

Review

Solar PV End-of-Life Waste Recycling: An Assessment of Mechanical Recycling Methods and Proposed Hybrid Laser and High Voltage Pulse Crushing Method

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Abstract: This research article investigates the recycling of end-of-life solar photovoltaic (PV) panels by analyzing various mechanical methods, including Crushing, High Voltage Pulse Crushing, Electrostatic Separation, Hot Knife Cutting, Water Jet Cutting, and Magnetic Separation. Each method's effectiveness in extracting materials such as glass, silicon, metals (copper, aluminum, silver, tin, lead), and EVA was evaluated. The analysis reveals that no single method is entirely sufficient for comprehensive material recovery. Based on the data analysis, a new hypothetical hybrid method, Laser and High Voltage Pulse (L&HVP), is proposed, which integrates the precision of laser irradiation with the robustness of high voltage pulse crushing. The laser irradiation step would theoretically facilitate the removal of the ethylene-vinyl acetate (EVA) encapsulant, preparing the materials for subsequent separation. The high high-voltage pulse crushing would then selectively fragment and separate the remaining components, potentially enhancing material recovery efficiency while minimizing contamination. The proposed approach is grounded in the observed limitations of existing techniques. This method aims to offer a more comprehensive and sustainable solution for solar PV module recycling. Further research and experimentation are necessary to validate the effectiveness of the L&HVP method and its potential impact on the field of solar PV recycling.

Keywords: solar PV waste; waste recycling; mechanical recycling methods



Citation: Ali, A.; Shahid, M.; Qadir, S.A.; Islam, M.T.; Khan, M.W.; Ahmed, S. Solar PV End-of-Life Waste Recycling: An Assessment of Mechanical Recycling Methods and Proposed Hybrid Laser and High Voltage Pulse Crushing Method. *Resources* **2024**, *13*, 169. <https://doi.org/10.3390/resources13120169>

Academic Editor: Angel F. Mohedano

Received: 31 October 2024

Revised: 21 November 2024

Accepted: 28 November 2024

Published: 29 November 2024



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1. Introduction

Solar power offers an endless and sustainable energy supply, positioning it as a superior choice compared to limited and polluting resources like coal, oil, and other conventional sources. It provides a dependable, economical, and eco-friendly method for electricity generation [1,2]. At present, solar photovoltaic (PV) technology is rapidly emerging as the leading energy source globally due to its sustainability and minimal environmental impact. Since 2015, solar PV has consistently shown a rise in investment, marking it as the only uninterruptedly growing electricity-generating technology. Projections indicate that the worldwide installed capacity of solar PV will keep increasing, potentially reaching 1630 GW by 2030 and as much as 4500 GW by 2050, as illustrated in Figure 1 [3–5].

In the 2016 publication by IRENA and IEA-PVPS, the agencies offered pioneering global forecasts for photovoltaic (PV) panel waste volumes through 2050. Their analysis included a standard loss scenario reflecting an average PV panel lifespan of 28 years and

an early loss scenario incorporating various failure phases, leading to a reduced average lifespan of 26 years [6,7].

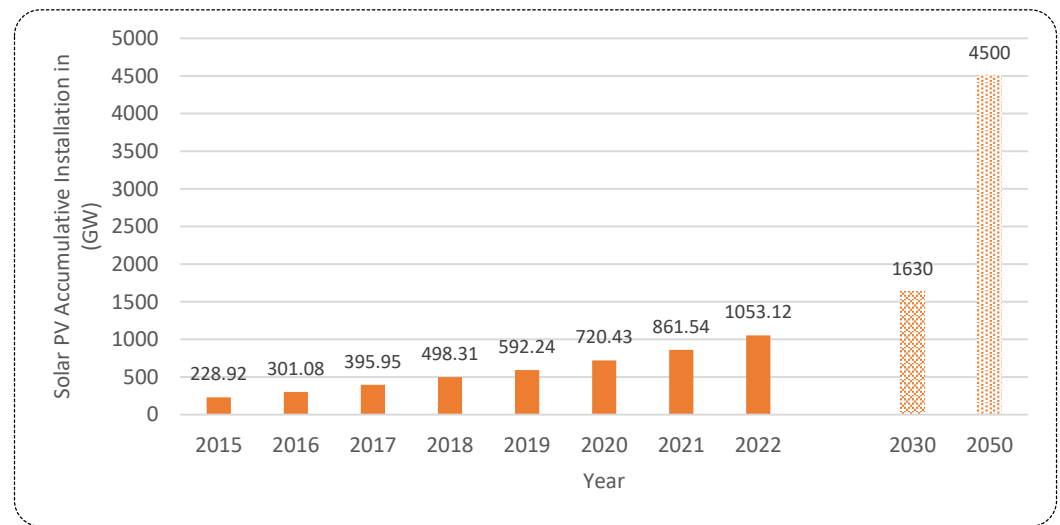


Figure 1. Solar PV accumulative instillation projection till 2030 and 2050 [1].

- Standard Loss Scenario:** This scenario predicts that PV panels will gradually degrade in efficiency over a typical lifespan of 25 to 30 years. As the panels age, their energy output declines progressively, eventually falling below the threshold for viable operational use. End-of-life options in this scenario include the decommissioning and disposal of the panels, with an emphasis on recycling to reclaim valuable components such as silicon and silver while preventing environmental contamination.

In this scenario, most panels are retired due to the natural decrease in performance over time. Recycling and waste management systems play crucial roles in handling these retired panels, focusing on the recovery of essential materials and mitigating environmental risks.

- Early Loss Scenario:** This scenario addresses premature failures and significant efficiency reductions before panels reach their expected lifespan, classified into ‘infant’, ‘mid-life’, and ‘wear-out’ stages.
 - Infant failures occur typically within the first four years, with the most common within two years of installation.
 - Mid-life failures are generally observed between the fifth and eleventh years.
 - Wear-out failures appear from the twelfth year onwards, leading up to the projected end-of-life at 30 years.

Such early failures can lead to increased waste production and pose additional challenges in waste management.

Both scenarios anticipate a decline in panel efficiency over time, projecting a minimum operational lifespan of 25–30 years. IRENA estimates that, under the early loss scenario, the total volume of end-of-life PV panels could amount to between 8 and 78 million metric tons from 2030 to 2050, as depicted in Figure 2 [6].

Predicting which countries will generate the most solar photovoltaic (PV) waste at end-of-life (EOL) is complex. This prediction depends largely on the adoption rate of solar PV systems, their durability, and the presence of recycling infrastructure. As highlighted in the previously referenced Figure 2, there is a pressing need to develop effective recycling strategies for solar PV waste to reduce environmental impacts.

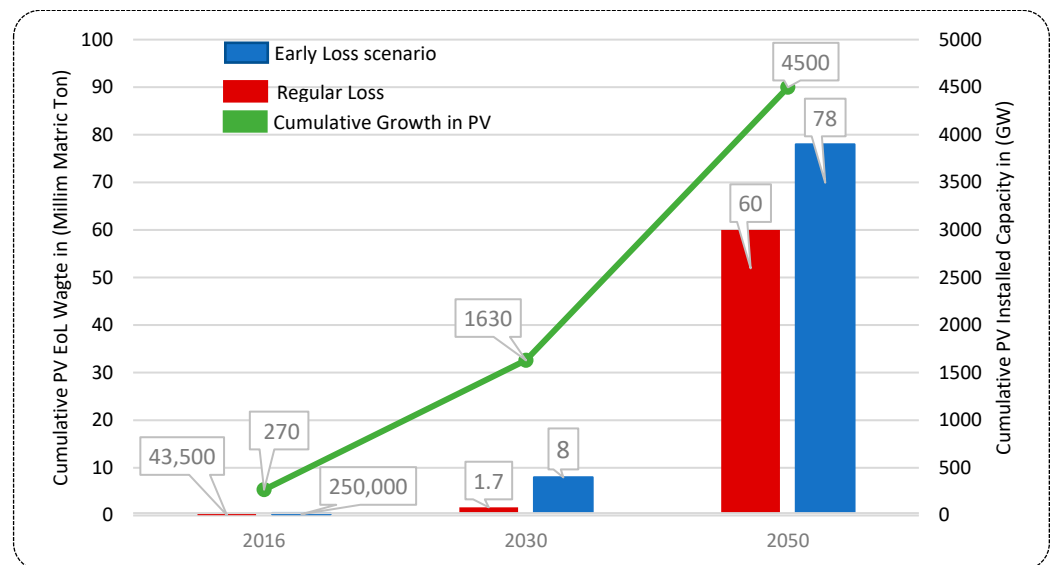


Figure 2. Projected generation of end-of-life waste from solar PV panels between 2030 and 2050 [5,6].

Solar PV waste comprises a variety of materials, including glass, metals, plastics, and semiconductors. Studies detailed in sources such as [8–15] indicate that a typical silicon-based solar panel consists of approximately 68% glass (used for the front cover), 20% aluminum (used for the frame), and 1% copper (found in junction boxes and cables). Additionally, it contains 5.5% ethylene-vinyl acetate (EVA) encapsulant, 1% polyvinyl fluoride (PVF) back sheet, and about 3.5% silicon, with small quantities of aluminum and copper. The solar cell itself contains around 0.2% of precious and hazardous metals, including silver, tin, and lead. It is important to note that these percentages can vary based on the specific type of solar module and the manufacturing processes used, as depicted in Figure 3.

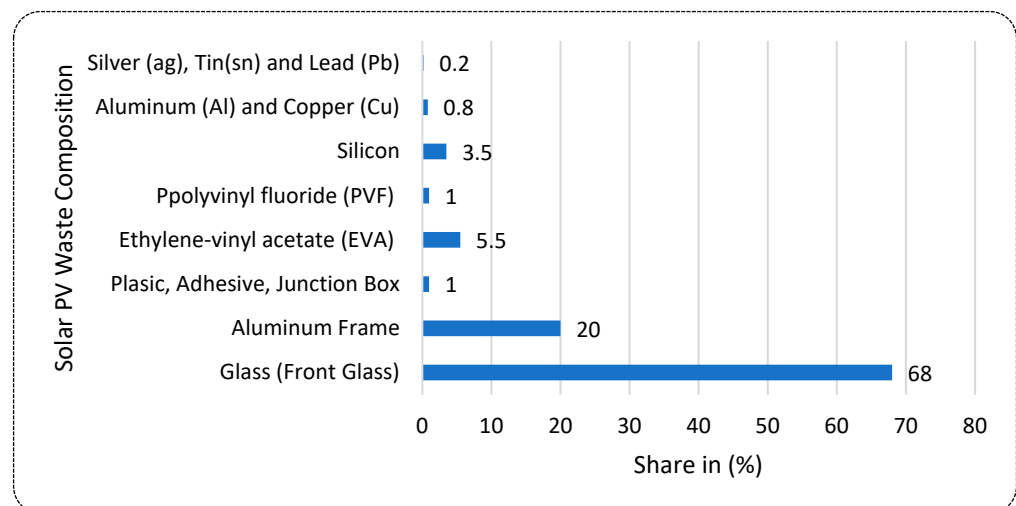


Figure 3. Solar PV Module Waste Composition in (%).

