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Review

Comprehensive Review of Crystalline Silicon Solar Panel Recycling: From Historical Context to Advanced Techniques

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Abstract: This review addresses the growing need for the efficient recycling of crystalline silicon photovoltaic modules (PVMs), in the context of global solar energy adoption and the impending surge in end-of-life (EoL) panel waste. It examines current recycling methodologies and associated challenges, given PVMs' finite lifespan and the anticipated rise in solar panel waste. The study explores various recycling methods—mechanical, thermal, and chemical—each with unique advantages and limitations. Mechanical recycling, while efficient, faces economic and environmental constraints. Thermal methods, particularly pyrolysis, effectively break down organic materials but are energy-intensive. Chemical processes are adept at recovering high-purity materials but struggle with ecological and cost considerations. The review also highlights multifaceted challenges in recycling, including hazardous by-product generation, environmental impact, and the economic feasibility of recycling infrastructures. The conclusion emphasizes the need for innovative, sustainable, and economically viable recycling technologies. Such advancements, alongside global standards and policy development, are crucial for the long-term sustainability of solar energy and effective management of PVM waste.

Keywords: photovoltaic module recycling; crystalline silicon solar panel; sustainable waste management

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1. Introduction

The global surge in solar energy adoption is a response to the imperatives of sustainability and the urgent need to combat climate change. Solar photovoltaic (PV) energy, harnessing solar radiation to produce electricity, has become a prevalent method for terrestrial power generation [1]. At the forefront of this shift are crystalline silicon photovoltaics modules (PVMs), the primary tools in PV systems for solar energy capture [2]. This growth is evidenced by a significant increase in installations, with an over 90% surge in the past decade, from 104 to 1053 gigawatts (GWs) [3].

These PVMs, predominantly silicon-based and representing 95% of global PV production in 2020 [4], have a lifespan of 20–30 years [5,6]. Projections indicate that by 2030, worldwide solar capacity might approach 2840 GW, and by 2050, it could climb to 8500 GW [7]. However, given their finite lifespan, it is estimated that approximately 78 million tons of solar panel waste will require recycling by 2050 [8]. This rise in end-of-life (EoL) PV modules, subject to variability due to type and mode of failure [9,10], presents significant waste management challenges. The International Renewable Energy Agency (IRENA) estimates that PV waste could range from 1.7 to 8 million tons in 2030, escalating to 60–78 million tons by 2050 [5]. Additionally, rapid advancements in PVMs could lead to premature replacements, increasing EoL waste beyond the projected 78 million tons by 2050 [4].

Currently, PV systems predominantly operate on a linear "take–make–use–dispose" model, leading to increased landfill waste and environmental concerns [11–14]. To mitigate these issues, transitioning towards circular strategies and establishing an efficient PV recycling infrastructure is essential [11]. Adopting a circular lifecycle methodology is vital for waste reduction and enhancing the sustainability of the expanding PV industry. Regions such as Europe, the UK, and Washington State have implemented stringent regulations, mandating up to 80% recycling rates for end-of-life solar panels [15]. Properly managing EoL PVMs can minimize resource usage, reduce waste, and offer substantial economic benefits, potentially enabling the production of 2 billion new PVMs by 2050 [2,16].

Therefore, a comprehensive understanding and optimization of PVM recycling are indispensable for addressing these waste management issues and supporting resource conservation and the industry's sustainable direction. As we delve into the intricacies of PV recycling, understanding the specific methodologies becomes crucial. The subsequent sections will explore the current state in PV recycling, the composition of crystalline silicon solar panels, and the mechanical, thermal, and chemical recycling approaches of crystalline silicon solar panels, discussing their significant findings, recovery efficiencies, advantages, challenges and limitations, and prospects for future development.

2. Current State in PV Recycling

The PV industry has heavily invested its research and development (R&D) resources in enhancing the efficiency of crystalline silicon panels [1]. However, there has been a relatively small emphasis on developing cost-effective strategies for the dismantling and recycling of PV panel waste [1]. This disparity in focus is partly because most of the PV systems in use today were installed after 2010, leading to most PV waste originating from pre-consumer sources such as manufacturing scrap and decommissioned defective panels, rather than EoL PVMs [17–19].

Recycling PV panels, composed of a mixture of materials such as glass, metals, and polymers, poses significant challenges [20]. Regions such as Japan, Europe, and the US are at the forefront of R&D efforts aimed at solar module recycling [21], primarily focusing on silicon-based panels to recover and recycle key components [21]. The evolution in the composition of PV panels and fluctuations in raw material prices have led to variations in recycling processes [10,22].

