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Review

From Waste to Resource: Exploring the Current Challenges and Future Directions of Photovoltaic Solar Cell Recycling

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Abstract: The rapid proliferation of photovoltaic (PV) solar cells as a clean energy source has raised significant concerns regarding their end-of-life (EoL) management, particularly in terms of sustainability and waste reduction. This review comprehensively examines challenges, opportunities, and future directions in the recycling of PV solar cells, focusing on mechanical, thermal, and chemical recycling techniques. It also evaluates the scalability and practicality of these methods to different PV technologies, including crystalline silicon and thin-film modules. It explores the economic and environmental impacts of these processes, highlighting the necessity of developing robust recycling infrastructure and innovative technologies to address the anticipated surge in PV waste. Additionally, this review discusses the critical role of government policies and industry collaboration in overcoming the barriers to effective recycling. Furthermore, the importance of integrating design-for-recyclability principles into PV module development is emphasized, as it can significantly enhance material recovery and process efficiency. By advancing these strategies, the solar industry can achieve greater sustainability, reduce resource depletion, and mitigate environmental risks, thereby ensuring the long-term viability of solar energy as a key component of global renewable energy initiatives.

Keywords: photovoltaic solar cells; PV recycling; end-of-life PV panels; circular economy

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1. Introduction

The global transition toward renewable energy sources has accelerated significantly in recent years, driven by the urgent need to mitigate climate change, reduce dependence on fossil fuels, and promote sustainable development. Among the various renewable energy technologies, photovoltaic (PV) solar cells have emerged as one of the most promising and rapidly growing sources of clean energy. PV solar cells, which convert sunlight directly into electricity, are now widely deployed across the world, from residential rooftops to large-scale solar farms [1–3]. This widespread adoption is a testament to the technology's effectiveness, scalability, and potential to contribute to a more sustainable energy future.

The growth of the solar energy sector has been driven by several factors, including technological advancements, declining costs of solar panels, supportive government policies, and increased awareness of environmental issues. Over the last decade, the cost of PV solar cells has dropped dramatically, making solar power more accessible and economically viable [4]. This price reduction, coupled with improvements in efficiency and manufacturing processes, has led to exponential growth in solar installations globally. According to the International Energy Agency (IEA) [5], solar power is expected to account for the largest share of renewable energy growth in the coming years, with PV technology leading the way.

Despite the many advantages of PV solar cells, their rapid proliferation has also given rise to new challenges, particularly in the context of sustainability and waste management. PV solar cells have a typical operational lifetime of 25 to 30 years [6]. As the first generation of mass-produced solar panels reaches the end of its useful life, a significant volume of waste is expected to be generated. The IEA estimates that by 2050, the world could be dealing with up to 78 million tonnes of PV panel waste [7]. This looming waste crisis presents a significant environmental challenge, as PV panels contain materials that, if not properly managed, could pose risks to human health and the environment.

The composition of PV solar cells is complex, involving a variety of materials such as silicon, glass, aluminium, and other metals, including silver, tin, and copper. While many of these materials can be recovered and recycled, the process is not straightforward. The encapsulation of cells in protective layers, the use of hazardous substances like cadmium and lead in some types of cells, and the economic feasibility of recycling processes are just a few of the challenges that need to be addressed. Additionally, the lack of standardized recycling processes and infrastructure, particularly in regions where solar adoption has been rapid, exacerbates the problem.

The environmental impact of PV solar cell disposal is compounded by the fact that the improper handling of waste can lead to the release of toxic substances into the environment. For instance, cadmium, used in some thin-film solar cells, is a highly toxic metal that can cause serious health problems if released into the soil or water. Similarly, lead, which is used in soldering the electrical connections in many solar panels, is another hazardous substance that poses significant risks. These concerns underscore the importance of developing effective recycling strategies to minimize the environmental footprint of PV solar technology.

Recycling PV solar cells not only addresses the waste management issue but also contributes to resource conservation. The materials used in PV panels, such as silicon, silver, and copper, are finite resources that are increasingly in demand for various technological applications. By recycling these materials, the solar industry can reduce its reliance on virgin resources, decrease the environmental impact of mining and material extraction, and create a more circular economy. Moreover, the recovery of valuable materials from end-of-life panels could also provide economic benefits, making recycling an attractive option from both an environmental and financial perspective.

In light of these challenges and opportunities, the recycling of PV solar cells has become a critical area of research and development. Governments, industry stakeholders, and academic institutions are increasingly focusing on finding innovative solutions to recycle PV panels in an efficient, cost-effective, and environmentally friendly manner. However, the field is still in its nascent stages, with many technical, economic, and regulatory hurdles to overcome. This review aims to provide a comprehensive overview of the current state of PV solar cell recycling, highlighting the key technologies, challenges, and future directions in this important area. As we delve deeper into the subject, it becomes clear that the recycling of PV solar cells is not merely a technical challenge but also a broader societal issue that requires coordinated efforts across various sectors. The development of effective recycling strategies will play a crucial role in ensuring that the solar energy industry remains sustainable in the long term, helping to achieve the full environmental and economic benefits of PV technology.

2. Problem Statement

The current infrastructure for recycling PV solar cells is insufficient to handle the anticipated volume of waste. Recycling technologies are still in the early stages of development, and there is a lack of standardized processes and policies across different regions.

Moreover, the economic viability of recycling PV panels remains uncertain, with the cost of recycling often exceeding the value of the recovered materials. This economic barrier, coupled with the technical complexities involved in recycling PV cells—such as the safe extraction of hazardous materials and the recovery of valuable components—presents a formidable challenge.

Furthermore, prior studies have often focused narrowly on specific recycling technologies without addressing the systemic barriers to scaling up these methods. Key gaps in the existing literature include the limited exploration of how regional policy variations impact recycling infrastructure, inadequate economic analyses of emerging recycling processes, and a lack of comparative studies evaluating the environmental and resource conservation impacts of different approaches.

This review bridges these gaps by offering a comprehensive examination of the challenges and opportunities in PV recycling across technical, economic, and regulatory dimensions. It builds on previous work by synthesizing insights from recent technological advancements and policy developments to identify actionable strategies for overcoming the barriers to effective recycling. Specifically, this review highlights:

- The necessity of innovative recycling technologies that balance cost-effectiveness with high recovery rates for valuable materials.
- The role of international collaboration and policy standardization in addressing regional disparities in recycling infrastructure and regulations.
- A forward-looking perspective on integrating circular economy principles to enhance the sustainability of the PV industry.

3. Overview of PV Solar Cells

PV solar cells, the fundamental building blocks of solar panels, come in various types, each distinguished by the materials used, manufacturing processes, and efficiency characteristics. Understanding these different types is crucial in comprehending the broader landscape of PV technology, particularly in the context of recycling and waste management. This section delves into the primary types of PV solar cells, including crystalline silicon cells, thin-film cells, and emerging technologies, examining their composition, applications, and implications for recycling.

3.1. Crystalline Silicon Solar Cells

Crystalline silicon (c-Si) solar cells are the most widely used and commercially dominant type of PV cells, accounting for approximately 90% of the global solar market [8]. These cells are made from silicon, the second most abundant element in the Earth's crust, which is processed into high-purity crystalline wafers. There are two main subtypes of crystalline silicon solar cells:

- Monocrystalline Silicon Solar Cells (Mono-Si): Monocrystalline silicon solar cells are made from a single continuous crystal structure. These cells are recognized for their high efficiency, typically ranging from 15% to 22%, due to the high purity of the silicon used [9,10]. The production process involves slicing thin wafers from a cylindrical silicon ingot, which is grown using the Czochralski method [11]. The uniformity of the crystal lattice in monocrystalline cells allows for efficient electron flow, resulting in better performance, especially in conditions of low sunlight. Monocrystalline cells are often characterized by their uniform black or dark blue color and their rounded edges [12], which result from the cylindrical shape of the silicon ingot. Due to their higher efficiency, monocrystalline solar panels are generally more expensive than other types [13]. They are widely used in residential and commercial applications where space is at a premium and high efficiency is desired.

- Polycrystalline Silicon Solar Cells (Poly-Si): Polycrystalline silicon solar cells, also known as multicrystalline silicon cells, are made from silicon crystals that are melted together and allowed to cool in a mould [14]. This process results in a cell composed of multiple small crystals, giving polycrystalline cells a distinctive bluish hue and a more fragmented appearance. Polycrystalline cells are generally less expensive to produce than monocrystalline cells because their manufacturing process is simpler and less energy-intensive [15]. The efficiency of polycrystalline cells typically ranges from 13% to 18% [16,17], slightly lower than that of monocrystalline cells. This lower efficiency is due to the presence of grain boundaries between the individual crystals, which can impede the flow of electrons and reduce the overall performance of the cell. Despite their lower efficiency, polycrystalline cells are popular in large-scale solar farms and residential installations.

3.2. Thin-Film Solar Cells

Thin-film solar cells represent a different approach to solar energy conversion, where layers of PV material are deposited onto a substrate, typically glass, plastic, or metal. These layers are much thinner than the crystalline wafers used in silicon cells, hence the name "thin-film". Thin-film solar cells are known for their flexibility, lightweight design, and ability to perform well in diffused sunlight and high temperatures. There are several types of thin-film solar cells, including the following:

- Cadmium Telluride (CdTe) Solar Cells: CdTe solar cells are the most commercially successful thin-film technology, accounting for the majority of the thin-film market share [18]. CdTe cells consist of a thin layer of cadmium telluride as the absorbing material, with cadmium sulfide (CdS) typically used as the window layer [19]. One of the key advantages of CdTe solar cells is their low production cost, which is achieved through a highly automated manufacturing process that involves the rapid deposition of materials onto a substrate. CdTe cells have an efficiency range of 10% to 16%, which is lower than crystalline silicon cells but comparable to other thin-film technologies [20]. However, they have the advantage of better performance in hot climates and under low-light conditions [21], making them suitable for large-scale solar farms in diverse environments. Despite their advantages, CdTe cells pose significant environmental concerns due to the toxicity of cadmium [22], a heavy metal that can be harmful to human health and the environment if not properly managed during disposal or recycling.
- Amorphous Silicon (a-Si) Solar Cells: a-Si solar cells are the earliest and most well-known thin-film technology. Unlike crystalline silicon cells, which have a well-ordered crystal lattice, amorphous silicon cells consist of a non-crystalline form of silicon [23]. This disordered structure allows for the production of very thin layers of silicon, reducing material costs and making the cells flexible and lightweight [24]. The efficiency of amorphous silicon cells is relatively low, typically ranging from 6% to 9% [25], due to the higher defect density in the amorphous structure, which impedes electron flow. However, a-Si cells have a unique advantage in that they can be deposited on a variety of substrates, including flexible materials, enabling their use in applications such as building-integrated photovoltaics (BIPVs) [26,27] and portable solar chargers [28]. The low cost and flexibility of a-Si cells make them attractive for specific niche markets, despite their lower efficiency.
- Copper Indium Gallium Selenide (CIGS) Solar Cells: CIGS solar cells are another promising thin-film technology, known for their high efficiency and versatility. CIGS cells consist of a compound of copper, indium, gallium, and selenium, which serves as the absorbing layer [29]. The composition of CIGS cells can be fine-tuned to optimize

performance, making them one of the most efficient thin-film technologies, with efficiencies ranging from 12% to >24% [30]. CIGS cells are typically more efficient than other thin-film technologies like CdTe and a-Si, and they offer greater flexibility in terms of substrate options, including glass, metal, and plastic [31]. This flexibility, combined with their relatively high efficiency, makes CIGS cells suitable for a wide range of applications, from rooftop installations to portable devices. However, the manufacturing process for CIGS cells is more complex and costly than those for other thin-film technologies [32], which has limited their market penetration.

