http://www.press.ierek.com

ISSN (Print: 2357-0849, online: 2357-0857)

Environmental Science and Sustainable Development

Research Paper

Received: 5 March 2025, Accepted: 3 June 2025, Published online: 30 June 2025

DOI: 10.21625/essd.v10i2.1191

Technologies for Resource-Efficient Recycling of End-of-Life Crystalline Silicon Photovoltaic Panels

Pradeep Padhamnath[1], Srinath Nalluri[3], Filip Kuśmierczyk[2], Mateusz Kopyściański[1], Mirosław Karbowniczek[4]

[1]*Assistant Professor, Faculty of Engineering Metals and Industrial Computer Science, AGH University of Krakow, Kraków, Poland*

[2]*Research Assistant, Faculty of Engineering Metals and Industrial Computer Science, AGH University of Krakow, Kraków, Poland*

[3]*Research Associate, Solar Energy Research Institute of Singapore, National University of Singapore, Singapore*

[4]*Professor, Faculty of Engineering Metals and Industrial Computer Science, AGH University of Krakow, Kraków, Poland*

Abstract

Global PV installations recently crossed the terawatt scale. The growth of photovoltaic (PV) installations is an important and desirable element in generating clean electricity and combating climate change. However, after the end of their useful life, the PV panels would also lead to the generation of PV waste that would need to be dealt with in a manner which is safe and environmentally responsible. In this work, we present early-stage research results based on experiments conducted with recycling end-of-life (EOL) crystalline silicon (c-Si) PV panels promoting resource efficiency and circularity. We explore experimental pathways for both closed-loop and open-loop recycling of EOL PV panels. For closed-loop recycling, we present experimental results using the recently developed electrohydraulic shock wave-based fragmentation (EHF) of PV panels. The EHF process allows for the recovery of almost all valuable materials used in the manufacturing of PV panels. We further provide a succinct literature review for further downstream treatment of the end products obtained after EHF processing of EOL PV panels to recover precious metals such as Silver. For open-loop recycling, we propose using the panels in the production of ferrosilicon compounds, thereby reducing the emissions of greenhouse gases associated with their production. Through experiments, it was observed that the size of the recycled Si does not impact the microstructure of the FeSi produced, which means that the technology could be easily used to handle different sizes of Si source. Through careful experiments and analysis, we provide recycling methods to improve the circularity and resource efficiency in the management of end-of-life c-Si PV panels. Both experimental recycling pathways discussed in this work could potentially provide sustainable technical pathways to recycle EOL PV modules, which do not involve producing harmful greenhouse gases.

Keywords

Recycling; Circular-economy; Resource-efficiency; Silicon-photovoltaic; Ferrosilicon, Fragmentation, Decarbonization

1. Introduction

Solar photovoltaic (PV) installations have grown rapidly since the early 2000s, increasing from 1.2 GW in 2000 to 1.6 TW in 2023, and, expected to reach 4.5 TW by 2050 (IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016, n.d.; Snapshot of Global PV Markets 2024, n.d.). PV installations are a viable alternative for generating clean electricity; nevertheless, challenges could arise in managing the waste generated due to decommissioned solar panels. While most commercially available PV panels have a technical lifespan of 25 to 30 years, not all panels remain serviceable for that duration. Some PV panels fail prematurely due to damage incurred at different stages, such as production, transportation or installation. Thus, with the increase in PV installations, a corresponding increase in the global cumulative PV waste is inevitable. The PV panel waste is estimated to reach up to 8 Mt by 2030 and 78 Mt by 2050, with annual waste in 2050 (6 Mt) almost matching the mass contained in new installations (6.7 Mt) (IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016, n.d.). Hence, it has become imperative for many companies to integrate End-of-life (EOL) PV recycling into the PV value chain to mitigate growing PV waste, ensure the technology remains environmentally friendly and sustainable, and create value by pursuing new economic avenues. Recycling of EOL PV modules also contributes directly to the United Nations' Sustainable Development Goal number 12, 'Responsible Consumption and Production' (Department of Economic and Social Affairs & United Nations, 2015). Efficient disposal and management of hazardous waste is crucial to achieve this goal. In many countries, stringent guidelines are already in place to deal with Waste Electrical and Electronic Equipment (WEEE) (Cucchiella & Rosa, 2015; Dias et al., 2016a). The European Union (EU) has published one of the most detailed regulations related to the recycling of PV modules. These regulations stipulate a minimum of 80-85% (by weight) recovery or reuse of materials (Deng et al., 2021; Padoan et al., 2019; Sica et al., 2018). A detailed review of the regulatory framework related to PV module recycling is available in these reviews. (Kastanaki, 2025; Nithya et al., 2021; Serpe et al., 2025). These recently formulated regulations provide a general guideline for recycling. Designing recycling processes to maximize the value of the materials recycled than the weight, could be more beneficial. For example, in PV panels, the glass and the aluminium frame, copper wires and external connectors constitute approximately 85% of the weight of the PV panel, but account for only 30-40% of the value (Padhamnath, Nalluri, et al., 2025). Regulatory frameworks for handling WEEE waste, including solar PV panels, have been formulated in different countries (Ali et al., 2023, 2024; Curtis et al., 2021; Jain et al., 2022; Serpe et al., 2025). A global review of regulatory frameworks highlighted that the popular business-to-customer model producers shall also be responsible for the end-of-life management of their product (Mahmoudi et al., 2021; Majewski et al., 2021; Sharma et al., 2019). Despite the existence of policies and guidelines pertaining to recycling EOL PV modules (Held & Wessendorf, 2024; Sharma et al., 2019; Y. Xu et al., 2018), PV module recycling has not achieved the desired commercial scale. First Solar, which produces Cadmium Telluride (Cd-Te) thin film panels, is considered the leader in PV recycling (Sharma et al., 2019). Few solar PV manufacturing industries launched initiatives for recycling c-Si-based PV modules in Europe; however, long-term commercial viability has not been established (Sharma et al., 2019; Y. Xu et al., 2018). According to a current report on the status of global PV recycling, six out of seven commercial entities engaged in recycling PV modules operate in Europe (Wambach et al., 2024).

However, the complex structure of the modules renders the recycling of photovoltaic (PV) modules challenging. About 97% of all the panel manufacturers are Crystalline silicon (c-Si) panels (Ise & Projects GmbH, 2024). These panels are made from materials that are distinct in properties and range in quantities from milligrams to several kilograms per panel. A c-Si PV panel includes materials such as glass, interconnected silicon solar cells, metals like aluminium, silver, and copper, encapsulants, and polymers. The aim of the fabrication process of PV panels is to prevent these layers from coming apart on their own. Hence, disassembling a panel requires a range of mechanical, thermal, and chemical processes for material recovery, purification and reuse (Chen et al., 2024).

Significant improvements have occurred recently in the research and development of PV recycling technologies. Around 123 patents related to the recycling of c-Si PV modules were filed between 1995 to 2016, highlighting the increasing demand and necessity of PV recycling. The Europe organization, PV Cycle, has processed ≈ 19 Mt of PV waste since its inception. Innovative recycling processes, which combine mechanical and thermal treatments, have been implemented, increasing the recycling rates to ≈96%. In Germany, Eltz Umwelt-Technology developed an advanced pyrolysis process to recover 95% of materials. France's Veolia uses a multistage recycling approach in its first commercial-scale PV recycling plant for PV modules. China leads in the number of PV patents, mostly focusing on module separation. Some of the innovative technologies include refrigerated grinding and hydrothermal prefractionation. Other technologies like heated cutting and thermal treatment are advancing PV recycling efficiencies in Japan and Korea (PVPS Task et al., 2018). Thus, advanced PV recycling technologies are being developed globally.

However, the technology of recycling PV modules is often fraught with environmental and economic challenges. Some technologies, such as incineration, could lead to harmful emissions. Chemical leaching could lead to the release of toxic chemicals. Some of these technologies can treat only limited volumes and could result in high operational costs that prevent economies of scale (Mulazzani et al., 2022). For the commercial success of PV module recycling, it is necessary to create scalable, sustainable and cost-effective technologies to improve the long-term viability of solar energy.

The recycling of EOL-PV modules can be done in either an open-ended cycle or a closed cycle. In open ended cycle, the products obtained from the EOL-PV panels could be used in manufacturing other commercially important substances, which may or may not be directly used for the fabrication of the new solar PV panels. The silicon in the PV panels could be used for the manufacturing of ferrosilicon (FeSi), which is widely used in the production of steel and other metal alloys (Tangstad, 2013; Blaesing et al., 2024). These recycling options have been found to be the most economically viable process (Mao et al., 2023). In closed-end recycling, also known as cradle-to-cradle recycling, the materials extracted from the discarded product are used, after suitable modification, in the fabrication of the same product. In the case of PV panels, this would require the separation of the various components, recovery, refining and then using them to manufacture new PV panels. However, close-ended recycling of PV panels could be an extremely complicated process involving multiple technologies involving high energy usage and hazardous chemicals, impacting the commercial viability of the recycling process. While it is necessary to keep the recycling process simple and low-cost, attention should also be paid towards the hazards and toxic materials created as a direct result of the recycling process. If a recycling process creates more hazardous wastes than the original component, then the process might involve heavy costs in terms of human toxicity and marine eutrophication (Mao et al., 2023; Seo et al., 2021).

The recyclability of the PV panels is determined at the delamination process, which is considered the most complicated step in PV recycling. Delamination is difficult to achieve as the aim of a successful PV panel design and manufacturing process is to enable them to withstand environmental impacts, ingress of moisture and air. Mechanical, chemical, or thermal processes, applied either separately or combined, can be used to delaminate EOL PV modules (Divya et al., 2023; Lunardi et al., 2018; Sanathi et al., 2024). Recently high voltage crushing or electrohydraulic fragmentation (EHF) has been proposed as an alternative to the existing delaminating processes. The EHF process can help achieve higher material selectivity and improved recycling efficiency than conventional processes, such as crushing (Akimoto et al., 2018; Nevala et al., 2019; Song et al., 2020; Zhao et al., 2020). Recent works have reported the optimization of the process parameters in small lab-scale equipment. (Song et al., 2020; Zhao et al., 2020). Specific details regarding the material recovery, their sorting and their end use have not been explicitly discussed. This does not provide clear information on the recovery of the process of recovery of important materials such as Ag and Si after processing the modules using the EHF process. Furthermore, the information available in the literature does not establish the suitability of integrating the EHF process into the already existing process line incorporating the crushing of EOL PV panels.

Ferrosilicon (FeSi) alloys are universally used in the metallurgical industry for alloying as carriers of Si or other alloying elements. They are also used for the deoxidation of steel and in the casting industries (Hawezy, 2017; Selema et al., 2023). Traditional silicon production from primary sources relies on coal and coke, generating approximately four tons of CO_2 per ton of FeSi (Haque & Norgate, 2013; Sævarsdottir et al., 2021). Most of these carbon emissions originate from the carbonaceous reduction process of SiO2. Utilizing an alternative production method, such as an induction furnace and eliminating the use of carbon for the reduction of SiO2 can significantly reduce these emissions. Consequently, FeSi production via recycled silicon offers a promising pathway in addressing modern environmental challenges. While recently researchers have tried to use electronic waste, including PV panels, to produce ferrosilicon, these proposed processes still involve the use of carbonaceous reductants, which leads to the evolution of greenhouse gases during the process (Blaesing et al., 2024; Farzana et al., 2014; Rajarao et al., 2018). The development of a process without using carbonaceous reductants to generate commercially important alloys such as FeSi from waste materials is missing from the literature.