Despite the limited availability of panels for recycling, academic research has been concentrated on addressing potential challenges [1]. These include the reduced electricity generation capacity of PV panels using recycled materials, inefficiencies arising from manual labor [1], risks of cross-contamination with other types of waste [19], and the high costs associated with dismantling, transporting, and recycling, especially given the hazardous elements in PV panel waste [12].

In the realm of PVM recycling, a variety of methodologies have been developed, each with its unique approach and focus. Bulk recycling, predominantly applied to crystalline silicon (c-Si) modules, concentrates on extracting basic materials such as glass and metals [23]. However, this method tends to overlook the recovery of semiconductor components and precious metals, often leading to the production of lower-grade recycled materials, especially glass [24].

Semi-high-value recycling, on the other hand, adopts a more selective recovery approach. This method often prioritizes specific components, such as the silicon wafer, but may neglect other valuable metals [25,26]. In contrast, high-value recycling encompasses a comprehensive approach, aiming to recover both basic and semiconductor materials [27,28]. This method strives to maximize the value of the recycled output by salvaging a broader range of components from the PV modules.

Beyond these methods, closed-loop recycling represents a progressive shift towards enhanced sustainability. Exemplified by practices at *Deutsche Solar AG*, this method integrates reclaimed cells back into standard PV module production. This approach not only focuses on resource efficiency but also significantly reduces waste, aligning closely with sustainable development goals [19,29].

3. Crystalline Silicon Solar Panel Composition

Understanding the composition and structure of crystalline silicon photovoltaic modules (PVMs) is critical in addressing the challenges and methods of recycling. These widely adopted panels feature a multi-layered design, each layer fulfilling specific functional and protective roles, as illustrated in Figure 1. This section delves into the detailed composition of crystalline silicon solar panels, exploring the function and significance of each component.

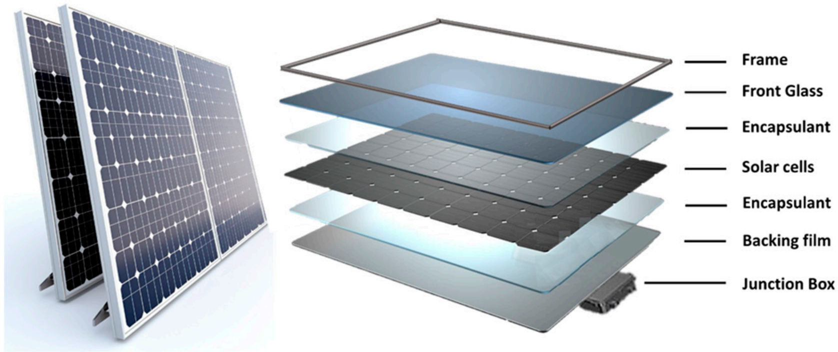

Figure 1. The Structure of a PVM.

3.1. Front Glass (or Cover)

Comprising tempered glass, the front cover serves as a protective layer for the solar cells, safeguarding them from environmental factors and ensuring optimal sunlight penetration. This component is crucial for maintaining the cells' functionality and preventing efficiency loss due to external damage [30].

3.2. Silicon Solar Cells

At the core of the panel, these cells are responsible for converting sunlight into electricity. Available as monocrystalline or polycrystalline silicon, they are enhanced with multiple coatings, including the n-p junction and anti-reflective layer, for optimized performance and minimize efficiency reductions [31,32], as depicted in Figure 2. The energy-intensive production of these cells, often reliant on fossil fuels, has significant environmental impacts [33,34].

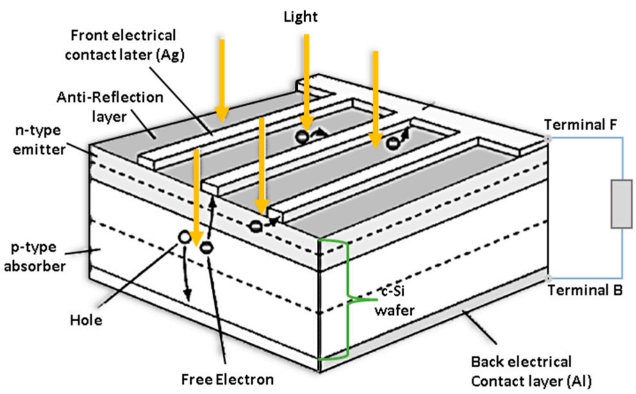

Figure 2. Layered structure of a silicon solar cell.

3.3. Anti-Reflective Coating

This coating enhances sunlight absorption, minimizing reflection loss and thereby ensuring the maximum amount of sunlight reaches the silicon solar cells for conversion into electricity [25].

3.4. Backing Film

Positioned behind the silicon cells, this film provides insulation and external protection. Available in various types, each backing film category has unique constructions and properties, which will be detailed in Table 1. The choice of film affects both cost and performance, with recent advancements improving UV durability.

