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Review

Advancements and Challenges in Photovoltaic Cell Recycling: A Comprehensive Review

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Abstract: This review examines the complex landscape of photovoltaic (PV) module recycling and outlines the challenges hindering widespread adoption and efficiency. Technological complexities resulting from different module compositions, different recycling processes and economic hurdles are significant barriers. Inadequate infrastructure, regulatory gaps and limited awareness are also hampering progress. In addition, this analysis draws parallels between the development of PV module recycling and recycling technologies for other high-tech products, such as lithium-ion batteries, highlighting similarities in regulatory and technical feasibility challenges. Amid these challenges, however, lie opportunities for a sustainable future. Technological advances, stakeholder collaboration and the adoption of circular economy principles emerge as key ways forward. This review highlights the need for concerted action to overcome barriers and drive the development of efficient and sustainable PV module recycling practices.

Keywords: photovoltaic cell recycling; sustainable technology for energy production; photovoltaic technology; environmental impact of PV module recycling

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1. Introduction

In the pursuit of sustainable energy solutions, photovoltaic (PV) technology has become a cornerstone in the transition to renewable power sources. The adoption of solar panels promises reduced carbon footprints and enhanced energy independence. However, a critical challenge lies in the management of end-of-life photovoltaic modules [1].

The global capacity of solar energy installations is growing rapidly, bringing the issue of photovoltaic waste management to the forefront. It is imperative to develop efficient and ecologically responsible recycling approaches to mitigate environmental risks and optimize the longevity of the renewable energy infrastructure [1,2].

The evolution of solar energy is the result of technological breakthroughs and a growing environmental consciousness. Projections show that worldwide cumulative PV capacity is expected to nearly triple (based on the data for 2022), exceeding 2350 GW by 2027 under an optimum scenario. This remarkable growth highlights the unprecedented expansion of solar energy, which is outpacing conventional energy sources at an unprecedented rate [2].

In a transformative development, solar power is set to surpass hydropower as the leading global installed electricity capacity source by 2024 (refer to Figure 1a). Furthermore, solar energy is projected to exceed natural gas by 2026 and coal by 2027, solidifying its position as the dominant contributor to the world's installed electricity capacity [2].

The global electricity generation landscape is undergoing a transformation, driven by a significant increase in renewable energy sources. Projections indicate that renewable electricity generation will increase by almost 60%, surpassing 12,400 TWh. Although hydropower remains the primary source of renewable electricity generation, its expansion rate lags behind the remarkable growth witnessed in wind and solar PV capacities. Forecasts predict a significant shift, with renewable energy set to surpass coal as the primary source of global electricity generation within the next three years. Renewable energy sources are expected to make up almost 40% of the world's electricity production by 2027, offsetting the decreasing proportions of coal, natural gas, and nuclear power in the energy mix [2].

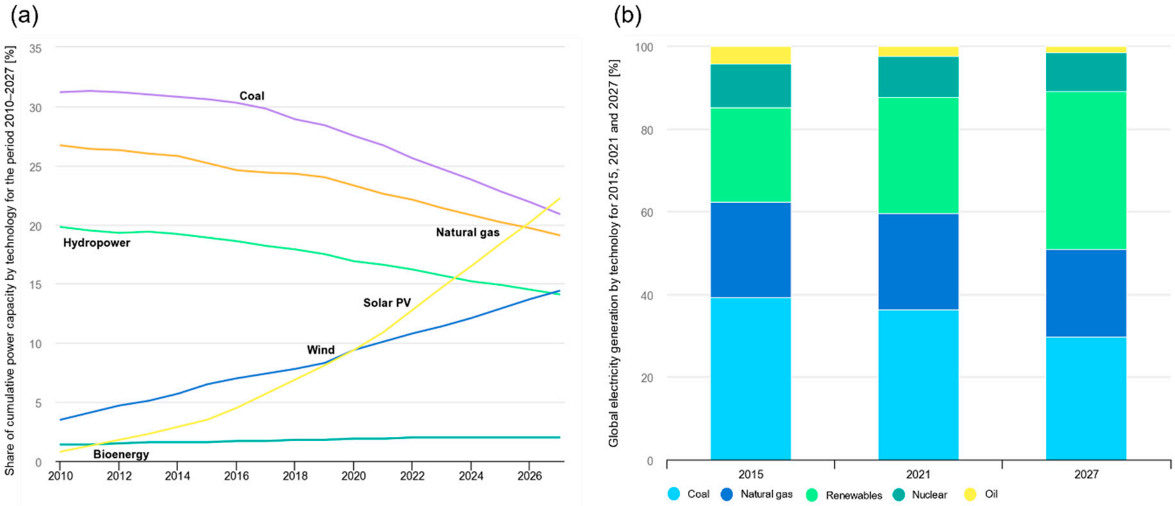

Figure 1. (**a**) Distribution of cumulative power capacity across various technologies from 2010 projected to 2027, and (**b**) Global electricity generation categorized by technology for the years 2015, 2021, and projected for 2027 after [2].

Since 2012, the recycling of PV modules has been mandatory in the European Union under the Waste Electrical and Electronic Equipment (WEEE) Directive [3]. This directive outlines specific objectives for the collection, recovery, and recycling of waste from such devices, including PV modules. PV modules are classified as Category 4 'Large Equipment' according to Annex III of the WEEE Directive. As of 2016, a minimum collection rate of 45% is required. Between 2016 and 2019, the collection rate has progressively increased, reaching a minimum of 65% annually from 2019. As of 15 August 2018, new minimum recovery targets have been established for each category. Devices falling under Category 4, including PV modules, are required to achieve an 85% recovery rate and an 80% rate for preparation towards reuse and recycling. The legal landscape regarding PV recycling in the European Union is constantly evolving, with a focus on increasing collection and recovery rates and preparing for reuse and recycling. These directives are part of the EU's efforts to promote a sustainable circular economy and reduce the ecological impact of electrical and electronic waste, including PV modules. These regulations outline the technical benchmarks and targets established by the European Union to promote efficient recycling of PV modules and sustainable waste management within the electronics industry [3].

Renowned solar PV markets are implementing new policies and targets to increase capacity growth. China led with an impressive addition of 100 GW in 2022, driven by ambitious goals outlined in the 14th Five-Year Plan for Renewable Energy. The European Union responded to the energy crunch in 2022 by accelerating solar PV deployment, achieving a 50% increase to 38 GW in 2022. The REPowerEU Plan and The Green Deal Industrial Plan are expected to be crucial in driving solar PV investment forward. In 2022, the United States implemented substantial funding for solar photovoltaic (PV) through the Inflation Reduction Act (IRA), which provides tax credits to increase capacity and expand the supply chain. India installed 18 GW of solar PV in 2022 and plans to hold annual capacity auctions of 40 GW, with a focus on developing its domestic supply chain. Brazil made significant strides by adding nearly 11 GW of solar PV in 2022, doubling its growth from 2021. Continuous demand from the industry and electricity retailers for renewable energy is expected to sustain this momentum in the medium term [2].

However, in countries experiencing rapid expansion in PV markets, such as China [4], Japan [5], India [6], Australia [7] and the USA [8], specific regulations for end-of-life (EoL)

PV modules are still relatively scarce. These nations typically manage PV waste within the broader framework governing hazardous and non-hazardous solid waste or under regulations for Waste Electrical and Electronic Equipment (WEEE), although there are some exceptions. For instance, Japan initiated a “feed-in tariff” [9] in 2012, ensuring fixed rates for electricity generated from renewable sources and exported to the grid, fostering a rapid surge in solar module installations. However, as these installations near their end-of-life (which is typically 20–30 years), Japan is now faced with a significant waste management challenge. In late 2017, the Japan Photovoltaic Energy Association (JPEA) released voluntary guidelines for the proper disposal of end-of-life (EoL) photovoltaic modules. JPEA strongly encourages industry adherence to these guidelines [10], urging manufacturers, importers and distributors to disclose chemical components and collaborate with waste disposal entities [10].

In the USA, certain states exceed the purview of the Resource Conservation and Recovery Act, which regulates hazardous and non-hazardous waste management [8]. California, for instance, has established additional thresholds for hazardous material classification via Senate Bill 489, designating end-of-life PV modules as Universal Waste, streamlining their transportation. This bill awaits approval from the United States Environmental Protection Agency [11].

Australia acknowledges the significance of implementing regulations addressing the issue of PV waste. Officials recognize the importance of ensuring adequate regulatory frameworks to manage PV waste. In a collaborative effort, Victoria leads innovative programs aimed at mitigating environmental impacts across the lifecycle of photovoltaic systems. These initiatives are part of a voluntary industry-led product management arrangement targeting potential risks associated with PV systems and their waste. Additionally, PV modules are catalogued under the National Product Administration Act, signalling intentions to develop a waste management scheme for such products [7].

