, a discussion will be presented on the different processes of delamination reported in the literature and their effectiveness in partial or complete recovery of the polymers.

4.1. Chemical Delamination

Chemical delamination can effectively remove the polymer layers in the PV panels. Most of the chemical processes are aimed at weakening the interaction between the EVA layer and the PVDF or PET backsheet. The primary aim of these processes is to recover Si wafers rather than the polymers [71,120]. The adhesive EVA layer can be dissolved using organic solvents. However, these solvents may not always facilitate recovery of the dissolved EVA at a later stage. Most chemical processes aim to dissolve the EVA as it responds more easily to the chemical treatment than the tougher backsheet layer. The EVA dissolution in the presence of an organic solvent usually occurs in two stages—solvent diffusion, followed by polymer chain disentanglement [25]. The dissolution process usually starts at the edges where the cross-linked EVA is dissolved first. This usually occurs at the areas where the EVA is more exposed to chemical activity due to any existing imperfections in the adhesion between the glass and the polymer backsheet layer. The dissolution of the edges enables the ingress of the solution inside the EVA matrix. As the reaction proceeds, it results in the formation of a gel-linked layer of EVA which swells. As a result, pressure builds up at these interfaces. The swelling of the EVA and the resulting pressure contribute to the weakening of the adhesion at the glass/backsheet interface [121].

A wide range of chemicals have been used to achieve the separation of EVA and the glass/solar cells/backsheet by aiming to dissolve the EVA. Table 1 lists some of the chemicals used for separating the EVA from the glass, solar cells, and the backsheet, along with the methods used. Acetone, benzene, chloroform, D-limonene, toluene, and hexane can swell the cross-linked EVA and result in its separation [51,71,121–123]. However, extended processing durations are needed for complete dissolution even at higher temperatures [124]. In almost all of these methods, no effort was expended in recovering the EVA or the backsheet. Rubino et al. tried to recover the backsheet while sacrificing the EVA to recover the Si and metals [125]. In recent work, researchers tried to recover a clean

backsheet by dissolving the EVA in chemicals such as ethylene glycol (EG), from which it could be later recovered by processes such as spin coating [21]. For this, the researchers used a two-step process where the pieces of the panels were immersed in the first chemical to allow for swelling of the layers, followed by immersion in the second chemical which completely separated the layers, thus dissolving the EVA.

Table 1. Chemicals used to achieve delamination of the PV modules by dissolving the EVA. The data/information are taken from the sources mentioned under the reference column.

Year	Chemical Used	Process Used	Results	Comments	Reference
2001	Lacquer thinner	Immersion in the liquid at room temperature for 48 h, followed by heating the liquid and polymer to 80 °C for 10 min	Only swelling but no separation	Standalone test for dissolving EVA. Samples were not from actual modules.	[122]
	Acetone		No effect		
	Toluene		Only swelling but no separation		
	Petroleum benzene		Only swelling but no separation		
	Ethanol		No effect		
	Isopropanol		No effect		
	Methyl ethyl Ketone		Only swelling but no separation		
	Methyl isobutyl Ketone		Only swelling but no separation		
	Tetrahydrofuran		Only swelling but no separation		
	Ethylene glycol		No effect		
2016	Trichloroethylene	Immersion in 70 °C for two hours	Separation achieved, complete dissolution after 10 days	EVA and polymers were burned to recover Si.	[121]
	Glycerine		No effect		
2019	Cyclohexane	Immersion in stationary solvent at 90 °C	Separation achieved in 120 min	Aimed to recover glass, no attempts were made to recover the polymers. Polymer fractions were later burnt to recover the glass.	[123]
	D-Limonene		Separation achieved in 30–60 min		
	Tetrahydrofuran		Separation achieved in 60–120 min		
	Toluene		Separation achieved in 30–60 min		
	Chloroform		Only swelling but no separation		
	Acetone		No effect		
2020	Ethyl alcohol	Immersing in a hydrothermal kettle inside a muffle furnace at 200 °C, dried at 130 °C for 8 h	No effect	Aimed at recovering silicon.	[124]
	NaOH + Ethanol		Separation achieved after 4 h of heating in chemical bath		
	KOH + Ethanol		Separation achieved after 4 h of heating in chemical bath		

2021	Toluene	Immersing at atmospheric pressure for 99 h	Complete separation	Recovery of EVA was not attempted.	[51]
2021	Cyclohexane	10 g of crushed material for 120 min at 70 °C in a jacketed cell reactor (250 mL) equipped with a bubble condenser	The separation of Tedlar (backsheet) and EVA.	Tedlar recovered while EVA was combusted to recover metal.	[125]
2025	CHCl ₃	Immersing in atmospheric pressure at 50 °C for 96 h	Swelling, but no separation between EVA and PET	Aimed at recovering the polymers for recycling. No attempts were made to recycle PET. EVA was partially recovered by spin coating.	[21]
	Toluene	Immersing in atmospheric pressure at 90 °C for 96 h	Swelling and partial separation between EVA and PET		
	CHCl ₃ , NaOH + (EG)	Immersing in CHCl ₃ at atmospheric pressure at 50 °C for 24 h, followed by immersing in NaOH + EG at 150 °C for two hours	75% of the samples were delaminated		
	Toluene, NaOH + EG	Immersing in toluene at atmospheric pressure at 80 °C for 24 h, followed by immersing in NaOH + EG at 150 °C for two hours	99% of the samples were delaminated		
	KOH + Methyl alcohol KOH + Ethyl alcohol	Glass + EVA layer dipped in the chemical	Complete removal of EVA from the glass	No attempts were made to recover or recycle the EVA.	[126]
2025	KOH + Propanol	at room temperature in the presence of a non-ionic surfactant (Triton X100)			