Table 1. Comparative table of the three backing film categories.

Characteristic	Double Fluoropolymer	Single Fluoropolymer	Non-Fluoropolymer
Composition	A Polyethylene Terephthalate (PET) core layer is encased by two external layers of fluoropolymer material, potentially Tedlar (Polyvinyl Fluoride, PVF) or Kynar (Polyvinylidene Fluoride, PVDF)	Tedlar or Kynar on the outer side; PET and primer or EVA layers on the inner side	Two PET layers and one primer or EVA layer
Protection Level	Superior	Satisfactory	Basic, but improving with advancements
Price	Most expensive	Moderate	Cheapest
UV Durability	High	Satisfactory	High (with recent advancements)
Historical Context	Preferred for high protection	Developed to balance cost and performance	Initially avoided due to degradation risks
Advancements	N/A	N/A	Significant, leading to highly UV-durable films

3.5. Junction Box and Electrical Connections

Located at the panel's rear, the junction box houses electrical components crucial for electricity collection and transfer. Features such as bypass diodes enhance panel performance by preventing power loss due to shading [35].

3.6. Frame

Constructed primarily from aluminum, the frame offers essential structural support, enabling the panel to endure environmental pressures such as wind and snow loads. The frame's material contributes significantly to the panel's total weight [4,21,36].

3.7. Encapsulants

Predominantly composed of ethyl vinyl acetate (EVA), encapsulants are a key component in PVMs, offering protection, electrical insulation, and moisture barrier functionalities. These encapsulants are placed as thin layers around the solar cells and undergo heating at 150 °C to initiate EVA polymerization, solidifying the module's structure [37]. They must exhibit high-temperature and UV stability, maintain optical transparency, and possess low thermal resistance for the module's efficient function [38,39].

3.8. Composition and Recyclability

A typical crystalline silicon solar panel comprises glass (70%), aluminum (18%), adhesive sealant (5%), silicon (3.5%), plastic (1.5%), and other materials (2%), as outlined in Table 2. While lacking rare metals found in thin-film solar panels, the materials in crystalline silicon panels are nonetheless valuable for recycling. The challenge lies in the separation and recycling of these materials, due to the compact and interconnected nature of PVMs [13].

Table 2. The composition of a crystalline silicon solar panel.

<table>
<tr><th>Unit</th><th>Main Component</th><th>[4]</th><th>[40]</th><th>[41]</th><th>[12]</th></tr>
<tr><td>Front Glass</td><td>Glass</td><td>70%</td><td>70%</td><td>63%</td><td>54.721%</td></tr>
<tr><td rowspan="6">Silicon solar cells</td><td>Silicon</td><td>3.56%</td><td>3.65%</td><td>4%</td><td>3.101%</td></tr>
<tr><td>Silver</td><td>0.05%</td><td>0.05%</td><td><0.01%</td><td>0.03%</td></tr>
<tr><td>Copper</td><td>1.14%</td><td>0.11%</td><td>Not Available</td><td>0.451%</td></tr>
<tr><td>Tin</td><td rowspan="2">0.053%</td><td rowspan="2">0.05%</td><td><0.1%</td><td rowspan="3">Not Available</td></tr>
<tr><td>Lead</td><td><0.1%</td></tr>
<tr><td>Aluminum</td><td>0.53%</td><td>0.53%</td><td rowspan="2">19%</td></tr>
<tr><td>Frame</td><td>Aluminum</td><td>18%</td><td>18%</td><td>12%</td></tr>
<tr><td>Junction Box and Electrical Connections</td><td>Box body (including copper or plastic terminal), lid, diode, cables, connectors</td><td>1%</td><td>Copper: 0.33%
Plastic: 0.67%</td><td>Copper: 0.6%
Others: Not available</td><td>Not Available</td></tr>
<tr><td>Encapsulants</td><td>EVA</td><td>5.1%</td><td>5.1%</td><td rowspan="2">Organic:11%</td><td>10%</td></tr>
<tr><td>Backing film</td><td>PVF, PVDF, PET, etc.</td><td>1.5%</td><td>1.5%</td><td>17.091%</td></tr>
</table>

The composition of the data will vary depending on the different methods of collection.

4. Mechanical Processes in PV Recycling

Mechanical recycling of PV panels has garnered significant research attention due to its implications for sustainable energy solutions. This process typically begins with the dismantling of panels, which involves removing components such as the aluminum (Al) frame, encapsulating layers, Ag-printed Si solar cells, back sheets, junction boxes, and embedded cables [42,43]. Following dismantling, the segregation of primary components, including Al frames, solar cells, wiring, and laminated glass, is carried out [27].

