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Review

End-of-Life Management of Photovoltaic Modules: Recycling, Second-Life Applications, and Disposal

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Abstract

The rapid global expansion of photovoltaic (PV) systems, driven by rising energy demand, is expected to generate substantial module waste at end-of-life, with global PV waste projected to exceed 4 million tonnes by 2030, 50 million by 2040, and 200 million tonnes by 2050. Based on 105 sources identified through a structured, keyword-based Google Scholar search complemented by backward reference screening, this review provides a comparative, literature-based assessment of recycling, second-life applications, and disposal as end-of-life (EoL) management strategies for PV modules, examining the relationship between module structure, waste management pathways, material recovery potential, and the technical and economic limitations of current practices. Recycling offers clear environmental benefits but remains economically constrained in many scenarios by high process costs and the complexity of separating laminated module structures. Second-life application emerges as a complementary strategy, delaying the premature entry of modules retaining residual functionality into the waste stream and enhancing resource efficiency. Nevertheless, landfilling continues to account for the majority of global PV waste despite the availability of more sustainable alternatives, revealing a marked gap between technical potential and field-level practice. Overall, no single approach is sufficient; effective PV waste management requires an integrated strategy combining recycling, second-life applications, and disposal in line with circular economy principles.

Keywords: photovoltaic module; end-of-life management; recycling; second-life application; disposal; circular economy

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1. Introduction

1.1. Background

Environmental problems such as climate change, acid rain, and stratospheric ozone depletion pose an increasingly serious threat to natural ecosystems and human life. Among these, climate change is widely regarded as the most critical environmental challenge of our time. At the root of these problems lies the continued reliance on fossil fuels, which still account for a substantial share of global energy production. Consequently, redirecting energy systems toward renewable sources has become imperative for mitigating environmental degradation and ensuring a sustainable future. To reduce greenhouse gas emissions and protect the environment, the global transition toward renewable energy has accelerated in recent years [1–3]. The share of renewable sources such as wind, hydropower, biomass, and solar energy in the global energy supply continues to grow. Among these sources,

photovoltaic (PV) technology has emerged as a particularly prominent solution owing to its ease of installation, low operating costs, scalability, and broad range of applications [4,5].

Indeed, the rising global energy demand directly influences energy generation systems, with renewable energy sources accounting for the largest share of this growth. As shown in Figure 1, an examination of the annual growth share among energy sources as of 2025 reveals that renewable energy sources hold the largest share at 38%, followed by natural gas (28%), coal (15%), oil (11%), and nuclear energy (8%) [6]. This trend indicates that the installed capacity of renewable sources, including PV, will continue to expand, making a corresponding increase in the number of PV modules reaching the end of their service life in the coming years virtually inevitable.

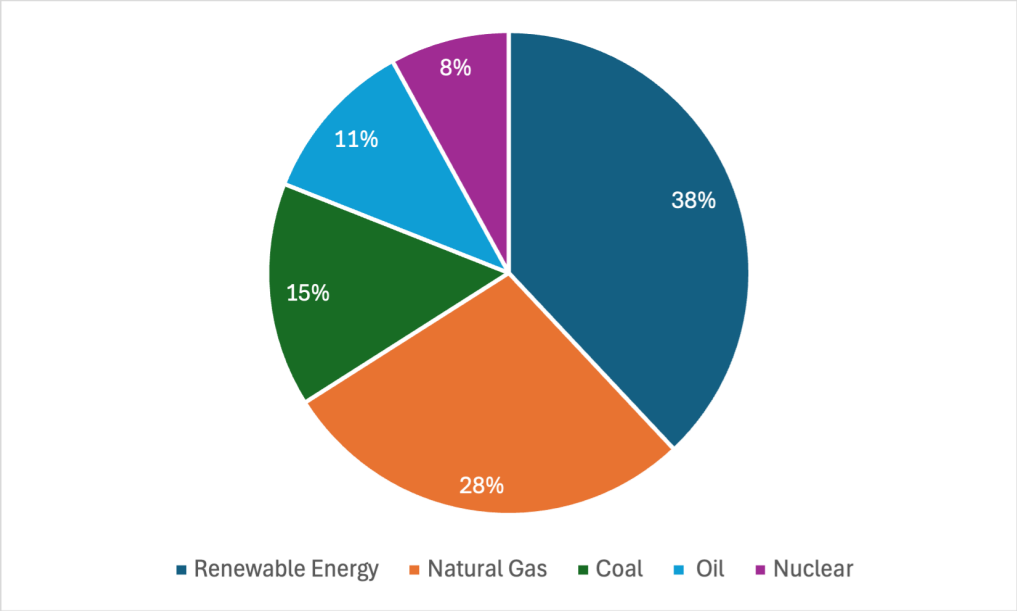


Figure 1. Annual growth share by energy source [6].

1.2. PV Systems

A PV system consists of photovoltaic modules interconnected in series or parallel configurations to form an array, together with the mechanical structures supporting these modules, the electrical connection components, and the auxiliary elements that regulate and convert the generated energy. Photovoltaic modules, the fundamental functional unit of PV technology, operate on the principle of converting light into electricity through the photovoltaic effect exhibited by semiconductor materials. This effect, discovered by Alexandre Edmond Becquerel, enables solar radiation to be converted directly into electrical energy.

Photons of different wavelengths reaching the surface of a photovoltaic module may be reflected from the surface, absorbed by the module, or transmitted through it. When a photon is absorbed, electron–hole pairs are generated within the semiconductor material; the separation of these pairs at the p–n junction within the module's internal structure creates an electrical potential difference. This process enables current flow through an external circuit connected to the module terminals, thereby generating electrical energy [7].

The PV module technologies most widely used in the current literature are presented in Table 1, based on the classification proposed by Arora et al. This classification is structured around three main categories: crystalline silicon-based technologies, thin-film technologies, and emerging/alternative technologies [8].

Table 1. Photovoltaic (PV) module types.

Technology	Cell Type
Silicon-based	Monocrystalline Polycrystalline/Multicrystalline ribbon a-Si (Amorphous/Micromorph)
Thin-film based	CIGS (Copper–Indium–Gallium–(Di)Selenide) CdTe (Cadmium Telluride)
Other	Concentrated PV (CPV) Organic PV/Dye-Sensitized Solar Cells (OPV/DSSC) Advanced Crystalline Silicon (advanced c-Si) Perovskite

Silicon-based PV modules, widely employed in the photovoltaic industry, are designed as a multilayer, laminated composite structure. This structure comprises a front glass layer providing mechanical strength and light transmittance, a central layer of silicon semiconductor cells where the photovoltaic conversion takes place, and a polymer-based backsheet on the rear surface that protects against environmental exposure.

The semiconductor silicon layer is laminated to both the front glass and the backsheet using two encapsulant layers, typically composed of ethylene-vinyl acetate (EVA), forming an integrated structure. This laminated assembly is mounted within an aluminium frame, which enhances the mechanical strength of the module and facilitates installation processes; the frame also provides structural rigidity and additional protection against external factors [9].

1.3. Global Growth of Renewable Energy and Photovoltaic Systems

An examination of current energy statistics reveals a marked increase in the share of renewable energy sources, paralleling the rising global energy demand [10]. As shown in Figure 2, the total installed renewable energy capacity increased from approximately 1.85 million MW in 2015 to approximately 4.45 million MW in 2024, representing an increase of roughly 2.4-fold over this period.

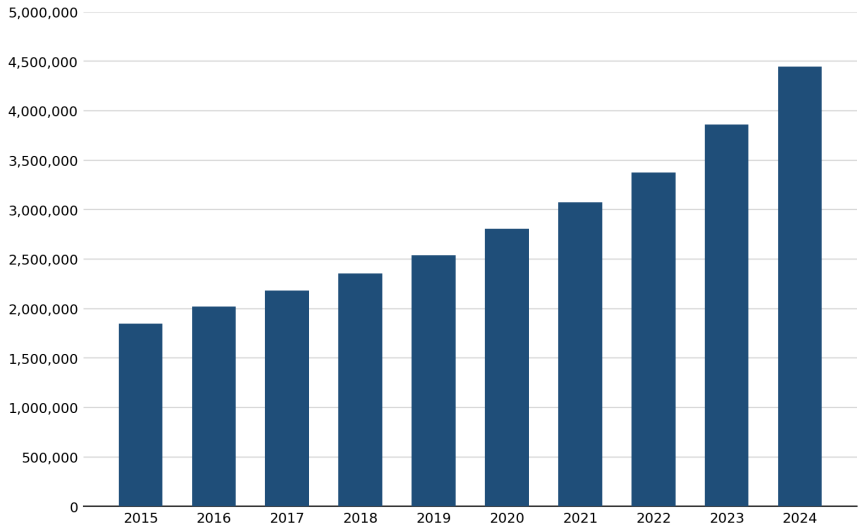


Figure 2. Installed renewable energy capacity between 2015 and 2024 (MW) [10].

This global increase in renewable energy capacity directly influences the growth of PV technology and progressively increases the share of PV within overall energy sys-

tems [10]. Indeed, as shown in Figure 3, global installed PV capacity rose from approximately 220,869 MW to 1,858,725 MW over the same period, corresponding to an approximately 8.4-fold increase, indicating that the growth rate of PV markedly exceeds that of total installed renewable energy capacity.

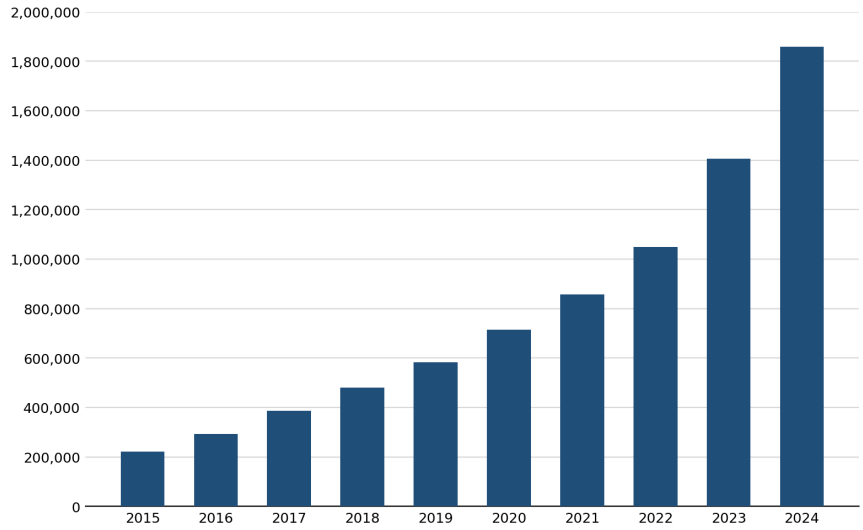


Figure 3. Global installed PV capacity between 2015 and 2024 (MW) [10].

