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Review

Sustainable Strategies for Crystalline Solar Cell Recycling: A Review on Recycling Techniques, Companies, and Environmental Impact Analysis

Mina Akhter [1], Ahmed Al Mansur [1], Md. Imamul Islam [2], M. S. Hossain Lipu [1,*], Tahia F. Karim [3], Maher G. M. Abdolrasol [4] and Thamer A. H. Alghamdi [5,6,*]

[1] Department of Electrical and Electronic Engineering, Green University of Bangladesh, Narayanganj 1461, Bangladesh; mina.akther8830@gmail.com (M.A.); mansur@eee.green.edu.bd (A.A.M.)
[2] Department of Electrical and Electronic Engineering, Universiti Malaysia Pahang Al-Sultan Abdullah, Pekan 26600, Malaysia; mes22003@student.umpsa.edu.my
[3] Department of Electrical and Electronic Engineering, University of Asia Pacific, Dhaka 1205, Bangladesh; tahiafkarim@gmail.com
[4] Institute of Sustainable Energy, Universiti Tenaga Nasional, Kajang 43000, Malaysia; maher.abdolrasol@gmail.com
[5] Wolfson Centre for Magnetics, School of Engineering, Cardiff University, Cardiff CF24 3AA, UK
[6] Electrical Engineering Department, Faculty of Engineering, Al-Baha University, Al-Baha 65779, Saudi Arabia
* Correspondence: shahadat@eee.green.edu.bd (M.S.H.L.); alghamdit1@cardiff.ac.uk (T.A.H.A.)

Abstract: Solar PV is gaining increasing importance in the worldwide energy industry. Consequently, the global expansion of crystalline photovoltaic power plants has resulted in a rise in PV waste generation. However, disposing of PV waste is challenging and can pose harmful chemical effects on the environment. Therefore, developing technologies for recycling crystalline silicon solar modules is imperative to improve process efficiency, economics, recovery, and recycling rates. This review offers a comprehensive analysis of PV waste management, specifically focusing on crystalline solar cell recycling. The classification of PV recycling companies based on various components, including solar panels, PV glass, aluminum frames, silicon solar cells, junction boxes, plastic, back sheets, and cables, is explored. Additionally, the survey includes an in-depth literature review concentrating on chemical treatment for crystalline solar cell recycling. Furthermore, this study provides constructive suggestions for PV power plants on how to promote solar cell recycling at the end of their life cycles, thereby reducing their environmental impact. Moreover, the techno-economic and environmental dimensions of solar cell recycling techniques are investigated in detail. Overall, this review offers valuable insights into the challenges and opportunities associated with crystalline solar cell recycling, emphasizing the importance of economically feasible and environmentally sustainable PV waste management solutions in the constantly evolving solar energy market.

Keywords: solar PV cell recycling; degradation; PV lifespan; efficiency; recycling techniques

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1. Introduction

The number of photovoltaic installations is increasing due to the rapid growth of solar power energy in industries. As these installations reach their end-of-life state, crystalline PV cell disposal and recycling have emerged as key aspects of sustainable energy management [1]. This paper explores the existing recycling procedures and technology used by crystalline PV cell recycling companies. If these modules are disposed of in landfills, toxic chemicals and heavy metals may be released into the environment and other valuable resources. Recycling crystalline solar cells has garnered significant interest in reducing uncertainties by reducing the overall environmental footprint of photovoltaic technology, reclaiming crucial elements, and producing fewer waste materials [2]. This research aims to shed light on the intricate landscape of recycling crystalline solar cells by thoroughly examining the available literature. In pinpointing these areas, information must be included suggesting possible strategies for transitioning toward a circular economy within the photovoltaic sector [3]. The research suggests directing future studies, policy formulation, and industry standards toward the sustainable and ethical handling of photovoltaic waste. Apart from that, existing PV panel recycling companies are actively addressing the environmental concerns caused by end-of-life solar panels worldwide. These companies are deeply concerned about sustainability, and their programs include a variety of procedures targeted at efficiently recycling and reusing PV waste [4].

The rising worldwide need for clean, renewable energy has driven the expanded utilization of photovoltaic technology [5], where crystalline silicon solar cells have emerged as a significant player in the renewable energy arena [2]. While this rapid expansion has led to notable progress in solar energy production, it has also raised a crucial environmental issue [6]. The rapid proliferation of solar systems highlights the need for a deep grasp of ecologically responsible recycling and disposal methods. This is necessary to limit potential ecological harm, such as soil and water contamination from hazardous compounds used in solar panels, and to avoid resource depletion. By putting in place efficient recycling procedures, solar panel trash may be recycled with less negative environmental impact, valuable resources recovered, and less demand for new raw materials [7]. One of the key components of sustainable waste management for renewable energy is the recycling of solar cells, as shown in Figure 1. As solar technology advances, effective management of the end-of-life disposal of PV panels is increasingly crucial to mitigate environmental impacts. Various methods, including mechanical, chemical, and thermal processes, are employed for the recycling of PV modules [8].

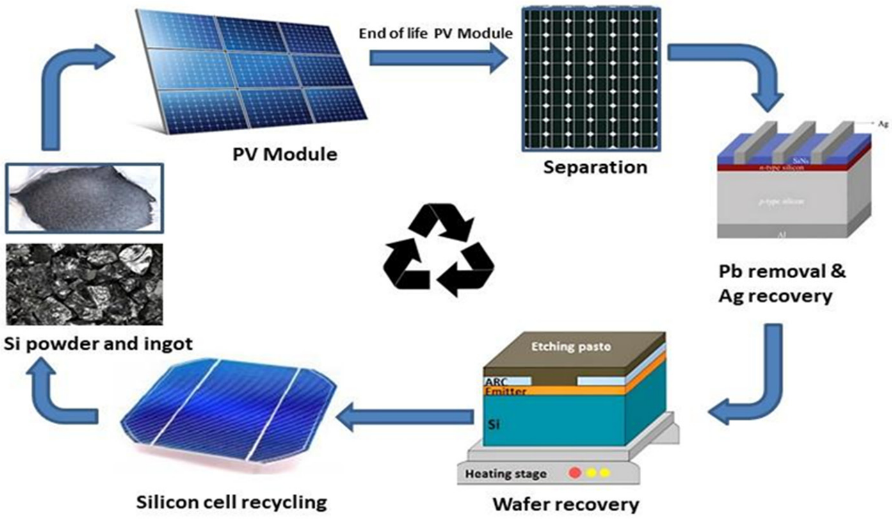

Figure 1. The process of recycling crystalline solar cells.

In this study, chemical etching or leaching methods are chosen for silicon recovery, with a primary emphasis on cell recycling [9]. The initial phase of solar cell recycling involves the collection and transportation of used panels to recycling facilities. Upon arrival, panels undergo careful disassembly, and various components such as glass, metals, and semiconductors are sorted and separated [10]. Once the semiconductor is extracted from the PV module, silicon wafers undergo a chemical process to yield silicon ingots and powder.

The renewable energy sector demonstrates its dedication to sustainable waste management by recycling crystalline silicon solar cells from PV modules. This practice reduces the environmental impact associated with solar module disposal while reclaiming valuable materials, thus promoting the circular economy and securing the enduring sustainability of solar energy as a clean power source [11]. To address the existing research gaps, this review offers a summary of the factors involved in solar PV recycling.

This study investigates the economic feasibility of using expensive chemical etching agents and complex etching procedures in industrial operations. Chemical etching finds extensive application in multiple industries, particularly in the production of electronic components. Additionally, there is significant concern regarding the environmental impact of secondary pollutants like nitrogen oxides generated during etching processes [12]. Poor disposal of these byproducts may result in environmental pollution and endanger ecosystems. An important issue is that solar cells crafted from recycled wafers often exhibit lower conversion efficiency than their commercially produced counterparts [13]. In the fiercely competitive photovoltaic (PV) market, efficiency significantly impacts the adoption of solar technology. It is crucial to understand the reasons behind lower conversion efficiencies in solar cells based on recycled wafers to overcome this obstacle and enhance the market competitiveness of sustainable energy solutions. When compared to newly made solar wafers, the recycled wafer's efficiency ranges from 85% to 90%. We learned this information from our earlier literature research. To eliminate the waste from solar cells by 2050, we urge production managers and businesses to recycle and regenerate these wafers [14].