Currently, two main recycling methods are prevalent: mechanical (physical) and chemical. This study will concentrate on a detailed evaluation of the recycling techniques for solar PV EOL waste, with a particular focus on the mechanical recycling method because of its potential as a sustainable and scalable approach to material recovery. Mechanical recycling methods, such as crushing, high-voltage pulse crushing, and electrostatic separation, offer several advantages over chemical techniques. They avoid the use of hazardous reagents, minimizing environmental and health risks, and are generally more cost-effective

due to lower operational and material handling costs. Furthermore, mechanical methods consume less energy and produce fewer byproducts, aligning with the principles of a circular economy.

Chemical recycling, while capable of achieving high material purity, often involves complex waste management and higher capital investments, making it less feasible for large-scale applications. In contrast, mechanical recycling is well-suited to regions with limited access to advanced chemical processing facilities and offers a pragmatic solution for initial material separation and recovery.

Despite considerable advancements in the field of solar PV recycling, existing mechanical methodologies face persistent challenges that limit their efficiency and scalability. Current mechanical techniques often struggle with precise material separation, leading to contamination and reduced recovery yields. Thermal methods, while effective in some cases, require high energy inputs, which increase operational costs and environmental impacts. Furthermore, these conventional approaches frequently fail to maintain the structural integrity of valuable components, such as silicon wafers and metallic elements, further reducing the economic viability of the recycling process.

In this paper, we propose the Laser and High Voltage Pulse (L&HVP) method as a hypothetical solution to address the challenges of solar PV module recycling. This conceptual approach combines the theoretical precision of laser irradiation with the anticipated efficiency and robustness of high-voltage pulse crushing. Laser irradiation is hypothesized to selectively remove the ethylene-vinyl acetate (EVA) encapsulant, potentially preserving the structural integrity of critical components such as silicon wafers and metallic elements. Following this, high-voltage pulse crushing is envisioned to facilitate efficient material fragmentation and separation, enabling the recovery of high-purity glass, silicon, and metals with minimal contamination. While this method has yet to be experimentally validated, it aims to address the limitations of current mechanical and thermal techniques by offering a potentially scalable, sustainable, and efficient solution. Future research and experimental studies will be carried out to confirm its feasibility, optimize its design, and evaluate its practical applications in solar PV recycling.

2. Literature Survey

From 2019 to 2024, a total of 40 research articles discussing solar PV end-of-life (EoL) waste recycling have been published in various ISI journals, as shown in Figure 4. These publications cover a wide array of topics, including the challenges and strategies for managing photovoltaic (PV) waste, technological advancements in recycling processes, policy recommendations, and comprehensive reviews of global trends and future perspectives. The primary focus has been on improving recycling efficiency, recovering valuable materials, and integrating sustainable practices within the circular economic framework. A detailed list of these published articles is provided in Table 1. However, it is noteworthy that none of these papers specifically focus on mechanical methods for PV waste recycling, highlighting a significant gap in the existing literature. This gap underscores the importance of our work, which aims to address this overlooked aspect and contribute to the advancement of PV waste recycling techniques.

Table 1. List of Papers published on Solar PV EoL waste Recycling.

S. No.	Article/Reference No.	Year of Publication	Paper Objectives
1.	The research progress on recycling and resource utilization of waste crystalline silicon photovoltaic modules [16]	2024	Reviews advancements in recycling and resource utilization techniques for waste crystalline silicon PV modules.
2.	Anticipating future photovoltaic waste generation in China: Navigating challenges and exploring prospective recycling solutions [17]	2024	Analyzes future PV waste generation in China and proposes recycling solutions to address anticipated challenges.

Table 1. Cont.

S. No.	Article/Reference No.	Year of Publication	Paper Objectives
3.	The Necessity for End-of-Life Photovoltaic Technology Waste Management Policy: A Systematic Review [18]	2024	Provides a systematic review of the need for policies governing the management of EoL PV technology waste.
4.	Challenges and strategies for managing end-of-life photovoltaic equipment in Brazil: Learning from international experience [19]	2024	Focuses on strategies and challenges in managing EoL PV waste in Brazil, drawing lessons from global practices.
5.	Recycling photovoltaic modules within a circular economy approach and a snapshot for Türkiye [20]	2023	Discusses recycling of PV modules within the circular economy framework with a specific focus on Türkiye.
6.	Comprehensive Review of Crystalline Silicon Solar Panel Recycling: From Historical Context to Advanced Techniques [21]	2023	Offers a thorough review of the historical and advanced techniques for recycling crystalline silicon solar panels.
7.	Recycling technology of end-of-life photovoltaic panels: a review [22]	2023	Reviews of various technologies available for recycling EoL PV panels.
8.	Comprehensive review of the global trends and future perspectives for recycling of decommissioned photovoltaic panels [23]	2023	Examines global trends and future perspectives on the recycling of decommissioned PV panels.
9.	Review on Separation Processes of End-of-Life Silicon Photovoltaic Modules [24]	2023	Focuses on separation processes involved in recycling EoL silicon PV modules.
10.	Current trends in silicon-based photovoltaic recycling: A technology, assessment, and policy review [25]	2023	Assesses current trends in silicon-based PV recycling technologies and reviews relevant policies.
11.	Recycling of Photovoltaic Modules for Recovery and Repurposing of Materials [26]	2023	Investigates methods for recycling PV modules to recover and repurpose materials.
12.	A review of end-of-life crystalline silicon solar photovoltaic panel recycling technology [27]	2022	Reviews existing technologies for recycling EoL crystalline silicon solar PV panels.
13.	Recycling of discarded photovoltaic solar modules for metal recovery [28]	2022	Discusses techniques for recovering metals from discarded PV modules.
14.	Recycling c-Si PV Modules: A Review, a Proposed Energy Model and a Manufacturing Comparison [9]	2022	Reviews c-Si PV module recycling and proposes an energy model along with manufacturing comparisons.
15.	Experimental, economic and life cycle assessments of recycling end-of-life monocrystalline silicon photovoltaic modules [29]	2022	Conducts economic and life cycle assessments for recycling monocrystalline silicon PV modules.
16.	Global Challenges and Prospects of Photovoltaic Materials Disposal and Recycling: A Comprehensive Review [30]	2022	Provides a comprehensive review of global challenges and prospects for PV material disposal and recycling.
17.	Recent progress in silicon photovoltaic module recycling processes [31]	2022	Reviews recent advancements in recycling processes for silicon PV modules.
18.	Recycling of solar photovoltaic panels: Techno-economic assessment in waste management perspective [32]	2022	Assesses the techno-economic aspects of recycling solar PV panels from a waste management perspective.
19.	A systematically integrated recycling and upgrading technology for waste crystalline silicon photovoltaic module [33]	2022	Proposes an integrated technology for recycling and upgrading waste crystalline silicon PV modules.
20.	An Integrated Thermal and Hydrometallurgical Process for the Recovery of Silicon and Silver from End-of-Life Crystalline Si Photovoltaic Panels [34]	2022	Discusses a combined thermal and hydrometallurgical process for recovering silicon and silver from EoL crystalline Si PV panels.
21.	A Green Method to Separate Different Layers in Photovoltaic Modules by Using Dmpu as a Separation Agent [35]	2022	Introduces an environmentally friendly method for separating layers in PV modules using Dmpu.

Table 1. Cont.

S. No.	Article/Reference No.	Year of Publication	Paper Objectives
22.	Improving the end-of-life management of solar panels in Germany [36]	2022	Examines strategies for enhancing EoL management of solar panels in Germany.
23.	Nondestructive silicon wafer recovery by a novel method of solvothermal swelling coupled with thermal decomposition [37]	2021	Presents a novel method for non-destructive recovery of silicon wafers using solvothermal swelling and thermal decomposition.
24.	Thermal delamination of end-of-life crystalline silicon photovoltaic modules [38]	2021	Explores thermal delamination techniques for recycling EoL crystalline silicon PV modules.
25.	Comprehensive recycling of silicon photovoltaic modules incorporating organic solvent delamination—technical, environmental and economic analyses [39]	2021	Analyzes technical, environmental, and economic aspects of recycling silicon PV modules using organic solvent delamination.
26.	A sustainable chemical process to recycle end-of-life silicon solar cells [40]	2021	Proposes a sustainable chemical process for recycling EoL silicon solar cells.
27.	Enhanced separation of different layers in photovoltaic panel by microwave field [41]	2021	Investigates the use of microwave fields for enhancing layer separation in PV panels.
28.	A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels [42]	2021	Conducts a life cycle assessment of a recovery process for EoL PV panels.
29.	Photovoltaic Module Recycling: Thermal Treatment to Degrade Polymers And Concentrate Valuable Metals [43]	2021	Explores the use of thermal treatment to degrade polymers and concentrate valuable metals in PV module recycling.
30.	Looming challenge of photovoltaic waste under China’s solar ambition: A spatial–temporal assessment [44]	2021	Provides a spatial-temporal assessment of the PV waste challenge in China.
31.	Multi-levels of photovoltaic waste management: A holistic framework [45]	2021	Proposes a holistic framework for multi-level PV waste management.
32.	Back EVA recycling from c-Si photovoltaic module without damaging solar cell via laser irradiation followed by mechanical peeling [46]	2021	Describes a method for recycling back EVA from c-Si PV modules using laser irradiation and mechanical peeling.
33.	An Investigation of the Recovery of Silicon Photovoltaic Cells by Application of an Organic Solvent Method [47]	2020	Investigates the recovery of silicon PV cells using an organic solvent method.
34.	Remanufacturing end-of-life silicon photovoltaics: Feasibility and viability analysis [48]	2020	Analyzes the feasibility and viability of remanufacturing EoL silicon PVs.
35.	An overview of solar photovoltaic panels’ end-of-life material recycling [2]	2020	Provides an overview of EoL material recycling for solar PV panels.
36.	Technical challenges and opportunities in realising a circular economy for waste photovoltaic modules [49]	2020	Discusses technical challenges and opportunities in achieving a circular economy for waste PV modules.
37.	A techno-economic review of silicon photovoltaic module recycling [50]	2019	Reviews the techno-economic aspects of silicon PV module recycling.
38.	Pyrolysis-based separation mechanism for waste crystalline silicon photovoltaic modules by a two-stage heating treatment [51]	2019	Investigates a pyrolysis-based separation mechanism for waste crystalline silicon PV modules.
39.	End-of-life photovoltaic modules: A systematic quantitative literature review [52]	2019	Provides a systematic quantitative literature review of EoL PV modules.
40.	Photovoltaic module recycling, a physical and a chemical recovery process [53]	2019	Examine both physical and chemical recovery processes in PV module recycling.

