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Technologies for resource-efficient recycling of end-of-life crystalline silicon photovoltaic panels

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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, with increased use of PV panels for energy production enormous volumes of PV waste would be generated that would need to be dealt with in an environmentally responsible manner. 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 close-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 accompanied with their production. Through experiments it was onbserved 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 does not involve producing harmful greenhouse gases.

Keywords

Recycling ; circular-economy; resource-efficiency; silicon-photovoltaic; ferrosilicon

1. Introduction

The global growth of solar photovoltaic (PV) installations since the early 2000s has been extraordinary, increasing from 1.2 GW in 2000 to 1.6 TW in 2023, with projections suggesting it will 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.). While this exponential growth is a crucial and desirable step in addressing climate change, challenges arise in managing decommissioned solar panels. PV panels have a technical lifespan of 25 to 30 years; however, some fail prematurely due to damage during production, transportation, installation, or field degradation. Thus, as PV installations increase, global cumulative PV waste is also projected to grow exponentially, reaching 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 to 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). The charter identifies as the efficient disposal and management of hazardous waste as a key 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). Especially the European Union (EU) has published one of the most detailed regulations related to 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 regulatory framework related to PV module recycling are available in these reviews. (Kastanaki, 2025; Nithya et al., 2021; Serpe et al., 2025). While these regulations have been recently formulated and provide a general guideline, recycling could be focussed on the value of the materials recycled rather than on the weight. For example, in PV panels, the glass and the aluminium frame, copper wires and external connectors constitute approx. 85% of the weight of the PV panel, but account for only 30-40% of the value (Padhamnath, Ślęzak, et al., 2023). Several other countries have been establishing regulatory frameworks for handling WEEE waste which also includes solar PV panels(Ali et al., 2023, 2024; Curtis et al., 2021; Jain et al., 2022; Serpe et al., 2025). A global review of regulatory frameworks highlighted the popular business to customer model the 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). Policies and guidelines pertaining to recycling EOL PV modules exist in several countries (Held & Wessendorf, 2024; Sharma et al., 2019; Y. Xu et al., 2018). However, instances of commercial scale adoption of PV module recycling are relatively low. Among the various initiatives by industries, First Solar is considered the leader in PV recycling (Sharma et al., 2019). However, they produce Cadmium Telluride (Cd-Te) thin film panels. Initiatives for recycling c-Si based PV modules were established in Europe by solar PV manufacturing industries; however, their long-term commercial viability has not been established (Sharma et al., 2019; Y. Xu et al., 2018). According to a current report on status of global PV recycling, a total of seven commercial entities are engaged in recycling PV modules out of which six have their operations in Europe (Wambach et al., 2024).

However, recycling photovoltaic (PV) modules is extremely challenging due to the complex structure of the modules. Crystalline silicon (c-Si) panels, which represent about 97% of the market (Ise & Projects GmbH, 2024), are made from a variety of materials—including glass, interconnected cells which have doped silicon, and metals like aluminium, silver, and copper, encapsulants, and polymers—all laminated together in heat and pressure to form a single structure. This intricate composition requires a range of mechanical, thermal, and chemical methods to disintegrate the layers, recover all the useful materials and purify them for reuse(Chen et al., 2024).

Research and development in PV recycling technologies have made significant strides in recent years. Between 1995 to 2016, there were around 123 effective patents from various countries related to the recycling of c-Si PV modules, highlighting the increasing demand and necessity of PV recycling. Europe has pioneered PV module recycling, with PV Cycle leading efforts since 2001, successfully processing over 19 Mt of PV waste. Innovations included processes combining mechanical and thermal treatments to increase recycling rates to 96%. In Germany, Eltz Umwelt-Technology devised an advanced pyrolysis process to recover 95% of materials. France's Veolia utilizes a multistage recycling approach for high-efficiency recovery. China leads in PV patents, focusing on module separation, with innovative technologies like refrigerated grinding and hydrothermal prefractionation. In Japan and Korea, technologies like heated cutting and thermal treatment are advancing PV recycling efficiency(PVPS Task et al., 2018). Thus, globally there has been increased demand for advanced PV Recycling technologies.

Despite the technical feasibility and the advancements, recycling of PV modules often face environmental and economic challenges, including harmful emissions from incineration and the use of toxic chemicals during leaching, coupled with high operational costs and limited waste volumes that prevent economies of scale(Mulazzani et al., 2022). Hence, the focus is being shifted towards creating sustainable, cost-effective and large-scale technologies to promote the long-term viability of solar energy.

