A comprehensive review on the recycling technology of silicon based photovoltaic solar panels: challenges and future outlook

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Review

A comprehensive review on the recycling technology of silicon based photovoltaic solar panels: Challenges and future outlook

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ABSTRACT

With the aim of realizing the goals of the Paris Agreement, annual solar power generation on a global scale using silicon PV panels had exceeded 1000 TWh by the end of 2021. Mass installation of silicon-based photovoltaic (PV) panels exhibited a socioenvironmental threat to the biosphere, i.e., the electronic waste (e-waste) from PV panels that is projected to reach 78 million tonnes by the year 2050. Recycling PV panels through e-waste management is crucial step in minimizing the environmental impact of end-of-life PV systems such as the release of heavy metals into the environment. An increasing amount of academic research on recycling approaches to PV panels that suggests different technology and policy challenges remain. The present review critically evaluates a range of recycling solutions, encompassing both lab-scale and pilot-scale research, and conducts analyses of their cost and environmental implications. A detailed discussion of the recycling policies adopted by governments worldwide to handle e-waste has also been provided. In this review article, the complete recycling process is systematically summarized into two main sections: disassembly and delamination treatment for silicon-based PV panels, involving physical, thermal, and chemical treatment, and the retrieval of valuable metals (silicon, silver, copper, tin, etc.).

Furthermore, technical, and non-technical challenges and prospects are identified to guide future exploration and innovation. In the pursuit of sustainable recycling of solar PV panels, technology convenience, cost-effectiveness, and social desirability should come together to develop innovative recycling technologies with a high recovery rate of valuable metals.

1. Introduction

Meeting the world's electricity demand has become a significant challenge amid a growing global population (Younas et al., 2022; Sadiq and Wen, 2022) and is predominantly fulfilled using fossil fuels (Greiner et al., 2022). According to reports from the International Energy Agency (Dechamps, 2023), global CO_2 emissions rose by 1.5 billion tonnes in 2021 compared to the previous year. The ongoing consumption of fossil fuels has been a double-edged sword. It has driven considerable societal, technological, and economic progress, improving quality of life. However, it has also brought about serious threats like droughts (Mukherjee et al., 2018), heatwaves (Zscheischler et al., 2022), and sea-level rise (Alhamid et al., 2022; Ellis et al., 2022) due to fossil fuel exploitation (Chen et al., 2022). Research communities are emphasizing the replacement of conventional energy sources with sustainable alternatives such as solar power (Khan et al., 2022), wind power, hydroelectric power, bioenergy, etc., to mitigate global greenhouse gas (GHG) emissions (Farhat et al., 2022). Geopolitical decisions, including the Paris Agreement and the Copenhagen Climate Change Conference, have been pivotal in securing countries' commitments to reduce carbon emissions (Sodiqjon et al., 2022) by promoting renewable energy sources (Dong et al., 2018) and limiting the rise in global temperature to below 2 °C (Schleussner et al., 2016) (International Renewable Energy Agency, 2017).

In 2022, the worldwide renewable energy sector grew by 250 GW (International Renewable energy agency, 2022), marking a 9.1% increase in power generation. Notably, solar and wind comprised 90% of the total capacity (Hassan et al., 2023). IRENA reports (International Renewable Energy agency, 2023) highlight solar photovoltaic (PV) panels as the leading renewable energy source, capable of satisfying around 60% of current electricity demand. Projections anticipate substantial global growth in solar PV production, reaching over 1630 GW by 2030 and a remarkable 4500 GW by 2050, as illustrated in Fig. 1. Developed nations, including the U.S.A, U.K., China, Canada, Australia,

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EU members, and Japan, have launched multiple solar PV projects aligned with the UN Sustainable Development Goals (Kumar et al., 2023; Marco-Lajara et al., 2023). In 2014, the Indian government initiated the Jawaharlal National Solar Mission (JNNSM) to foster sustainable energy growth through solar and wind sources, initially aiming for 100 GW (Thakur et al., 2022), later raised to 450 GW by Prime Minister Narendra Modi (Khanna et al., 2023).

PV technology is expected to play a crucial role in shifting the economy from fossil fuels to a renewable energy model (T. Kåberger, 2018). Among PV panel types, crystalline silicon-based panels currently dominate the global PV landscape, recognized for their reliability and substantial investment returns (S. Preet, 2021). Researchers have developed alternative PV technologies, including thin-film-based options such as amorphous silicon (a-Si) (Zendehdel et al., 2020), Cadmium telluride (CdTe) (Mohr et al., 2007), etc., as well as organic and hybrid solar cells (Wang et al., 2011; Zhitomirsky et al., 2014) for electricity generation applications (Allouhi et al., 2022). The average lifespan of PV panels, typically around 25 years (S. Preet, 2018), can be extended to 30 years with new materials (Kant and Singh, 2022). Damaging factors such as severe weather events (Jathar et al., 2023), natural disasters, fires (Santhakumari and Sagar, 2019), inadequate maintenance, hotspots (Aghaei et al., 2022), and damage during transportation and installation can shorten their lifespan (Calì et al., 2022). PV panels pose challenges in their end-of-life (EOL) phase, becoming hazardous waste for the biosphere after 25–30 years or due to the impact of the aforementioned factors (Aghaei et al., 2022). Projections suggest that e-waste from silicon PV panels may reach 60 to 78 million tonnes by 2050 (Song et al., 2023; Guinée, 2002), with environmental and health risks due to the presence of aluminum, silicon, lead, cadmium, and tin (Tan et al., 2022; Jain et al., 2022). Improper disposal can result in soil and water contamination (Bang et al., 2018), harming the biosphere (Zhang et al., 2023), while the polymers in PV panels release toxic gases (Rathore and Panwar, 2022).

The recycling of PV panels provides opportunities to address the environmental impact mentioned above by reclaiming valuable materials, including over half of the silicon content, for reuse in manufacturing new PV panels (Włodarczyk, 2022; Ardente et al., 2019). Researchers have developed diverse physical, thermal, and chemical methods to recycle silicon-based PV panels, aiming to repurpose damaged panels and prioritize economic and environmental sustainability (Granata et al., 2022; Ravichandran and Ganesan, 2012). The environmental sustainability of PV recycling processes is closely linked to the chosen methods [E. Aschenbrand, 2022). While some methods enable material recovery, others, such as those involving the recovery of materials like copper wires, may rely on outdated techniques releasing carcinogens and teratogens from unwanted materials (such as plastic) (Hagfeldt et al., 2010; Yella et al., 2011). These outdated methods can contribute to global warming, acidification, and eutrophication of water bodies (Piotrowska et al., 2022; Rathi et al., 2022). The present review article discusses different types of recycling methods, including innovative methods for sustainable recycling of silicon-based PV panels, with environmental implications.

Numerous researchers, including Doni and Dughiero. (2012), Kang et al. (2012), Kim and Lee. (2012), Dubey et al., 2013, Tammaro et al. (2015), Tammaro et al. (2016), Latunussa et al. (2016), Ardente et al. (2019), Majewski et al. (2021), Huang et al. (2017), Shin et al. (2017), Fiandra et al., 2019a,b, Smith and Bogust. (2018); Klugmann-Radziemska and Kuczyńska-Łażewska, 2020, have authored articles focusing on the recycling of crystalline silicon (c-Si) PV panels. A few researchers, such as Pagnanelli et al. (2016); Pagnanelli et al. (2017), have presented methods to recycle PV panels made of different materials. Various researchers have also quantified the environmental impact of the techniques adopted to recycle silicon PV panels, like Maani et al. (2020), Seo et al. (2021), Dias et al. (2021), L.L. Barnes, 2017 and Daniela-Abigail et al., 2022. Authors such as Giacchetta et al. (2013), Tammaro et al. (2015), Rocchetti and Beolchini, 2015, Raugei et al. (2012), Malandrino et al., 2017, Latunussa et al. (2016), Aravelli and Ramavathu. (2021), Chowdhury et al. (2020), Majewski et al. (2021), Frisson et al. (2000), Marwede and Reller, 2012, Sica et al. (2018), Xu et al. (2018), Padoan et al. (2019), Fiandra et al., 2019a,b, Rabaia et al. (2021), Dias et al. (2022), Wang et al. (2022), Divya et al. (2023); Deng et al. (2022), have provided a detailed review of various processes involved in recycling PV panels. This current review article offers an extensive and thorough review of both primary and secondary treatment processes, including the top recycling processes (mechanical, thermal, and chemical), medium recycling processes, and bottom recycling processes adopted for recycling silicon PV panels. Moreover, techniques for recovering silicon and valuable metals such as silver, copper, aluminium, lead, etc., from silicon-based solar PV panels have also been presented. The economic viability and environmental implications of the recycling process, encompassing the recovery of valuable metals, which are still to be identified, have been covered. The review article

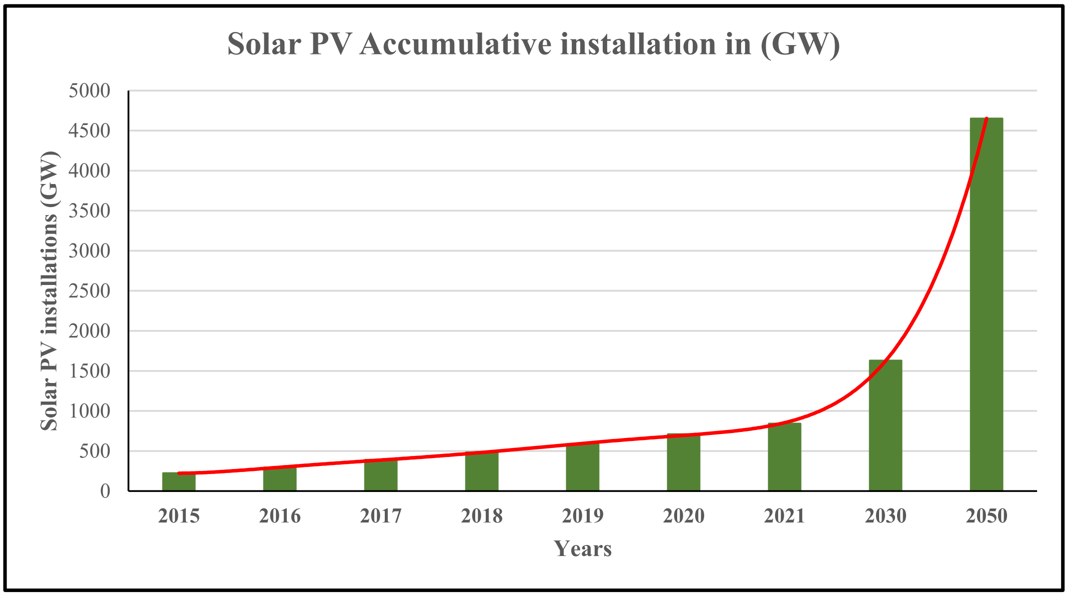


Fig. 1. Solar PV installation projection till 2030 and 2050 (IRENA., 2023).

extensively analyzes the global policies implemented by different countries to address the e-waste associated with photovoltaic (PV) panels. Additionally, it discusses both technical and non-technical challenges, offering valuable insights into the sustainable recycling of silicon PV panels. The article also presents future recommendations aimed at overcoming these barriers for the long-term environmental sustainability of PV panel recycling. This review will prove highly beneficial for policymakers, researchers, and industrial partners involved in the effective management of e-waste from PV panels.

2. Review methodology

The literature review employs content analysis as the primary method for study of literature from ScienceDirect, Google Scholar, Web of Science, Scopus, and IEEE Xplore. The search for relevant articles utilizes carefully selected keywords, forming thematic combinations such as 'Recycling of PV panels,' 'Environmental impact of recycling PV panels,' 'Sustainable recycling process of electronic waste,' 'Policies on recycling PV panels,' and 'Handle e-waste of PV panel.' A total amount of 470 articles were selected after above primary search. In secondary search, a stringent filtering process is applied to select the most relevant ones such as mechanical, thermal, and chemical delamination process, chemical etching process, economic and environmental analysis of recycled and recovered PV materials. The selection criteria involve a thorough evaluation of content, title, abstract, and keywords, specifically focusing on peer-reviewed articles published in English within the last 10 years and open-access articles. Therefore, 330 articles were specified. This meticulous approach ensures the inclusion of pertinent and recent literature in the review. Third selection process utilized the procedure of review and research methodology adopted in the articles, its impact factor and citation. Finally, 260 articles were chosen available in journals, conference proceedings and reports to review literature, analysis, policies, challenges, and future recommendations.

The concluding literature synthesis outlines 8 key aspects for comprehending silicon-based PV recycling. The initial three points focus on understanding the waste issue by (i) assessing global e-waste from end-of-life PV technology; (ii) detailing environmental impacts of various PV materials, and; (iii) estimating future trends in PV panel e-waste. The subsequent four points delve into PV e-waste recycling, addressing (iv) processes like mechanical, thermal, and chemical treatments with metal recovery; (v) economic and environmental implications; (vi) national-level policy adoption, and; (vii) technical and non-technical challenges in PV recycling sustainability. The final point (vii) explores opportunities for future action in PV recycling.

3. E-waste of photovoltaic panels

Despite being recognized for environmentally friendly clean energy production, it's crucial to acknowledge that the manufacturing process of PV panels involves the use of various flammable chemicals, including acids and solvents, which can result in harmful environmental impacts (Dupont et al., 2020; Solanki, 2015). The first-generation PV cells, consisting of mono-crystalline (Rezk et al., 2019a,b), polycrystalline (Bagher et al., 2015), or multi-crystalline silicon cells (Yablonovitch et al., 1987), are widely implemented due to their higher return on investment (Rezk et al., 2019a,b; Siddharth et al., 2022). These PV panels use the Czochralski (CZ) (Moreno Ruiz et al., 2013) or floatzone (FZ) methods (Angermann, 2008; Sørensen, 2017) and involve silicon, aluminium, boron, copper, and lead as their manufacturing materials (Peeters et al., 2017; Kamel et al., 2021; Ratner and Lychev, 2019). Lead and aluminium are primarily responsible for the contamination of water and soil Bagher et al. (2015); Zhou et al. (2022); Muteri et al. (2020); Mahmud et al. (2018); Gong et al. (2015), using the Raw Materials Flow methodology, and Liu et al. (2019); Fukurozaki et al. (2013), employing the IPCC method, examined emissions from PV panels and their components, as shown in Fig. 2. The figure emphasizes that cables and

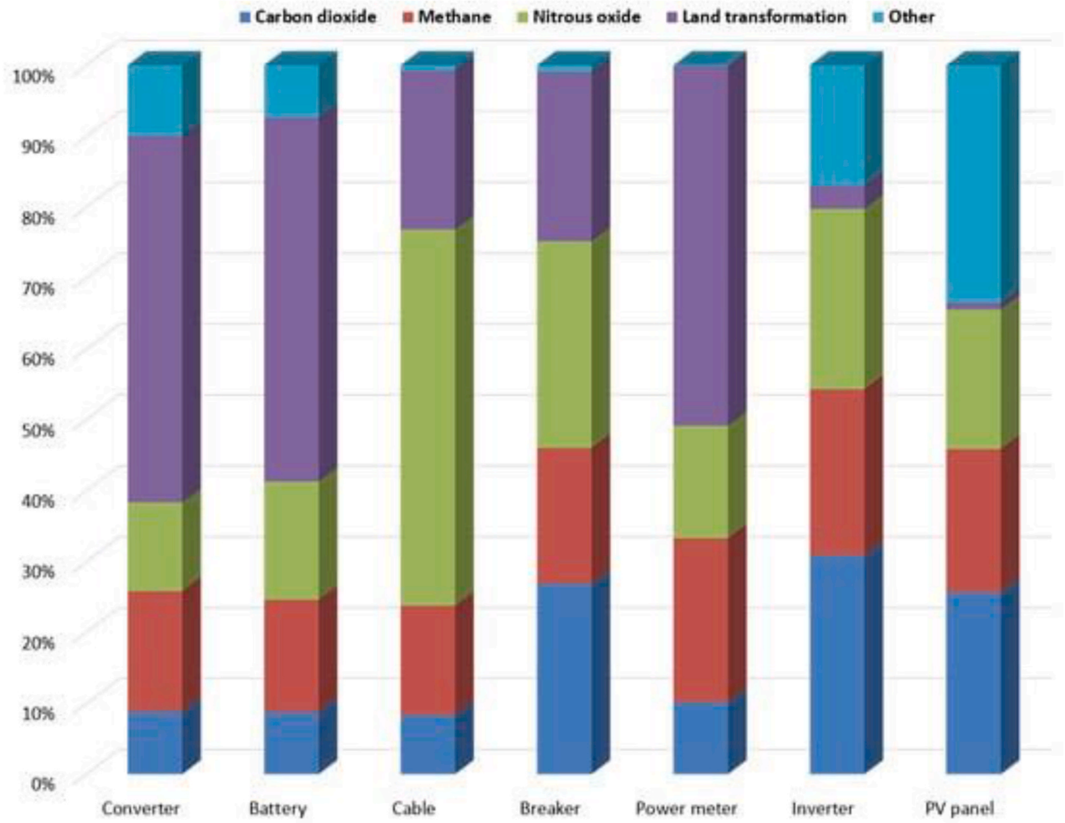


Fig. 2. Percentage share of CO_2 emissions of PV components with period of 100 years (Mahmud et al., 2018).

inverters are primary contributors to harmful gas emissions like nitrous oxide and carbon dioxide. For a detailed overview of the characteristics, advantages, and disadvantages of each type of solar cell, refer to Table 1.