In light of these data, the management of modules that have reached the end of their service life is projected to become one of the most critical challenges facing PV systems in the near future. As a natural consequence of increasing installed capacity, the volume of PV waste generated globally is also expected to rise rapidly. Based on historical installed capacity data (Table 2) and assuming a nominal 25-year service life for PV modules, the minimum volume of PV waste attributable solely to natural end-of-life is presented in Figure 4 [11]. Accordingly, the effective management of end-of-life (EoL) PV modules requires the combined consideration of multiple strategies, including recycling, second-life applications, and disposal. The advantages and limitations of these approaches, from environmental, economic, and technical perspectives, are discussed comparatively in the following sections.

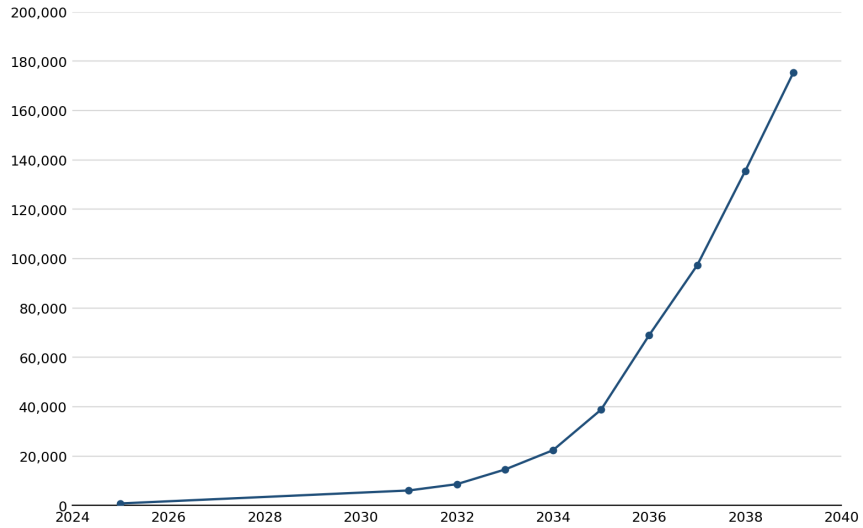


Figure 4. Projected installed PV capacity reaching end-of-life (MW), calculated by the authors based on historical installed capacity data and an assumed 25-year module service life [11].

Table 2. Installed solar PV capacity in past years [11].

Year	Installed Solar PV Capacity (MW)
2000	805
2006	6060
2007	8611
2008	14,541
2009	22,372
2010	38,795
2011	68,956
2012	97,290
2013	135,503
2014	175,305

1.4. Methodology

This study is a literature review conducted to provide a comprehensive assessment of current approaches to the end-of-life management of PV modules. Relevant publications were identified using three exact-phrase keyword queries: "PV waste management," "photovoltaic module recycling," and "second-life PV."

To provide a transparent and reproducible account of this search process, the keyword-based search was conducted in Google Scholar in June 2026, restricted to publications from 2016 to 2026. Records were screened against explicit criteria for publication type, language, peer-review status, and topical scope. At this stage, only peer-reviewed journal articles in English were sought through the keyword search; conference papers, institutional/technical reports, book chapters, and theses were not targeted by the keyword search itself but were subsequently considered through backward snowballing, as described below. Topical scope was defined as studies addressing the end-of-life management of PV modules—recycling, second-life/reuse applications, or disposal. This search returned a total of 2049 records ("PV waste management": $n = 566$; "photovoltaic module recycling": $n = 1390$; "second-life PV": $n = 93$). Of these, the first 400 records, ranked by relevance, were examined. Following title screening, 224 records were excluded as duplicate or off-topic, leaving 176 records for abstract review. Abstract-level screening subsequently excluded a further 111 records as insufficiently relevant to the scope of this review, yielding 65 records that proceeded to full-text evaluation.

In a second stage, the reference lists of the included publications were screened (backward snowballing) to identify additional studies, international institutional reports (IRENA, IEA, IEA-PVPS, TERI, EPRI, and First Solar), and book chapters that were relevant to the scope of this review but not directly captured by the keyword search. This process identified 40 additional sources. Of these, 14 had initially been excluded at the abstract-screening stage but were subsequently reconsidered and included on the grounds that their frequent citation within the included literature indicated a relevance to this review's scope that had not been fully apparent from the abstract alone. Of the remaining 26 sources, 25 predated the initially defined 2016–2026 window; their inclusion was justified on the grounds that they constitute foundational, frequently cited references within the field. The remaining source is an international technical standard (IEC 61215) that is directly cited within the included literature as the certification benchmark for module durability and was therefore incorporated through the same reference-screening process.

This two-stage process yielded a final set of 105 sources, comprising 86 peer-reviewed journal articles, 11 institutional/technical reports, 4 conference papers, 2 book chapters, 1 master's thesis, and 1 international technical standard (see Figure 5). The 105 sources thus identified were evaluated according to the prominent themes emerging from the

literature. This review examined the challenges associated with the end-of-life management of PV modules, recoverable materials, economic feasibility, second-life application scenarios, the geographic distribution of waste volumes and regulatory practices across countries, and sustainability dimensions; the resulting findings were synthesized to contribute to the existing body of knowledge and to inform future research directions. The overall organizational structure of this review is outlined in Figure 6.

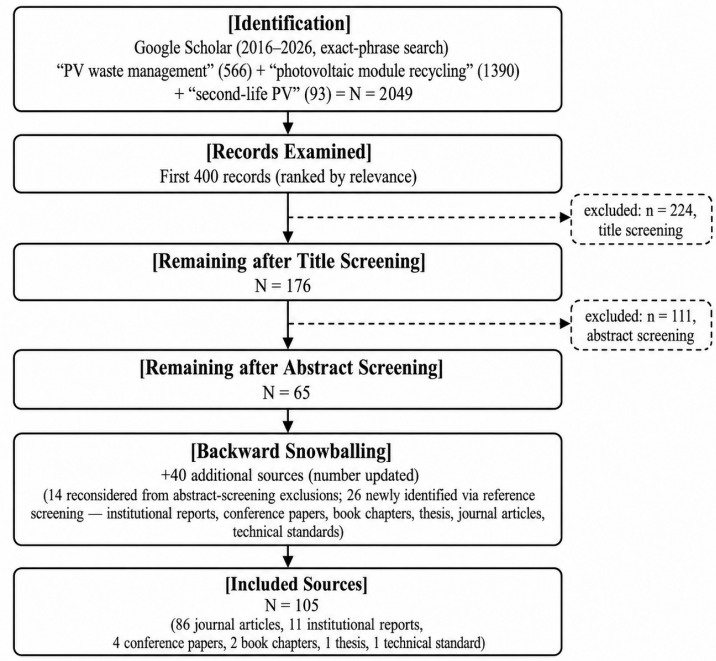


Figure 5. Literature search and inclusion flow diagram, prepared by the authors. Downward arrows indicate the sequential screening process; side arrows indicate records excluded at each stage, with the corresponding exclusion count and reason.

It should be noted that this study constitutes a structured narrative review rather than a systematic review in the strict methodological sense (e.g., following the full PRISMA 2020 protocol with dual independent screening and formal risk-of-bias assessment). While the search and screening process described above was designed to be transparent and reproducible, a single-reviewer screening process and the restriction of full-text evaluation to the top-ranked 400 records (out of 2049 total matches) introduce a degree of selection subjectivity common to narrative reviews. These limitations are not expected to materially affect the qualitative synthesis presented in this review, but they should be considered when interpreting the completeness of the underlying evidence base.

Several recent reviews have addressed individual dimensions of PV end-of-life management, yet none has combined recycling, second-life reuse, and disposal within a single, cross-nationally comparative treatment. Mahmoudi et al. contributed both a systematic bibliometric mapping of the PV waste literature and a detailed country-level forecast of waste volumes and material composition for Australia, but did not extend this work into a comparative economic and policy assessment across countries or into a treatment of second-life reuse pathways [12,13]. Chowdhury et al. provided a technology- and policy-oriented overview of recycling processes—physical, thermal, and chemical treatment routes—together with a country-by-country comparison of regulatory frameworks centred on the European Waste Electrical and Electronic Equipment (WEEE) Directive, but did not address second-life reuse pathways or provide a quantitative economic assessment [14]. Farrell et al. offered an in-depth technical assessment of circular-economy-oriented recycling strategies, module-design constraints that limit component recovery, and the relative merits of closed-loop

versus open-loop material cascades, without incorporating a systematic economic feasibility analysis or a comparative second-life framework [15]. Deng et al. compiled a quantitative techno-economic comparison of landfill disposal against glass, mechanical, and thermal recycling routes, identifying the collection- and processing-cost thresholds at which recycling becomes competitive with disposal, but this comparison does not extend to second-life reuse pathways [16]. Tsanakas et al. offer the most comprehensive treatment to date of second-life and reuse pathways, including updated global waste projections and a four-stage reuse-suitability framework, but centre their analysis on repair and reuse processes rather than on a systematic comparison with recycling economics and disposal practices [17,18]. Building on and synthesizing these contributions, the present review distinguishes itself by (i) integrating recycling, second-life applications, and disposal within a single comparative assessment; (ii) cross-referencing country-level waste and policy data—including Australia, South Korea, the United States, and China—against updated global waste projections; (iii) explicitly identifying and reconciling discrepancies among frequently cited quantitative estimates in the literature (see Sections 2.1 and 2.2.1); and (iv) synthesizing second-life reuse pathways within agrivoltaic systems (Section 2.3.5) as an emerging, integrated application of decommissioned modules, thereby providing a more internally consistent and comprehensive evidentiary basis for future research and policy design.