1.1. Objective, Scope, and novelty of the present work

The objective of this work is to suggest and share the initial results of technologies for recycling EOL c-Si PV panels developed in our laboratories. In this work, we present initial results with two technologies for recycling EOL c-Si PV modules; one each for open-ended and closed-ended recycling approaches as developed on a laboratory scale. For open ended recycling approach, we develop a process of manufacturing FeSi from EOL c-Si PV panels and scrap steel. This is a novel process which does not involve any reducing agents to produce FeSi. It utilizes Si from the EOL PV panels and clean scrap iron to produce FeSi using a simple induction furnace. This eliminates the use of any reducing agents. Since this can be produced in an induction furnace, the only energy input required is in terms of electricity, which can be generated using renewable energy sources. No further sources of heating are necessary. For a closed-end recycling process, an energy-efficient electrohydraulic fragmentation process was developed for delaminating PV modules, which enables the near-complete separation and recovery of the different components of PV modules. In this work, we have shown the compatibility of the EHF process with the crushing process, which is widely used in industry for several recycling applications. We have shown that the EHF process is capable of handling crushed modules, which makes it feasible to be integrated into existing waste handling systems with crushing units to enable handling EOL PV modules.

This work focuses on technology and the engineering development of the processes. In this work, no attempts have been made to assess the economic feasibility or scalability of the process, as the process is at a developmental stage. At this stage, the data collected is insufficient to assess any environmental impact. The authors are in the process of collecting more data from the experimental process to be able to perform a thorough environmental impact assessment, which shall be addressed in future work. Further, no attempts have been made to assess the relationship with the existing or future policies, as it is beyond the scope and expertise of the authors. In this work, the authors have attempted to present technical aspects of the recycling process, which has been developed in a laboratory environment. Both these processes are compared with the current state-of-the-art in terms of energy use and toxic/hazardous products created as a result of the process. Further, a succinct review of the state-of-the-art in the recovery of silver and silicon is also presented. Finally, the inferences are drawn, and the conclusion is presented.

2. Materials and Methods

2.1. Fabrication of Ferrosilicon using EOL PV panels and scrap steel.

FeSi was prepared using an induction furnace. In this work, FESi45 was prepared, which means that for 100gm of the FeSi45, Si is approximately 45% by mass while the remaining is iron (Fe). Discarded and damaged solar PV panels were collected from a commercial supplier. The solar PV panels were cleaned with water and dried. The aluminium frames and the external electrical connections of the panels were removed mechanically. The solar panels were crushed using a twin-blade mechanical crusher. The crushing was conducted in multiple passes to obtain the desired particle size of 1-3 mm. Between each pass of the crushing process, the glass, silicon, and polymer pieces that were successfully separated were removed manually. The process was repeated until enough silicon pieces were obtained. Two types of silicon pieces were obtained – those which were stuck to the polyethylene film used as the backsheet and those which were completely removed from the polyethylene layer. This was done by a simple sieving process using a sieve of 1 mm opening, as the polymer silicon pieces were all larger than 1 mm. Silicon powder obtained after the sieving process ranged from 0.1-0.8 mm.

The Scrap iron was collected from the discarded materials in the lab (such as stirrers, steel wires, etc). The pieces were washed in warm (≈50°C) soapy water to remove any traces of oil, debris, and organic and inorganic residues on the surface. The rust on the samples was removed using commercial rust-removing spray and scrubbing with a metal brush. The cleaned samples were washed again in warm soapy water to remove the chemicals and dried by placing them in an oven at 150 ℃ for 20 min. The cleaned and dried scrap steel was cut into smaller pieces (≈20-30mm) and prepared for melting. The total mass of the sample prepared was kept constant at 100g. For all samples, the amount of Fe taken was 55g, while the remaining 45g included either the silicon pieces or the powder obtained after the crushing process. The amount of iron required for preparing the sample was measured and placed in the alumina crucible. The alumina crucible was placed inside a larger graphite crucible. The crucibles were covered with an alumina lid with an opening in the centre through which a thermocouple could be inserted to record the temperature. Both crucibles were placed in a cylindrical induction furnace. After the iron melted, Si pieces/powder were added to the crucible. The contents were stirred (intermittently) with the help of a clean quartz tube to check for complete dissolution. After the complete dissolution of the Si in Fe, the furnace was turned off. The sample was left in the crucible, which was covered with the alumina lid, and the sample was allowed to cool down naturally to room temperature. After the sample and the crucible had cooled down, the alumina crucible was broken to retrieve the sample. The samples were cut and embedded in conductive carbon resin, and subsequently, metallographic cross-sections were prepared from the embedded samples by grinding using different grades of sandpaper and polishing with diamond suspension.

2.2. Delamination of crushed PV module pieces using the Electrohydraulic fragmentation (EHF) process.

For the work reported here, the pieces of modules obtained after crushing were sorted manually. The crushed pieces (with polymer and glass) with a size exceeding 5 mm were selected for processing using shock wave fragmentation for further separation into individual components. The pieces were placed in the process chamber of 5L volume. Deionized water was used as the fluid medium. The voltage input to the electrode was 50 kV while the processing duration was 240s. The EHF process exploits the differences in the mechanical properties of the materials in a PV panel. A high voltage pulse is applied to a fluid in an insulated container in which a solid is immersed. The arcing between the electrodes generates a shockwave which travels through the fluid and interacts with the solids. The interaction between the pressure wave front in the liquid and the solid causes fractures at the weak points between the interfaces of dissimilar materials, resulting in crushing and separation of the materials (Akimoto et al., 2018).

3. Results

The fractions obtained after manually sieving the material produced after EHF were analysed optically and with the naked eye. The largest fractions included polymers with or without Si particles sticking to them. Figure 1 shows the pieces of silicon sticking to the polymer backsheet, while Figure 2 shows the silicon powder particles as observed under an optical microscope. This initial separation was done by a simple manual sieving process. The material recovered after the EHF process usually consists of fine powder containing metals and silicon from the solar cells, along with glass powder. After the processing, the water was drained through the retaining filters, which removed the polymer pieces (> 5mm) as shown in Figure 3. Silicon and glass were obtained as coarse powder, as shown in Figure 4.

Figure 1: Pieces of silicon sticking to the polymer backsheet. (Taken using a DSLR camera) (Source: by authors)

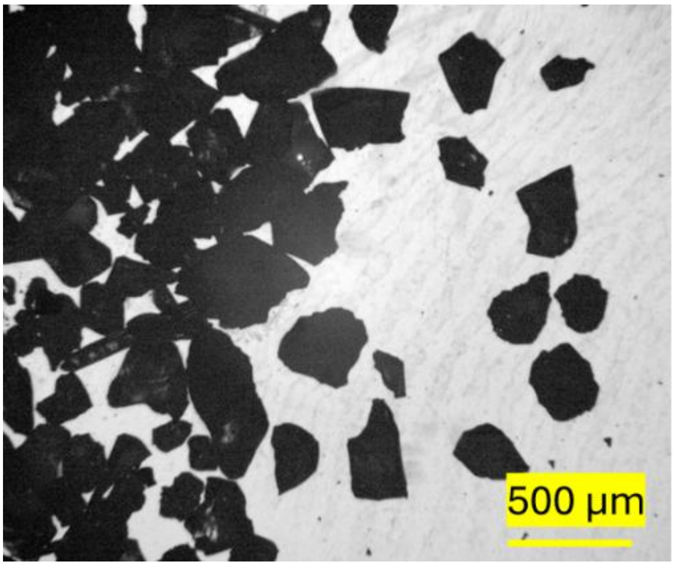

Figure 2: Pieces of silicon less than 1mm obtained after serving as observed under optical microscope(Source: by authors)

Figure 3: Pieces of polymers obtained after the EHF processing (> 5mm). (Taken using a DSLR camera) (Source: by authors)

Figure 4: Glass and silicon pieces obtained after the EHF processing (0.1-0.5mm). (Taken using a DSLR camera) (Source: by authors)

3.1. Characterization of the FeSi prepared using recycled silicon.

The metallographic FeSi prepared using the silicon recovered from the panels was observed with a scanning electron microscope (SEM). The composition of the distinct phases was analysed using energy dispersive spectroscopy (EDS) integrated with the SEM. FeSi prepared using the silicon pieces stuck with the polymer sheet are denoted as FeSi-pc, and those prepared with the Si powder are denoted as FeSi-po. Figure 5 shows the SEM image and the elemental maps obtained by EDS for the FeSi-pc samples. The polymer sheets used in PV modules are usually Polyethylene Terephthalate (PET) and Ethyl Vinyl Acetate (EVA), as mentioned earlier. Both are polymers involving C, H and O (Królikowski et al., 2024). Therefore, the combustion products generated due to their combustion would be carbon dioxide and water vapour. Some carbon is also expected to be incorporated in the samples. This could be observed in the elemental maps in Figure 5. The FeSi comprised a silicon-rich matrix with a composition of Si ranging between 42-45% (atomic) and a composition of Fe between 48-52% (atomic). The Fe-rich dendrites present in the matrix, on the other hand, had Fe in the range of 60-65% while Si varied between 30-33%. A comparison with the Fe-Si binary phase diagram and experimental phase analysis (Han et al., 2022; Kubaschewski & Okamoto, 1993) reveals the presence of FeSi (Si-rich) and Fe2Si (Fe-rich) phases. The composition of the two phases of FeSi determined by EDS closely corresponds to the stoichiometric composition of the phases expected to be present in FeSi45. The overall percentage of Al in the samples ranged from 2.5-3.5% (atomic). The aluminium is expected to come from the metal contacts on the silicon solar cells, as well as the interconnection wires used to connect the solar cells in a module (Zarmai et al., 2015).

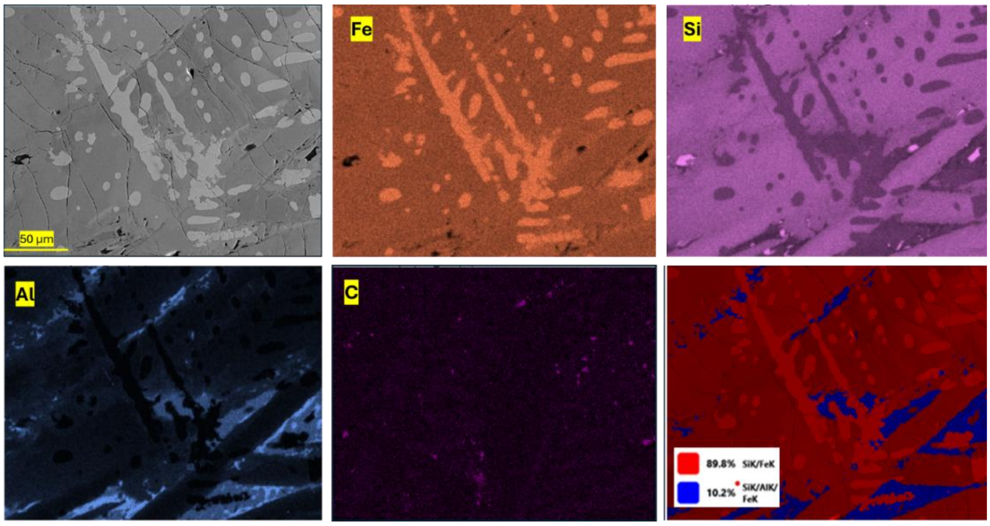

Figure 5: SEM image and the elemental composition map and phase map obtained by EDS for the FeSi-pc samples. Different elements identified by the EDS are labelled accordingly. (Source: by authors)

Figure 6 shows the SEM image and the elemental maps obtained by EDS for the FeSi-po samples. In this case, since the polymer pieces were absent, carbon could not be found (reliably) in the samples. However, in this case, Ag was present in the FeSi45 samples prepared. While crushing, most of the metal contacts on the solar cells, which are composed of Al and Ag, are expected to form fine particles under the mechanical stress. Hence, the percentage of metal fraction in the silicon powder obtained after the crushing process would be slightly higher than that found on the silicon fractions still stuck to the polymer pieces. The presence of Fe2Si dendrites in the FeSi matrix was clearly visible, as in the case of FeSi-pc samples. Additionally, Ag could be seen scattered in the microstructure. Since the solid solubility of Ag in Fe and Si is extremely low (Rollert et al., 1987; Wriedt et al., 1973), Ag is expected to precipitate during cooling and distribute throughout the microstructure. The percentage of Ag in the samples was found to range between 0.1%-0.3% (atomic). The percentage of Al in these samples was found to be between 5-7.5% atomic. Correspondingly, the overall percentage of Si was slightly lower in these samples than that in the FeSi-pc samples. The overall percentages in terms of mass for different constituents for both FeSi-pc and FeSi-po samples obtained from EDS measurements are shown in Table 1. The composition of the commercially purchased FeSi45 is also shown alongside for comparison. There was a loss of 1-3% wt. in the mass of the FeSi product as compared to the total mass of the raw materials used. This can be attributed to the loss due to natural oxidation, loss of volatile compounds and the mechanical loss while recovering the sample (some part of the sample sticking to the crucible). Table 1 shows that Al in the FeSi prepared with pieces is similar to that present in the commercial FeSi. The overall impurity content in the FeSi produced using recycled Si is less than that present in the commercial FeSi. This further supports the suitability of using recycled Si for producing FeSi.