3.1. Global PV installation status and waste projection

The global PV generation is experiencing exponential growth as the world shifts towards PVs to achieve a net-zero carbon future (Ganesan and Valderrama, 2022; Fazal and Rubaiee, 2023). The worldwide installation of PVs is illustrated in Fig. 3. According to reports published by Solar Power Europe in 2018 (Schmela et al., 2018), the global market share of PV panels increased from 3.5% to 5.7% from 2015 to 2017. The Asia-Pacific region, particularly China, leads the world in electricity generation through solar PV panels, with Europe following in second place, America in third place, the Middle East in fourth, and other parts of the world, as depicted in Fig. 4 (Padoan et al., 2019).

Table 1
Types of solar cells with advantage and disadvantage.

Type of PV Technology	Materials	Advantage	Disadvantage
Mono-Crystalline silicon PV panel (Bagher et al., 2015)	Single Crystal silicon	•High durability •High electrical efficiency	•High investment •Very Fragile
Polycrystalline silicon PV panel (Koroneos et al., 2006)	Multiple silicon fragments	•Less cost compared to mono-crystalline	•Low electrical efficiency
Amorphous silicon PV panels (Mohr et al., 2007; Staebler and Wronski, 1977)	Silicon with other materials	•Less expensive compared to mono and poly crystalline silicon PV panels •Can be used as building envelopes due to its flexible nature	•Less efficient
Gallium Arsenide (Poortmans and Arkhipov, 2006; Zimmermann et al., 2014)	GaAs	•Can be used in less space area	•Less electrical efficiency
Cadmium Telluride (H. Steinberger, 1998) (Fthenakis et al., 2005)	Cadmium	• Can be used in less space area	•Low electrical efficiency •Highly expensive
Hetero junction solar cells (Kessler and Rudmann, 2004)	Combination of Crystalline and amorphous	•More efficient than mono and poly crystalline silicon	•Highly expensive
Bifacial solar cells (Kwak et al., 2020)	Silicon solar cells	•Can produce electricity from front as well as back •Can be very beneficial	•Not suitable for roof installation •Expensive
Transparent solar cells (Todorov et al., 2013; Ravichandran and Ganesan, 2012)	Transparent solar cells comprises of organic salt	•Low cost •Can be used for commercial purpose	•Low efficiency
Dye sensitized solar cells (Hailegnaw et al., 2015; Babayigit et al., 2016)	TiO_2	•Low cost •Can generate electricity in low solar radiation	•Electrolyte not suitable for every situation •Can not be used on large scale
Perovskite solar cells (Assadi et al., 2018) Ansari et al. (2018)	Organic-inorganic lead or tin halide-based material	•Good efficiency •Low cost	•Toxic materials •Short life span
Bio hybrid solar cells (Liu et al., 2013; Babayigit et al., 2016b)	Organic and inorganic matter	•High conversion rate •Good efficiency	•Very low life span

International Energy Agency, 2022 and IRENA., 2016 approximated that by the end of 2016, there was a waste volume of 250,000 metric tonnes of solar PV panels. Projections indicate that this volume is poised to grow to 8 million tonnes by the close of 2030, considering both early and regular losses in PV panels, reaching 78 million tonnes. At the end of 2016, the Government of Japan estimated an increment in the production of solar panels from 10,000 tonnes to 80,000 tonnes by the end of 2040 (Fiandra et al., 2019a,b; Yi et al., 2014). China and the USA, as leaders in solar PV panels, have not put forth any proposals for disposing of solar panels in a manner that would harm the environment (El-Khawad et al., 2022) (Frischknecht et al., 2016). The extensive deployment of PV panels worldwide is poised to generate a substantial amount of e-waste from PV panels in the upcoming years (Nain and Kumar, 2023). Researchers have employed two approaches to predict PV e-waste.

In the first approach, as suggested by Ardente et al. (2019), it is assumed that amount of PV panels completing their end of life in year t is equal to the amount of PV panels installed in year t-t_p, t_p is taken as an average lifetime of PV panel gives:

$$F\ (t) = g\left(t - t_p\right) \tag{1}$$

F(t) and g(t) are the PV panels installed and dismissed in year t, respectively.

The second approach to the lifetime distribution was suggested by Granata et al. (2022), wherein the possibility of earlier or later EOL of PV panels than average EOL. It is given as follows:

$$F\ (t) = \sum_{a=o}^{t} p(a)g(t-a) \tag{2}$$

Where p (t) denotes the fraction of PV panels with age t reaching the end of life.

$$p(t) = \int_{t}^{t+1} f\ (t)dt \tag{3}$$

Where f(t) denotes panel lifetime density probability distribution.

Marwede and Reller, 2012 gave PV panel lifetime probability distribution called Weibull distribution for breakthrough and slow progress scenarios. It is given as follows:

$$f\ (t) = \frac{\alpha}{\beta}\left(\frac{t}{\beta}\right)^{\alpha-1} e^{-\left(\frac{t}{\beta}\right)^{\alpha}} \tag{4}$$

For CdTe PV modules, α and β are 12.8 and 32.2 for the breakthrough scenario and 8.2 and 32.2 for the slow progress scenario, respectively (Scarpulla et al., 2023). Using the above equations, researchers have projected the waste of PV panels up to 2050, as shown in Fig. 5. The waste of PV panels will exhibit a sharp peak between 2035 and 2040. Fig. 6 illustrates the primary causes of PV panel failures.

4. Recycling process of silicon-based PV panel

Widespread production and deployment of silicon-based Solar PV panels, aligned with the Paris Agreement for climate change mitigation, pose a significant socio-environmental challenge. This revolves around the growing waste generated as these PV panels reach the end of their life cycle, with estimates projecting potential quantities in the millions of tons by 2050 (Daniela-Abigail et al., 2022; Goedkoop, 1999). Researchers have introduced innovative techniques and conducted extensive studies to pinpoint energy-efficient, sustainable, and economically viable approaches to manage the e-waste produced by silicon PV panels.

Disassembly serves as the initial step in recycling silicon PV panels, achievable through manual or machinery methods. This process involves the removal of the junction box, aluminium frame, and wires. The aluminium frame often requires mechanical and pyrolysis treatment for

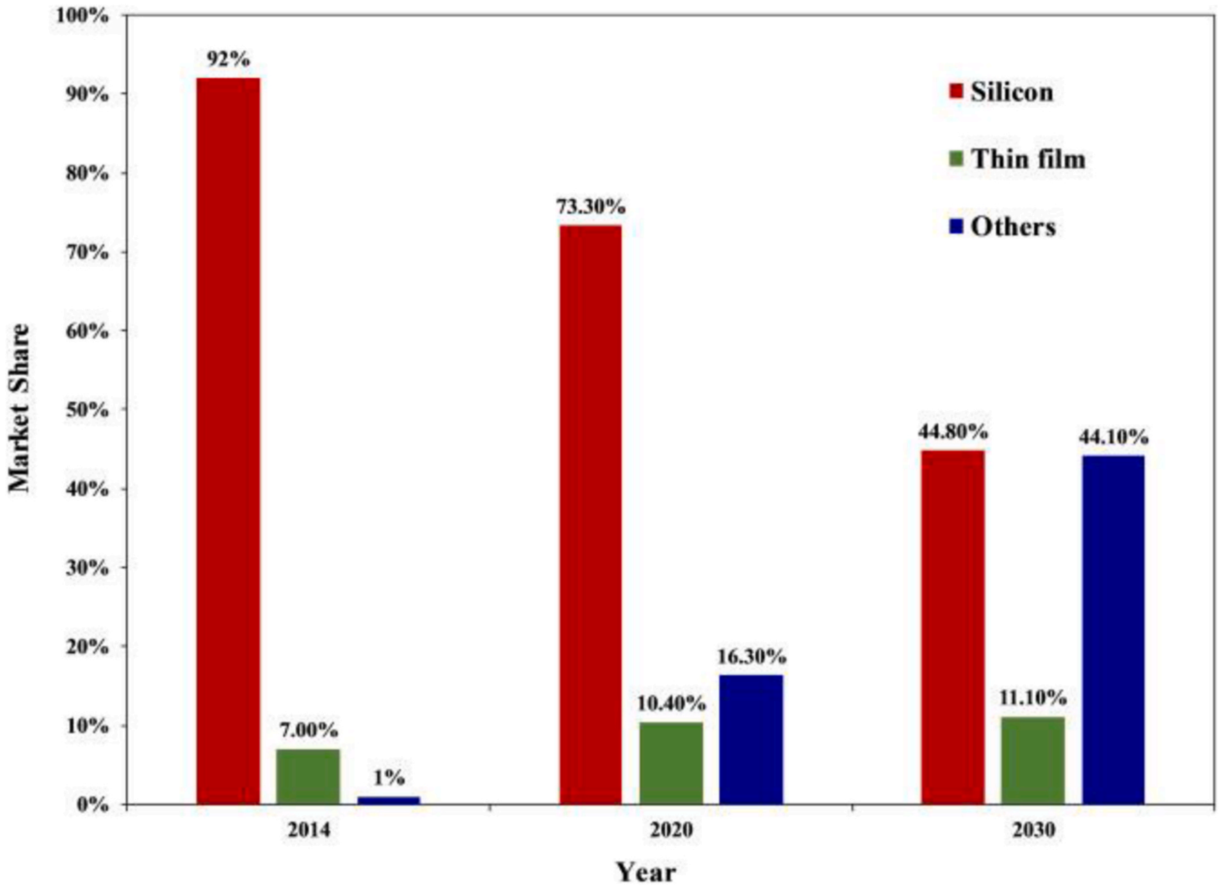


Fig. 3. Recent historical and near future predicted global market share of three categories of PV technologies. Other includes Gallium arsenide (GaAs) and Tandem PV technologies (Xu et al., 2018).

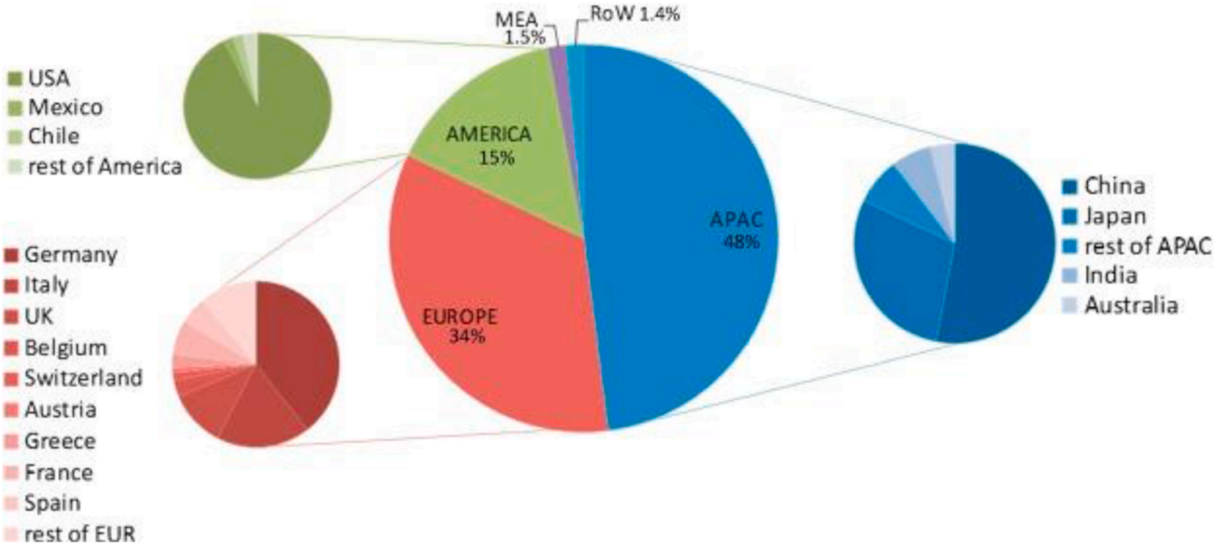
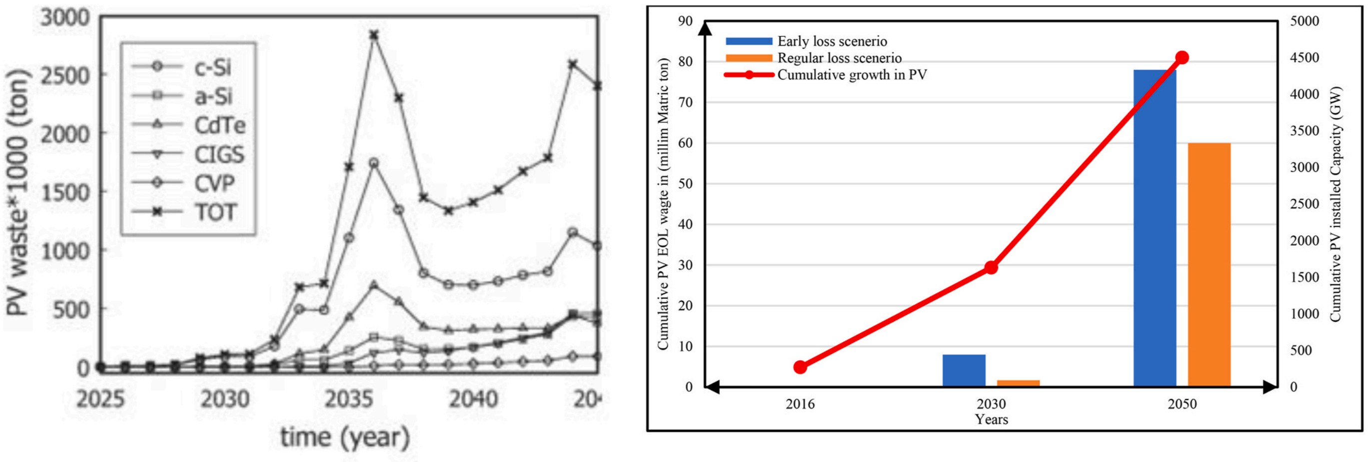


Fig. 4. Installed PV capacity in different regions around the world (Padoan et al., 2019).

metallurgical recovery (Tao and Yu, 2015; Jung et al., 2016). Following this pre-treatment, the PV panel adopts the structure EVA-Solar cells--back layer. Three distinct recycling treatments—top recycling treatment, medium recycling treatment, and bottom recycling treatment—are applied based on the material grade to be recovered.

Various firms worldwide have embraced medium and bottom recycling processes, employing mechanical treatments like hammering, crushing, and shredding PV panels. The resulting glass cullet can be used to manufacture fiberglass, and metals are sold to smelters, while the remaining material is sent to landfills (Wambach et al., 2018; Kokul and Bhowmik, 2021 implemented a recycling process in which, after removing cables, the junction box, frame, and glass, a silicon PV panel was powered and blended with polypropylene and polyethylene to create molded floor tiles. Despite minimizing landfill waste with



(a) (b)

Fig. 5. Future predictions of PV waste generation in (a) Europe (Marwede and Reller, 2012) and (b) worldwide (Marwede and Reller, 2012).