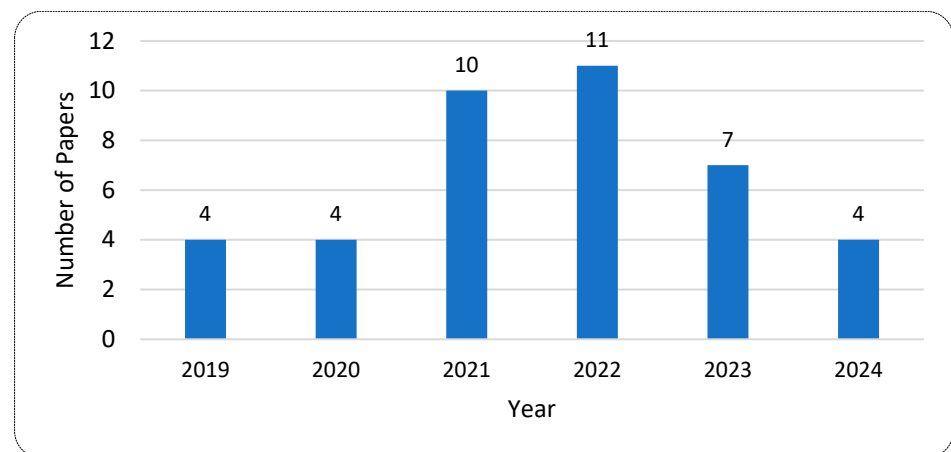


Figure 4. Numbers of Papers Published on Solar PV EoL waste Recycling from (2019–2024).

3. Research Methodology

The research methodology for this study follows a structured approach, as illustrated in Figure 5.

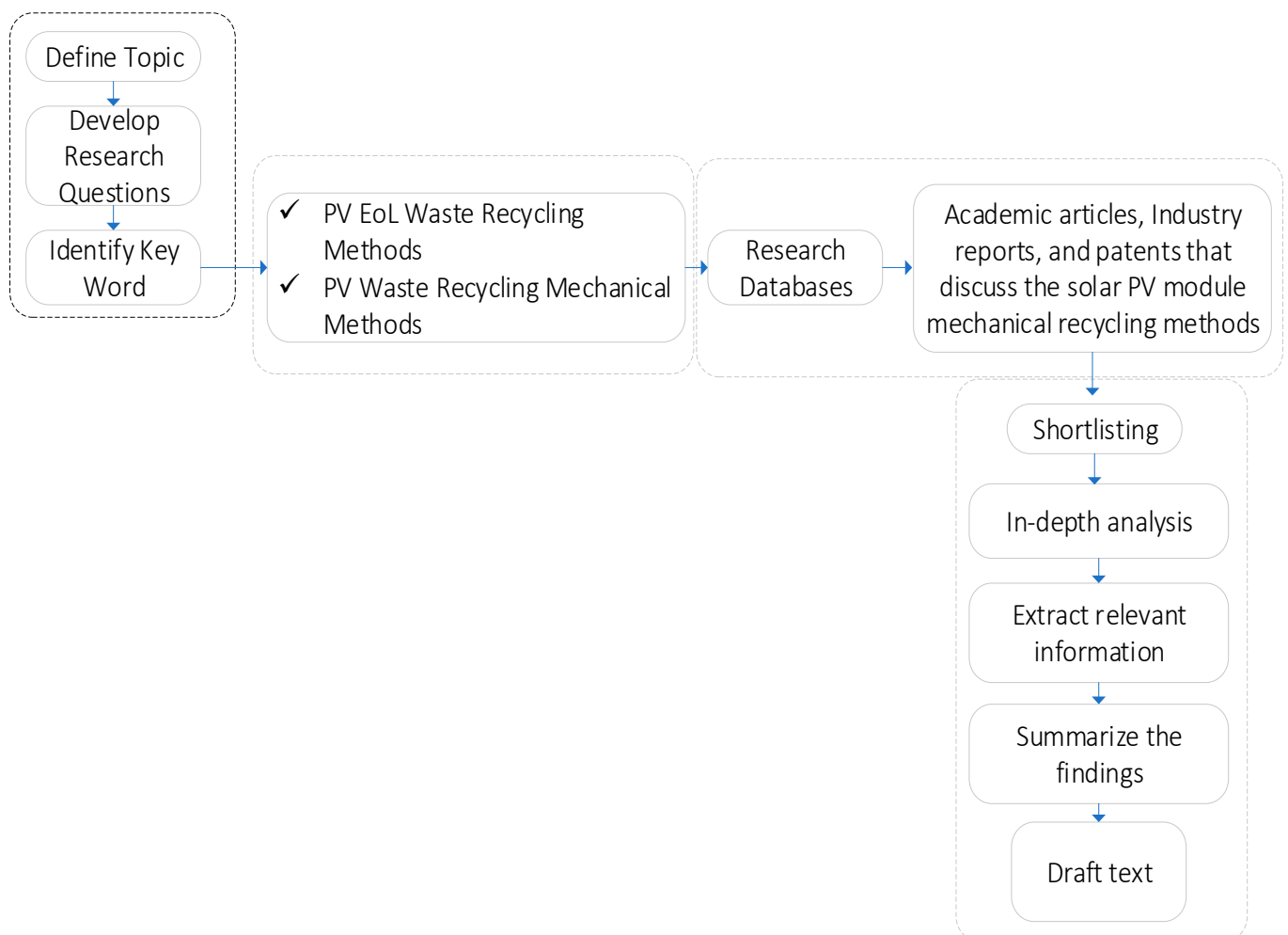


Figure 5. Methodology for Mechanical Recycling Method.

1. Define the Research Topic: focuses on assessing the mechanical recycling methods for solar photovoltaic (PV) end-of-life (EoL) waste. This involves understanding the

various mechanical techniques employed in recycling PV modules that have reached the end of their operational life.

2. Develop Research Questions to address the following key research questions:
 - What are the current mechanical recycling methods available for PV EoL waste?
 - How effective are these mechanical methods in recycling PV modules?
 - What are the benefits and limitations of each method?
3. Identify Key Words include:
 - PV EoL Waste Recycling Methods
 - PV Waste Recycling Mechanical Methods
4. Literature Review: begins with an extensive literature review to gather existing knowledge and data on the topic. This involves searching for:
 - Academic Articles: Peer-reviewed papers that discuss mechanical recycling methods for PV modules.
 - Industry Reports: Documents from industry stakeholders that provide insights into practical applications and the effectiveness of recycling methods.
 - Patents: Information on patented technologies and innovations in mechanical recycling of PV waste.
5. Data Collection from Research Databases: The identified keywords are used to search various research databases, including but not limited to:
 - Google Scholar
 - ScienceDirect
 - IEEE Xplore
 - Scopus

This ensures a comprehensive collection of relevant academic articles, industry reports, and patents.

6. Shortlisting Relevant Sources
 - The collected literature is then shortlisted based on relevance to the research questions. Criteria for shortlisting include:
 - Direct discussion on mechanical recycling methods for PV modules.
 - Recent publications to ensure up-to-date information.
 - Sources that provide empirical data and detailed descriptions of recycling processes.
7. In-depth Analysis involves:
 - Evaluating the effectiveness of different mechanical recycling methods.
 - Analyzing the processes, technologies, and outcomes reported in the literature.
 - Comparing the benefits and limitations of each method.
8. Extraction of Relevant Information focusing on:
 - Descriptions of mechanical recycling techniques.
 - Performance metrics and results from practical implementations.
 - Comparative analysis of different methods.
9. Summarizing the Findings
 - The extracted information is summarized to provide a clear and concise overview of the current state of mechanical recycling methods for PV EoL waste. This summary highlights:
 - The most commonly used methods.
 - Innovations and advancements in the field.
 - Gaps and challenges that need further research.
10. Drafting the Research Article
 - Based on the summarized findings, the research article is drafted.

4.1. Crushing

In the mechanical recycling process, simple crushing plays a critical role in size reduction [56]. Sometimes, the crushing process is categorized into mechanical crushing [57] and high-pressure pulse crushing [58]. Broadly, crushing is considered a basic or initial process of the mechanical recycling process of waste solar PV panels. In [59], a new mechanical treatment process called “Conventional Crushing” is discussed. Figure 7 shows the step-by-step process of the experimental investigation.

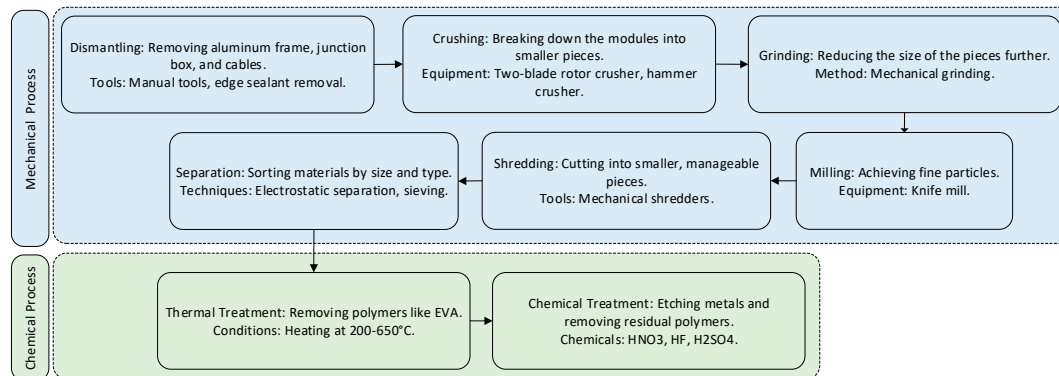


Figure 7. Mechanical processing proposed by [26].

In the conventional crushing (industrial processing) of crystalline silicon (c-Si) based photovoltaic (PV) panels, after removing the aluminum frame and junction box, the panels were cut into smaller sections (approximately 20 cm × 30 cm) and subjected to an industrial crushing process using a rapid granulator with a multi-blade, triple knife rotor.

The crushing of c-Si PV panels using this method proved to be challenging due to the strong bonding between the ethylene vinyl acetate (EVA) encapsulant and the glass and PV cells. The process resulted in a heterogeneous material with various particle size fractions, requiring multiple crushing runs to achieve the desired particle size. The distribution of materials across different size fractions is visually represented in Figure 8, which shows the images of sieved fractions of the crushed photovoltaic panel at different particle size ranges (>4 mm, 2–4 mm, 1–2 mm, 1–0.5 mm, 0.25–0.5 mm, and <0.25 mm).