3.3. Emerging PV Technologies

In addition to the established crystalline silicon and thin-film solar cells, several emerging PV technologies are under development, offering the potential for higher efficiencies, lower costs, and novel applications. These emerging technologies include the following:

- Perovskite Solar Cells: These solar cells have garnered significant attention in recent years due to their remarkable efficiency improvements and the potential for low-cost production. The term "perovskite" refers to the crystal structure of the materials used in these cells [33], typically a compound of lead or tin halide with an organic component. Perovskite cells have achieved efficiencies exceeding 25% in laboratory settings [34], rivalling those of crystalline silicon cells, and they are continuing to improve rapidly. One of the key advantages of perovskite cells is the ability to manufacture them using solution-based processes, such as printing or coating, which could significantly reduce production costs. Moreover, perovskite materials can be tuned to absorb different wavelengths of light [35], enabling their use in tandem with other PV technologies to create highly efficient multi-junction cells. However, challenges remain, particularly in terms of the long-term stability of perovskite cells and the toxicity of lead-based materials, which must be addressed before commercialization on a large scale.
- Organic Photovoltaic (OPV) Cells: OPV cells represent a class of PV technology that uses organic molecules or polymers to absorb light and generate electricity. OPV cells are flexible, lightweight, and can be produced using low-cost, roll-to-roll manufacturing techniques [36]. While the efficiency of OPV cells is currently lower than that of other PV technologies, typically ranging from 5% to 20% [37], their unique properties make them attractive for applications where flexibility and a low weight are critical, such as in wearable electronics or portable solar chargers. The main challenges facing OPV technology are the relatively low efficiency and limited stability of organic materials [38], which degrade more quickly than inorganic materials when exposed to sunlight and environmental conditions. Nevertheless, ongoing research is focused on improving the efficiency and durability of OPV cells, with the goal of making them competitive with other PV technologies in specific markets.
- Quantum Dot Solar Cells: Quantum dot solar cells are an emerging technology that uses nanoscale semiconductor particles—known as quantum dots—to absorb sunlight and generate electricity [39]. Quantum dots have unique optical and electronic properties that can be tuned by changing their size, enabling the development of solar cells with tailored absorption spectra. This tunability offers the potential for highly efficient multi-junction cells [40], where different layers of quantum dots are optimized to absorb different parts of the solar spectrum [41]. While still in the experimental stage, quantum dot solar cells have shown promise in achieving high efficiencies, particularly when used in tandem with other PV technologies. The main challenges facing quantum dot cells include the scalability of production [42], stability of the

materials, and potential environmental and health risks associated with the use of heavy metals in quantum dots.

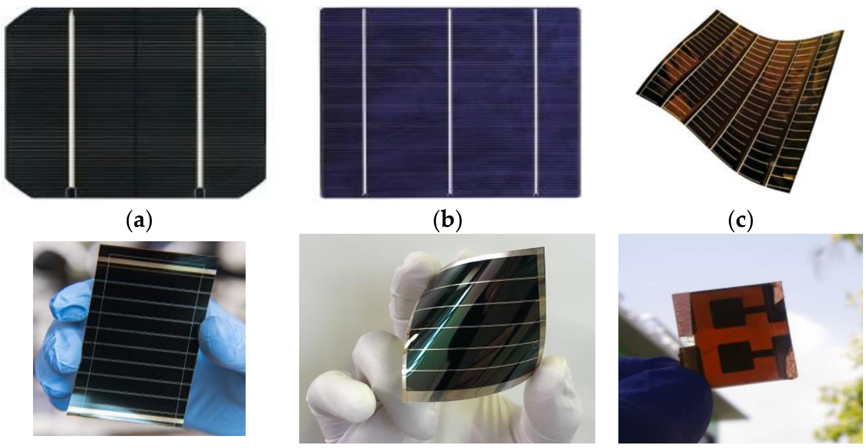
3.4. Summary

In this section, we have provided a comprehensive overview of various PV solar cell technologies, including crystalline silicon, thin-film, and emerging technologies such as perovskite and quantum dot cells. These technologies vary significantly in efficiency, material composition, and recyclability, each presenting unique advantages and challenges. Crystalline silicon remains the most widely deployed due to its high efficiency and proven reliability, while thin-film technologies offer flexibility and cost advantages, but face challenges related to toxic materials. Emerging technologies such as perovskite and quantum dot cells promise higher efficiencies and novel applications but are still limited by stability and scalability issues. To enhance clarity, Table 1 summarizes these key aspects, offering a side-by-side comparison of their efficiency ranges, materials used, recyclability challenges, and applications. This comparison highlights the critical trade-offs between performance and sustainability, underscoring the importance of tailored recycling strategies for each technology to ensure a circular economy in the solar industry.

Table 1. Comparative summary of advancements in PV solar cell technologies, highlighting their efficiency ranges, materials used, recyclability challenges, and typical applications.

Technology	Efficiency Range (%)	Materials Used	Recyclability Challenges	Applications
Crystalline Silicon	15–22	Silicon, silver, aluminium	Difficulty in separating encapsulants	Residential, commercial
Thin-Film (CdTe, CIGS)	10–16	Cadmium, tellurium, indium, selenium	Toxic materials requiring careful handling	Large-scale solar farms
Perovskite	20–25	Lead halides, organic components	Stability and toxicity of lead compounds	Experimental, niche
Organic PV (OPV)	5–20	Conjugated polymers, fullerenes	Limited lifespan and recyclability	Wearable electronics, BIPV
Quantum Dot	6–16	CdSe, PbS, other nanoparticles	Scalability and toxicity of materials	Research, specialized uses

Figure 1 showcases the diversity of PV solar cell technologies, including monocrystalline and polycrystalline silicon, CdTe thin-film, perovskite, OPV, and quantum dot cells. This visual representation highlights the variation in material composition and design.



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 1. Visual representation of PV solar cell technologies: (**a**) monocrystalline silicon solar cell (source: https://korvustech.com/crystalline-vs-thin-film-solar-panels/, accessed on 3 December 2024),

(**b**) polycrystalline silicon solar cell (source: https://korvustech.com/crystalline-vs-thin-film-solar-panels/, accessed on 3 December 2024), (**c**) CdTe thin-film solar cell (source: https://www.empa.ch/web/s604/solarzellen, accessed on 3 December 2024), (**d**) perovskite solar cell (source: https://www.energy.gov/eere/solar/perovskite-solar-cells, accessed on 3 December 2024), (**e**) OPV solar cell (source: https://www.toyobo-global.com/news/2020/release_117.html, accessed on 3 December 2024), and (**f**) quantum dot solar cell (source: https://www.pv-magazine.com/2021/08/12/ligand-free-perovskite-quantum-dot-solar-cell-with-9-3-efficiency/, accessed on 3 December 2024).

4. Materials Used in the Production of PV Solar Cells

The materials used in the production of PV solar cells are critical not only to their performance and efficiency but also to the challenges and opportunities associated with recycling these cells at the end of their life cycle. Each type of PV cell—whether made using crystalline silicon, thin films, or emerging technologies—utilizes a distinct set of materials that contribute to its electrical properties, stability, and overall effectiveness in converting sunlight into electricity.

4.1. Materials in Crystalline Silicon Solar Cells

The c-Si solar cells are predominantly composed of silicon, along with a variety of other materials that are essential to the cell's structure and function. Silicon is the cornerstone of crystalline silicon solar cells, serving as a semiconductor material that absorbs sunlight and converts it into electricity [43]. High-purity silicon is required to achieve the efficiency levels characteristic of c-Si cells. The production of this silicon involves a series of energy-intensive processes, starting from the reduction of quartz to metallurgical-grade silicon [44], followed by purification to produce polysilicon. The purified silicon is then crystallized into ingots [45], which are sliced into thin wafers for use in solar cells.

The purity and crystalline structure of the silicon are crucial to the performance of the solar cell. Monocrystalline silicon cells, for instance, use silicon with a single crystal structure, resulting in fewer defects and higher efficiency. In contrast, polycrystalline silicon cells are made from silicon that crystallizes in multiple directions [46], leading to a lower-cost, but slightly less efficient, product. Silicon's abundance in the Earth's crust makes it an attractive material for solar cells, but the energy-intensive production process and the need for high purity present challenges in terms of sustainability and cost reduction [47].

Doping is a process used to alter the electrical properties of silicon by introducing small amounts of other elements. In crystalline silicon solar cells, silicon is typically doped with phosphorus to create n-type (negative-type) semiconductors [48] and with boron to create p-type (positive-type) semiconductors [49]. This doping process is essential in forming the p-n junction, where the interaction between the p-type and n-type layers generates an electric field that drives the flow of electrons, producing electricity.

Phosphorus and boron are chosen because they have five and three valence electrons, respectively, compared to silicon's four [50]. This difference in electron numbers creates the necessary charge carriers (electrons and holes) when these elements are introduced into the silicon lattice. The precise control of doping levels is crucial in optimizing the efficiency and performance of the solar cell.

Metals play a vital role in the electrical conductivity and structural integrity of crystalline silicon solar cells. Silver is commonly used for the front-side metallization of the cell [51], where it forms the gridlines that collect and conduct electrons generated by the silicon. Silver's excellent conductivity and reflectivity make it an ideal material for this purpose, though its high cost is a concern for large-scale production.