Based on the complex legal and technical situation described above, there is a need for a structured and analytical discussion of the current situation and future challenges in PV recycling. This review aims to navigate the complex terrain of developments in PV cell recycling, shedding light on the spectrum of methodologies, emerging innovations and inherent complexities that define this central aspect of sustainable energy production. It seeks to dissect the diverse strategies, novel techniques and intricate nuances that underpin the efficient recycling processes that are integral to sustaining the lifecycle of photovoltaic cells within the renewable energy sector.

2. Review Scope and Approach

This review comprehensively examines the recycling options available for photovoltaic modules, with a keen focus on assessing the sustainability of these recycling processes. It delves into the various methodologies currently employed in the industry to recycle PV modules, thereby providing a realistic overview of existing practices and their environmental implications. By exploring both established and emerging recycling techniques, the review aims to highlight the efficiency, challenges, and potential advancements in the recycling of PV materials. Special emphasis is placed on understanding the alignment of these processes with broader sustainability goals. Through this approach, the review seeks to offer valuable insights into the current state of PV module recycling and its contribution to a more sustainable future in solar energy utilization. With a particular emphasis on EU initiatives, this review aims to provide a comprehensive overview of the progress and challenges of PV cell recycling in the context of EU-wide efforts. The review was conducted using various online databases, such as PubMed, Science Direct, Web of Science, Google Scholar and Scopus. The keywords “photovoltaic cell recycling”, “photovoltaic technology”, “waste management”, “development of photovoltaic technology”, “metal recovery”, “recycling of critical raw materials”, “sustainable processes”, etc. were used to narrow down the search. The articles were checked for quality, topicality and relevance based on the journal’s impact factor and cite score as well as the year of publication. During the literature research, the focus was on peer-reviewed journal articles with impact factors according to the "Journal Citation Reports" (JCR) and "Scimago Journal & Country Ranking (SJR) indicator".

3. Photovoltaic Technologies

The sustainable design of recycling processes requires an understanding of the structure and composition of photovoltaic modules and the differences between the various technologies. For this reason, the main components and structure of the different technologies are briefly explained below.

3.1. Crystalline Silicon Technology

Crystalline silicon technology is the foundation of the photovoltaic industry and is widely used for solar cell production. The unique composition and structural characteristics of crystalline silicon cells make them essential for harnessing solar energy [12].

Crystalline silicon solar cells consist mainly of high-purity silicon wafers. These wafers are carefully manufactured using the Czochralski or Float Zone methods to ensure a crystalline structure that facilitates efficient electron movement. Specific elements, usually phosphorus and boron, are added to the silicon wafers to create an intrinsic layer that generates an electric field when exposed to sunlight. The solar cell structure consists of several layers. A front contact grid is used to collect electrons, while an antireflective coating improves light absorption. The back contact layer completes the circuit, allowing for the extraction of generated electricity [12,13].

In a typical crystalline silicon (c-Si) photovoltaic module, the weight is distributed as follows: approximately 75% belongs to the module surface, which is primarily made up of glass (refer to Figure 2a); around 10% is attributed to polymer components, including the encapsulant and the backsheet foil; and aluminum, which is largely present in the frame and constitutes approximately 8% of the module weight. The silicon material used in solar cells accounts for around 5% of their weight, while copper, used in the interconnectors, represents about 1%. Trace amounts of silver, which form the contact lines, make up less than 0.1% of the module weight, alongside other metals, mainly tin and lead. The remaining components within the module contribute to the overall weight in smaller percentages, as indicated in previous studies. Crystalline silicon technology has several inherent advantages. Firstly, its widespread availability and well-established production processes contribute to scalability and cost-effectiveness. Secondly, the durability and stability of crystalline silicon cells ensure a prolonged operational lifespan, often exceeding 25 years, making them a reliable and long-term sustainable energy solution. Crystalline silicon cells are considered one of the most efficient commercially viable solar technologies due to their high efficiency in converting sunlight into electricity, which ranges from 15 to 22%. Ongoing research and development promise even higher yields in the future. The versatility of crystalline silicon cells is demonstrated by their ability to be installed in various environments, from rooftop arrays to large-scale solar farms. Furthermore, improvements in manufacturing techniques have led to reduced production costs, making them more widely accessible [13,14].

3.2. Thin-Film Technology

Thin film technology has become an important player in the field of photovoltaics, providing distinctive compositional features and structural configurations that complement and diversify the solar cell production landscape [15].

Thin film solar cells differ from crystalline silicon cells in their manufacturing process and material composition. They are composed of thin layers of semiconductor materials deposited onto substrates using various deposition techniques, such as sputtering, chemical vapor deposition (CVD), or physical vapor deposition (PVD). Semiconductor materials used in thin film technology are diverse, including compounds such as cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) and amorphous silicon (a-Si). Each material has unique optical and electronic properties that affect the cell's efficiency and performance. These materials are frequently applied to substrates, such as glass, metal, or flexible polymers, enabling flexibility and lightweight applications in specific designs. In summary, thin-film modules consist of thin layers of semiconductor materials, such as CdTe, CIGS, or a-Si, that are deposited on substrates like glass, polymer, or metal (refer to Figure 2b,c) [16,17].

Thin film technology has distinct advantages that make it appealing in the photovoltaic landscape. One key advantage is its potential for cost-effectiveness due to lower material usage and simplified manufacturing processes compared to crystalline silicon cells. The flexibility of substrates allows for applications on curved surfaces and lightweight constructions, enabling innovative design possibilities for integrated solar solutions in buildings and portable devices. In addition, certain thin film materials demonstrate greater tolerance to low-light conditions and improved performance in diffuse or indirect sunlight, expanding their potential use in diverse environmental settings. The manufacturing process for these materials typically involves lower energy consumption and a reduced carbon footprint compared to crystalline silicon, which aligns with sustainability objectives. However, achieving comparable efficiencies to crystalline silicon cells remains a challenge for thin film technologies, which typically exhibit lower conversion efficiencies ranging from 10 to 20%. Ongoing efforts aim to enhance efficiency levels through material advancements, innovative deposition techniques, and optimization of device structures [18–20].

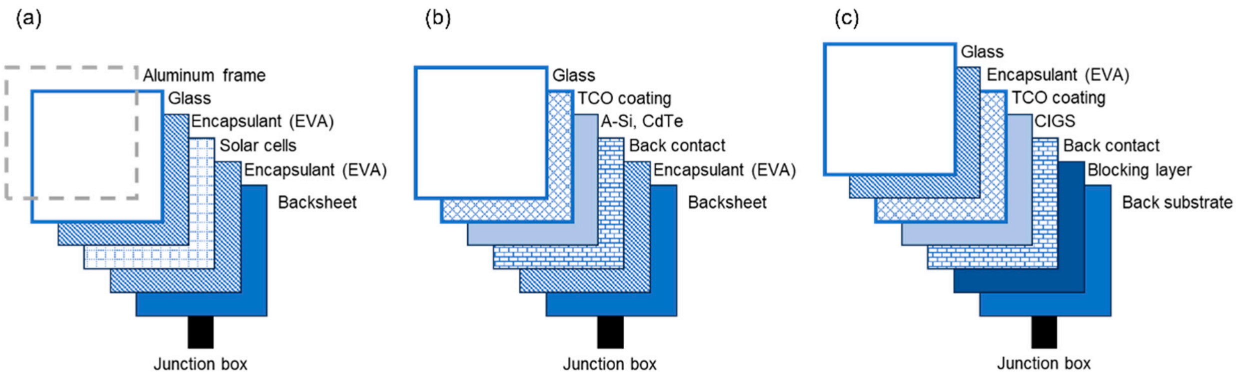

Figure 2. Schematic overview of photovoltaic modules basic structure: (**a**) crystalline silicon technology, (**b**,**c**) thin-film technology after [21].

3.3. Alternative Technologies

Perovskite solar cell technology is a significant addition to the realm of photovoltaics, alongside crystalline silicon and thin film technologies. These cells are based on a material called Perovskite, which has a crystal structure that facilitates efficient light absorption and charge separation. Typically, the composition involves a hybrid organic–inorganic material that often incorporates lead, halides and organic cations. Solar cells can be fabricated through solution-based processes, which allow for low-cost and scalable production methods. The flexible nature of Perovskite materials enables diverse applications, including lightweight and cost-effective manufacturing procedures [22,23].