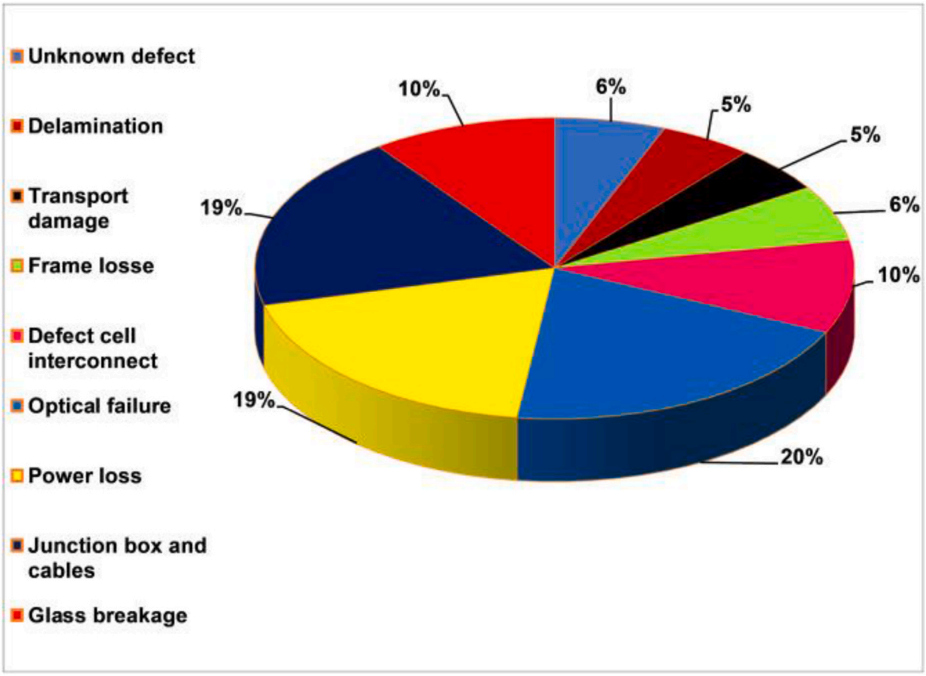


Fig. 6. PV panel failure reasons (Komoto et al., 2018).

reduced energy and cost, the recovered materials may lack high quality, making them unsuitable for the secondary market and hindering economic recycling and metal recovery.

The top recycling treatment is employed to recover high-quality silicon wafers, glass, and valuable materials such as silver, aluminium, and copper. This process involves two key steps: (1) Module delamination and (2) silicon and metals recovery. Module delamination employs physical, thermal, and chemical treatment methods, as depicted in Fig. 7. While the usage of materials in thin-film PVs is lower than in crystalline silicon solar cells, concerns arise regarding the toxicity of tellurium, indium, and cadmium. Additionally, the recycling process of PV panels can lead to the release of highly toxic greenhouse gas emissions (Giacchetta et al., 2013; Rocchetti and Beolchini, 2015).

Fig. 8 outlines the sequence of operations in the recycling process of silicon and other types of PV panels. In this process, the separation of the aluminium frame from the PV panels is achieved using a hammer. Subsequently, the back polymer layer is removed using a blade roller or another mechanical process. The EVA layer from the PV panel is subsequently removed in the form of chips. Following this step, the glass is crushed using a hammer or crusher and rolled over to weaken the adhesive forces between the glass and the EVA layer. In the subsequent step, pieces of the EVA layer, silicon, and metals are sent to a grinding machine to crush into small pieces. The crushed materials are passed through a densimetric separator, resulting in a metal-rich fraction and a polymer-rich fraction (Xuefeng et al., 2021). After this process, the extracted materials undergo thermal and chemical processes aimed at recovering pure valuable metals. Fig. 9 illustrates the recycling process employed by First Solar for CdTe solar cells, boasting a glass recovery rate of around 90% and a claimed 95% recovery of silicon solar cells (Komoto et al., 2018). A detailed exploration of the combined application of these approaches is discussed separately. For ease of reference, Table 2 and Table 3 provide summaries of research articles and patents,

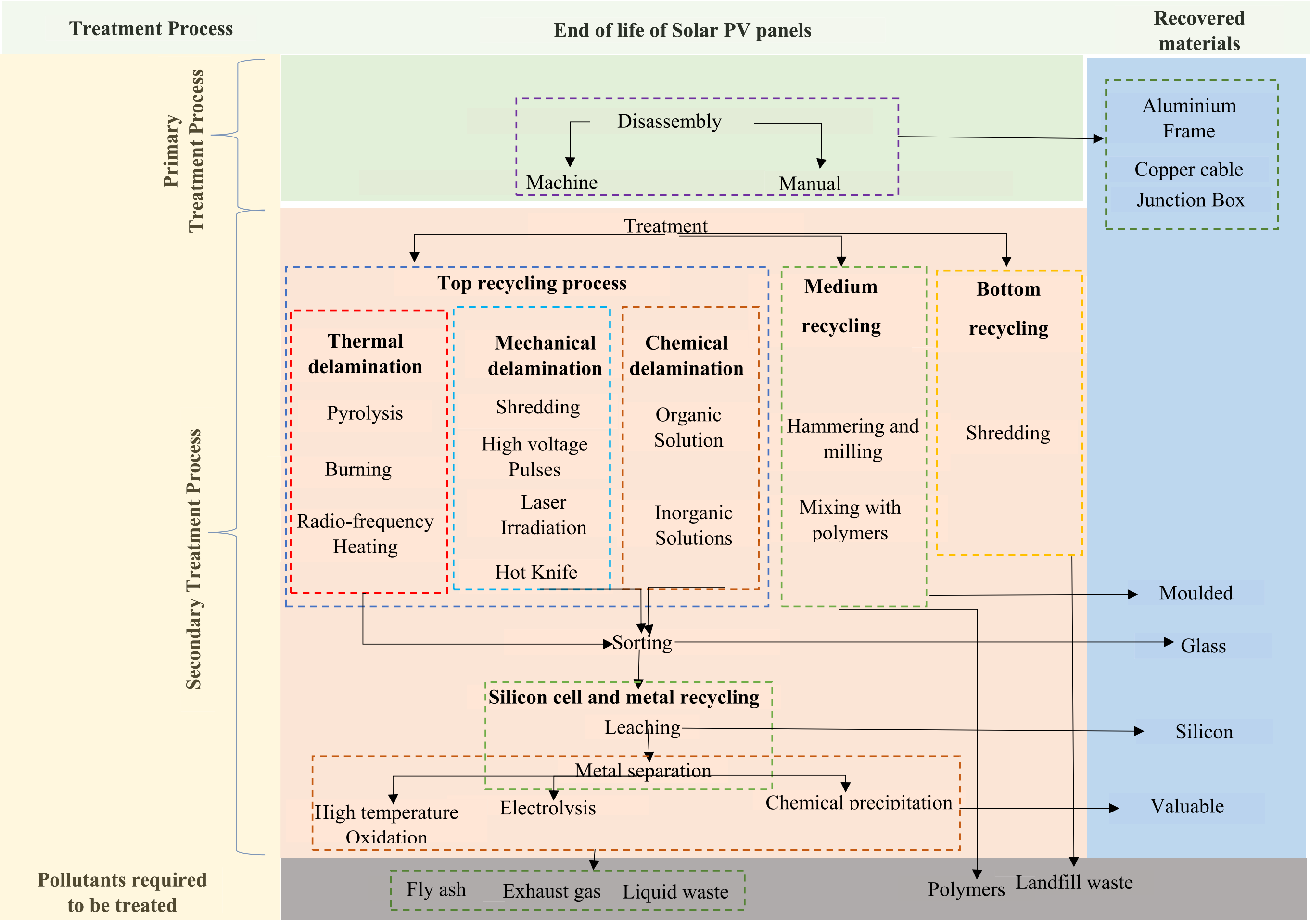


Fig. 7. The Recycling Process for E-waste of silicon-based solar PV Panels. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

respectively, on the recycling methods examined in this review article.

4.1. *Mechanical treatment process*

Physical processes involve mechanical treatments applied to the PV panel, such as shredding and milling (B. Sorensen., 2017) (Granata et al., 2014) (M. Ito, 2016) (Azeumo et al., 2019; Xuefeng et al., 2021). High-voltage pulse (Akimoto et al., 2018; Song et al., 2020; Zhao et al., 2020; Nevala et al., 2019), hot knife (Ramon et al., 2014) (M. Ito, 2016), and laser irradiation methods (Li et al., 2022) are also employed.

In the shredding treatment process, the surrounding aluminium frame, junction box, and cables are removed and then shredded. Subsequently, the toxicity of each component is examined (Savvilotidou et al., 2017). Once the frame component is separated from the PV module, other materials such as iron, silicon, and nickel are extracted through metallurgy [Dias et al. (2018); Granata et al. (2014) recycled silicon solar cells (poly and amorphous) and CdTe PV panels through a two-blade rotor crushing and hammer crushing process. Various processes, including size distribution, X-ray diffraction, and X-ray fluorescence analysis, were conducted to characterize solar cells. After the two-blade crushing process, around 70% of the sample of more than 8 mm was stuck with the EVA layer, as shown in Fig. 10 (a). However, with hammer crushing, EVA cut sheets and back sheets were distributed in more than 8 mm and between 5 mm and 8 mm. Glass was distributed between 1 mm and 5 mm, as shown in Fig. 10 (b). The hammer-crushing process is better than the two-blade crushing process as the pyrolysis process time was less. Strachala et al. (2017) used a physical separation treatment process to recover metals from PV panels. This method selected two damaged and broken polycrystalline silicon solar panels. After removing the aluminium frame, junction boxes, and wires, hydraulic shears were used to roll PV modules and cut them into two pieces, as shown in Fig. 11. A chain crusher shredded these PV modules into pieces, as shown in Fig. 12. After that, spectroscopy of the crushed material was carried out to determine the composition of materials.

Pagnanelli et al. (2017) employed several hammer-crushing processes to obtain appropriate sizing of crushed solar panels. After this process, a sample with a coarse size of more than 1 mm was pyrolyzed, with a size between 0.4 mm and 1 mm directly recovered glass, and less than 0.4 mm reduced metals after the chemical treatment process. Azeumo et al. (2019) initially shredded solar panels using a knife mill. Following processing through medium separation, milling, and sieving, the results showed a recovery of 76% of glass at approximately 100% grade and 100% of metals at around 67% grade. Dias et al. (2018), after mechanical milling for crushing the silicon PV panels, used an electrostatic separator to segregate metal fractions of solar panels. This method predominantly recovered 100 % grade glass by recycling solar PV panels. However, it is found difficult to recover 100 % grade of metals. Shi et al. (2013) implemented a high-voltage pulse method to recover better grades of metals from solar panels. Nevala et al. (2019) conducted a comparison between the conventional crushing method and the high-voltage pulse method to assess the quantity and quality of metals recovered. In the high pulse method, the PV panel was cut into six sample pieces, then inserted into 2 L of a reactor filled with water after crushing the silicon PV panel, used high voltage pulse method to recover

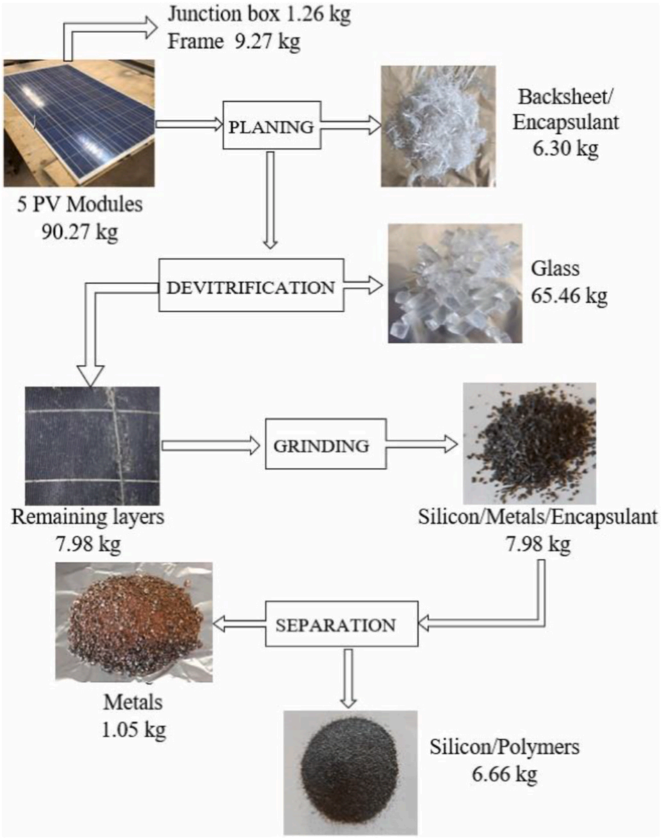


Fig. 8. Block diagram of the recycling process to recycle the PV panels (Fiandra et al., 2023).

valuable metals such as silver, tin, copper, silicon, and aluminium. It was observed that most amounts of metals found in coarse >4 mm and <0.5 mm, and 100 % of copper, aluminium, and 90 % of silver were recovered. Akimoto et al. (2018) implemented a high-voltage pulse method at two stages to crush the PV panel. In the first stage, 20 pulses of around 110 kV separate glass and back sheet solar panels, followed by sieving and dense medium. In the second separation method, the glass layer was crushed to a size fraction of 45–850 μm using 250 pulses at a rate of 90 kV. After separation, there was a 30% increment in silver concentration. Moreover, the processing cost of this method is found to be around 0.0019 $/W, making it an economical solution for recycling PV panels. Zhao et al. (2020) performed a parametric investigation on a high-voltage pulse method to enrich PV panel waste. The observation indicated that an increase in pulse rate resulted in an enhanced degree of crushing. Low pulse number and field strength enhanced the enrichment rate of silver. An appropriate gap between the electrodes may further enhance the recovery of silver. Song et al. (2020) implemented a high voltage fragmentation method wherein under optimized parameters, 95 % of copper, 96 % of silver enriched in <1 mm coarse fraction, 85% of aluminium enriched in 0.25–2 mm, 85 % of lead, and 87 % of silicon in a coarse fraction less than 0.5 mm was obtained. Latunussa et al. (2016) developed a quick hot knife method, funded by the EU Life program, to efficiently separate glass from solar cells within 50 s while preserving the integrity of the glass. Li et al. (2022) innovatively proposed the laser irradiation method to gently separate the Ethylene Vinyl Acetate (EVA) layer from the back of solar PV cells. This process ensures the separation without causing damage to the cells and minimizes environmental emissions as shown in Fig. 13. Xiaoliang et al. (2021) patented a method for separating and recovering photovoltaic modules, involving the removal of the aluminum frame, junction box, and peeling off the Ethylene Vinyl Acetate (EVA) layer to extract tempered glass and silicon solar cells.

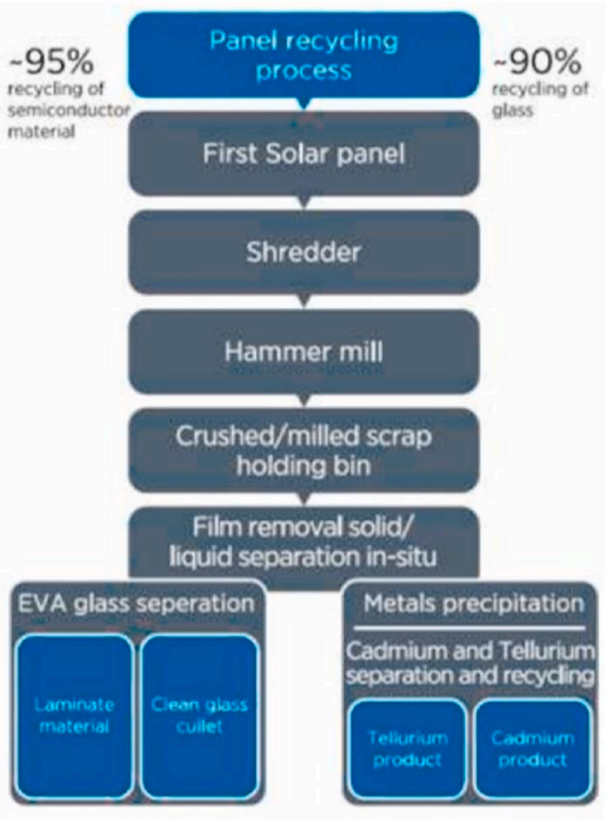


Fig. 9. Stages and flow of recycling process of crystalline silicon and CdTe PV cells adopted by First Solar (Komoto et al., 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.2. *Thermal treatment process*

Pyrolysis is an effective thermal treatment process wherein high heat is applied to the silicon PV panel, leading to the delamination of glass and the EVA layer from silicon-based PV panels. However, it has also been reported that a problem arises with the generation of toxic fumes and gases due to the burning of the EVA layer and the Tedlar layer of the PV panel. Some researchers have introduced a delamination method before the pyrolysis treatment, wherein silicon PV wafers are physically separated from glass (Doni and Dughiero, 2012). There is difficulty in separating glass from PV wafers due to the adhesive material between silicon solar cells and glass. Even when glass is mechanically removed, adhesive material remains stuck to silicon solar cells, making recovery difficult. The pyrolysis thermal treatment process effectively removes adhesive material and all other materials from the PV panel (Dias et al., 2016).

Bohland and Anisimov, 1997 proposed a pyrolysis method to recycle solar PV panels in an inert environment, allowing the recovery of glass, silver, and lead without disposing of them in water. Frisson et al. (2000) introduced another thermal treatment method called pyrolysis in conveyor belt furnaces and fluidized bed reactors. This method introduces the entire PV panel to the furnace, and the EVA layer is decomposed under nitrogen at 450 °C. The reclaimed wafers from the furnace have low efficiency, requiring deep cleaning. Berger et al. (2010) recycled CdTe and CIS PV panels using the attrition and vacuum blasting processes. Wang et al. (2012) used thermal and chemical treatments to recover and recycle silicon solar cells. In the first step, the PV panel was heated at 330 °C to separate Tedlar. In the second step, the EVA layer was burnt at 400 °C to recover solar cells and glass. Further, silicon and copper were recovered through chemical treatment. Doni

Table 2
Non-Patented Literature of delamination Process specified by the various treatment process.