Aluminium is typically used for back-side metallization [52,53], forming a layer that serves as both an electrical contact and a reflector to enhance light absorption. Additionally, copper is often used in the wiring and connectors that transport the electricity generated by the cells to the external circuit [54]. The use of these metals, particularly silver, presents both economic and environmental challenges, as they are finite resources, with significant environmental impacts associated with their extraction and processing.

To protect the delicate silicon wafers and metal contacts from environmental damage, crystalline silicon solar cells are encapsulated in protective layers. These typically include a layer of ethylene-vinyl acetate (EVA) as the encapsulant [55], which cushions the cells and bonds them to the glass cover on the front and the backsheet, usually made of a polymer like polyvinyl fluoride (PVF) [56]. The glass cover provides physical protection and allows sunlight to pass through, while the backsheet protects the cell from moisture and mechanical damage. These encapsulants and protective layers are crucial in ensuring the longevity and durability of the solar panels [57], but they also pose challenges for recycling. The materials used are often difficult to separate and process, contributing to the complexity and cost of recycling PV panels.

As an example, Figure 2 illustrates the production process for both monocrystalline and multicrystalline silicon solar PV modules, which are the most widely used types of PV cells in the solar energy industry. The process begins with polysilicon material, which is derived from high-purity silicon, an abundant element in the Earth's crust. The polysilicon undergoes different processing steps depending on whether monocrystalline or multicrystalline cells are being produced. For monocrystalline cells, the polysilicon is subjected to the Czochralski process, where it is melted and grown into a single crystal ingot, as depicted in the upper part of Figure 2. This ingot is then sliced into thin wafers, which are the basic building blocks of the solar cells. On the other hand, multicrystalline silicon cells are produced by melting the polysilicon into a brick, as shown in the lower part of Figure 2. The molten silicon is allowed to cool and solidify into a block composed of multiple small crystals, which is then cut into wafers. Both types of wafers undergo a doping process, where specific impurities are introduced to alter the electrical properties of the silicon, making it capable of converting sunlight into electricity. After doping, the wafers are wired and coated to form the final solar cells, which are assembled into solar PV panels or modules.

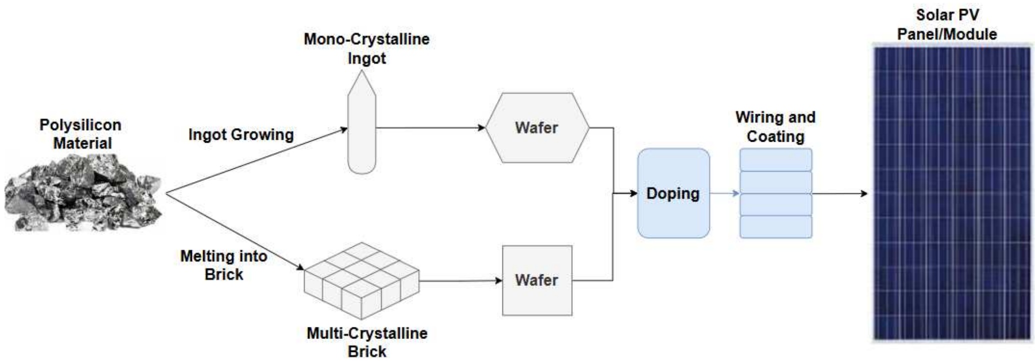


Figure 2. Schematic representation of the production process for monocrystalline and multicrystalline silicon solar PV modules. The diagram illustrates the key stages in the production of solar PV panels, from polysilicon material to the processes of ingot growing (for monocrystalline) and melting into brick (for multicrystalline), followed by wafer production, doping, and final assembly into solar PV panels or modules.

4.2. Materials in Thin-Film Solar Cells

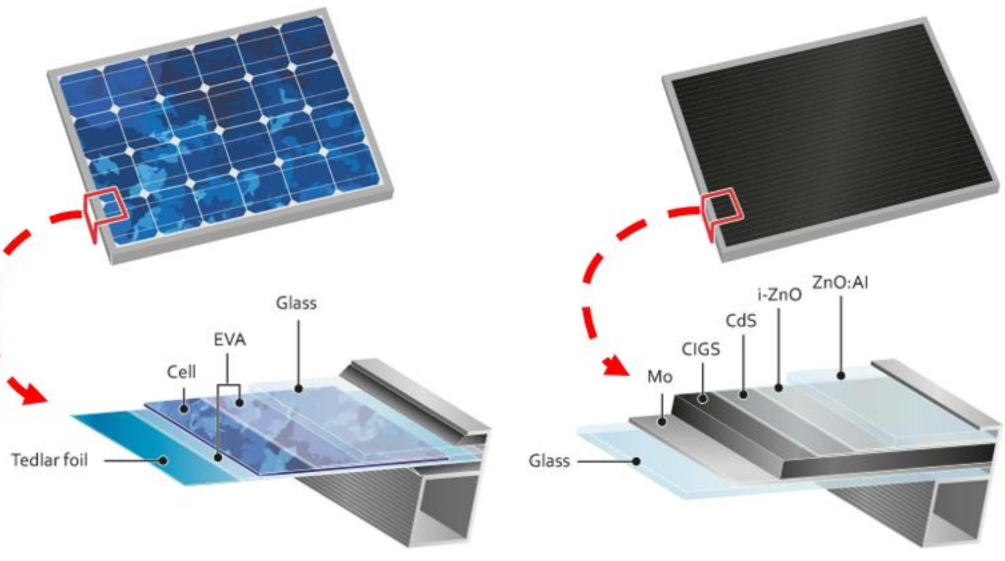
Thin-film solar cells, unlike crystalline silicon cells, use a variety of semiconductor materials deposited in thin layers onto a substrate. Cadmium telluride is the primary material used in CdTe thin-film solar cells [58], where it acts as the light-absorbing semiconductor.

CdTe has a high absorption coefficient, meaning that it can absorb a significant amount of sunlight with a very thin layer, typically around 1–2 micrometres thick. This allows for lower material usage compared to silicon-based cells, which require much thicker layers. However, the use of cadmium, a toxic heavy metal, raises significant environmental and health concerns [59]. Cadmium is highly toxic, and the improper handling or disposal of CdTe solar cells could lead to environmental contamination. Tellurium [60], although less toxic, is a rare element with limited availability, which could pose supply chain challenges as CdTe technology scales up. These factors underscore the need for effective recycling methods to safely recover and reuse these materials.

CIGS is another popular thin-film material, known for its high efficiency and versatility [61]. CIGS is a complex compound semiconductor that can be deposited on flexible or rigid substrates, making it suitable for a wide range of applications. The composition of CIGS can be adjusted by varying the ratios of copper, indium, gallium, and selenium, allowing for the optimization of the cell's electrical properties [62,63]. The materials used in CIGS cells, particularly indium and gallium, are relatively rare and expensive, which could limit the scalability of this technology. Additionally, the extraction and processing of these materials have significant environmental impacts. Recycling CIGS cells is therefore crucial not only for environmental protection but also for conserving these valuable resources.

Amorphous silicon is used in a-Si thin-film solar cells, which, as mentioned earlier, consist of a non-crystalline form of silicon. Unlike crystalline silicon, a-Si is deposited as a very thin layer onto a substrate, using significantly less material. This makes a-Si cells more flexible and lightweight, albeit at the cost of lower efficiency. Amorphous silicon cells also often incorporate hydrogen into the silicon layer to improve performance [64], a process known as hydrogenation. The inclusion of hydrogen helps to passivate defects in the silicon structure, improving the cell's efficiency [65]. While the materials used in a-Si cells are relatively non-toxic and abundant, the lower efficiency and shorter lifespan of these cells pose challenges for their economic and environmental sustainability.

Figure 3 illustrates the structural composition of solar modules made from two different types of PV technologies: crystalline silicon and thin-film types. Figure 3a shows the layered structure of a crystalline silicon solar module, which is the most frequently used technology in the solar industry. The module consists of several key components, including the glass cover that protects the module, the EVA encapsulant that cushions and secures the silicon cells, and the Tedlar foil that serves as a durable backsheet. The silicon cells, which are responsible for converting sunlight into electricity, are sandwiched between the EVA layers. This construction provides the necessary mechanical support and environmental protection, ensuring the long-term performance and durability of the solar panel. Figure 3b depicts the structure of a thin-film solar module, specifically one using CIGS technology. Unlike crystalline silicon modules, thin-film modules are characterized by their use of multiple thin layers of different materials deposited onto a substrate, typically glass. In this case, the layers include molybdenum (Mo), CIGS, cadmium sulphide (CdS), intrinsic zinc oxide (i-ZnO), and aluminium-doped zinc oxide (ZnO). Each layer plays a crucial role in the module's functionality, from serving as a conductive layer to forming the junction where the PV effect occurs. The thin-film structure is more flexible and less material-intensive compared to crystalline silicon, making it suitable for a variety of applications where a light weight and flexibility are required. However, thin-film technologies like CIGS also involve the use of potentially hazardous materials, such as cadmium, which necessitates careful consideration during the recycling process.



(**a**) (**b**)

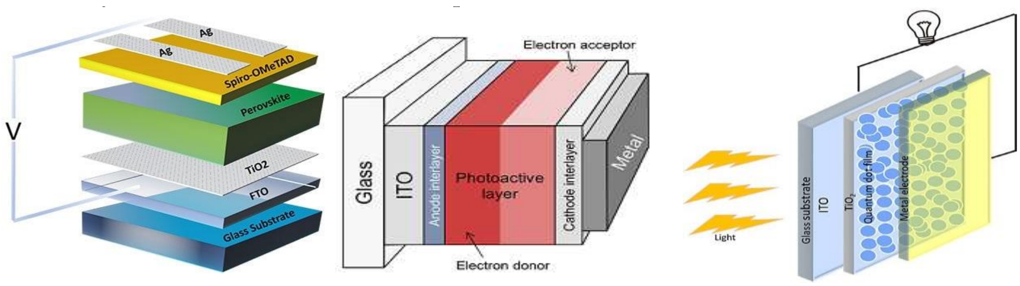
Figure 3. The structure of solar modules made from (**a**) crystalline silicon, (**b**) thin-film technology. Part of this figure is taken from https://www.zsw-bw.de/en/research/photovoltaics/topics/thin-film-solar-cells-and-modules.html, accessed on 3 December 2024.

4.3. Materials in Emerging PV Technologies

Emerging PV technologies, such as perovskite solar cells, OPVs, and quantum dot solar cells, use a diverse range of materials that differ significantly from those used in traditional crystalline silicon and thin-film cells.