Country-specific legislation and policy data discussed in Section 2.1 (e.g., the EU WEEE Directive, South Korea's EPR scheme, and China's Green Design Technical Standards) were drawn directly from the reviewed publications identified through the search strategy above, rather than from additional, separately searched grey-literature sources.

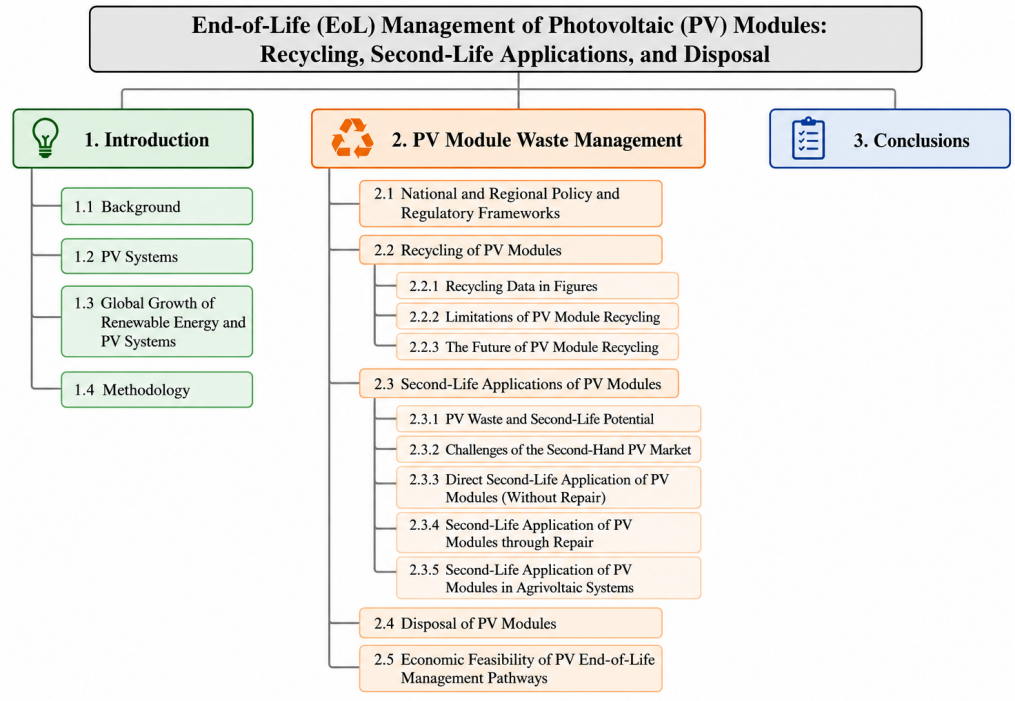


Figure 6. Organizational chart, prepared by the authors.

2. PV Module Waste Management

This section presents a literature-based comparative discussion of the three principal approaches to the post-service-life management of photovoltaic modules—recycling, second-life applications, and disposal. The hierarchical relationship among these approaches is summarized in Figure 7. Throughout this comparison, each approach is assessed, where the underlying literature permits, along the following four consistent axes: (i) environmental

performance, encompassing life-cycle impacts, mitigation of hazardous-substance release, and net resource conservation; (ii) economic feasibility, comprising collection, processing, and disposal costs weighed against the market value of recovered materials and energy; (iii) technical maturity, reflecting process complexity, achievable recovery yields, and readiness for industrial-scale deployment; and (iv) material and value recovery, concerning the purity, quantity, and downstream reusability of recovered glass, metals, polymers, and semiconductor material. This four-axis framework is applied consistently across the recycling, second-life, and disposal discussions that follow, enabling a like-for-like comparison among the three pathways.

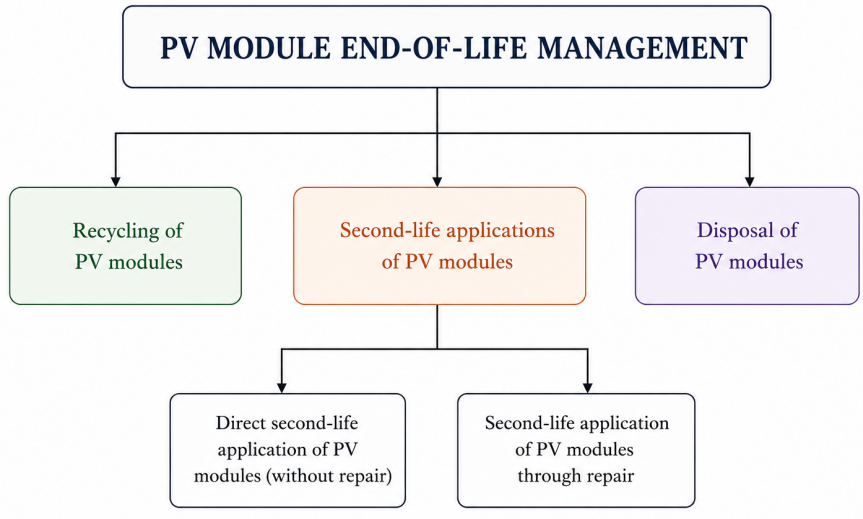


Figure 7. Approaches to the end-of-life management of PV modules, prepared by the authors.

With the widespread deployment of photovoltaic systems, environmentally sound end-of-life strategies for modules reaching the end of their service life have gained increasing importance. Although landfilling is a technically feasible option, it remains the least preferable approach owing to the loss of recoverable materials and the associated risk of pollution. Recycling, in contrast, plays a critical role in ensuring environmental sustainability; however, its economic feasibility—particularly for silicon-based modules—has not yet been clearly established in the literature. The main reasons underlying this uncertainty include the relatively low economic value of recoverable materials, the high cost of processing, and the still insufficient development of recycling infrastructure specific to PV modules.

Owing to the relatively recent emergence of PV technologies and the fact that the service life defined by manufacturers has not yet elapsed for most installed modules, the volume of PV waste currently entering recycling processes remains limited. Nevertheless, given the rapid growth of global installed PV capacity, recycling and reuse practices are expected to become considerably more critical in the future, both for securing silicon supply and for shaping waste management strategies [19].

2.1. National and Regional Policy and Regulatory Frameworks

At the national level, marked differences are observed in the maturity of EoL management practices. In Australia, the end-of-life (EoL) management of PV modules is still at an early stage, and current recycling capacity remains quite limited; consequently, only a small proportion of modules reaching the end of their service life are directed toward recycling, while the majority are sent to landfill sites. Similarly, in South Korea, recovery policies for PV waste are only recently being established; with the entry into force of regulations under the Extended Producer Responsibility (EPR) scheme in 2023, PV modules will be treated as

a distinct product category under the legislation, thereby strengthening the legal framework for enhanced recycling [20].

In the United States, legislation governing the end-of-life management of PV modules varies by state. Some states have introduced specific regulations for PV modules, establishing initial requirements for module recovery and disposal processes. Nevertheless, the PV recycling infrastructure in the country has not yet fully matured. The limited technical capability of recycling facilities operating at varying capacities, the high recycling costs associated with crystalline silicon (c-Si) modules, and the inadequacy of current capacity to accommodate the rapidly growing volume of PV waste in the future are identified as the principal barriers to PV waste management in the United States [20].

In China, by contrast, policy development and technological capacity for the end-of-life management of photovoltaic modules have advanced rapidly. The "Green Design Technical Standards for PV Modules," supported by the Ministry of Industry and Information Technology, were published in 2020, formally establishing the principles of environmentally sustainable module design. In line with this, the "Action Plan for the Innovation and Development of the Intelligent Photovoltaic Industry (2021–2025)" was enacted to promote the transformation of the photovoltaic sector toward intelligent manufacturing, recycling, and circularity. In addition, the first pilot facility dedicated to the development of panel recycling infrastructure was commissioned in 2021, paving the way for industrial-scale recycling practices [19].

Beyond national regulatory maturity, PV end-of-life policy is increasingly framed within broader sustainability agendas. The EU's WEEE Directive, which since 2012 has classified PV panels as a distinct product category subject to minimum collection and recycling targets, remains the most comprehensive legislative benchmark to date and has directly informed the design of Extended Producer Responsibility (EPR) schemes now being adopted elsewhere, including South Korea's 2023 EPR regulation for PV modules [20]. From a Sustainable Development Goals (SDG) and Environmental, Social, and Governance (ESG) perspective, the circular-economy transition that these regulatory instruments aim to enable connects most directly to SDG 12 (Responsible Consumption and Production), while its downstream effects on hazardous-substance mitigation, resource conservation, and green employment also touch on SDG 3 (Good Health and Well-Being), SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action) [15]. For manufacturers and investors, alignment with these frameworks is increasingly reflected in ESG reporting and disclosure practices, positioning proactive EoL compliance not merely as a regulatory cost but as a component of corporate sustainability performance. Nonetheless, the cross-country comparison above indicates that regulatory maturity remains highly uneven: comprehensive, binding collection-and-recycling targets exist only in the EU and, more recently, South Korea, whereas the United States' state-by-state patchwork and China's technology-oriented but not yet fully binding standards illustrate a persistent gap between policy ambition and enforceable EoL obligations, one that continues to constrain the growth of PV-specific recycling infrastructure worldwide.