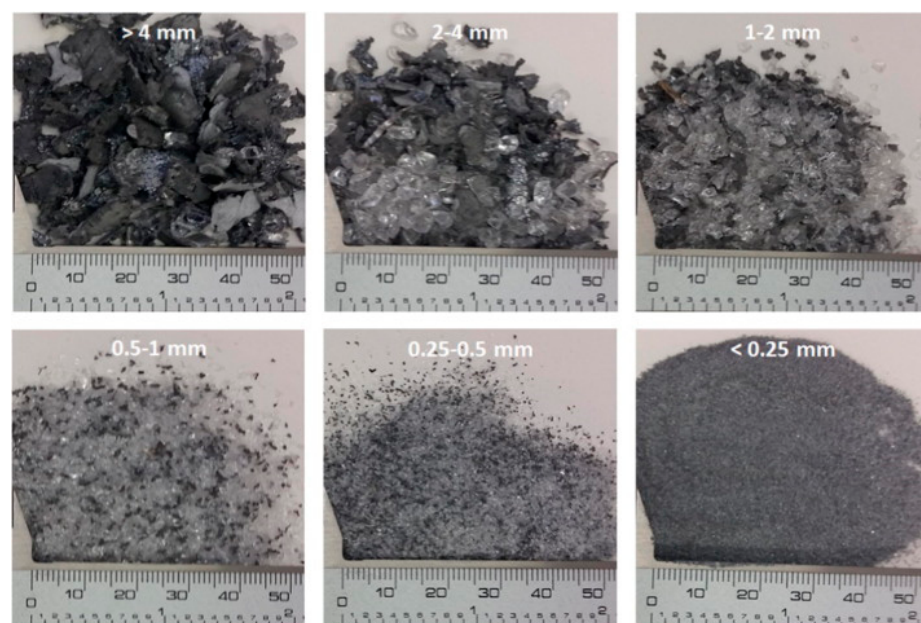


Figure 8. Visual breakdown of photovoltaic panel fragments post-crushing, categorized by particle size ranges (>4 mm, 2–4 mm, 1–2 mm, 1–0.5 mm, 0.25–0.5 mm, and <0.25 mm) [58].

Figure 9 provides a detailed breakdown of the distribution of aluminum (Al), silver (Ag), tin (Sn), lead (Pb), copper (Cu), and organic matter (wt%) among the different size fractions. The results indicated that nearly 90% of the organic matter from the industrially crushed PV panels was found in fractions larger than 2 mm. Conversely, copper was predominantly present in fractions larger than 1 mm, with significant amounts in the 2–4 mm and >4 mm fractions. The metals Pb and Sn showed a similar distribution pattern, with most of these metals located in the >2 mm size range. Additionally, the results highlighted a lack of selectivity in material distribution among the screened fractions, which could complicate subsequent recovery steps in a recycling process.

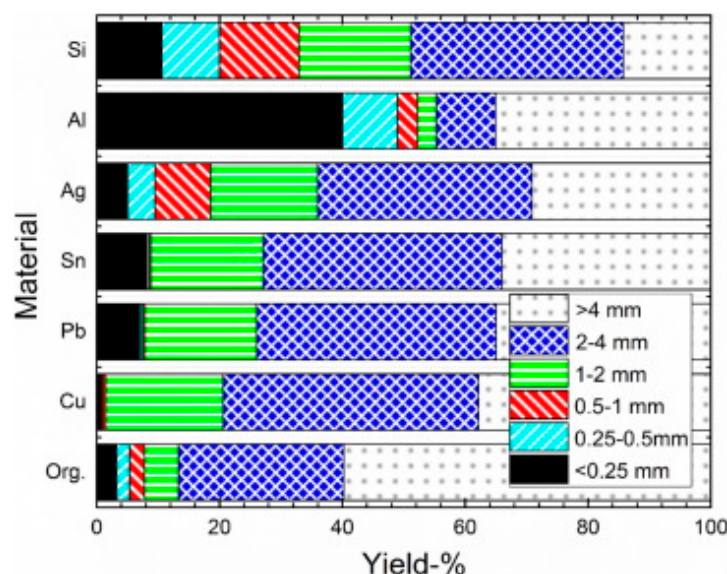


Figure 9. Weight percentage distribution of Al, Ag, Sn, Pb, Cu, and organic matter across sieved size fractions (>4 mm, 2–4 mm, 1–2 mm, 1–0.5 mm, 0.25–0.5 mm, and <0.25 mm) from industrially crushed PV panels [58].

The conventional crushing method, as employed in this study, demonstrated significant limitations in its ability to selectively separate the various materials embedded within the crystalline silicon (c-Si) based photovoltaic (PV) panels. This process involves mechanically breaking down the panels into smaller particles using an industrial granulator, which is effective in reducing the overall size of the material but does not effectively differentiate between the different components, such as metals, glass, and polymers.

One of the primary challenges observed with this method is its inability to achieve a clear separation of valuable metals from the rest of the panel materials. The strong bonding between the ethylene vinyl acetate (EVA) encapsulant and the glass and PV cells results in a heterogeneous mix of materials after crushing, where metals like copper (Cu), silver (Ag), tin (Sn), and lead (Pb) are dispersed across a wide range of particle sizes. As a result, the recovery of valuable metals becomes more complex and less efficient.

4.2. High Voltage Pulse Crushing (HVPC)

The use of HVPC technology is prevalent in the recycling of electronic waste circuit boards. Similarly, there are similarities between PV and electronic waste, prompting researchers to investigate the use of HVPC in the recycling of PV modules. It intends to improve the effectiveness and sustainability of recycling methods for abandoned PV modules, hence advancing environmentally friendly solutions in the field of electronic waste management. HVPC technology is capable of successfully separating different layers of material in the waste solar PV modules, and it has the potential to lead to environmentally acceptable recycling operations. The HVPC process flowchart is presented in Figure 10.

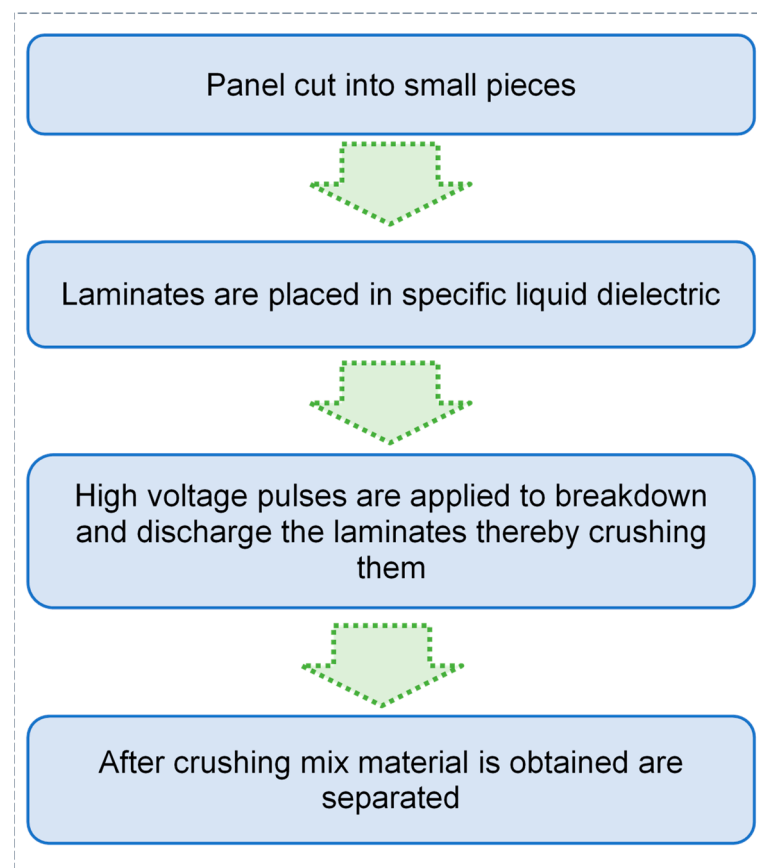


Figure 10. Process flowchart of HVPC.

The application of HVPC involves crushing and separating solar cell materials using high-voltage (HV) pulses [60]. HVPC is the most appropriate technology to replace conventional crushing. With HV application to the recycling material, stress is generated, which causes its fragmentation [61]. This process is useful to separate elements such as silicon from glass or other components within the solar cell [62]. The use of HVPC for crushing the waste PV modules is an efficient and cost-effective approach, particularly for large-scale recycling projects. Several research studies have examined the HVPC process with different parameters.

Akimoto et al. [63] study utilized high-voltage pulse crushing technology combined with sieving and dense medium separation to selectively separate and recover materials from polycrystalline silicon photovoltaic panels. Their methodology for crushing involves two steps of crushing, i.e., primary crushing and secondary crushing

4.2.1. Primary Crushing Step

In this step, the objective was to separate the photovoltaic panel into two distinct layers: the glass layer and the back sheet layer. The experiments were performed under various conditions to determine the optimal parameters for effective separation without significant material destruction. The experiments were conducted at discharge voltages of 90 kV, 110 kV, 130 kV, and 180 kV with a gap of 10–20 mm between the electrodes and a discharge frequency of 5 Hz, as given in Figure 11.

Figure 11 presents the outcomes of the primary crushing step, showing the separation of the photovoltaic panel into the glass layer (left) and the back sheet layer (right) under two sets of conditions: 110 kV for 20 pulses and 180 kV for 10 pulses. The results indicated that the condition of 110 kV with 20 pulses was optimal for achieving mutual separation of the layers while retaining their form. This condition was preferred over the 180 kV condition because it allowed for better handling of the crushed products and reduced contamination risks. The primary crushing process involved two main mechanisms: electrical disintegra-

tion (ED) and electrohydraulic disintegration (EHD), where the optimal condition likely balanced these mechanisms for effective material separation.

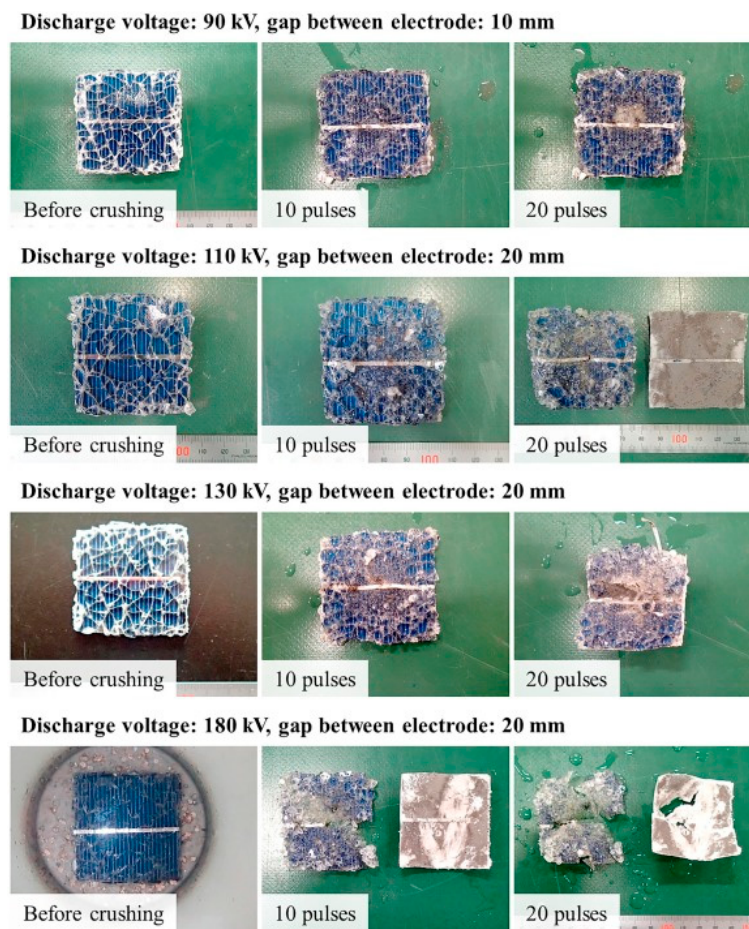


Figure 11. Results from the primary crushing step under different processing conditions [63].