Certain additional processes have been investigated to enhance the process kinetics and enable rapid dissolution of the EVA in the chemicals. With the help of ultrasonic irradiation, EVA could be dissolved in toluene, trichloroethylene, benzene, and ortho-dichlorobenzene [127]. The ultrasonic power ranged between 450 W and 900 W, while the temperature of the solvents varied between 55–70 °C. In some cases, the use of ultrasonic power caused pyrolytic reactions; however, the aim was to recover Si along with the metals, hence the breakdown of polymers was not considered an issue. Microwave baths have been shown to increase the swelling of EVA, resulting in complete separation of the polymer layers when processed in trichloroethylene at 70 °C for around 120 min [128]. Using supercritical carbon dioxide (scCO₂) can also help with the separation of the polymers, primarily by dissolving the EVA [129]. A solubilization step is carried at atmospheric pressure prior to the delamination step using an organic solvent. Different solvents were experimented with to find the optimum solvent for solubilization. The temperature of the solubilization for each solvent was kept 20% lower than the boiling point. Ethyl acetate (63 °C), acetone (46 °C), ethyl alcohol (63 °C), isopropyl alcohol (67 °C), dichloromethane (32 °C), hexane (58 °C), and toluene (90 °C) were used in experiments with an agitation of 300 rpm. The process was carried out for different durations ranging from 210–510 min. Finally, toluene was selected as the optimum solvent and with the help of scCO₂,

delamination could be achieved within 60 min [129]. Figure 4 shows an overview of the chemical delamination process, including the additional treatments and the chemicals usually found to be helpful in swelling and separating the polymer layers.

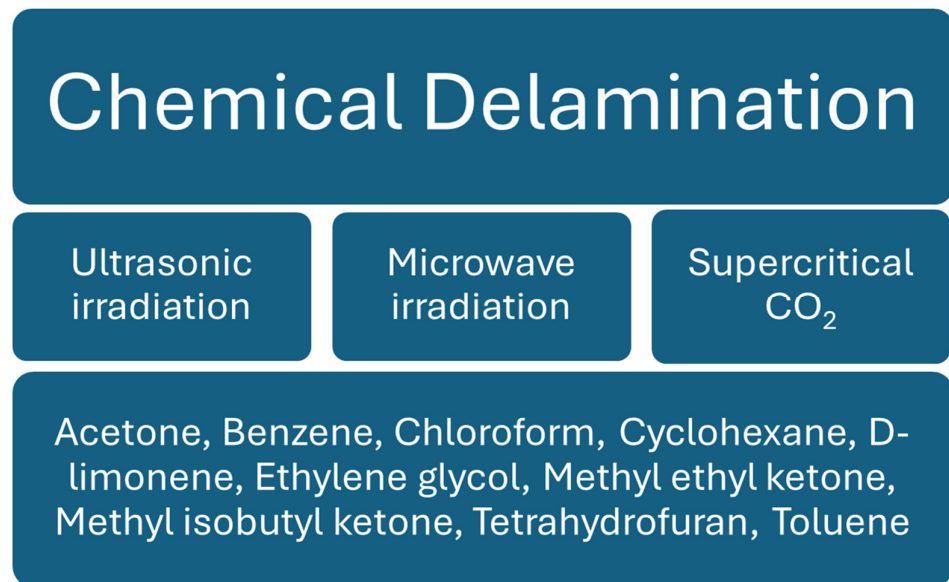


Figure 4. An overview of the chemical delamination process including the additional treatments and the chemicals usually found to be helpful in swelling and separating the polymer layers.

4.2. Mechanical, Thermo-Mechanical, and Electro-Mechanical Processes

Mechanical approaches to remove and recover the backsheet may include both fragmenting and non-fragmenting processes. This is a popular approach and is most widely used [13,14]. Fragmenting processes can be further contact or contactless. Fragmenting by contact processes includes crushing, grinding, milling, shredding, and scraping. For this purpose, different types of mills or shredders could be implemented. Crushing or shredding the modules appears to be a versatile process and can be applied to thin-film, c-Si, and CdTe PV panels [130]. In one of the early works, several different process combinations were experimented on for the separation of PV modules, which did not always result in the recovery of the polymer layers [131]. Panels were crushed by two blade rotor crushers followed by thermal treatment to decompose the polymers. Hammer crushing was also used in combination with rotor crushing to cause delamination, where polymers and glass were recovered as a fine powder mixture, and was again treated thermally to recover glass powder [131]. In some cases, the PV panels are first cut into smaller pieces with the help of a circular saw and then crushed with a knife mill (Retsch SM 2000, Retsch GmbH, Haan, Germany). The crushing was carried out in multiple steps by feeding the crushed materials again and again into the crusher until the desired size was reached [132]. In some cases, the PV panels were sheared into smaller pieces only to improve the material handling. The sheared pieces were then crushed using an impact swinging hammer mill. In this process, the polymer and the plastics were separated using vibrating separators as they were intended for further use in the waste-to-energy process and did not undergo recycling [133]. In most of the approaches, the mechanical treatment was applied to facilitate size reduction, and the obtained coarse fraction were thermally treated to burn away the polymers [121,134,135]. Shredders have also been employed for delaminating and facilitating the separation of glass, polymer, and silicon PV modules [136–138]. While crushing seems to be an easy process, this does not lead to a high degree of separation between the glass, polymers, and the silicon wafers. Furthermore, dust and noise abatement

systems are often needed for such treatment processes [139]. The effectiveness of the material recovery depends on the separation process employed after the mechanical process has been used for delamination. However, thermal treatment is often employed to burn away the polymers to recover the glass and the silicon.

Recently, electrohydraulic fragmentation (EHF) has attracted the attention of researchers as an alternative process for delaminating EOL PV panels. In the EHF process, the panels are submerged in a fluid medium. An arc is generated in the fluid medium with the help of an electrode. The generation of the arc results in the formation of pressure waves which interact with the panels and result in the delamination of the panels and separation of the individual components [21,140–146]. Since the process is carried out at room temperature, the polymers can be recovered without suffering thermal damage and then cleaned and recycled using chemical routes [21]. This process does not create any toxic emissions or effluents, generates less noise, and is among the most energy-efficient processes for the delamination of PV modules [144].