The recycling of EOL-PV modules can be done in either open-ended cycle or close-ended 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 ferrosilicon (FeSi) which is widely used in 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 close ended 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 it to manufacture new PV panels. However, close-ended recycling of PV panels could be 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).

Delamination is among the most complicated steps which decides the further recyclability of the PV panels. Since PV panels are designed to withstand environmental impacts an ingress of moisture and air, delamination of the panels is not easily achieved. Delamination of the PV panels could be achieved by mechanical, chemical or thermal processes, or a combination of them (Divya et al., 2023; Lunardi et al., 2018; Sanathi et al., 2024). Recently delamination of end-of-life PV panels using high voltage crushing or electrohydraulic fragmentation (EHF) has gathered attention of the researchers as an excellent alternative to the existing delaminating processes for achieving higher recycling efficiency and material selectivity than conventional crushing (Akimoto et al., 2018; Nevala et al., 2019; Song et al., 2020; Zhao et al., 2020). While the researchers have tried optimized the process parameters, they have been limited to the parameters of the process chamber 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 a clear information of the recovery of the process of recovery of important materials such as Ag and Si after processing the modules using EHF process. Furthermore, the information available in the literature does not establish the suitability of integrating EHF process into the already existing process line incorporating crushing of EOL PV panels.

Ferrosilicon (FeSi) alloys are universally used in metallurgical industry for alloying, deoxidation and casting operations (Hawezy, 2017; Selema et al., 2023). Traditional silicon production from primary sources relies on coal and coke, generating approximately 4 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 SiO_2. Utilizing an alternative production method, such as induction furnace and eliminating the use of carbon for the reducing of SiO_2 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 using 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). Development of a process without using carbonaceous reductants to generate commercially important alloys such as FeSi from waste materials is largely 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 close-ended recycling approaches as developed on 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 for the production of FeSi. It utilizes Si from the EOL PV panels and clean scrap iron to produce FeSi using 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 close-ended recycling process, an energy efficient electrohydraulic fragmentation process was developed for delaminating of PV modules which enable 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 EHF process is capable of handling crushed modules which makes it feasible to be integrated into existing wate 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 under 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 thorough environmental impact assessment which shall be addressed in a 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 under 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 for 100gm of the FeSi45, Si is approximately 45% by mass while remaining is the 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 carried out in multiple passes to obtain the desired particle size of 1-3 mm. Between each pass of crushing process, the glass, silicon and the polymer pieces there were successfully separated were removed manually. The process was carried out until sufficient quantity of silicon pieces was 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. Figure 1 shows the pieces of silicon sticking to the polymer while figure 2 shows the silicon powder particles as observed under an optical microscope. 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) soap water to remove any traces of oil, debris and organic and inorganic residues on the surface. The rust on the samples were removed using commercial rust removing spray and scrubbing with a metal brush. The cleaned samples were washed again in warm soap water to remove the chemicals and dried by placing in an oven at 150 °C for 20 min. The cleaned and dried scrap steel was cut into smaller pieces (≈20-30mm) and prepared for melting.

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

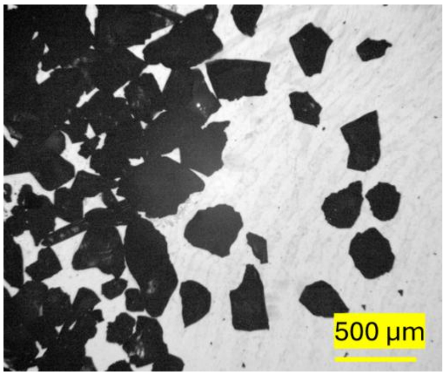

Figure 2: Pieces of silicon less than 1mm obtained after serving as observed under optical microscope

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 placed inside the induction furnace and covered with an alumina lid with an opening in the centre through which a thermocouple was inserted to record the temperature. 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 embed in conductive carbon resin, and subsequently metallographic cross-sections were preparing from the embedded samples by grinding using different grades of sandpaper and polishing with diamond suspension.

2.2 Delamination of crushed PV modules pieces using 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 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. Its principle of operation includes applying a high voltage pulse to a solid immersed in a fluid to generate a shockwave. The shockwave travels through the fluid and interacts with the solids, causing fractures at the weak points between the interfaces of dissimilar materials, along with crushing of the material (Akimoto et al., 2018). The material recovered after the fragmentation 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 powder as shown in figure 4.