Treatment	Authors	PV panel's type	Method adopted	Recycled Products	Keynotes
Physical	Granata et al. (2014)	Polycrystalline solar cells, Amorphous silicon solar cells CdTe solar cells	Two blade rotors crushing Hammer crushing process	Magnesium, Aluminium, silicon, calcium, Iron, Titanium, zinc, cadmium, tellurium	•Around 70% of fraction was more than 8 mm size was obtained with two blade rotor crushing. •Hammer crushing is found better due to less pyrolysis time.
Physical	Strachala et al. (2017)	Silicon solar panels	Pre-treatment process + Shredding using chain crusher	Crushed solar cells and other materials	•After dismantling, silicon solar cell crushed into pieces by chain crusher •Spectroscopy was performed to analyse recovered material. •100% glass grade and 60% of metal grade recovered
Physical	Pagnanelli et al. (2017)	Silicon solar panels	Multiple hammer crushing process	Crushed solar cells and other materials	•Crushed solar panels of different sizes were obtained which further moved for pyrolysis and chemical treatment process.
Physical	Azeumo et al. (2019)	Silicon solar panels	Shredding on knife mill + magnetic separator + heavy medium separator	Crushed solar cells, glass and metals	•After separation, 76% of glass at grade of around 100 % and 100% of metals at grade of around 67% were recovered.
Physical	Dias et al. (2018)	Silicon solar panels	Milling and crushing with electronic separator	Silicon solar cells and other metals	•Obtained 100 % glass grade and around 70% metal grade
Physical	Nevala et al. (2019)	Silicon solar panels	High voltage pulse method	Silver, tin, copper, silicon and Aluminium	•Copper and aluminium of 100% grade and silver of around 90% grade is recovered.
Physical	Akimoto et al., 2018	Silicon solar panels	High voltage pulse method at two different stages	Glass and Solar cells	•More than 30% increment in silver. •Low operation cost and economic viable.
Physical	Zhao et al. (2020)	Silicon solar panels	High voltage pulse method	Glass and solar cells	•Low pulse number and field strength enhanced the enrichment rate of silver
Physical	Song et al. (2020)	Silicon solar panels	High voltage fragmentation method	Copper, silver, aluminium, lead, silicon	•Copper, silver, silicon, lead and aluminium were obtained in different coarse fractions.
Physical	Latunussa et al. (2016)	Silicon solar panels	Hot knife method (169 kV, 300 pulses, 192.99 J/g + Sieving infrared radiation heating, pulsating knife)	Glass of 100% grade	•High metal enrichment rate •More economical •Reduced greenhouse gas emissions
Physical	Li et al. (2022)	Silicon solar panels	Laser irradiation method (hot air gun + 1064 mm NIR pulsed laser)	Glass and solar cells	•Complete removal of EVA layer. •Reduced greenhouse gas emissions •No effect on PV panels
Thermal	Bohland and Anisimov, 1997	Silicon solar panels	Pyrolysis heating in inert environment	Glass, silver, lead	•Heating PV panels in inert environment (Nitrogen).
Thermal	Frisson et al. (2000)	Crystalline silicon solar cells	Pyrolysis in a conveyer belt furnace Pyrolysis in a fluidized bed reactor	Silicon solar cells	•High quality of solar cells were obtained after processing. •Ecological impact of recycling is high. •Payback period decreases due to more usage of solar cells.
Thermal	Doni and Dughiero. (2012)	Crystalline silicon PV panel	Dielectric heating	Silicon solar cells	•The solar cells heated at 450 °C to delaminate it. •The emit harmful gases needed to be treated. •This process is expensive and energy intensive.
Thermal	Wang et al. (2012)	Crystalline silicon PV panel	Thermal heating	Silicon solar wafers, glass	•Silicon solar PV panel was heated to 330 °C and 400 °C to recover glass and silicon wafers •Silicon and copper was recovered using chemical treatment.
Thermal	Orac et al. (2015)	Crystalline silicon solar cells	Thermal pre-treatment, Acid Leaching	Copper and Tin	•Implemented thermal treatment followed by acid leaching to recover copper and tin from solar PV panel circuit boards.
Thermal	Pagnanelli et al. (2017)	Crystalline silicon cells	Pyrolysis method	Glass	•Glass of silicon solar cells was crushed into granules less than size of 1 mm. •More than 91% of glass was recovered.
Thermal	Shin et al. (2017)	Crystalline silicon solar panels	Pyrolysis treatment	Silicon solar wafers	•Silicon solar panels kept in furnace having temperature around 480 °C. •Unbroken silicon solar wafers recovered which further processed for chemical treatment.
Thermal	Strachala et al. (2017)	Crystalline silicon solar cells	Pyrolysis treatment	Silicon wafers	•Silicon wafers were heated inside the furnace at around 420 °C for 25 min. •The recovery rate and cost was less than chemical process.
Thermal	Fiandra et al., 2019	Polycrystalline silicon solar cells	Pyrolysis in Lenton tubular furnace	Silicon, glass	•Silicon PV panel was cut into pieces of 10 cm × 10 cm

(*continued on next page*)

Table 2 (*continued*)

Treatment	Authors	PV panel's type	Method adopted	Recycled Products	Keynotes
					•Cut pieces were placed into furnace kept at 500 °C. •90% of silicon was recovered.
Thermal	Riech et al. (2021)	Polycrystalline silicon solar cells	1st stage: quartz halogen lamp 2nd stage: 600 °C for 30 min	Silicon, glass	•Complete combustion of polymers
Chemical	Doi et al. (2001)	Polycrystalline silicon solar cells	Immersion in trichloroethylene at 80 °C for 10 days	Silicon wafers	•EVA layer was removed without any damage to solar cells.
Chemical	Kim and Lee. (2012)	Crystalline silicon solar cells	Immersion in O-dichlorobenzene (O-DCB), trichloroethylene (TCE), benzene, and toluene under ultrasonic radiations	Silicon solar cells	•O-dichlorobenzene (O-DCB) is found most effective in dissolution of EVA layer without any damage to silicon solar cells
Chemical	Shin et al. (2017)	Crystalline Silicon solar panels	Organic solvent method	Silicon solar wafers	•Aluminium and silver electrodes were recovered by dissolving in HNO_3 and KOH solution. •Recycled solar cells showed electrical efficiency equal to new silicon solar cells
Chemical	Azeumo et al. (2019)	Crystalline silicon solar panels	Organic solvent method	Silicon wafers	•Immersion of EVA layer in toluene kept at 60 °C for 60 min led to recovery of 95% of silicon solar cells
Chemical	Lovato et al. (2021)	Crystalline silicon solar panels	supercritical CO_2 technology + organic solvent method	Glass, silicon wafers, metal solder tape and back sheet	•Glass, metal solder tape and back sheet were recovered at 100 % rate. •Delamination rate using $ScCO_2$ was reduced by 3.5 times the rate at atmospheric pressure.
Chemical	Tembo et al. (2021)	Crystalline silicon solar panels	Organic solvent method	Silicon solar wafers	•92% of solar wafers were recovered after 24 h s
Chemical	Pang et al. (2021)	Crystalline silicon solar panels	microwave enhanced organic solvent method	Silicon solar wafers	•Trichloroethylene was found most effective to separate EVA layer from solar panels within 2 h.
Chemical	Bruton, 1994	Crystalline silicon solar panels	Inorganic solvent method; Nitric acid, 24 h	Silicon wafers	•Dangerous emissions
Chemical	Yan et al. (2020)	Crystalline silicon solar panels	Inorganic solvent method; KOH-ethanol, 200 °C in muffle furnace for 3 h	Silicon wafers	•!00% recovery rate of silicon wafers •Low environmental emissions •High energy consumption

Table 3
Patented Literature of recycling Process specified by the various treatment process.

Treatment	Patent No	Inventors	PV panel's type	Products	Observation
Physical	CN114226415 A	Wang Xiaoliang He Longguan, Luo Jian	Crystalline Silicon solar cells	Aluminium frame, tempered glass, Silicon,	•Aluminium frame and junction box was removed •Further, EVA layer was peeled off to recover the solar cells.
Thermal	US6063995 A	John Bohland Igor Anisimov	Crystalline solar cells	Glass, Lead, Solar cells	•Crystalline silicon PV panel heated to 500 °C in an inert atmosphere. •Recovered solar cells have electrical efficiency of around 80% of delaminated solar cells.
Thermal	DE4418573 C1	John Weinfurtner	Laminated glass panels	Glass and metals	•Laminated PV panel heated in the furnace for 1 h. •Combusted PV panel supplied to water spray section for quenching. •Metals are separated for further recycling.
Thermal	EP0893250 B1	Karsten Wambach Eberhard Stozel	Crystalline silicon, CIS, CdTe solar cells	Glass and metals	•Laminated solar PV panels are heated at 300 °C in the presence of oxidants to decompose plastic layer. •Metals are further transported for quenching process.

and Dughiero. (2012) employed an electro-thermal process in which silicon solar panels were heated below the decomposition temperature of the EVA layer. This facilitated the removal of glass and solar silicon wafers. Orac et al. (2015) first implemented the pyrolysis method and then followed the leaching method to recover valuable metals such as silver and copper from PV panels. Shin et al. (2017) utilized pyrolysis thermal treatment on polycrystalline silicon solar panels for layer separation. The solar panels were positioned inside the furnace and maintained at 480 °C, as depicted in Fig. 14. The orientation during the process had the glass of the PV panel facing downward, while the Tedlar sheet was facing upward. After this thermal treatment, unbroken solar cells were recovered and processed for chemical treatment.

Pagnanelli et al. (2017) achieved glass recovery by crushing silicon solar panel glass into fine granules (<1 mm) and subjecting it to a 1-h treatment at 650 °C in a furnace, resulting in over 91% recovery. Strachala et al. (2017) proposed a method in which PV module was inserted inside the vessel and heated at 420 °C inside the furnace for over 25 min, as shown in Fig. 15. Fiandra et al., 2019a,b used a Lenton tubular furnace for the thermal treatment of silicon solar cells. After dismantling the aluminium frame, a diamond blade cut the PV panel into 10 cm × 10 cm pieces. The cut pieces were heated in a furnace for 1 h at 500 °C. Ardente et al. (2019) proposed a FRELP method to recycle PV panels after completing their life cycle and recover metals from them. The fundamental steps of the process are illustrated in Fig. 16. This process involved all physical, thermal, and chemical processes in recovering maximum silicon and other metals from silicon PV panels. It has been found that although FRELP is an energy-intensive process, recovery of metals was higher, i.e., 94% aluminium, 90% Copper, 88% Glass, 95% silicon, and 94% silver. Wang et al. (2019) implemented a two-stage heat treatment process for the separation of silicon solar panels. In the first stage, the Tedlar layer was removed by heating at 150 °C for 5 min, followed by pyrolysis treatment at 500 °C to remove the EVA layer. It

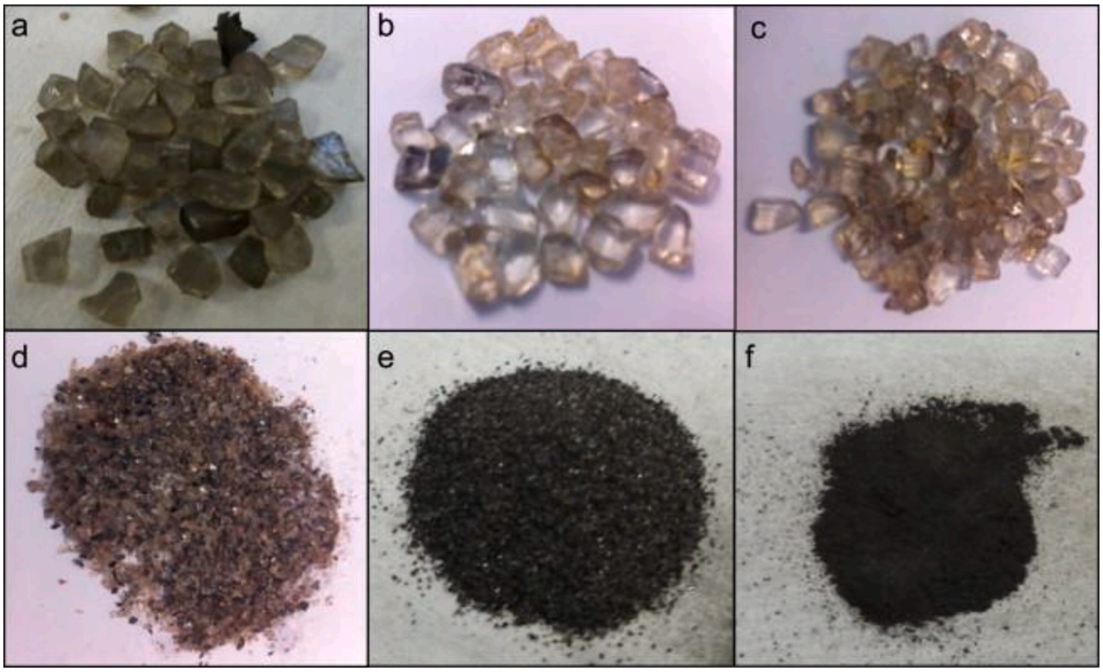


Fig. 10(a). Fractions obtained after two-blade rotor crushing of silicon PV panel (a) > 8 mm, (b) 5 mm–8 mm, (c) 1 mm–5 mm, (d) 0.4 mm–1 mm, (e) 0.08 mm–0.4 mm, (f) < 0.08 mm (Granata et al., 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

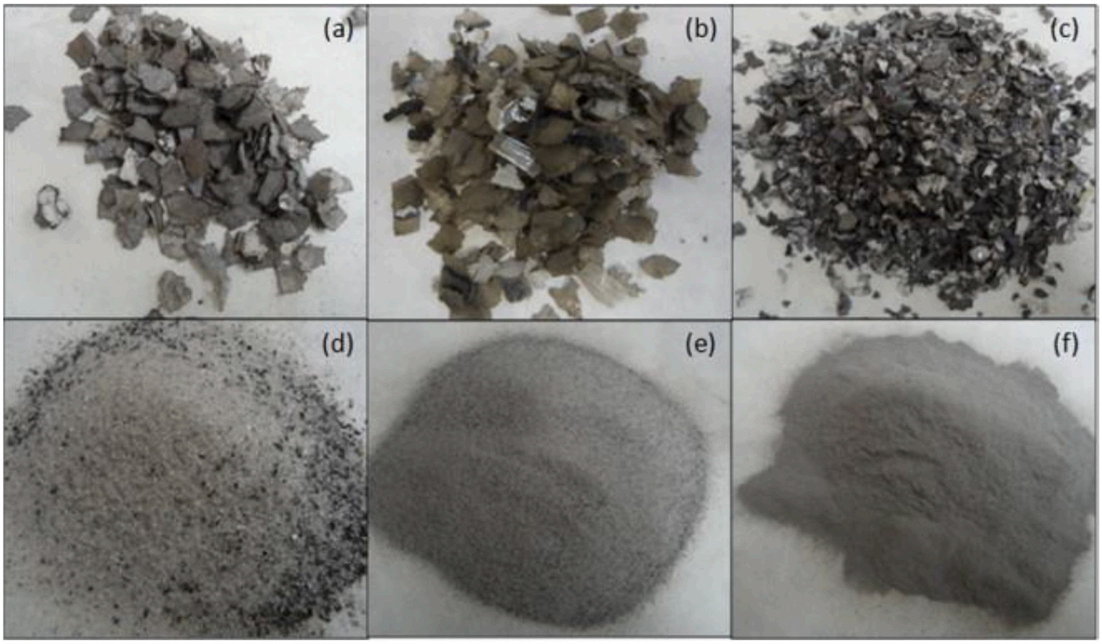


Fig. 10(b). Fractions obtained after hammer crushing of silicon PV panel (a) > 8 mm, (b) 5 mm–8 mm, (c) 1 mm–5 mm, (d) 0.4 mm–1 mm, (e) 0.08 mm–0.4 mm, (f) < 0.08 mm (Granata et al., 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

has been observed that pyrolysis treatment involves two processes, i.e. deacetylation of the EVA layer at 300–400 °C and generations of olefins in temperatures over 400 °C. Farrell et al. (2019) observed that the calorific value of EVA encapsulated in crystalline silicon PV panels is around 39.87 MJ kg^{-1}, the same as that of biodiesel. It means that there is a potential for energy in the polymers of crystalline silicon PV panels which is required to achieve. Dobra et al. (2022) investigated the environmental impact of the pyrolysis process, comparing scenarios with and without the pre-removal of the Tedlar sheet from the PV panel. It has been observed that without the removal of the Tedlar sheet releases a large amount of fluorine and white powder residue after the heat treatment process, which severely impacts the environment and human health. However, pre-peeling of the Tedlar sheet reduces this kind of problem, along with a 45% reduction in the separation time in subsequent components. Riech et al. (2021) employed a two-stage heating process wherein in the initial stage, a quartz halogen lamp was firstly used to loosen the EVA layer and Tedlar layer, which was removed from the PV panel by burning at 600 °C for 30 min in the second stage. In various patented literature, J. Weinfurtner, 1996 filed a patent DE 4418573 C1 on the recycling of laminated PV panels in which

Fig. 11. (a) Removal of an aluminium frame, junction box and wires, (b) cutting of PV panel into two halves (Strachala et al., 2017).