There are other mechanical processes that do not involve shredding or milling the panels. Pressurized water jets have been used to remove the polymer and the silicon solar cells from the glass surface. While this could help recover and clean the glass in a single process, the separation of the polymer and Si can be performed chemically or thermally, resulting in the decomposition of polymers and the extraction of high purity metals. Several thermo-mechanical processes have also been developed to enable the separation of the glass and polymer layers. Separation of the glass from polymers can be performed using hot knife cutting techniques [15,147]. In this process, the module or the blade is heated to a sufficient temperature ($\approx 200\text{--}250\text{ }^{\circ}\text{C}$) to soften the polymers. The heated blade is then inserted into the softened panel and then moved to separate the glass from the polymer layer. Using this process, the entire glass layer can be recovered in one piece without much damage [15,148]. In some instances, this process has been used in combination with an electrical pulse discharge method, using wires or electrical pulses in water to recover Cu and Ag [40,149]. The panels can also be heated to soften the EVA layers, after which the backsheet layer (PET or PVDF) can be simply peeled off mechanically [64,150–152]. Lasers can be used as a heat source as well [153]. While such processes have been able to separate the glass and the solar cells layers from the polymers, only in a few cases have attempts have been made to recover and recycle the polymers [21,68,153]. Figure 5 shows an overview of the mechanical delamination process, including the sub-categories and the processes normally associated with them.

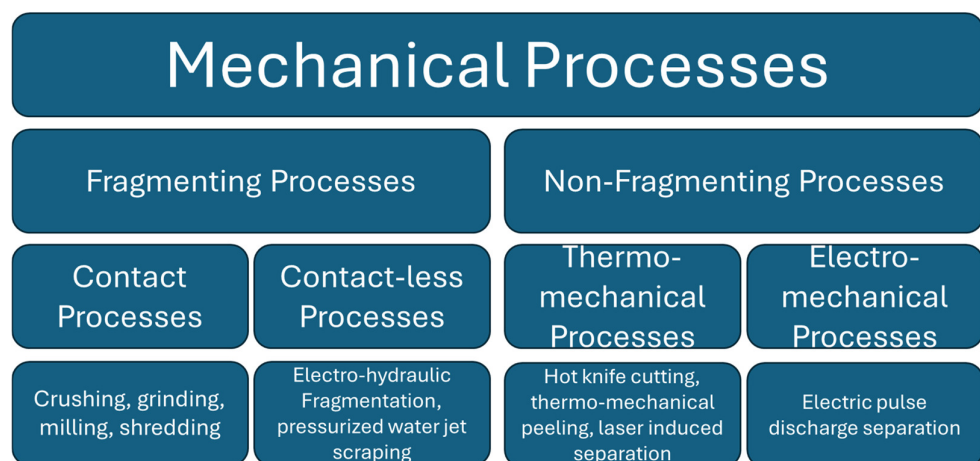


Figure 5. Overview of the mechanical delamination process, including the sub-categories and the processes associated with them.

4.3. Comparison of the Different Delamination Processes

The process of recovery of the polymers begins with the delamination process. Hence, this is the most crucial step which determines the recoverability and recyclability of the polymers from the end-of-life PV panels. The advantages, disadvantages, and suggested changes to the different delamination processes with the aim of recovering polymers along with other valuable materials is presented in Table 2. Thermal processes that lead to the disintegration of the polymers have not been included in this table. Therefore, the delamination processes could be purely chemical, thermo-mechanical, or mechano-chemical processes. From the perspective of current technology, mechanical + chemical processes appear to be the most feasible pathway of recycling the EOL PV modules. The mechanical processes such as crushing or shearing are established and could result in high throughput. However, these processes may generate noise and dust that may cause health hazards if proper precautions are not taken. Furthermore, processes such as EHF prevent the formation of dust and generation of noise. Since crushing or fragmenting the modules increases the surface area available for chemical reactions, the chemical dissolution of the polymers in the chemicals following mechanical pretreatment processes is faster than in the case of chemical processes alone. The combination of mechanical and chemical processes enables the recovery of other important materials such as metals, silicon, and glass from the EOL PV panels along with the polymers. Some researchers have reported the reusability of the chemicals used; further research is required to understand the usable life of such chemicals and the reagents or chemicals that cannot be regenerated and are lost in the process [21,71,124,128,154]. Further improvements in developing non-toxic chemicals or processes that enable quicker dissolution of the polymers and recycling of the chemicals, used at the end of the process after the polymers have been recovered, would further increase the attractiveness of these processes.

Table 2. Advantages, disadvantages, and the potential improvements in the different delamination processes with the potential of recovering polymers for further recycling from EOL PV modules.

Delamination Process	Potential of Recovering Polymers	Advantages	Disadvantages	Possible Improvements
Thermo-mechanical	- Backsheet can be recovered - Some damage to the EVA may render it non-recyclable	- Low energy consumption than for the thermal decomposition of polymers - Less toxic emissions - The possibility of recovering other materials along with polymers	- Low throughput - Higher operating costs - Technology is not established	The possibility of recovering the EVA by processing at lower temperatures
Chemical	Both the backsheet and EVA can be recovered using this process	- May need lower energy input than thermal processing - The possibility of recovering other materials along with the polymers - No dust generation, minimal noise during the process	- Expensive process due to the huge amount of chemicals required - Extremely low throughput - The generation of chemical wastes requiring further treatments	- The process can be improved if the chemicals used are regenerated - Suppression of the formation of any volatile compounds that can cause potential health hazards - Newer chemicals that can dissolve the

		polymers quicker and are non-toxic	
Mechano-chemical	Both the backsheet and EVA can be recovered using this process	- Low processing costs - High process throughput - Versatile process capable of handling different types of modules - Some delamination processes such as EHF generate no dust or noise - The possibility of recovering other materials along with the polymers	- The process can be improved if the chemicals used are regenerated or recycled - Suppression of the formation of any volatile compounds that can cause potential health hazards - Newer chemicals that can dissolve the polymers quicker and are non-toxic
		- Process throughput limited by the chemical process - The generation of dust and noise during crushing or shearing	

5. Recycling of the Polymers

In the case of PV panels, the polymers that can be recycled are EVA, PET and PVDF. The usual approach to recycling polymers using a chemical route involves steps such as the removal of impurities, then dissolution followed by devolatilization and reprecipitation. In some cases, solvents are used that can dissolve all the polymers which can be selectively reprecipitated or crystallized later. Alternatively, a solvent can dissolve either a targeted polymer or all other polymers except the targeted polymer, which can lead to selective dissolution. However, selecting the appropriate solvent for a polymer is not easy, especially when the polymer is available as a heterogeneous mixture as in the case of PV panels.