To facilitate separation, various techniques are employed, ranging from manual methods to thermal treatments and automated systems [44–53]. Mechanical crushing and shredding are prevalent approaches, aiming to extract valuable components from the panels [45,54]. The frame, which provides mechanical strength to the panel, can be reclaimed through secondary metallurgy after separation [50,55,56]. Additionally, methods such as flotation yield crushed glass fragments sized between 45 and 850 μm [4,57], and mechanical screening techniques have proven successful in recovering over 85% of glass [4,45]. It is emphasized that prioritizing glass recycling is crucial for maximizing mass recovery and ensuring the economic feasibility of the process [54].

Fernández et al. [58] explored recycling's potential by integrating recycled silicon solar cells into cement-based systems. Extensive research has refined the mass recovery process across various PVM types, incorporating rotor crushing, hammer crushing, thermal treatment for larger fragments, and sieving. This process enables the recovery of nearly 85% of the total panel weight as glass for certain size fractions [45], aligning with Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) [59] and facilitating the recovery of materials such as silicon from finer fragments [15,45].

Despite these advancements, mechanical recycling faces challenges related to cost, environmental impact, and energy efficiency [60]. Innovative solutions such as high-voltage pulsing, originally developed in the 1930s and recognized for its crushing effects by the 1950s, are being explored. This technology, effective in diverse sectors such as ore enrichment [56,60–64], requires operational voltages exceeding 100 kV for efficient material separation of Cu, Al, Pb, Ag, and Sn in PVMs [65,66]. Furthermore, addressing the issue of low purity and subsequent low utilization rates after mechanical crushing remains a challenge. This is due to difficulties in isolating various materials. Lovato et al. [60] has introduced a method using supercritical CO_2 fluid for the rapid delamination of composite materials in solar panels. Under conditions of pressure greater than 7.39 MPa and temperatures above 31.06 °C, CO_2 achieves a supercritical state. Supercritical CO_2 ($ScCO_2$) fluid exhibits a rapid penetration rate, allowing it to swiftly permeate the interface between the solar cell and the EVA layer. This permeation into the EVA induces swelling, causing the EVA to expand in volume. This expansion generates internal stresses that counteract the bonding forces between the solar cell and EVA, thus achieving automatic delamination. Notably, using $ScCO_2$ reduces the delamination time of photovoltaic panels to about one-third of that at atmospheric pressure [60].

For a comprehensive understanding of these methods and their efficacies, Table 3 compares several mechanical recycling methods and highlights their respective advantages and limitations.

Table 3. Comparative analysis of mechanical recycling methods on silicon PV panels.

Method	**High Voltage Fragmentation, Sieving, and Dense Medium Separation**	**Incorporation in Cement Matrices**	**Crushing and Thermal treatment**	**Electro-Hydraulic Fragmentation (EHF)**
Primary Use	Selective separation and recovery of PV panel materials	Recycling in construction materials	Glass recovery	Recovery of valuable metals from PV modules
Recovery Rate	Not specified	Not specified	Approx. 85% (by weight)	99% Cu, 60% Ag, 80% Pb/Sn/Al
Materials Recovered	Glass, Cu, Sn, Pb, Ag	Not specified	Glass, potential for various metals	Si (0.5–2 mm), Ag, Cu, Sn, Pb, Al
Challenges	Improving Ag recovery ratio	Decreased mechanical strength, increased porosity, durability confirmation needed	Emissions management, ensuring clean recovered glass	Not specified
Environmental and Economic Impact	0.21 JPY/W processing costs, potential commercial viability	Not detailed	Reduces energy and chemical consumption	Economically attractive
Advantages	Effective separation and recovery of various materials, economically viable	Utilization of PV waste, potential for creating insulation and soundproofing materials	Applicable to various PV types, high glass recovery rate	Selective concentration of metals, straightforward metal recovery
Disadvantages	Additional methods needed for higher Ag recovery	Does not recover materials for direct reuse in PV manufacturing	Emission management, further processing for metal recovery	Not specified
Ref.	[57]	[58]	[45]	[66]
Method	**Triple Crushing along with Thermal or Chemical Treatment for Selected Fractions**	**Electrostatic Separation**	**High Voltage Fragmentation**	**Supercritical CO_2**
Primary Use	Recycling of PV panels	Separation of Cu and Al from waste wires	Recovery of valuable metals from PV modules	Separation of solar cell from encapsulation and glass layer
Recovery Rate	91%	68.6% Cu (99% purity)	95% Cu, 96% Ag	Over 96% (glass, Pb filaments, back sheet)
Materials Recovered	Glass, Al, Cu, (Ag)	Cu, Al	Cu, Al, Pb, Ag (<1 mm), Sn	Glass, Pb filaments, back sheet
Challenges	Not specified	Not specified	Not specified	Not specified
Environmental and Economic Impact	Economically feasible (PBT < 6 years for 75,000 ton/y)	Not specified	Not specified	Use of toluene