This study examines chemical processes employed in recycling crystalline solar cells, with a focus on advanced technologies. It highlights the superior efficacy of chemical methods in extracting silicon from PV modules compared to alternative techniques and technologies [15]. This study evaluates chemical processes with compositions conducive to greater silicon extraction. It also conducts a comprehensive assessment to tackle the increasing challenges linked to end-of-life solar modules [16]. This study also explores crystalline photovoltaic cell recycling in depth, focusing on opportunities, challenges, and prospects. It investigates the current state of crystalline PV cell recycling companies. Recycling companies dedicated to the recovery and reprocessing of decommissioned PV panels play a vital role in mitigating the environmental impact associated with photovoltaic waste [17]. The approach of different countries to recycling PV waste is briefly described here. It promotes sustainable solutions to save energy and ecology by creating awareness and encouraging different countries to recycle PV panels [18]. In the typical linear economy, resources are gathered to make things that are subsequently landfilled as they reach the end of their useful life. To replace them, new products are made from raw and virgin materials mined from the Earth's surface. The circular economy gives new life to waste by encouraging material recovery and component reuse, allowing value to be created from waste [19]. This alternate method prevents the end-of-life phase by converting waste into resources for the manufacturing supply chain. It reduces material depletion and carbon emissions while eventually balancing the renewable energy transition. The future of solar PV should be based on a circular economy [20]. Currently, recycling silicon PV panels at the end of their useful lives is now prohibitively expensive. The recycling method, recycling yield, module design, module transportation, and pollution discharge all have an impact on the cost of recycling to some extent. As yet, no one has attempted to calculate these expenses collectively [21,22]. The cost of recycling is a critical enabler of the circular economy shift. For effective future development, we need new techno-economic insights into the challenge.

This study explores recent global megaprojects and emphasizes their significant influence on the development of the sustainable energy landscape. Governments, companies, and investors are increasingly collaborating to design and build large-scale photovoltaic (PV) projects that cross borders [23]. These initiatives not only provide significant contributions to the renewable energy sector, but they also represent a critical turning point toward a more ecologically conscious and strong energy infrastructure [24]. With their enormous solar panels and state-of-the-art equipment, these megaprojects are shining examples of innovation that are bringing in a new chapter in the history of energy around the globe [10]. These large-scale solar projects showcase global collaboration and technological advancements in renewable energy. They signify a worldwide dedication to transitioning to cleaner energy sources. As the world faces the imperative to adopt sustainable energy solutions, these photovoltaic megaprojects stand out as examples of excellence, embodying cooperation and groundbreaking achievements [25].

This research delves into an analysis of the diverse technologies employed in the recycling process of silicon, an essential element in photovoltaic modules. It explores different levels of purity, investigating the chemical processes implicated in recycling cells from higher to lower purity grades. This comprehensive exploration furnishes a deep understanding of the highly efficient solutions offered by innovative methodologies. The focus on recycling underscores the industry's commitment to minimizing the environmental impact and maximizing resource efficiency, contributing to the overarching goal of sustainability. This study also provides a comprehensive analysis of several chemical treatment recycling systems, emphasizing their effectiveness, potential effects on the environment, and viability from an economic standpoint. This research aims to provide insights into the most effective and sustainable method of recycling crystalline PV cells, taking into account parameters such as material recovery rates and overall environmental footprint. This study aims to shed light on the techno-economic challenges associated with each recycling method through a comparative analysis. This research contributes to continuing efforts to develop a more circular and sustainable photovoltaic industry by bridging the gap between technology advancements and environmental responsibility. The summary of this research contributes the following:

- A thorough investigation of environment-friendly recycling procedures that focuses on chemical processes of high-purity silicon for recycling to increase its sustainability.
- Discussion of new opportunities and problems to assess the advantages of the current PV recycling system and pinpoint the obstacles of recycling companies.
- Identify recycling companies across the world that are approaching and developing new technologies for reducing the current environmental issues.
- Impact of Pb, Cu, Ag, and Si after disposing of the cell from the PV module in the environment.

2. Global PV Capacity and Estimated Projection of PV Waste

Table 1 gives an estimate of the potential global PV capacity from 2020 to 2050, together with the expected regular and early losses [26–29]. Talk about this in-depth. PV capacity worldwide (GW): The cumulative installed capacity of solar photovoltaic systems worldwide is represented by the total PV capacity, which is expressed in gigawatts (GW). It is anticipated that the capacity will rise dramatically over time, from 777 GW in 2020 to 4512 GW in 2050 [30]. This demonstrates that the usage of solar energy has grown drastically on a global basis in depth. Regular loss per GW (ton waste): The amount of waste produced per gigawatt of PV capacity under typical operating conditions is referred to as regular loss. It is anticipated that in 2050, the regular loss will drop from 128.7 tons of garbage per GW in 2020 to 13,297.85 tons of waste per GW [9]. This indicates the use of materials more efficiently through technological developments or better waste management techniques. Early loss (in tons of waste/GW): The amount of waste produced early in the PV system life cycle—possibly as a result of manufacturing or installation procedures—is indicated by the term "early loss". From 1093.95 tons of garbage per GW in 2020 to 17,287.23 tons of waste per GW in 2050, it is anticipated that the early loss will decline. As with normal loss, this drop could indicate improvements in production methods or more recycling initiatives [31].

Table 1. Cumulative projection of waste in 2020 to 2050.

Year	2020	2030	2040	2050
Total PV capacity (GW)	777	1632	2895	4512
Regular loss (Ton waste/GW)	128.7	1041.67	5181.35	13,297.85
Early loss (Ton waste/GW)	1093.95	4901.96	11,053.45	17,287.23

2.1. Global Projection of Cumulative Capacity, Cumulative PV Waste, and Recycling Cost

In the coming decades, cumulative photovoltaic PV capacity is expected to rise dramatically over the worldwide solar energy landscape [2]. Figure 2 shows the projected cumulative capacity, cumulative PV waste, and recycling cost for 2030, 2040, and 2050, respectively [4]. However, managing end-of-life PV panels and the resulting PV waste generation is a rising difficulty that comes with production growth. The global photovoltaic landscape is estimated to reach 1600 GW by 2030, demonstrating the world's expanding adoption of solar energy [32]. Apart from that, with this optimistic growth comes the unavoidable difficulty of managing EoL PV panels, with a total PV waste production of 1.7–8 million tons projected. An investment of USD 628.5 million is predicted to be necessary for a targeted recycling effort to resolve this. By 2040, the cumulative PV capacity is estimated to reach 2895 GW. With such a considerable rise, PV waste is estimated to reach 15–32 million tons [33]. This increase in waste needs a larger financial investment in recycling activities, with a cost estimate of USD 2 billion. The increase in cost indicates the PV industry's expansion and increased knowledge of appropriate PV waste management. Cumulative PV capacity is predicted to be 4512 GW by 2050. However, it may result in 60–80 million tons of PV waste. A 5 billion USD investment in recycling is critical to address this problem, emphasizing the importance of development [34].

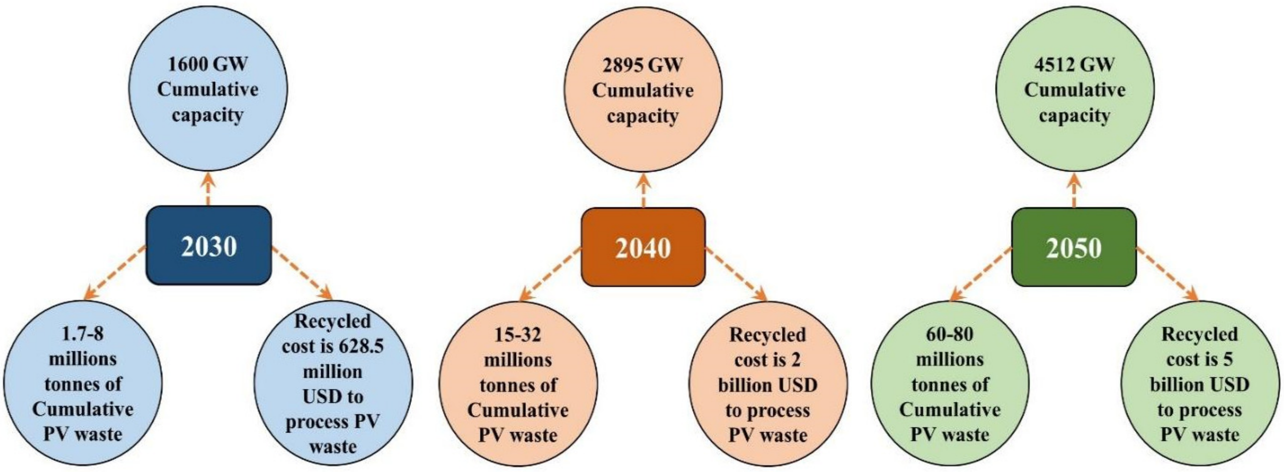

Figure 2. Cumulative projection of capacity, PV waste, and recycling cost globally.