4.2.2. Secondary Crushing Step

Following the primary separation, each layer (glass and back sheet) underwent a secondary crushing step under varying conditions to further liberate materials. This step was designed to enhance the separation of encapsulated components, particularly to isolate the glass particles from the encapsulant and to separate the bus-bar electrode from the back sheet.

Figure 12 illustrates the products obtained after the secondary crushing step of the glass layer. The results show that glass particles were effectively removed under all tested conditions, with the encapsulant being destroyed at higher discharge voltages. The optimal condition for the secondary crushing step was identified as 90 kV for 250 pulses. Under this condition, the bus-bar electrode was effectively separated from the encapsulant, and mutual separation of materials was achieved without significant destruction of each component. The study highlights that maintaining the structural integrity of the materials during separation is crucial for enhancing the purity of the recovered glass and facilitating further material recovery processes.

High-voltage pulse crushing has proven to be a highly effective technique for the selective separation and recovery of valuable materials from end-of-life photovoltaic (PV) waste panels. This method leverages the unique ability to target specific material interfaces, enabling the liberation of valuable components, such as metals and silicon, with greater precision compared to traditional crushing techniques. By generating high-intensity electrical pulses, the method induces micro-explosions and shock waves that facilitate the disintegration of bonded materials, leading to cleaner separation.

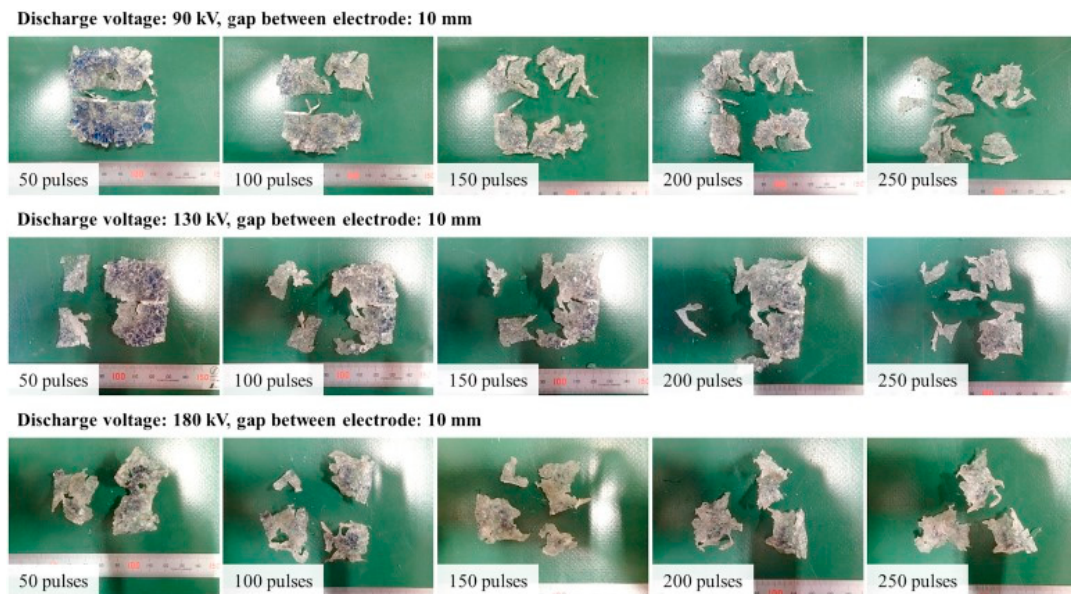


Figure 12. Results from the secondary crushing step of the glass layer following the removal of glass particles [63].

4.3. Electrostatic Separation (ESS)

Electrostatic separation (ESS) is a useful method for sorting charged or polarized particles using an electric field. It is extensively employed in the recycling of PCBs and PV waste. This procedure uses a roll-type corona electrostatic separator with grounded and active electrodes to separate conductive and nonconductive particles based on their electrical conductivities [64–66]. The generalized process flowchart is shown in Figure 13.

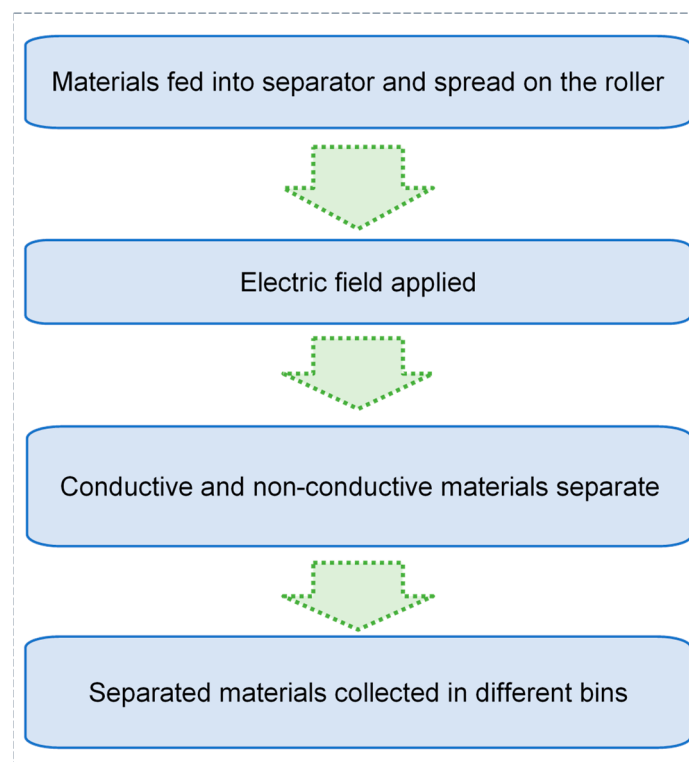


Figure 13. Process flow of Electrostatic separation.

ESS has proved its efficiency in concentrating metals like silver, aluminum, and silicon from solar panel fragments, obtaining high recovery rates of up to 95% for specific minerals [9,56,67]. By altering parameters such as electric potential difference, rotation speed, and electrode spacing, ESS is demonstrated to be a low-cost, energy-efficient technology for extracting important metals with high purity levels. After mechanical crushing, the majority of the silicon is converted to powder, which can be recovered by electrostatic separation.

ESS involves segregating conductive and non-conductive objects. A vibrating feeder is used to deliver a mixture of metals intended for separation onto a grounded, moving metal roller, as shown in Figure 14. The combination is then transported to a corona electrode region and charged by exposing it to a high voltage of up to 35 kVs. Conductive components, such as metals, quickly discharge their electrical charge to the roller as it rotates, causing them to be evacuated. Non-conductive materials, on the other hand, keep their charge for a longer period of time and adhere to the roller's surface until cleaned using a brush. Corona roll separators are an important technology in the electrostatic separation process because they effectively separate conductive and non-conductive components of the material combination.

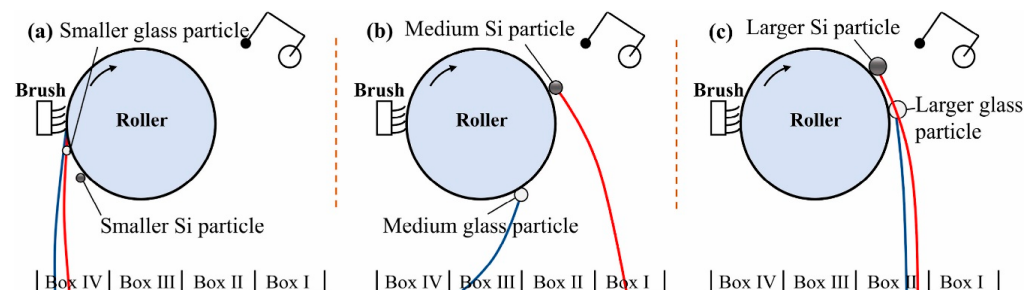


Figure 14. Electrostatic Separation process for various particle sizes [56].

Dias et al. also used the ESS technique to extract the valuable material from the PV waste modules. They fixed the splitter angles and feeder speed while changing the voltage and roller speed to determine the optimal parameters for the ESS process. They also evaluated the efficiency of the separation using ICP-OES for the metals, XRD for glass and silicon, and mass difference for the EVA. Their study suggested that the voltage of 24–28 kV and rotation speed of the roller of 30 is ideal for the highest yield [65].

De Souza and Veit recycled the PV panels using ESS. They initially separated the aluminum frame from the PV panels and ground the rest of the material using knife mills to reduce the size of the material. The material is then divided into three sets based on the size of the particle. An electrostatic separator with a roller type is used to further separate the conductive and non-conductive material. Various experiment settings are examined to effectively separate the various metal concentrations presented in the mixture. An electric potential difference of 38 kV is found to be the optimal voltage with a rotation speed of 75 rotations per minute (rpm). The ionization electrode is placed 25 cm from the roller at an angle of 55 degrees to obtain the highest metallic concentrations from the grounded PV mixture. These experimental settings for the ESS are able to achieve the highest metallic concentrations [67].

Li et al. used ESS to recover Si from crushed PV panels. The panel was mechanically broken into chunks and blended powder. The blended powder includes 82.8% silicon. The ESS technique is used to determine the impacts of particle size, voltage, and roller rotation speed. The particle size range of 0.30–0.45 mm was determined to be ideal for the separation process. The voltage given to the electrostatic electrode ranged from 15 to 22 kV, and the roller's rotation speed was regulated between 20 and 60 rpm. The best results were obtained with a voltage of 15 kV and a rotation speed of 30 rpm, resulting in a Si proportion of 91.0% and a Si recovery rate of 48.9%. Li et al. concluded that combining mechanical crushing with ESS is a potential technology for recovering Si from waste PV panels, providing both economic and environmental benefits [56].

4.4. Hot Knife Knife-Based Delamination Process

A hot Knife is one of the mechanical cutting techniques used for the separation of glass of Solar PV from panel cells [68–72]. This technique was invented by Japan's c-Solar PV Recycling company. It performs only one function of the recycling process [73–76]. The flow diagram of the Hot Knife technique is shown in Figure 15.

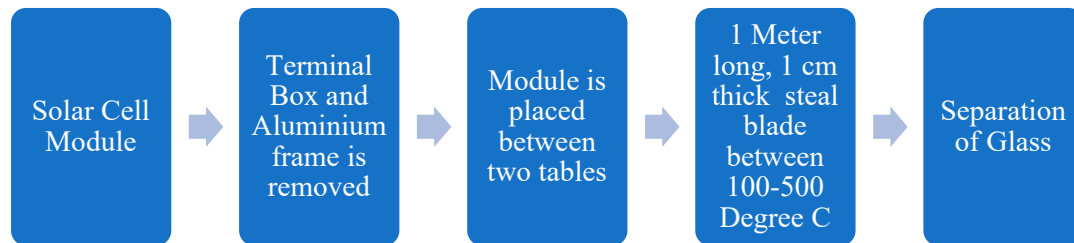


Figure 15. Process Flow Diagram for Hot Knife.