Table 3. *Cont.*

Method	Triple Crushing along with Thermal or Chemical Treatment for Selected Fractions	Electrostatic Separation	High Voltage Fragmentation	Supercritical CO_2
Advantages	Single scheme for different PV types, reduced thermal waste, single equipment uses	High purity in recovered metals, adaptable to industrial scale	Specific size crushing, concentration of select materials in size fractions	High recovery rate, reduced solvent usage, and delamination time shortened to one-third compared to atmospheric pressure
Disadvantages	Not specified	Model improvement for Al particles needed and further development for industrial application	Not specified	Not specified
Ref.	[54]	[56]	[65]	[60]

5. Thermal Processes in PV Recycling

Thermal processes play a crucial role in the recycling of encapsulated crystalline silicon photovoltaic modules (c-Si PVMs), particularly in disassembling them into individual components. A key step involves the removal or debonding of the ethylene vinyl acetate (EVA) copolymer layers used as adhesives [67,68]. Although techniques such as mechanical crushing and chemical soaking have been explored, thermal decomposition is often favored [47,68]. This preference stems from the fact that thermal methods, compared to chemical methods which might involve hazardous and expensive chemicals, tend to better preserve the integrity of the glass and silicon cells [5,69]. However, this approach is not without drawbacks, as significant energy consumption and consequent emissions are primary concerns [70].

In this context, pyrolysis stands out as a prominent technique. It involves thermochemical decomposition at high temperatures in an oxygen-deprived environment, breaking down organic elements into gases and liquids while leaving inorganic components such as metals and glass largely intact [68]. This method is particularly effective in handling complex waste compositions, such as those found in waste from electrical and electronic equipment (WEEE) streams, which often contain diverse plastics mixed with other materials [68]. The anoxic conditions in pyrolysis help prevent oxidation and the formation of harmful by-products such as dioxins and PCBs [71].

Numerous studies have demonstrated that pyrolysis treatments can effectively remove over 99% of the polymers from photovoltaic (PV) modules [70]. Kang's research [72] emphasized thermal decomposition's effectiveness in separating the adhesive layer, thereby aiding semiconductor recovery to a purity of 99.999%. During the thermal decomposition process, EVA typically undergoes carbonization. However, in this experiment, the PV cells were heated at 600 °C for 1 h under an inert gas atmosphere, with a flow rate of 200 mL/min. EVA starts to decompose at around 350 °C, reaching complete decomposition at 520 °C. Consequently, by maintaining the temperature at 600 °C for 1 h in a furnace, the EVA was entirely removed, resulting in the retrieval of PV cells that showed no evidence of surface carbonization. Wang [70] introduced a two-stage thermal technique for delaminating the c-Si PVM. The process began by setting the temperature to 150 °C for 5 min, which softened the EVA binder and facilitated the effortless and complete removal of the TPT backing materials from the solar panels. The next step involved the elimination of the EVA binder through pyrolysis, conducted at 500 °C. The study further revealed that at lower temperatures (300–400 °C), acetic acid was the primary product, while at higher temperatures (above 410 °C), a range of olefins were produced.

Other studies have underscored the environmental advantages of thermal treatments over methods involving organic solvents [68]. Pyrolysis's role in efficiently salvaging undamaged silicon cells, a valuable market commodity, has been particularly highlighted in recent research [73,74]. To provide a comprehensive overview of these methodologies, Table 4 details various pyrolysis-based recycling approaches for removing EVA.

Table 4. Synthesis of pyrolysis-based recycling approaches for EVA removal.

Method	**Thermal Treatment at 170 °C and Mechanical Force**	**500 °C Pyrolysis for 30 min to 1 h**	**Organic Solvents, Thermal Treatment (600 °C for 1 h), and Chemical Etching**
Significant Findings	EVA extracted with similar properties to commercial EVA; thermally stable until 215 °C	A > 99% polymer removal; 75% of polymers degrade between 400 °C and 500 °C	An 86% silicon recovery yield; a purity of 99.999%
Advantages	Eco-friendly, no material degradation or gas emission	Significant removal of polymers	Efficient silicon recovery
Challenges and Limitations	Not specified	Mass loss rate decreases significantly above 500 °C	Not specified
Potential Applications	Reuse of extracted EVA in solar modules and possibly in packaging and textile industries	Not specified	Solves issues related to silicon supply, manufacturing costs, and PV module end-of-life management
Ref.	[49]	[68]	[72]

Method	**Thermal Treatment up to 600 °C**	**Two-Stage Heating (150 °C and 500 °C)**
Significant Findings	Detection of metals (including hazardous ones) in gas emissions and solid residues	Integral recovery of TPT backing materials; EVA binder removed
Advantages	Highlights the emission of hazardous metals for management	Detailed analysis of EVA pyrolysis; potential for environmental friendliness
Challenges & Limitations	Emissions need to be adequately managed to prevent environmental impact	Management/treatment of pyrolysis products
Potential Applications	Not specified	Environmentally friendly and efficient recycling of waste crystalline silicon solar panels
Ref.	[48]	[70]

6. Chemical Processes in PV Recycling

Chemical processes are integral to the recycling of photovoltaic (PV) panels, especially given the high purity levels required for silicon in solar applications. These methods excel in recovering high-purity silicon, silver, and other valuable metals, optimizing the use of resources [43,75,76].