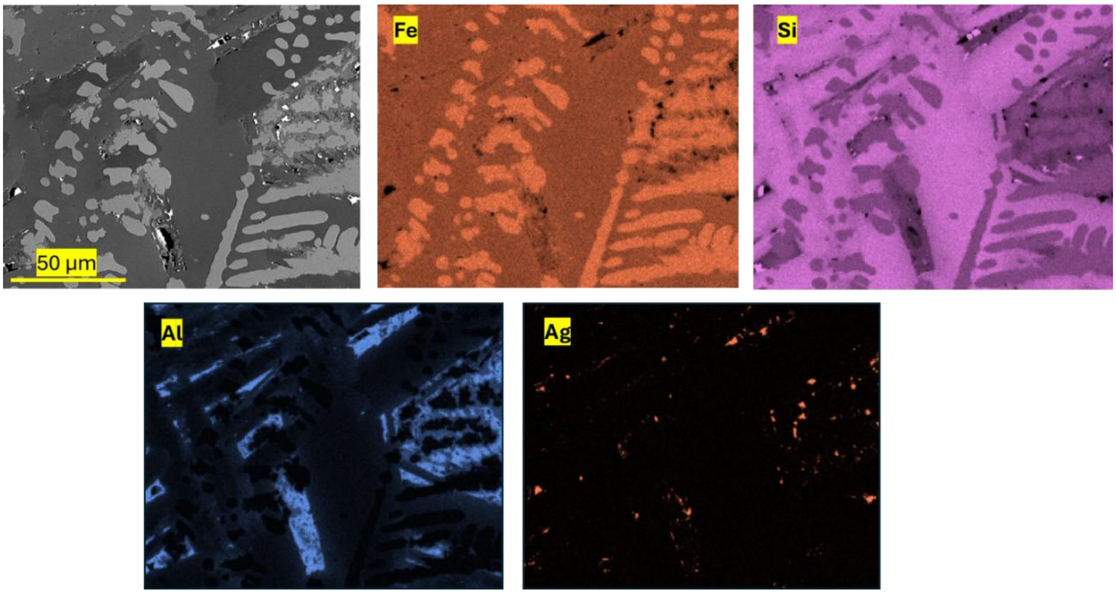

Figure 6: SEM image and the elemental composition map and phase map obtained by EDS for the FeSi-po samples. Different elements identified by the EDS are labelled accordingly. (Source: by authors)

Table 1: Average wt. % of the main components identified using SEM-EDS in the FeSi samples prepared using the Si obtained from recycled PV panels. Composition of the commercial FeSi45 purchased from the market is also given for reference

	FeSi-pc (wt.%)	FeSi-po (wt.%)	FeSi45-commercial
Fe	54.1±1.8	53.9±1.8	52.7±3.8
Si	42.1±2.1	42.3±2.8	41.5±5.2
C	2.1±1.6	-	1.4±0.4
Ag	-	0.11±0.02	-
Al	1.5±1.1	3.1±0.6	1.5 ±2.1

other	0.5±1.2	0.5±0.1	3.5±1.7

3.2. Characterization of the components received after EHF treatment of the c-Si PV panels.

After the EHF treatment, while most of the glass and silicon were separated from the polymer pieces, the polymer pieces were not completely clean. However, it is known that the degree of separation of the glass and silicon is also dependent on the various process parameters, such as process duration, feed volume, pulse power, among others (Akimoto et al., 2018; Song et al., 2020; Zhao et al., 2020). Further optimization of the process parameters could lead to a higher degree of separation and subsequent recovery of the silicon, polymer, and glass. Figure 7 shows the crushed pieces before and after undergoing the EHF treatment.

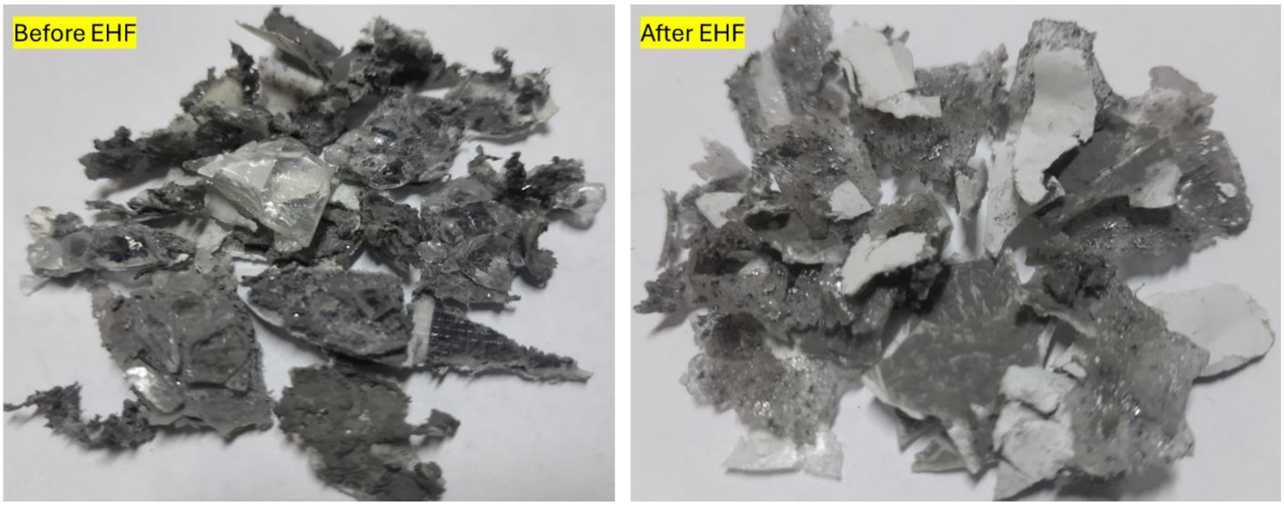

Figure 7: Polymer pieces recovered after crushing the PV panels and treating the recovered polymer pieces using EHF process. (Taken using a DSLR camera) (Source: by authors)

The powder obtained after the treatment is mostly comprised of glass with a small amount of Si and metal particles. The separation of silicon and glass from the polymer pieces can be explained by the operating principle of the EHF process. The process is based on the difference in the mechanical properties of the materials when subjected to mechanical stress. Since glass is amorphous and brittle, it is easily broken into tiny pieces and separated from the underlying polymer layer. Further, the glass is the thickest layer in the sandwich. The glass thickness is usually between 3 – 5mm. In comparison, both polymers and the Si wafers used for making the solar cells are just a few hundred microns thick. Hence, the impact of the mechanical force is greatest on the glass, and it is easily separated from the underlying polymer sheet. Further, it was seen that the last layer of silicon particles sticking to the polymer layers was not a continuous layer of Si, but rather tiny particles of size less than 100µm. In this form, the particles are discontinuous and less constrained. Therefore, the impact of the pulse on them is further minimized, as they can move with the polymer layer as it deforms under the impulse. Nevertheless, as mentioned earlier, optimization of the process parameters could further help in the higher recovery of the particles after the EHF treatment. Hence, with this treatment, it is possible to retrieve the polymer layers in whole, while recovering silicon (along with the Ag and Al) powder and glass particles. In several test runs conducted, more than 99% of the material was recovered. Since the process uses only water as the medium and the process occurs at room temperature, no toxic gases or effluents are produced. Since water is used as a non-consumable medium, the additional water consumption is also almost negligible. Hence, using the EHF process provides an alternative pathway for recovering all the components of EOL c-Si PV panels. Figures 8 and 9 show the SEM images of the coarse and the fine powders obtained after the EHF processing of the EOL modules.

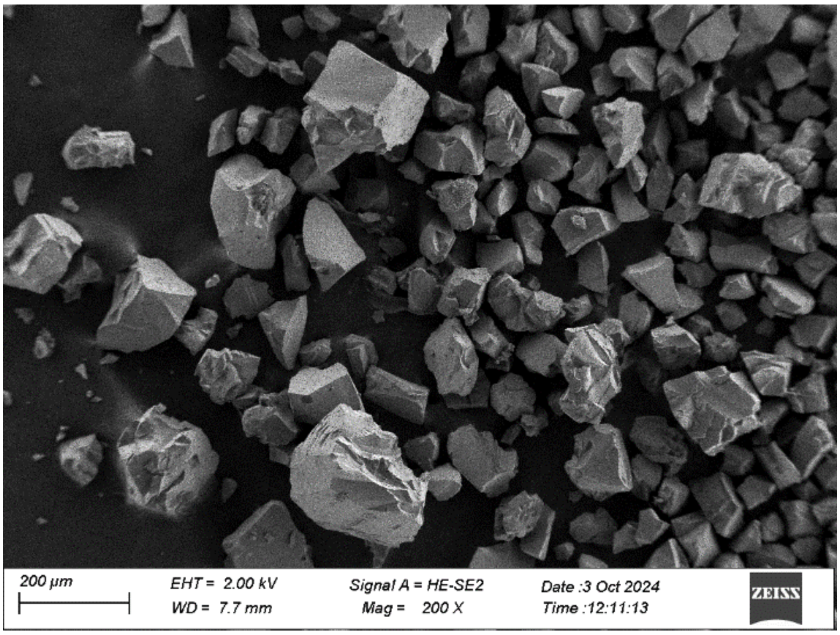

Figure 8: SEM image (magnification – 200X) of the coarse glass powder obtained after the EHF processing of crushed EOL PV modules (Source: by authors)

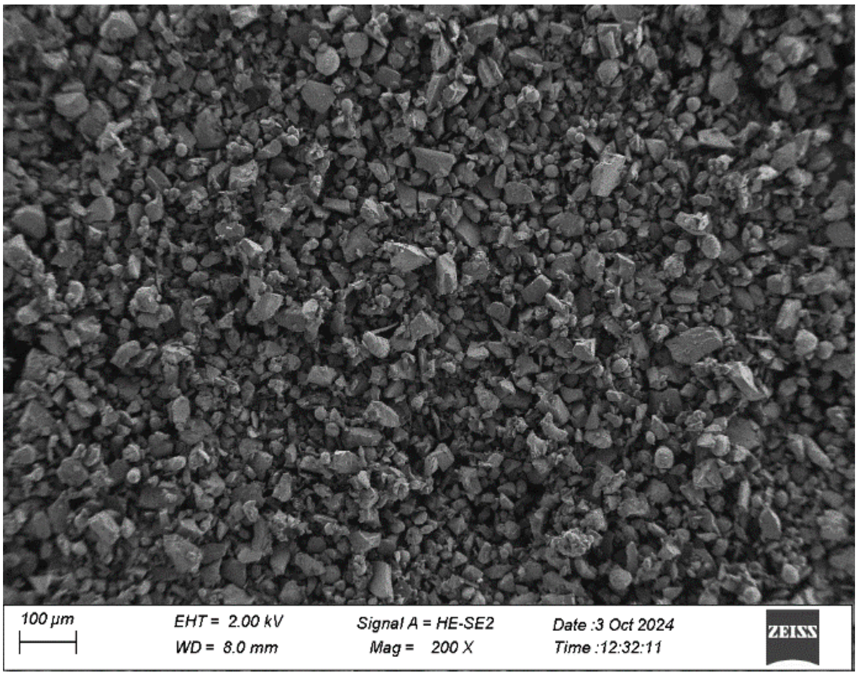

Figure 9: SEM image (magnification – 200X) of the fine silicon and metal powder obtained after the EHF processing of crushed EOL PV modules (Source: by authors)

4. Discussion

In this work, it was shown that it is possible to recover the silicon and metal as a powder using a combination of mechanical crushing and EHF processing. The metal powder comprises Ag and Al. The total percentage of Ag in the material recovered from the EOL c-Si PV panels is less than 0.1% of the entire weight of the panel; nevertheless, it accounts for more than 40% of the value of the materials recovered (Padhamnath, Nalluri, et al., 2025). Ag and Si are the most valuable materials recovered from the EOL c-Si PV panels. Further, recovering and recycling Si, either as ferrosilicon (Blaesing et al., 2024; Farzana et al., 2016) or for making c-Si for the production of new solar cells (Derbouz Draoua et al., 2017) is beneficial as this prevents the CO_2 emissions linked to the production of new silicon from quartz (Blaesing et al., 2024; Tao et al., 2020). Although separation and extraction of Ag and Si were not attempted in this work, a succinct discussion on the processes involved based on the available literature is presented.