In [77], the study explores the application of the hot knife technique for the efficient separation and recovery of the back sheet from crystalline silicon (c-Si) photovoltaic (PV) modules. This method employs a thin, highly conductive knife heated by a hot air gun to temperatures ranging from 100 °C to 500 °C. The objective is to soften the adhesives by bonding the back sheet to the PV module, facilitating clean separation without damaging other layers, especially the sensitive photovoltaic cells.

Nine samples from a monocrystalline silicon PV panel were subjected to varying temperatures to determine the optimal conditions for back sheet separation. As given in Figure 16a–r, the temperatures tested were 100 °C, 150 °C, 200 °C, 250 °C, 300 °C, 350 °C, 400 °C, 450 °C, and 500 °C. The effectiveness of the hot knife process was evaluated based on the recovery rate, purity of the back sheet material, and the condition of the remaining PV module layers.

Figure 16 demonstrates the impact of varying temperatures on the separation process. At 100 °C and 150 °C, the hot knife was insufficiently effective, requiring manual peeling to complete the separation. This resulted in significant damage to the back sheet and other layers, with recovery rates of 4.28% and 4.44%, respectively, and purities of 95.65% and 99.19%. As the temperature increased to 200 °C, the separation process became more efficient, with the knife sliding smoothly between layers, achieving a recovery rate of 4.45% and the highest purity of 99.42%. Higher temperatures (250 °C to 500 °C) led to faster separation but also caused thermal deformation of the back sheet, with a significant decrease in purity to as low as 68.36% at 500 °C.

The hot knife technique at 200 °C provided the best balance between efficiency and material integrity, as evidenced by the high purity and minimal damage to the remaining layers.

Figure 17a–f details the condition of the knife after each temperature stage from (100–500 °C), correlating the physical state of the knife with the separation quality. The knife remained clean at lower temperatures, while higher temperatures led to material buildup on the knife, indicating excessive melting and adhesion of the back sheet material, which correlates with the decreased purity at those temperatures.

The study successfully demonstrates the hot knife technique's effectiveness in recovering high-purity back sheets from c-Si PV modules, particularly at an optimal temperature of 200 °C. This method offers significant advantages over traditional thermal treatments by reducing environmental impact and preserving the material quality, making it a promising solution for sustainable PV panel recycling.

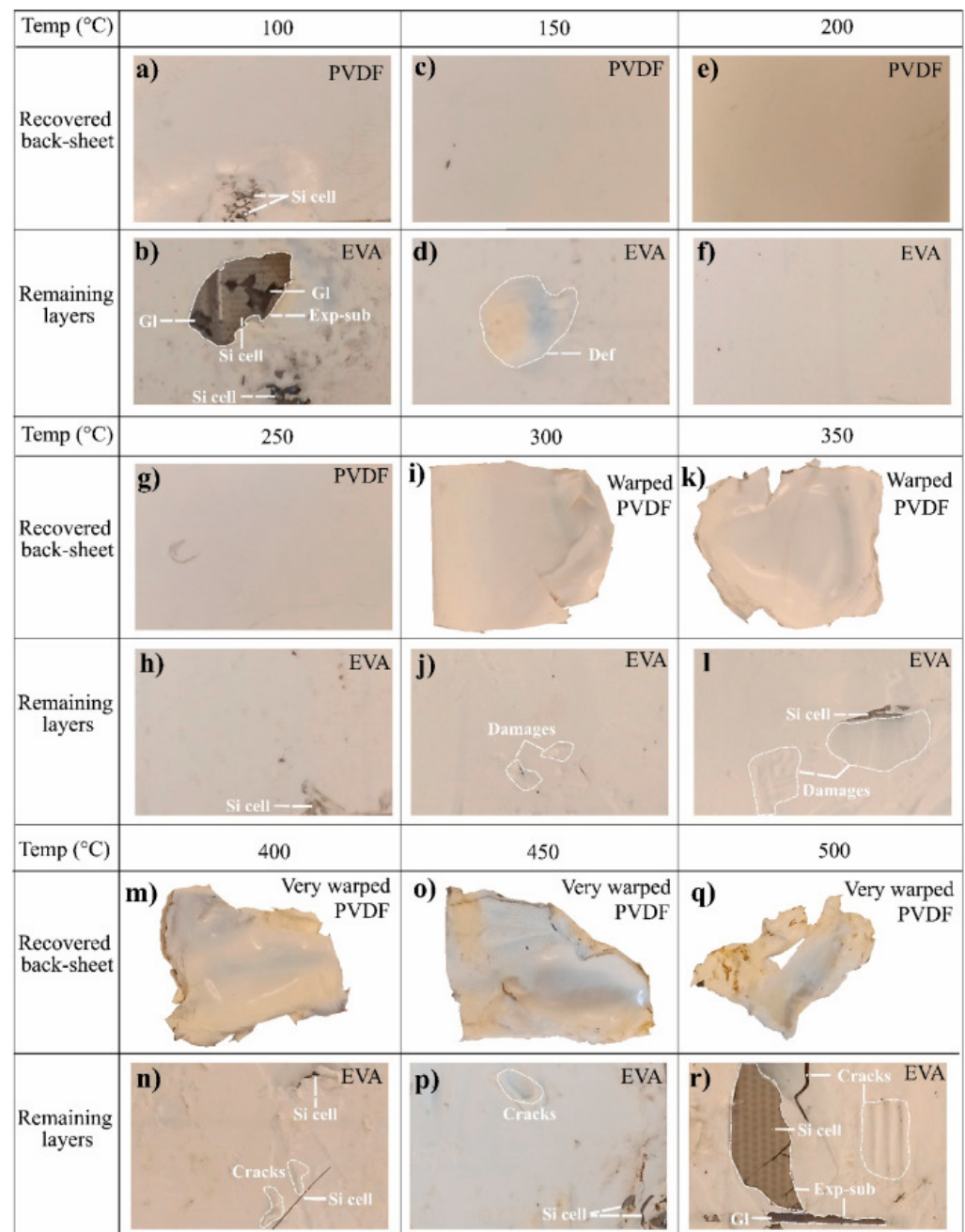


Figure 16. Condition of the back sheet (PVDF) and remaining layers (EVA) in the panel sample after exposure to varying hot knife temperatures, ranging from 100 °C to 500 °C [77].

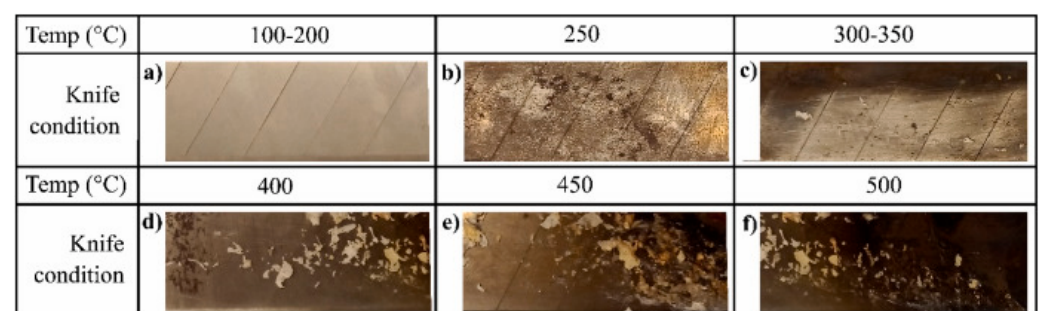


Figure 17. Condition of the knife after exposure to each temperature level during the hot knife technique experiments [77].

4.5. Water Jet Cutting of Solar PV

The water jet process utilizes a high-pressure stream of water, frequently combined with an abrasive substance, to cut a diverse range of materials. Widely acknowledged as one of the most versatile and rapidly advancing processes across industries, it has been demonstrated to offer greater benefits and cost-effectiveness compared to traditional methods such as laser cutting, EDM wire cutting, machining, oxy-fuel cutting, plasma cutting, and diamond tool cutting. Water jets have virtually limitless capabilities when it comes to cutting and machining various materials [78].

Shintora Kosan, a Japanese company, has pioneered an innovative water jet technology specifically designed for reclaiming glass from end-of-life PV modules. Water jet cutting makes recycling glass from these units affordable, efficient, and beneficial. After damaging the glass, whatever the success rate of any method, more energy is required to recycle the glass than can be saved by removing the glass. This technology can separate the solar cells and the back sheets by spraying water without damaging the glass. Following this process, the glass exhibits no signs of harmful substances or damage. Additionally, the machine incorporates a special filtration device to remove wastewater [79,80].

It was discovered during the early 1970s that water pressure ranging between (40,000 PSI to 60,000 PSI) and 276 MPa and 414 MPa could precisely cut soft materials using a 0.1 mm water jet stream. By the early 1980s, a specialized nozzle was developed alongside standard water jet components, allowing for the introduction of a minor quantity of abrasive power into the waterjet. This innovation, known as “abrasive jets,” propelled materials like garnet from the nozzle at high speeds, enabling the cutting of hard and tough materials like stainless steel, titanium, glass, and ceramics with excellent results. Consequently, this technology is now effectively converting waste into valuable commodities [81].

Presently, companies are offering waterjet cutting services mainly for thin film panels and the separation of glass plates from EoL Si PV panels. Two Two-axis industrial robotic waterjet systems for metal cutting are available commercially. The energy consumption for glass separation is about 20 kilowatts, and one operator is required for this purpose. The separated glass is neat and clean and needs no further processing for EVA removal. CNC CNC-based water jet jet-cutting machines having robotic arms can also be used for water jet jet-cutting purposes. The process flow diagram can be elaborated as in Figure 18.

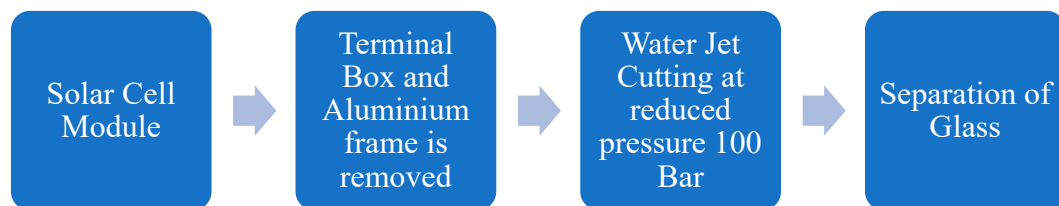


Figure 18. Process Flow Diagram for Water Jet Cutting.

4.6. Laser Irradiation

The study in [46] investigated laser irradiation as a method for recycling the ethylene-vinyl acetate (EVA) layer from crystalline silicon (c-Si) photovoltaic (PV) modules, which presents a significant advancement in sustainable recycling technologies. The research focuses on optimizing the laser parameters to effectively debond the EVA layer from the solar cells without causing damage to the cells themselves. The laser irradiation process is outlined in Figure 19. This figure illustrates the sequence of steps, starting with the removal of the back sheet, followed by laser irradiation to weaken the EVA bond, and concluding with the mechanical peeling of the EVA layer.