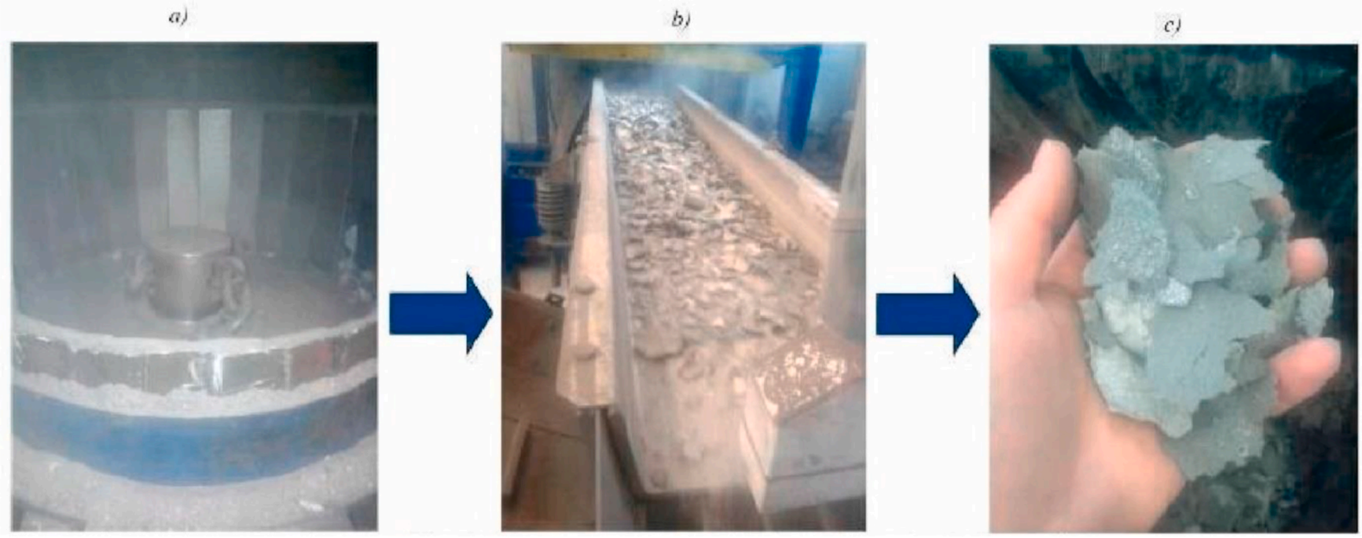


Fig. 12. (a) Chain crusher, (b) Shredding of PV wafers, (c) crushed silicon PV wafers (Strachala et al., 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

laminated solar panel is charged into a fluidized bed furnace kept at 500 °C for 1 h. All organic substances are combusted first and then moved to the water spray section for quenching. The glass and other metals are segregated separately. Bohland and Anisimov. (2000) patented a c-Si solar panel recycling method for First Solar Company (US6063995 A). It involved heating the PV panel at 500 °C, recovering solar cells with 80% electrical efficiency compared to non-recycled cells. Stötzel and Wambach, 2003 patented a thermal recycling method for crystalline silicon, CIS, and CdTe solar cell components. The panels are heated to 300 °C with oxidant agents to decompose the plastic layer, and after cooling, the remaining metal components are recovered. The pyrolysis heating process effectively removes glass and EVA layers from silicon solar panels, recovering 90% of silicon wafers (Nieland et al., 2012). However, concerns about its environmental and economic sustainability have been raised. Pyrolysis consumes high energy, is deemed uneconomical due to gas treatment processes, and emits fluorine gas, posing challenges. Future research needs to address these issues, exploring low-energy combustion fuels and innovative heat recovery for economic and environmentally sustainable PV panel thermal treatment (International Renewable Energy Agency and International Energy Agency, 2016; Wang et al., 2022; Divya et al., 2023).

4.3. *Chemical treatment process*

The delamination of the EVA layer through chemical treatment involves the dissolution of the polymer layer, leading to plasticization of the polymer and the generation of the gel polymer layer (Miller-Chou and Koenig, 2003). However, it has also been observed that different swelling pressures within the EVA layer can cause shattering of the Si-PV cells (Ouano and Carothers, 1980). Chemical delamination is based on organic and inorganic reagents, depending on the solvent types, as shown in Table 2.

In organic delamination methods, Doi et al. (2001) used trichloroethylene to dissolve the EVA layer at 80 °C. Through mechanical swelling and immersion of solar panels in trichloroethylene for 10 days, silicon solar cells were recovered without any damage. Kim and Lee.

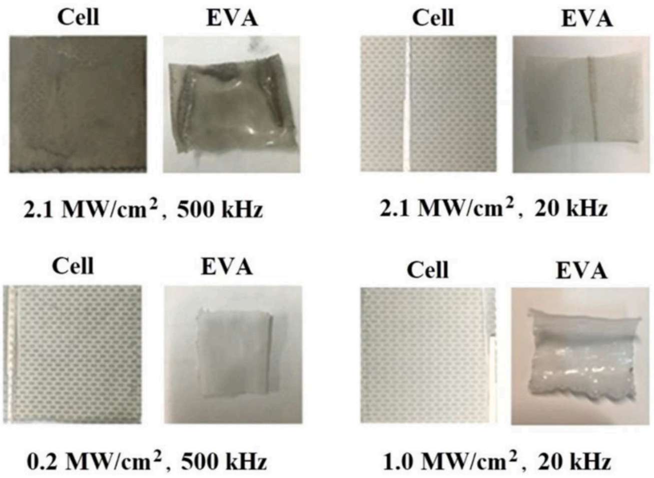


Fig. 13. Influence of power density and pulse repetition rate of laser on EVA debonding effect (Li et al., 2022).

(2012) dissolved the EVA layer of Si-PV panels by immersing it in various organic solvents, including O-dichlorobenzene (O-DCB), trichloroethylene (TCE), benzene, and toluene under ultrasonic radiation. The EVA layer was entirely dissolved in toluene. However, silicon cells were damaged, and in the case of TCE and benzene, pyrolysis and pyrolytic reactions occurred, resulting in the ineffectiveness of dissolving the EVA layer. O-dichlorobenzene (O-DCB) was found efficient in dissolving the EVA layer without damaging silicon solar cells. The dissolution of the EVA layer has been noted to necessitate an extended processing time and results in the generation of volatile organic liquids. The optimization of dissolution processes can be a different research topic in the chemical treatment process (Xu et al., 2018).

Shin et al. (2013) recovered the silicon wafer by dissolving silver and aluminium connections into HNO_3 and KOH solution. The recovered silicon solar cells had an efficiency equivalent to real solar cells based on thermal cycling tests. Azeumo et al. (2019) experimentally observed that immersion of the EVA layer in toluene kept at 60 °C for 60 min led to the recovery of 95% of silicon solar cells. Lovato et al. (2021) used supercritical CO_2 technology to enhance the dissolution rate of the EVA layer in the toluene solution. It has been observed that the delamination rate using $ScCO_2$ was reduced by 3.5 times the rate at atmospheric pressure. Glass, metal solder tape, and back sheets were recovered at a 100 % rate. Tembo et al. (2021) recovered silicon solar cells by immersing PV panels in hexane to separate the EVA layer. Under optimal experimental conditions, 92% of solar wafers were recovered after 24 h. Pang et al. (2021) proposed a microwave-enhanced EVA layer method in which microwaves were used to enhance the separation speed of different layers of PV panels. Among different swelling agents, trichloroethylene was identified to be the most effective in separating the EVA layer from solar wafers within 2 h.

Among inorganic solutions, Bruton, 1994 proposed an effective solution in which nitric acid is used to separate the EVA layer from the PV panel. A problem with nitric acid is the emission of toxic gases such as NO_2 during leaching Nover et al. (2017); Finke et al. (1996); Yan et al. (2020) used KOH-ethanol solutions to separate the EVA layer from the PV panel. Silicon solar cells were recovered at a 100% rate when treated for 3 h in a muffle furnace kept at 200 °C. In comparison to benzene and trichloroethylene, KOH-ethanol demonstrated a superior recovery rate with lower environmental emissions.

4.4. *Methods of recycling silicon wafers and recovery of silicon*

Table 4 represents the chemical etching processes adopted by various authors to recover silicon from silicon solar PV wafers. This technique eliminates silver electrodes, anti-reflective (AR) layers, n-p junctions, and aluminium coatings from PV panels. The composition ratio, temperature, and treatment duration of the etching solution are crucial parameters that strongly influence the purity of the recovered silicon. The silicon recovery process from silicon wafers is segmented into two categories.

In the first category, low-grade silicon powder is recovered by a simple etching process to produce anode materials for lithium-ion batteries. Eshraghi et al. (2020) conducted a leaching process on the recovered silicon wafers using an alkali acid, resulting in the elimination of substantial impurities such as silver, lead, and aluminium. The

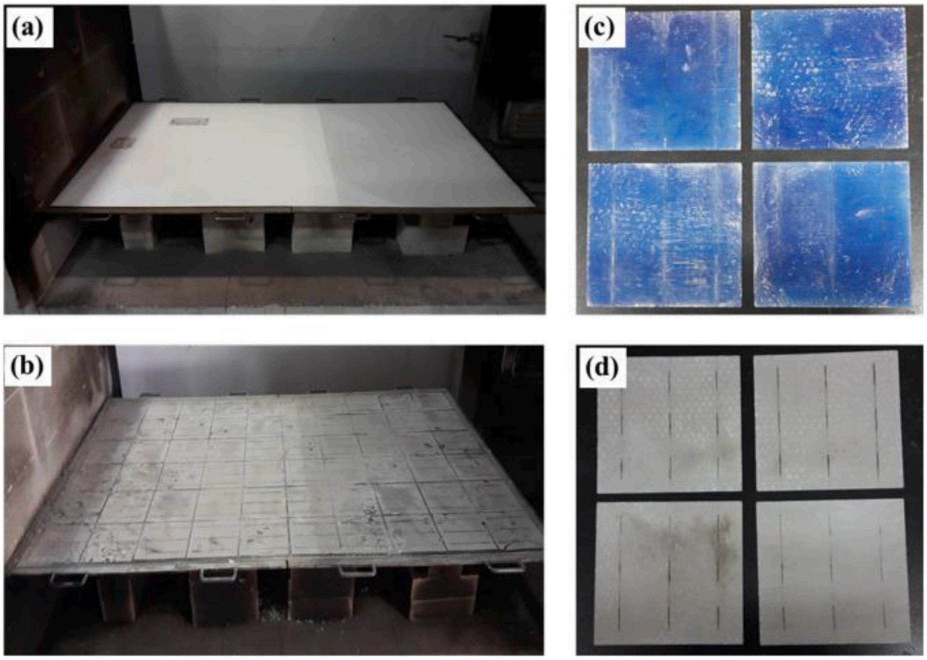


Fig. 14. Solar module kept in furnace to recover silicon solar wafers. (a) Before thermal process; (b) after thermal process; (c) Solar panel surface; (d) Tedlar surface of Solar panels (Shin et al., 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

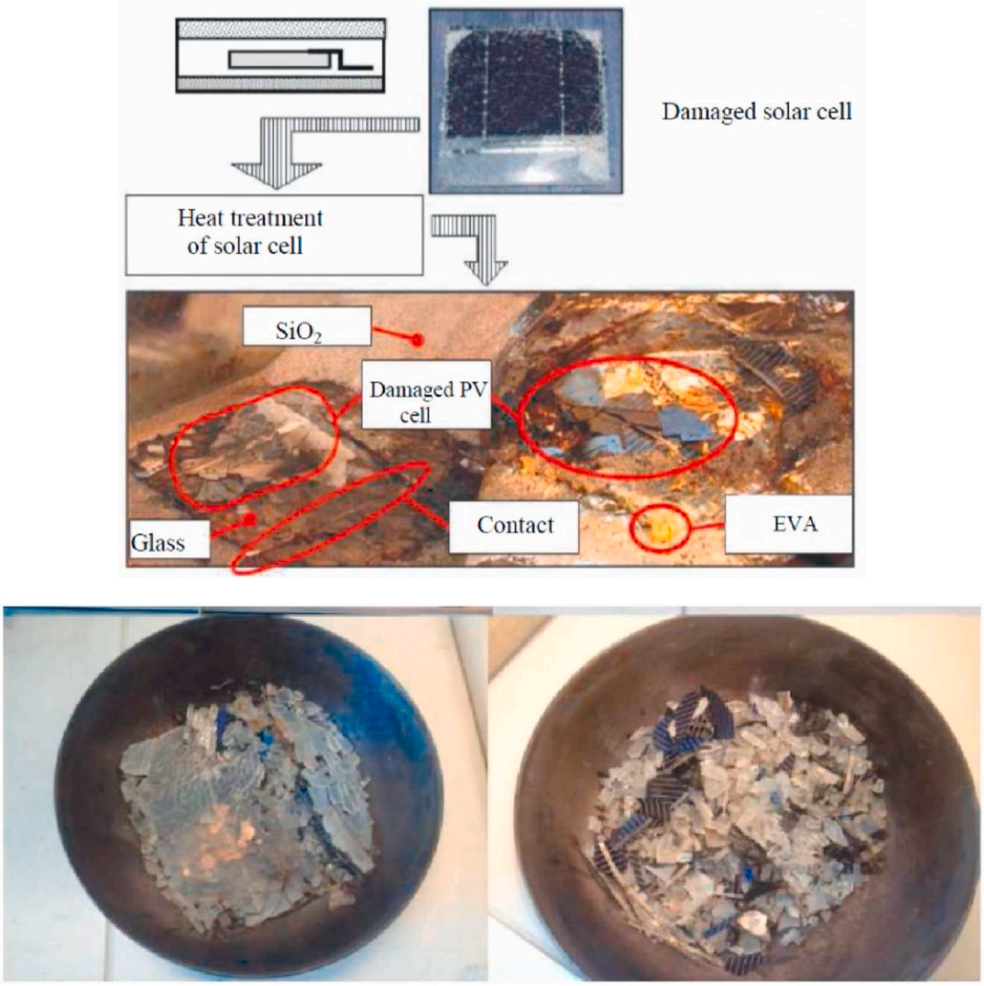


Fig. 15. Thermal recycling of Crystalline silicon PV wafers (Strachala et al., 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

recovered silicon was Nano-sized through a milling process to make anode materials for lithium batteries. Zhang et al. (2021) adopted a chemical etching process to remove silver and aluminium electrodes from silicon wafers and convert micronized silicon to porous silicon using an alloying/dealloying approach in molten salt.