2.2. Market Share of PV Panel Module Type

The crystalline silicon photovoltaic (PV) panel is the most innovative and effective technology in solar energy technology, with a market share of around 92% [35]. Polycrystalline silicon accounts for 51% of the global market, whereas monocrystalline silicon accounts for 41% [36]. When compared to thin-film technology, these panels use high-quality, commonly available silicon as its fundamental material, providing higher efficiency. The module efficiency of crystalline silicon technology typically ranges between 14% and 22%, with the more efficient solutions being more expensive [37]. Monocrystalline silicon, known as the "workhorse of the industry", is the most expensive but also the most efficient technology [38].

It is made of single-crystal wafer cells that are cut from cylindrical ingots. On the other hand, multi- or polycrystalline modules, in which cells are made from square-cast ingots, are less costly but have poorer efficiency [39]. Ribbon silicon, a third less expensive and less efficient method, is created by pulling thin films from molten silicon, resulting in a multi-crystalline structure. Individual cells are coupled in various combinations to generate a full module in all circumstances [29]. However, in the solar energy landscape, alternative technologies like cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) have smaller market shares of 2.5% and 5.5%, respectively. The PV systems' global market share is depicted in Figure 3.

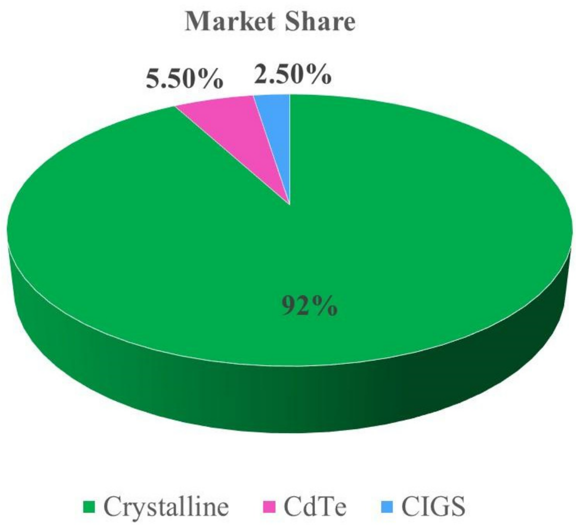

Figure 3. Market share of crystalline silicon PV modules globally.

2.3. Technologies for Recycling Crystalline Silicon Cells

Table 2 describes the technologies for recovering silicon. Various technologies have been used to recover silicon from crystalline silicon PV modules, each with distinct efficiency and techniques [18]. Yen-Chih Lin developed a phase-transfer separation method in 2010, yielding a remarkable 71.1% recovery of silicon powder. This method was improved by incorporating centrifugal technology, as approached by Lin's work the same year, in which impurities in the silicon were effectively removed through redispersion and centrifugal separation, yielding an impressive 74.1% recovery of pure silicon powder. Centrifugation separation is an advanced process that evolved from phase-transfer separation technology [20]. Another notable method, implemented in 2016, achieves a satisfactory silicon recovery rate of 62% through a two-step heating process that involves both acid and alkali. Currently, the most successful method in 2022 is chemical treatment, which recovers an astounding 90% of pure silicone [25]. This approach, which was highlighted in 2010, developed its superiority in the reclamation of silicon from PV modules. Silicon powder was recovered at a rate of 48.9% using electrostatic separation, which was accepted in 2023 [26]. While this procedure is viable, it falls short of the efficiency reached by chemical treatment. In conclusion, the comparative analysis reveals that the chemical treatment method is the most effective, with a remarkable 90% pure silicon recovery rate, outperforming other technologies such as centrifugation separation, phase-transfer separation, two-step heating processes, and electrostatic separation. These developments highlight the ongoing innovation and optimization of technology for the long-term recovery of valuable materials from crystalline silicon photovoltaic modules [27].

Table 2. PV cell recycling technologies according to the purity of silicon.

Refs.	Technologies	Year	Purity of Si (%)
[11]	Centrifugation separation	2010	74.1%
[12]	Phase-transfer separation	2010	71.1%
[13]	A heating procedure involves both acidic and alkaline treatments	2016	62%
[14]	Chemical treatment	2022	90%
[21]	Electrostatic separation	2023	48.9%

2.4. An Overview of the c-Si PV Panel EoL Recycling Process

When crystalline silicon photovoltaic (c-Si PV) panels are end-of-life treated, important components including aluminum, copper, and steel must be carefully separated and recovered. Component separation is the term for the thermal procedure that is usually used to separate these components [40]. The EoL c-Si PV panels are first gathered and taken to a recycling plant, where they go through a first check to make sure there are no pollutants present. After that, the panels are proceeded through a thermal treatment operation [41]. This process breaks down steel, copper, and aluminum components by carefully delivering heat to melting temperatures. Because of its low melting point, aluminum can be efficiently separated from other materials by liquefaction. The molten aluminum is then gathered and used in various ways [42]. Even though copper has a higher melting point than aluminum but a lower melting point than steel, there is still a separation phase for copper [43]. Throughout the process, the residual steel components—which have a higher melting point—maintain their structural integrity. Moreover, the PV cells in the c-Si panels are carefully treated to eliminate key components while enabling recycling. This process involves separating the PV cells from other components to recover materials such as silicon, silver, and other semiconductor elements [44]. Once the PV cells have been removed, additional processing can be performed to recover these materials for use in the manufacture of new solar panels or other electrical products. The segmentation of components in PV cells is outlined below.

- Glass, encapsulation layers, semiconductor components, and other materials make up PV cells.
- Thermal methods are used to break down the covering layers and remove the PV cells.
- The glass, EVA sheet, ribbon, and back sheet from the module are removed after the metal frame. Lead, silver, silicon, and other module components are recovered from the semiconductor by further recycling processes using etching techniques.

Silicon wafers of the photovoltaic cell are separated using several types of chemical processes to recover pure silicon. Silicon wafers are initially removed from abandoned photovoltaic cells, which are typically included in silicon-based semiconductors. Commonly, mechanical methods serve as the initial step in the separation process to remove any supplementary materials, like covering layers or metal contacts, adhered to the wafers [23]. The remaining layers and impurities are then intended to be removed by a chemical treatment that is applied to the wafers after that. For the pure silicon to be isolated from the PV cells' composite structure, a chemical procedure is essential [45]. The silicon wafers are left in a reasonably pure state after the different components are broken down, usually using acidic solutions or other specialized chemicals. Making the silicon wafers into a powder is the next step once they have been effectively separated [14]. This is usually accomplished by crushing the wafers into small particles using a mechanical procedure called milling. To guarantee a high level of purity of the resultant silicon powder, further purification procedures might be applied [7]. The chemical-based recycling process of the c-Si panel is shown in Figure 4.

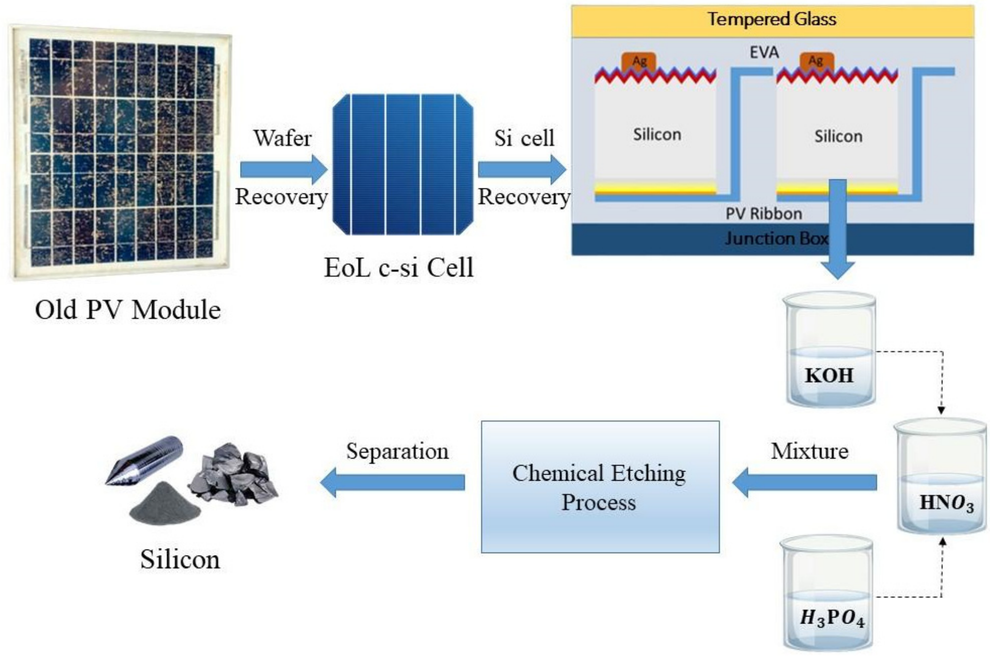

Figure 4. Crystalline Si cell recycling process (chemical base).