Perovskite solar cells have gained attention due to their potential for high efficiencies, which can reach levels comparable to traditional crystalline silicon cells. Their solution-based manufacturing offers a promising avenue for cost-effective large-scale production. Additionally, their ability to absorb a broad range of sunlight wavelengths contributes to their efficiency potential. Perovskite materials are flexible and tunable, which makes them suitable for innovative applications in various solar cell designs. These designs include transparent and semi-transparent solar panels, as well as flexible devices [23,24].

Perovskite solar cells face challenges despite their promise. Long-term stability is a significant concern due to material degradation, particularly in humid or high-temperature environments, which hinders their commercial viability. Ongoing efforts to improve stability include material engineering and encapsulation techniques. Additionally, concerns about the scalability of production processes and the environmental impact of lead-based Perovskite materials persist. The aim of the research is to develop lead-free alternatives or safer encapsulation methods to reduce environmental risks. In conclusion, while Perovskite solar cell technology holds immense promise in terms of efficiency, low-cost production and versatility, further research and development efforts are required to address challenges related to stability, scalability and environmental impact. This is necessary to ensure the viability and potential widespread adoption of this technology in the future of photovoltaics [25,26].

Another emerging market in this area of research are tandem PV cells to increase the efficiency of captured solar energy. Tandem photovoltaic cells, also known as multi-junction solar cells, are a type of solar cell designed to increase the efficiency of converting sunlight into electricity. This is achieved by stacking several layers of light-absorbing materials, each tuned to capture a different segment of the solar spectrum. This structure allows tandem PV cells to utilise a wider range of the solar spectrum than conventional single-junction solar cells, which typically use only one light-absorbing layer and are limited in their efficiency by the bandgap of the material. The layers in tandem PV cells are carefully chosen to complement each other; for example, a common configuration includes a top cell made of materials such as perovskite or gallium indium phosphide (GaInP), which efficiently capture high-energy photons (short wavelengths), and a bottom cell made of silicon or gallium arsenide (GaAs), which are better at converting lower-energy photons (long wavelengths) [27–29].

The combination of these materials can significantly increase the overall conversion efficiency, potentially exceeding the theoretical maximum efficiency of single-junction cells, known as the Shockley–Queisser limit [30,31].

4. Photovoltaic Recycling Technologies

Photovoltaic (PV) technology has undergone rapid growth and has become a fundamental component of sustainable energy generation worldwide. As the installed base of PV systems continues to expand, the management of end-of-life and recycling of these systems becomes increasingly important. This chapter explores the developing landscape of recycling methods designed specifically for PV modules. This section examines the different recycling options for various types of PV modules, including crystalline silicon (c-Si) and thin-film technologies such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (a-Si). It provides detailed insights into the disassembly, sorting, separation and material recovery processes. Additionally, it comprehensively examines the challenges, opportunities and advancements in PV recycling. This chapter aims to provide a comprehensive understanding of sustainable end-of-life practices in the field of photovoltaics by explaining the complexities of PV recycling technologies [32].

4.1. Recycling of Crystalline Silicon Modules

The recycling of crystalline silicon (c-Si) modules is a complex and multi-step process that aims to recover valuable materials and reduce environmental impact. In general, the process starts with the collection and transportation of used modules to specialized recycling facilities. Upon arrival, the modules undergo initial sorting and pre-processing, which involves cleaning and removing external components such as frames, junction boxes, and cables [33]. The next stage involves disassembling the module, usually through mechanical shredding or cutting [34]. This process separates the glass, which makes up a significant portion of the module's weight, from the solar cells and other materials. The glass that has been separated is then further processed to remove any impurities or contaminants [33]. The clean glass fragments resulting from the process can be reused in glass manufacturing or repurposed for various applications, significantly reducing the need for new raw materials. The solar cells, which are primarily composed of silicon, undergo thermal processes to remove plastic and metal layers [35,36]. This purification process results in refined silicon, which can be reintroduced into the production of new solar cells or used in diverse silicon-based industries [37,38]. The metal framing, typically made of aluminium, is also separated and sent for recycling. Recycling facilities use techniques such as melting or refining to recover the aluminium, which can be reused across various industries. Finally, any remaining plastics from encapsulation layers are processed into secondary materials or used for energy recovery through methods such as incineration, contributing to waste-to-energy processes [39]. The primary objective of recycling c-Si modules is to recover valuable materials, such as glass and silicon, while minimizing waste generation. The differences in the recycling process between amorphous silicon (a-Si) and crystalline silicon (c-Si) modules are primarily due to the material properties and composition. Crystalline silicon modules typically contain higher purity silicon materials than amorphous silicon modules, which can affect the recycling process. Contaminants present in a-Si modules, such as organic materials or other impurities, may require different recycling techniques or additional cleaning steps compared to c-Si modules. Understanding these differences is essential to optimise recycling processes and ensure efficient recovery of materials from both a-Si and c-Si modules. The recycling process significantly contributes to resource conservation and environmental sustainability within the photovoltaic industry by systematically separating, purifying and repurposing these materials [38–40].

4.2. Recycling of Thin-Film Modules

Recycling thin-film modules, such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (a-Si), requires specific methodologies tailored to each type [13].

CdTe module recycling requires careful handling due to the presence of cadmium, a toxic element [41]. In general, the process begins with shredding the modules, followed by thermal treatment to separate the materials. CdTe can be reclaimed for reuse in new module production after purification processes to mitigate environmental risks [42,43].

Thermal treatments play a crucial role in the recycling of photovoltaic modules, especially in the separation and recovery of valuable materials. Different module compositions require specific thermal treatments tailored to their materials and construction. For example, thermal treatments can include processes such as heating, melting or pyrolysis to separate and recover materials such as silicon, metals and glass. Understanding the specific thermal treatments that are used for different module compositions can provide valuable information for the optimisation of recycling processes and for overcoming challenges in module composition, and is therefore of great importance [44–46].

CIGS modules have a complex composition containing copper, indium, gallium, and selenium. Recycling methods aim to separate and recover these valuable materials. Advanced processes focus on maximizing material recovery while minimizing environmental impact [26].

a-Si modules contain fewer hazardous materials. The recycling process typically involves thermal treatment or acid leaching to recover silicon and other valuable components [47]. However, achieving high material recovery rates can be challenging due to the module's composition. The recycling process for a-Si modules usually begins with collection and transportation to recycling facilities, followed by disassembly involving mechanical shredding or cutting to separate components [34]. Specialized processes are used to recover valuable materials, such as semiconductor elements or silicon, while ensuring proper handling of any toxic elements present. The goal of these technologies is to recover valuable materials while minimizing environmental impact and contributing to a circular economy within the photovoltaic industry [38,48].

4.3. Recycling of Alternative PV Technologies

Recycling tandem PV cells presents unique challenges and opportunities due to their complex multi-layer structure and the use of different materials, some of which are rare or expensive. The recycling process for these cells is more complicated than for conventional single-junction cells, requiring advanced techniques to separate and recover the various materials without degrading their quality. Research in this area is ongoing, with a focus on developing sustainable and economically viable recycling methods. These efforts are critical to reducing the environmental impact of solar modules at the end of their life cycle and supporting the circular economy in the solar industry. As the adoption of tandem PV cells increases, the development of effective recycling processes will become increasingly important to ensure that the environmental benefits of solar energy are maximised [49,50].

In terms of current academic research on PV recycling, recent studies have explored various ways to address the challenges and improve the efficiency of recycling processes. Research is investigating novel materials and techniques to improve the recovery of valuable materials such as silicon, silver and other semiconductor materials from end-of-life PV modules. There is also a growing focus on developing sustainable and cost-effective recycling methods, including innovative separation techniques, chemical processes and advanced sorting technologies. In addition, interdisciplinary collaborations between materials scientists, engineers, environmental researchers and policy makers are driving innovation in this area, with the aim of developing efficient and environmentally friendly recycling strategies for the burgeoning solar industry [49,50].

4.4. Discussion of Selected Representative Industrial Recycling Processes in Europe

This chapter aims to analyse industry-driven approaches for recovering valuable materials from retired or end-of-life solar panels. It will evaluate their efficacy, environmental impact, and potential for widespread adoption in sustainable waste management practices within the solar industry.

4.4.1. Veolia Environment, S.A. (Rousset, France)

Veolia Environment S.A. operates a PV module processing plant in Rousset, France, in collaboration with PV Cycle Association AISBL. Figure 3a shows the plant's flow diagram. PV Cycle collects EoL (end-of-life) modules from across Europe and transports them to Rousset. The first step involves manual dismantling of cables, junction boxes and aluminium frames. The modules are then subjected to shear stress to break the glass, which is separated by crushing and sieving. The residual materials undergo two rounds of crushing and screening to separate mixed composite materials, followed by a separation of copper and composite materials. The remaining fraction is then fed into an eddy current separator to extract the copper. Two additional screening processes are carried out to remove silicon of varying quality. The valuable fractions are sold, and the residual materials are disposed of [51].