	
Figure 3: Pieces of polymers obtained after the EHF processing (> 5mm) . (Taken using a DSLR camera)	Figure 4: Glass and silicon pieces obtained after the EHF processing (0.1-0.5mm). (Taken using a DSLR camera)

3. **Results**

3.1 **Characterization of the FeSi prepared using recycled silicon.**

The metallographic FeSi prepared using the silicon recovered from the panels were observed with a scanning electron microscope (SEM). The composition of the different 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 module 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 composition of Si ranging between 42-45% (atomic) and 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 Fe_2Si (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).

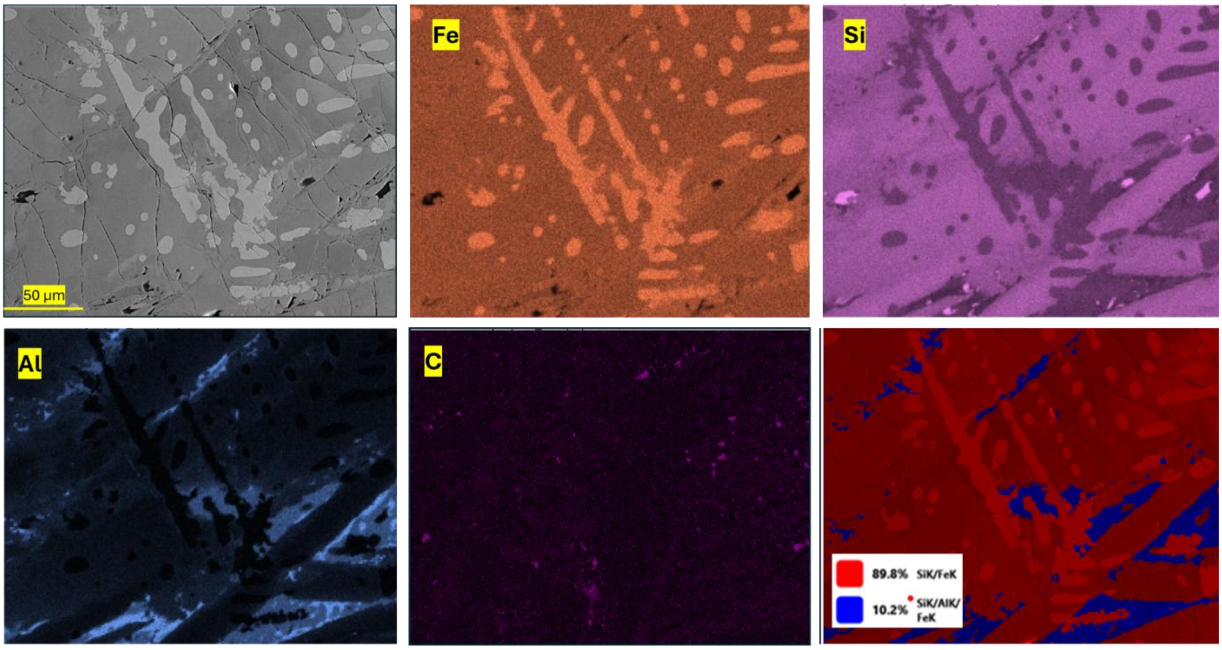

Figure 5: SEM image and the elemental composition map and phase map obtained by EDS for the FeSi-pc samples. Different elements identified by the EDS are labelled accordingly. The phase map is obtained using the software integrated with the EDS measurement system.

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. This is due to the fact that while crushing, most of the metal contacts on the solar cells which is composed of Al and Ag (Padhamnath, Choi, et al., 2023; Padhamnath et al., 2024), is 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 Fe_2Si dendrites in 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 impurities 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.