3. Recent Studies and Research on Crystalline Silicon Cell Recycling

Saving raw materials and reducing waste are essential aspects of reducing the environmental impact of manufacturing processes [46]. Life cycle assessment is an increasingly common approach for analyzing the environmental impacts of processes. There have been several articles recently on this concern. PV module production entails many steps including the material extraction of metals, semi-raw material production, solar cell production, PV module transportation, installation, and waste disposal, etc. [47]. They believed that, in terms of harmful substances, wastewater outcomes, and high consumption of energy, silicon ore extraction, industrial silicon melting process, and solar-grade silicon purification, in particular, had a significantly greater environmental impact. The advantages of recycling old PV waste go beyond environmental concerns to include economic and resource efficiency factors. Despite the challenges and obstacles connected with recycling old solar panels, increasing recycling options is critical for building a circular economy and maintaining solar energy's long-term sustainability [48].

It is possible to recycle approximately 95% of the materials used in the manufacture of a solar panel and approximately 90% of silicon, 95% of the semiconductor material, and 85% of cells from PV modules, making it a useful resource for recovering high-value components such as silicon, aluminum frames, and silver present in the module's front contacts [40].

Tables 3–5 illustrate the latest etching procedures for the chemical recovery of silicon wafers with recovery rates ranging from 80% to 100%. These chemical reactions are separated into three segments based on their recovery rating, making it easy to identify the method with the best outcome. To achieve silicon wafers of specific thickness and high purity, suitable etching conditions must be chosen. Depending on the chemical composition, the etching solution can be divided into several etching solutions. Lineesh Punathil [11] employed a $KOH/HNO_3/H_3PO_4$ etchant blend, achieving purity levels of up to 99.99% with a range of up to 90%. Chen [9] employed HNO_3 (5 mol L^{-1}), operating at 80 °C for 1 h, with a chemical reagent of 25 mL g^{-1}, resulting in the recovery of 99.9% of the silicon. Wang [10] utilized HNO_3 (3 mol L^{-1}), ultrasonic cleaning at 150 W power, operating at 60 °C for 90 min, to achieve a silicon recovery rate of 99.24%. A significant quantity of silicon was also recovered by other techniques between 2018 and 2022. Kang [3] employed an etchant mixture containing 48% HF, 70% HNO_3, 97% H_2SO_4, and 99% CH_3COOH, achieving an 86% recovery of silicon wafers with a range of 85–90%. Park J's use of a chemical composition comprising 60% HNO_3, combined with mechanical grinding and 30% KOH, led to an 80% recovery of silicon [4]. Huang [2] achieved a 90% silicon recovery by employing a combination of etchants (HNO_3, HF (10%)) for 15 min, followed by NaOH (3%) treatment at 50 °C for 20 min. Huang [2] utilized an extra chemical solution comprising HNO_3, 10% HF, NaOH, 60% HNO_3, and 45% KOH, operating at 80 °C, along with an etching paste primarily composed of H_3PO_4, to achieve 90% pure silicon. Huang [8] also achieved a 90% silicon yield by employing etching with a combination of HF acid, comprising 38% HCl, operating at 50 °C, and 10% HF, along with NaOH alkali. Aluminum (Al) is removed using a mixture of HCl, H_2O_2, and H_2O at a range of 60–84%. Silicon nitride (SiNx) and silver (Ag) are removed with 5% HF, and silicon is etched with 25% NaOH. Despite obtaining a purity of 62%, the NaOH etching stage results in a significant 38% silicon loss. The second method involves 5 M HNO_3 to dissolve Ag and Cu wire, 90% H3PO4 to eliminate SiNx at high temperatures, and 45% KOH to remove Al. Although this approach produces a higher purity of silicon at 80%, it has the disadvantage of causing partial silicon loss during the etching process. Notably, the procedure does not employ HF, which reduces environmental issues. The third approach involves removing Ag with a 30% KOH solution at 60 °C, followed by selective acidic etching with a combination of 65% HNO_3, 40% HF, 99.5% CH_3COOH, and Br_2. NaOH treatment completes the process. As a result, the silicon purity is 74.5%. The remarks emphasize the need to adapt the recycling process to the specific materials involved, suggesting the need for modifications in etching solutions dependent on the type of PV cells to be recycled.

Table 3. Chemical process considering the purity of Si at the range of 60–84%.

Refs and Year	Chemical Process (Etching/Leaching)	Purity (%)	Remarks
[7] 2011	$HCl/H_2O_2/H_2O$ (1:1:5) to remove Al; 5% HF to remove SiNx and Ag; 25% NaOH to etch silicon.	62%	Because of the NaOH etching procedure, 38% of silicon is lost.
[1] 2016	5 M HNO_3 to dissolve Ag and Cu wire: 90% H_3PO_4 to remove SiNx; (160 °C, 60 min) 45% KOH to remove Al (80 °C, 10 min).	80%	Etching without hydrofluoric acid leads to partial silicon loss.
[16] 2010	30% KOH, 60 °C to remove Ag, 65% HNO_3, 40% HF + 99.5% CH_3COOH + Br_2. Selective acidic etching, NaOH.	74.5%	Depending on the kind of PV cells to be recycled, etching solutions must be adjusted.

Table 4. Chemical process considering the purity of Si at the range of 85–90%.

Refs and Year	Chemical Process (Etching/Leaching)	Purity (%)	Remarks
[19] 2017	(1) H_3PO_4 to remove Al along with HNO_3 and HF to remove Ag, SiNx (solid to liquid ratio 0.03 g/mL).	85%	N/A
[8] 2015	(2) 48% HF + 70% HNO_3 + 97% H_2SO_4 + 99% CH_3COOH at room temperature to remove electrode, SiNx, and etch silicon.	86%	This process is free from hydrofluoric acid and comparatively less time-consuming than treatment involving HF.
[17] 2022	(3) HNO_3 (30 wt%), 50 °C, 120 min, HCl (36 wt%), RT, 60 min.	86.5%	N/A
[4] 2016	(4) 60% HNO_3 to remove Ag, mechanical removal of other layers, and 45% KOH to etch back silicon.	90%	The silicon weight diminishes as a result of etching on the emitter and back surface field.
[2] 2017	(5) HNO_3, 10% HF, NaOH 60% HNO_3, 45% KOH, 80 °C, etching paste (mostly H_3PO_4).	90%	The solar-grade silicon specification aligns with the recovered silicon.
[2] 2017	(6) HNO_3, HF (10%), 15 min, NaOH (3%), 50 °C, 20 min.	90%	HF usage can present dangers and corrosive properties.

Table 5. Chemical processes consider the purity of Si at a range of up to 90%.