4.4.2. Lfficiency Holding GmbH (Tangermünde, Germany)

LFFICIENCY Holding GmbH operates a processing plant in Tangermünde, with Loser Chemie GmbH responsible for developing the chemical process and TESOMA GmbH for constructing the plant. The process sequence is illustrated in Figure 3b. The end-of-life (EoL) modules undergo dismantling, during which cables, junction boxes, and the aluminium frame are removed. Subsequently, a laser is used to break open the sandwich connection. The glass panes are carefully separated using vacuum suction to prevent breakage. Alkane sulphonic acid is used to clean both the glass panes and the solar cells. This hydrometallurgical treatment occurs at room temperature, and the acid used is completely biodegradable and recycled in the process after cleaning. The end products are high-purity glass and pure silicon. This process is particularly suitable for double glass or thin-film modules. For PV modules with a backsheet, the laser separation process is more complex [52,53].

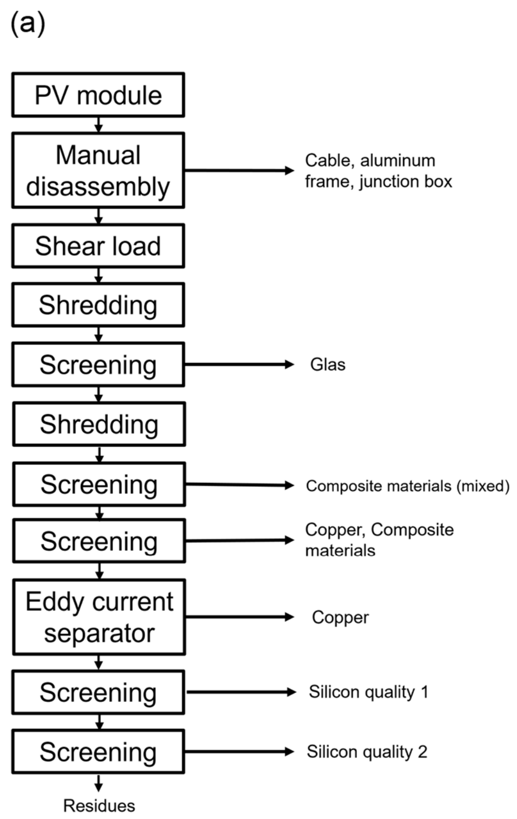

Figure 3. Process flow diagram of the treatment option from (**a**) Veolia Environment, S.A. in France and (**b**) Lfficiency Holding GmbH in Germany, after [51,53].

4.4.3. Suez Deutschland GmbH (Knittlingen, Germany)

The SUEZ Deutschland GmbH plant in Knittlingen is a collaborative effort with Geltz Umwelt-Technologie GmbH and the Fraunhofer Institute, among others. The objective of this process is to recover over 90% of the materials present in PV modules. The process starts with dismantling cables and junction boxes. Next, the modules undergo thermal treatment, which decomposes the polymers via pyrolysis. The gas mixture resulting from the process mainly comprises methane, propane and butane. After cooling the reactor, the glass, solar cells and aluminium frame are removed. The pyrolysis process preserves all materials except the polymers. The glass and aluminium frame can be directly reused in production after thermal treatment. The solar cells, which are free from polymers, undergo further electrochemical processes to recover valuable metals. Figure 4a illustrates the process flow diagram [54].

4.4.4. Reiling Glas Recycling GmbH & Co. KG (Marienfeld, Germany)

Reiling Glas Recycling GmbH & Co. KG carries out the initial treatment on the EoL modules delivered to the recycling plant. During this process, the cables, junction boxes, and aluminium frame are separated. The glass film composite is then broken down through shredding. Finally, this fraction is sent to the flat glass processing plant. Magnets, crushers, classifiers, eddy current separators, air classifiers, optical and induction sorters, and possibly XRF sorters are used to separate impurities. The treatment process yields three fractions: metals, foils and glass. The metal fraction includes aluminium frames, cables, and ferrous and non-ferrous metals. The foil fraction varies depending on the module, and the glass fraction may contain some impurities. Due to the presence of non-ferrous components, such as busbars and fine non-ferrous particles, as well as films adhering to the glass, this fraction is only suitable for alternative glass applications, such as glass wool, glass beads, or glass blocks, as well as insulating materials. The non-ferrous load in the PV glass product is less than 1 kg/t. The processing scheme is shown in Figure 4b [55].

In addition to France and Germany, several other EU Member States have made notable efforts in the field of photovoltaic cell recycling. For example, countries such as Italy, Spain and the Netherlands have implemented various policies and initiatives to promote sustainable end-of-life management of PV modules. These efforts include a range of activities such as research funding, industry cooperation and regulatory frameworks to facilitate the collection, treatment and recycling of PV waste [56,57].

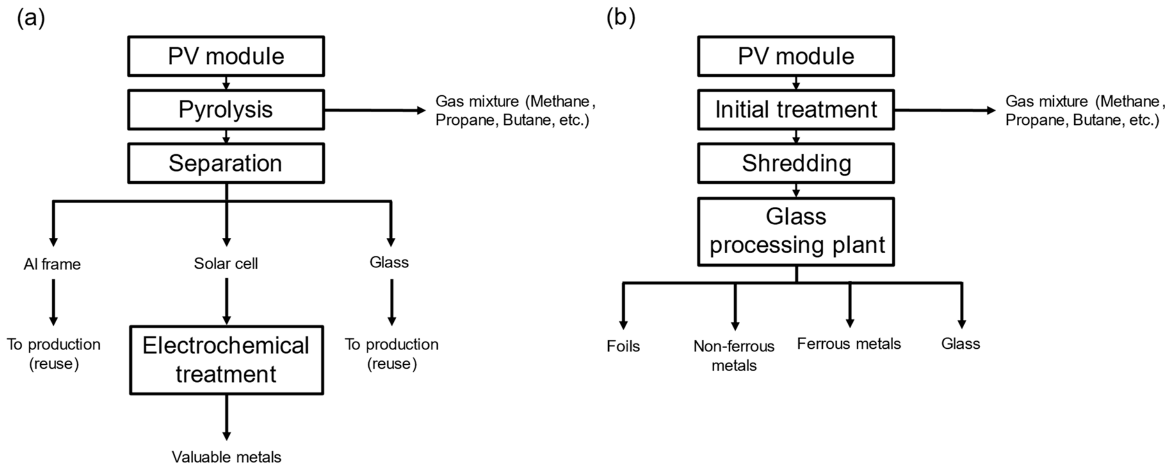

Figure 4. Process flow diagram of the treatment option from (**a**) Suez Deutschland GmbH and (**b**) Reiling Glas Recycling GmbH & Co. KG, both in Germany, after [54,55].

5. Environmental and Economic Aspects

Photovoltaic (PV) recycling is a multi-faceted approach, intertwined with various environmental considerations that are central to sustainable practices within the solar industry [58]. At the core of PV recycling lies the conservation of resources. This process is instrumental in reclaiming valuable materials, such as silicon, glass and metals, from retired solar panels. Recycling significantly reduces the need for fresh resources, making the use of materials more sustainable and efficient. Additionally, diverting used modules from landfills is a crucial aspect of sustainable waste management, substantially mitigating electronic waste accumulation and its associated environmental hazards. Recycling PV modules prevents toxic elements, such as cadmium or lead, from leaking into the environment [59,60]. This curtails potential soil and water contamination, preserving ecosystem integrity. PV recycling has an inherent advantage in its energy-saving capabilities, as the process requires notably less energy than manufacturing new modules from raw materials [46,61]. This aspect highlights a substantial decrease in the carbon footprint linked to conventional manufacturing methods, thus aiding in the mitigation of climate change. Additionally, by appropriately managing hazardous materials during the recycling process, environmental and health hazards associated with improper disposal are minimized [62]. Strong recycling practices guarantee the secure extraction and handling of these substances, reducing the potential harm to both the environment and human health [58,63].

PV recycling is a catalyst for establishing a circular economy within the solar industry. In the context of photovoltaic cell technology, while recycling remains a pivotal aspect due to the complex materials and potentially hazardous components involved, reuse and repair also play crucial roles. Reusing intact PV modules or components that are still functional can conserve resources and reduce energy consumption compared to manufacturing new units from scratch. Additionally, repairing damaged or degraded PV cells can help optimize their performance and extend their operational lifespan, contributing further to resource conservation and waste reduction [64,65].