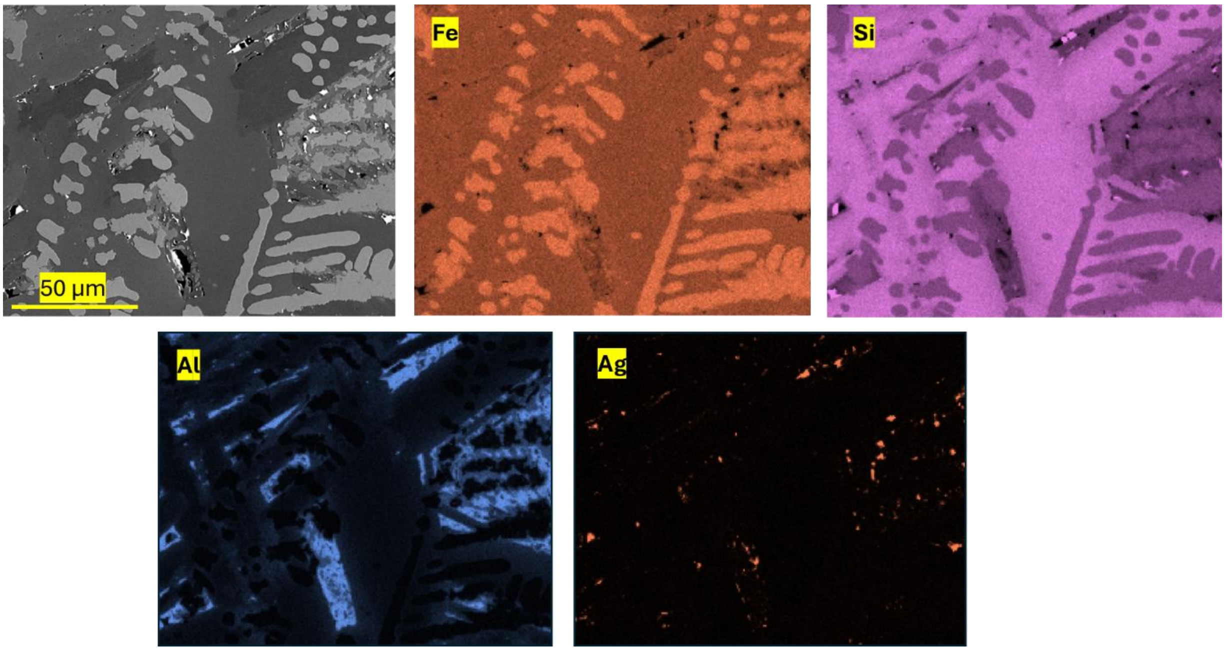

Figure 6: SEM image and the elemental composition map and phase map obtained by EDS for the FeSi-po samples. Different elements identified by the EDS are labelled accordingly. The Ag can be seen distributed through the microstructure and specifically along the grain boundaries between the Fe rich and Si rich phases.

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 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 higher degree of separation and subsequent recovery of the silicon, polymer and glass. Higher Figure 7 shows the crushed pieces before and after undergoing the EHF treatment.

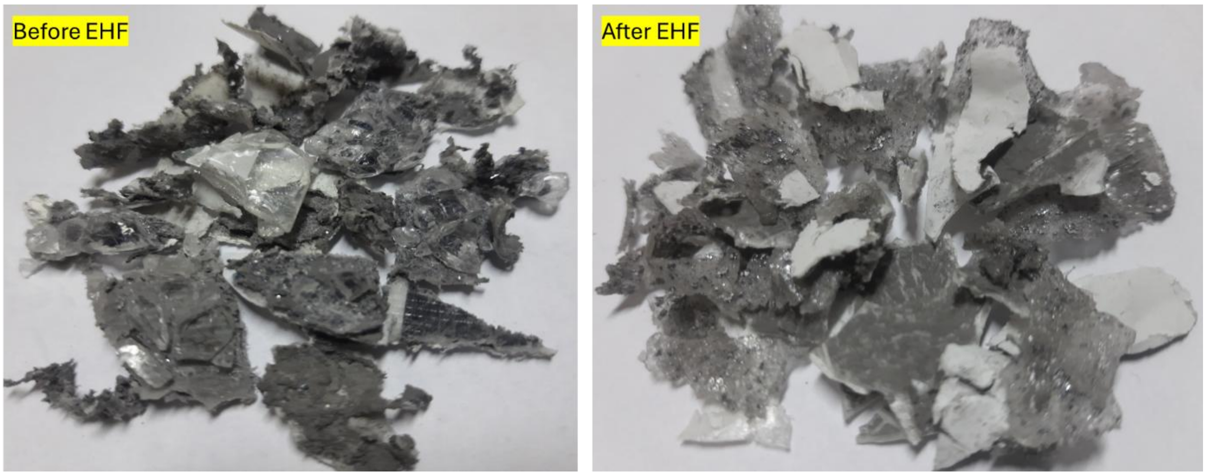

Figure 7 – Polymer pieces recovered after crushing the PV panels and treating the recovered polymer pieces using EHF process. (Taken using a DSLR camera)

The powder obtained after the treatment is mostly comprised of glass with 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 few hundreds of 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 were not continuous layer of Si, 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 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 EHF process provides an alternative pathway of 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.