Refs and Year	Chemical Process (Etching/Leaching)	Purity (%)	Remarks
[9] 2021	(1) HNO_3 (5 mol L^{-1}), 80 °C, 1 h, 25 mL g^{-1} KOH (2 mol L^{-1}), 80 °C, 1 h, 50 mL $g^{-1.}$	99.9%	This process does not involve HF, but it does take longer to complete compared to HF treatment.
[11] 2021	(2) $KOH/HNO_3/H_3PO_4$ etchant.	99.99%	KOH is more efficient than sodium hydroxide NaOH and does not involve the use of HF.
[10] 2022	(3) HNO_3 (3 mol L^{-1}), ultrasonic (150 W), ultrasonic cleaning, 60 °C, 90 min.	98.9%	The cavitation effect of an ultrasonic cleaner improves silicon recovery and purity without the use of HF.
[10] 2022	(4) HCl (3 mol L^{-1}), ultrasonic (150 W), ultrasonic cleaner, 60 °C, 90 min.	99.24%	The cavitation effect of an ultrasonic cleaner boosts silicon recovery and purity while avoiding the use of HF.
[18] 2019	(5) 60% HNO_3 to dissolve 100% Ag and break chemical bonds between spherical Al microparticles in Al paste under ultrasonic; microfiltration to extract Si; centrifugal process to separate Al; HCl to precipitate Ag.	98%	Break the chemical connections between the spherical Al microparticles in the Al paste and dissolve 100% Ag.
[21] 2020	(6) 8 mol/L KOH at 60 °C to remove Al; 8 mol/L HNO_3 at 80 °C to remove Ag and Pb.	99%	The ultra-pure silicon powder was nano-sized to fulfill the expansion-tolerant Si criteria. Anodes used in lithium-ion batteries.
[20] 2018	(7) 64% HNO_3 and HCl to dissolve Ag and break chemical bond of Al layers; ultrasound yreatment 75 °C, 2 h etching of SiNx layer in an HF-based solution.	98.3%	Electrode removal and anti-reflection coating performed at the same time

3.1. Comparison of Chemical Treatment

The initial method illustrated in Figure 5 involves a combination of 48% hydrofluoric acid (HF), 70% nitric acid (HNO_3), 97% sulfuric acid (H_2SO_4), and 99% acetic acid (CH_3COOH). This mixture's silicon wafer recovery rate is 86%, indicating a considerable achievement in silicon recovery [40]. However, further research could enhance the efficiency of the procedure. In the second step, a combination of 38% hydrochloric acid (HCl) and 10% hydrofluoric acid (HF) is added as an alkali, reaching temperatures up to 50 °C, alongside the inclusion of sodium hydroxide (NaOH) as an alkali. The silicon wafer recovery rate increased to 90% with this process. Combining acids and alkalis usually allows the silicon to dissolve more completely, increasing the recovery rate [49]. The third method includes a potassium hydroxide (KOH), nitric acid (HNO_3), and phosphoric acid (H_3PO_4) composite etchant. This mixture achieved an impressive silicon recovery rate of 99.99%, which is exceptionally noteworthy. In terms of silicon recovery, this result is particularly noteworthy since it shows that a specific etchant mixture may achieve nearly 100% recovery [50]. However, among the three methods, the one employing a $KOH/HNO_3/H_3PO_4$ etchant mixture emerges as the most efficient and produces the most favorable results, despite all three processes being successful in silicon recovery [51]. With an incredible 99.99% recovery rate, this method shows promise for nearly complete PV cell silicon extraction. This particular chemical composition appears to have a part in this technique's amazing outcome. In summary, each technique uses an individual sequence of chemical treatments to remove substances from silicon during PV cell recycling. The choices between purity and silicon loss, as well as environmental effects and solution changes, highlight the challenges in establishing efficient and environmentally friendly silicon cell recycling methods [52]. Several risks must be properly controlled when handling chemicals and equipment for recycling crystalline solar cells to protect employees, the environment, and the health of everyone. The scientific community uses a variety of strategies, ideas, and best practices to manage these risks:

Ammonia (NH_3): antireflective coating manufacturing results in irritation of the skin and eyes, infections of the throat and lungs, and stomach burns.

Hydrochloric Acid (HCl): manufacturing of electrical high-quality silicon grades, as well as in cleaning and etching semiconductors, food digestion, respiratory depression, irritated skin, and infections.

Hydrochloric Acid (HF): to remove silver (Ag) skin discoloration, limit the growth of bacteria and other germs in the environment

Sodium Hydroxide (NaOH): for the etching process to recover silicon. It breaks down and swells the soils; it also ruins the structural elements of ceramic items and things made of organic materials.

H_2SO_4 (sulfuric acid): often used for etching and cleaning procedures, these acids are extremely toxic and can result in serious burns.

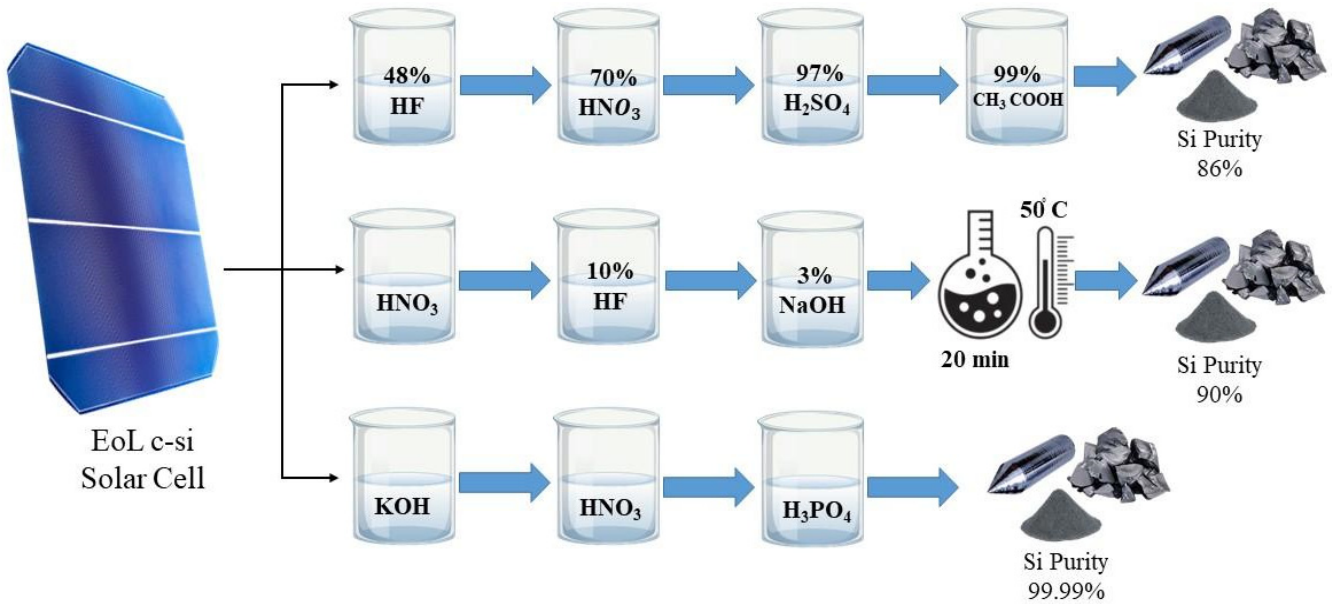

Figure 5. The recent advancements in chemical processes prioritize the purity of Si.

3.2. An Overview of Recycling Companies

The end-of-life management of PV panels has become a vital issue as the globe is dealing with the fast progress of PV panels that utilize solar energy [53]. This literature analysis investigates the initiatives and practices of existing PV panel recycling companies worldwide, highlighting their environmental stewardship and their actions to utilize PV waste efficiently. The environmental impact of inadequately managed PV waste is an ongoing concern among PV panel recycling companies [54]. The literature highlights the need to resolve this issue to reduce the environmental impact of the solar energy industry. Companies understand the limited availability of resources utilized in PV panels, notably high-value elements such as silicon. This insight motivates them to develop recycling processes that enhance resource recovery [55]. Major PV panel manufacturers, such as First Solar, are putting in place extensive recycling schemes for their products. These projects entail the recovery of a considerable proportion of manufacturing materials, which contributes to a closed-loop approach inside the manufacturing chain. Reclaim PV, for example, is a specialized company that only recycles end-of-life PV panels. It highlights their distinct techniques for separating components such as glass, aluminum, and silicon, indicating a dedication to maximum material recovery [56]. The existing literature emphasizes the significance of international collaboration in solving the global problem of PV waste. Initiatives such as the European Association PV Cycle build collection point networks and collaborate with qualified partners to ensure appropriate recycling processes. According to the research, approaches to PV recycling differ by area, driven by legal frameworks, industry practices, and technological capabilities. This variety necessitates a sophisticated understanding of regional settings to build efficient recycling systems. Customers and owners of various industrial plants and companies install these panels but need help dealing with them after 25 to 30 years [57]. Manufacturing companies producing new panels must recycle these abandoned modules at the end of their productive lifespans.

3.3. Technical Comparison and Economic Potential of Recyclable Materials

Table 6 presents a comprehensive overview of the specifications for photovoltaic (PV) modules used worldwide. It includes essential details such as the module brand, model name, module type, weight in kilograms, number of cells per module, and power rating in watts. The table showcases a variety of modules from renowned brands like Trina Solar, JA Solar, and JinKo Solar, featuring mono-crystalline silicon module types. The power ratings vary across the different models, providing a range of options suited for various solar energy applications.

Table 6. Specification of PV modules used worldwide.