However, it's important to recognize that recycling remains indispensable within the broader framework of the circular economy, especially concerning end-of-life PV products. Unlike certain consumer goods, where reuse and repair may be more feasible and economically viable, PV modules often undergo significant degradation over time or become obsolete due to technological advancements. As a result, recycling becomes essential for recovering valuable materials such as silicon, silver and other metals, which can then be reintegrated into new PV cell manufacturing processes [62].

Recycling promotes a more sustainable approach characterised by reusability and resource efficiency by reintegrating recovered materials back into the production cycle [66]. Ongoing research in PV recycling methodologies aims to optimise processes and reduce environmental impacts. This concerted effort ensures that photovoltaic systems maintain a minimal environmental footprint throughout their lifecycle, fostering a more sustainable and eco-friendly solar energy landscape. Solar panels made from recycled materials can vary in quality and efficiency depending on several factors, such as the type and quality of recycled materials used, the recycling process used, and the manufacturing techniques. In general, the quality and efficiency of recycled panels can be comparable to those made from virgin materials when proper recycling methods are used and strict quality control measures are in place. Efforts are ongoing to improve the efficiency and quality of recycled panels through advances in recycling technologies and material selection [61,62].

Photovoltaic recycling has significant economic implications across various dimensions [67]. Recycling PV modules offers a cost-efficient way to recover valuable materials such as silicon, glass and metals [68]. Reusing these materials reduces the need to purchase new resources, contributing to cost savings in manufacturing processes. Several studies have investigated this aspect and demonstrated the economic viability of using recycled materials [50,66,69]. For example, research by [50] conducted a comparative analysis of the production costs of using recycled silicon versus virgin silicon for the manufacture of photovoltaic cells. Their findings indicated that the use of recycled materials resulted in cost savings. In addition, other studies have highlighted the potential for price stability and reduced supply chain risks associated with recycling, further enhancing its economic attractiveness compared to reliance on virgin materials. The establishment and growth of PV recycling facilities also creates job opportunities across different stages of the recycling process [14,61]. Incorporating recycled materials into the production of new PV modules not only has the potential to lower manufacturing costs but also bolsters local economies, fosters innovation, and expertise within the recycling industry [61]. Reusing reclaimed materials, especially those meeting quality standards, can offset expenses linked with procuring raw materials [66]. Mitigating potential fines or penalties can be achieved by adhering to recycling regulations and environmental standards [70]. In countries such as France [51] and Germany [53–55], the development of specialised recycling facilities, including those for importing panels for recycling, offers multiple opportunities to improve the local economic landscape. The establishment of such recycling infrastructures not only catalyses job creation, but also cultivates a cadre of skilled workers in the surrounding area. In addition, the recycling sector creates ancillary markets for recovered materials, thereby revitalising local businesses and stimulating innovation in adjacent sectors. In addition, the introduction of community-based recycling programmes plays a key role in promoting environmental sustainability, which in turn increases the region's attractiveness for investment and wider economic development. Compliance with recycling mandates establishes credibility, fosters positive public perception, and potentially benefits companies in terms of brand reputation and market competitiveness. It is important to note that the use of clear and objective language is crucial in conveying the message of compliance with recycling mandates and Extended Producer Responsibility (EPR) principles. Effective photovoltaic recycling aligns with EPR principles, wherein manufacturers take responsibility for their products throughout their lifecycle [71]. Embracing recycling initiatives enables companies to demonstrate environmental stewardship, potentially enhancing their brand image and consumer trust. Establishing a robust photovoltaic recycling infrastructure reduces dependency on external resource suppliers, contributing to market diversification and resource security [62]. It creates internal loops for materials used in solar panel production, enhancing sustainability and resilience. The integration of photovoltaic recycling aligns with the principles of a circular economy, emphasising resource efficiency and sustainability [63]. By reintegrating materials into the production cycle, PV recycling fosters a more sustainable and self-sufficient industry ecosystem, embodying economic prudence and environmental responsibility. Nevertheless, according to the latest available data, the market share of recycled panels is still relatively small compared to new panels. However, it is growing steadily as awareness of environmental sustainability increases and recycling technologies continue to advance. Exact figures may vary by region and market segment, but the trend is towards increasing use of recycled panels in various applications [72,73].

6. Challenges

The field of photovoltaic (PV) recycling faces several challenges that hinder its widespread adoption and effectiveness. The technological complexity arising from the diverse composition of PV modules is a major challenge. Each module type, such as c-Si, CdTe, CIGS, or a-Si, requires distinct recycling processes, which complicates standardization efforts. Efficiently separating materials and recovering valuable components from PV modules is challenging due to their intricate structure [74]. Achieving high-quality material recovery while minimizing waste and maintaining material purity is a technical challenge. Recycling processes for various PV technologies are still underdeveloped [75]. Although recycling of mono- or multi-crystalline silicon is advanced, other thin films, such as CdTe, have room for improvement [41]. Recycling technologies for newer generation materials are still in early stages [46].

The call for standardized recycling efforts that account for the diversity in module compositions arises from the inherent variability in photovoltaic technologies. PV cells are made from a wide range of materials, including but not limited to, crystalline silicon (c-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and perovskites. Each of these technologies not only has a distinct light-generating mechanism but also entails different encapsulation materials and manufacturing processes. This diversity results in varied challenges and opportunities in the recycling process. For instance, the recycling process for silicon-based modules, which constitute the majority of the market, is markedly different from that of thin-film modules like CdTe or CIGS. Silicon PV recycling primarily focuses on the recovery of high-purity silicon, glass, and metals like silver and aluminium. In contrast, thin-film module recycling must also address the safe handling and recovery of potentially toxic elements like cadmium in CdTe cells [32,76].

Cost-effectiveness presents a significant hurdle, as the expenses associated with collection, transportation, disassembly and specialized recycling technologies often exceed the value of the recovered materials, making recycling economically less feasible [76,77]. Developing and scaling up efficient recycling infrastructure is a challenge in many regions. The absence of specialised facilities equipped with advanced recycling technologies, combined with the complicated logistics of collecting and transporting used modules, is hindering progress [74]. The management of hazardous materials found in certain PV modules, such as cadmium or lead, requires specialised handling during recycling to reduce environmental and health risks [1]. The lack of consistent and comprehensive regulations or standards tailored to PV recycling complicates the establishment of a cohesive recycling ecosystem. Limited consumer awareness regarding the significance of PV recycling often leads to improper disposal of end-of-life modules [78]. Additionally, the absence of well-established collection systems further complicates efficient collection and sorting. In certain countries, PV residues are excluded from waste legislation due to various factors. Limited research has been conducted on end-of-life (EoL) aspects, primarily due to the lengthy lifespan of new solar modules (25–30 years) [1]. Additionally, the relatively small quantity of this waste compared to other WEEE discourages the establishment of dedicated recycling plants [58]. Defining mandatory EoL treatment requirements also poses an obstacle to efficient recycling processes. Continuous scientific focus on the potential impacts and benefits of treating photovoltaic residues is crucial [79,80].

Globally, only approximately 10% of photovoltaic modules are recycled due to regulatory deficiencies [81]. Currently, recycling silicon-based modules is economically unfavourable as they lack sufficient valuable materials for cost-effective recovery compared to landfilling. However, by 2050, the cumulative recoverable value could exceed USD 15 billion, which would encourage sustainability in the supply chain, energy recovery, reduction in CO_2 emissions, and the energy payback time of the solar PV industry [82,83].

Overcoming these challenges will require collaborative efforts among policymakers, industry stakeholders, research entities, and the public. Technological innovation, regulatory support, economic incentives, and heightened public awareness are essential to drive the growth and efficacy of photovoltaic recycling endeavours.

There are some parallels between the development of PV recycling and the recycling of lithium-ion batteries, which is currently a topic of various public debates. Initially, due to the multi-year service life, there was a limited flow of material for recycling. For both areas, the lack of recycling processes was not immediately addressed at the start of production of these high-tech products [75]. When discussing PV modules, it is often compared to other WEEE scrap, and the proportion is declared insignificant [26]. The same comparison can be made for lithium-ion batteries and other battery technologies, such as zinc-carbon batteries. For this reason, the construction of specific recycling plants for PV recycling was previously considered uneconomical. However, this hypothesis has now been refuted due to the quantities of used PV modules that are being recycled. Nevertheless, development is still progressing slowly. A similar situation can also be seen for lithium-ion batteries, although the first recycling plants are currently being built in this area. It is evident that research and development, in particular, have suffered as a result of the low quantities generated in the recycling sector in the first years of the application of the technology. Therefore, there is a corresponding need to catch up.