Perovskite solar cells use a class of materials known as perovskites, which have the general formula ABX_3 [66], where 'A' is typically an organic cation, 'B' is a metal cation (commonly lead), and 'X' is a halide anion (such as iodine or bromine [67]). The most frequently studied perovskite material for solar cells is methylammonium lead iodide ($MAPbI_3$) [68], which has demonstrated high efficiency and ease of processing. The use of lead in perovskite solar cells raises environmental and health concerns similar to those associated with CdTe cells. The potential leaching of lead from damaged or improperly disposed perovskite cells could lead to environmental contamination. Researchers are actively exploring lead-free perovskite materials, but these alternatives have yet to match the performance of lead-based perovskites. The scalability and stability of perovskite materials also remain major challenges. A general structural diagram of a perovskite solar cell is shown in Figure 4a.

OPV cells use organic molecules or polymers to absorb sunlight and generate electricity. These materials include conjugated polymers (such as polythiophenes [69] and polyfluorenes [70]), small molecules (such as phthalocyanines and squareness [71]), and fullerene derivatives (such as [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) [72] and [6,6]-phenyl-C71-butyric acid methyl ester (PC71BM) [73]), which can form flexible, lightweight, and low-cost solar cells. A general structural diagram of an OPV solar cell is shown in Figure 4b. The organic materials used in OPVs can be synthesized with a wide range of properties, allowing for the development of customized solar cells for specific applications. However, the stability and durability of organic materials are significant challenges, as they tend to degrade more quickly than inorganic materials under exposure to sunlight and environmental conditions [74]. This degradation limits the lifespan of OPV cells and poses challenges for recycling, as the materials may not be recoverable in a usable form after extended use.



(**a**) (**b**) (**c**)

Figure 4. Structural diagrams: (**a**) perovskites (source: https://www.sigmaaldrich.cn/CN/zh/technical-documents/technical-article/materials-science-and-engineering/photovoltaics-and-solar-cells/quantum-dot-solar-cells, accessed on 3 December 2024), (**b**) OPV (source: https://www.oe.phy.cam.ac.uk/research/photovoltaics/ophotovoltaics, accessed on 3 December 2024), (**c**) quantum dot solar cell (source: https://www.sigmaaldrich.cn/CN/zh/technical-documents/technical-article/materials-science-and-engineering/photovoltaics-and-solar-cells/quantum-dot-solar-cells, accessed on 3 December 2024).

Quantum dot solar cells utilize nanoscale semiconductor particles known as quantum dots, typically made from materials like cadmium selenide (CdSe) [75], lead sulfide (PbS) [76], or other metal chalcogenides. An overview structural diagram of a quantum dot solar cell is shown in Figure 4c. Quantum dots have unique electronic and optical properties that can be precisely tuned by adjusting their size, enabling the development of highly efficient solar cells. The use of toxic materials, such as cadmium and lead, in quantum dot solar cells raises environmental concerns similar to those associated with CdTe and perovskite cells. Additionally, the production and stability of quantum dots are still areas of active research, with challenges remaining in terms of scalability, cost, and environmental impact.

5. Recycling Techniques

5.1. Mechanical Recycling

Mechanical recycling is one of the most common and straightforward methods for recovering materials from end-of-life PV solar cells. This approach involves physically breaking down the solar panels into smaller components, followed by processes such as crushing, milling, and sorting to separate and recover valuable materials [77]. Mechanical recycling is particularly relevant in c-Si solar cells, which dominate the global solar market, but it can also be applied to certain types of thin-film and emerging solar technologies. As depicted in Figure 5, the mechanical recycling process includes the automated separation of components like junction boxes, aluminum frames, and glass/cell/EVA sheets. The separated materials are then directed to various recycling pathways, with certain components like glass and cell/EVA sheets being sold at a high price due to their recyclability. This Figure highlights the efficiency of mechanical recycling in minimizing environmental impact by effectively recovering and repurposing valuable materials from PV panels, including those with broken glass.

Crushing is the initial step in the mechanical recycling of PV solar cells [78]. This process involves using industrial crushers or shredders to break down the solar panels into smaller, more manageable pieces. The goal of crushing is to reduce the size of the panels, making it easier to separate the different materials in subsequent processing steps. For crystalline silicon solar cells, crushing typically reduces the panels to fragments of glass, silicon, and metal. The encapsulant materials, such as EVA, which are used to protect the silicon wafers, are also broken down during this process. However, these encapsulants can complicate the recycling process because they tend to adhere to the glass and silicon fragments [79], making it difficult to achieve clean separation.

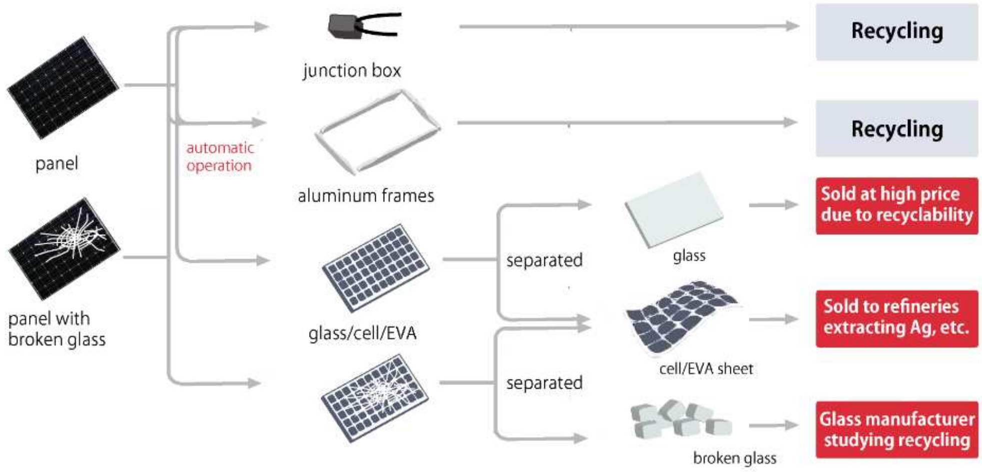


Figure 5. Schematic of the mechanical recycling process for PV solar panels. This Figure illustrates the automated separation of components from both intact and broken-glass PV panels, including junction boxes, aluminum frames, and glass/cell/EVA sheets. These components are subsequently directed to different recycling streams, with recyclable materials being sold to refineries or glass manufacturers for further processing. This process ensures a low environmental impact by efficiently recovering valuable materials from end-of-life solar panels. Figure source: https://www.npcgroup.net/eng/solarpower/reuse-recycle/dismantling, accessed on 3 December 2024.

In thin-film solar cells, such as those made from CdTe or CIGS, the crushing process similarly reduces the panels to small pieces of the substrate (usually glass), along with fragments of the thin-film materials and any metallic contacts. The presence of toxic materials, such as cadmium in CdTe cells, requires careful handling during crushing to prevent environmental contamination and to ensure that these materials can be safely recovered [80]. Emerging PV technologies, like perovskite solar cells, may also undergo crushing as part of their recycling process. However, the delicate and often toxic nature of the materials used in these cells, such as lead in perovskites, presents additional challenges. Special care must be taken during crushing to contain hazardous substances and prevent their release into the environment.

Following the initial crushing, the next step in mechanical recycling is milling. Milling further reduces the size of the fragments obtained from crushing, grinding them into fine particles [81,82]. This process is essential for liberating the valuable materials within the solar cells and preparing them for subsequent separation and purification steps.

In the case of crystalline silicon solar cells, milling helps to break down the silicon wafers and metal contacts into smaller particles. This fine material can then be processed to recover silicon, silver, and other metals. The glass from the panels, now in the form of fine particles, can also be recycled, often for use in the production of new glass products or as a filler material in construction [83]. For thin-film solar cells, milling serves a similar purpose but with additional considerations. For example, in CdTe cells, milling is used to liberate the cadmium and tellurium from the glass substrate [84]. These materials can then be recovered through further processing, such as chemical leaching or smelting [85]. In CIGS cells, milling helps to separate the copper, indium, gallium, and selenium compounds, which can be processed and purified for reuse. The milling of emerging PV technologies like perovskites presents unique challenges due to the sensitive and potentially hazardous materials involved. The process must be carefully controlled to avoid damaging the material's structure or causing environmental harm. The fine particles produced during milling can then be processed using techniques tailored to the specific materials used in the cells, such as chemical extraction or thermal treatment; both techniques will be discussed in the following sections.

Sorting is the final step in the mechanical recycling process and is crucial in separating the different materials recovered from the solar cells. Effective sorting ensures that each material can be processed in the most appropriate and efficient manner, maximizing the recovery of valuable resources and minimizing waste. For crystalline silicon solar cells, sorting typically involves separating the glass, silicon, and metals [86]. Glass is often separated using density-based methods, where the lighter glass particles are separated from the denser silicon and metal particles. Magnetic and eddy current separators [87,88] are commonly used to sort out ferrous and non-ferrous metals, such as aluminum and copper. The separated silicon can be further purified and potentially reused in the production of new solar cells or other semiconductor applications.

In the case of thin-film solar cells, sorting is more complex due to the presence of toxic materials and the finer particle size of the milled materials. Techniques such as flotation [89], electrostatic separation [90], or chemical methods may be used to separate the different components. Sorting is also a critical step in the recycling of emerging PV technologies. For perovskite solar cells, sorting may involve separating the lead-based compounds from the other materials [91,92].

As shown in Figure 6, the mechanical recycling of PV solar cells involves a highly automated process designed to handle the diverse materials found in solar panels. This Figure illustrates the various stages of the recycling process, beginning with feeding the solar PV panels into a shredder, followed by the processing of solar cell materials into strips of specific dimensions and further grinding them into fine particles. The machinery comprises one of the few PV recycling machinery systems developed worldwide and was made public in early 2023 by SUNY Group, a joint-stock machinery manufacturing enterprise located in China. The machine includes advanced systems for the separation of copper from other materials and the collection of dust, ensuring a clean and efficient recycling operation. The automated process not only facilitates the efficient recovery of valuable materials but also minimizes the environmental impact of recycling by ensuring the safe handling and processing of potentially hazardous components.