Module Brand	Name of Model	Module Type	Weight (Kg)	Cells/Module	Power Rating
Trina Solar	TSM-NE09RC.05	Mono-c-Si	21.8	144	435 W
	TSM-DE06X.05(II)		19.7	132	355–380 W
	TSM-DE15V(II)		26	252	470–490 W
JA Solar	JAM72D42	Mono-c-Si	34.6	144	630 W
	JAM72D40		31.8	144	580 W
JinKo Solar	JKM635N-78HL4-BDV	Mono-c-Si	34	156	615–635 W
	JKM440N-54HL4		21	108	440 W

Trina Solar's modules generally have a lighter weight compared to those of JA Solar and JinKo Solar, making them potentially more manageable during installation. Despite this, Trina Solar's power ratings remain competitive, ranging from 355 W to 490 W, providing solid options for energy production. In contrast, JA Solar's modules stand out with the highest power ratings, with their JAM72D42 model reaching an impressive 630 W, potentially indicating superior efficiency and energy output. JinKo Solar's modules showcase a high number of cells per module in their top model (156 cells), possibly translating to increased efficiency and power output, despite having a weight similar to JA Solar's. These differences allow consumers to select modules tailored to their specific energy needs, considering factors such as power output, weight, and efficiency.

It is well recognized that raw material quantity and price changes are always difficult tasks while conducting efficient production. As a result, secondary materials for PV modules provide a cost of profit to makers. Approximately 90% of the original raw material investment expenses can be returned by recovering the fundamental components of crystalline silicon PV modules. PV modules have an expected life of 20 to 30 years and consist of a significant amount of glass, aluminum, copper, and silver waste products. The World Bank expects copper, aluminum, and silver prices for 2030 at 7000 USDt^{-1}, 2200 USDt^{-1}, and 514.47 USDkg^{-1}, respectively [58]. While aluminum and copper prices have risen, silver prices are expected to fall. In these circumstances, copper, aluminum, and silver prices are estimated to average 7500 USDt^{-1}, 2350 USDt^{-1}, and 495.18 USDkg^{-1} between 2040 and 2050 (See Table 1) [23]. This is the information on various PV modules. Here are the brands, power capacities, total numbers of cells, module weights, and unit powers of PV modules mentioned briefly [59].

The quality and purity of these materials after recycling will impact the economic potential cost. In recycling markets, high-purity materials frequently attract higher prices. The economic value of recycled materials is inextricably linked to market demand. The economic potential cost may be lower if there is a significant demand for recycled glass, aluminum, or other PV panel components. Prices may be lower if there is overstock or low demand. Under regular test circumstances, the new 60-cell Multi-crystalline Aluminum BSF module outputs about 275 Wp per module [23] (see Table 7). The current market price for these new modules is USD 0.20/Wp, 18 per module, or USD 55 per module. Each module is worth $22 if old modules are sold for half the price of new modules. In Table 7, three forms of recycling are compared. It goes without saying that as the number of processing steps grows, so does the potential profit [60]. The primary message is that components often have a higher value than the parts from which they are built, and parts have a higher value than the resources used to make them. Approximately 10% to 20% of the total number of countries in the world have companies dedicated to the recycling of solar panel components considering different challenges and strategies. We can assume that solar panel companies exist in around 30 countries whereas we mention around 16 countries and their company names. Therefore, we can say that roughly 15% of countries are recycling solar panels on average till now.

Table 7. Potential revenue of recycling components.

Scenario	Potential Profit
Module reuse	USD 22
Component extraction	USD 18.14
Material extraction	USD 10.6

3.4. Concerns of Recycling Companies

It is important to look at this concern and take the initiative to dispose of these hazardous components or recycle these abandoned panels. Many recycling companies are working on this; if not, it will harm the environment. The current state of crystalline PV cell recycling companies is also investigated. One of the most important ways to reduce the environmental effect of solar waste is through recycling companies that recover and recycle old PV panels. The approach of different countries to recycling PV waste is briefly described here. This study promotes sustainable solutions to save energy and ecology by creating awareness and encouraging different countries to recycle PV panels.

Many PV panel recycling companies have developed as proactive trustees of sustainability in response to the rising environmental concerns faced by end-of-life solar panels around the world. These companies, which are deeply committed to reducing the environmental impact of wasted PV modules, have created extensive programs targeted at efficiently recycling and reusing PV waste. With a strong emphasis on sustainability, these companies use various kinds of techniques to ensure the responsible treatment of end-of-life solar panels. Their initiatives include advanced recycling systems that prioritize the recovery and reuse of precious materials like silicon, glass, and aluminum. Table 8 shows recycling companies from sixteen different countries [7]. Their efforts in PV waste management and responsibility for reusing are greatly appreciated. However, the number of recycling companies is lower than the number of PV module production companies, which is a problem for addressing the global warming crisis. Several activities of some renowned manufacturing and recycling companies are described here and the country-by-country recycling companies list is shown in Tables 8–12.

Table 8. Solar panel recycling companies.

Country	Number	Name of Companies
USA	13	CEM, Cleanlites Recycle, Dynamic Lifecycle Innovations, Recycle PV Solar, Echo Environmental, FabTech, First Solar, Green Light Recycling, Inteco- A Metaltronics Recycler, Mitsubishi Electric, Recycler 123, Surplus Service, We Recyler Solar
Australia	6	Reclaim PV, Cyber Computer Recycling & Disposal, Elecsome, Infoactiv, Ojas Infrastructure, PV Industries
Germany	5	SolarWorld, Envaris, Reiling, Reiger and Kraft Solar, Rinovasol
UK	4	H&H Pro, ILM Highland, Recycle Solar Technologies, Solar2Recycle
Switzerland	3	Immark, KWB Planreal, SENS eRecycle
China	3	GCL-Poly Energy Holdings Limited, Jiangxi LDK Solar Hi-Tech, CNBM
Canada	1	Sunset Renewable Asset Management
Italy	1	La Mia Energia, Yousolar
Japan	3	Okaishi Construction, NPC, New Energy and Industrial Technology Development Organization
South Africa	1	Reclite
Singapore	1	EtaVolt
Brazil	1	SunR
Hong Kong SAR	1	IBA
Russia	10	AltEnergia, Astantsiya, B-Eco, Eco Energy, Energon, Energy Center, Green Energy, Moscow Solar Group, NSiA, Real Solar

Table 9. Glass recycling companies.

Country	Number	Name of Companies
USA	2	CEM, Recycle PV Solar
Australia	2	Elecsome, PV Industries
Switzerland	1	KWB Planreal
Italy	1	La Mia Energia
Israel	1	Silcontel
Brazil	1	SunR
Russia	1	Green Energy

Table 10. Al, frame, and ribbon recycling companies.

Country	Number	Name of Companies
USA	2	Dynamic Lifecycle Innovations, Recycle PV Solar
Australia	1	PV Industries
UK	1	Recycle Solar Technologies
India	1	Jumbo Solar
Italy	1	La Mia Energia
Israel	1	Silcontel
Russia	1	Moscow Solar Group

Table 11. Plastic recycling companies.

Country	Number	Name of Companies
USA	1	Dynamic Lifecycle Innovations
Australia	1	Elecsome, PV Industries
Italy	1	La Mia Energia
Israel	1	Silcontel
Brazil	1	SunR
Russia	2	Real Solar, B-Eco

Table 12. Silicon recycling companies.

Country	Number	Name of Companies
USA	6	Metal and Catalyst Resources, Moegen Industries, Silicon Specialist, Silrec, SRS, We Recyler Solar
Australia	3	Elecsome, PV Industries, Reclaim PV Recycling
Germany	2	SolarWorld, Aurubis, SiC Processing
China	2	Suzhou Minlai Photovoltaic New Energy, Chaoqiang Silicon Material
Canada	1	Globe Metal
India	2	Jumbo Solar, Poseidon Solar Services
Italy	1	La Mia Energia
Japan	1	Trinity
Israel	1	Silcontel
Brazil	1	SunR
Hong Kong SAR	1	IBA
Russia	3	B-Eco, Moscow Solar Group, Real Solar

A prominent focus is noticed among the surveyed companies on the recycling of PV panels, with 53 companies dedicated to this specific component. Following closely shortly after are 24 companies specializing in silicon recycling, the primary component in PV technology. Furthermore, eight companies recycle aluminum, ribbon, and frame, and nine companies recycle glass, demonstrating their dedication to handling a variety of components involved with PV modules. Seven companies are dedicated to recycling plastics, suggesting a recognition of the different materials utilized in PV technology. Finally, the figure highlights the different efforts of companies around the world in addressing the recycling difficulties related to PV technology. The differences in recycling methods and the reasons outlined for the limited comprehensive efforts demonstrate the complexities and factors to be considered in effectively managing the end-of-life cycle of PV modules on a global scale [3].