There is an area of overlap in the costs incurred for recovering value fractions from products. Currently, the costs for recovering valuable materials pose a challenge for developing adequate and high-quality recycling processes. This is because these costs are usually higher than landfill costs [58]. This is partly due to the expectation that larger quantities to be recycled will only be available in the next 3–5 years [84]. These statements apply to both lithium-ion batteries and used PV modules.

Furthermore, legal differences in various regions worldwide pose a significant obstacle. However, in the European Union, overlaps can be identified in future technologies. The European Union mandates a recycling rate of 65% by mass for PV modules [85]. This can be achieved with relatively simple methods, as meeting this requirement is already feasible through the recycling of the glass and aluminium fractions [75]. However, it is important to note that valuable components, such as Si-wafers in PV modules or active material in lithium-ion batteries, are often disregarded in the recycling process. Although recycling the housing and smaller components of the battery may be sufficient to meet the European Union's prescribed recycling rate of 50% by mass, critical elements such as Co, Ni and Li in the black mass are not always recovered. The New Battery Directive, issued in June 2023, introduces element-specific recycling rates to promote efficient recycling processes for valuable metals [85]. Similar approaches could be considered for PV modules, but specifications are essential due to the diversity of this technology's composition. One of the key similarities between Si recycling in photovoltaic cells and lithium-ion battery recycling is the importance of resource recovery and material efficiency. Both contain valuable materials that can be recovered and reused, thereby reducing reliance on virgin resources and minimising the environmental impacts associated with extraction and processing. In addition, the challenges associated with recycling both often relate to the complex nature of the materials and the need for effective separation and purification techniques. Studies focusing on one process can provide transferable knowledge and methodologies that can be applied to the other, facilitating advances in recycling technologies for both. Furthermore, given the increasing demand for both photovoltaic cells and lithium-ion batteries in the renewable energy and electric vehicle sectors, synergistic approaches to recycling could lead to enhanced resource recovery and improved circular economy practices. Collaborative research efforts that bridge the gap between PV recycling and lithium ion battery recycling can foster innovation and accelerate the development of sustainable recycling strategies for both sectors. In conclusion, exploring the links between PV recycling processes and LIB recycling can indeed provide valuable insights and contribute to the strategic development of recycling methodologies for both processes. By exploiting similarities and sharing knowledge across disciplines, researchers and industry stakeholders can work towards more efficient and sustainable recycling practices, ultimately contributing to the transition towards a circular economy.

Raising consumer awareness is crucial to increasing the uptake and support of photovoltaic (PV) cell recycling initiatives as well as for the save collection of used lithium ion batteries. Educational campaigns targeting both the general public and specific consumer segments should be included. This could include outreach through various channels such as social media, educational workshops and collaboration with environmental organisations. By highlighting the environmental benefits and long-term cost savings associated with PV cell recycling, consumers can be incentivised to choose environmentally friendly options and properly dispose of end-of-life solar panels.

Engaging stakeholders across the PV industry value chain is essential to foster collaboration and advance recycling efforts. Platforms between manufacturers, policy makers, recyclers and research institutions should be established for dialogue and collaboration. Promoting industry-wide initiatives, such as voluntary recycling programmes or incentives for sustainable practices, can drive collective action and innovation. In addition, fostering partnerships with academia and government agencies can facilitate knowledge sharing and the development of standardised recycling practices.

Cost reduction strategies are key to improving the economic viability of PV cell recycling. Focusing on technological innovation, economies of scale and regulatory incentives, a multi-faceted approach should be sensitive. Investment in research and development to optimise recycling processes and develop cost-effective technologies can reduce operating costs. Promoting economies of scale through centralised recycling facilities or collaborative networks can also increase efficiency and reduce unit costs. In addition, implementing policies such as Extended Producer Responsibility (EPR) frameworks or tax incentives for recycling can create financial incentives for manufacturers to invest in sustainable practices.

By addressing these key areas, research and industry will be able to drive the development of PV cell recycling towards a more sustainable and economically viable future.

7. Conclusions and Outlook

A thorough examination of current and developing technologies in the photovoltaic field revealed the complex variety of PV module types, including crystalline silicon (c-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si). Each type requires specific recycling strategies due to their unique compositions and materials. Strategies for PV recycling include disassembly, material separation, and recovery techniques, as well as reintroducing reclaimed materials into production cycles.

The economic potential and environmental benefits of PV recycling are significant, as material reclamation reduces manufacturing costs and fosters resource conservation, waste reduction, and energy efficiency. Economically, the focus is on cost savings, job creation, compliance advantages, market diversification, and integration with the circular economy. Environmentally, the emphasis is on resource conservation, waste reduction, energy efficiency, and responsible hazardous material management, all aligned with sustainability objectives.

The seamless adoption and efficacy of PV recycling face numerous challenges. Significant hurdles have been identified in the recycling of PVs, including technological complexities in material separation, cost-effectiveness, deficient recycling infrastructure, management of hazardous materials, regulatory frameworks, and limited consumer awareness and collection systems.

However, ongoing technological advancements and research efforts are promising to overcome these challenges and enhance the cost-effectiveness of PV recycling. Collaborative efforts among stakeholders are pivotal in establishing robust recycling infrastructure and standardized regulations. To streamline recycling processes, it is important to augment consumer awareness and fortify collection systems. These endeavours are guided by the circular economy framework, which strives towards resource efficiency and sustainability.

In conclusion, the efficient and environmentally responsible future of PV recycling requires concerted efforts from stakeholders across industries, policymakers, researchers, and the public. It is necessary to tackle challenges, refine strategies, and foster a sustainable and circular approach.

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References

1. Fthenakis, V.M. End-of-life management and recycling of PV modules. *Energy Policy* **2000**, *28*, 1051–1058. [CrossRef]
2. International Energy Agency. *Renewables 2022: Analysis and Forecast to 2027*; International Energy Agency: Paris, France, 2023.
3. *Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE)*; European Union: Brussels, Belgium, 2012.
4. *Waste Electrical and Electronic Products Recycling Regulations*; European Commission: Brussels, Belgium, 2012.
5. *Guidelines on End-of-Life Management of PV Modules*; Ministry of Economy Trade and Industry Japan; Ministry of Environment Japan: Osaka, Japan, 2011.
6. *Solid Waste Management Rules and Hazardous and Ohter Wastes Rules*; Ministry of Environment, Forest and Climate Change India: New Delhi, India, 2016.
7. Product Stewardship Act. The Australian Government. Available online: https://www.legislation.gov.au/C2011A00076/latest/text (accessed on 20 February 2024).
8. Andersen, R.W. Resource Conservation and Recovery Act of 1976. *Wis. L. REv.* **1978**.
9. Muhammad-Sukki, F.; Abu-Bakar, S.H.; Munir, A.B.; Yasin, S.; Ramirez-Iniguez, R.; McMeekin, S.G. Feed-in tariff for solar photovoltaic: The rise of Japan. *Renew. Energy* **2014**, *68*, 636–643. [CrossRef]
10. *Guidelines for Proving Information for Proper Treatment of Used Solar Cell Modules*; JPEA: Dublin, Ireland, 2017.
11. Senate Bill No. 489—Hazardous Waste: Photovoltaic Modules. State of California, USA. Available online: https://pluralpolicy.com/app/legislative-tracking/bill/details/state-ca-20152016-sb489/1579697 (accessed on 20 February 2024).
12. Ranjan, S.; Balaji, S.; Panella, R.A.; Ydstie, B.E. Silicon solar cell production. *Comput. Chem. Eng.* **2011**, *35*, 1439–1453. [CrossRef]
13. Sander, K. Study on the Development of a Take Back and Recovery System for Photovoltaic Products. 2007. Available online: https://www.oekopol.de/oekopol_archiv/en/Archiv/Stoffstrom/pv-cycle/Report%20PVCycle%20en.pdf (accessed on 20 February 2024).
14. Müller, A.; Wambach, K.; Alsema, E. Life Cycle Analysis of Solar Module Recycling Process. *MRS Online Proc. Libr.* **2005**, *895*, 0895-G03. [CrossRef]
15. ITRPV. *International Technology Roadmap for Photovoltaic Results 2016*, 8th ed.; ITRPV: Frankfurt, Germany, 2017.
16. Fraunhofer Institute for Solar Energy Systems. Photovoltaics Report. 2017. Available online: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf (accessed on 20 February 2024).
17. Green, M.A. Thin-film solar cells: Review of materials, technologies and commercial status. *J. Mater. Sci. Mater. Electron.* **2007**, *18*, 15–19. [CrossRef]
18. Raugei, M.; Isasa, M.; Fullana Palmer, P. Potential Cd emissions from end-of-life CdTe PV. *Int. J. Life Cycle Assess.* **2012**, *17*, 192–198. [CrossRef]
19. Fthenakis, V.M.; Moskowitz, P.D. Thin-film Photovoltaic Cells: Health and Environmental Issues in their Manufacture Use and Disposal. *Prog. Photovolt.* **1995**, *3*, 295–306. [CrossRef]
20. Polman, A.; Knight, M.; Garnett, E.C.; Ehrler, B.; Sinke, W.C. Photovoltaic materials: Present efficiencies and future challenges. *Science* **2016**, *352*, aad4424. [CrossRef]
21. Lunardi, M.M.; Alvarez-Gaitan, J.P.; Bilbao, J.I.; Corkish, R. A Review of Recycling Processes for Photovoltaic Modules. *Sol. Panels Photovolt. Mater.* **2018**. [CrossRef]