This unevenness is not arbitrary but tracks three structural factors identifiable in the literature. First, waste volume and market scale directly shape the economics of dedicated recycling infrastructure: in Australia, EoL PV volumes remain fragmented across a residential-dominated market (over 70% of installed capacity) and dispersed across a large, sparsely populated territory, driving up collection and transport costs and leaving insufficient waste volume as, in the assessment of Komoto et al., the most fundamental barrier to achieving economies of scale for recycling [20]; by contrast, within the EU, individual national markets large enough to support a dedicated recycling plant—Bošnjaković et al. estimate a profitability threshold of approximately 19,000 t/year, reduced to approximately 9000 t/year

under more favourable co-financing and higher assumed recycling efficiency—are reached earliest by the largest markets (Germany, Spain, and Italy), while several smaller EU states are projected not to reach even the reduced threshold at all, or only after 2047, despite being bound by the same EU-wide mandate [19]. Second, manufacturer concentration shapes which point in the value chain policy targets: approximately 93% of global PV module production took place in China in 2021, a concentration that Bošnjaković et al. directly associate with policies favouring local production [19], plausibly helping to explain why China's regulatory focus to date has centred on upstream, design- and manufacturing-stage standards—such as the Green Design Technical Standards discussed above—rather than the downstream, collection-based mandates that dominate EU policy. Third, landfill cost structures directly shape the economic case for mandatory recycling: in the United States, comparatively low landfill tipping fees mean that recycling a silicon PV module costs approximately USD 15–45, compared with only USD 1–5 to landfill it (see Section 2.5) [21], removing much of the cost-based pressure that has driven EPR adoption elsewhere and helping to explain the persistence of a state-by-state patchwork rather than a binding federal mandate. Notably, these factors do not operate uniformly: China's PV manufacturing scale is the largest in the world, yet its EoL regulatory framework remains less binding than the EU's, indicating that market size alone does not determine regulatory maturity and that policy design is also shaped by where in the supply chain a jurisdiction's PV industry is concentrated. This pattern—in which the translation of a global sustainability target such as SDG 12 into enforceable national policy is mediated by domestic market structure—is consistent with what is sometimes termed SDG localization.

With regard to market share and future projections, Peplow—writing in a science-news commentary piece rather than a peer-reviewed research article—notes that crystalline silicon (c-Si) technology, which accounts for the vast majority of installed PV modules, holds a market share exceeding 90% and has a service life of approximately 30 years [21]. Based on 2020-vintage data cited in that commentary, global c-Si module waste was projected to reach approximately 8 million tonnes by 2030 and 80 million tonnes by 2050 [21]. More recent projections, grounded in updated 2022 IRENA and IEA market data (see Section 2.3.1), estimate global PV waste at 4 million tonnes (Mt) by 2030, 50 Mt by 2040, and 200 Mt by 2050; given their more recent data basis, these figures are used consistently as this review's primary reference points for global PV waste volumes throughout. Nevertheless, current recycling practices are reported to remain below the desired level in terms of both efficiency and prevalence, such that a substantial proportion of EoL c-Si modules continue to enter the waste stream [21].

Managing a waste volume of this magnitude necessitates the development of effective procedures. Ko et al. emphasized the need to develop effective waste management procedures to mitigate the environmental impacts of the growing volume of PV waste globally and to support the transition to a circular economy; the authors provided a detailed assessment of dismantling processes for crystalline silicon (c-Si) modules and examined design improvements that would facilitate recycling. Similarly, Sica et al. analysed the recycling potential of PV modules and proposed the adoption of a circular economy approach aimed at enhancing resource efficiency and minimizing waste generation [22,23].

Regarding the scope of the recovery process, Tao and Yu examined three principal approaches to the recovery of photovoltaic modules: the recycling of manufacturing waste, the recovery of malfunctioning yet reusable modules, and the recycling of modules that have reached the end of their service life (EoL). For each of these approaches, the performance and feasibility of existing technologies, along with their technical and economic advantages and limitations, were comprehensively assessed; the environmental benefits of PV module

recycling were discussed alongside key challenges faced by the sector, including cost, infrastructure, and process efficiency [24].

With respect to dismantling and separation techniques, Isherwood highlights that the rapidly expanding global solar energy market is making the sustainable management of end-of-life PV modules an increasingly critical issue. In this context, the recovery of cell materials from PV modules can be achieved through manual dismantling, mechanical separation, dry or wet chemical processes, or a combination of these methods. The selection of a given technique varies depending on criteria such as module structure, material composition, recovery yield, and economic feasibility [25].

Consistent with these findings, Tembo and Subramanian focused specifically on high-value recycling processes, providing a detailed examination of the processes applied during material recovery from PV panels and the resulting recovered products. The study also assessed the environmental impacts associated with recycling, compared the environmental performance of different recovery strategies, and analysed the current state of global photovoltaic waste management policies, identifying areas for improvement and policy gaps within major markets [26].

The average service life of a PV module is generally estimated at 25–30 years. However, this period may be significantly shortened by physical damage occurring during manufacturing, transport, or installation; early-stage failures following commissioning; performance degradation resulting from prolonged environmental exposure; and unforeseeable external factors such as natural disasters [27,28].

The end of a PV module's service life is generally defined by a performance decline of approximately 20% relative to initial output, a level typically corresponding to an average service period of 25 years as defined by manufacturers. At this stage, modules do not become entirely non-functional and continue to generate energy; however, their performance falls below a level considered economically viable. Whether such modules are then replaced with new ones depends on factors including the system owner's financial circumstances, prevailing government incentives, unit energy prices, and the feasibility of recycling or reuse options [19].

According to projections by Bošnjaković et al., among European countries, the highest volume of PV waste by 2030 is expected to occur in Germany (26,100 tonnes). Germany is followed by the Netherlands (2760 tonnes), Italy (1560 tonnes), Austria (1380 tonnes), Spain (1320 tonnes), and Switzerland (1320 tonnes); this upward trend is expected to accelerate further after 2030, becoming particularly pronounced during the 2031–2040 and 2041–2049 periods [19].

According to the same source, among the EU-27 member states, the countries projected to generate the lowest volumes of PV waste by 2049 are Latvia (3369 tonnes), Ireland (8116 tonnes), Croatia (10,938 tonnes), Malta (13,260 tonnes), Luxembourg (19,150 tonnes), and Cyprus (25,860 tonnes). Among non-EU European countries, Iceland (420 tonnes), Montenegro (1332 tonnes), Albania (1716 tonnes), North Macedonia (5096 tonnes), Bosnia and Herzegovina (6448 tonnes), Serbia (9220 tonnes), and Norway (19,280 tonnes) are among those with the lowest projected PV waste volumes.

2.2. Recycling of PV Modules

The recycling of PV modules that have reached the end of their service life is regarded as one of the most environmentally effective waste management options (see Figure 8). Indeed, the systematic literature review conducted by Mahmoudi et al. demonstrates that PV waste management has become a rapidly growing research field in recent years, with recycling and forecasting/projection studies emerging as particularly prominent research themes. Compared with landfilling, recycling processes substantially prevent toxic elements such as lead (Pb)

present in the module structure from leaching into soil and groundwater, thereby mitigating environmental contamination and associated health risks [12,24,29–31].

Furthermore, effective recycling practices enable the reintroduction into the economy of rare and valuable metals such as silver (Ag), gallium (Ga), indium (In), germanium (Ge), cadmium (Cd), and tellurium (Te); common industrial materials such as aluminium (Al), copper (Cu), and glass; and energy-intensive raw materials such as high-purity silicon (Si) [32–34].

This approach not only prevents the loss of raw materials but also substantially reduces energy consumption and carbon emissions associated with manufacturing. In this respect, the recycling of PV modules is regarded as a strategic step that alleviates resource depletion across the life cycle and strengthens the environmental sustainability of renewable energy technologies [35].

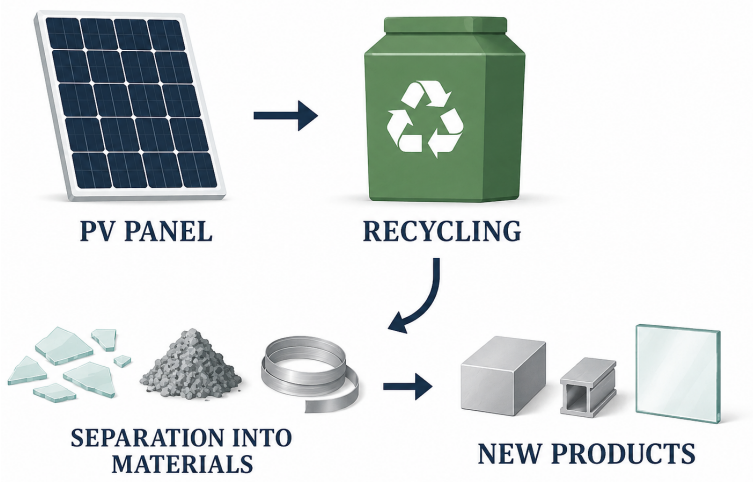


Figure 8. Schematic overview of the PV module recycling process (illustrative diagram).

The recycling process begins with the transport of modules to a recycling facility, where they are unloaded and inspected. At this stage, modules are tested for potential defects: those retaining usable functionality are separated for second-life applications (see Section 2.3), while those no longer usable are directed toward recycling.

The recycling of solar modules is a multi-step process involving the combined or sequential application of various physical and chemical treatments. This process generally begins with the removal of the junction box and the aluminium frame from the module. The encapsulant EVA layer, which forms part of the module's laminated structure, is then separated using chemical, thermal, or mechanical delamination methods [36]. The chemical method offers the advantage of achieving the highest purity in material recovery; however, its major drawbacks include the high cost of chemical reagents and the need for monitoring and treatment of the resulting waste liquids [1,37].

Finally, the valuable metals contained within c-Si cells are separated and purified through dedicated electrical and chemical processes. This multi-stage recycling approach enables the high-purity recovery of module components, thereby contributing to circular economy objectives [14,38].

Regarding the general framework of this process, Wang emphasizes that the volume of waste generated as a result of the rapid expansion of photovoltaic systems will reach considerable proportions, underscoring the strategic economic and environmental importance of PV module recycling. The study notes that the recycling processes for PV modules differ markedly from conventional e-waste recycling methods, indicating that module components can be separated through mechanical processes as well as recovered with high efficiency through chemical methods [39].

2.2.1. Recycling Data in Figures

Material recovery rates in recycling processes vary considerably from one material to another. According to Sica et al., recovery rates for glass and aluminium are notably high (97% and 100%, respectively); for copper and tellurium, this rate is approximately 80%, while for rare metals such as indium and gallium, it reaches 75% and 99%, respectively [22].

Crystalline silicon (c-Si) panels represent one of the most common examples in this regard. The mass composition of a typical 1000 kg c-Si PV panel consists of 70% glass, 18.5% aluminium, 5.1% EVA, 3.65% silicon, 1.5% backsheet, 0.11% copper, 0.053% silver, 0.035% lead, and 0.018% tin [40]. The recovery and recycling of these materials embedded within the panel can be achieved through alternative pathways categorized as physical, thermal, and chemical processes, or a combination thereof [14].