5.1. Classification of the Recycling Process

The recycling of materials can generally be classified into three categories—primary recycling also known as closed-loop recycling, secondary recycling which is also referred to as open-loop recycling or downcycling, and tertiary recycling which involves waste-to-heat generation and incineration. The selection of the recycling process depends on several factors, including the available technology, resources, desired end products, and policies and regulations pertaining to the particular place where the recycling activities are being performed.

Primary recycling or closed-loop recycling involves recycling the material to return it to the form of raw materials from which the material can be made again. The process cycle of closed-loop recycling is shown in Figure 6. In the case of the EOL modules, several components can be readily recycled in this manner. Examples include the Al frame, copper wires and interconnectors, and the glass sheet. Using closed-loop recycling options, materials can be recycled infinitely. This is the most ideal recycling option for materials. However, for the closed-loop recycling option, the process has to effectively remove the different additives, dyes, pigments, and filler materials added to the product to increase its lifetime or appearance or both. Hence, while closed-loop or primary recycling could be the most environmentally favorable recycling process, it is not always the most feasible or most economical of the processes.

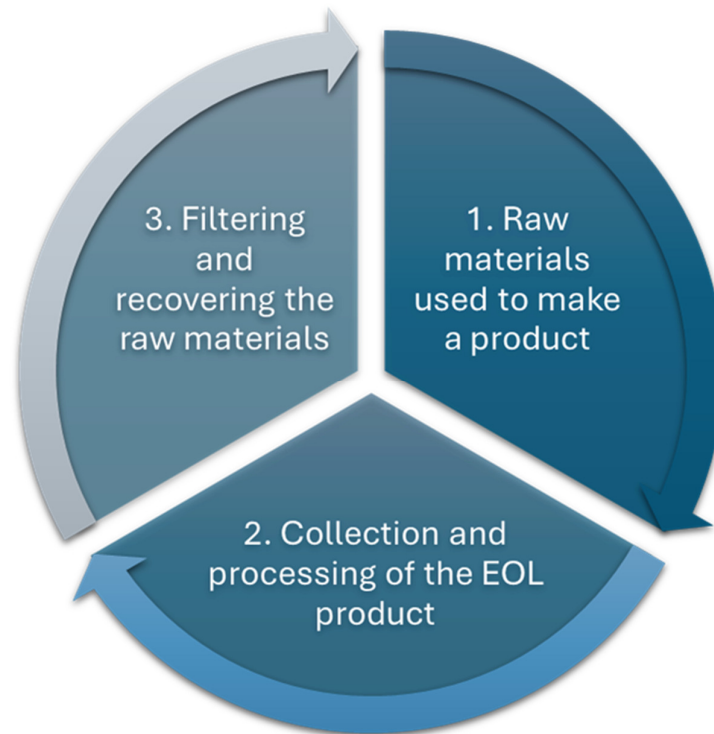


Figure 6. Schematic of the closed-loop recycling process.

Open-loop recycling or secondary recycling options allow for the production of useful materials/products from the materials obtained from the initial product after the end of its usable lifetime. A schematic of the open-loop or secondary recycling process is shown in Figure 7. A useful product2 obtained after the recycling process can be used for any other application, but it cannot be used in any way to regenerate the original raw materials used for making the product1. An example of this, in the case of the EOL PV modules, could be using the crushed glass and polymers as construction materials [155–158]. Another example could be using the Si and glass recovered from the EOL PV modules to prepare alloys such as ferrosilicon [17,159–161]. Recently, authors have investigated secondary recycling options for discarded backsheets from EOL PV panels by converting them to insulating material [162].

Tertiary recycling processes are primarily concerned with the handling of non-recyclable wastes and wastes that could be hazardous if left in the environment, such as fluorinated polymers. Tertiary recycling includes examples such as waste-to-heat generation and incineration. In waste-to-heat processes, heat is generated by using the waste as a fuel, which in most cases leads to the generation of carbon dioxide and water, along with heat. This process is not the most preferred way of handling waste due to the generation of greenhouse gases [163,164]. The pyrolysis of EVA has been studied by several researchers and is currently among the most preferred way of handling waste EVA from EOL PV modules [151,165–170].

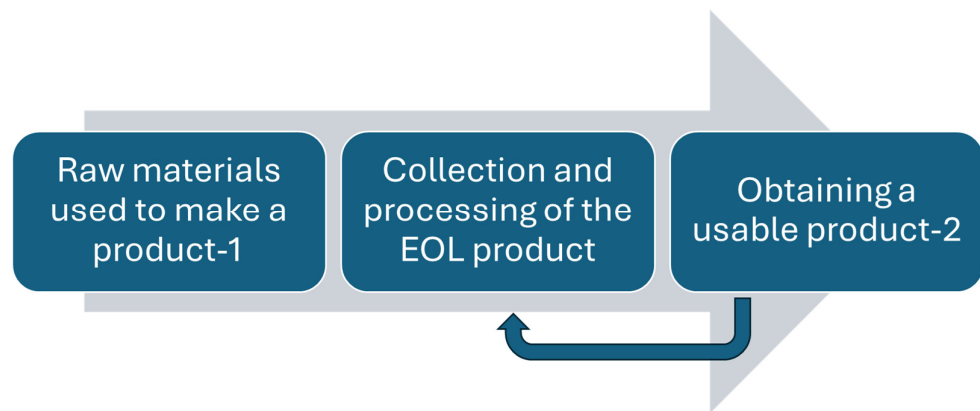


Figure 7. Schematic of the open-loop/secondary recycling process.

The pyrolysis of non-fluorinated backsheets such as PET from EOL PV modules has also been explored by researchers [151,166,171,172]. The PET supply chain emits approximately 534.6 Mt of carbon dioxide equivalent annually, where 90% is emitted during the manufacturing stage [173]. The energy recovered from the pyrolysis of PET is significantly lower than that required to manufacture it. Moreover, since it is possible to recycle PET using closed-loop recycling options, pyrolysis is not the preferred method for nonfluorinated backsheets.

Incineration is the last option (albeit the most widely used) to handle non-recyclable wastes. The incineration of plastic products globally generates approximately 40.5 Mt of CO₂ equivalents. This leads to high environmental costs. Additionally, the incineration of fluorinated polymers such as PVDF releases harmful pollutants which, if not captured and treated, could cause health hazards [61,70,173–176]. Reducing the requirement of such materials either by lowering their consumption or replacing them with a more environmentally benign material is more helpful in managing such wastes [61].