In the second category, the silicon wafers of a certain thickness and high purity are recovered using a highly precise etching process. Two distinct types of etching solutions are utilized for the recovery of silicon wafers, namely, etching solutions containing hydrofluoric acid and those without hydrofluoric acid. Klugmann-Radziemska and Ostrowski, 2010 employed a 30% aqueous KOH solution to eliminate the aluminium coating, and a mixture of HNO_3, HF, CH_3COOH, and Br_2 to remove the silver coating, anti-reflective (AR) coating, and n-p junctions. Kang et al. (2012) submerged silicon wafers in an etching solution comprising hydrofluoric acid (HF), nitric acid (HNO_3), sulphuric acid (H_2SO_4), acetic acid (CH_3COOH), and distilled water (H_2O) for a duration of 20 min. This process resulted in the recovery of 86% of 99.999-grade silicon. Wang et al. (2012) used chemical etching in three different steps. In the first step, solar wafers were immersed in $HCL/H_2O_2/H_2O = 1:1:5$ solutions at 80 °C to remove aluminium electrodes. In the subsequent step, hydrofluoric acid (5%) was utilized to eliminate the anti-reflection coating and silver electrodes. In the third step, sodium hydroxide (25%) was employed to remove the n-p junction. 62% of the Silicon of 99.99 grade was recovered after completing the chemical etching. Due to the toxic nature of the hydrofluoric solution, various research used phosphoric acid (H_3PO_4) in the chemical etching process. Jung et al. (2016) used HNO_3/H_3PO_4/KOH solution to remove aluminium and silver electrodes, AR coating, and n-p Junctions, respectively, with a recovery rate of 80% of silicon. Park et al. (2016) used a grinding process to remove the anti-reflection coating and n-p junction, which was very suitable for reducing the cost of the chemical etching process. Huang et al. (2017) immersed silicon wafers in nitric acid (HNO_3), hydrofluoric solution (HF), and sodium hydroxide (NaOH) for 20 min and recovered silicon at a recovery rate near 90%. Shin et al. (2017) recovered silicon from EOL solar panels and fabricated lead-free silicon solar panels in three steps. In the first step, nitric acid (HNO_3) and potassium hydroxide (KOH) were used to dissolve silver and aluminium, respectively. In the second step, phosphoric acid (H_3PO_4) contained in the paste removes the anti-reflection coating. In the final step, silicon wafers were immersed in KOH solution to extract silicon to make lead-free solar panels using 60Sn–38Bi–2Ag solder. Punathil et al. (2021) recovered 99.9% of pure silicon by immersing silicon wafers in the $NaOH/HNO_3/H_3PO_4$. Xu et al. (2022) used $HCL/HNO_3/HF$ to remove the aluminium coating, silver electrodes, and anti-reflection coating. A novel method named metal-assisted chemical etching (MACE) is adopted to manufacture ultra-low reflective silicon wafers.

Chemical etching silicon processing for recycling PV panels faces challenges, including high costs, emissions of pollutants, silicon loss, and less efficient solar cells compared to commercial ones (Huang et al., 2017; Shin et al., 2017). Ongoing research aims to address these issues and improve the efficiency and sustainability of the chemical etching process for recycling PV panels in the future.

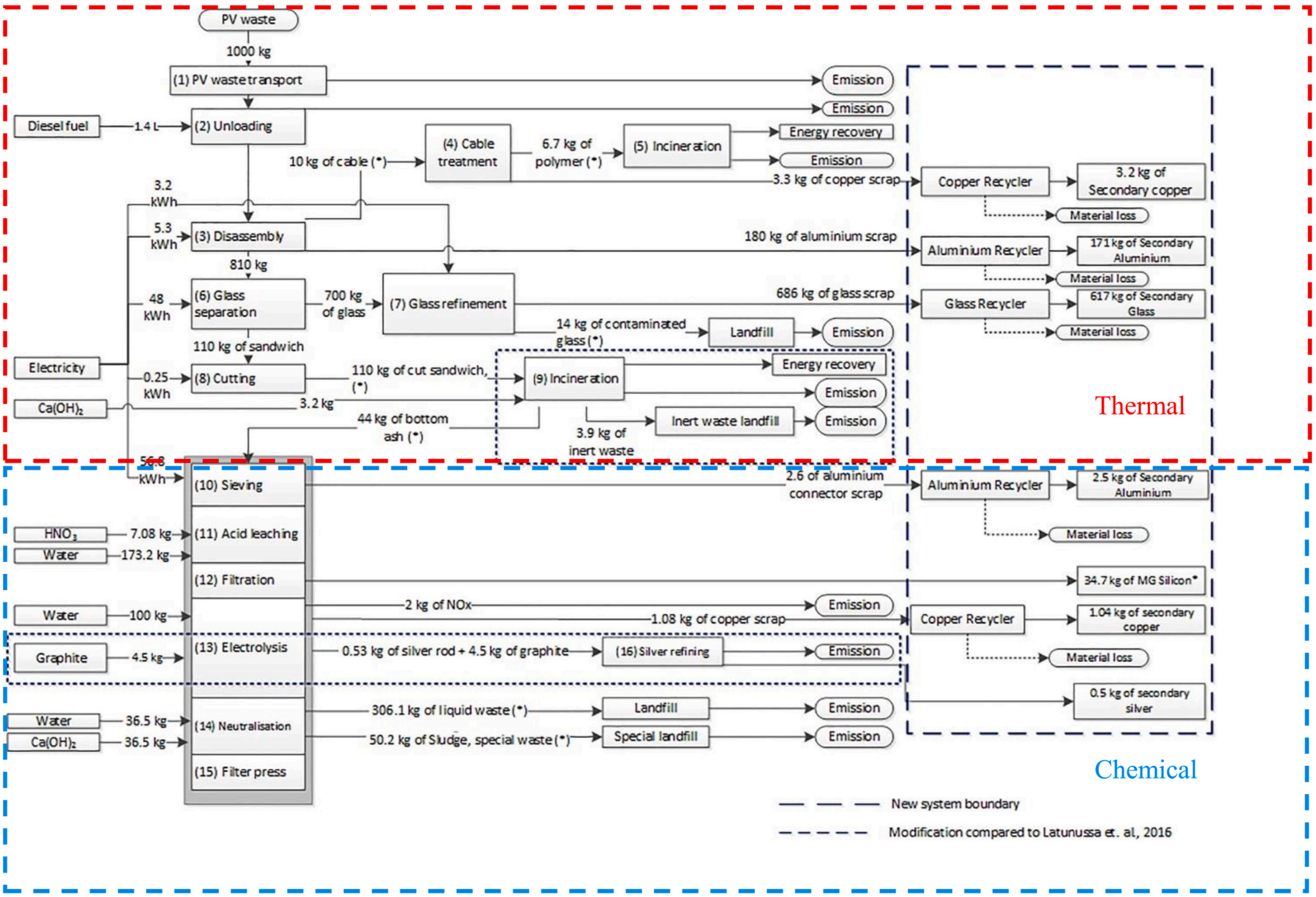


Fig. 16. Input and output flows of FRELP recycling process (Ardente et al., 2019).

4.5. *Methods of recovery of valuable metals*

Silicon photovoltaic panels contain valuable metals such as copper, aluminium, and silver, which must be extracted after EOL. Table 5 represents the methods adopted by various researchers to recover valuable metals from silicon-based Photovoltaic solar panels. Wang et al. (2012) adopted a chemical etching process wherein Nitric acid with sulphuric acid as an oxidation agent is used to extract copper from PV panels. Dias et al. (2016) immersed solar PV panels in nitric acid and sodium chloride solution, which led to the extraction of 94% pure silver. Savvilotidou and Gidarakos. (2020) evaluated the amount of silver extracted from mono, poly, and copper indium selenide photovoltaic panels in three different recycling methods, i.e. (a) pyrolysis and gravimetric separation method (b) mechanical milling and pyrolysis method, as well as (c) pyrolysis and chemical treatment. Pyrolysis and gravimetric separation methods are the most effective, which recovered 91.42 %and 94.25 % silver from crystalline panels and 96.10% silver from CIS PV panels. Yang et al. (2017) used methane sulphonic acid (MSA) with an oxidation agent (hydrogen peroxide) to extract silver from photovoltaic panels. Using MSA led to the extraction of 99.99% pure silver after electrorefining. Chung et al. (2021) used iodine potassium iodide solution to recover silver from the PV panel during leaching. Over 95% of silver was extracted from the PV panel within 5 min of leaching. Modrzynski et al. (2021) introduced an electrochemical leaching process wherein boron-doped diamond was used as an electrode and sulphuric acid as an oxidant, leading to the recovery of 88% pure silver and 99% pure copper. Lim et al. (2021) proposed a wire explosion method using a high voltage pulse, which proved to be more environmentally friendly than pyrolysis and chemical leaching methods, as it didn't involve the use of chemical agents. The problem associated with this specific method is the low recovery rate of silver (69%), which must be resolved in future research work.

5. Economic analysis of recycling of solar PV panels

Recycling solar photovoltaic panels to recover materials, especially silicon, is a critical sustainability challenge. Recovering materials from waste for use in manufacturing new products can significantly reduce the demand for virgin materials, offering notable environmental and economic benefits (A. Paiano, 2015) (Cucchiella and Dadamo, 2012).

The economic potential of the recycling process is typically assessed through various factors and calculations which are discussed below:

$$EP = \sum_{i=1}^{n} (r_i \times a_i \times p_i) \tag{5}$$

where ri, ai, and pi are the recovery rate (%), the content (g/ton), and the price ($/g).

Fig. 17 illustrates the cost analysis (Private and external) conducted by Markert et al. (2020) in the PV recycling process. The costs are categorized into process cost, investment cost, environmental externality cost, equipment cost, recovered metals cost, transportation cost, policy benefit cost, and landfill tipping cost.

$$\text{Total cost of PV recycling} = \sum \text{private cost} + \sum \text{external cost} - \sum \text{benefits} \tag{6}$$

$$\text{The private cost} = \text{Investment cost} + \text{Process cost} + \text{Transport cost.} \tag{7}$$

In calculating private costs, PV recyclers need to cover expenses

Table 4
Recycling process of silicon from PV panels.

Authors	Process and key parameters	Recovery rate	Observation
Klugmann-Radziemska and Ostrowski, 2010	Etching process: KOH (30%), 60 °C–80 °C, 2–3 min for removal of Aluminium coating HNO_3 (65%), HF (40%), CH_3COOH (99.5%) + Br_2 40 °C, 9 s	NA	Etching solutions needed to be modified as per the kind of PV cells to be recycled.
Kang et al. (2012)	Etching process: HNO_3 (70%), HF (48%), CH_3COOH (99%), H_2SO_4 (97%)	86% of 99.999 grade silicon	The addition of surfactants improved recovery rate of silicon.
Wang et al. (2012)	HCl: H_2O_2:H_2O (1:1:5), 80 °C used for removal of aluminium coating HF (5%) for removal of anti-reflection coating NaOH (25%) for removal of n-p junction	62%	Huge loss of silicon during NaOH chemical etching process.
Jung et al. (2016)	HNO_3 (5 mol/L), RT, 1 h for removal of aluminium coating H_3PO_4 (90%), 160 °C, 60 min for removal of silver electrodes KOH (45%), 80 °C, 10 min for removal of AR and n-p Junctions	80%	Partial loss of silicon during the etching process.
Park et al. (2016)	Removal of Ag electrodes: HNO_3 (60%), RT, 120s Removal of AR layer and n-p junctions: Mechanical grinding, Removal of Al coating: KOH (45%), 80 °C, 10 min	N/A	Recovered silicon meet requirement of solar cell fabrication.
Huang et al. (2017)	Etching process: HNO_3 (30%), HF (10%), NaOH(3%), 50 °C, 20 min	90%	The recovered silicon meets the requirement to manufacture new silicon solar cells.
Shin et al. (2017)	HNO_3 (60%), RT, 5 min for removal of silver electrodes KOH (45%), 80 °C, 8 min for removal of aluminium coating Etching paste containing H_3PO_4, 320 °C, 2 min for removal of AR layer and n-p junction	NA	Extracted silicon is used to make lead free silicon solar cells
Eshraghi et al. (2020)	Etching process: KOH (8 mol/L), 60 °C, 8 min for removal of Aluminium coating HNO_3 (8 mol/L), 80 °C, 8 min for removal of silver electrodes Ball milling	N/A	•Recovered nanosized silicon fulfilled the need of expansion resistant silicon anodes for lithium Ion batteries •Provided 1400 mA h/g capacity
Punathil et al. (2021)	NaOH (10 mol/L), 63 °C, 5 min for removal of aluminium coating HNO3 (6 mol/L), 70 °C, 5 min for removal of silver electrodes H_3PO_4 (90%), 70 °C, 45 min for removal of anti-reflection coating and n-p junction.	99.99%	• NaOH is found more economical than KOH solution.
Zhang et al. (2021)	Etching Process: $HNO_{3,}$ 80 °C, 10 min for removal of silver electrodes H_3PO4 (90%), 180 °C, 30 min, magnetic stirring for removal of AR layer NaOH (45%), 80 °C, 5 min for removal of aluminium layer	NA	•Recovered silicon powder used to made lithium ion batteries that provided capacity of 2427.7 mA h/g
Xu et al. (2022)	HCl (18–24 wt%, RT, 10–15 min) for removal of silver electrodes, HNO_3 (30 wt%, 50 °C, 10 min) for removal of aluminium electrodes, HF (20–30 wt%, RT, 5 min) for removal of anti-reflection layer MACE (Cu2+, Ag+), HF, H_2O_2, RT, 5 min for removal of Removal of n-p junctions and anti- reflection texture fabrication processes HNO_3 (30 wt%, RT, 15 min), HCL: H_2O_2: H_2O (1:1:6), 80 °C, 20 min for Removal of residual Nanoparticles	NA	•Recycled solar silicon wafers are manufactured having high electrical efficiency than the commercially available solar cells.

related to various aspects of the recycling process, including investments in instruments, materials, and electricity for operation. Recyclers also incur transportation costs for moving damaged PV panels to recycling plants and tipping or disposal costs for non-hazardous waste. These disposal costs include expenses for handling contaminated glass, fly ash, liquid waste, and sludge on land. Throughout the recycling process, various resources such as electricity, diesel, nitric acid, water, and calcium hydroxide are consumed. External costs encompass environmental damage caused by the release of pollutants during recycling and by vehicles transporting damaged PV panels. Incineration during the landfilling process is also considered in the analysis.

In the investment cost, it is crucial to consider both one-time costs and operating costs related to machines used for recycling PV panels, labour costs, and the collection of PV panels. Transportation costs are derived from data provided by Latunussa et al. (2016), considering factors such as distance traveled, fuel costs, and vehicle efficiency. The environmental cost is determined by multiplying the emissions generated during the recycling process by the cost associated with the damage caused by those emissions. This approach aims to quantify the environmental impact in economic terms (Celik et al., 2016).

$$\text{Environmental cost} = \text{Emissions (Kg)} \times \text{Damage cost (\$/kg)} \tag{8}$$

According to the study by Latunussa et al. (2016), approximately 375 kg of waste is generated in the recycling process for every 1000 kg of solar panels.

Fig. 18 illustrates the comprehensive cost breakdown for the complete recovery of End-of-Life (EOL) PV panels. Negative costs represent the revenue generated from the recycling of PV panels, while positive costs represent the private and external costs incurred in the recycling process. Specifically, for recycling crystalline silicon PV panels, the private cost and external cost are approximately \$6.72/m^2 and \$5.71/m^2, respectively. The economic value of the valuable metals is \$13.62/m^2, resulting in a profit of \$1.19 per recycling of 1 m^2 of crystalline silicon PV panels. The breakdown of total revenue generated after selling the recovered valuable materials is as follows: 46% (aluminium), 25% (silver), 15% (glass), 11% (silicon), and 3% (copper). This total revenue can be further increased by enhancing the recovery rate of silver. It is estimated that with a 25% increase in the recovery rate of silver,

Table 5
Recycling process of silicon from PV panels.

Authors	Process and key parameters	Recovery rate	Observation
Savvilotidou and Gidarakos. (2020)	pyrolysis and gravimetric separation method., mechanical milling and pyrolysis method, pyrolysis and chemical treatment.	91.42 %and 94.25 % silver from crystalline panels, and 96.10% from CIS PV panel.	•Pyrolysis and gravimetric separation method is found to be most effective
Yang et al. (2017)	Chemical leaching process; MSA:H_2O_2 (90:10)	99.99% pure silver	•MSA is found better than nitric acid with environmental friendly benefits.
Chung et al. (2021)	Chemical leaching process; I_2-KI	More than 95% pure silver	•Less environmental impact with good rate of silver extraction
Modrzynski et al. (2021)	Electro-Chemical leaching process; H_2SO_4 (5 mol/L) as oxidising agent and Boron doped diamond as electrode	Silver: 88% Copper: 99%	•No hazardous and volatile chemical
Lim et al. (2021)	wire explosion method	Silver; 69%	•Low recovery rate of silver •No chemical agents and environmental friendly
Wang et al. (2012)	Chemical leaching process; NHO_3, H_2SO_4	Copper: 85%	•Copper loss during the acid etching process adopted to remove lead/silicon alloy.
Dias et al. (2016)	Chemical leaching; Nitric acid (64%) + NaCl (99%)	Silver concentration yield: 94%	•Mechanical milling with chemical etching method is found more effective than pyrolysis and chemical method in extraction of silver from the PV panel.

the revenue would rise to \$16.22/m^2 (Fortier et al., 2019).

In a comparison between the private and external costs of virgin materials and materials recovered after the recycling of PV panels conducted by D'Adamo et al. (2017), Fig. 19 illustrates that the recycling and recovery process yield societal and environmental benefits. The private and external cost of virgin materials sourced from the earth's crust is estimated to be around USD 90/m^2. The recycling cost, encompassing all expenses, is approximately \$12.43/m^2, without factoring in the benefits of recovered materials. When considering the benefits of recovered materials, the total cost of recycling PV panels is estimated to be around \$1.19/m^2. This suggests that it is economically and environmentally advantageous to fabricate PV panels from recovered materials rather than using virgin materials (Li et al., 2018).