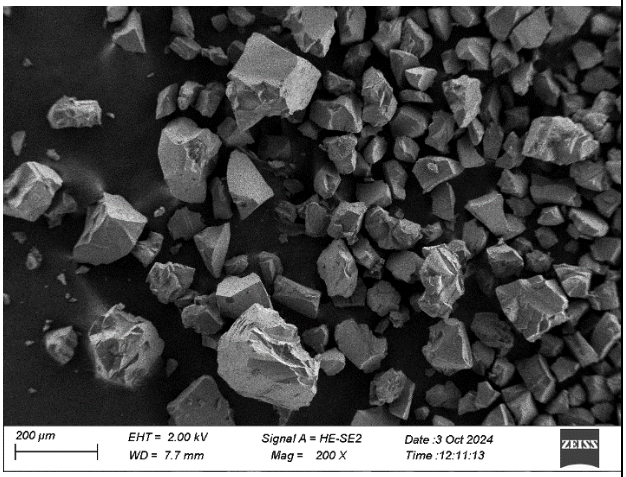

Figure 8: SEM image (magnification – 200X) of the coarse glass powder obtained after the EHF processing of crushed EOL PV modules.

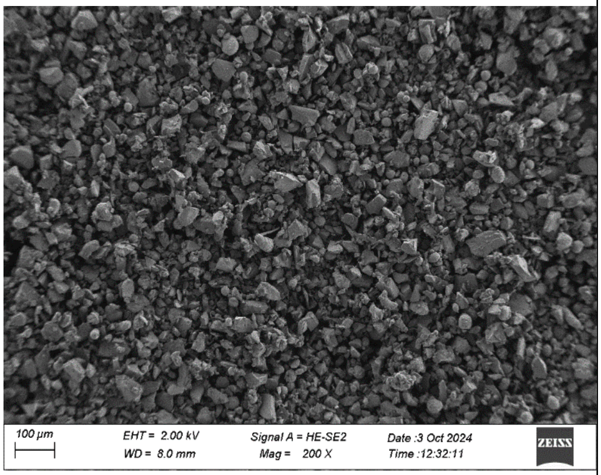

Figure 9: SEM image (magnification – 200X) of the fine silicon and metal powder obtained after the EHF processing of crushed EOL PV modules.

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, Ślęzak, et al., 2023). 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 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 was not attempted in this work, a succinct discussion on the processes involved based on the available literature is presented.

4.1 Extraction of Silver

In c-Si PV modules, electrons generated in the silicon wafer are collected through a grid-patterned contact printed on the cells, which is typically made of silver paste. While the silver content in the PV panel is minimal by weight (~0.05%), it accounts for 47% of the overall cost in terms of 'value standpoint'(*IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016*, n.d.)(Chen et al., 2024). Furthermore, the shift in the photovoltaic (PV) industry from Passivated Emitter and Rear Cell (PERC) to newer technologies like Tunnel Oxide Passivated Contact (TOPCon) and Heterojunction Technology (HJT) is driving an increase in silver usage, with TOPCon utilising at least 1.3 times and HJT utilising at least 1.6 times more silver than PERC. According to the World Silver Survey 2023 by The Silver Institute, as demand rises amidst tight supply, silver consumption in PV panels is projected to grow by 4%, while production is forecasted to increase by only 2%, resulting in PV industry exhausting up to 98% of the global silver reserves in 2050 (World Silver Survey 2023, n.d.). Therefore, inclusion of effective recovery of silver into the recycling line of PV modules is very much vital to enhance the cost viability of the entire recycling process, offset the production costs of new panels as well as meet the growing demand of silver. In the early days of PV recycling plants, the primary goal was high-volume material recycling to glass, aluminium, and silicon as it made up over 80% of module mass, simpler to separate and cost-effective because of established recycling markets. Furthermore, recovery of intact solar cells for reuse in module production was prioritised, as the price of PV panels was largely driven by the cost of silicon wafers (PVPS Task et al., 2018). Consequently, silver was discarded during the etching of solar cells in sodium hydroxide to recover silicon, as it was considered uneconomical to retrieve trace amounts of silver, despite its high value.