5.2. Recycling of the Encapsulant (EVA)

EVA that has not undergone cross-linking can easily be dissolved in solvents such as chloroform and can be recovered by processes such as spin-coating or spreading over other flat heated surfaces [21] which allows for the evaporation of the solvent. Theoretically, this solvent can be recovered by condensation and recycled. However, recycling cross-linked EVA is not a straightforward process. The chemical dissolution of cross-linked EVA occurs through multiple stages as proposed by researchers. When the polymer is submerged in the organic solvent, it penetrates the polymers through any partial openings and fills the voids existing within the polymer [177]. The solvent molecules interact with the cross-linked chains in the polymer and can settle around the polymer chains. This initial interaction results in an increase in the volume of the polymer. The EVA used as encapsulant is also cross-linked during the module fabrication process, and hence, when submerged in an organic solvent, it easily swells due to the penetration of the organic solvent and forms an organic gel [109,178,179]. The swelling of the EVA due to the formation of the gel could be the reason behind the loss of mechanical strength of the polymer, due to which the layer can be separated easily. Delinking the cross-linked polymer chains can take a long duration, sometimes even days, with constant/intermittent mechanical stirring to achieve even partial dissolution [68,180]. The duration can be shortened by using a non-ionic surfactant and non-hazardous solutions such as KOH–ethanol solution [126]; still, the recovered EVA cannot be broken down to its monomeric form easily. Hence, the complete recycling of EVA polymer to achieve EVA monomer may not be an attractive option, since most chemicals that could be used for this process are

extremely hazardous and, in some cases, are not allowed for common industrial applications [180].

Therefore, most researchers have focused on utilizing the swelled EVA recovered from the EOL PV panels for other uses so that they do not end up in landfills. Furthermore, such processes could be commercially viable, leading to greater acceptance by the industry. EVA polymer recovered from the EOL PV modules could be used as an energy source. The calorific value of EVA recovered from the PV modules is assessed to be 39.51 MJ/Kg, which is comparable to the calorific values of biodiesel and natural gas (38.7 and 39.8 MJ/Kg, respectively) [181]. EVA is composed of carbon, hydrogen, and oxygen without any fluorinated compounds. It may include some small amounts of catalysts to promote cross-linking [182]. Researchers have pyrolyzed EVA under inert conditions to produce a polymer oil which could be used as a lubricant [183]. The thermal pyrolysis of EVA can produce acetic acid, alkanes, alkynes, and other aromatic cyclic compounds [165–168].

5.3. Recycling of the FP-Based Backsheet

As mentioned in Section 2, most of the commercially available backsheet layers comprise a FP (PVDF/PVF) and PET. PVDF-based backsheets were widely used in early PV modules. Along with the EVA, the backsheets are prone to failure and are the major cause for the premature end-of-service life of PV modules [8–10,184–189]. For the backsheets that contain a combination of PVDF and PET layers, individual layers cannot be easily separated. In the case of backsheets with combined PVDF and PET layers, researchers have tried applying alkaline hydrolysis to degrade the PET and to recover the PVDF; however, no attempts were made to recycle the recovered PVDF [190]. In other applications, such as PVDF membranes for water filters, the regenerating of such membranes have been attempted [191]. There is no accepted recycling process for fluoropolymers such as PVDF/PVF [61,72]. Hence, the fluorinated backsheet can only be disposed by either incineration or dumping in a landfill. Moreover, pyrolysis results in the formation of fluorinated exhausts along with other aromatic hydrocarbons [192]. Hence, any incineration needs to be carried out carefully and gas treatment is mandatory to comply with local emission regulations [61,72,166,172].

5.4. Recycling of the PET-Based Backsheet

PET is among the most recycled of all polymer materials, as a majority of plastic bottles are made of PET [193]. The first attempt at recycling PET was performed in 1977 [194]. Since then, several technological advances have been made in the field of recycling PET. Most of the methods of recycling PET involve chemical processing. Researchers developed a selective dissolution process using N-methyl-2-pyrrolidinone to purify the recycled PET [195]. Researchers have also used N-methyl-2-pyrrolidinone, n-octane, and n-hexane as a solvent/nonsolvent system in the dissolution/precipitation method for recycling PET [196]. PET can be recycled either chemically or mechanically. The chemical recycling of PET, also known as chemolysis, results in the complete depolymerization of the PET into monomers or the partial depolymerization of PET into oligomers [197]. Different chemicals have been used for depolymerization including ammonia (ammonolysis), amines (aminolysis), water (hydrolysis), methanol (methanolysis), and ethylene glycol (glycolysis), with or without the presence of some transesterification catalysts [198,199]. Among these, mainly glycolysis and methanolysis have been adopted at a commercial scale [198]. Figure 8 presents a summary of the possible available options for recycling PET-based backsheets from EOL PV panels.

In methanolysis, methanol is used to depolymerize PET under high temperatures (160–380 °C) and pressures (0.9–20 MPa), where dimethyl terephthalate and ethylene glycol are obtained as the end products [200]. The polymer is broken down to release ethylene

glycol in the presence of transesterification catalysts such as zinc acetate, magnesium acetate, cobalt acetate, and lead dioxide [201–204]. Recently, the use of catalysts with biological origins has also been suggested [205]. Dimethyl terephthalate obtained in the reaction is precipitated, centrifuged, and crystallized and is used again in the production of PET. Recently, researchers have used supercritical methanol to improve the process efficiency [206]. Methanolysis is considered to be an environmentally friendly and renewable process of recycling PET [207,208].

Glycolysis is one of the most widely used processes to recycle PET. Glycolysis can be carried out using ethylene glycol [209–215], diethylene glycol [214,216,217], propylene glycol [218,219], and dipropylene glycol [214,219]. The process is carried out within a temperature range of 180–250 °C and pressures between 0.1–0.6 MPa. Depending on the process and chemicals used, it can take anywhere between 0.5–8 h to complete. The product obtained after glycolysis is bis(2-hydroxyethyl) terephthalate (BHET), which can be separated, purified, and used to make PET. Zinc acetate, NaCl, and urea can be used as catalysts [220–225]. Researchers have also recently used niobium-based catalysts [226,227]. Usually, the rate of the reaction is proportional to the square of the EG concentration while maintaining a constant temperature, pressure, and PET concentration [198]. Glycolysis has been shown to be less energy intensive due to its moderate temperature range and shorter processing duration than other chemical recycling processes [228,229].