One significant focus of chemical recycling is the removal of the ethylene vinyl acetate (EVA) layer. Doi's study [77] explored the effectiveness of organic solvents, such as trichloroethylene, in debonding EVA from crystalline silicon solar panels. Another research investigated various organic solvents, including toluene, for EVA dissolution, finding that ultrasound significantly accelerates this process [47]. However, concerns arise due to the production of hazardous by-products, such as lead, raising environmental safety issues [72].

The recovery of silver (Ag) from PV modules is a paramount area of research due to its economic and technological value. Studies have shown the efficacy of nitric acid leaching, enhanced by electrolysis, as a method for Ag extraction [78–81]. Characterization experiments, involving steps such as immersion in H_2SO_4, HNO_3 leaching, and X-ray fluorescence analysis, have been conducted to locate and measure the silver content in modules [82].

Dias' comprehensive study [67] assessed two methodologies for Ag extraction from PVMs: one combining mechanical and hydrometallurgical techniques, and the other incorporating a pyrolysis stage. Results indicated that a pyrolysis stage did not improve Ag extraction, suggesting that silver recovery should precede pyrolysis. The mechanical and hydrometallurgical combined procedure that efficiently concentrated up to 94% of the silver from PV modules, involving manual frame removal, module milling, sieving, and nitric acid leaching, was followed by AgCl precipitation using sodium chloride.

For Ag recovery, methods such as extraction with cyanide solution or nitric acid have been proposed [83]. However, these methods pose environmental risks, including waste acid solution production and harmful fume emissions [82,83]. In response, researchers have proposed using a methanesulfonic acid (MSA) mixture with an oxidant for Ag oxidation [84]. This approach offers several advantages, including increased metal salt solubility, conductivity, and environmentally responsible effluent treatment. Additionally, the ability to regenerate MSA during the AgCl precipitation process underscores its sustainability [75]. Optimal conditions for Ag dissolution were found with a 90:10 MSA to oxidizing agent ratio [75], achieving 99.8% (2N8) purity in recovered Ag, which could be further refined to 99.995% (4N5) through electrorefining, reducing contaminants such as Sn and Pb [75].

While chemical processes hold considerable promise in PV recycling, particularly for precious metal recovery, their application must be carefully balanced with environmental sustainability and economic feasibility. To provide a systematic overview of these chemical methods, Table 5 summarizes the chemical approaches discussed throughout this context.

Table 5. Summary of chemical methods for the recycling of a silicon PV panel.

Method	**Mechanical and Nitric Acid Leaching**	**Nitric Acid Leaching**	**Organic Solvent**	**Organic Solvent**
Target Material	Ag	Si, Cu, Ag, Pb	Si	Si
Key Process /Agent	Milling, Sieving, Leaching in HNO_3, Precipitating with NaCl	5M Nitric Acid, Agitation at 200 rpm	Trichloroethylene at 80 °C with mechanical pressure	o-Dichlorobenzene at 120 °C
Efficiency /Outcome	94% silver concentration yield	Si: 80%, Cu: 79%, Ag: 90%, Pb: 93% removal	Successfully recovered without damage after 7–10 days	Successfully recovered without damage after 1 week
Concerns /Issues	Energy consumption	Handling of acids and heavy metal disposal	Swelling and cracking of PV cells if pressure not applied	Swelling of EVA, potential for cracking
Ref.	[68]	[28]	[77]	[77]
Method	**Solvent Extraction and Electrowinning**	**Acid Precipitation**	**Sulfurization and Neutralization Treatment**	**Chemical Etching**
Target Material	Cu	Ag	Pb	Si
Key Process /Agent	LIX84-I extraction, H_2SO_4 Stripping, Electrowinning	HCl Precipitation, NaOH, Hydrazine Hydrate Reduction, Electrolytic Refining	NaOH Neutralization, Na_2S Sulfurization	HF, HNO_3, H_2SO_4, CH_3COOH, surfactant
Efficiency /Outcome	Not specified	99.99% purity after refining	93% removal	86% yield, 99.999% purity
Concerns /Issues	Handling of chemicals	Handling of chemicals, high-temperature processes	Handling of toxic Pb compounds	Handling of strong acids
Ref.	[28]	[28]	[28]	[72]
Method	**Ultrasonic Irradiation**	**Chemical Refinement**	**Chemical Refabrication**	**Chemical Recovery and Electrorefining**
Target Material	EVA	Si	Si	Ag
Key Process /Agent	O-DCB, TCE, Benzene, Toluene, Ultrasonic Power	Thermal or Chemical Separation, followed by Chemical Refinement	Wet chemical process using a mixture of HNO_3 and HF	Methanesulfonic acid (MSA) mixed with H_2O_2. Purification by Electrorefining