Recovering silver from PV modules kickstarted only in 2000s and the common technique used was hydrometallurgical processes. Chemicals like nitric acid were used to leach metals from the recovered solar cells. The silver which is dissolved in the nitric acid is precipitated as a salt and silver is recovered from it through electrolysis and metal replacement techniques (Deng et al., 2022). Around 99% silver could be recovered through these processes. Researchers have developed more efficient methods in recent years. For instance, a combined hydrometallurgical and electrochemical approach has been shown to achieve a 98% recovery rate. This process employs leaching followed by electrodeposition-redox replacement (EDRR) to recover pure silver, offering high efficiency and environmental advantages by minimizing chemical use(Russo et al., 2024). Another promising method is laser debonding, where silver electrodes are removed using laser techniques. This method has been explored by the University of Virginia and has shown potential for selectively recovering silver while preserving the integrity of the silicon wafers. The laser method also generates silver nanoparticles, which are valuable for reuse in various industries. The use of machine learning to optimize laser processing is an innovative trend aimed at automating and scaling the recovery process, reducing both cost and energy consumption (Khetri & Gupta, 2024). Recent advancements have focused on increasing the recovery efficiency while reducing the environmental footprint of the recycling processes (Gajare et al., 2025; Qi et al., 2025; Zheng et al., 2025). For example, research has shown that using iron and aluminum chloride in brine solutions can recover up to 95% of silver in under 10 minutes. This method is touted for its low cost, low toxicity, and scalability compared to conventional acid-based recovery techniques(Zante et al., 2022). In some cases, biological methods have also been employed to recover Ag from the PV panels (C. Pang et al., 2025). Additionally, the shift from silver to copper in PV module design due to cost considerations has driven the development of more efficient methods for extracting silver from older module designs.

Despite these advancements, several challenges persist in silver recovery from PV modules. One significant issue is the low concentration of silver in PV cells, which can make the recovery process economically unviable at scale. The cost of extraction is often high due to the need for complex chemical processes or specialized equipment such as lasers. Additionally, the presence of other metals, such as copper, which have similar chemical properties, complicates the leaching and separation processes (Rout et al., 2025; Russo et al., 2024). The development of methods that can selectively recover silver without affecting other valuable materials, such as silicon, remains a technological hurdle. While traditional hydrometallurgical techniques are being optimized for higher efficiency, novel methods such as laser debonding, directional solidification and electrochemical recovery offer promising avenues for enhancing sustainability in the PV industry(J. Li et al., 2025; Yue et al., 2025). However, challenges related to the economic viability of recovery and the low silver content in modules must be addressed to scale these technologies effectively.