The hydrolysis of PET can be performed to obtain terephthalic acid and ethylene glycol. Hydrolysis processes can be carried out in acid, basic, or neutral environments. Acid hydrolysis is usually carried out with the help of concentrated sulfuric acid (87–90% wt.). This process can take place in atmospheric pressure and does not need an external heating source [230]; however, higher temperatures may be used to reduce the reaction duration [231,232]. In some cases, diluted acids have been used, resulting in a higher process duration (≈ 6 h). Acid hydrolysis performed with diluted acids needs a higher temperature (≈ 150 °C) and pressure [233,234]. Alkaline hydrolysis can be performed with a diluted NaOH solution (4–20% wt.) at temperatures between 210–250 °C and a pressure of 1.4–2 MPa. With these conditions, the process duration could be reduced to 3–5 h for the complete degradation of PET [235–241]. Neutral hydrolysis is carried out with only water or steam, at a pressure of 1–4 MPa, and temperatures between 200–300 °C [242–246]. These conditions are referred to as high-temperature water (HTW) [247] or hot-compressed water (HCW) [248], or subcritical or supercritical water [249]. For neutral hydrolysis, alkali-metal acetates could be used as transesterification catalysts [250,251]. Supercritical water is heated under pressure beyond its critical point (374 °C and 218 atm), where it exhibits unique solvent properties. On the other hand, sub-critical water is kept at temperatures and pressures below the critical point in the liquid state. However, at these increased temperature and pressure levels, it still offers enhanced reactivity and solubility characteristics [249].

Hydrolysis can be an extremely cost-effective process and has huge potential for large-scale commercial applications. Water is among the most environmentally friendly processes from the different chemical processes discussed [190,233,238]. Hence, recycling PET using neutral hydrolysis mitigates the hazards associated with the use of chemicals. Additionally, its abundance and availability further make it an excellent option for industrial applications [252–254].

The aminolysis of PET has been suggested to be performed using methylamine [255–257], ethylamine [257,258], or ethanolamine [257] at temperatures ranging from 20–100 °C. Ammonolysis is performed using anhydrous ammonia in the presence of ethylene glycol and zinc acetate at a temperature of 70 °C [259–261].

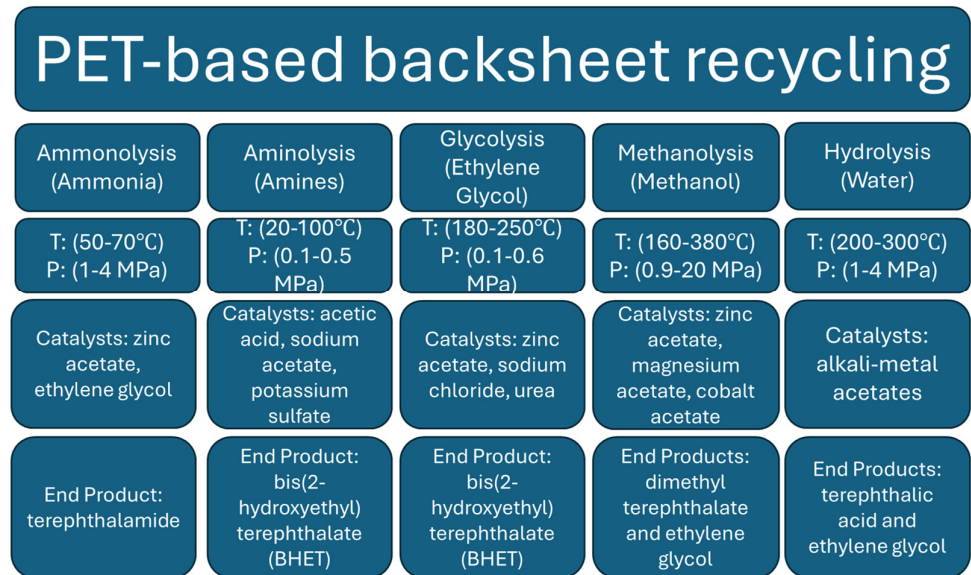


Figure 8. The possible available options for recycling PET-based backsheets from EOL PV panels.

6. Policies and Commercial Efforts Related to the Recycling of PV Panels

The recycling of EOL PV modules also contributes directly to the United Nations' Sustainable Development Goal number 12, 'Responsible Consumption and Production' [262]. The charter identifies the efficient disposal and management of hazardous waste as a key to achieve this goal. In several countries, stringent guidelines are already in place to deal with waste electrical and electronic equipment (WEEE) [42,263]. In particular, the EU has published one of the most detailed regulations related to the recycling of PV modules. These regulations stipulate a minimum of 80–85% (by weight) recovery or reuse of materials [69,71,264]. Details of the regulatory frameworks related to PV module recycling are available in these reviews [265–267]. While these regulations have been recently formulated and provide a general guideline, the recycling of PV panels should focus on the value of the materials recycled rather than on the weight. For example, in PV panels, the glass, aluminum frame, copper wires, and external connectors constitute approximately 85% of the weight of the PV panel, but account for only 30–40% of the value [17]. Several other countries have been establishing regulatory frameworks for handling WEEE waste, which also includes solar PV panels [266,268–271]. A global review of regulatory frameworks highlighted the popular business-to-customer model that the producers will also be responsible for the end-of-life management of their products [272–274]. Policies and guidelines pertaining to recycling EOL PV modules exist in many countries [55,274,275]. However, instances of the commercial-scale adoption of PV module recycling are relatively lower.