6. Environmental impact of the recycling treatments

The recycling of silicon-based solar PV panels is still in its early stages, and researchers have identified both advantages and disadvantages associated with this process. Here are some key points.

6.1. Advantages

Carbon footprint reduction: As per the findings of Shao et al. (2023), the recycling of photovoltaic (PV) waste holds the capability to decrease carbon dioxide (CO_2) emissions by 1.1 E+11 kg, conserve 1.1 E+12 kg of industrial water and produce 3.6 E+11 MJ for primary energy consumption. Additionally, the net economic benefits are expected to reach 13 billion USD. In another investigation by Riahi et al. (2023), it was discovered that utilizing recovered silicon from recycled PV panels could lead to a substantial reduction in carbon dioxide (CO_2) emissions compared to the conventional silicon carbide production using the Acheson Process.

Resource Conservation: Recycling PV panels is crucial to prevent the leaching of hazardous metals into natural resources, preserving both natural resources and rare metals (Zhang et al., 2023; Breyer et al., 2015), thereby contributing to the prevention of water contamination (Tawalbeh et al., 2021).

Energy Savings: Studies indicate that solar PV silicon wafers manufactured from recovered silicon require less energy compared to producing new wafers (Müller et al., 2005).

Reduced Environmental Impact: Incorporating reclaimed glass, silicon, and metals into the manufacturing of silicon photovoltaic (PV) panels has been noted to alleviate the environmental impact across diverse categories of environmental effects (Corcelli et al., 2015).

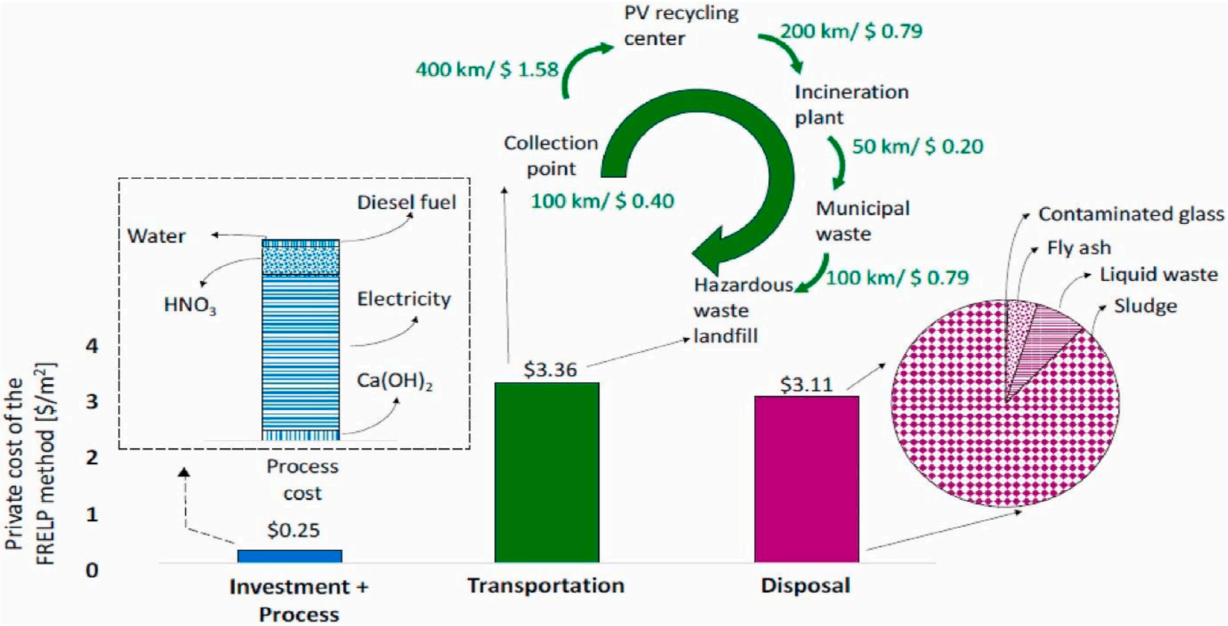
6.2. Disadvantages

Emissions of toxic gases and chemicals: There are apprehensions regarding the environmental consequences associated with the recycling process, including emissions of toxic gases during pyrolysis, energy consumption in mechanical processes, and emissions of reagents in chemical recycling Tammaro et al. (2015); Masoumian and Kopacek, 2015; Bogacka et al. (2020) explored the pyrolysis technique for recycling photovoltaic (PV) panels on a laboratory scale in their study. The thermal treatment of 0.589 kg of crushed PV panels was conducted using 4.9 kWh of electricity, lasting 75 min. Throughout the pyrolysis process, the original solid waste was transformed into 0.313 kg of solid material, 0.143 kg of liquid containing hydrocarbons, and 0.133 kg of gases consisting of CO_2, CO, H_2, as well as halogen gases such as bromine, chlorine, and fluorine. The associated indirect emissions were measured at around 1.7 kg CO_2 equivalent per kilogram of silicon (CO_2e/kg Si) during pyrolysis method.

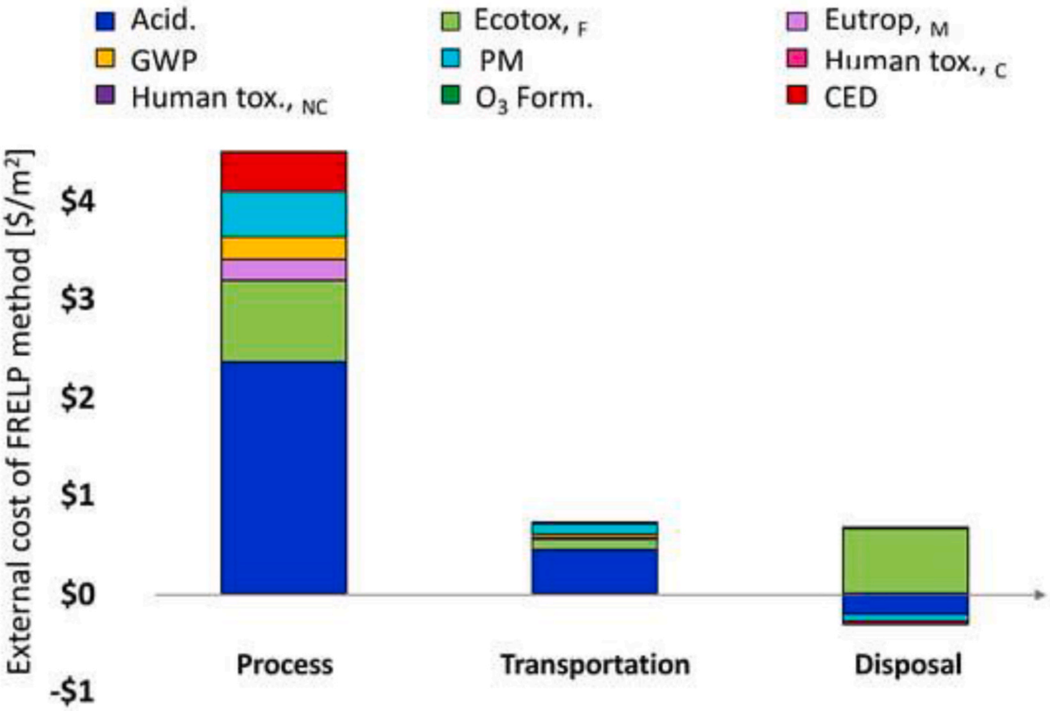
Emissions of Hazardous Elements: During the pyrolysis process, the occurrence of hazardous elements such as lead (Pb) and cadmium (Cd) in flue gases necessitates treatment to avert environmental damage. It can be treated with the use of an electronic precipitator or fabric filter (Jayapradha and Barik, 2023). The chemical treatment process may produce toxic by-products such as nitrogen oxides, fluorides, and silicon species, posing challenges for disposal (Klugmann-Radziemska and Ostrowski, 2010). The environmental impact associated with chemical-based processes like nitric acid dissolution, solvent usage, and chemical etching is considerably higher when compared to the thermal pyrolysis method (Maani et al., 2020).

7. Policies for recycling PV panels and recovery of metals

Researchers, including S.F. Baldwin, 2015, anticipate that solar photovoltaic (PV) panels will generate the highest volume of waste per unit of energy compared to other electricity generation sources. The disposal of over 60 million tons of electronic waste from PV panels, containing hazardous substances like lead, chromium, and cadmium, poses significant environmental risks if landfilling is the chosen disposal method (Weckend et al., 2016). Projections indicate that the PV recycling industry's value is poised to reach US\$ 450 million by 2030 and is forecasted to experience significant growth, reaching US\$ 15 billion by 2050 (Domínguez and Geyer, 2017). To address the environmental impact of products like solar PV panels, governments worldwide have implemented environmental management strategies, including product stewardship schemes and extended producer responsibility (EPR). However, specific directives and responsibilities for PV panel e-waste



(a)



(b)

Fig. 17. (a) Represents private cost (a) and external costs or environmental cost (b) occur in the recycling process of PV panels (Markert et al., 2020).

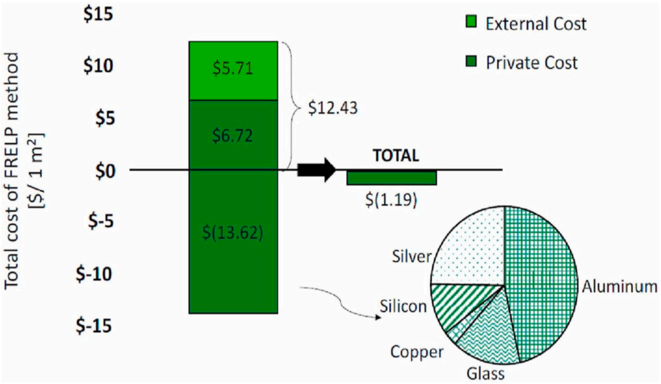


Fig. 18. Total cost breakdown of full recovery of recycled PV panels (Divya et al., 2023).

are often lacking. Comprehensive legislative measures are crucial for the collection, transportation, and recycling of PV panel e-waste to ensure sustainable development. Several countries, especially those with substantial solar PV capacity, have already implemented legislation for the recycling and management of electronic waste, particularly from photovoltaic panels.

European Union recycling regulations: In 2003, Europe introduced recycling directives, namely the Waste Electrical and Electronic Waste Directive (WEEE) (Shittu et al., 2021) and Hazardous Material Restriction (RoHS) (Michalak et al., 2023), with the aim of reducing electronic waste disposal in landfills. RoHS specifically regulated and monitored the usage of certain materials, while WEEE oversaw the collection, treatment, and disposal of electronic items, imposing design restrictions to facilitate recycling. According to these regulations, producers manufacturing electronic items within Europe or introducing electronic products into the EU market must comply with Product Conformity Assessment (PCA) requirements (Liu et al., 2023). Additionally, they are responsible for managing electronic waste, regardless of the product's manufacturing location (Ali et al., 2023). In 2012, the WEEE directive underwent a revision (2012/19/EU) to encompass the management of electronic waste, including PV panels, across all European countries. The directive set targets to achieve a recycling/recovery rate of 75%/65% in 2016, increasing to 80%/75% in 2018 and 85%/80% in 2020 (Majewski et al., 2021). The EU mandated that companies contribute a specified amount of funds dedicated to treating e-waste from electrical and electronic items. The deposit amount depends on the units of electrical and electronic products sold to private consumers, regulated by the Business-to-Consumer regulation (B2C). Producers are also responsible for managing e-waste generated by entities other than private consumers, termed Business-to-Business equipment. Presently, B2C regulations cover 90% of e-waste, but the potential growth of extensive solar farms in the future may elevate the significance of B2B regulations ((Majewski et al., 2021; Ali et al., 2023; Weckend et al., 2016).

Germany entered the photovoltaic (PV) market in 1990, steadily expanding its installation capacity to meet the growing demand for clean and renewable energy. In 2015, Germany revised its Waste Electrical and Electronic Equipment (WEEE) regulations, known as Elektroaltgerategesetz or ElektroG, effective from October of that year. To ensure complete recycling treatment, each manufacturer must provide financial security for every PV panel sold (Aşkın et al., 2023). The German government enforces both business-to-consumer (B2C) and business-to-business (B2B) regulations to manage the electronic waste of PV panels (Sharma et al., 2019). Pay-as-you-go (PAYG) systems are widely utilized to cover the expenses associated with the collection system operation, instantaneous system, and recycling of PV waste products. Solar World AG, a German company specializing in monocrystalline PERC solar cells, actively recycles PV modules, following Germany's guidelines.

In 2014, Italy adopted the EU's Waste Electrical and Electronic Equipment (WEEE) directive, classifying PV panels as WEEE. Legislation mandates PV module manufacturers to join a National Register, contributing to the WEEE handling system. Manufacturers must ensure proper PV panel collection, disposal, and recycling (Khetriwal et al., 2009).

In 1991, the Swiss government initiated the Swiss Environment and Energy Systems (SENS), primarily focusing on white goods recycling. By 2014, Swiss policies aligned with European standards for Waste Electrical and Electronic Equipment (WEEE). SWICO RECYCLING, founded under the Swiss Industrial Association, supports the collection and recycling of electronic equipment. In 2015, it expanded to include photovoltaic (PV) panels, setting up dedicated collection points. SENS' facilities have proven effective, recovering 80–90% of silicon from PV panel waste (Sharma et al., 2019).

The Norwegian environmental agency established EE-Registeret, financially supporting five companies—Elretur AS, Elsirk AS, ERP Norge AS, RENAS AS, and Eurovironment AS—for electronic item

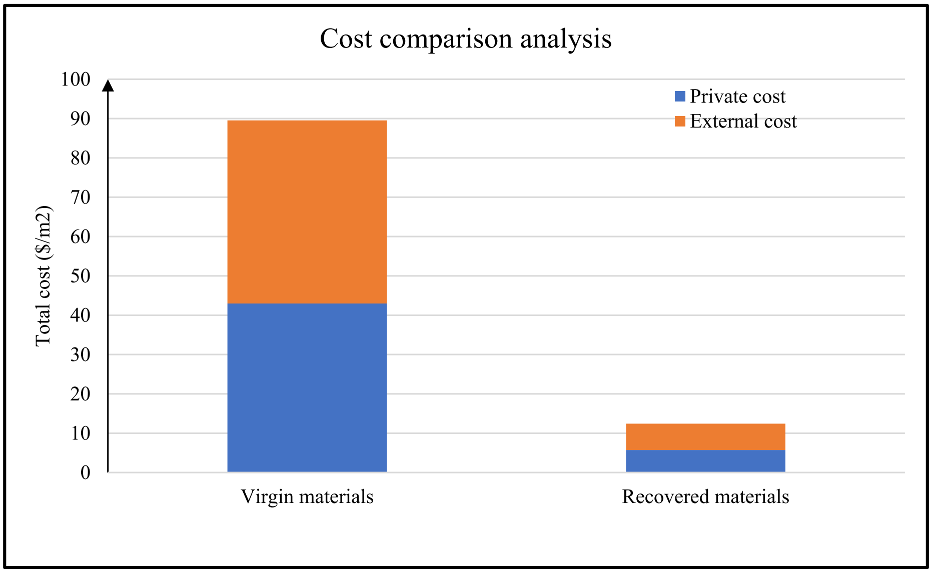


Fig. 19. Cost Comparison Between Virgin Materials and Materials Recovered from PV Panel recycling (D' Adamo et al., 2017).

recycling (Huisman et al., 2019). However, there is currently no specific legislation addressing the recycling of photovoltaic (PV) panels and the recovery of valuable materials in Norway.

In 2012, the Czech Republic embraced the EU WEEE regulation, enforcing full producer responsibility for recycling photovoltaic (PV) panels. The directive targets reducing landfill percentages to below 20% by increasing material reuse (80%) and recycling (70%) (Zemkova et al., 2016). PV Cycle, a non-profit, collaborates on solar PV panel recycling in the Czech Republic. Stringent legal requirements mandate companies to register all PV panels and components (Kastanaki and Giannis, 2022; Kastanaki and Giannis, 2023). Additionally, WEEELABEX, an organization in the Czech Republic, is tasked with recycling electronic equipment, including solar panels, across Europe (Czajkowski et al., 2022).

In the UK, pre-WEEE, electronic waste from photovoltaic (PV) panels was managed voluntarily (Majewski et al., 2021). Post-2013, the UK implemented the WEEE legislative directive, with special guidelines emphasizing PV panel producer responsibility. Producers must register via the Producer Compliance Scheme (PCA plan), complying with data requirements for both business-to-business (B2B) and business-to-consumer (B2C) regulations (Ali et al., 2023). Producers are also obligated to participate in the distributor takeback scheme (Cucchiella et al., 2015).