4.1. Extraction of Silver

Electrical current is extracted from silicon solar cells using grid-patterned contacts printed on the solar cells. These metal contacts are typically made of silver paste, along with small quantities of some other proprietary metals. The quantity of silver in the panel is almost negligible in terms of weight (~0.05%); however, the silver accounts for ≈47% of the value of the recoverable materials (IEA-PVPS Report Number: T12-06:2016, 2016; Chen et al., 2024). Due to the recent technological advances, PV production is gradually shifting from Passivated Emitter and Rear Cell (PERC) to newer technologies like Tunnel Oxide Passivated Contact (TOPCon) and Heterojunction Technology (HJT). These technologies use more silver in each solar cell, with TOPCon and HJT utilising at least 1.3 times and 1.6 times more silver than PERC, respectively. The World Silver Survey 2023 by The Silver Institute projects the silver consumption in PV panels to increase by 4%, while production is forecasted to increase by only 2%. If the trends remain steady, the PV industry could use up to 98% of the global silver reserves in 2050 (World Silver Survey 2023, n.d.). Therefore, effective recovery of silver from EOL PV modules is crucial to the economic sustainability of the entire recycling process. Recovered silver could also help to offset the production costs of new panels, as well as meet the growing demand for silver. The initial efforts in PV recycling focused on high-volume recovery of glass, aluminium, and metallurgical grade silicon, as these made up over 80% of module mass, were simpler to separate, and the process was cost-effective. Furthermore, recovery of intact solar cells for reuse in module production was prioritised, as the price of PV panels was driven by the cost of silicon wafers (PVPS Task et al., 2018). Consequently, silver was discarded while recovering silicon by etching the solar cells in sodium hydroxide, as the process was not economically viable, despite the high value of silver.

In the early 2000s, the first attempts were made to recover the silver using hydrometallurgical processes. Nitric acid was used to leach silver from the recovered solar cells. Electrolysis and metal replacement techniques were later employed to recover silver from the precipitated salts from the nitric acid (Deng et al., 2022). The process was 98% efficient in recovering silver from the solar cells. Other methods have been developed in recent years with similar or improved process efficiencies. A 98% recovery rate has also been achieved using a combined hydrometallurgical and electrochemical approach. In this process, silver is leached and then subjected to electrodeposition-redox replacement (EDRR) reaction to recover pure silver. This process minimizes chemical use, thus offering high efficiency and reduced environmental damage (Russo et al., 2024). In the newly developed laser debonding process, silver electrodes are removed using a laser. This method is unique in its ability to selectively recover silver while minimizing the damage to the silicon wafers. Using lasers results in the generation of silver nanoparticles, which can be readily supplied to various industries. Machine learning techniques have been used to optimize laser processing and increase automation for industrial applications, reducing both cost and energy consumption (Khetri & Gupta, 2024). Improving the process efficiency while simultaneously reducing the environmental footprint of the recycling processes is the requirement of a successful and industrially scalable process (Gajare et al., 2025; Qi et al., 2025; Zheng et al., 2025). Iron and aluminium chloride in brine solutions have been used to recover up to 95% of silver in under 10 minutes. This process offers the advantages of low cost, low toxicity, and scalability compared to conventional acid-based recovery techniques (Zante et al., 2022). Ag from the PV panels has also been recovered using biological methods (Pang et al., 2025).

While recent advances have made the extraction of silver more efficient and environmentally friendly, challenges still persist. Low concentration of silver in the solar cells is one of the crucial factors which determines the economic feasibility of the process. The process of extracting silver from the panels could be expensive due to the complex chemical processes or specialized equipment. As mentioned earlier, the metal contacts often include other metals, such as cadmium, lead and copper alongside silver. Since these metals have similar chemical properties, the leaching and separation process becomes complicated (Rout et al., 2025; Russo et al., 2024). One of the biggest technological challenges is recovering silver selectively without affecting silicon and other valuable materials or contaminants. To achieve this goal, the traditional hydrometallurgical techniques need to improve, while simultaneously novel and sustainable methods such as laser debonding, directional solidification and electrochemical recovery need to be developed further (Li et al., 2025; Yue et al., 2025). Additionally, the economic viability of the recovery process remains a challenge for scaling up the technology, which is being exacerbated due to the decreasing silver content in modules.

4.2. Recovery of Silicon from EOL PV panels

Silicon recovered from end-of-life Si PV panels has been used to manufacture new silicon solar cells. Crushing of the panels and separating the constituents can yield metallurgical grade Silicon (Komoto et al., 2018; Latunussa et al., 2016a; Tao et al., 2020), which is valued around $2-3/kg depending on the region (IMARC, 2024). The higher cost of solar-grade silicon, which is valued between $6-9/kg (Bellini, 2024), could provide motivation for its production from EOL PV panels. Successful demonstrations of closed-loop recycling of Si have been done (Tao et al., 2020). Recycled silicon from broken solar cells and wafer production has been used to fabricate ingots and subsequently solar cells (Derbouz Draoua et al., 2017). The solar cells made from recycled Si achieved an efficiency of 18.1% while those made from virgin Si exhibited efficiencies of 18.5%. Solar cells were prepared from recycled Si with efficiencies exceeding 20%. For this purpose, the Si was obtained after chemical etching (Palitzsch et al., 2020). Researchers have demonstrated the effectiveness of the etching process in removing metal contamination from silicon (Huang et al., 2017a; Park et al., 2016; Park & Park, 2014). Among the earliest attempt of recovering silicon, researchers used thermal delamination and chemical etching using a combination of HCl, HF and NaOH to recover 62% of the Si of 8N quality from the EOL PV panels (Wang et al., 2012). Using a slightly different chemicals, such as Hydrofluoric Acid (HF), Nitric Acid (HNO3), Sulfuric Acid (H2SO4), phosphoric acid (H3PO4) and acetic acid (CH3COOH), researchers recovered 79-86% of 5N silicon, using chemical delamination process to remove the glass and the polymers (Kang et al., 2012). Mini-modules were fabricated, and the glass and the EVA layers were removed using thermal delamination (Park et al., 2016). HNO3 and potassium hydroxide (KOH) were used to recover 90% of the silicon. The solar cells prepared from these reclaimed wafers achieved ≈90% of the initial efficiency (Park et al., 2016). HNO3, H3PO4 and KOH have also been used to remove metal and recover 80-90% of the silicon (Eshraghi et al., 2020; Huang et al., 2017b; Jung et al., 2016; Latunussa et al., 2016b; Latunussa et al., 2016a). Solar cells that have not been incorporated in a panel could also be effectively recycled to retrieve ≈ 99% of the silicon (Yousef et al., 2019). Centrifugal separation, microfiltration, and ultrasonic treatment have been used to separate and purify the recycled Si. While recycling Si from EOL modules is a complicated process, there is underlying interest in the research community, as it has been established that silicon recovered from EOL PV panels could be reused for fabricating new solar cells(Lee et al., 2024; Ramírez-Cantero et al., 2025; Sah et al., 2023; Tembo & Subramanian, 2023).

4.3. Effect of impurities in the recovered material

Al is among the most common impurities in the FeSi alloys. Commercially produced ferrosilicon usually contains between 0.5-2% of Al as an impurity (Tangstad, 2013; Tomé-Torquemada et al., 2017). However, since Al is used as an electrical contact in most electronic devices, due to its excellent electrical conductivity, less weight, and not easily diffusing into Silicon below 300 °C (Kim et al., 2016; Krause et al., 2002; McCaldin & Sankur, 1971). While this work shows the feasibility of preparing FeSi from the recycled Si, the impact of the impurities in the FeSi on the downstream applications needs to be assessed (Tomé-Torquemada et al., 2017; Wijk & Brabie, 1996). Presence of Al in FeSi is not considered to be an issue, as there is a market for FeSiAl specifically in casting and metallurgical industries (Arunkumar et al., 2025; Jochymczyk et al., 2025; Zhang et al., 2023). The impact of Ag in the downstream applications needs to be understood in order to assess the viability of using FeSi prepared from recycled Si. Nevertheless, the percentage of Ag in FeSi is ≈ 0.1% wt., and with any further downstream use, its concentration would get even further diluted, and hence, Ag may not pose a grave concern for such applications. For example, such recycled ferrosilicon could be used for the oxidation of steels, and the mechanical properties of such steels could be analysed to assess the impact of the impurities in the FeSi on the properties of the final product. However, assessing the impact of the final product is out of the scope of this work and will be considered in future work.

Similarly, the products obtained after the EHF recycling are found to have cross-contamination. For example, some pieces of Si were found in the glass pieces and vice versa. Some silicon and glass were also found sticking to the polymer surface. However, all these impurities and cross-contamination can be removed using different chemical processes (Ramírez-Cantero et al., 2025). Pieces of polymer and Si can remain attached to the glass pieces after EHF processing. A combination of organic chemical and water treatment can remove the polymer particles easily. Si content in the glass cullet is estimated to be less than 0.001% wt. Silicon removal can be done using chemicals that selectively etch Si without affecting glass, such as sodium hypochlorite (NaOCl) or potassium hydroxide (KOH) (Basu et al., 2013; Divan et al., 1999; Wind et al., 2002). The composition of the fine powder would dictate the design of the separation process. For the samples prepared in this work, the Si content was higher than that of the glass. The glass was dissolved in HF to retrieve Si (Padhamnath, Nalluri, et al., 2025). HF also helps in removing the ARC coating on the solar cells (Brunet et al., 2017; Jeon et al., 2006; Knotter & Denteneer, 2001). Finally, the fine powder fraction comprising Si, Ag, Al and some amount of glass is highly valuable, especially due to the presence of Ag from solar cells. The Ag in the mixture can be recovered by treating it with HNO3, which will dissolve the silver. The dissolved Ag can be recovered from the acid solution by treating it with other chemicals or using electrolysis (de Oliveira et al., 2020; Dias et al., 2016b; Li et al., 2024; Yiwei et al., 2007). The glass and Si left behind can be separated by dissolving the glass in HF.

EHF recycling could enable the recycling of the polymer used in the PV panels, which helps towards achieving 1000% recycling. By a careful optimization of the process parameters, the amount of Si sticking to the surface could be minimized. Further chemical treatment (with KOH and HNO3) can clean the polymer pieces of any remaining silicon and metal particles. Several specialized processes have been developed for recycling such polymers (Królikowski et al., 2024; Sinha et al., 2010).