The recycling of silicon PV panels is a developing field and is continuously evolving, with new methods and technologies being developed. Initiatives for recycling c-Si-based PV modules were established in Europe by solar PV manufacturing industries; however, their long-term commercial viability has not been established [55,274]. According to a current report by IEA PVPS on the status of global PV recycling, a total of seven commercial entities are engaged in recycling PV modules, out of which six have their operations in Europe [14]. The recycling of PV panels (non c-Si) is led by the first solar recycling platform [274,276] which has set industry standards on the recycling of modules. The efforts in recycling of c-Si PV modules began with the establishment of the pilot lines using the

FRELP process in Spain [277] and later, the commercial PV recycling plant established by Veolia in France in 2017 [50]. Recently, a few other commercial PV recycling plants have emerged in the US and Europe [278,279] and China [280,281]. While the details of the recycling processes used in these industries are not publicly available, most of these likely recover the glass, silicon, and precious metals from the EOL PV panels, with polymers mostly pyrolyzed for energy. Commercial recycling could be considered to be heavily dependent on the supply of EOL PV panels as well as on the availability of the market for the materials produced as a result of the recycling process. Hence, commercial recycling facilities need to consider these factors for successful operations in the long run. The challenges related to the recycling of PV panels in a highly linear market is underlined by the recent shutting down of the Reclaim PV in Australia [282]. To the best of the available knowledge, the commercial recycling of polymers and plastics from EOL PV panels has not yet been reported.

7. Challenges and Future Outlook

The recycling of polymers used in PV modules is necessary to mitigate the environmental impact of disposing the end-of-life PV modules. While some progress has been made in the separation of the polymers and their recycling, as reviewed earlier, very few instances exist of successful attempts at recycling the EVA, PET, and PVDF polymers used in the PV modules [21,68,147,153,166]. Recently there have been some efforts in reusing the recycled PET in fabricating backsheets for new PV modules [25]. There are several reasons for the slow progress in the recycling of polymers from the EOL PV modules. The PV modules do not contain a single type of polymer. As mentioned earlier, the backsheet could be made from a single type of polymer or a combination of several layers of different types of polymers. The materials used in the PV module design are selected mainly based on their performance and longevity, and seldom for their recyclability. Furthermore, most of the polymers used in the PV modules contain several additives such as UV absorbers, photo-antioxidants, and thermo-antioxidants [94,112–114]. These additives further interfere with the chemical dissolution process and hinder the reaction of the polymers with the chemicals [21]. As a result, the process parameters need to be adjusted depending on the polymer and the additives. Since different manufacturers use different additives, which could be their proprietary information, developing a blanket process for recycling the polymers irrespective of the additive used becomes a challenge that needs to be addressed. Figure 9 shows the advances in the different fronts required to enable the adoption of large-scale recycling of the polymers from EOL PV panels.

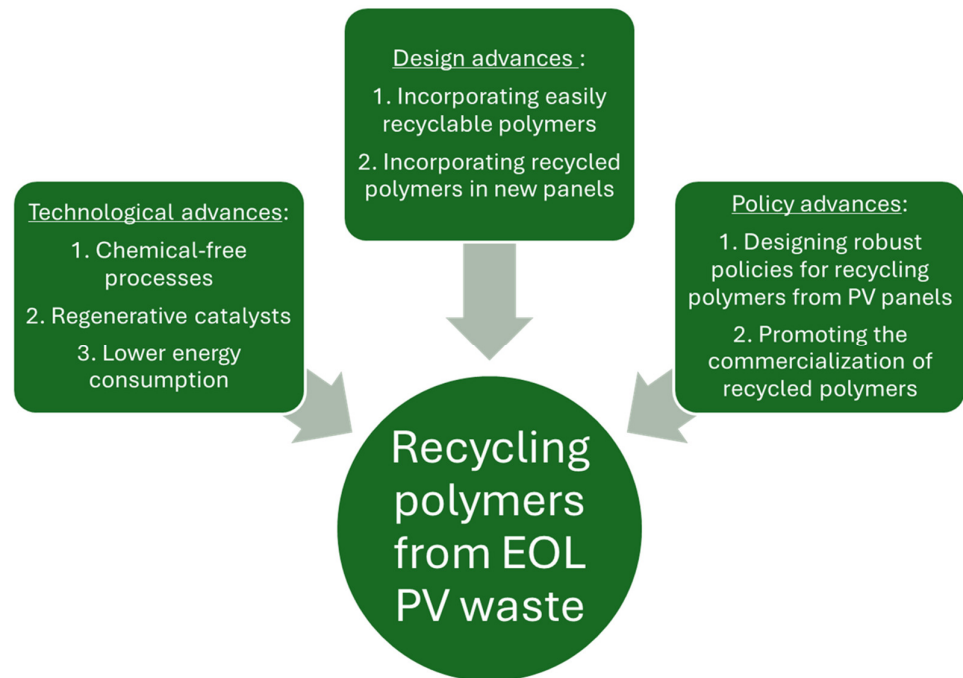


Figure 9. The advances in different fronts required to enable the adoption of large-scale recycling of the polymers from EOL PV panels.

The technical and economic feasibility of such complex recycling processes need to be established. Since only a few examples of pilot-line implementation exist, it is difficult to obtain concrete experimental data on the commercial and technical feasibility of the large-scale implementation of different recycling technologies. However, in some situations, researchers have presented techno-economic analysis of some hypothetical situations. Most studies focus on recovering Ag from the modules as it contributes the most towards the financial sustainability of the process [283]. A change in the Ag content in the solar cell can deeply impact the minimum amount of EOL PV panels to be processed to attain a positive return on investment while maintaining a lower fee to be paid to the recyclers [283]. In the study, a chemical process was proposed to be used for the delamination of the modules while the EVA was pyrolyzed. The backsheet was separated from the other valuable materials but no further processing of the backsheet was assumed. In another study, researchers pointed out the challenges in determining the economic viability of the PV module recycling process due to the possibility of several alternative technical possibilities at each stage of the process. In another recent study [284], researchers compared the four different hypothetical combinations of recycling technologies involving simple to complex recycling process flows using Monte Carlo simulations [284]. In this study, while none of the recycling processes achieved net revenue generation, the simple recycling of Al-frame panels with an aim to recycle only the glass achieved the lowest net costs compared to landfilling [284]. The researchers highlighted that the imposition of the landfill-disposal charge and optimizing the collection of PV panels to achieve lower collection costs might help in the increased commercial viability of recycling processes. Recently, different processes to recycle c-Si PV modules were analyzed with the help of models. In this comparison, one of the processes was a hypothetical process created by combining the other two processes [48]. For all three processes, the potential revenue generated from recycling was less than the cost of recycling, which underscores the challenges in the commercial acceptance of such technologies. While researchers have shown the possible economic viability of special recycling processes, such as PhotoLife for

huge recycling volumes (30,000 t/year), they did not target the recovery of Si, metals from the solar cells, and polymers [285]. Recently, researchers showed that using a combination of electrostatic separation and hydrometallurgy, profitability in PV recycling can be achieved with processing volumes as low as 1000 t/year [51,138]. However, the process did not include the recovery and recycling of polymers, which were considered to be incinerated in the study. Other studies have pointed out landfilling as the most economically viable method of disposing EOL PV modules and postulate the requirement of significant financial incentives to kickstart PV recycling [286]. In all of these economic analyses of the recycling processes, either the recovery of the polymers was not attempted, or the value of the recovered polymers was assigned to have no value in terms of the revenue. This further highlights the challenges in the commercial recycling of polymers from EOL PV modules.