One of the earliest initiatives in PV panel recycling was developed by Deutsche Solar in 2003. In this process, the plastic components of panels were separated through heating, after which photovoltaic cells and metals such as glass, aluminium, copper, and steel were recovered using manual methods [22].

Another notable initiative was implemented by First Solar. The company launched a collection and recycling program for cadmium telluride (CdTe) modules in 2003, which became fully operational in 2007. The program is based on a two-stage crushing process: in the first stage, modules are superficially fragmented to facilitate transport, while in the second stage, hammer mills are used to reduce the glass plates into small fragments approximately 5 mm in diameter. The semiconductor films are then subjected to a leaching process using sulfuric acid and hydrogen peroxide, and the resulting solution is refined through precipitation into a material suitable for use in the manufacture of new CdTe modules. The glass is separated first from the semiconductor solution and subsequently from the laminate bonding the two glass layers together. This process achieves recovery rates of approximately 90% for glass and 95% for semiconductor material, thereby substantially reducing the environmental risk associated with cadmium release into the environment [22].

In addition to such pioneering initiatives, country-based waste projections at the global scale are increasingly represented in the literature. A study conducted in India projected the country's cumulative solar PV and balance-of-system (BOS) waste between 2020 and 2047 using a Weibull-reliability-based forecasting model [41]. While the source's abstract reports this cumulative waste as "2.95 billion tonnes" and its recoverable economic value as "USD 452 trillion," these headline figures are inconsistent with the source's own detailed, tabulated model outputs: the year-by-year waste inventory reported therein sums to approximately 295 million tonnes, and the corresponding metal commodity and recovery values, computed at the unit level (price per tonne multiplied by mass), sum to approximately USD 645 billion and USD 452 billion, respectively—one order of magnitude lower for waste mass and three orders of magnitude lower for the monetary values than stated in the source's abstract. We therefore report the mass-balance-consistent figures derived from the source's own tabulated calculations: approximately 295 million tonnes of cumulative PV and BOS waste in India by 2047, with an estimated USD 452 billion in recoverable material value out of a total commodity value of USD 645 billion. An analysis of the composition of this waste indicates that it will consist of approximately 51% glass, 31% aluminium, 6% copper, 5% EVA, and 1% silicon, among other materials (see Figure 9) [41].

The same study also examined the distribution of this waste by module type and system component. The findings indicate that silicon-based modules account for approximately 59% of total PV waste, reflecting their widespread use in the market. Cadmium telluride (CdTe) panels and copper–indium–gallium–selenide (CIGS) panels are projected to contribute 6% and 2% of the waste, respectively. Meanwhile, among the system's auxiliary components, inverters account for 7% and cabling and connection equipment for

26% of total waste, representing a substantial share. These findings indicate that module recycling alone is insufficient, and that all system components must be addressed through an integrated waste management approach.

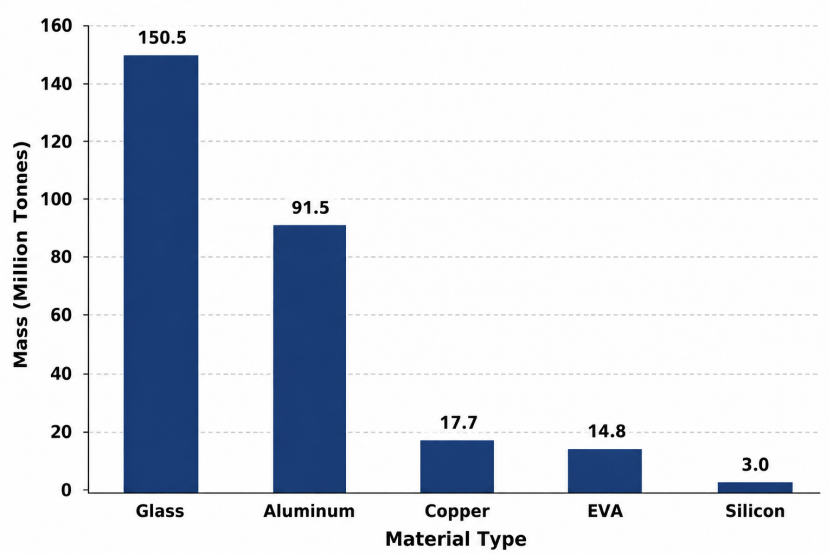


Figure 9. Material composition of PV waste in India by 2047, calculated by the authors from the mass-balance-consistent figures derived from [41] (see Section 2.2.1).

According to Paiano [7], published in 2015, the majority of PV waste projected to be generated in Italy will originate from crystalline silicon (c-Si) panels (see Figure 10). The source models waste generation over two horizons, 2012–2038 and 2039–2050, assuming a 25-year module service life; the figures reported below are therefore cumulative totals projected through 2050, not waste arising in the source's 2015 publication year. A cumulative total of 4,843,891 tonnes of c-Si panel waste is projected by 2050, consisting predominantly of 3,592,229 tonnes of glass, 498,921 tonnes of aluminium, 317,275 tonnes of EVA, and other components. This cumulative total also includes 27,610 tonnes of copper, 242 tonnes of silver, and 162,270 tonnes of silicon. For thin-film cadmium telluride (CdTe) panels, approximately 1,252,617 tonnes of waste were calculated cumulatively over the same 2012–2050 horizon, with a composition of approximately 1,189,986 tonnes of glass, 877 tonnes of cadmium, 877 tonnes of tellurium, and 12,526 tonnes of copper [7].

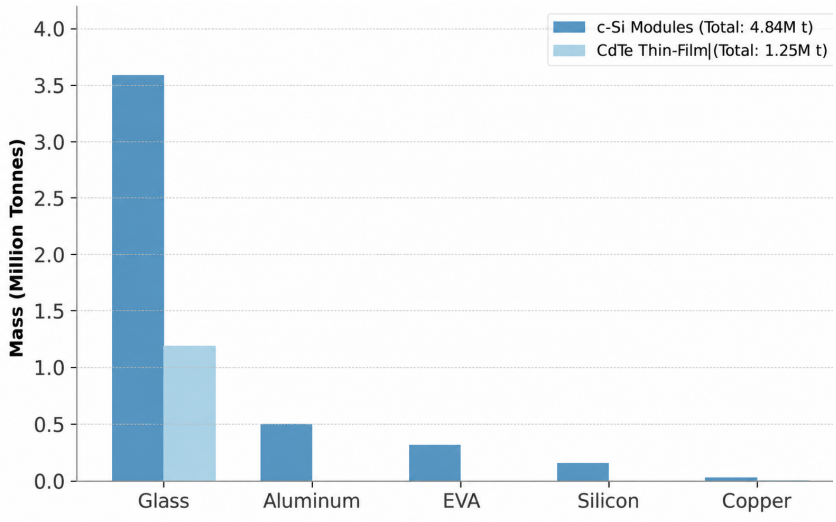


Figure 10. Cumulative material distribution of PV waste projected to be generated in Italy by 2050 (crystalline silicon [c-Si] panels; cadmium telluride [CdTe] panels), based on Paiano (2015) [7].

According to studies conducted in Australia, the cumulative volume of PV waste generated by 2047 is estimated to reach approximately 0.8 million tonnes (see Figure 11). The majority of this waste consists of core structural materials such as glass (541,209 tonnes) and aluminium (116,483 tonnes), followed by copper (8375 tonnes) and steel (71,329 tonnes). Over the same period, PV waste is also expected to contain approximately 299 tonnes of hazardous substances (cadmium, lead, and selenium) and 3860 tonnes of critical raw materials, together corresponding to approximately 0.5% of total waste. The remaining 10% consists of silicon and various other metals, amounting to 76,363 tonnes [13].

In addition to quantitative distribution, the economic value of PV waste components represents a decisive criterion in determining waste management and recovery strategies. Assessments conducted in this context indicate that, among the PV waste projected to be generated by 2047, the glass component holds the highest economic value. Glass is followed by other recoverable materials such as silver (18%), aluminium (18%), and steel (17%). These findings demonstrate that an approach based solely on mass quantities is insufficient for PV waste management, and that an economic value-oriented prioritization framework is also required [13].

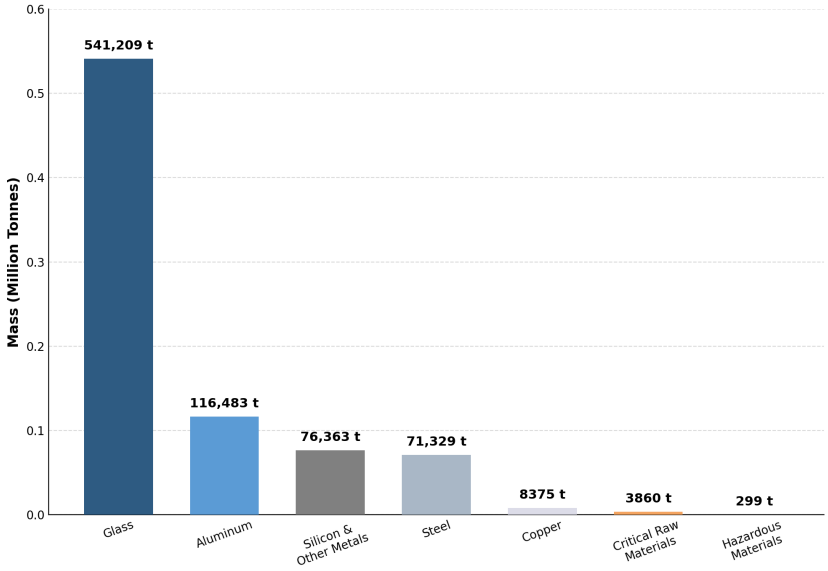


Figure 11. Projected material composition of PV waste in Australia by 2047 [13].

According to Domínguez and Geyer, the estimated cumulative waste volumes originating from end-of-life PV systems in the United States (see Figure 12) encompass installations with a capacity of 1 MW or above, totalling 69.7 GW, which represented approximately 50% of nationwide PV installations as of 2016. The increase in PV capacity during this period was driven predominantly by the expansion of utility-scale systems.