22. Wang, H.; Qin, Z.; Miao, Y.; Zhao, Y. Recent Progress in Large-Area Perovskite Photovoltaic Modules. *Trans. Tianjin Univ.* **2022**, *28*, 323–340. [CrossRef]
23. Lee, D.-K.; Park, N.-G. Materials and Methods for High-Efficiency Perovskite Solar Modules. *Solar RRL* **2022**, *6*, 2100455. [CrossRef]
24. Kim, H.-J.; Kim, H.-S.; Park, N.-G. Progress of Perovskite Solar Modules. *Adv. Energy Sustain. Res.* **2021**, *2*, 2000051. [CrossRef]
25. Werner, J.; Boyd, C.C.; Moot, T.; Wolf, E.J.; France, R.M.; Johnson, S.A.; van Hest, M.F.A.M.; Luther, J.M.; Zhu, K.; Berry, J.J.; et al. Learning from existing photovoltaic technologies to identify alternative perovskite module designs. *Energy Environ. Sci.* **2020**, *13*, 3393–3403. [CrossRef]
26. Snaith, H.J.; Hacke, P. Enabling reliability assessments of pre-commercial perovskite photovoltaics with lessons learned from industrial standards. *Nat. Energy* **2018**, *3*, 459–465. [CrossRef]
27. Celik, I.; Phillips, A.B.; Song, Z.; Yan, Y.; Ellingson, R.J.; Heben, M.J.; Apul, D. Environmental analysis of perovskites and other relevant solar cell technologies in a tandem configuration. *Energy Environ. Sci.* **2017**, *10*, 1874–1884. [CrossRef]
28. Lal, N.N.; Dkhissi, Y.; Li, W.; Hou, Q.; Cheng, Y.-B.; Bach, U. Perovskite Tandem Solar Cells. *Adv. Energy Mater.* **2017**, *7*, 1602761. [CrossRef]
29. You, J.; Dou, L.; Hong, Z.; Li, G.; Yang, Y. Recent trends in polymer tandem solar cells research. *Prog. Polym. Sci.* **2013**, *38*, 1909–1928. [CrossRef]
30. Nelson, C.A.; Monahan, N.R.; Zhu, X.-Y. Exceeding the Shockley–Queisser limit in solar energy conversion. *Energy Environ. Sci.* **2013**, *6*, 3508. [CrossRef]
31. Ehrler, B.; Alarcón-Lladó, E.; Tabernig, S.W.; Veeken, T.; Garnett, E.C.; Polman, A. Photovoltaics Reaching for the Shockley—Queisser Limit. *ACS Energy Lett.* **2020**, *5*, 3029–3033. [CrossRef]
32. Granata, G.; Pagnanelli, F.; Moscardini, E.; Havlik, T.; Toro, L. Recycling of photovoltaic panels by physical operations. *Sol. Energy Mater. Sol. Cells* **2014**, *123*, 239–248. [CrossRef]
33. Kim, Y.; Lee, J. Dissolution of ethylene vinyl acetate in crystalline silicon PV modules using ultrasonic irradiation and organic solvent. *Sol. Energy Mater. Sol. Cells* **2012**, *98*, 317–322. [CrossRef]
34. Berger, W.; Simon, F.-G.; Weimann, K.; Alsema, E.A. A novel approach for the recycling of thin film photovoltaic modules. *Resour. Conserv. Recycl.* **2010**, *54*, 711–718. [CrossRef]
35. Frisson, L.; Lieten, K.; Bruton, T.; De Clercq, K.; Szlufcik, J.; de Moor, H.; Goris, M.; Benali, A.; Aceves, O. Recent improvements in industrial PV module recycling. In Proceedings of the 16th European Photovoltaic Solar Energy Conference, Glasgow, UK, 1–5 May 2000.
36. Doni, A.; Dughiero, F. Electrothermal heating process applied to c-Si PV recycling. In Proceedings of the 2012 38th IEEE Photovoltaic Specialists Conference, Austin, TX, USA, 3–8 June 2012.
37. Park, J.; Kim, W.; Cho, N.; Lee, H.; Park, N. An eco-friendly method for reclaimed silicon wafers from a photovoltaic module: From separation to cell fabrication. *Green Chem.* **2016**, *18*, 1706–1714. [CrossRef]
38. Klugmann-Radziemska, E.; Ostrowski, P. Chemical treatment of crystalline silicon solar cells as a method of recovering pure silicon from photovoltaic modules. *Renew. Energy* **2010**, *35*, 1751–1759. [CrossRef]
39. Wang, T.-Y.; Hsiao, J.-C.; Du, C.-H. Recycling of materials from silicon base solar cell module. In Proceedings of the 2012 38th IEEE Photovoltaic Specialists Conference, Austin, TX, USA, 3–8 June 2012; pp. 2355–2358.
40. Krueger, L. Overview of Rist Solar's Module Collection and Recycling Program. In Proceedings of the 1st International Conference on PV Module Recycling, Berlin, Germany, 26 January 2010.
41. FirstSolar. Leading the World's Sustainable Energy Future. 2023. Available online: https://www.firstsolar.com/en-Emea/ (accessed on 20 February 2024).
42. Latunussa, C.; Mancini, L.; Blengini, G.; Ardente, F.; Pennington, D. *Analysis of Material Recovery from Silicon Photovoltaic Panels*; Publications Office of the European Union: Brussels, Belgium, 2016.
43. Campo, M.D.; Bonnet, D.; Gegenwart, R.; Beier, J. Process for Recyxcling CdTe/Cds Thin Film Solar Cell Modules US6572782B2. Available online: https://patents.google.com/patent/US6572782B2/en?oq=US6572782 (accessed on 15 December 2023).
44. Dobra, T.; Vollprecht, D.; Pomberger, R. Thermal delamination of end-of-life crystalline silicon photovoltaic modules. *Waste Manag. Res.* **2022**, *40*, 96–103. [CrossRef]
45. Camargo, P.S.S.; Da Domingues, A.S.; Palomero, J.P.G.; Kasper, A.C.; Dias, P.R.; Veit, H.M. Photovoltaic module recycling: Thermal treatment to degrade polymers and concentrate valuable metals. *Detritus* **2021**, *16*, 48–62. [CrossRef]
46. Bakhiyi, B.; Labreche, F.; Zayed, J. The photovoltaic industry on the path to a sustainable future—Environmental and occupational health issues. *Environ. Int.* **2014**, *73*, 224–234. [CrossRef] [PubMed]
47. Doi, T.; Tsuda, I.; Unagida, H.; Murata, A.; Sakuta, K.; Kurokawa, K. Experimental study on PV module recycling with organic solvent method. *Sol. Energy Mater. Sol. Cells* **2001**, *67*, 397–403. [CrossRef]
48. Kang, S.; Yoo, S.; Lee, J.; Boo, B.; Ryu, H. Experimental investigations for recycling of silicon and glass from waste photovoltaic modules. *Renew. Energy* **2012**, *47*, 152–159. [CrossRef]
49. Alberi, K.; Berry, J.J.; Cordell, J.J.; Friedman, D.J.; Geisz, J.F.; Kirmani, A.R.; Larson, B.W.; McMahon, W.E.; Mansfield, L.M.; Ndione, P.F.; et al. A roadmap for tandem photovoltaics. *Joule* **2024**, *8*, 1–35. [CrossRef]
50. Peters, I.M.; Hauch, J.; Brabec, C. Cradle-to-cradle recycling in terawatt photovoltaics: A vision of perpetual utility. *Joule* **2024**, *8*, 1–14. [CrossRef]