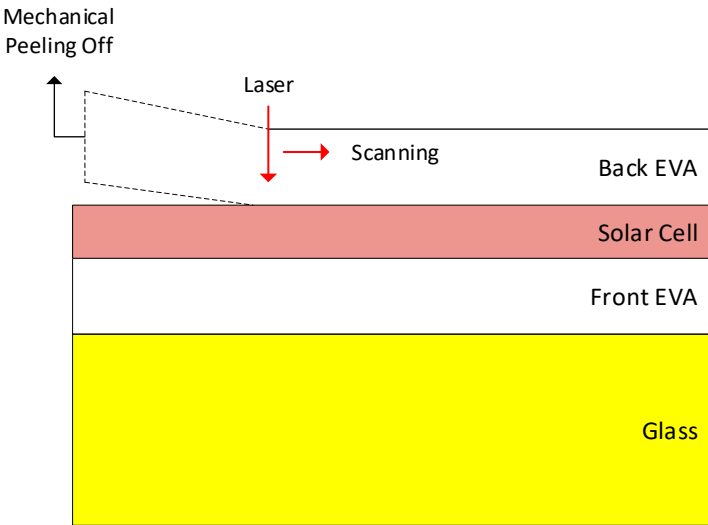


Figure 19. Process Flow of EVA Layer Recycling Using Laser Irradiation and Mechanical Peeling in c-Si PV Modules [46].

Figure 20 provides a detailed analysis of how the power density (P) and pulse repetition rate (PRR) of the laser impact the debonding process. As shown in Figure 20, higher P and PRR values enhance the debonding efficiency by increasing the energy delivered to the EVA layer, facilitating its separation from the solar cell. However, this also leads to a trade-off, as excessive energy can cause thermal damage to the underlying materials, including the solar cell's aluminum electrodes. Figure 20 underscores the delicate balance required to optimize these parameters—sufficient energy must be applied to weaken the adhesive bonds without crossing the threshold where material degradation occurs.

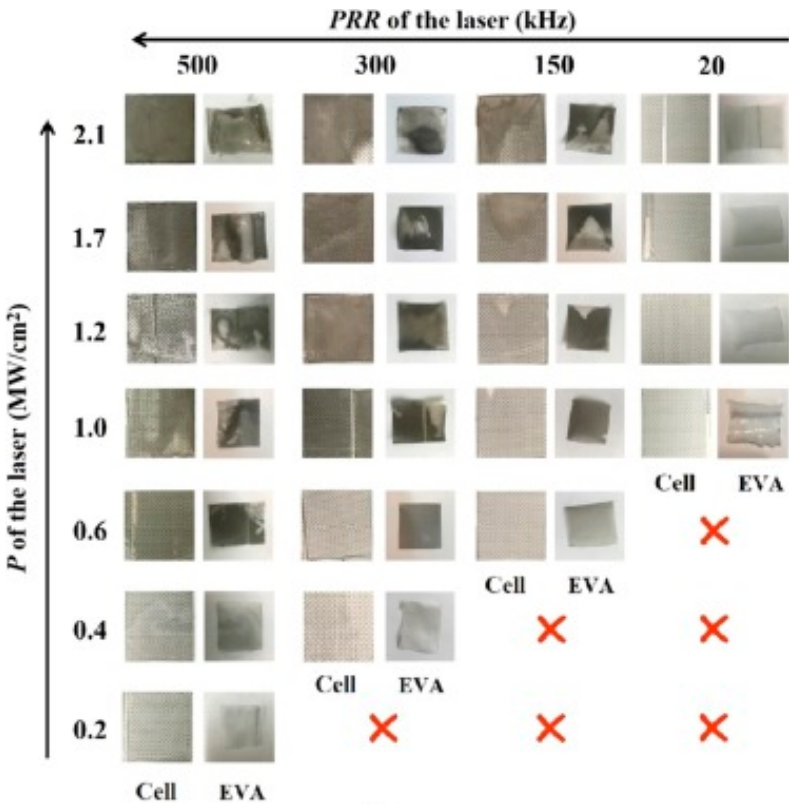


Figure 20. Effects of Laser Power Density and Pulse Repetition Rate on EVA Layer Separation Efficiency [46].

Furthermore, Figure 21a–d expands on this by illustrating the effects of different PRR settings on the physical condition of the solar cells post-EVA removal. SEM images reveal that at lower PRR settings, such as 20 kHz, the aluminum electrodes on the solar cells remain largely intact, preserving the functionality and structural integrity of the cells. However, as PRR increases, significant damage is observed, with the aluminum electrodes showing signs of deterioration and exposing the underlying silicon. This exposure can compromise the performance of the solar cells, highlighting the importance of maintaining a low PRR to protect the cells during the recycling process.

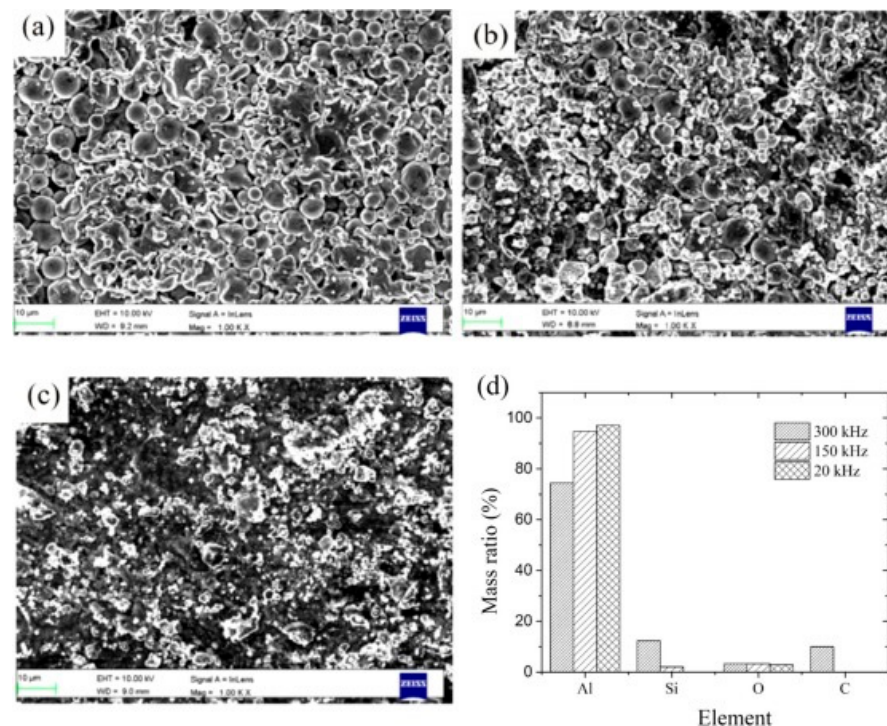


Figure 21. SEM Analysis of Solar Cell Surface Post-EVA Removal Using Different Laser Settings [46].

5. Discussion

This study comprehensively examines various mechanical recycling technologies for photovoltaic (PV) modules, focusing on their material recovery and their advantages and disadvantages, as given in Table 2. The methods analyzed include Crushing, High Voltage Pulse, Electrostatic Separation, Hot Knife Cutting, Water Jet Cutting, and Laser Irradiation. Furthermore, in Table 3, for all the techniques, material extraction is given.

Table 2. Recycling Methods with Their Advantages and Disadvantages.

Technique	Advantages	Disadvantages	Energy Consumption	Economic Feasibility	Material Recovery Efficiency
Crushing	- Lower energy consumption compared to traditional mechanical methods. - Selective fragmentation allows for easier recovery of valuable metals. - Environmental benefits are due to less waste generation and no additional contamination. - Economic feasibility due to lower processing costs and higher metal recovery rates	- Relatively low Si recovery rate. - Challenges in controlling particle size during mechanical crushing. - Requires further research to improve recovery efficiency	Low	High	Moderate (~50%)
High Voltage Pulse Crushing	- Efficient and relatively cost-effective, especially for large-scale recycling operations. - The possibility of recycling metals through particle size reduction is greater when compared to conventional crushing methods. - Provides superior crushing performance with minimal material waste. - Recommended for recovering glass, Si powder, silver, copper, lead, and zinc.	- Incomplete separation and recovery of valuable materials - Lower recovery rates of precious metals like silver and copper - Need for specialized equipment and safety measures to handle high-voltage operation - High voltage pulse crushing creates harmful dust during PV recycling. - Dust produced can pose health risks if inhaled.	Medium	Medium	High (~90%)
Electrostatic Separation	- Can handle dry materials - Suitable for initial coarse separation of metals, glass, and plastics - High disposal rate, recovery rate, purity, added value, and automation - Electrostatic separation is cost-effective and energy-efficient in recycling processes. - It efficiently recovers metals from electronic waste with high concentrations - Recovering materials requires less energy than processing raw materials - Electrostatic separation offers non-polluting Si recovery from waste c-Si PV panels	- Limited to materials with significantly different electrical properties - Not effective for similar conductivity materials - Exposure to heavy metals poses health risks - Small powder size hinders material movement and separation during recycling - Glass particles difficult to distinguish from Si particles in recycling process.	Low to Medium	Medium	High (~80%)

Table 2. Cont.

Technique	Advantages	Disadvantages	Energy Consumption	Economic Feasibility	Material Recovery Efficiency
Hot Knife Cutting	- Fast Processing - No CO₂ Emissions - More Economic - Peeled Glass intact - Can handle any type of Module	- Does not remove rare glass - EVA present on glass - Further Processing is required to extract elements - Steel blade increases iron content in residue	Low	Low	Moderate (~60%)
Water Jet Cutting	- No CO₂ Emissions - More Economic - Peeled Glass intact - Can handle any type of Module - Rare glass can also be removed - No EVA on glass	Further Processing is required to extract elements	High	Medium	High (~85%)
Laser Cutting	- Easy access to the EVA - High precision and control - Efficient in selective material separation - Non-contact process	- Slow process - Expensive equipment - Complex operation - Requires proper maintenance and calibration	Medium to High	Low	High (~90%)

Table 3. Material Extraction Table of Investigated Methods.

Techniques	Glass	Silicon (Si)	Aluminum (Al)	Silver (Ag)	Copper (Cu)	Tin (Sn)	Lead (Pb)	EVA
Crushing	✓	✓	✓	✓	✓	✓	✓	✗
High Voltage Pulse Crushing	✓	✓	✓	✓	✓	✓	✓	✗
Electrostatic Separation	✗	✓	✓	✓	✓	✓	✓	✗
Hot Knife Cutting	✓	✗	✗	✗	✗	✗	✗	✓
Water Jet Cutting	✓	✓	✓	✓	✓	✓	✓	✗
Laser Irradiation	✗	✓	✓	✓	✓	✓	✓	✓

1. **Crushing:** This method is notable for its low energy consumption and its ability to selectively fragment PV modules, which facilitates the recovery of valuable metals. Despite these advantages, it has a relatively low silicon recovery rate and presents challenges in controlling the particle size, necessitating further research to enhance its efficiency.
2. **High Voltage Pulse Crushing:** This technique offers efficient processing and is especially suitable for large-scale operations. It improves the possibility of recovering materials like glass, silicon powder, silver, copper, lead, and zinc. However, it suffers from incomplete separation of materials and produces potentially harmful dust, posing health risks during operations.
3. **Electrostatic Separation:** Effective for handling dry materials, this method is characterized by its high recovery rate and purity, adding significant value. The main limitation is its effectiveness only with materials that exhibit significantly different electrical properties, which restricts its applicability.
4. **Hot Knife Cutting and Water Jet Cutting:** Both techniques ensure fast processing with intact peeled glass and no CO₂ emissions. Water Jet Cutting has the added advantage of removing rare glass without leaving ethylene-vinyl acetate (EVA) residues. Nonetheless, both require further processing to extract valuable elements from the modules.
5. **Water Jet Cutting:** Provides a clean and precise method for separating materials in solar PV waste recycling. It effectively cuts through glass, silicon, and metals without generating heat, which helps to avoid thermal damage. However, it may struggle with EVA removal and requires a substantial amount of water and abrasive materials.
6. **Laser Irradiation:** Offers high precision and control, proving efficient in selective material separation. However, it is a slow process, involves expensive equipment, and requires complex operation and maintenance.