Table 5. *Cont.*

Method	Ultrasonic Irradiation	Chemical Refinement	Chemical Refabrication	Chemical Recovery and Electrorefining
Efficiency /Outcome	Complete dissolution in 3 M O-DCB at 70 °C, 900 W, 30 min	Silicon recovery with resultant new cells achieving 13–15% efficiency	Re-fabrication achieved a high efficiency of 17.6%, an 18.9% rise compared to the original efficiency	Optimal Ag extraction was achieved with a 90:10 MSA:H_2O_2 ratio. Initial purity of Ag powder was around 99% (2N), improved to 99.995% (4N5) after electrorefining.
Concerns /Issues	PV cell damage in other solvents	Absence of SiN_x antireflective coating on resultant cells	Determining the optimal ratio of HNO_3 to HF to avoid incomplete etching or deposition of Ag particles	Managing the balance between MSA and H_2O_2 to avoid excessive H_2O_2 decomposition and ensuing H_2O generation which dilutes the solution.
Ref.	[47]	[25]	[85]	[75]

7. Current Challenges in Solar Panel Recycling

The recycling of silicon solar panels, pivotal to the sustainability of solar energy, is confronted with a multitude of challenges. These challenges span technical, environmental, and economic aspects, each intertwining to influence the feasibility and effectiveness of the recycling process. The rapid growth in solar panel installations worldwide has not been matched by equally swift advancements in recycling technologies, leading to significant gaps in capability and capacity. This section delves into the primary challenges faced by the recycling of silicon solar panels, highlighting the complexities and constraints that hinder the development of efficient recycling methods.

7.1. Volume Concern

The surge in silicon solar panel installations, particularly in regions such as China, has led to an increase in EoL panels. Current recycling methods in these areas often fall short of international standards, struggling to keep pace with the growing volume of solar waste [15]. There is a pressing need for the development of scalable and advanced recycling solutions to manage EoL silicon solar panels efficiently and sustainably. Additionally, the high costs associated with transporting large quantities of EoL panels, especially those installed at high altitudes for maximum sun exposure, pose a significant challenge. To mitigate this, simple and quick pretreatment methods at local sites are suggested to reduce the volume of solar panels, thereby decreasing transportation costs. Given that glass is the main component of solar panels, prioritizing its recycling and local utilization could offer a more sustainable waste management approach [54]. The remaining components, which contain valuable metals, can then be collected, and processed at specialized solar panel recycling facilities, further enhancing the efficiency and sustainability of the recycling process.

7.2. Material Recovery

Recovering materials from silicon solar panels is fraught with challenges, including the production of harmful dust which contains glass and noise pollution during the crushing process [21]. The loss of materials, including rare and conventional ones such as silver, aluminum, and glass, is a significant issue during disposal [76]. For instance, nitric acid dissolution can effectively remove the EVA and metal layer from the wafer, potentially enabling the recovery of the entire cell. However, this process can lead to cell defects due to the use of inorganic acid, consequently reducing the recovery rate of valuable metals contained within the cells [21]. A high recovery rate method, such as vacuum blasting, has the advantage of removing the semiconductor layer without chemical dissolution, and the recovery of glass. However, this technique also has drawbacks, including the emission of metallic fractions and a relatively long processing time [21]. The risk of releasing hazardous substances such as lead from damaged encapsulating glass of silicon PV cells raises environmental and health concerns [86]. Silicon dust inhalation and the release of compounds from EVA and other manufacturing chemicals also pose serious risks [42,86]. Innovative, efficient recovery and recycling processes are crucial to mitigate these risks, optimize resource utilization, minimize environmental impact, and ensure the sustainable use of silicon PV technology.