51. Defrenne, N. New Challenges of PV Life Cycle. 2018. Available online: https://www.ask-eu.de/Artikel/31027/MechanischeVerbundsauftrennung-beim-Recycling-von-c-Si-Photovoltaikmodulen-Aktueller-Standund-neue-Ans%C3%A4tze.htm (accessed on 12 December 2023).
52. Kempe, M. Encapsulant Materials for PV Modules. *Photovolt. Sol. Energy* **2017**, 478–490. [CrossRef]
53. Tesoma GmbH. Recycling von ausgedienten Photovoltaik-Panels mit weltweit einzig sinnvollem Verfahren. 2019. Available online: https://tesoma.de/anwendungen-de/solar/ (accessed on 12 December 2023).
54. Suez Deutschland GmbH. Wiederverwertung von Photovoltaikmodulen. Available online: https://www.pv-magazine.de/2018/09/07/suez-nimmt-innovative-anlage-zum-photovoltaik-recycling-in-betrieb/ (accessed on 12 December 2023).
55. Heitmann, B. Recycling von siliziumbasierten Photovoltaikmodulen. 2018. Available online: https://www.ressource-deutschland.de/themen/kreislaufwirtschaft/innovative-recyclingtechnologien/pv-module/ (accessed on 20 February 2024).
56. Serafin, A. Say Voltaic. Three Europe-Based Industrial Experts Develop Recycling of Photovoltaic Panels That Would Otherwise End Up in Landfills. 2023. Available online: https://www.eib.org/en/stories/recycle-photovoltaic-panels (accessed on 21 February 2024).
57. European Commission. Recycling of Photovoltaic Waste Boosts Circular Economy. 2018. Available online: https://cordis.europa.eu/article/id/240250-recycling-of-photovoltaic-waste-boosts-circular-economy (accessed on 21 February 2024).
58. Huang, B.; Zhao, J.; Chai, J.; Xue, B.; Zhao, F.; Wang, X. Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process. *Sol. Energy* **2017**, *143*, 132–141. [CrossRef]
59. Kwak, J.I.; Nam, S.-H.; Kim, L.; An, Y.-J. Potential environmental risk of solar cells: Current knowledge and future challenges. *J. Hazard. Mater.* **2020**, *392*, 122297. [CrossRef] [PubMed]
60. Nain, P.; Kumar, A. Metal dissolution from end-of-life solar photovoltaics in real landfill leachate versus synthetic solutions: One-year study. *Waste Manag.* **2020**, *114*, 351–361. [CrossRef] [PubMed]
61. Piasecka, I.; Bałdowska-Witos, P.; Piotrowska, K.; Tomporowski, A. Eco-Energetical Life Cycle Assessment of Materials and Components of Photovoltaic Power Plant. *Energies* **2020**, *13*, 1385. [CrossRef]
62. Sica, D.; Malandrino, O.; Supino, S.; Testa, M.; Lucchetti, M.C. Management of end-of-life photovoltaic panels as a step towards a circular economy. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2934–2945. [CrossRef]
63. Bošnjaković, M.; Santa, R.; Crnac, Z.; Bošnjaković, T. Environmental Impact of PV Power Systems. *Sustainability* **2023**, *15*, 11888. [CrossRef]
64. Deng, R.; Chang, N.; Lunardi, M.M.; Dias, P.; Bilbao, J.; Ji, J.; Chong, C.M. Remanufacturing end-of-life silicon photovoltaics: Feasibility and viability analysis. *Prog. Photovolt.* **2021**, *29*, 760–774. [CrossRef]
65. Tsanakas, J.A.; van der Heide, A.; Radavičius, T.; Denafas, J.; Lemaire, E.; Wang, K.; Poortmans, J.; Voroshazi, E. Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification. *Prog. Photovolt.* **2020**, *28*, 454–464. [CrossRef]
66. Trivedi, H.; Meshram, A.; Gupta, R. Recycling of photovoltaic modules for recovery and repurposing of materials. *J. Environ. Chem. Eng.* **2023**, *11*, 109501. [CrossRef]
67. D'Adamo, I.; Ferella, F.; Gastaldi, M.; Ippolito, N.M.; Rosa, P. Circular solar: Evaluating the profitability of a photovoltaic panel recycling plant. *Waste Manag. Res.* **2023**, *41*, 1144–1154. [CrossRef]
68. Allouhi, A.; Rehman, S.; Buker, M.S.; Said, Z. Up-to-date literature review on Solar PV systems: Technology progress, market status and R&D. *J. Clean. Prod.* **2022**, *362*, 132339.
69. Deng, R.; Zhuo, Y.; Shen, Y. Recent progress in silicon photovoltaic module recycling processes. *Resour. Conserv. Recycl.* **2022**, *187*, 106612. [CrossRef]
70. Dias, P.; Veit, H. Recycling Crystalline Silicon Photovoltaic Modules. *Emerg. Photovolt. Mater. Silicon Beyond* **2018**, 61–102. [CrossRef]
71. Khawaja, M.K.; Ghaith, M.; Alkhalidi, A. Public-private partnership versus extended producer responsibility for end-of-life of photovoltaic modules management policy. *Sol. Energy* **2021**, *222*, 193–201. [CrossRef]
72. Fortune Business Insights. Solar Panel Recycling Market Size, Share & Industry Analysis, by Type (Monocrystalline, Polycrystalline, Thin-Film), by Process (Thermal, Mechanical, Laser) and Regional Forcast 2024–2032. 2024. Available online: https://www.fortunebusinessinsights.com/industry-reports/solar-panel-recycling-market-101756 (accessed on 21 February 2024).
73. Mordor Intelligence. Solar Panel Recycling Market Size & Share Analysis. Growth Trends & Forecasts (2024–2029). 2024. Available online: https://www.mordorintelligence.com/industry-reports/solar-panel-recycling-market (accessed on 21 February 2024).
74. Chowdhury, M.S.; Rahman, K.S.; Chowdhury, T.; Nuthammachot, N.; Techato, K.; Akhtaruzzaman, M.; Tiong, S.K.; Sopian, K.; Amin, N. An overview of solar photovoltaic panels' end-of-life material recycling. *Energy Strategy Rev.* **2020**, *27*, 100431. [CrossRef]
75. Isherwood, P.J.M. Reshaping the Module: The Path to Comprehensive Photovoltaic Panel Recycling. *Sustainability* **2022**, *14*, 1676. [CrossRef]
76. Granata, G.; Altimari, P.; Pagnanelli, F.; de Greef, J. Recycling of solar photovoltaic panels: Techno-economic assessment in waste management perspective. *J. Clean. Prod.* **2022**, *363*, 132384. [CrossRef]
77. Liu, C.; Zhang, Q.; Wang, H. Cost-benefit analysis of waste photovoltaic module recycling in China. *Waste Manag.* **2020**, *118*, 491–500. [CrossRef]

78. Ardente, F.; Latunussa, C.E.L.; Blengini, G.A. Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling. *Waste Manag.* **2019**, *91*, 156–167. [CrossRef]
79. Monier, V.; Hestin, M. Study on photovoltaic panels supplementing the impact assessment for a recast of the WEEE directive. *Final. Rep.* **2014**. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf (accessed on 20 February 2024).
80. Weckend, S.; Wade, A.; Heath, G. *End-of-Life Management Solar Photovoltaic Panels. IRENA and IEA-PVPS*; National Renewable Energy Lab.: Golden, CO, USA, 2016.
81. Zobel, F. EoL—Development of an Industrial Recycling Process for PV Modules. 2019. Available online: https://www.ise.fraunhofer.de/en/research-projects/eol.html (accessed on 20 February 2024).
82. Sener, C.; Fthenakis, V. Energy policy and financing options to achieve solar energy grid penetration targets: Accounting for external costs. *Renew. Sustain. Energy Rev.* **2014**, *32*, 854–868. [CrossRef]
83. Bustamante, M.L.; Gaustad, G. Challenges in assessment of clean energy supply-chains based on byproduct minerals: A case study of tellurium use in thin film photovoltaics. *Appl. Energy* **2014**, *123*, 397–414. [CrossRef]
84. Deetman, S.; Pauliuk, S.; van Vuuren, D.P.; van der Voet, E.; Tukker, A. Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances. *Environ. Sci. Technol.* **2018**, *52*, 4950–4959. [CrossRef] [PubMed]
85. Regulation of the European Parliament and the Council Concerning Batteries and Waste Batteries, Repealing Directive 2006/66/EC and Amending Regulation (EU) No2019/1020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020PC0798 (accessed on 20 November 2023).

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