4.4. Comparison with existing PV recycling technologies

Recycling of EOL PV panels is still in its infancy and is generating huge interest among researchers and technologists alike. For example, in open-ended recycling of PV panels, the panels are crushed, and the glass recovered is used to manufacture fibreglass(Duflou et al., 2018; Feih et al., 2011; Scelsi et al., 2011), construction of pavements (Emersleben & Meyer, 2012) or for fabricating other construction components (Mohajerani et al., 2017; Ogundairo et al., 2019; Robert et al., 2021). However, these are low-end uses of the valuable material in PV panels and do not justify the economics for large-scale implementation. Recently, researchers tried to use the EOL PV panels along with red mud (waste from the aluminium industry) to produce ferrosilicon (Blaesing et al., 2024). They devised a reduction process using coal and argued that the greenhouse gas emissions from the production of Si were mitigated. However, this was an experimental process, and such endeavours have not seen large-scale commercial applications. FeSi, using the method proposed in this work, can be produced without requiring any complicated process or equipment, and without the release of greenhouse gases. Hence, open-ended recycling of PV panels to produce commercially important products would help in the commercial feasibility of the process and enable large-scale adoption of the technology.

Disassembly, delamination, material sorting and material extraction are the four process steps common to all recycling processes designed to extract valuable materials from the end-of-life PV panels. Each of these steps could further comprise single or multiple process steps (Deng et al., 2022; Divya et al., 2023). Recycling the external wiring (copper) and the aluminium frames is the easiest (Einhaus et al., 2018). In some instances, commercial recycling of PV panels has been reported to include only these steps, while the remaining portions are discarded (Deng et al., 2022). The most valuable recyclable component in a PV panel is undoubtedly Ag, followed by Silicon. They are usually recovered by etching them in chemicals and later precipitating the metal out of the chemicals (de Oliveira et al., 2020; Dias et al., 2016a; Tembo & Subramanian, 2023). The amount of polymer used in a PV panel depends on its design. These polymers could include Ethylene-vinyl acetate (EVA), Polyethylene terephthalate (PET) and polyvinylidene difluoride (PVDF). However, owing to the complex and hazardous recovery process and negligible commercial value, these polymers are almost never recycled (Achilias & Karayannidis, 2004; Deng et al., 2022; Divya et al., 2023; Sinha et al., 2010).

As mentioned earlier, delamination of the PV panels is among the most crucial steps in recycling EOL PV modules. Delamination is usually achieved by chemical, mechanical, thermal processes, or a combination of processes such as thermos-mechanical or thermo-chemical. In thermal delamination, the PV panels are heated to ≈550°C to decompose the cross-linked polymers in the PV panels, such as Ethyl Vinyl Acetate (EVA), polyethylene terephthalate (PET) or Polyvinylidene fluoride (PVDF) (Dobra et al., 2022). The polymer decomposition allows for the easy separation and subsequent recovery of the glass, the interconnecting metallic ribbons and the solar cells (Fiandra et al, 2019b; Fiandra et al., 2019a; J. Lee et al., 2018; Park & Park, 2014). However, the heating process is energy-intensive. Polymer decomposition is often associated with the generation of toxic gases. Scrubbing and treatment of the flue gases make the process expensive to implement (Deng et al., 2021; Lunardi et al., 2018; Tammaro et al., 2015, 2016). In chemical delamination, the modules (crushed or whole) are immersed in inorganic or organic chemicals, with or without heating and mechanical stirring. The chemicals weaken the cross-linked polymers, separating the modules and their components. The chemicals used in such processes are extremely hazardous and require long processing times, sometimes extending more than 10 days (Deng et al., 2022; Divya et al., 2023; Lunardi et al., 2018). Researchers have combined chemical treatment with microwaves (Pang et al., 2021), ultrasonic waves (Kim & Lee, 2012) or supercritical carbon dioxide (Lovato et al., 2021) to shorten the process durations. In all these cases, it was difficult to achieve complete separation of EVA and PET/PVDF. Some researchers employed a second process step (pyrolysis or glycolysis) Xu et al., 2021. Furthermore, disposal of such large quantities of organic chemicals could be environmentally challenging. Mechanical fragmentation techniques are the most widely reported and used approach for delamination (Komoto et al., 2018; Libby et al., 2018). Mechanical approaches such as shredding, crushing, milling and grinding have been used for the fragmentation of PV panels (Dias et al., 2018; Pagnanelli et al., 2016). After these processes, some physical separation methods are employed which can separate the glass, polymers and the silicon combined with metals (Azeumo et al., 2019; Klejnowska et al., 2024; Libby et al., 2018; Martínez et al., 2024). However, such processes result in the separation of glass, which is the main product obtained in such processes. The polymer is often pyrolyzed or burned to generate heat. Mechanical recycling of PV modules using crushing and shredding is the most widely used technology to handle PV waste due to the low cost. However, such processes create a lot of dust and noise and need active dust and noise suppression systems.

The electrohydraulic delamination process provides flexible processing of the end-of-life c-Si PV panels. Different types of PV panels (Glass-glass, glass-backsheet, Glass-free) can be delaminated with the EHF process. The EHF process can be used if the panels are cut or crushed. However, to maintain uniformity in the process, different panel types should not be mixed in one feed. Through process optimization high high-throughput and high-quality materials could be obtained. The capability of the EHF process in enabling complete recyclability of EOL PV panels and recovery of high-quality materials, including polymers, was demonstrated in this work. The materials could easily be separated employing a simple mechanical sieving process. However, the process has immense capabilities, and we have just scratched the surface. Ongoing and future research would aim at optimizing the process to improve the quality of the output materials. Efforts are underway to develop a multistage processing sequence, including automatic and continuous separation of the materials. Investigations into implementing density-based separation of materials, recovering and purification of high-quality silicon and metals (especially Ag) would further increase the effectiveness and efficiency of the EHF process.

4.5. Advantages and limitations of the proposed process

The EHF process effectively delaminates the EOL PV modules, providing an alternative to the thermal or chemical delamination processes. The HDF process delaminates c-Si PV panels easily and quickly, without the generation of toxic or hazardous by-products. It also allows for the complete recovery and recycling of different components of the EOL PV panel. These benefits align with the current standards of the EU WEEE directive (Deng et al., 2021; European Standardization Organisation CENELEC, 2012; Padoan et al., 2019; Sica et al., 2018). The process can be adapted to process different types of PV modules undergoing varied pretreatment processes (crushing, cutting). The only working medium required is non-potable water which is not consumed in the process and can be recycled easily. It needs only electricity to operate, which can be generated by renewable resources. It does not lead to the emission of any hazardous or toxic by-products. This points towards the easy scalability of the technology for commercial applications. A concept of the industrial machine using EHF applications could involve a dryer and sieve-based separators after the EHF process steps, allowing for automation and easy control of the process. However, some cross-contamination of the materials obtained after processing could not be ruled out, and probable steps for remediation have been discussed earlier. A simple mechanical filtration of the processed material leads to the distinct fractions. The large glass pieces can be separated from the finer particles and can be immediately sent for cleaning and recycling. The coarse fraction may contain glass + silicon (from solar cells), and further processing could be decided based on the target material and the composition of the fraction. Similarly, the fraction containing fine powder mostly comprises Si and metal, but can also contain a varying amount of fine glass powder. Density-based medium separation could be used to separate the materials with dissimilar densities (Akimoto et al., 2018) . Ongoing and future efforts would optimize the process parameters to minimize cross-contamination and continuous material separation and recovery using an automated sieving process. Improving the metals recovery yield, purification of Si and metals, and estimating the environmental impact of the process have also been left for future work.

The production of FeSi using recycled Si is an effective way to obtain valuable FeSi product from the waste and discarded PV modules. This is a novel process which does not involve any reducing agents to produce FeSi. It utilizes Si from the EOL PV panels and clean scrap iron to produce FeSi using a simple induction furnace. This eliminates the use of any reducing agents. Further, since this can be produced in an induction furnace, the only energy input required is in terms of electricity, which can be generated using renewable energy sources. No further sources of heating are necessary. This aligns with the sustainable development goal of Responsible consumption and production (Department of Economic and Social Affairs & United Nations, 2015). Since induction furnaces are already used for recycling metal wastes (especially steel), the FeSi production using recycled steel and EOL PV panels can easily be scaled up for commercial applications. Further, it was found that the FeSi produced from recycled Si has overall lower impurities than those present in the commercial FeSi. The recycled Si obtained from EOL panels contain Al (1-3% wt.), which is an advantage, and FeSiAl is a valuable material used in the metallurgy industry. Al is among the most common impurities in the FeSi alloys. Commercially produced ferrosilicon usually contains between 0.5-2% of Al as impurity, which supports the deoxidation and alloying properties (Tangstad, 2013; Tomé-Torquemada et al., 2017). Further, researchers have tried to produce FeSi using Al-rich clay(Amanov et al., 2017; Shevko et al., 2016). Using this process, FeSiAl could be produced easily without any additional source of Al. There could be some additional impurities associated with Si recovered from EOL PV panels; however, these impurities are in extremely small quantities (<0.1% wt.) and hence are not expected to impact the quality of the final product achieved.

5. Conclusions

In this work, we have shown experimental results for pathways for effective management of end-of-life c-Si PV modules, enabling circularity and resource efficiency. We have proposed pathways for both open-loop and closed-loop recycling options. The silicon-metal powder, with or without the polymer layer, recovered after crushing the panels, can be used in the production of ferrosilicon. This process will directly reduce the amount of CO_2 evolved in the production of FeSi through carbonaceous reduction methods. We presented the newly developed EHF process for delaminating EOL PV modules. The EHF process enables more than 99% material recovery, both by weight and by value. The yield can be further improved by process optimization. The Si and Ag recovered after the EHF process can be separated and extracted to be reused in the manufacturing of new solar cells and PV modules. However, the separation and recovery of Ag and Si is a chemically intensive process, and careful process selection is required to minimize the energy and resource utilization. The EHF process is an environment-friendly process which can delaminate EOL PV modules without generating any hazardous gases or toxic effluents. In this work, the EHF process was optimized to perform efficiently at lower voltages (50 KV) and shorter process durations than reported earlier, which results in lower energy consumption. This further helps in reducing the carbon footprint of the recycling process. Future work shall focus on the separation and purification processes of metals, Si and polymers obtained from EOL PV modules using the EHF process. Similarly, we produced FeSi using recycled Fe and Si, without using any carbonaceous material for reduction. This eliminated the emissions of any greenhouse gases during the process. While other alloying elements, such as Cu and Sn, can form multicomponent alloys with Al and Si (Padhamnath, Kuśmierczyk, et al., 2025) at higher concentrations, their impact at concentrations less than 1% needs to be investigated thoroughly. Understanding such impact of a small number of impurities on downstream applications of FeSi is left for future studies. Furthermore, future research work should focus on using the recycled FeSi as the source of Si in iron alloys and comparing their characteristics with those prepared from commercial-grade FeSi. Future work should focus on evaluating the economic feasibility, environmental impact assessment and life cycle assessment of these processes to identify the appropriate scenarios where such solutions may be applied most effectively.

Acknowledgments

The abstract of this paper was presented at the Sustainable Economy and Ecotechnology (SEE) Conference which was held on the 27th - 28th of November 2024.

The authors would like to acknowledge the support of colleagues at AGH University of Krakow, Solar Energy Research Institute of Singapore, National University of Singapore and Singapore Polytechnic.

Funding declaration:

This research is a part of the project No. 2022/45/P/ST5/02712, executed at AGH University of Krakow, co-funded by the National Science Centre, Poland and the European Union Framework Programme for Research and Innovation Horizon 2020 under the Marie Skłodowska-Curie grant agreement No. 945339. For the purpose of Open Access, the author has applied a CC-BY public copyright licence to any Author Accepted Manuscript (AAM) version arising from this submission.