The results indicate that a total of 9.8 million tonnes of PV waste is expected to be generated over the period examined, comprising 6.6 million tonnes of PV modules, 2.7 million tonnes of balance-of-system (BOS) components, 0.3 million tonnes of inverters, and 0.2 million tonnes of transformer components. Approximately 9.2 million tonnes of this waste stream is estimated to contain metals that are recoverable. Recoverable precious metals include 1816 tonnes of silver and 27 tonnes of gold, while recoverable critical metals include 4469 tonnes of cadmium, 1073 tonnes of gallium, 515 tonnes of indium, and 2010 tonnes of tellurium.

In addition to quantitative projections, the material composition and distribution of economic value were also analysed. Steel predominates in mounting structures (46%), aluminium in module frames (30%), silicon in c-Si modules (17%), and copper in cabling

(4%). In terms of economic value, the distribution among metals in PV waste is as follows: aluminium (27%), silicon (23%), gold (13%), steel (13%), copper (12%), and silver (6%). These figures indicate that base and precious metals account for the majority of the total economic value, while critical metals hold a comparatively smaller share (e.g., gallium 1.6%, magnesium 0.7%, tellurium 0.9%, and indium 1.2%) [42].

According to a study conducted by Domínguez and Geyer for Mexico, approximately 1.2 million tonnes of PV waste are projected to be generated in the country by 2045 (see Figure 13). Of this total, 691 thousand tonnes consists of module waste originating from approximately 31 million PV modules.

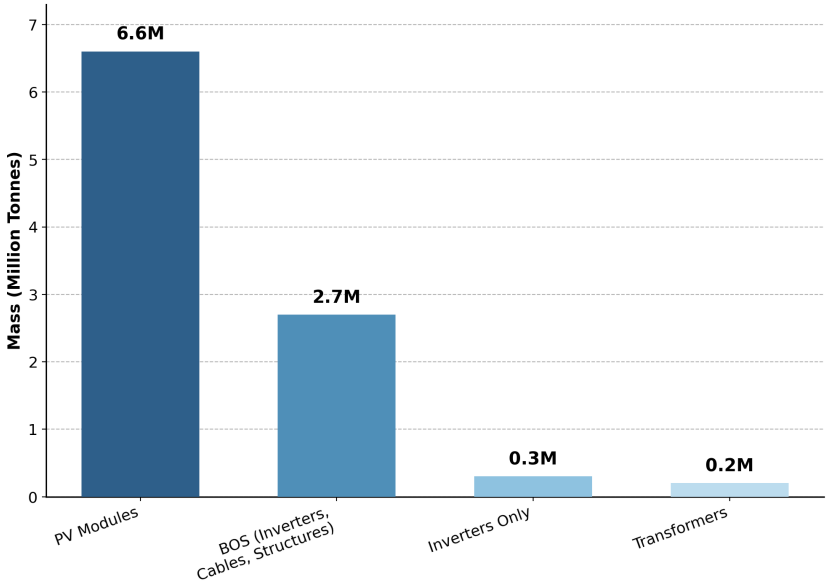


Figure 12. Projected PV waste composition based on cumulative PV installations in 2016 [42].

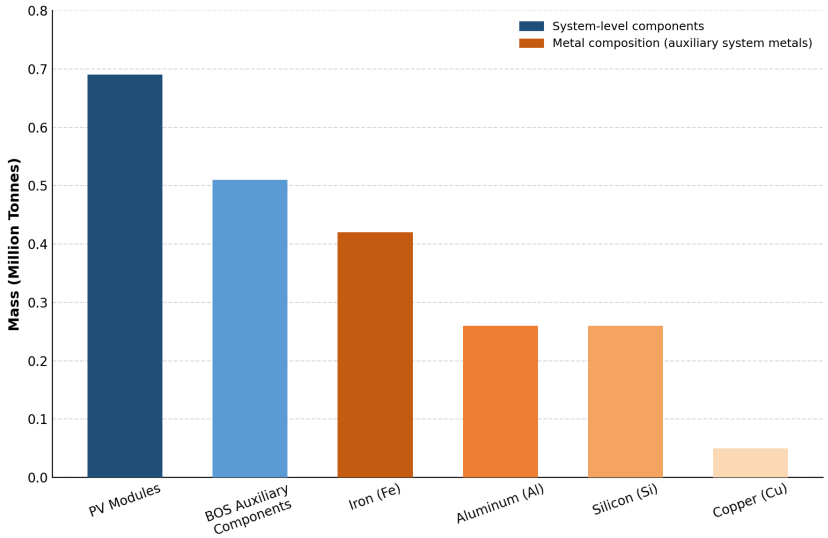


Figure 13. Projected PV waste composition in Mexico by 2045 [43].

According to the same study, when auxiliary system components (BOS)—including inverters, transformers, cabling, mounting structures, and monitoring equipment—are taken into account, the PV waste stream is projected to contain approximately 1 million tonnes of metal, with a composition of approximately 42% iron (Fe), 26% aluminium (Al), 26% silicon (Si), and 5% copper (Cu).

If the best currently available recycling technologies are applied, approximately 920 thousand tonnes of the total PV waste is estimated to be recoverable. This process is also projected to enable the recovery of valuable and strategic metals, including 271 tonnes of silver, 10 tonnes of gold, 17 tonnes of gallium, 10 tonnes of indium, 139 tonnes of cadmium, and 100 tonnes of tellurium, for reintroduction into the economy [43].

According to a study by Liu et al., the cumulative PV waste capacity in China was approximately 5 GW in 2022 (see Figure 14), and is projected to reach 26 GW by 2030, 100 GW by 2040, and approximately 400 GW by 2050. With this growth expected to continue at an accelerating pace, the cumulative capacity is projected to reach between 1100 and 1450 GW by 2060 [44].

Various studies in the literature indicate that recycling waste generated from PV modules offers substantial economic and environmental benefits. For example, Cucchiella et al. estimate that recycling one tonne of silicon-based PV modules, instead of sending it to landfill, saves approximately 0.8–1.2 tonnes of CO_2-equivalent emissions [45]. According to assessments conducted specifically for China, the average economic gain obtainable from recyclable materials is estimated at USD 340 per tonne [46]. Findings from Liu et al. indicate that PV waste generated in China could exceed 20 million tonnes by 2060, representing a recyclable material potential valued at approximately USD 6.8 billion, with recycling estimated to prevent 160–240 million tonnes of CO_2-equivalent emissions. Accordingly, the recycling or redesign for reuse of materials employed in solar panel manufacturing holds strategic importance for the PV sector, both in reducing costs and enhancing profitability [44].

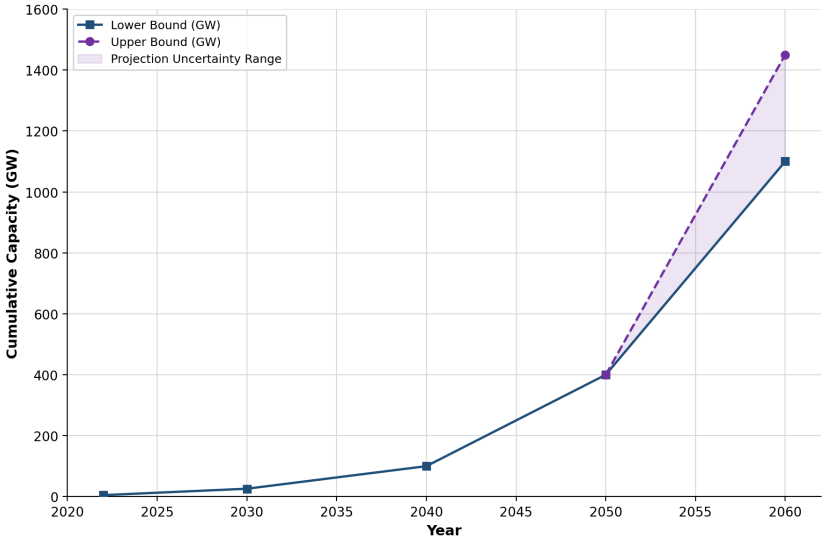


Figure 14. Projected cumulative PV waste capacity in China (2022–2060) [44].

It should nonetheless be noted that not all materials can be recovered at a 100% rate in recycling processes. In a study by Huang et al., the inputs and outputs associated with the recycling process of a 1 kW multicrystalline silicon (multi-Si) PV module were assessed, and the resulting material losses were quantified. The analysis found recovery rates of 89% for glass, 80% for silicon, 81% for aluminium, 80% for EVA, and 89% for silver, corresponding to approximately 42.3 kg of glass, 10.3 kg of aluminium, 12.47 kg of EVA, 2 kg of silicon, and 0.024 kg of silver recoverable per kW of module [22,35].

Across these country-level studies, critical raw materials (CRMs)—principally silver, gallium, indium, cadmium, and tellurium—consistently represent a disproportionately small mass fraction of PV waste yet carry outsized economic and strategic importance. Silver typically accounts for well under 0.1% of total module mass [15], yet the US-based estimate discussed above projects 1816 tonnes of recoverable silver alongside 1073 tonnes

of gallium, 515 tonnes of indium, and 2010 tonnes of tellurium [42], while the Italian CdTe-specific estimate reports 877 tonnes each of cadmium and tellurium cumulatively by 2050 [7]. Reported recovery rates for these elements vary considerably across studies and technologies: Sica et al. report recovery rates of approximately 75% for indium and 99% for gallium [22], whereas Huang et al. report an 89% silver recovery rate specific to multicrystalline silicon modules [22,35], and Teknetzi et al. demonstrate that leaching conditions—pH, surface-to-liquid ratio, and acid concentration—strongly influence both the yield and purity of silver and indium recovered from CIGS modules [47]. This variability, combined with the currently low absolute quantities entering the waste stream, is compounded by a longer-term supply-security concern: global silver production is projected to peak by 2030 and to come under supply pressure by 2075 [15]. PV recycling therefore represents not only a waste management issue but an emerging critical-materials security concern, and consolidating recovery efforts specifically around these five elements—rather than treating them as incidental by-products of glass and aluminium recovery—constitutes both an economic opportunity and a strategic necessity for the sector.

Taken together, the country-based studies discussed above reveal substantial variation in estimated PV waste volumes, both in terms of geographic scale and reference year. To enable a comparative overview of these differences, the key findings of the relevant studies are summarized in Table 3.

Table 3. Comparative summary of country-based estimated PV waste volumes and dominant components.