Japan recycling regulation: In 2015, Japan initiated a PV panel recycling roadmap, proposing a scheme for secure handling, collection, and recycling. Although guidelines are still under development, the Ministry of Economy, Trade, and Industry (METI) and the Ministry of Environment (MOE) actively address the issue (Committee on reuse, 2015). The National Institute of Advanced Industrial Science and Technology (NEDO) in Japan is developing recycling technology, and the Japan Photovoltaic Energy Association (JPEA) has introduced a voluntary guideline on proper disposal (Huisman et al., 2019). NPC, a Japanese solar company, collaborates with Hamada, an industrial waste processor, in a program supported by the New Energy Industrial Technology Development Organization (NEDO) (Deng et al., 2022; Tsang et al., 2016).

United States of America recycling regulation: In the United States, federal laws for the safe disposal and recycling of end-of-life PV modules are lacking. However, states like Washington and California have developed their regulations (California Legislature). In California, Senate Bill 489 addresses hazardous PV waste, while Washington passed Senate Bill 5939, providing tax incentives, and establishing a recycling program for PV modules (Washington States Legislature, 2017). The U. S. initiated a National PV Exercise Program in 2016, led by the Solar Energy Industries Association (SEIA), and SEIA's National PV Recycling Program (SEIA., 2016) aims to raise awareness about responsible recycling. First Solar, a U.S.-based manufacturer, has established recycling facilities globally (Kant and Singh, 2022; Cui et al., 2022; Nain and Kumar, 2022).

China recycling regulation: China, a major player in the solar photovoltaic market, has witnessed substantial growth in manufacturing and deployment. However, as per reports from the National Energy Administration, China lacks distinct obligations/regulations for handling the e-waste of solar PV panels (Klugmann-Radziemska and Kuczyńska-Łażewska, 2020). The country's comprehensive national solid waste regulations do not explicitly cover electronic waste from photovoltaic panels (De Souza and Veit, 2023). The National High-tech R&D Programme in China is actively proposing ongoing recommendations to introduce specialized policies, rules, and regulations specifically addressing the recycling and safe disposal of end-of-life PV panels and the waste generated by PV modules (Pereira et al., 2023; Shao et al., 2023).

In January 2023, China initiated recycling policies for managing 10 MW of crystalline solar PV panels, reflecting a growing awareness of managing e-waste in the solar industry (Guo et al., 2023; Srinivasan and Kottam, 2018).

Korea recycling regulations: In Korea, there are presently no dedicated guidelines or regulations specifically addressing the disposal of photovoltaic (PV) module waste. However, efforts have been made to encourage proper disposal and recycling of PV module waste through amendments to the law on renewable energy under the "Act on the Promotion of the Development, Use, and Diffusion of New and Renewable Energy" (Kim et al., 2014). The amendments are crafted to encourage responsible practices in the management and recycling of PV modules.

India recycling regulations: As of now, India lacks specific rules and regulations dedicated to the management of photovoltaic (PV) panel waste, and it is currently treated under general waste regulations (Preet et al., 2023). The responsibility for developing policies related to waste, including PV panel waste, falls under the purview of the Ministry of Environment, Forest and Climate Change by the Solid Waste Management Rules and the Hazardous and Other Wastes (Management and Transboundary Movement) Rules (2016a and 2016b) (Rathore and Panwar, 2022). The lack of specific guidelines for PV panel waste within existing waste regulations suggests a potential need for more targeted regulations and policies in the future.

8. Discussion: challenges and outlook

The recycling of c-Si PV panels is associated with various technical and non-technical challenges, impacting the upcycling recycling process and favouring practices such as stockpiling, landfilling, and downcycling (Tao et al., 2020). These challenges hinder the generation of high-quality recycled materials, crucial for producing high-quality photovoltaic solar panels (Farrell et al., 2020; Heath et al., 2020).

8.1. Technical challenges

Cost of Recycling: The primary challenge is the high cost of recycling silicon PV panels, estimated to be around $600–1000 per ton (excluding material revenue) (Heath et al., 2020). Lowering this cost to $300–400 per ton is essential for making the recycling process economically viable (Deng et al., 2019).

Recycling Techniques: Innovative and energy-efficient techniques are needed, such as delamination (Li et al., 2021), automated material selection (Dias et al., 2022), optimized thermal and chemical treatments (Prasad et al., 2022), high recovery of silver (Ag) (De Souza and Veit, 2023), waste reduction (Wang et al., 2022), to reduce the overall cost of recycling. Some existing chemical and thermal treatment processes are either not applicable to damaged solar silicon PVs or contribute significantly to their treatment costs (Zhang et al., 2022).

Emissions and Pollutants: One critical barrier to PV panel recycling is the emission of pollutants into the biosphere during the recycling process (Mahmoudi et al., 2019; Salim et al., 2019b). Pollutants released during the recycling process (Wang et al., 2022), including toxic gases in pyrolysis, dust during mechanical delamination processes (Artas et al., 2023), chemical sludge in leaching processes and metal extraction processes (Ramos-Ruiz et al., 2017), and disposal of non-recyclable material such as fluorinated back sheet (Chowdhury et al., 2020). Catalytic converters and waste treatment plants can help address this issue.

Infrastructure: There is a need for more recycling infrastructure dedicated to solar PV panels (Chowdhury et al., 2020; Xu et al., 2018, 2022). Existing facilities, often focused on non-ferrous metals, WEEE, and glass recycling, need optimization to handle PV panels effectively (Neubauer et al., 2021).

Global Recycling Facilities: Limited facilities worldwide are equipped to achieve high recycling and recovery yields. Notable examples include 'Sasil S. r.l.' in Italy which has a capacity of more than 8000 tonnes/year and demonstrates the capability to recover nearly 100% of materials, including silver and copper, from solar PV panels (Latunussa et al., 2016). A recycling plant named ''Veolia France' in France, demonstrates high material recovery rates (Neubauer et al.,

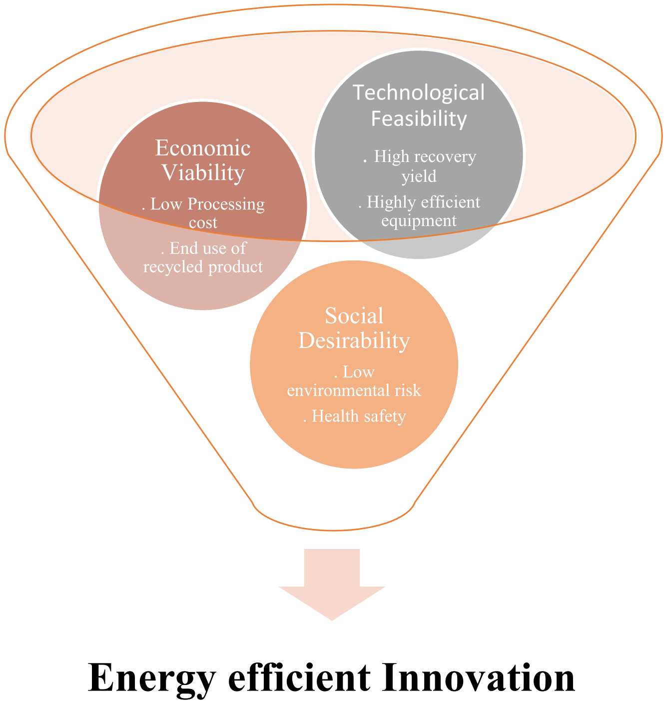


Fig. 20. Sustainable recycling process achievement.

2021). The first solar company in the USA has set up a recycling plant to recycle specifically CdTe-based Solar panels with a recycling rate of nearly 95% (A. Wade, 2014).

Ensuring a sustainable recycling process for solar PV panels requires addressing technological feasibility, economic viability, and socio-desirability challenges, leading to an energy-efficient and innovative recycling approach as illustrated in Fig. 20.

8.2. Non-technical challenges

Market Barriers: Low waste volume and insufficient waste collection networks create market barriers (Faircloth et al., 2019). Collection rates of waste solar PV panels less than 10,000 tonnes are often insufficient to trigger economies of scale (Mahmoudi et al., 2020).

Geographical Challenges: The collection of end-of-life solar PV panels from different geographical locations is a challenging task for recyclers (M. Peplow, 2022). The insufficient collection rate of damaged solar panels undermines the sustainability of the recycled panel market (Mathur et al., 2020). Legislation on compulsory collection and recycling is needed to address this.

Legislation and Regulation challenges: In many countries, the lack of specific legislation or regulations on recycling, coupled with the high processing cost, prompts consumers to choose the disposal of damaged solar panels at landfill sites with low gate fees (Curtis et al., 2021). However, few countries in the EU and the UK have implemented recycling regulations under the WEEE directive. According to an article by Neubauer et al. (2021), the EU has introduced a new WEEE directive to manage e-waste, including solar panels. All EU member states are required to adhere to CENELEC (European Committee for Electrotechnical Standardisation) standards governing the collection, logistics, and treatment of electronic waste (e-waste) products. Twenty-six facilities for recycling solar PV panels were established in the UK, Cyprus, Germany, Finland, France, Croatia, and Portugal. Unfortunately, only 2 facilities are reported to be operating in compliance with the standards of CENELEC (Genovese et al., 2023; Joshi et al., 2023). Apart from this, Victoria State in Australia implemented a ban on the landfilling of e-waste, including solar panels, starting in 2019 (Fiandra et al., 2023). Similarly, in the USA, California has enacted legislation addressing the management of PV panels and prohibiting the direct landfilling of damaged solar panels (Curtis et al., 2021; Mahmoudi et al., 2021).

A comprehensive approach is essential, considering technological feasibility, economic viability, and social desirability. Sustainable recycling processes should be energy-efficient and innovative to overcome existing barriers and facilitate widespread and effective recycling of solar PV panels.

8.3. Future outlook for research and development in the recycling process

Current recycling technologies face challenges such as low efficiency, high processing costs, and the emission of harmful gases and chemicals. Addressing these technical challenges requires the development of an energy-efficient and cost-effective recycling process with a high extraction rate for valuable materials. Achieving this necessitates interdisciplinary research in pro-metallurgy and hydrometallurgy. In mechanical treatment, the electrostatic separator stands out as an environmentally friendly and economically efficient technology (Li et al., 2023), particularly effective for separating conductive from non-conductive materials (Cenci et al., 2021). Parametric investigations into methods like the hot knife, high-voltage pulse, and microwave field may yield effective results in separating the EVA layer from PV panels with minimal pollution. The thermal treatment process in recycling should incorporate the vacuum and gas refining process for a non-polluting recycling process for silicon, producing electronic-grade silicon. Utilizing this recycled material in silicon carbide production through a Bridgeman furnace offers energy and material savings, along with reduced greenhouse gas emissions. In the chemical treatment process, the use of iodine and iodide (I_2–K_2) instead of HNO_3 contributes to a reduction in acidification and eutrophication, enhancing material recovery with less impact on human health (Vallejos-Michea et al., 2022). Supercritical water technology, utilizing wastewater instead of clean water and employing efficient gas treatment methods, shows promise in reducing environmental impact and ensuring a high material recovery rate (Pereira et al., 2023).

To address non-technical challenges, effective collaboration between consumers and industry partners is crucial for the efficient collection, logistics, and packaging of recycled solar PV panels. Establishing large-scale PV recycling plants and wisely distributing economic resources among recyclers, recycling consortia, PV manufacturers, and governments is necessary. Improved coordination among governments, international agencies, institutions, industry policymakers, and PV stakeholders is vital for responsible waste management of PV panels and their sustainable development. Implementing subsidies with reasonable standards and a timely retreat mechanism can enhance the return on investment and encourage a better recovery rate of valuable materials. Countries with significant PV installation rates, such as the USA, China, India, and Korea, should consider formulating recycling policies aligned with the WEEE regulation adopted in Europe to regulate the recycling of PV panels (Y. Qu, 2015). Implementing extended producer responsibility (EPR) programs is key to holding companies accountable for the entire life cycle of their products, fostering eco-friendly and energy-efficient recycling methods (X. Miao, 2015).

Simulation modelling enables virtual testing and refinement, providing valuable insights before industrial implementation and contributing to efficient and economically sustainable recycling practices for solar PV panels. For that reason, computer-aided modelling is required to analyse the impact of critical parameters on the recycling process and developing cost-effective design.

8.4. Limitation of the study

Recycling photovoltaic (PV) panels is essential for the sustainable growth of the PV sector on a global scale. This review explores different techniques employed by researchers for recycling and recovering metals from PV panels. However, it is important to note certain limitations in the current review study regarding the recycling treatment of PV panels, which are outlined below.

- In this current review article, the examination of studies on PV panel recycling reveals a lack of comprehensive analysis of entire material recovery from the wasted PV panels. However, knowledge gaps may exist in how different parts of recovery process are interlinked.
- Data for analysis of overall performance of PV panel recycling treatment are limited.
- Besides silicon, PV panels comprise various materials like amorphous and cadmium oxide. The current review article does not address how the effectiveness of recycling treatments and material recovery processes may vary based on these specific compositions, representing a potential knowledge gap.
- The present review article does not provide an exhaustive picture of the regional variations in the recycling of PV panels, including unique regulations, recycling infrastructures, policies, and environmental conditions in different regions.
- The present review article did not thoroughly explore the feasibility of scaling up successful laboratory-scale recycling and recovery processes to commercial-scale operations. Consequently, it is not possible to comment on the likelihoods of different technical and commercial pathways to future economies of PV recycling.
- The mechanical, thermal, and chemical recycling processes in PV panel recycling contribute to energy consumption and the release of toxic pollutants into the biosphere. However, the variability in these factors across different studies presents a large band of uncertainty in the environmental assessments of recycling processes. The present review article does not provide an analysis of this uncertainty.

9. Conclusion

Silicon-based photovoltaic panels play a crucial role in electricity generation, offering a significant reduction in carbon footprints. However, their lifecycle introduces a concerning aspect—the generation of electronic waste (e-waste) upon reaching end-of-life (EOL). E-waste from silicon PV panels is experiencing exponential growth, projected to peak between 2035 and 2040. Improper disposal, such as landfilling, not only threatens ecosystems and human health but also depletes valuable metals. Sustainable management of PV panel e-waste is imperative to avoid a fate akin to plastic, potentially facing bans from society.

This review comprehensively outlines various photovoltaic (PV) technologies, with a specific emphasis on the electronic waste (e-waste) generated by PV panels. It delves into the environmental impact of PV panels and provides a global status overview of PV panel e-waste. The article also conducts an in-depth examination of PV recycling technologies, encompassing mechanical, thermal, and chemical processes. Furthermore, it thoroughly explores techniques for valuable metal recovery, offering a detailed analysis of their economic and environmental aspects.

Delamination, a crucial step in the recycling process, involves three primary methods: mechanical, thermal, and chemical. Thermal treatment, specifically pyrolysis, is effective in removing layers but faces challenges such as wafer brittleness and high energy consumption. While mechanical delamination is financially viable, it encounters complexities in handling crushed compositions. On the other hand, chemical delamination works well at low temperatures but requires addressing concerns related to toxicity and cost viability. The chemical recycling process for all silicon-based solar cells comprises two main steps. Initially, a 30% aqueous KOH solution is employed to eliminate aluminium metal coatings at a temperature of 60–80 °C for 2–3 min. Subsequently, etching occurs using a mixture of 250 ml HNO_3 (65%), 150 ml HF (40%), 150 ml CH_3COOH (99.5%), and 3 ml Br_2. This step, conducted at a temperature of 40 °C for 9 s, eliminates silver coatings, anti-reflective coatings (ARC), and n-p junctions.

Metal recovery in the context of PV panel recycling aims to extract glass, pure silicon, and valuable metals. Chemical etching is an efficient method for recovering pure silicon, but cost reduction is crucial for competitiveness. Cost analysis reveals that the collection and processing phases collectively contribute over 90% to the total costs. The recovery of valuable metals, such as silver, aluminium, copper, and lead, can be improved through methods like chemical precipitation and electrostatic recycling, potentially increasing revenue by up to 95%. Further research is needed to enhance metal enrichment rates, particularly for silver (Ag), contributing to a reduction in recycling costs.

Several nations, including the United States, China, European Union member states, India, and Japan, have independently developed distinct local directives and policies to address the challenges associated with managing and recycling electronic waste generated by photovoltaic (PV) panels. This review article thoroughly explores the recycling policies and initiatives implemented by countries with high PV installation rates. Innovation must align with technical feasibility, economic viability, and socio-desirability to address the technical and non-technical challenges discussed in the present review article. Recommendations include the use of computer-based simulation models, enhanced lab-scale experiments, and industry-scale implementation to ensure the sustainable recycling of silicon PV panels.

CRediT authorship contribution statement

Sajan Preet: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Stefan Thor Smith:** Writing – review & editing, Supervision, Resources, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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