Overall, the choice of recycling method depends significantly on the specific needs for material recovery, the scale of operations, and environmental considerations. Future research should aim at enhancing these technologies to increase recovery rates, reduce environmental impacts, and address the challenges noted in operational risks like dust generation and health safety in high high-voltage applications. This will help in aligning with global sustainability goals and the growing demand for raw materials in the photovoltaic industry.

6. New Proposed Method

Building on the analysis provided in Tables 1 and 2, this study proposes a novel and hypothetical technique that synergizes the capabilities of Laser Irradiation and High Voltage Pulse Crushing, referred to as the “Laser and High Voltage Pulse (L&HVP)” method. This hybrid approach is conceptually designed to address the limitations of existing recycling methods for end-of-life solar PV modules by combining the precision of laser technology with the efficiency of high-voltage pulses. The L&HVP method aims to maximize material recovery, particularly for delicate components such as silicon and metals, while minimizing the risk of degradation or contamination.

The novelty of the L&HVP method lies in its integration of two advanced techniques: laser irradiation for selective removal of the EVA encapsulant and high-voltage pulse crushing for targeted fragmentation and material separation. Laser irradiation ensures precise removal of the encapsulant without damaging the underlying materials. However, the application of High Voltage Pulse (HVP) crushing following EVA removal is critical for overcoming the limitations of conventional crushing and sorting methods. Conventional techniques often result in non-uniform particle sizes and contamination due to inefficient separation of components, such as silicon, glass, and metals. In contrast, HVP crushing leverages the dielectric properties of these materials, allowing for selective fragmentation and achieving higher recovery efficiency with minimal cross-contamination. This dual-stage process enhances the overall recycling performance, ensuring that delicate materials like silicon maintain their integrity and can be recovered at high purity.

The conceptual workflow of the proposed L&HVP technique is illustrated in Figure 22, outlining the sequential steps involved. The process begins with laser irradiation, which precisely removes the EVA encapsulant. Subsequently, high-voltage pulse crushing is applied to selectively fragment and separate key materials such as glass, silicon, and metals. By integrating these two techniques, the L&HVP method ensures both precision in encapsulant removal and efficiency in material separation, addressing the shortcomings of standalone methods.

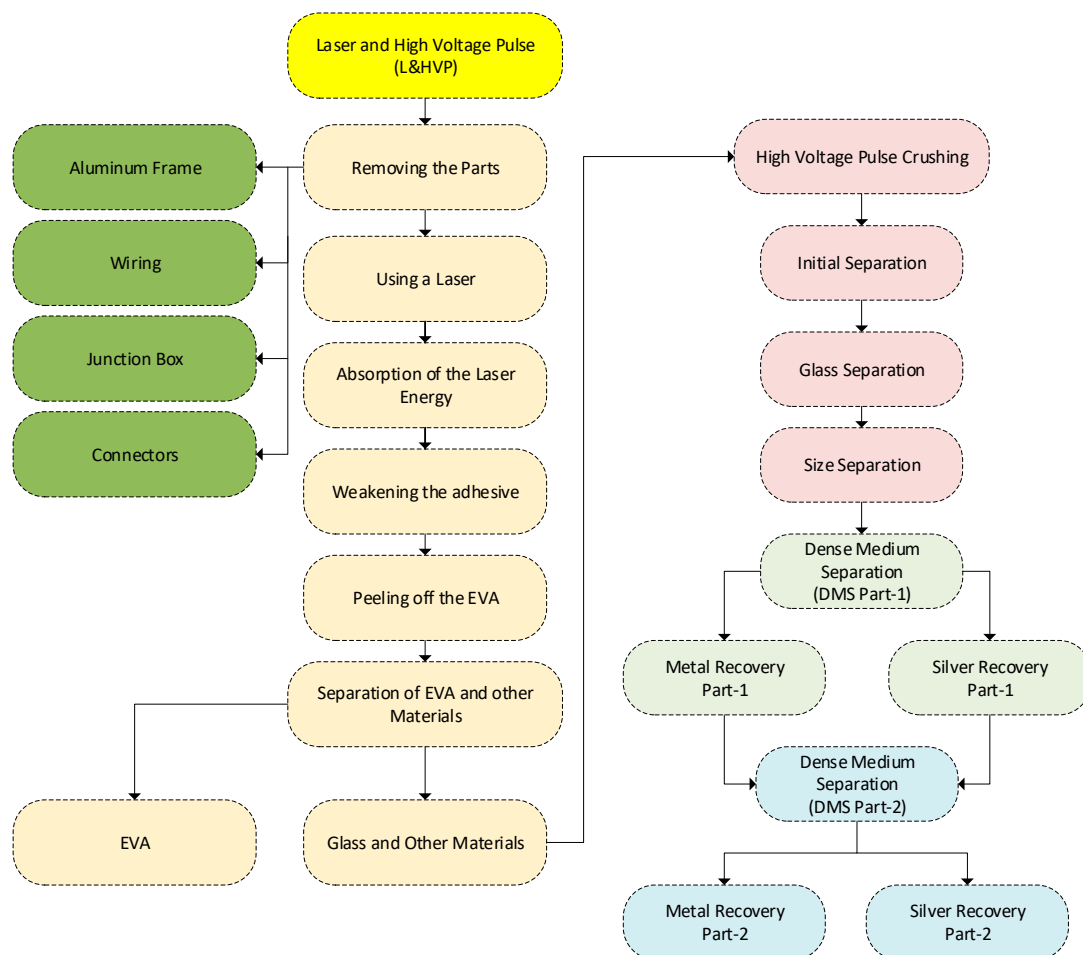


Figure 22. L&HVP Crushing Process.

This proposed workflow not only mitigates contamination risks but also demonstrates the potential for scalability and industrial application, subject to further experimental validation. While the L&HVP method is a conceptual framework, its potential advantages include enhanced material recovery, energy efficiency, and alignment with the principles of

a circular economy. Future research will focus on experimental validation, optimization of process parameters, and addressing practical considerations such as equipment design and energy requirements.

6.1. Laser and High Voltage Pulse (L&HVP)

The L&HVP proposed technique integrates both laser irradiation and high voltage pulse crushing to achieve comprehensive recycling of waste solar panels. This innovative approach allows for the efficient recovery of valuable materials within a single processing unit, making it a highly effective solution for solar panel recycling.

6.2. How It Works

Step 1: Removing the Parts:

- Prior to recycling, specific components are removed from the solar panels to prepare them for subsequent processing steps.

Step 2: Laser Irradiation:

Laser irradiation is employed to facilitate the handling and disassembly of aged solar panels. The process provides two key benefits:

- Enhanced Component Separation: Lasers are used to sever connections between different components, making disassembly and material recovery more efficient.
- EVA Recovery: The laser effectively breaks the bonds within the ethylene-vinyl acetate (EVA) encapsulant, allowing for its easy extraction. Recovering EVA is crucial for sustainable recycling, as it can either be reused or safely disposed of.

Step 3: High Voltage Pulse Crushing:

Following laser irradiation, high high-voltage pulse crushing is applied. This stage involves the controlled discharge of high-voltage pulses to dismantle and fragment the laser-treated materials. The energy from the pulses induces the breakdown of these materials into their individual components, facilitating efficient separation and recovery.

This combined L&HVP approach ensures the complete processing and recycling of solar panels, maximizing material recovery while minimizing waste.

7. Conclusions

This study provides a comprehensive analysis of various mechanical recycling methods for end-of-life solar photovoltaic (PV) panels, including Crushing, High Voltage Pulse Crushing, Electrostatic Separation, Hot Knife Cutting, Water Jet Cutting, and Magnetic Separation. Each method was evaluated for its effectiveness in recovering valuable materials such as glass, silicon, metals (copper, aluminum, silver, tin, lead), and EVA. The findings reveal that while each method has its strengths, none is fully capable of efficiently recovering all materials without significant limitations.

Crushing and High Voltage Pulse Crushing methods demonstrated strong performance in recovering glass and metals, but they struggle with efficiently separating EVA and maintaining the integrity of the materials. Electrostatic Separation is effective for isolating conductive materials but is less useful for non-conductive components like glass and EVA. Hot Knife Cutting excels at separating glass but does not address metal recovery. Water Jet Cutting is versatile but less effective at managing the EVA encapsulant. Magnetic Separation is limited to ferromagnetic materials, which are less relevant in PV panel recycling.

To address these challenges, the study proposes a hypothetical hybrid method, Laser and High Voltage Pulse (L&HVP), which integrates the strengths of laser irradiation and high voltage pulse crushing. Laser irradiation effectively removes the EVA encapsulant without damaging underlying materials, allowing for subsequent high high-voltage pulse crushing to efficiently separate and recover glass, silicon, and metals. While the L&HVP method is currently theoretical, its design is based on data-driven insights from the limitations of existing techniques.

The L&HVP method offers a promising solution for optimizing material recovery and enhancing the sustainability of solar PV module recycling. By addressing the shortcomings of conventional methods, this approach aligns with the principles of the circular economy, contributing to the responsible management of solar PV waste. Future research should focus on the experimental validation of the L&HVP method, exploring its practical applications, scalability, and economic feasibility in the context of large-scale PV recycling operations. The successful implementation of this hybrid technique could significantly advance the field of solar PV recycling, paving the way for more efficient and sustainable practices.

Author Contributions: Conceptualization, A.A.; methodology, A.A.; formal analysis, A.A. and M.S.; investigation, A.A., S.A. and S.A.Q.; resources, A.A.; data curation, M.W.K. and A.A.; writing original draft preparation, A.A.; writing—review and editing, S.A. and M.T.I.; project administration. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to express their profound gratitude to King Abdullah City for Atomic and Renewable Energy (K.A. CARE) for their financial support in accomplishing this work. As well as the Interdisciplinary Research Center for Sustainable Energy Systems (IRC-SES), King Fahd University of Petroleum and Minerals, under project No. INRE2105.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to express their profound gratitude to King Abdullah City for Atomic and Renewable Energy (K.A. CARE) for their financial support in accomplishing this work. As well as Interdisciplinary Research Center for Sustainable Energy Systems (IRC-SES), King Fahd University of Petroleum and Minerals, under project No. INRE2105.

Conflicts of Interest: The authors declare no conflicts of interest.

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