3.5. Comparative Analysis of Recycling Companies

Veolia: As a global service provider of environmental services, Veolia prioritizes sustainability and environmental responsibility. Veolia offers full waste management services, including PV panel recycling. Their recycling systems employ innovative separation techniques for components such as glass, aluminum, and silicon, enabling optimal recovery and reuse [61]. Reclaim PV: Reclaim PV is an Australian recycling company that specializes in the recycling of used solar PV panels. The company uses a unique technique that focuses on the separation of components such as glass, aluminum, and silicon. This method is intended to maximize the reuse of valuable materials [62]. PV Cycle: As a European association, developing solutions for the recycling and bringing back of regaining processes of end-of-life PV panels are required for the PV cycle. The company has established a network of collection locations around Europe to facilitate appropriate disposal. To ensure ecologically friendly recycling operations, certified recycling partners are engaged. First Solar: First Solar, a prominent American manufacturer of solar panels, has created a complete recycling program for its panels. The company achieves a high level of material recovery, with recycling systems reclaiming up to 90% of the materials used in manufacturing. Recycle PV: Patented Recycling Technology [14]: Based in the United States, Recycle PV recycles solar PV panels using patented techniques. The company is dedicated to effectively separating the various PV panel components, assuring the recovery of elements like silicon, glass, and aluminum for subsequent use. Figure 6 displays the global PV recycling companies.

Figure 6. Worldwide PV recycling companies.

3.6. Impact of Improper Disposal of Si Solar Cells

Old and damaged silicon solar cells, if not properly managed and recycled, can pose several environmental and health risks. When left untreated and exposed in open fields, they can contribute to various problems affecting soil, humans, animals, and the overall ecosystem [2]. Over time, the heavy metals and chemicals found in damaged and abandoned Si solar cells could leach into the soil, which is also known as soil contamination. This pollution has the potential to reduce soil fertility and disturb microbial populations that are vital to the cycling of nutrients. Polluting elements such as lead and cadmium, which are frequently present in solar cells, can build up in the soil and endanger plant development as well as make their way up the food chain [63]. People who live or work close to these solar panels may be exposed to potentially harmful elements from broken solar cells, which increases human health risk. Airborne pollutants and polluted soil particles can cause respiratory problems, problems with the skin, and other health issues when inhaled or consumed [64]. Additionally, toxic materials can also pollute drinking water if they leak into sources of underground water, which would raise further health risks. There may be negative effects on wildlife living in places close to open fields that have old, damaged solar panels [65]. Toxic compounds can be consumed by animals either directly from the soil or through contaminated food sources, which can result in poisoning and possible reproductive problems. Furthermore, animals that come into contact with sharp edges or broken sections of solar panels run the risk of becoming physically trapped or injured [66]. A larger-scale environmental deterioration is a result of the improper disposal of silicon solar cells. Electronic waste buildup in open fields pollutes the view and disturbs natural ecosystems. Furthermore, solar cell manufacturing methods are energy-intensive, contributing to greenhouse gas emissions and the depletion of natural resources [67]. The cycle of environmental destruction is sustained when these materials are not recycled, which increases the demand for new resources. To describe resource depletion, silicon is a primary component of solar cells that is a limited resource. Failure to recycle outdated panels leads to the loss of vital resources that could have been retrieved and used for the development of new solar technologies. Due to this, the environmental impact of producing new panels is increased and resource depletion is accelerated. In general, there are several hazards to soil quality, human health, animal welfare, and environmental sustainability associated with the inappropriate disposal of old and Si solar cell waste. To reduce these dangers and support solar energy's long-term sustainability as a sustainable solution, it is extremely important to implement efficient recycling systems and appropriate disposal techniques [68].

3.7. Severe Problems of Improper Disposal

Soil contamination: crystalline solar cells contain many dangerous components, including silicon (Si), lead (Pb), copper (Cu), and silver (Ag). If these materials are disposed of improperly, they could leach into the soil and contaminate it. Plant development and the ecosystem as a whole are in danger from this pollution, which also has an impact on soil fertility [69]. Lead and copper are two examples of heavy metals that can contaminate both groundwater and surface waters by leaching into adjacent water sources. The contamination has the potential to cause significant harm to aquatic ecosystems and even humans by contaminating fish and water, which might then find its way into the food chain [70,71]. In addition, human health problems can arise from exposure to heavy metals and other harmful compounds from crystalline solar cells [66]. Respiratory issues, neurological conditions, organ damage, and even cancer can result from breathing in airborne pollutants, consuming contaminated food or water, and coming into direct touch with dangerous items [72]. Moreover, improper disposal of crystalline solar cells can contaminate soil, which can be harmful to plants and trees [73]. Because they may hamper root growth, nutrient uptake, and photosynthesis, toxic substances can lead to slower growth, lower crop yields, and even the mortality of vegetation in areas where they are present [74]. Furthermore, exposure of wildlife to contaminated soil, water, or food sources might have adverse effects on the animals that may consume poisonous materials directly or indirectly through the food chain, which can result in poisoning, problems with reproduction, and population decrease [75,76].

3.8. Minor Problems of Improper Disposal

Abandoned or incorrectly disposed of crystalline solar cells contribute to visual pollution in natural environments, reducing the environment's aesthetic attractiveness [77]. Solar panels that are not installed correctly can upset ecosystems, uproot native species, and disturb natural habitats [78]. A substantial number of resources are wasted when important materials like silicon, lead, copper, and silver from outdated solar cells are not recycled. This also increases the need for new materials, which feeds the cycle of resource depletion [79,80]. The cumulative effects of the improper disposal of crystalline solar cells contribute to long-term environmental degradation, affecting biodiversity, ecosystem services, and overall environmental health [81]. Addressing these severe and minor problems requires effective recycling programs, proper disposal practices, and increased awareness of the environmental impacts of solar panel waste. By implementing sustainable solutions, such as responsible end-of-life management and material recovery processes, the detrimental effects of improper disposal can be mitigated, safeguarding soil, water, human health, and the broader ecosystem [82,83]. Figure 7 illustrates the issues caused by the contamination of soil with Pb, Cu, Si, and Ag.

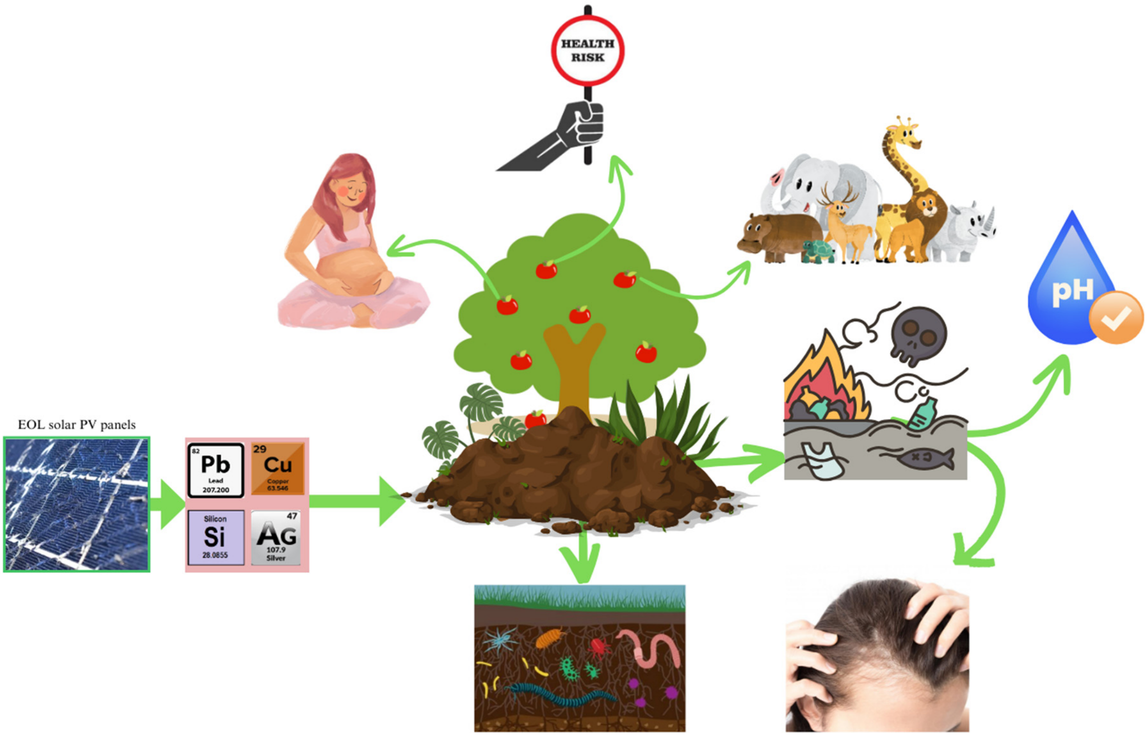

Figure 7. Problems caused by Pb, Cu, Si, and Ag contamination in soil.