4.2 Recovery of Silicon from EOL PV panels

Researchers have demonstrated the prospects of reusing the silicon recovered from end-of-life Si PV panels to manufacture new silicon solar cells. Silicon recovered from the end-of-life PV panels. Silicon recovered after the usual recycling process involving crushing and separating us usually metallurgical grade (Komoto et al., 2018; C. E. L. Latunussa et al., 2016; Tao et al., 2020) , which is valued around \$2-3/kg depending on the region (IMARC, 2024). There could be motivation to recover solar grade silicon, which is valued between \$6-9/kg (Emiliano Bellini, 2024). Closed loop recycling of Si in the solar industry has been reported to be feasible (Tao et al., 2020). Researchers have used the recycled silicon from broken solar cells and wafer production to fabricate ingots and subsequently solar cells (Derbouz Draoua et al., 2017). The recycled solar cells achieved efficiency of 18.1% compared to a reference of 18.5%. Recently, researchers fabricated solar cells with efficiencies exceeding 20% from recycled silicon, obtained after chemical etching (Palitzsch et al., 2020). Researchers have demonstrated the effectiveness of 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 (HNO_3), Sulfuric Acid (H_2SO_4), phosphoric acid (H_3PO_4) and acetic acid (CH_3COOH), researchers recovered 79-86% of 5N silicon, using chemical delamination process to remove the glass and the polymers (Kang et al., 2012). Park et.al fabricated single cell panels and used thermal delamination to remove the glass and the EVA layers (Park et al., 2016). By using HNO_3 and potassium hydroxide (KOH), they were able to recover 90% of the silicon, in the original size of the wafer (albeit thinner). These reclaimed wafers were used to make solar cells, which achieved ≈90% of the original efficiency (Park et al., 2016). Similar approach to remove metal using HNO_3 , H_3PO_4 and KOH was used to recover 80-90% of the silicon (Eshraghi et al., 2020; Huang et al., 2017b; Jung et al., 2016; C. Latunussa et al., 2016; C. E. L. Latunussa et al., 2016). By recycling solar cells rejected during production, which have not been incorporated in a panel, researchers were able to retrieve ≈ 99% of the silicon (Yousef et al., 2019). For this advanced process such as ultrasonic treatment, centrifugal separation and microfiltration were employed. The succinct literature review presented here demonstrates the underlying interest in recycling silicon from the solar cells and the complicated process required. In all the instances, silicon was recovered by employing either a thermal or a chemical delamination process. Nevertheless, it has been established that silicon recovered from EOL PV panels could be reused for fabricating new solar cells(J.-K. 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 impurity in the FeSi alloys. Commercially produced ferrosilicon usually contains between 0.5-2% if Al as 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 (Y.-M. Kim et al., 2016; Krause et al., 2002; McCaldin & Sankur, 1971). While this work shows the feasibility of preparing FeSi from the recycled Si, impact of the impurities in the FeSi in 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 oxidation of steels and the mechanical properties of such steels could be analysed to assess the impact of the impurities in the FeSi on 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 a 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). The glass pieces obtained after the EHF processing might have some polymer and Si pieces which could be undesirable. While the polymer pieces could be easily removed by washing with water, removal of Si particles could be difficult. However, the percentage of Si in the glass cullet is estimated to be less than 0.001% by wt. To remove Si from these glass pieces, they can be treated with sodium hypochlorite (NaOCl) or potassium hydroxide (KOH), both of which would preferentially react with Si while leaving the glass particles intact (Basu et al., 2013; Divan et al., 1999; Wind et al., 2002). For fine silicon and glass powder the material targeted for extraction would depend on the composition of the powder. In the context of this work, the fine powder was found to contain more Si than glass. To retrieve Si, the glass needs to be dissolved which can be done by treating the powder with HF(Padhamnath, Nalluri, Kuśmierczyk, Kopyściański, Karbowniczek, Kozieł, et al., 2025; Padhamnath, Nalluri, Kuśmierczyk, Kopyściański, Karbowniczek, Leow, et al., 2025). The HF would preferentially dissolve glass, while not etching the Si appreciably. Another advantage of this process is the removal of the ARC coating on the solar cells (Brunet et al., 2017; Jeon et al., 2006; Knotter & Denteneer, 2001). Finally, the fine powder mixture of Si, Ag, Al and some glass is among the most valuable material to be recovered, especially due to the presence of Ag in this mixture. The Ag in the mixture can be recovered by treating it with HNO_3, 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; W. Li et al., 2024; Yiwei et al., 2007). Further, the remaining glass and Si can be separated as mentioned earlier by dissolving the glass in HF.

One of the advantages of EHF recycling is that the polymer used in the PV module could be recycled as well. The polymer pieces were delaminated from the module due to EHF treatment but still contained some Si sticking to the surface. While the amount of Si sticking to the surface could be minimized by a careful optimization of the process parameters, treating the polymer pieces with KOH and HNO_3 would further dissolve any remaining silicon and metal pieces sticking to the surface. The cleaned polymer pieces could then be recycled using the specialized process developed for recycling them (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 interests among researchers and technologists alike. For example, in open ended recycling of PV panels, the panels are crushed and 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 aluminum 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 commercial feasibility of the process and enable large scale adoption of the technology.

To extract valuable materials from the end-of-life PV panels, usually four steps are required – disassembly, delamination, material sorting and material extraction. Each of these steps could further comprise single or multiple process steps (Deng et al., 2022; Divya et al., 2023). The external wiring (copper) and the aluminium frames are the easily extracted and recycled or in some cases reused entirely (Einhaus et al., 2018). In some cases, commercial recycling of PV panels could only include these steps, while discarding the remaining unframed panels or PV laminates (Deng et al., 2022). Metals, notably Ag, Cu and Al are among the most valuable recyclable component in a PV panel followed by Silicon. They are usually recovered be 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 polymers such as Ethylene-vinyl acetate (EVA), polyvinylidene difluoride (PVDF) and Polyethylene terephthalate (PET) are almost never recycled, owing to their lower economic value and hazardous nature of recovery process(Achilias & Karayannidis, 2004; Deng et al., 2022; Divya et al., 2023; Sinha et al., 2010).