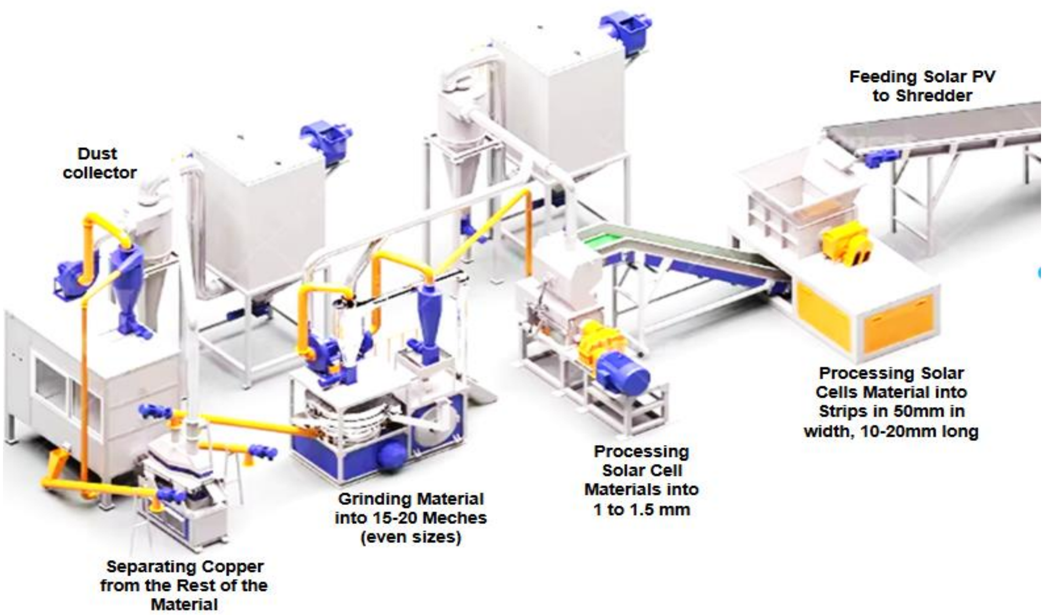


Figure 6. Automated mechanical recycling process for PV solar panels. The figure illustrates the step-by-step process of recycling PV solar cells using advanced machinery developed by SUNY Group

in China. The process begins with feeding the solar panels into a shredder, followed by the processing of the materials into strips and further grinding them into fine particles. The machinery is equipped with systems for separating copper from other materials and collecting dust, ensuring a low environmental impact and the efficient recovery of valuable resources.

5.2. Thermal Recycling

Thermal recycling is a process that involves the use of heat to break down PV solar cells and recover valuable materials. This method is particularly effective for dealing with the complex materials found in solar cells, especially those that are difficult to separate through mechanical means alone. Thermal recycling techniques such as pyrolysis and incineration are employed to decompose organic components, recover metals, and facilitate the separation of materials. These processes are relevant in a variety of PV technologies, including crystalline silicon, thin-film, and emerging solar cells.

5.2.1. Pyrolysis

Pyrolysis is a thermal recycling process that involves heating materials in the absence of oxygen [93], causing them to decompose into simpler substances without combustion. As depicted in Figure 7, this technique is particularly useful for breaking down the organic components of solar panels, such as encapsulants, backsheet materials, and adhesives, while preserving the integrity of the inorganic materials like silicon, metals, and glass. The pyrolysis process enables the separation of valuable materials, such as aluminium frames, glass, copper, and silicon, which can then be further processed and recycled. The encapsulants and backsheet vaporize due to the heat, allowing for the recovery of high-purity silicon and other critical materials that are essential in the production of new solar cells.

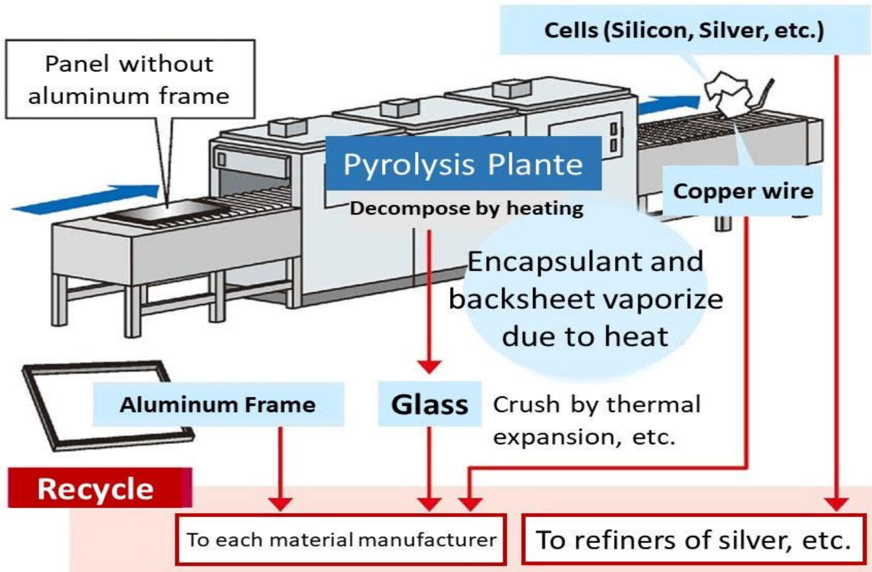


Figure 7. Illustration of the pyrolysis process for recycling PV solar panels. This Figure demonstrates how a pyrolysis plant processes solar panels by decomposing organic components, such as encapsulants and backsheet materials, through heat. The process allows for the recovery of key materials, including aluminium frames, glass, copper wires, and silicon, which are then directed to recycling streams for reuse in manufacturing. Figure source: https://j4ce.env.go.jp/en/casestudy/153, accessed on 3 December 2024.

In the context of crystalline silicon solar cells, pyrolysis is used to remove the encapsulant materials, such as EVA [94], which are used to protect the silicon wafers. During the pyrolysis process, the encapsulants decompose into gases and oils, leaving the silicon wafers, glass, and metal contacts largely intact [95]. The remaining solid residues, including the silicon wafers and metals, can then be processed further to recover valuable materials. This process is advantageous because it allows for the recovery of high-purity silicon, which can potentially be reused in the production of new solar cells.

For thin-film solar cells, pyrolysis can be employed to decompose the organic layers and separate the thin-film materials from the substrate. In CdTe solar cells, for example, pyrolysis can break down the backsheet materials and encapsulants [96], allowing for the recovery of the glass substrate and the CdTe layer. Similarly, in CIGS cells, pyrolysis helps to separate the CIGS compound from the substrate and other materials, facilitating the recovery of metals like copper, indium, gallium, and selenium [97].

In emerging PV technologies, such as perovskite solar cells, pyrolysis is less commonly used due to the sensitivity of the perovskite materials to high temperatures [98]. However, in some cases, pyrolysis may be used to decompose the organic components and recover the inorganic materials, such as lead compounds, for further processing. The process must be carefully controlled to prevent the release of toxic substances, such as lead, and to ensure that the recovered materials can be safely reused.

5.2.2. Incineration

Incineration is a more aggressive form of thermal recycling, where materials are subjected to high temperatures in the presence of oxygen, leading to combustion [99]. This process is typically used to reduce the volume of waste by burning off the organic components, leaving behind ash and residual metals that can be further processed [77,100]. While incineration is effective for destroying organic materials and reducing waste, it also presents significant environmental challenges, particularly in the context of PV solar cells.

For crystalline silicon solar cells, incineration can be used to burn off the encapsulants and other organic components, leaving behind the silicon wafers, glass, and metals. However, this process can lead to the oxidation of metals, such as silver and aluminium, making them more difficult to recover [100]. Additionally, the combustion of materials like EVA can produce harmful emissions, including volatile organic compounds (VOCs) and dioxins [101,102], which require careful management through air pollution control systems. The residual ash, containing metals and silicon, must then be treated to recover these materials, adding complexity to the recycling process.

In thin-film solar cells, incineration is generally less favoured due to the presence of toxic metals, such as cadmium in CdTe cells and selenium in CIGS cells. The high temperatures involved in incineration can lead to the release of toxic fumes and residues, which pose serious environmental and health risks. For instance, cadmium oxide, a byproduct of incinerating CdTe cells, is highly toxic and requires specialized equipment to capture and neutralize. As a result, alternative recycling methods, such as pyrolysis or chemical processing, are often preferred in thin-film technologies, to minimize environmental impacts. Similarly, emerging PV technologies, particularly those involving perovskites, are generally unsuitable for incineration due to the presence of sensitive and potentially hazardous materials. The high temperatures of incineration can destroy the perovskite structure and lead to the release of harmful substances, such as lead compounds, into the environment. Therefore, incineration is typically avoided in favour of less destructive methods that allow for the safe recovery of materials.

5.3. Environmental Considerations and Challenges

Figure 8 illustrates the environmental challenges associated with thermal recycling. While thermal recycling techniques like pyrolysis and incineration can be effective for recovering materials from PV solar cells, they also present significant environmental challenges. The decomposition of organic materials during pyrolysis or the combustion of these materials during incineration can produce harmful emissions, including greenhouse gases, VOCs, and toxic fumes. These emissions must be carefully controlled to prevent environmental contamination and ensure compliance with environmental regulations.

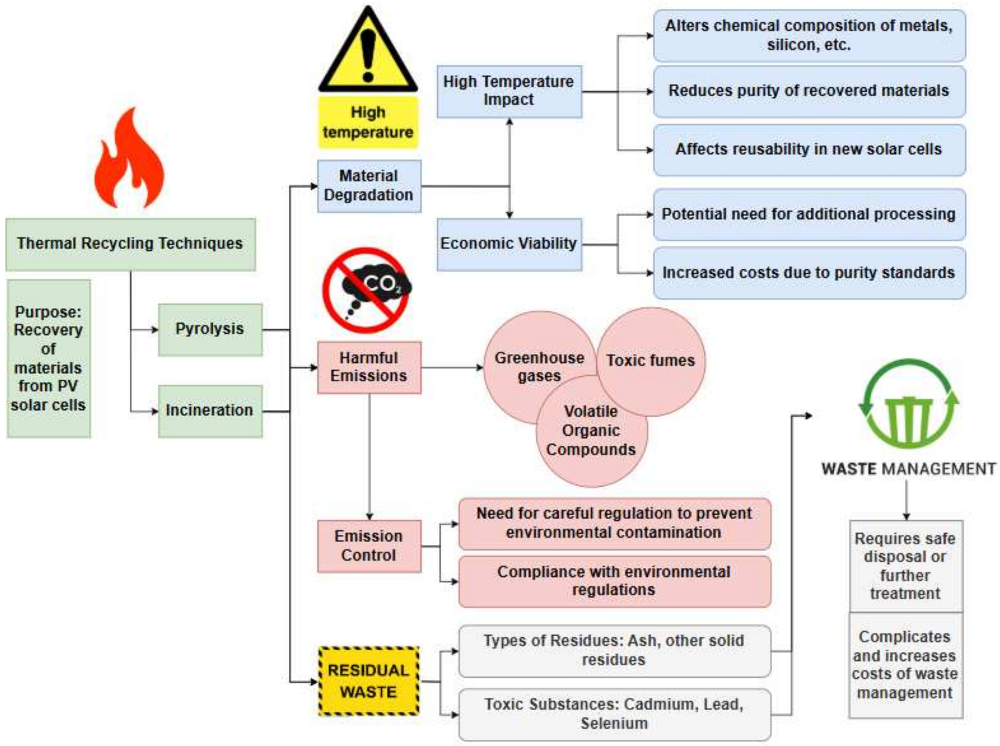


Figure 8. Environmental challenges in thermal recycling techniques for PV solar cells, including harmful emissions, material degradation, and waste management issues.