A part of this research is also supported by the Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS). SERIS is supported by the National University of Singapore (NUS), the National Research Foundation (NRF), the Energy Market Authority of Singapore (EMA) and the Singapore Economic Development Board (EDB). The work was also supported by the National Research Foundation, Singapore, the Ministry of National Development and the National Environment Agency, under the Urban Solutions and Sustainability Integration Fund (USS-IF-2019-5).

Ethics approval:

Not applicable

Conflict of interest:

The author(s) declare that there is no competing interest.

References

Achilias, D. S., & Karayannidis, G. P. (2004). The chemical recycling of PET in the framework of sustainable development. Water, Air and Soil Pollution: Focus, 4, 385–396. https://doi.org/10.1023/B:WAFO.0000044812.47185.0f

Akimoto, Y., Iizuka, A., & Shibata, E. (2018). High-voltage pulse crushing and physical separation of polycrystalline silicon photovoltaic panels. *Minerals Engineering*, *125*, 1–9. https://doi.org/10.1016/j.mineng.2018.05.015

Ali, A., Islam, M. T., Rehman, S., Qadir, S. A., Shahid, M., Khan, M. W., Zahir, M. H., Islam, A., & Khalid, M. (2024). Solar Photovoltaic Module End-of-Life Waste Management Regulations: International Practices and Implications for the Kingdom of Saudi Arabia. *Sustainability*, *16*(16), 7215.

Ali, A., Malik, S. A., Shafiullah, M., Malik, M. Z., & Zahir, M. H. (2023). Policies and regulations for solar photovoltaic end-of-life waste management: Insights from China and the USA. *Chemosphere*, *340*, 139840.

Amanov, D., Shevko, V., Karatayeva, G., & Serzhanov, G. (2017). Thermodynamic analysis of obtaining ferroalloy from silicon-aluminum-containing silica clay. *Chemistry & Chemical Technology, 4 (11), 2017*, *11*(4), 410–414.

Arunkumar, D. T., Basavakumar, K. G., Sathees Kumar, S., Pattanaik, A., & Pati, P. R. (2025). Enhancement of aluminium-silicon hypereutectic cast alloys properties by forging with refiner and modifier. *Interactions*, *246*(1), 1–9.

Azeumo, M. F., Germana, C., Ippolito, N. M., Franco, M., Luigi, P., & Settimio, S. (2019). Photovoltaic module recycling, a physical and a chemical recovery process. *Solar Energy Materials and Solar Cells*, *193*, 314–319. https://doi.org/https://doi.org/10.1016/j.solmat.2019.01.035

Basu, P. K., Sarangi, D., & Boreland, M. B. (2013). Single-component damage-etch process for improved texturization of monocrystalline silicon wafer solar cells. *IEEE Journal of Photovoltaics*, *3*(4), 1222–1228.

Blaesing, L., Walnsch, A., Hippmann, S., Modrzynski, C., Weidlich, C., Pavón, S., & Bertau, M. (2024). Ferrosilicon Production from Silicon Wafer Breakage and Red Mud. *ACS Sustainable Resource Management*, *1*(3), 404–416. https://doi.org/10.1021/acssusresmgt.3c00035

Brunet, M., Aureau, D., Chantraine, P., Guillemot, F., Etcheberry, A., Gouget-Laemmel, A. C., & Ozanam, F. (2017). Etching and chemical control of the silicon nitride surface. *ACS Applied Materials & Interfaces*, *9*(3), 3075–3084.

Chen, P. H., Chen, W. S., Lee, C. H., & Wu, J. Y. (2024). Comprehensive Review of Crystalline Silicon Solar Panel Recycling: From Historical Context to Advanced Techniques. In *Sustainability (Switzerland)* (Vol. 16, Issue 1). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/su16010060

Cucchiella, F., & Rosa, P. (2015). End-of-Life of used photovoltaic modules: A financial analysis. *Renewable and Sustainable Energy Reviews*, *47*, 552–561. https://doi.org/https://doi.org/10.1016/j.rser.2015.03.076

Curtis, T. L., Buchanan, H., Heath, G., Smith, L., & Shaw, S. (2021). *Solar photovoltaic module recycling: a survey of US policies and initiatives*. National Renewable Energy Lab.(NREL), Golden, CO (United States).

de Oliveira, L. S. S., Lima, M., Yamane, L. H., & Siman, R. R. (2020). Silver recovery from end-of-life photovoltaic panels. *Detritus*, *10*, 62–74. https://doi.org/10.31025/2611-4135/2020.13939

Deng, R., Chang, N., Lunardi, M. M., Dias, P., Bilbao, J., Ji, J., & Chong, C. M. (2021). Remanufacturing end-of-life silicon photovoltaics: Feasibility and viability analysis. *Progress in Photovoltaics: Research and Applications*, *29*(7), 760–774. https://doi.org/10.1002/pip.3376

Deng, R., Zhuo, Y., & Shen, Y. (2022). Recent progress in silicon photovoltaic module recycling processes. *Resources, Conservation and Recycling*, *187*, 106612. https://doi.org/10.1016/j.resconrec.2022.106612

Department of Economic and Social Affairs, & United Nations. (2015). *Sustainable Development Goals*. https://sdgs.un.org/goals

Derbouz Draoua, A., Martel, B., Dubois, S., Audoin, C., Sérasset, M., Fauveau, A., Radhakrishnan, H. S., Denafas, J., Petreniene, L., & Severino, N. (2017). On the Fabrication of Solar Cells Based on Newly Produced Recycled Silicon Feedstocks From CABRISS-A Comparative Study Between Material Properties and Solar Cell Performances. *EU PVSEC 2017-33rd European Photovoltaic Solar Energy Conference and Exhibition*, 483–487. https://doi.org/10.4229/EUPVSEC20172017-2AV.1.3

Dias, P., Javimczik, S., Benevit, M., Veit, H., & Bernardes, A. M. (2016a). Recycling WEEE: Extraction and concentration of silver from waste crystalline silicon photovoltaic modules. *Waste Management*, *57*, 220–225.

Dias, P., Javimczik, S., Benevit, M., Veit, H., & Bernardes, A. M. (2016b). Recycling WEEE: Extraction and concentration of silver from waste crystalline silicon photovoltaic modules. *Waste Management*, *57*, 220–225.

Dias, P., Schmidt, L., Gomes, L. B., Bettanin, A., Veit, H., & Bernardes, A. M. (2018). Recycling waste crystalline silicon photovoltaic modules by electrostatic separation. *Journal of Sustainable Metallurgy*, *4*, 176–186. https://doi.org/10.1007/s40831-018-0173-5

Divan, R., Moldovan, N., & Camon, H. (1999). Roughning and smoothing dynamics during KOH silicon etching. *Sensors and Actuators A: Physical*, *74*(1–3), 18–23.

Divya, A., Adish, T., Kaustubh, P., & Zade, P. S. (2023). Review on recycling of solar modules/panels. *Solar Energy Materials and Solar Cells*, *253*, 112151. https://doi.org/https://doi.org/10.1016/j.solmat.2022.112151

Dobra, T., Vollprecht, D., & Pomberger, R. (2022). Thermal delamination of end-of-life crystalline silicon photovoltaic modules. *Waste Management & Research*, *40*(1), 96–103. https://doi.org/10.1177/0734242X211038184

Duflou, J. R., Peeters, J. R., Altamirano, D., Bracquene, E., & Dewulf, W. (2018). Demanufacturing photovoltaic panels: Comparison of end-of-life treatment strategies for improved resource recovery. *CIRP Annals*, *67*(1), 29–32.

Einhaus, R., Madon, F., Degoulange, J., Wambach, K., Denafas, J., Lorenzo, F. R., Abalde, S. C., García, T. D., & Bollar, A. (2018). Recycling and Reuse potential of NICE PV-Modules. *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC)(A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC)*, 561–564. https://doi.org/10.1109/PVSC.2018.8548307

Emersleben, A., & Meyer, N. (2012). The use of recycled glass for the construction of pavements. In *GeoCongress 2012: State of the Art and Practice in Geotechnical Engineering* (pp. 1642–1649).

Bellini, E. (2024, April 16). Polysilicon price will stay above $5.50/kg for at least a year. PV Magazine. https://www.pv-magazine.com/2024/04/16/polysilicon-price-will-stay-above-5-5-kg-for-at-least-a-year-says-analyst/

Eshraghi, N., Berardo, L., Schrijnemakers, A., Delaval, V., Shaibani, M., Majumder, M., Cloots, R., Vertruyen, B., Boschini, F., & Mahmoud, A. (2020). Recovery of nano-structured silicon from end-of-life photovoltaic wafers with value-added applications in lithium-ion battery. ACS Sustainable Chemistry & Engineering, 8(15), 5868–5879. https://doi.org/10.1021/acssuschemeng.9b07434

European Standardization Organisation CENELEC. (2012, August). *Waste from Electrical and Electronic Equipment (WEEE)*. https://environment.ec.europa.eu/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_en#contact

Farzana, R., Rajarao, R., & Sahajwalla, V. (2014). Synthesis of ferrosilicon alloy using waste glass and plastic. *Materials Letters*, *116*, 101–103. https://doi.org/10.1016/j.matlet.2013.10.105

Farzana, R., Rajarao, R., & Sahajwalla, V. (2016). Characteristics of waste automotive glasses as silica resource in ferrosilicon synthesis. *Waste Management & Research*, *34*(2), 113–121. https://doi.org/10.1177/0734242X15617010

Feih, S., Boiocchi, E., Mathys, G., Mathys, Z., Gibson, A. G., & Mouritz, A. P. (2011). Mechanical properties of thermally-treated and recycled glass fibres. *Composites Part B: Engineering*, *42*(3), 350–358.

Fiandra, V., Sannino, L., Andreozzi, C., Corcelli, F., & Graditi, G. (2019a). Silicon photovoltaic modules at end-of-life: Removal of polymeric layers and separation of materials. *Waste Management*, *87*, 97–107. https://doi.org/10.1016/j.wasman.2019.02.004

Fiandra, V., Sannino, L., Andreozzi, C., & Graditi, G. (2019b). End-of-life of silicon PV panels: A sustainable materials recovery process. *Waste Management*, *84*, 91–101. https://doi.org/10.1016/j.wasman.2018.11.035

Gajare, O., Jadhav, N. B., Zele, S., Lucas, N., & Gogate, N. (2025). Sustainable silver recovery by chemical treatment of metal rich fines from solar panel waste. *Solar Energy Materials and Solar Cells*, *279*, 113259.

Han, K., Saito, M., Xia, J., Ohnuma, I., & Kainuma, R. (2022). Experimental determination of phase diagram involving silicides in the Fe-Si binary system. *Journal of Alloys and Compounds*, *919*, 165810.

Haque, N., & Norgate, T. (2013). Estimation of greenhouse gas emissions from ferroalloy production using life cycle assessment with particular reference to Australia. *Journal of Cleaner Production*, *39*, 220–230. https://doi.org/10.1016/j.jclepro.2012.08.010

Hawezy, D. (2017). The influence of silicon content on physical properties of non-oriented silicon steel. *Materials Science and Technology (United Kingdom)*, *33*(14), 1560–1569. https://doi.org/10.1080/02670836.2017.1295519

Held, M., & Wessendorf, C. (2024). Status of PV Module Take-Back and Recycling in Germany. *International Energy Agency (IEA)*.