As mentioned earlier, Delamination of the PV panels could be achieved by mechanical, chemical or thermal processes, or a combination of them. Thermal delamination involves heating the PV panels to temperatures in the range of 550°C which decomposes the cross-linked polymers such as Ethyl Vinyl Acetate (EVA), Polyvinylidene fluoride (PVDF) or polyethylene terephthalate (PET) (Dobra et al., 2022). This separates the glass, the interconnecting metallic ribbons and the solar cells, and allows subsequent recovery of high-quality materials (Fiandra, Sannino, Andreozzi, & Graditi, 2019; Fiandra, Sannino, Andreozzi, Corcelli, et al., 2019; J. Lee et al., 2018; Park & Park, 2014). However, this process is energy intensive, generates toxic emissions and is expensive to implement (Deng et al., 2021; Lunardi et al., 2018; Tammaro et al., 2015, 2016). Chemical delamination of modules is achieved by immersing the modules or crushed pieces of modules in organic or inorganic chemicals which could dissolve the cross-linked polymers. Usually, they involve extremely hazardous chemicals and long process 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 (S. Pang et al., 2021), ultrasonic waves (Y. Kim & Lee, 2012) or supercritical carbon dioxide (Lovato et al., 2021) to shorten the process durations. However, complete separation of EVA and PET/PVDF was not always achieved, and in some cases a secondary treatment such as pyrolysis or glycolysis could be necessary (X. Xu et al., 2021). Furthermore, disposal of such large scale 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 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 process result in mainly separation of glass which is the main product obtained in such processes. The polymer is often pyrolyzed or burnt to generate heat. Mechanical recycling of PV modules using crushing and shredding are the most widely used technologies to handle PV waste due to the low cost. However, such processes create lot of dust and noise and need active dust and noise suppression systems.

Through this work we have demonstrated the flexibility of the electrohydraulic delamination process in the processing of the end-of-life c-Si PV panels. EHF process can be used for different panel types and is compatible with different pre-processing options such as cutting or crushing. However, different panel types should be processed separately to maintain the uniformity of the process. Further the process can be customised for high throughput or high-quality process. Furthermore, we have shown that recycling end-of-life PV panels using electrohydraulic fragmentation can lead to a high yield and high quality of materials enabling almost complete recovery of components from end-of-life crystalline silicon PV panels. We demonstrated that it is possible to recover and separate clean polymer pieces with process optimization. While most of the materials could be segregated with simple mechanical sieving, intermixing of the materials could be completely avoided. Future research could further optimize the process, for example, by including a multistage processing sequence involving continuous separation of the materials, investigation of the methods of separation of materials leveraging the differences in their densities, and recovering and recycling high-quality silicon, metals and polymers recovered in this process.

4.5 Advantages and limitations of the proposed process

EHF defragmentation of the EOL c-Si PV modules provides a way to effectively delaminate the PV modules, without the use of thermal or chemical decomposition. The electrohydraulic delamination process for recycling c-Si PV panels provides the easiest and quickest method of delaminating c-Si PV panels, leading to near total material recovery of different components of the PV panel. This agrees with the current standards of EU WEEE directive (Deng et al., 2021; European Standardization Organisation CENELEC, 2012; Padoan et al., 2019; Sica et al., 2018). This delamination process enables recovery of all the components of the PV module. The process is adaptable and can be tailored to suit different module types and can be combined different pretreatment processes such as mechanical crushing to further improve the throughput. The EHF process requires only water (which need not be potable) and electricity to operate. It does not create any hazardous gasses or toxic effluents/wastes. 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 automations 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. It was possible to separate the large glass pieces from the finer particles using simple filtration, which could be easily recycled. However, the coarse glass particles included some pieces of Si solar cells. Similarly, the fine powder, while mostly composed of Si and metal powder, contained some fine glass powder too. One way to separate the different materials could be density based medium separation(Akimoto et al., 2018) . Further research efforts would be focussed on optimization of process parameters to minimize the mixing of the individual components to facilitate their separation and recovery using simple mechanical sieving process. Additionally, further efforts would be directed towards developing the process for continuous operations, improving the metals recovery efficiency and estimating the environmental impact of the process.

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 for the production of FeSi. It utilizes Si from the EOL PV panels and clean scrap iron to produce FeSi using 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 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 impurity than 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 metallurgy industry. Al is among the most common impurity in the FeSi alloys. Commercially produced ferrosilicon usually contains between 0.5-2% if 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. 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 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 chemical intensive process, and a careful process selection is required to minimize the energy and resource utilization. The EHF process is a clean, environment friendly process which does not generate any toxic effluents or gases during its operation. We have shown that the process can be carried out efficiently at lower voltages (50KV) 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 EHF process . Similarly, we produced FeSi using recycled Fe and Si, without using any carbonaceous material for reduction. This completely 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 concentration, their impact at concentrations less than 1% needs to be investigated thoroughly. Understanding such impact of small amount of impurities for 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 the 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 .

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