Another challenge is the potential for material degradation during thermal processing. High temperatures can alter the chemical composition of metals, silicon, and other materials, reducing their purity and making them less suitable for reuse in new solar cells. This degradation can limit the economic viability of thermal recycling, as the recovered materials may require additional processing to meet the purity standards required for PV manufacturing.

The disposal of residues from thermal recycling is another concern. The ash and other solid residues left after pyrolysis or incineration may contain toxic substances that require safe disposal or further treatment. The presence of hazardous materials, such as cadmium, lead, and selenium, in the residues complicates waste management and increases the costs associated with thermal recycling.

Despite these challenges, thermal recycling remains a valuable tool in the overall recycling strategy for PV solar cells. When combined with mechanical recycling and other techniques, thermal processes can help to maximize the recovery of valuable materials and reduce the environmental impact of PV waste. However, careful consideration must be given to the environmental risks and economic feasibility of these processes, particularly as the volume of end-of-life solar panels continues to grow.

In addition to emission control and material degradation concerns, the scalability and integration of thermal recycling into a circular economy framework pose significant challenges. The high energy demands of thermal processes, particularly when powered by non-renewable energy sources, can offset the environmental benefits of material recovery. Transitioning to renewable energy-powered recycling facilities could mitigate this impact and align thermal recycling with broader sustainability goals. Furthermore, advancements in emission capture technologies, such as carbon capture and storage (CCS) and advanced filtration systems, hold promise for minimizing greenhouse gas emissions and toxic fumes. Another consideration is the potential for hybrid recycling approaches, where thermal methods are combined with mechanical or chemical processes to optimize material recovery and purity. Such integrated strategies could address the limitations of standalone thermal techniques while improving economic feasibility. As the PV industry evolves, it will be essential to invest in research and innovation to overcome these barriers, ensuring that thermal recycling remains a viable and sustainable option for managing PV waste.

5.4. Chemical Recycling

Chemical recycling is a sophisticated process that involves the use of chemical treatments to recover valuable materials from end-of-life PV solar cells. This method is particularly effective for separating and purifying materials that are difficult to extract through mechanical or thermal recycling. Chemical recycling is especially relevant in the recovery of metals and semiconductors from various types of PV technologies, including crystalline silicon, thin-film, and emerging solar cells. The techniques involved in chemical recycling can vary widely depending on the specific materials and the desired end products.

5.4.1. Leaching

Leaching is one of the most common chemical recycling techniques used to recover metals from PV solar cells. The process involves the use of chemical solutions, often acidic or basic, to dissolve the target materials, which can then be separated from the undissolved components [103]. Leaching is particularly effective for extracting valuable metals, such as silver, copper, indium, gallium, and rare-earth elements, from solar cells.

- In crystalline silicon solar cells, leaching is primarily used to recover metals like silver and aluminium. The process typically involves crushing the solar cells into small pieces, followed by immersion in a leaching solution, such as nitric acid (HNO_3) [104] or hydrochloric acid (HCl) [105]. The acid dissolves the silver contacts, separating them from the silicon and glass. The dissolved silver can then be precipitated out of the solution, purified, and reused in the production of new solar cells or other electronic applications. Additionally, leaching can be used to recover aluminium from the back-side metallization of the cells. The aluminium is dissolved in a basic solution, such as sodium hydroxide (NaOH) [106], and then precipitated and purified. The remaining silicon and glass are usually left intact, allowing for potential recovery and reuse.
- In thin-film solar cells, leaching plays a crucial role in recovering the semiconductor materials that are embedded in the glass or other substrates. For example, in CdTe solar cells, leaching can be used to extract cadmium and tellurium. The process typically involves using acids, such as sulfuric acid (H_2SO_4) [107], to dissolve the CdTe layer from the glass substrate. The cadmium and tellurium can then be separated, purified, and reused. Given the toxicity of cadmium, careful control of the leaching process is essential to prevent environmental contamination. For CIGS solar cells, leaching is used to recover copper, indium, gallium, and selenium. A combination of acids, such as hydrochloric acid and nitric acid [108], may be used to selectively dissolve these metals. The resulting solutions are then treated to precipitate the individual metals, which can be purified and reused. The remaining glass substrate can often be recycled separately.
- In emerging technologies like perovskite solar cells, leaching is used to recover lead and other materials from the cells. Given the potential environmental and health risks associated with lead, the leaching process must be carefully managed. Acidic solutions,

such as acetic acid [109] or nitric acid [92,110], can dissolve the lead compounds in perovskite cells, allowing for their recovery and safe disposal or reuse. Researchers are also exploring less toxic alternatives to lead in perovskites, which would simplify the recycling process and reduce the need for stringent environmental controls.

The environmental and economic impacts of leaching as a chemical recycling technique are multifaceted and must be carefully considered to optimize its use. As illustrated in Figure 9, while leaching offers significant benefits, such as waste reduction and resource conservation, it also poses challenges, including the potential for environmental contamination and the economic burden of managing chemical waste. Balancing these factors is crucial to ensure that leaching remains a viable and sustainable option for the recycling of PV solar cells.

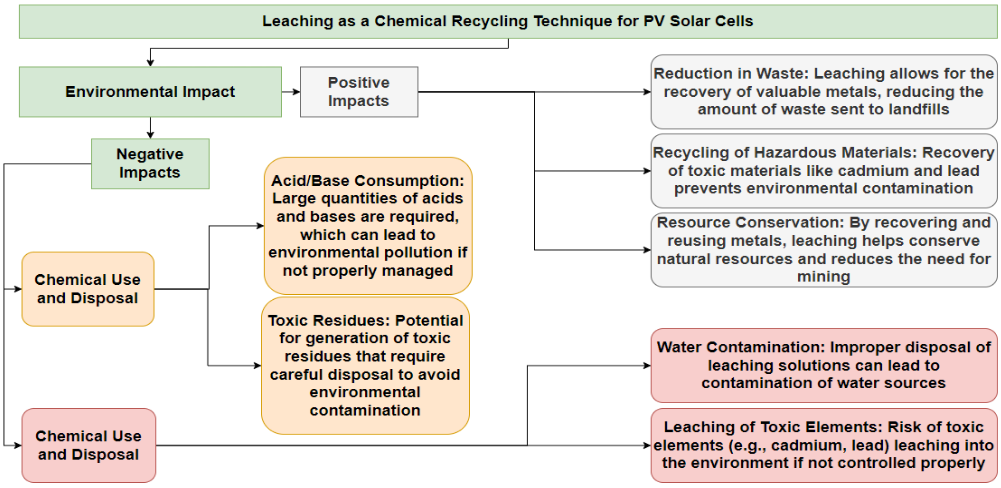


Figure 9. Schematic representation of the environmental and economic impacts of leaching in the recycling of PV solar cells, highlighting both the positive outcomes (e.g., waste reduction and resource conservation) and the challenges (e.g., chemical use and potential for environmental contamination).

5.4.2. Solvent Extraction and Electrochemical Recovery

Solvent extraction is another chemical recycling technique used to separate and purify specific components from a mixture. This method involves the use of organic solvents to selectively dissolve certain materials, which can then be separated from the undissolved components. Solvent extraction is particularly useful for recovering organic materials or for purifying metals that have been dissolved in a leaching solution.

- In crystalline silicon solar cells, solvent extraction is less commonly used, but it can play a role in purifying the metals recovered during the leaching process. For example, solvent extraction may be employed to separate silver from other metals dissolved in the acid leachate [111,112]. By carefully choosing the solvent and adjusting the pH of the solution, the silver can be selectively extracted, leaving other metals behind.
- In thin-film technologies, solvent extraction is more commonly applied, particularly for complex mixtures of metals. For instance, in the recycling of CIGS cells, solvent extraction can be used to separate copper, indium, gallium, and selenium from each other after they have been dissolved by leaching. Different solvents, such as kerosene [113] or aliphatic hydrocarbons [114], can be used to selectively extract each metal, which can then be recovered by further chemical processing.
- For emerging technologies like perovskite solar cells, solvent extraction may be used to recover organic components or to purify the metals extracted during leaching [115]. Given the organic nature of many perovskite materials, solvent extraction offers a way to separate these components from the inorganic materials in the cells. Researchers

are also investigating the use of green solvents—solvents that are environmentally friendly and less toxic—to improve the sustainability of the recycling process [116,117].

Electrochemical recovery is a technique that uses electrical energy to drive chemical reactions that recover metals from solutions [118–120]. This process is particularly useful for recovering high-purity metals from the solutions produced by leaching or solvent extraction. Electrochemical recovery involves passing an electric current through the solution, causing the metal ions to deposit onto an electrode, where they can be collected and purified.

- In crystalline silicon solar cells, electrochemical recovery is often used to purify the silver recovered from the leaching process. The silver ions in the leachate are reduced and deposited onto a cathode, forming high-purity silver that can be reused in new solar cells or other electronic applications [121]. This method is highly efficient and allows for the recovery of silver with minimal impurities.
- Electrochemical recovery is also applicable to thin-film technologies, particularly for the recovery of metals like copper and indium from CIGS cells. After leaching and solvent extraction, the metal ions in the solution can be electrochemically reduced and deposited onto electrodes. This process can produce high-purity metals that are suitable for reuse in new solar cells or other industries [119]. In the case of CdTe cells, electrochemical recovery can be used to recover tellurium from the leachate [122]. The tellurium ions are reduced and deposited onto an electrode, where they can be collected, purified, and reused. The electrochemical process is carefully controlled to ensure that the recovered tellurium is of high purity, which is critical in its reuse in new solar cells.
- Electrochemical recovery is also being explored for use in emerging technologies like perovskite solar cells. Given the presence of lead in many perovskite cells, electrochemical methods can be used to recover and purify lead from the leachate [92,123], minimizing environmental risks and allowing for safe disposal or reuse. Researchers are also investigating the use of electrochemical techniques to recover other materials from perovskite cells, including organic components [124] and alternative metals.