Huang, W.-H., Shin, W. J., Wang, L., Sun, W.-C., & Tao, M. (2017a). Strategy and technology to recycle wafer-silicon solar modules. *Solar Energy*, *144*, 22–31. https://doi.org/10.1016/j.solener.2017.01.001

Huang, W.-H., Shin, W. J., Wang, L., Sun, W.-C., & Tao, M. (2017b). Strategy and technology to recycle wafer-silicon solar modules. *Solar Energy*, *144*, 22–31. https://doi.org/10.1016/j.solener.2017.01.001

IEA-PVPS Report Number: T12-06:2016. (2016). *IEAPVPS Report on End-of-Life Solar PV Panels*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf

IMARC. (2024). Metal Silicon Prices, Trend, Chart, Demand, Market Analysis, News, Historical and Forecast Data Report 2024 Edition. https://www.imarcgroup.com/metal-silicon-pricing-report

IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016. (n.d.).

Ise, F., & Projects GmbH, P. (2024). *Photovoltaics Report-Fraunhofer Institute for Solar Energy Systems, ISE with the support of PSE Projects GmbH*. www.ise.fraunhofer.de

Jain, S., Sharma, T., & Gupta, A. K. (2022). End-of-life management of solar PV waste in India: Situation analysis and proposed policy framework. *Renewable and Sustainable Energy Reviews*, *153*, 111774.

Jeon, M. S., Dhamrin, M., Saitoh, T., & Kamisako, K. (2006). Effect of HF treatment on hydrogenated silicon nitride anti-reflection films quality and optical properties. *2006 IEEE 4th World Conference on Photovoltaic Energy Conference*, *2*, 1425–1428.

Jochymczyk, D., Warzecha, M., & Hutny, A. (2025). Industrial Investigations of S355 Steel-Grade Homogenization in a 100-Tonne Ladle Furnace. *Materials*, *18*(1), 180.

Jung, B., Park, J., Seo, D., & Park, N. (2016). Sustainable system for raw-metal recovery from crystalline silicon solar panels: from noble-metal extraction to lead removal. *ACS Sustainable Chemistry & Engineering*, *4*(8), 4079–4083. https://doi.org/10.1021/acssuschemeng.6b00894

Kang, S., Yoo, S., Lee, J., Boo, B., & Ryu, H. (2012). Experimental investigations for recycling of silicon and glass from waste photovoltaic modules. *Renewable Energy*, *47*, 152–159. https://doi.org/10.1016/j.renene.2012.04.030

Kastanaki, E. (2025). Dynamic assessment of photovoltaic waste streams in the EU-27 countries under the circular economy principles of 'Reduce, Reuse and Recycle.' *Resources, Conservation and Recycling*, *214*, 108033.

Khetri, M., & Gupta, M. C. (2024). Recycling of silver from silicon solar cells by laser debonding. *Solar Energy*, *270*. https://doi.org/10.1016/j.solener.2024.112381

Kim, Y., & Lee, J. (2012). Dissolution of ethylene vinyl acetate in crystalline silicon PV modules using ultrasonic irradiation and organic solvent. *Solar Energy Materials and Solar Cells*, *98*, 317–322. https://doi.org/10.1016/j.solmat.2011.11.022

Kim, Y.-M., Choi, S.-W., & Hong, S.-K. (2016). The behavior of thermal diffusivity change according to the heat treatment in Al-Si binary system. *Journal of Alloys and Compounds*, *687*, 54–58. https://doi.org/10.1016/j.jallcom.2016.06.080

Klejnowska, K., Mijal, W., Golebiewska-Kurzawska, J., & Strzelczuk, J. (2024). Recycling of end-of-life PV panels-a review of technologies. *E3S Web of Conferences*, *550*. https://doi.org/10.1051/e3sconf/202455001040

Knotter, D. M., & Denteneer, T. J. J. D. (2001). Etching mechanism of silicon nitride in HF-based solutions. *Journal of The Electrochemical Society*, *148*(3), F43.

Komoto, K., Lee, J.-S., Zhang, J., Ravikumar, D., Sinha, P., Wade, A., & Heath, G. A. (2018). *End-of-life management of photovoltaic panels: trends in PV module recycling technologies*. National Renewable Energy Laboratory (NREL), Golden, CO (United States). https://doi.org/https://doi.org/10.2172/1561523

Krause, O., Ryssel, H., & Pichler, P. (2002). Determination of aluminum diffusion parameters in silicon. *Journal of Applied Physics*, *91*(9), 5645–5649. https://doi.org/10.1063/1.1465501

Królikowski, M., Fotek, M., Żach, P., & Michałowski, M. (2024). Development of a Recycling Process and Characterization of EVA, PVDF, and PET Polymers from End-of-Life PV Modules. *Materials*, *17*(4), 821. https://doi.org/10.3390/ma17040821

Kubaschewski, O., & Okamoto, H. (1993). Phase diagrams of binary iron alloys. *ASM International*, 364–366.

Latunussa, C. E. L., Ardente, F., Blengini, G. A., & Mancini, L. (2016a). Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. *Solar Energy Materials and Solar Cells*, *156*, 101–111. https://www.vdma.org/international-technology-roadmap-photovoltaic

Latunussa, C., Mancini, L., Blengini, G., Ardente, F., & Pennington, D. (2016b). Analysis of material recovery from silicon photovoltaic panels. *JRC Publications Repository*, *JRC100783*. https://doi.org/10.2788/786252

Lee, J., Lee, J., Ahn, Y., Kang, G., Song, H., Kang, M., Kim, Y., & Cho, C. (2018). Simple pretreatment processes for successful reclamation and remanufacturing of crystalline silicon solar cells. *Progress in Photovoltaics: Research and Applications*, *26*(3), 179–187. https://doi.org/10.1002/pip.2963

Lee, J.-K., Ko, S.-W., Hwang, H.-M., Shin, W.-G., Ju, Y.-C., Kang, G.-H., Song, H.-E., Eo, Y.-J., Bae, S., & Palitzsch, W. (2024). Crystalline silicon solar cell with an efficiency of 20.05% remanufactured using 30% silicon scraps recycled from a waste photovoltaic module. *Solar Energy Materials and Solar Cells*, *277*, 113102. https://doi.org/10.1016/j.solmat.2024.113102

Li, J., Li, Y., Yu, F., Hu, Z., Gao, Q., Li, P., Tan, Y., & Jiang, D. (2025). Co-recovery of Ag and Si from PV cell panels: Directional solidification assisted by PV glass. *Separation and Purification Technology*, *353*, 128428.

Li, W., Liu, B., Wang, S., Jiao, F., Qin, W., & Liu, W. (2024). Short-process leaching and kinetic behaviour of aluminium and silver from waste photovoltaic modules. *Chemical Engineering Journal*, *495*. https://doi.org/10.1016/j.cej.2024.153455

Libby, C., Shaw, S., Heath, G., & Wambach, K. (2018). Photovoltaic recycling processes. 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC)(A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), 2594–2599. https://doi.org/10.1109/PVSC.2018.8547376

Lovato, E. S., Donato, L. M., Lopes, P. P., Tanabe, E. H., & Bertuol, D. A. (2021). Application of supercritical CO2 for delaminating photovoltaic panels to recover valuable materials. *Journal of CO2 Utilization*, *46*, 101477. https://doi.org/10.1016/j.jcou.2021.101477

Lunardi, M. M., Alvarez-Gaitan, J. P., Bilbao, J. I., & Corkish, R. (2018). A review of recycling processes for photovoltaic modules. *Solar Panels and Photovoltaic Materials*, *30*. https://doi.org/10.5772/INTECHOPEN.74390

Mahmoudi, S., Huda, N., & Behnia, M. (2021). Multi-levels of photovoltaic waste management: A holistic framework. *Journal of Cleaner Production*, *294*, 126252.

Majewski, P., Al-shammari, W., Dudley, M., Jit, J., Lee, S.-H., Myoung-Kug, K., & Sung-Jim, K. (2021). Recycling of solar PV panels-product stewardship and regulatory approaches. *Energy Policy*, *149*, 112062.

Mao, D., Yang, S., Ma, L., Ma, W., Yu, Z., Xi, F., & Yu, J. (2023). Overview of life cycle assessment of recycling end-of-life photovoltaic panels: A case study of crystalline silicon photovoltaic panels. *Journal of Cleaner Production*, 140320.

Martínez, M., Barrueto, Y., Jimenez, Y. P., Vega-Garcia, D., & Jamett, I. (2024). Technological Advancement in Solar Photovoltaic Recycling: A Review. *Minerals*, *14*(7), 638.

McCaldin, J. O., & Sankur, H. (1971). Diffusivity and solubility of Si in the Al metallization of integrated circuits. *Applied Physics Letters*, *19*(12), 524–527. https://doi.org/10.1063/1.1653799

Mohajerani, A., Vajna, J., Cheung, T. H. H., Kurmus, H., Arulrajah, A., & Horpibulsuk, S. (2017). Practical recycling applications of crushed waste glass in construction materials: A review. *Construction and Building Materials*, *156*, 443–467.

Mulazzani, A., Eleftheriadis, P., & Leva, S. (2022). Recycling c-Si PV Modules: A Review, a Proposed Energy Model and a Manufacturing Comparison †. *Energies*, *15*(22). https://doi.org/10.3390/en15228419

Nevala, S.-M., Hamuyuni, J., Junnila, T., Sirviö, T., Eisert, S., Wilson, B. P., Serna-Guerrero, R., & Lundström, M. (2019). Electro-hydraulic fragmentation vs conventional crushing of photovoltaic panels–Impact on recycling. *Waste Management*, *87*, 43–50.

Nithya, R., Sivasankari, C., & Thirunavukkarasu, A. (2021). Electronic waste generation, regulation and metal recovery: a review. *Environmental Chemistry Letters*, *19*, 1347–1368. https://doi.org/10.1007/s10311-020-01111-9

Ogundairo, T. O., Adegoke, D. D., Akinwumi, I. I., & Olofinnade, O. M. (2019). Sustainable use of recycled waste glass as an alternative material for building construction–A review. *IOP Conference Series: Materials Science and Engineering*, *640*(1), 012073.

Padhamnath, P., Kuśmierczyk, F., Kopyściański, M., Gondek, Ł., Migas, P., & Karbowniczek, M. (2025). Realization of a Novel FeSiAlCuSn Multicomponent Alloy and Characterization of Intermetallic Phases Formed at Different Temperatures During Cooling. *Metals*, *15*(5), 479.

Padhamnath, P., Nalluri, S., Kuśmierczyk, F., Kopyściański, M., Karbowniczek, J., Kozieł, T., Leow, S. W., & Reindl, T. (2025). Development of PV panel recycling process enabling complete recyclability of end-of-life silicon photovoltaic panels. *Solar Energy Materials and Solar Cells*, *286*, 113571. https://doi.org/https://doi.org/10.1016/j.solmat.2025.113571

Padoan, F. C. S. M., Altimari, P., & Pagnanelli, F. (2019). Recycling of end of life photovoltaic panels: A chemical prospective on process development. *Solar Energy*, *177*, 746–761.

Pagnanelli, F., Moscardini, E., Abo Atia, T., & Toro, L. (2016). Photovoltaic panel recycling: from type-selective processes to flexible apparatus for simultaneous treatment of different types. *Mineral Processing and Extractive Metallurgy*, *125*(4), 221–227. https://doi.org/10.1080/03719553.2016.1200764

Palitzsch, W., Rover, I., Lee, J., & Yook, Y. (2020). Single crystalline Si ingot by use of recycled silicon as an example for circular economy. *EUPVSEC 2020*.

Pang, C., Wu, Y., Zhu, J., Qin, B., & Ruan, J. (2025). The study of adsorption mechanisms and kinetics of recovering Ag and Al on the bioleaching of end-of-life crystalline silicon photovoltaic cells. *Separation and Purification Technology*, *354*, 128999.