While recycling processes for PET exist, they all have their own set of limitations. Generation of the waste effluents at the end of chemical processes used for recycling PET is among the largest challenges. Among all the chemical processes, glycolysis appears to be the most widely accepted and used. The glycolysis process is established, versatile, and can be easily integrated into the existing recycling facilities. The end products of the glycolysis process can be used for manufacturing a range of polymers such as epoxy resins, polyesters, polyurethanes, and vinyl esters. Hence, it is the most widely used for the commercial recycling of PET [287].

Methanolysis is an emerging and efficient process; however, separating, purifying, and extracting the end products is a complicated process and hence, the cost associated with the process increases. This process is extremely sensitive to water contamination. The presence of water can slow down or completely deactivate the catalysts leading to the formation of an azeotropic mixture that is difficult to separate [288].

Acid and alkaline hydrolysis require the use of corrosion-resistant equipment and regular maintenance which significantly increase the operating costs of such a process. This process also generates a large amount of wastewater, often containing residual acids and other inorganic salts that require special post-processing and treatment before disposal or reuse [238,289]. Even neutral hydrolysis has its own set of challenges. This is primarily due to the additives present in the polymers which are incorporated into the products. Nevertheless, the absence of a corrosive environment, and the non-toxic nature and recyclability of the effluents make the process highly attractive and viable for large-scale commercial applications. Continual research into making the process more efficient would be the key to the large-scale commercial success of neutral hydrolysis.

Another way to improve the recyclability of the PV polymers would be to adopt sustainable design and production of the modules. Some researchers have already voiced concerns at using recycled materials in PV modules and argue that module durability and reliability are more important than easy-recycling features [25]. Hence, the philosophy for designing PV modules must see a major shift towards making sustainability an important design parameter in addition to sustainability and durability. Researchers in both industry and academia have shown that the total recycling of certain types of the PV modules is possible if designed appropriately [24,290]. While several alternatives to the fluoropolymer-based backsheet exist, including PET, polyamides, and polyolefins, robust and prolonged reliability studies are needed to promote their widespread acceptance. On the other hand, the use of polymers in a module could be substantially reduced by adopting a bifacial module design. In a bifacial module, thin glass sheets are used on both the front and rear sides of the modules (2–3 mm), which is expected to further reduce to less than 2 mm [7]. This eliminates the use of a backsheet, and the EVA becomes the only polymer used for encapsulation purposes. Such modules not only generate higher energy for a given area when deployed over a suitable surface [291–293] but have been reported as

easier to recycle [17,21,145]. This also aligns with the fact that almost 90% of the commercially produced solar cells and more than 50% of the modules manufactured in 2024 were bifacial [7]. Government and regulatory policies can also have an impact on the development and acceptance of polymer recycling from EOL PV modules [294], as it has had on consumer plastic recycling [295–299]. However, a detailed analysis of these policies and their impact is beyond the scope of this work.

The future research direction in terms of PV module design should be towards eliminating fluoropolymers from the modules without compromising the performance and reliability of the PV modules. Fluorine-free PET backsheets are commercially available and have been shown as viable alternatives to fluorinated polymer backsheets. However, the market share of PET is substantially less than fluoropolymers [7]. Concurrently, more research should be performed to develop new recyclable encapsulant and backsheet materials and additives, which are not difficult to recycle or can be completely decomposed when in contact with natural elements. The direction of material development should head towards enabling primary or closed-loop recycling followed by open-loop options (secondary or tertiary), while materials intended for waste-to-heat recovery and incineration should be avoided.

On the other hand, research is also needed to improve the recycling processes of polymers. In particular, some suggested areas of research could be as follows:

- Optimization of the neutral hydrolysis process to minimize the energy requirement and the process duration, while maximizing the process yield.
- Combining neutral hydrolysis with a complimentary process such as glycolysis to minimize effluent generation and maximize solvent recovery.
- The development of new environmentally benign catalysts that can minimize the energy consumption, maximize the process yield, and can be regenerated towards the end of the process without a complicated process.

In recent years, perovskite–silicon-based tandem technology has gained the attention of researchers worldwide due to its higher efficiency potential and lower costs [300–302]. Since the most popular perovskite materials used in such solar cells use lead, their sustainability needs to be investigated [303–306]. While these modules are similar in construction to the c-Si modules, the use of perovskite and transparent conducting oxides (TCOs) in such panels could further complicate the recycling process and the associated recovery of materials [307–309]. Researchers have already undertaken efforts to achieve sustainability in both the recovery of the perovskite material [310] and the associated TCOs [311,312]. While degradation of the polymer layers in perovskite-based tandem modules has been studied [313–315], research into their recycling, purification, and recovery need to be explored to establish the feasibility of recycling polymers from such modules.

Recycling of the polymers used in the PV modules is among the last of the steps needed to enable the closed-loop recycling of PV modules. Almost all other materials used in a PV module could be recycled using either closed-loop or open-loop strategies. The commercial success of the recycled polymers would depend solely on the costs as it would face stiff competition from the production of virgin polymers from raw materials. Therefore, further research towards reducing the cost of recycling polymers is crucial for the success of the process. The recycling of polymers from EOL PV waste could receive a boost from the intensive global efforts in combating plastic pollution. Several organizations are transitioning to a sustainable and circular economy for consumer PET waste [207], which shows the success of collaborative research and innovation. Recycling polymers from the PV module has the potential to improve the sustainability of the PV modules and further enhance their contribution to a cleaner, more sustainable future.

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