Country/Region	Reference Year	Estimated Total PV Waste	Dominant Component(s)
India	2047	~295 million tonnes	Glass (51%), aluminium (31%)
Italy	Cumulative to 2050 (study published 2015)	~6.1 million tonnes (c-Si + CdTe)	Glass (dominant), aluminium, EVA
Australia	2047	~0.8 million tonnes	Glass, aluminium; silver prominent in economic value
United States	Based on 2016 capacity	~9.8 million tonnes (module + BOS)	Steel, aluminium, silicon, copper
Mexico	2045	~1.2 million tonnes	Iron, aluminium, silicon, copper (including BOS)
China	2060 (projection)	>20 million tonnes	c-Si-based modules (~USD 6.8 billion recovery potential)

When the data presented in the table are considered together, it becomes evident that the absolute waste volume depends largely on a country's installed PV capacity and the reference year adopted; notably, the estimate for India stands out as exceptionally large relative to other countries, owing to its 27-year projection horizon and its comprehensive inclusion of BOS components. In terms of component distribution, glass and aluminium emerge as the dominant components in module-focused studies (India, Italy, and Australia), whereas steel/iron gains prominence in studies that jointly consider modules and balance-of-system (BOS) components (United States; Mexico). This difference stems less from technological variation than from differences in system boundaries across studies—namely, whether only the module or the module plus BOS was considered. This finding suggests that investments in recycling infrastructure should be planned primarily around high-volume glass/aluminium or metal-dominant waste streams, while being supplemented by separate, more specialized processes dedicated to the recovery of precious and critical metals.

2.2.2. Limitations of PV Module Recycling

Photovoltaic panels contain critical raw materials, toxic components, and valuable materials such as silver, high-purity silicon, lead, and solar-grade glass. Recycling is therefore regarded as one of the most appropriate solutions for panels that have reached the end of their service life. However, one of the most significant challenges encountered to date lies in the laminated sandwich structure of panels (see Figure 15); this sealed structure hinders the separation of individual components and renders recycling processes considerably more complex [48,49].

Accordingly, the efficiency of the recycling process at the end-of-life (EoL) stage depends heavily on the effectiveness of the process selected, a task that is particularly challenging owing to the sealed, "sandwich-type" structure of c-Si PV panels [15]. Nevertheless, a pilot recycling method developed for c-Si PV panels has achieved a silicon recovery rate of approximately 95% [49].

Furthermore, the literature widely reports that recycling processes remain relatively costly in comparison with the manufacturing costs of photovoltaic panels. Research on the end-of-life (EoL) management of photovoltaic solar panels remains at an early stage in many countries, underscoring the need for comprehensive global assessments of waste panel recycling. Consequently, alongside recycling, second-life scenarios that enable the reuse of panels reaching the end of their service life are also gaining importance [50].

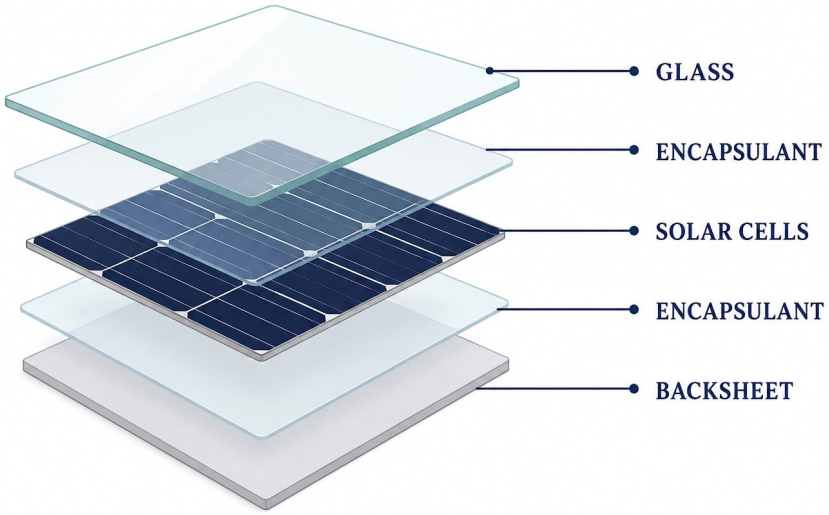


Figure 15. Schematic illustration of the laminated sandwich structure of a PV module (illustrative diagram).

One example illustrating the challenges of recycling is provided by the study of Kadro and Hagfeldt on perovskite-based PV cells. The recycling process for perovskite PV technology poses substantial challenges from the standpoint of sustainable energy policy; the perovskite PV cells examined in this context represent a current example demonstrating that recycling processes can be both hazardous and technically demanding.

Perovskite panels can be manufactured from raw materials that are readily available worldwide and offer high efficiency potential. However, owing to their structural instability, they have not yet achieved widespread commercial deployment and remain largely confined to laboratory-scale research applications. Although the manufacturing process is practical and low-cost, the environmental and technical challenges encountered at the recycling stage introduce considerable uncertainty regarding the long-term sustainability of this technology. Perovskite PV cells therefore clearly illustrate how complex the recycling process can be for solar panel technologies [51].

Compared with other categories of electronic waste, the economic value per kilogram of silicon-based PV modules is considerably low, rendering their recycling economically unattractive. The high sensitivity of new PV module market prices to increases in recycling costs further undermines the financial sustainability of the process. In an analysis conducted by Cucchiella et al. for the European market, the recycling profitability of 14 products across different WEEE (Waste Electrical and Electronic Equipment) categories was assessed; PV modules were found to yield the lowest economic returns among these categories, owing to the limited quantity and low economic value of their recoverable materials [52,53].

For instance, when compared with electronic products containing high-density metals, such as smartphones, the recovery potential of PV modules per kilogram was found to be approximately half as high. This low recovery potential is regarded as a key factor diminishing the economic incentive for the proactive recycling of photovoltaic waste [16].

Several studies have examined this economic landscape in greater depth. Dias and Veit conducted a comprehensive assessment of the potential risks and value components associated particularly with first-generation photovoltaic modules. The study highlights that these modules contain both hazardous substances posing potential environmental threats and materials of substantial economic value. The authors comparatively evaluated the feasibility of mechanical, thermal, and hydrometallurgical recycling methods, analysing the recovery rates, economic outcomes, and environmental impacts achievable through each approach, and offered important insights into different recycling scenarios [54].

Regarding economic feasibility, D'Adamo et al. analysed the economic viability of PV module recycling processes under various market conditions and cost scenarios. Their findings indicate that recycling operations are not economically attractive when landfill disposal fees are not factored into the analysis; however, recycling can become financially profitable when sufficient market value is attributed to the recovered materials [55].

Similarly, Wang et al. conducted a comprehensive assessment of the principal barriers to PV module recycling. Their findings identify the technical difficulty of implementing recycling processes at mass-production scale, high capital requirements, insufficient government support, and the still-limited size of the recycling market as the most significant constraints. While the study anticipates that economic feasibility may improve in the coming years as investment costs decline and market volume expands, it notes that existing infrastructure deficiencies may become an increasingly pronounced challenge over the medium to long term [56].

Consistent with these findings, a more recent techno-economic and policy review by Tiwari et al. confirms that mechanical recycling remains the most commercially mature route, achieving 80–90% recovery of bulk glass and aluminium, while highlighting that harmonized global policy frameworks—alongside advances in eco-friendly solvents and low-energy thermal processes—will be critical to achieving cost-competitive circularity in silicon PV recycling [57].

2.2.3. The Future of PV Module Recycling

The life cycle of PV panels follows a linear trajectory, from raw material extraction ("cradle") to the end of service life ("grave"), whereby only a limited proportion of panels currently reach the recycling stage. In contrast, the advanced recovery concept based on the Cradle-to-Cradle (C2C) approach aims to enable the circular reuse of all materials, whereby panels reaching the end of their service life become a primary resource for the manufacture of new panels [40].

In this context, Farrell et al. assessed the most appropriate recycling strategies for end-of-life PV modules and identified the most effective methods applicable in this field. Taking into account the structural limitations arising from module design, the study pro-

poses solutions aimed at maximizing component recovery and provides a comprehensive review of current recycling technologies developed in both industry and academia. Open-loop cascaded reuse scenarios and closed-loop recycling options are examined in terms of the technical challenges they present, the opportunities they offer, and their potential contributions to the circular economy [15].

Beyond process-level improvements, ecodesign principles applied at the point of manufacture offer a complementary route toward more circular PV end-of-life outcomes. Farrell et al. note that first-generation c-Si modules have not altered significantly in structure since the 1980s, and that the strongly bonded, EVA-based laminate that has become the industry standard inherently constrains closed-loop recovery, since disintegrating it requires either aggressive thermal treatment or hazardous chemicals [15]. Life-cycle evidence cited in the same study indicates that the silicon wafer and EVA layer, despite contributing only a minor share of total module mass, account for a disproportionate share of embodied energy and climate-change impact—approximately 83% and 66%, respectively—underscoring that closed-loop recovery of silicon and aluminium in particular offers the greatest environmental and economic return [15]. Several design-for-disassembly concepts have been proposed to reduce this recovery barrier: for example, a "double-encapsulation" module design using additional non-adhesive interlayers between the EVA and the solar cells allows the backsheet to be cut away and undamaged cells recovered without chemical delamination, while an alternative design replacing EVA with thermoplastic encapsulants, and a further design using vacuum-pressure cell interconnection without soldering or lamination, have both been shown to simplify disassembly and increase the likelihood of recovering intact solar cells [15]. However, none of these design concepts has yet achieved meaningful market penetration, and manufacturers continue to prioritize minimizing material use over designing for future disassembly [15]. A complementary and more immediately implementable measure is component-level labelling—for example, embedding RFID tags or QR codes recording a module's layer structure and material composition at the point of manufacture, as discussed below—since the current absence of any such information at end-of-life constrains sorting efficiency and can lead treatment facilities to default to less efficient, higher-emission pathways [9]. Embedding these ecodesign and labelling principles into manufacturing standards would allow the environmental and economic benefits identified in the recycling and second-life literature reviewed above to be more fully realized in practice. A recent comprehensive review by Sim et al. reinforces these findings at the global level, concluding that design-for-recycling practices, expanded data transparency on recycling performance, and coordinated policy incentives for material upcycling remain the most pressing open challenges for the PV recycling sector [58].