Pang, S., Yan, Y., Wang, Z., Wang, D., Li, S., Ma, W., & Wei, K. (2021). Enhanced separation of different layers in photovoltaic panel by microwave field. *Solar Energy Materials and Solar Cells*, *230*, 111213. https://doi.org/10.1016/j.solmat.2021.111213

Park, J., Kim, W., Cho, N., Lee, H., & Park, N. (2016). An eco-friendly method for reclaimed silicon wafers from a photovoltaic module: from separation to cell fabrication. *Green Chemistry*, *18*(6), 1706–1714. https://doi.org/10.1039/C5GC01819F

Park, J., & Park, N. (2014). Wet etching processes for recycling crystalline silicon solar cells from end-of-life photovoltaic modules. *RSC Advances*, *4*(66), 34823–34829. https://doi.org/10.1039/C4RA03895A

PVPS Task, I., Heath, G., Wade SolarPower Europe, A., Authors Keiichi Komoto, B., Lee, J.-S., Jia Zhang, C., Sinha, P., & Garvin Heath, B. (2018). *End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies Operating Agent*.

Qi, Z., Wang, S., Gao, D., Bao, G., & Wu, Z. (2025). A novel ion exchange method for recover silver and aluminum from waste crystalline silicon photovoltaic modules. *Solar Energy*, *286*, 113142.

Rajarao, R., Farzana, R., & Sahajwalla, V. (2018). Transforming waste printed circuit boards and compact discs for the synthesis of valuable ferrosilicon alloy. *Journal of Sustainable Metallurgy*, *4*, 461–469. https://doi.org/10.1007/s40831-018-0194-0

Ramírez-Cantero, J., Pérez-Huertas, S., Muñoz-Batista, M. J., Pérez, A., Calero, M., & Blázquez, G. (2025). State of the art of end-of-life silicon-based solar panels recycling with a bibliometric perspective. *Solar Energy Materials and Solar Cells*, *281*, 113312.

Robert, D., Baez, E., & Setunge, S. (2021). A new technology of transforming recycled glass waste to construction components. *Construction and Building Materials*, *313*, 125539.

Rollert, F., Stolwijk, N. A., & Mehrer, H. (1987). Solubility, diffusion and thermodynamic properties of silver in silicon. *Journal of Physics D: Applied Physics*, *20*(9), 1148.

Rout, S., Jana, P., Borra, C. R., & Önal, M. A. R. (2025). Unlocking silver from end-of-life photovoltaic panels: A concise review. *Renewable and Sustainable Energy Reviews*, *210*, 115205.

Russo, R. E., Awais, M., Fattobene, M., Santoni, E., Cavallera, R., Zamponi, S., Conti, P., Berrettoni, M., & Giuli, G. (2024). Silver recovery from silicon solar cells waste by hydrometallurgical and electrochemical technique. *Environmental Technology and Innovation*, *36*. https://doi.org/10.1016/j.eti.2024.103803

Sævarsdottir, G., Kvande, H., & Magnusson, T. (2021). Greenhouse Gas Emissions from Silicon Production -Development of Carbon Footprint with Changing Energy Systems. *SSRN Electronic Journal*, *September*, 27–29. https://doi.org/10.2139/ssrn.3926088

Sah, D., Upadhyay, N. K., Muthiah, S., & Kumar, S. (2023). Growth and analysis of polycrystalline silicon ingots using recycled silicon from waste solar module. *Solar Energy Materials and Solar Cells*, *261*, 112524. https://doi.org/10.1016/j.solmat.2023.112524

Sanathi, R., Banerjee, S., & Bhowmik, S. (2024). A technical review of crystalline silicon photovoltaic module recycling. In *Solar Energy* (Vol. 281). Elsevier Ltd. https://doi.org/10.1016/j.solener.2024.112869

Scelsi, L., Hodzic, A., Soutis, C., Hayes, S. A., Rajendran, S., AlMa'adeed, M. A., & Kahraman, R. (2011). A review on composite materials based on recycled thermoplastics and glass fibres. *Plastics, Rubber and Composites*, *40*(1), 1–10.

Selema, A., Beretta, M., Ibrahim, M. N., Verwimp, J., Rombouts, M., Vleugels, J., Kestens, L. A. I., & Sergeant, P. (2023). Material Engineering of 3D-Printed Silicon Steel Alloys for the Next Generation of Electrical Machines and Sustainable Electromobility. *Journal of Magnetism and Magnetic Materials*, *584*(June), 171106. https://doi.org/10.1016/j.jmmm.2023.171106

Seo, B., Kim, J. Y., & Chung, J. (2021). Overview of global status and challenges for end-of-life crystalline silicon photovoltaic panels: A focus on environmental impacts. *Waste Management*, *128*, 45–54.

Serpe, A., Purchase, D., Bisschop, L., Chatterjee, D., De Gioannis, G., Garelick, H., Kumar, A., Peijnenburg, W., Piro, V. M. I., & Cera, M. (2025). 2002–2022: 20 years of e-waste regulation in the European Union and the worldwide trends in legislation and innovation technologies for a circular economy. *RSC Sustainability*.

Sharma, A., Pandey, S., & Kolhe, M. (2019). Global review of policies & guidelines for recycling of solar PV modules. *International Journal of Smart Grid and Clean Energy*, *8*(5), 597–610.

Shevko, V. M., Amanov, D. D., Karataeva, G. E., & Aitkulov, D. K. (2016). Complex ferroalloy obtaining from silicon-and aluminum–containing silica clay. *Kompleksnoe Ispolzovanie Mineralnogo Syra= Complex Use of Mineral Resources*, *4*, 39–45.

Sica, D., Malandrino, O., Supino, S., Testa, M., & Lucchetti, M. C. (2018). Management of end-of-life photovoltaic panels as a step towards a circular economy. *Renewable and Sustainable Energy Reviews*, *82*, 2934–2945. https://doi.org/10.1016/j.rser.2017.10.039

Sinha, V., Patel, M. R., & Patel, J. V. (2010). PET waste management by chemical recycling: a review. *Journal of Polymers and the Environment*, *18*(1), 8–25. https://doi.org/10.1007/s10924-008-0106-7

Snapshot of Global PV Markets 2024. (n.d.). www.iea-pvps.org

Song, B.-P., Zhang, M.-Y., Fan, Y., Jiang, L., Kang, J., Gou, T.-T., Zhang, C.-L., Yang, N., Zhang, G.-J., & Zhou, X. (2020). Recycling experimental investigation on end of life photovoltaic panels by application of high voltage fragmentation. *Waste Management*, *101*, 180–187. https://doi.org/10.1016/j.wasman.2019.10.015

Tammaro, M., Rimauro, J., Fiandra, V., & Salluzzo, A. (2015). Thermal treatment of waste photovoltaic module for recovery and recycling: Experimental assessment of the presence of metals in the gas emissions and in the ashes. *Renewable Energy*, *81*, 103–112. https://doi.org/10.1016/j.renene.2015.03.014

Tammaro, M., Salluzzo, A., Rimauro, J., Schiavo, S., & Manzo, S. (2016). Experimental investigation to evaluate the potential environmental hazards of photovoltaic panels. *Journal of Hazardous Materials*, *306*, 395–405. https://doi.org/10.1016/j.jhazmat.2015.12.018

Tangstad, M. (2013). Ferrosilicon and silicon technology. In *Handbook of ferroalloys* (pp. 179–220). Elsevier. https://doi.org/10.1016/B978-0-08-097753-9.00006-X

Tao, M., Fthenakis, V., Ebin, B., Steenari, B., Butler, E., Sinha, P., Corkish, R., Wambach, K., & Simon, E. S. (2020). Major challenges and opportunities in silicon solar module recycling. *Progress in Photovoltaics: Research and Applications*, *28*(10), 1077–1088. https://doi.org/10.1002/pip.3316

Tembo, P. M., & Subramanian, V. (2023). Current trends in silicon-based photovoltaic recycling: A technology, assessment, and policy review. *Solar Energy*, *259*, 137–150.

Tomé-Torquemada, S., Glaser, B., Hildal, K., & Sichen, D. (2017). Experimental Study on the Activities of Al and Ca in Ferrosilicon. *Metallurgical and Materials Transactions B*, *48*, 3251–3258. https://doi.org/10.1007/s11663-017-1119-1

Wambach, K., Libby, C., & Shaw, S. (2024). *IEA PVPS Task 12 report - Advances in Photovoltaic Module Recycling*.

Wang, T.-Y., Hsiao, J.-C., & Du, C.-H. (2012). Recycling of materials from silicon base solar cell module. *2012 38th IEEE Photovoltaic Specialists Conference*, 2355–2358. https://doi.org/10.1109/PVSC.2012.6318071

Wijk, O., & Brabie, V. (1996). The purity of ferrosilicon and its influence on inclusion cleanliness of steel. *ISIJ International*, *36*(Suppl), S132–S135.

Wind, R. A., Jones, H., Little, M. J., & Hines, M. A. (2002). Orientation-resolved chemical kinetics: using microfabrication to unravel the complicated chemistry of KOH/Si etching. *The Journal of Physical Chemistry B*, *106*(7), 1557–1569.

World Silver Survey 2023. (n.d.). www.silverinstitute.org

Wriedt, H. A., Morrison, W. B., & Cole, W. E. (1973). The solubility of silver in γ-Fe. *Metallurgical Transactions*, *4*(6), 1453–1456.

Xu, X., Lai, D., Wang, G., & Wang, Y. (2021). Nondestructive silicon wafer recovery by a novel method of solvothermal swelling coupled with thermal decomposition. *Chemical Engineering Journal*, *418*, 129457. https://doi.org/10.1016/j.cej.2021.129457

Xu, Y., Li, J., Tan, Q., Peters, A. L., & Yang, C. (2018). Global status of recycling waste solar panels: A review. *Waste Management*, *75*, 450–458.

Yiwei, A., Yunxia, Y., Shuanglong, Y., Lihua, D., & Guorong, C. (2007). Preparation of spherical silver particles for solar cell electronic paste with gelatin protection. *Materials Chemistry and Physics*, *104*(1), 158–161.

Yousef, S., Tatariants, M., Denafas, J., Makarevicius, V., Lukošiūtė, S.-I., & Kruopienė, J. (2019). Sustainable industrial technology for recovery of Al nanocrystals, Si micro-particles and Ag from solar cell wafer production waste. *Solar Energy Materials and Solar Cells*, *191*, 493–501. https://doi.org/10.1016/j.solmat.2018.12.008

Yue, Q., Wen, J., Zhou, Y., & Zheng, Y. (2025). Resource utilization of waste solar photovoltaic panels for preparation of microporous silicon nanoparticles. *Waste Management*, *193*, 495–505.

Zante, G., Marin Rivera, R., Hartley, J. M., & Abbott, A. P. (2022). Efficient recycling of metals from solar cells using catalytic etchants. *Journal of Cleaner Production*, *370*. https://doi.org/10.1016/j.jclepro.2022.133552

Zarmai, M. T., Ekere, N. N., Oduoza, C. F., & Amalu, E. H. (2015). A review of interconnection technologies for improved crystalline silicon solar cell photovoltaic module assembly. *Applied Energy*, *154*, 173–182.

Zhang, C., Chen, Y., Feng, S., Kan, X., Zhu, Y., Li, Y., Sun, W., Shen, J., & Liu, X. (2023). Improvement of electromagnetic properties of FeSiAl soft magnetic composites. *Journal of Materials Science*, *58*(23), 9698–9707. https://doi.org/10.1007/s10853-023-08610-4

Zhao, P., Guo, J., Yan, G., Zhu, G., Zhu, X., Zhang, Z., & Zhang, B. (2020). A novel and efficient method for resources recycling in waste photovoltaic panels: High voltage pulse crushing. Journal of Cleaner Production, 257, 120442. https://doi.org/10.1016/j.jclepro.2020.120442

Zheng, R., Luo, M., Li, B., Jia, M., Zhang, H., Liu, S., Lu, Y., Jiang, L., Zhang, Z., & Liu, F. (2025). Eco-friendly recovery and preparation of high purity nano silver powders from retired photovoltaic solar cells. Separation and Purification Technology, 359, 130343.