Figure 10 illustrates the environmental impact of the combined solvent extraction and electrochemical recovery processes in the recycling of end-of-life solar panels. The flowchart demonstrates how solvent extraction uses organic solvents to selectively dissolve metals or organic components. This process carries potential environmental risks, especially when conventional solvents are used, as they can negatively impact the environment, human health, and groundwater quality. However, the adoption of green solvents significantly reduces these risks by minimizing toxicity and environmental impacts. On the other hand, electrochemical recovery leverages electrical current to drive the reduction of metal ions onto an electrode, facilitating the recovery of high-purity metals. While this technique is highly effective, its environmental impact is closely tied to energy consumption. The energy demand, particularly if not sourced from renewable resources, could potentially increase the carbon footprint of the recycling process. Both methods ultimately contribute to the recovery of valuable materials, which can be recycled and reused in new solar cells or other applications, thus supporting resource conservation and reducing waste.

The scalability of recycling technologies remains a critical factor in addressing the growing volume of end-of-life solar panels. Crystalline silicon modules, which dominate the global PV market, exhibit significant potential for large-scale recycling due to established mechanical methods. However, challenges in separating encapsulated materials, such as glass and polymer films, limit the efficiency and economic feasibility. Pyrolysis offers an alternative approach by enabling the thermal decomposition of encapsulants, thereby recovering high-purity silicon, glass, and metals. For CdTe modules, the scalability is supported by robust chemical recycling processes, but the safe handling of toxic cadmium remains a barrier in underdeveloped regions. Additionally, the recycling of glass, a major component by volume, is generally scalable and well integrated into existing industries. In contrast, polymer films, such as EVA, require further technological innovation to improve recovery rates and economic viability. Addressing these scalability challenges is essential in creating a sustainable recycling framework capable of meeting future demands.

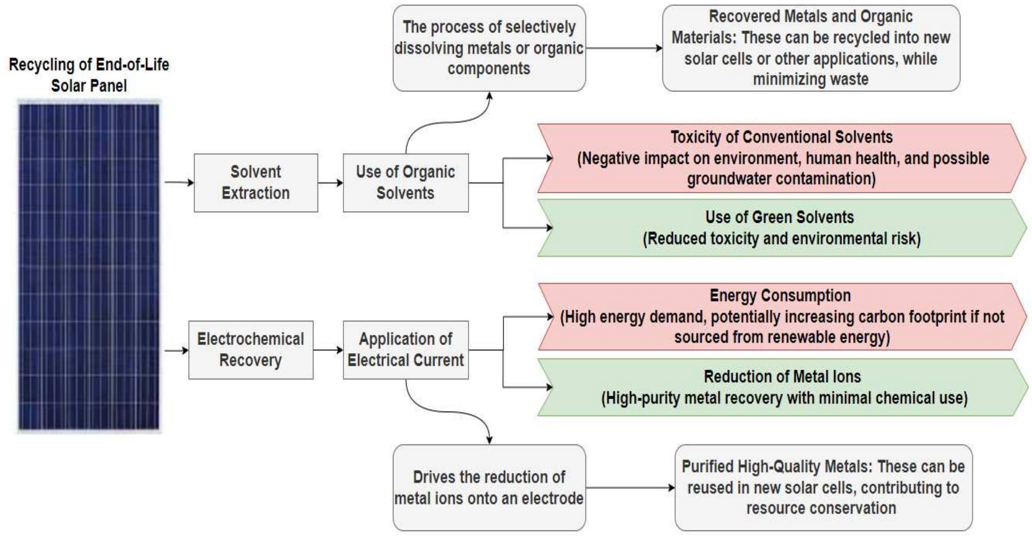


Figure 10. Flowchart depicting the environmental impact of solvent extraction and electrochemical recovery in solar panel recycling. This Figure outlines the environmental considerations associated with solvent extraction and electrochemical recovery processes. It highlights the trade-offs between solvent toxicity and energy consumption, as well as the benefits of using green solvents and recovering high-purity metals. The recovered materials contribute to sustainable resource use by being reintroduced into the manufacturing cycle, thereby reducing the need for virgin resources and minimizing environmental impacts.

The efficiency and suitability of recycling processes also vary between silicon-based and thin-film PV modules, reflecting differences in material composition and structure. For silicon-based modules, mechanical methods such as crushing and milling are effective in recovering glass and silicon, though additional processes like pyrolysis are often required to handle encapsulants like EVA and recover high-purity materials. These methods are suitable for large-scale recycling due to the high market share of crystalline silicon modules. In contrast, thin-film modules, including CdTe and CIGS, require chemical recycling techniques like leaching and solvent extraction to recover rare and valuable materials such as cadmium, tellurium, and selenium. These processes achieve high material recovery rates but face challenges related to the handling of toxic substances and the scalability of operations. Thermal methods, while effective for certain materials, are less commonly applied to thin-film modules due to the potential release of harmful emissions. This underscores the importance of tailoring recycling strategies to the specific material and structural characteristics of each PV technology to optimize efficiency and sustainability.

6. Economic Impact of Recycling Solar PV Panels

6.1. Economic Considerations: Cost-Effectiveness of Recycling Processes

While the environmental benefits of recycling PV solar cells are clear, the economic considerations of recycling processes are equally important in determining the feasibility and sustainability of these efforts. The cost-effectiveness of recycling PV panels depends on several factors, including the type of solar cells, the materials used, the recycling methods employed, and the market value of the recovered materials.

One of the key economic challenges in PV recycling is the cost associated with the collection, transportation, and processing of end-of-life solar panels. These costs can vary depending on the location of recycling facilities, the volume of panels being processed, and the complexity of the recycling methods used. For example, mechanical recycling processes, such as crushing and milling, are generally less expensive but may yield lower-purity materials, requiring additional processing steps that can increase costs. In contrast, chemical and thermal recycling methods, while potentially more effective in recovering high-purity materials, often involve higher operational costs due to the need for specialized equipment, chemical reagents, and energy-intensive processes [125–127].

Another important economic consideration is the potential to create new markets and job opportunities through the development of a robust PV recycling industry. As the volume of end-of-life solar panels increases, so does the demand for recycling services. This presents an opportunity for economic growth in the form of new businesses, innovations in recycling technology, and the creation of jobs in recycling facilities, logistics, and related industries. Moreover, the recovered materials can be reintroduced into the manufacturing supply chain, reducing the reliance on imported raw materials and enhancing the competitiveness of domestic industries.

Government policies and incentives play a crucial role in shaping the economic landscape of PV recycling. Subsidies, tax incentives, and regulations that mandate recycling can help to offset the costs and encourage investment in recycling infrastructure. For example, extended producer responsibility (EPR) programmes [128,129], which require that manufacturers take responsibility for the end-of-life management of their products, can drive the development of more cost-effective and efficient recycling processes. Additionally, research and development (R&D) funding can support the advancement of new recycling technologies that reduce costs and improve material recovery rates.

Looking ahead, the future of PV panel recycling is poised to embrace a more integrated and streamlined approach, as illustrated in Figure 11. This framework begins with a thorough inspection phase, using advanced techniques such as thermal imaging [130–132] and electroluminescence [133–136] tests to assess the condition of end-of-life solar panels. By estimating power loss and determining whether panels can be repaired, this process emphasizes the importance of reducing waste through repair and refurbishment. Panels that can be fixed are restored for further use, while those that are still functional but less efficient are redirected to secondary markets. Ultimately, only the panels that are beyond repair are sent to recycling facilities, where valuable materials are recovered and reintroduced into the manufacturing cycle. This future-orientated approach not only enhances the economic viability of PV recycling by minimizing waste and maximizing resource recovery but also aligns with the broader goals of sustainability by promoting the principle of reduce, reuse, recycle.

The adoption of such an integrated framework not only supports economic feasibility but also fosters innovation in recycling practices. By prioritizing repair and refurbishment wherever possible, this approach reduces the costs associated with full-scale recycling while extending the lifespan of PV panels. Furthermore, the emphasis on secondary market utilization provides an additional revenue stream, creating economic incentives for stakeholders. The successful implementation of this framework will require collaboration among manufacturers, recyclers, and policymakers to establish standards and develop efficient logistics systems.

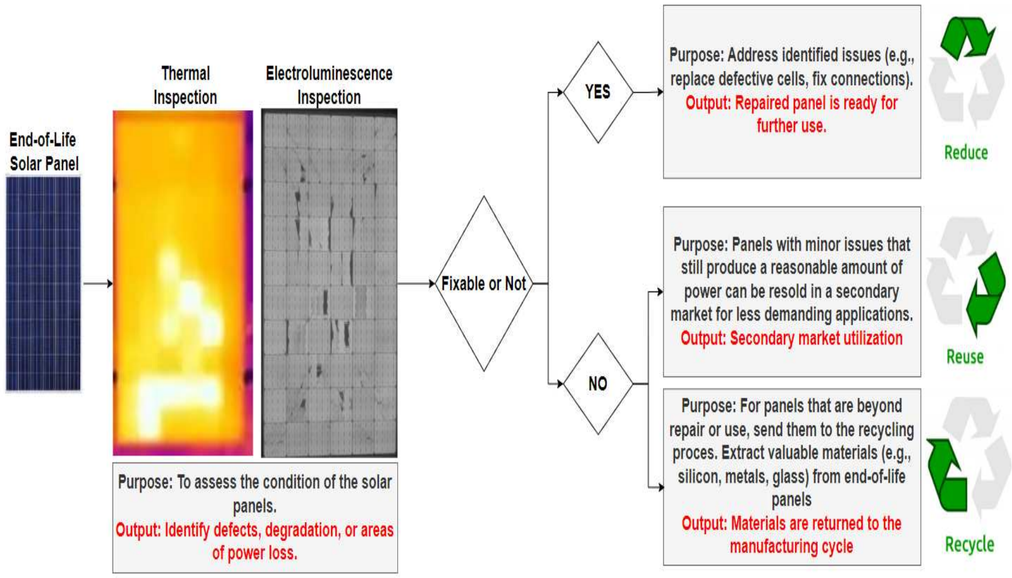


Figure 11. Future recycling framework for PV solar panels integrating inspection, repair, and recycling processes.

6.2. Challenges and Barriers: Addressing the Cost of Recycling, Lack of Infrastructure, and Technical Limitations

While the environmental and economic benefits of PV solar cell recycling are significant, the process is not without its challenges. Several barriers must be overcome to make recycling more widespread and efficient. These challenges include the high cost of recycling processes, a lack of adequate infrastructure, and various technical limitations that complicate the recovery of valuable materials.