4. Discussion and Recommendation

4.1. Barriers to Recycling PV Waste

The NREL identified many hurdles to PV panel recycling prospects in the US in an assessment of US policies and initiatives. Data gaps, insufficient recycling technology and infrastructure, and regulatory concerns are among them. Limited research and publicly accessible data exist regarding the economic value and markets for recovered photovoltaic materials, the quantity and total amount of near-term end-of-life PV modules, the advancement of PV module recycling technology, the required facilities, and the total expenses related to PV module recycling. PV module recycling infrastructure, techniques, and technology are currently not optimized for the economically viable recovery of high-value materials, making recycling less appealing than less expensive and more accessible disposal options. PV module management and disposal practices vary across Australia's states and territories. Only Victoria has an official ban on the disposal of solar panels in landfills. Residents in Victoria must recycle their solar panels at specified e-waste drop-off locations [84]. In Queensland, a new recycling expansion program is being planned, to prohibit the dumping of solar panels in landfills within the next ten years. This program reflects a growing awareness of the significance of efficient PV module disposal and recycling to reduce the environmental effects and encourage sustainable practices. Unfortunately, the cost of recycling is \$10–\$20 per panel, not counting transportation or removal fees. The ideal recycling disposal of ten panels from the roof will cost at least \$200. The challenges are (a) recycling processes are expensive: separating materials such as glass, metals, silicon, and other rare elements from solar panels requires the use of specialist equipment and etching solutions that can be costly to operate. (b) Apart from that, the recycling process involves the recruitment and training of skilled manpower, which is costly. Although solar cells use clean energy and do not emit any pollutants into the atmosphere, certain harmful compounds are used during the production process that hurt the environment.

Furthermore, following the life cycle of solar cells, harmful residues are left behind that must be recycled, (c) infrastructure shortage, and (d) lack of conscience [85].

4.2. Incentives for Waste Disposal

To solve the ongoing issue of end-of-life PV disposal, it is critical to establish worldwide incentives and rules that are supported by manufacturers, regulators, researchers, and the solar industry, regardless of the recycling option chosen. This proactive approach guarantees that the management and disposal of PV panels are successfully addressed internationally, recognizing the persistent nature of this challenge [86]. Germany and the Netherlands, two countries that were among the first to install small-scale rooftop PV systems, demonstrate an urgency in looking for feasible alternatives to recycle existing PV panels as they approach the end of their useful lives. Separation technology prototypes have been created in Europe, and many pilot lines have been established to assess their practicality. The predicted waste issue caused by end-of-life PV modules has yet to materialize in Australia; therefore, the sense of urgency is not as strong. As a result, nearby companies have less motivation to invest in recycling technologies. However, it is critical to recognize that PV modules will eventually run out of space in landfills, and there will not be enough resources to produce new panels. As a result, finding a sustainable strategy for recycling them is imperative [87].

4.3. Approaches of Different Countries in PV Recycling

In regions where solar energy adoption is rapidly increasing, such as certain parts of Asia, there may be an emphasis on establishing comprehensive recycling infrastructures to manage the anticipated surge in end-of-life solar panels [88]. Collaboration between governments, companies, and recycling facilities can play a pivotal role in achieving effective and sustainable PV waste management systems. In addition, recycling old PV modules reduces pollution and saves raw materials. However, it reduces the country's carbon emissions by being a substantial source of carbon released into the environment. This pollution is currently visible at the global level but, because of climate change and increased levels of industry and population, recycling will become much more significant in the coming years [89]. However, the approaches of different countries in PV recycling are as follows:

(i) Australia: The Australian government has made it a priority to ensure that systems for dealing with complaints about solar PV waste are in place. Modern systems that decrease the environmental impact of solar PV technology throughout their lives will be the consequence of the Australian Ministry's decision [90].
(ii) USA: Since the state of California DTSC has raised its recycling capacity and renewed its facilities for the disposal of PV waste management, the responsibility for solar waste recycling has also been taken by them when the capacity of European facilities is reduced. First Solar manufacturing company, which is a USA-based firm, has factories in different regions such as the USA, Germany, and Malaysia that use recycling technologies.
(iii) Japan: solar panel producers collaborate with local companies on recycling technology research connected to recycling technology in Europe, while the Japanese Environment Ministry oversees the recycling of waste from solar panels.
(iv) China: The Chinese government aggressively encourages the recycling and remanufacturing of solar panel components through several laws and programs. For instance, the Ministry of Industry and Information Technology (MIIT) is elevating standards and promoting the creation of new technologies to control the anticipated rise in solar panel waste. Likewise, several provinces have established demonstration lines and pilot programs for recycling technologies, including Jiangxi, Hebei, Henan, Jiangsu, and Ningxia (PV Tech) (GovCN) (Yicai Global) (PV magazine International). Dedicated recycling firms in China include China National Building Material Group Corporation

(CNBM), Jiangxi LDK Solar Hi-Tech, GCL-Poly Energy Holdings Limited, and Ningbo Solar Electric Power Co., Ltd.

(v) India: waste management regulations for solar PV waste recycling are still under consideration by the Indian authority.

5. Conclusions

This study highlights the value of recycling crystalline solar cells and the contribution of cutting-edge technology to a sustainable future. One of the main conclusions is that recycling technology can be economically viable through improvements in recovery efficiency and process simplification, making it environmentally and financially sound. We must apply new regulatory frameworks and circular economy principles for sustainable photovoltaic (PV) waste management. To foster innovation, regulatory support, and responsible waste disposal, cooperation between researchers, stakeholders, and governments is essential. With the potential for 78 million metric tons of trash by 2050, the global PV recycling environment offers both considerable problems and possibilities. This makes efficient recycling activities imperative. Numerous businesses are developing cutting-edge solutions to recover and repurpose valuable materials, despite their high prices, to maximize the recycling of PV waste. This study emphasizes the need for environmentally conscious and economically sound ways to manage photovoltaic waste and advocates for coordinated actions to ensure a more sustainable and environmentally friendly future for the solar energy industry. The key findings and concluding remarks are as follows:

- Advancements in recovery efficiency, process streamlining, and identification of key components are critical for bridging the financial gap in recycling technology.
- Implementing circular economy concepts and modifying legislative and regulatory frameworks are essential for sustainable photovoltaic (PV) waste management.
- Collaboration among researchers, stakeholders, governments, and industry players is crucial to promote innovation, provide regulatory support, and establish responsible disposal structures for waste modules.
- The present state of PV recycling, including opportunities, challenges, and prospects, is examined. Without appropriate disposal, the future production of PV waste could reach 78 million tons by 2050, necessitating large-scale recycling initiatives.
- Companies worldwide are developing technologies and processes to maximize PV waste recycling. Commendable programs focus on advanced recycling systems to recover and reuse valuable materials.
- The high cost of recycling remains a significant barrier to the widespread adoption of PV recycling systems, limiting scalability and practicality despite the environmental need.

In conclusion, it identifies companies across the world for their worthy attempts to address the environmental concerns related to PV waste, and it also highlights the challenging barriers given by the costly nature of recycling methods. The highlighted prospects for sustainable solutions must be balanced against the economic limitations that limit the widespread adoption of PV recycling programs at the moment. Additionally, this study encourages the growth of recycling businesses that produce PV modules. Its insights are highlighted broadly so that the government takes steps to ensure the reuse of these wastes. Collaboration among stakeholders, governments, and industry players becomes vital as the industry navigates these crossroads to overcome difficulties, capitalize on opportunities, and promote the development of cost-effective and ecologically friendly PV recycling solutions. It not only provides a detailed review of the current state of PV recycling, but it additionally follows up as a call to action for collective efforts to guarantee the solar energy sector has a greener and more sustainable future.

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A.A.M. and M.I.I.; project administration, A.A.M. All authors have read and agreed to the published version of the manuscript.

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