7.3. Environmental Impact

Recycling solar panels presents several environmental challenges. These include the release of harmful gases such as hydrofluoric acid during chemical treatments, exposure to toxic dust and noise during physical processes such as high voltage crushing, and the high energy consumption of thermal methods [23,42,85,87]. Additional issues such as nitrogen oxide emissions during EVA layer separation by nitric acid dissolution [21,56], waste disposal complications, and the prolonged dissolution time of the EVA layer using traditional organic solvents [88]. Typically, the utilization of organic solvents in the dissolution of EVA from PV panels needs extended time periods, resulting in less efficiency and the additional challenge of wastewater treatment. For example, isopropanol is used to dissolve the polymer over a span of two days, and trichloroethylene requires a duration of ten days at a temperature of 80 °C. Moreover, an alternative method combining organic solvent and ultrasonication has been explored. In this process, EVA is fully dissolved in 3 M *O*-dichlorobenzene (*O*-DCB) at 70 °C, with an irradiation power of 900 W, achieving dissolution in 30 min. However, this ultrasonic approach increases processing costs and leads to the generation of organic liquid waste, presenting further environmental and handling challenges. Given these constraints, there is a growing need to develop more environmentally sustainable and cost-effective methods for EVA dissolution. Future research could focus on identifying solvents that balance efficiency, environmental impact, and economic feasibility.

7.4. Economic Viability

The economics of recycling silicon solar panels are currently not favorable. The costs of establishing and operating recycling infrastructure are high compared to the benefits, especially considering the limited number of panels being decommissioned [14,89]. This economic challenge diminishes the incentive for manufacturers to engage in recycling efforts, pushing them towards landfilling or low-value recycling without material separation. Evaluating the potential for the recovery of valuable materials to offset overall recovery costs is essential to enhance the economic feasibility of silicon solar panel recycling and boost the competitiveness of PV technologies [90].

Many studies have carried out life cycle assessments (LCA) on the EoL PVM recycling. These LCAs have established that recycling PV panel waste can reduce both energy demands and the emissions linked to landfill disposal [91]. Additionally, while some studies analyzing energy and resource use, as well as air emissions during panel recycling, suggest that under current conditions, recycling PV waste might not be economically feasible [14,89]. Yet, a comprehensive understanding in this area remains limited. The task of comparing the economic and environmental impacts of different PV recycling technologies is hindered by several factors. These include variations in system boundaries, functional units, the degree of material recycling, and the ways in which LCA results are interpreted [91].

Pablo et al. [92] performed an LCA study comparing a simplified recycling method with a full recovery approach and landfilling. This simplified method involves deframing the module, shredding the laminate, and concentrating materials through electrostatic separation. This process results in two fractions: one being a valuable mix (comprising only 2–3 wt%) of silver, copper, aluminum, and silicon, and the other primarily consisting of glass, silicon, and polymers. An economic assessment of this method suggests it could be more profitable than full recovery, particularly for lower waste volumes (less than 4 kt/y), due to reduced capital costs for equipment. This study indicates that, under certain conditions, streamlined recycling processes can offer a more cost-effective alternative to comprehensive methods, potentially leading to more sustainable and economically viable solutions in the field of PV waste management.

8. Conclusions

The transition to sustainable energy sources, epitomized by the global surge in solar photovoltaic (PV) energy adoption, presents both opportunities and significant challenges. This review has explored the intricate aspects of crystalline silicon photovoltaic module (PVM) recycling, delving into the current state, methodologies, and challenges associated with this crucial process.

The examination of the recycling landscape reveals that while technological advancements in PV module production have been remarkable, recycling practices have not kept pace. The growing volume of EoL silicon solar panels, particularly in rapidly expanding markets such as China, underscores the urgency for scalable and advanced recycling solutions.

Our exploration into the composition of crystalline silicon solar panels underscores the complexity involved in recycling these multi-layered devices. Each component, from the protective front glass to the crucial silicon cells, poses unique challenges in recycling, necessitating diverse strategies such as mechanical, thermal, and chemical processes. Mechanical processes, while efficient in certain aspects, face challenges in terms of cost, environmental impact, and energy efficiency. Thermal processes, particularly pyrolysis, offer promising results in breaking down organic elements but are not without significant energy demands and emissions. Chemical processes, effective in recovering high-purity materials, must contend with balancing environmental sustainability and economic feasibility.

The primary challenges in recycling silicon solar panels are multifaceted, encompassing technical, environmental, and economic aspects. The production of harmful dust, the potential release of hazardous substances, and the environmental impact of various recycling processes are key concerns that need addressing. Additionally, the current economic model of solar panel recycling is not incentivizing enough for manufacturers, suggesting a need for more cost-effective and resource-efficient methods.

As the solar industry continues to grow, it is imperative that recycling strategies evolve concurrently. Future research and development should focus on creating more energy-efficient, environmentally friendly, and economically viable recycling methods. Innovations in mechanical separation, advancements in thermal processing techniques, and the development of less hazardous chemical processes are critical areas for exploration. Furthermore, the establishment of global standards and policies that mandate recycling and encourage the development of sustainable recycling infrastructure is essential.

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