One of the most pressing challenges in PV solar cell recycling is the high cost associated with the processes involved. Recycling PV panels is often more expensive than simply disposing of them in landfills, particularly in regions where landfill costs are low and recycling incentives are minimal. The costs include not only the collection and transportation of end-of-life panels but also the expenses related to the actual recycling processes, such as mechanical crushing, chemical leaching, or thermal treatment. High energy consumption, the need for specialized equipment, and the use of costly chemicals further drive up the cost. Additionally, the economic viability of recycling is closely tied to the fluctuating market prices of recovered materials, such as silicon, silver, and rare metals. When commodity prices are low, the revenue generated from selling these materials may not be sufficient to cover the recycling costs, making the process economically unfeasible without subsidies or regulatory support.

The lack of a robust recycling infrastructure is another major barrier to the widespread adoption of PV recycling [137–139]. In many regions, especially in developing countries, there is limited access to facilities that are capable of processing end-of-life solar panels. This lack of infrastructure is compounded by the absence of standardized procedures and regulations governing the recycling of PV panels. Without a well-established network of recycling facilities, the logistics of collecting, transporting, and processing solar panels become complex and costly. Furthermore, the lack of infrastructure also limits the scalability of recycling efforts. As the volume of decommissioned solar panels increases in the coming decades, the current infrastructure may be inadequate to handle the growing demand for recycling services. This situation could lead to an increase in the illegal disposal or improper handling of solar panels, exacerbating environmental risks.

The technical complexity of recycling PV solar cells presents another set of challenges [140]. Solar panels are composed of various materials, including glass, metals, silicon, and encapsulants, which are often tightly bonded together. This makes the separation and recovery of individual components difficult and time-consuming [141]. For instance, the encapsulant materials used in crystalline silicon solar cells are designed to protect the delicate silicon wafers from environmental damage, but these same materials can be challenging to remove during recycling [142]. Similarly, in thin-film solar cells, the presence of hazardous materials like cadmium and selenium requires specialized techniques to safely extract and recover these substances without causing environmental contamination. The diversity of PV technologies also adds to the complexity. Emerging technologies, such as perovskite solar cells, introduce new materials and combinations that are not yet fully understood in the context of recycling, necessitating further research and development to create effective recycling methods.

Moreover, the quality and purity of the materials recovered through recycling can represent a limiting factor. Recycled silicon, for example, may not always meet the stringent purity requirements needed for the production of new solar cells, which can limit its reuse and reduce the overall economic viability of recycling. Similarly, the recovery of metals from thin-film and emerging technologies often involves complex chemical processes that can introduce impurities, reducing the value of the recovered materials. In addition to the technical and infrastructural challenges, there are also regulatory and market barriers that hinder the expansion of PV recycling. In many regions, there is a lack of clear regulations mandating the recycling of solar panels, which reduces the incentive for manufacturers and consumers to participate in recycling programmes. Furthermore, the absence of EPR schemes, where manufacturers are held accountable for the end-of-life management of their products, limits the motivation for companies to invest in recycling infrastructure and research.

The market for recycled materials is also a significant barrier. The demand for recycled silicon, metals, and other materials recovered from PV panels may not always be strong, particularly when compared to the demand for virgin materials. This disparity can make it difficult for recycling operations to achieve profitability, especially in regions where the cost of extracting and processing virgin materials is low.

Addressing these challenges and barriers requires a multifaceted approach. Governments and policymakers need to implement stronger regulations and incentives to promote PV recycling, such as mandating recycling targets, providing subsidies or tax incentives, and establishing EPR schemes. Investment in recycling infrastructure is also critical, particularly in regions that currently lack the capacity to handle large volumes of solar panel waste. This investment should be coupled with research and development to improve the efficiency, cost-effectiveness, and scalability of recycling technologies. In addition, public awareness and industry collaboration are also essential in overcoming these barriers. Educating consumers about the importance of recycling and the environmental risks associated with improper disposal can help increase participation in recycling programmes. Meanwhile, collaboration between manufacturers, recycling companies, and research institutions can drive innovation and the development of standardized recycling processes that are both effective and economically viable.

Table 2 highlights the advancements and strategies employed by leading companies in the solar module recycling industry [143–150]. First Solar in the USA has implemented a closed-loop recycling system that successfully recovers up to 90% of materials from thin-film panels, supported by a global network of facilities. Veolia, based in France, leads Europe with the continent's first dedicated recycling plant for crystalline panels, processing approximately 1300 tons annually. In Australia, Reclaim PV focuses on end-of-life recycling services, excelling in the recovery of high-value materials such as silicon and aluminium. Meanwhile, PV Cycle, a European organization, operates voluntary take-back programmes across the EU, achieving a material recovery rate of up to 95% for solar modules. Lastly, Norway's Rystad Energy emphasizes research-driven recycling, exploring advanced mechanical separation techniques to enhance efficiency. These examples collectively underscore the global push toward sustainable solar module management through innovation and collaboration.

Table 2. Overview of solar module recycling efforts by key industry players.

Company/ Organization	Recycling Approach	Progress/Outcome
First Solar (USA)	Closed-loop recycling	Recycling up to 90% of materials from thin-film panels; has established recycling facilities globally [143].
Veolia (France)	Mechanical recycling for crystalline panels	Europe's first dedicated plant for solar panel recycling, processing 1300 tons annually [144].
Reclaim PV (Australia)	End-of-life recycling services	Specialized in recovering high-value materials like silicon and aluminium [145].
PV Cycle (Europe)	Voluntary take-back programmes	Offers collection and recycling across EU; has recovered 95% of materials from PV modules in recent years [146].
Rystad Energy (Norway)	Advanced mechanical separation	Conducting research and pilot projects to improve recycling efficiency for solar modules [147].
RESOLAR Energy Technology (China)	Utilizes the "GST Green Separation Method" to recycle PV modules into glass, metals, and high-grade silicon	Operates China's first 10,000-ton recycling line, processing 900 tons/month; collaborated on a fully recycled PV module [148].
Trina Solar (China)	Developed chemical and wet silver extraction technologies for recycling high-value materials	Produced the world's first fully recycled crystalline silicon PV module with over 20% efficiency [149].
Yellow River Upstream Hydropower Development (China)	Integrates a closed-loop system for PV module recycling	Established the first module recycling line in Qinghai Province, reducing resource waste [150].

Additionally, China has emerged as a leader in solar module recycling. RESOLAR Energy Technology has developed the "GST Green Separation Method", which allows the efficient recycling of PV modules into glass, metals, and high-grade silicon, with a processing capacity of 900 tons per month. Trina Solar has implemented chemical and wet silver extraction techniques to produce the world's first fully recycled crystalline silicon PV module, achieving over 20% efficiency. Yellow River Upstream Hydropower Development established the first module recycling line in Qinghai Province, utilizing a closed-loop system to reduce resource waste and enhance sustainability. These examples collectively underscore the global push toward sustainable solar module management through innovation and collaboration.

Building on these industrial advancements, the integration of design strategies at the PV module development stage offers significant potential to enhance recyclability at end-of-life. Design principles such as material selection, layer structure optimization, and easily dismantled configurations can reduce the complexity and cost of recycling processes. For instance, incorporating alternative encapsulants that are easier to separate or biodegradable materials can simplify material recovery. Similarly, modular designs that facilitate disassembly enable efficient access to critical components such as silicon, glass, and metals.

By adopting 'design for recyclability' principles, manufacturers can align with the broader circular economy goals demonstrated by leading industry players. This approach not only promotes sustainability but also ensures that future PV modules are better suited to meet the evolving demands of global recycling frameworks. The combination of innovative industrial practices and forward-looking design strategies is key in addressing the growing challenge of solar module waste management.

7. Conclusions

The rapid expansion of PV solar energy systems presents a dual challenge: the need to manage the environmental impact of EoL solar panels while sustaining the momentum of renewable energy adoption. This review has systematically explored the current state of PV solar cell recycling, emphasizing the importance of developing efficient and economically viable recycling processes. The analysis has highlighted several critical areas:

- Recycling Techniques: The study identified mechanical, thermal, and chemical recycling as the primary methods employed in PV solar cell recycling. Each technique presents unique advantages and challenges, with mechanical processes being more straightforward but less efficient in material recovery, while chemical methods offer higher purity but are costlier and more complex. Emerging hybrid approaches, combining mechanical and chemical processes, have shown the potential to enhance efficiency and scalability, providing a promising direction for future developments.
- Economic and Environmental Impacts: The economic feasibility of recycling remains a significant barrier. The high costs associated with the recovery of valuable materials, such as silver and silicon, and the complexity of the processes involved often outweigh the financial returns. However, the environmental benefits, including significant reductions in waste and resource conservation, underscore the importance of advancing these technologies. Developing cost-effective recycling methods and integrating renewable energy into recycling operations are highlighted as crucial steps to enhance both economic and environmental outcomes. The paper underscores that investment in recycling infrastructure and innovation is crucial in achieving these benefits on a larger scale.
- Policy and Regulations: The paper emphasizes the critical role of government policies and regulatory frameworks in facilitating the development of a sustainable PV recycling industry. EPR schemes, incentives for recycling, and international collaboration are highlighted as key mechanisms to drive industry engagement and ensure compliance with environmental standards. Furthermore, harmonized international regulations could standardize recycling practices, promoting a global approach to PV waste management.
- Future Directions: A significant takeaway from the review is the need for continued research and development in this field. Innovations in material science, such as the development of more easily recyclable PV materials, and advancements in recycling technology, particularly in reducing process costs and increasing efficiency, are vital. The integration of these advancements into existing solar energy infrastructure will be essential in achieving a circular economy in the solar industry. The paper also highlights the potential of "design-for-recyclability" principles, which could streamline material recovery and reduce waste, making future PV systems inherently more sustainable.
- Industry Collaboration: The paper stresses the importance of collaboration across the solar industry, from manufacturers to recyclers, to create a cohesive and efficient recycling ecosystem. The standardization of processes and materials, coupled with a shared commitment to sustainability, will be critical in overcoming the current challenges.

In conclusion, the transition to a sustainable solar energy future depends not only on the widespread adoption of PV systems but also on the development of effective strategies for managing their end-of-life phase. By addressing the challenges identified in this review—through innovation, policy support, and industry collaboration—the solar industry can enhance its environmental stewardship, contribute to the global circular economy, and solidify its role as a cornerstone of the renewable energy landscape. The path forward requires a concerted effort to balance economic realities with environmental imperatives, ensuring that solar energy remains a truly sustainable solution for generations to come. The integration of advanced technologies, supportive policy measures, and proactive industry initiatives will be essential in aligning economic realities with environmental imperatives, ensuring that solar energy remains a truly sustainable solution for generations to come.

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