Contrary to the low economic return findings discussed in the previous section [16,53], a different picture may emerge under certain conditions. According to the economic framework compiled by Deng et al., First Solar's recycling program provides a concrete example of this: when end-of-life PV modules can be collected at a cost below USD 150 per tonne, the recycling of glass components is likely to become profitable; this cost corresponds to approximately half the average cost observed in Europe [31,45,59].

Within the same framework, it is emphasized that in cases where disposal fees for PV waste directed to landfill sites are high (e.g., USD 100 per tonne), recycling becomes an economically more advantageous option as long as transport costs remain below USD 200 per tonne. These findings indicate that, given appropriate logistical planning and collection infrastructure, PV recycling processes can constitute a viable option not only environmentally but also economically [16].

In addition to economic feasibility, Gahlot et al. focused on technical recovery strategies, providing a detailed examination of recycling techniques for first- and second-generation PV modules and the principal challenges encountered in these processes. The study addresses the application of various pretreatment and extraction methods for the effective recovery of metals and other valuable components across different module technologies, and offers a comprehensive assessment of the economic value, environmental impacts, and global development trends associated with PV recycling processes. In addition, the study presents an integrated strategy aimed at enhancing metal recovery efficiency, along with a projection of future directions for the recycling industry [60].

Dias et al. developed an alternative method for the recycling of silicon-based photovoltaic modules. This method comprises frame removal, module fragmentation, and electrostatic separation stages, and enables the recovery of a valuable fraction in which metal and silicon are jointly recovered. Although the economic value of the remaining fraction—containing a mixture of glass, silicon, and polymer—is relatively low, the overall performance of the method demonstrates advantages over existing complete recycling processes and landfill disposal options in terms of technological feasibility, environmental benefit, and cost-effectiveness. The study's findings indicate that, in certain scenarios, this approach may be more cost-effective than complete recycling systems and environmentally superior to landfilling [61].

Lin et al. examined development trends in the crystalline silicon (c-Si) solar cell market and provided a detailed analysis of the structural components of this module type. The study also assessed current recycling technologies for c-Si cells, comprehensively examining techniques such as manual disassembly, chemical dissolution using inorganic acids, hybrid methods combining thermal and chemical processes, and delamination using organic solvents. The technical limitations and process-efficiency drawbacks associated with each of these methods are identified, and the research needs for improving recycling practices are highlighted [62].

Another notable example in this context is provided by Teknetzi et al., who examined the effect of varying nitric acid concentrations on the recovery of valuable metals from decommissioned CIGS (copper–indium–gallium–selenide) PV modules. The study specifically assessed the leaching-based recovery efficiency of silver and indium, and analysed the potential for removing impurities such as zinc. The results show that higher pH levels and larger surface-to-liquid ratios increase recovery efficiency but also lead to higher impurity levels. The authors noted that lower acid concentrations enable the selective removal of zinc, thereby potentially improving the purity of the recovered silver [47].

According to Protopapa et al., the detailed characterization of PV module structure enables the selection of appropriate material recycling facilities and the customization of process parameters to the identified structure. In particular, Attenuated Total Reflectance (ATR) and Raman analyses were applied to the layers obtained following mechanical or chemical delamination of a PV module, with results verified through cross-sectional analysis; advanced techniques such as Energy-Dispersive X-ray Spectroscopy (EDS) and thermal analysis were also employed to support these investigations [9].

Such characterization of multilayer PV structures is of critical importance for informing the subsequent steps of module-specific recycling processes. Optimizing incineration or pyrolysis processes from both environmental and economic perspectives would substantially contribute to maximizing the recovery of recyclable materials. Furthermore, equipping newly marketed PV modules with labels containing information on their compositional structure (e.g., RFID or QR codes), or with indicators pointing to a recycling process optimized for the given module, would considerably facilitate the future identification, sorting, and recycling of end-of-life PV panels [9].

2.3. Second-Life Applications of PV Modules

Second-life application of PV modules refers to the reuse, as second-life photovoltaic panels, of modules that have not entirely lost their functionality but have been decommissioned for various reasons [63]. The CIRCUSOL project, for instance, defines such modules as "second-life PV panels" and notes that they can be reintroduced into different use pathways through repair, refurbishment, or remanufacturing processes [17,48]. This approach holds critical potential for reducing waste and enhancing resource efficiency within the PV sector.

Repair and reuse are regarded as valid and preferred options, within the context of the circular economy, for PV panels that have not yet reached the end of their technical service life. The circular economy is founded on the principle of retaining products in their original and highest-value state for as long as possible, prioritizing the full realization of a product's service life before recycling is considered [17]. Life Cycle Assessment (LCA) findings support this approach: allowing PV panels to complete their technical service life is environmentally more advantageous than early replacement or recycling [64,65]. In particular, early panel replacements carried out at intervals of 10–15 years have been shown to increase the environmental burden per unit of electricity generated; moreover, even the higher efficiency of new modules or improved recycling processes cannot fully offset this negative effect [66,67].

Distinguishing between PV modules that have reached the end of their service life and those that retain functionality and are suitable, based on their performance, for second-life applications is of considerable importance. Modules that remain operational and suitable for reuse can offer economic advantages—through resale in the secondary market or deployment in second-life scenarios—in the form of revenue or tax incentives. Module recycling or disposal, by contrast, often entails substantial economic costs and environmental impacts [68,69].

A comprehensive assessment of potential applications for second-hand PV modules reveals considerable variation across contexts. In high-income economies, second-hand modules are typically used to replace defective panels within systems operating under feed-in tariff schemes, thereby extending the economic service life of existing systems. In low-income countries, by contrast, second-hand PV modules are more commonly employed in the installation of new, small-scale PV systems in off-grid or remote areas. These modules are generally sourced from large-scale power plants that have either withstood demanding environmental conditions or completed their feed-in tariff incentive periods [70,71].

According to studies in the literature, PV modules exhibit performance decline after an average service life of 25–30 years. Nevertheless, it has been reported that, following approximately 27 years of operation, modules can acquire a second service life through the application of specific repair and refurbishment procedures. The annual efficiency degradation rate of crystalline silicon (c-Si) modules has been reported to range between 0.56% and 2.96%, indicating that such modules can continue to retain technical functionality. Accordingly, for applications that do not require high efficiency, the reuse of PV modules that have reached the end of their nominal service life but have not entirely lost their functionality may be feasible. The reuse process involves thorough cleaning of the modules, identification of structural and electrical defects, repair or replacement of faulty components where necessary, and, as a final stage, functionality testing. Modules that successfully pass these tests can be recertified and reintroduced into the second-life use cycle [17,27].

2.3.1. PV Waste and Second-Life Potential

According to Tsanakas et al., approximately 2.7–3.3 million PV modules are installed worldwide every day. Given an average field failure rate of 0.2%, an estimated 7–9 million installed PV modules (including those currently in operation) are projected to fail annually,

corresponding to approximately 162 kt of PV waste attributable solely to failures per year. When factors such as end-of-service-life retirement, early-loss failures, and repowering are additionally taken into account, the global volume of PV waste is projected to reach 4 Mt by 2030, 50 Mt by 2040, and 200 Mt by 2050 [18,72,73].

The literature emphasizes that a substantial proportion of this waste could be recovered through second-life applications. According to Tsanakas and H2020 CIRCUSOL experts, approximately two-thirds of PV modules reaching the end of their service life are repairable, refurbishable, or reusable [17,18].

A four-stage framework has been proposed for assessing the suitability of PV modules for reuse: off-site compliance checks; on-site inspections and functionality tests; classification for collection and transport; and in-depth technical inspection. In addition, three main criteria are used to determine the suitability of modules for reuse: technical feasibility, economic feasibility, and safety. As shown in Table 4, PV modules are classified into three classes based on these criteria [17,74].

The concept of PV waste itself inherently involves a degree of definitional ambiguity. From a manufacturer's perspective, a PV module is considered technically inadequate once its maximum power loss exceeds 20%. However, such performance decline does not necessarily indicate complete loss of function; in many cases, the module continues to generate a certain level of energy. Assessments based solely on nominal power loss therefore do not fully reflect a module's actual functional status. Modules falling within this category may not enter the waste stream unless decommissioned by system owners for economic or operational reasons. Furthermore, even modules withdrawn from use owing to serious technical faults can be reassessed following appropriate repair or refurbishment procedures. This approach not only enhances resource efficiency but also contributes to reducing the environmental impacts of PV waste within the waste electrical and electronic equipment (WEEE) category, thereby supporting circular economy and green growth objectives [75].

Table 4. Classification of PV modules for reuse. Adapted from [17,18,70,74].

Class	Definition	Required Action	Example Case
Class 1	Modules directly suitable for reuse	No further processing required	Modules with no physical damage and adequate performance
Class 2	Modules requiring repair/ additional testing	Technical inspection and repair	Modules with low insulation resistance
Class 3	Non-repairable modules	Directed to recycling	Severely damaged or non-functional modules

Reports published in recent years indicate that the service life of many IEC 61215 [76]-certified PV panels—particularly those operating under harsh or tropical climatic conditions—is shorter than 12 years [77–81]. In some cases, this period falls below 4 years, while in others the annual degradation rate exceeds 2%. Although these panels are typically rated for a 25-year service life up to an 80% output-power threshold, as stated in manufacturer warranties or technical documentation, they reach the expected 80% power-degradation limit considerably earlier than anticipated. A review of the existing literature on the reliability of photovoltaic modules indicates that the actual service life of modules is often shorter than that stated in manufacturer warranties [82–86]. This finding underscores the importance of assessing both service life and reuse potential.

For a PV module to be reused within a second-life framework, certain technical conditions must be satisfied. The fundamental requirements include operating at an efficiency level still deemed acceptable relative to original performance, posing no safety risk, and retaining sufficient remaining technical service life to justify the investment required for reuse.

In this context, the development of standardized quality control and sorting procedures is of critical importance for determining the suitability of decommissioned PV modules for reuse. From an economic standpoint, second-hand PV modules, despite offering lower efficiency and shorter remaining service life compared with new modules, are expected to provide a cost advantage in practical applications. The relatively low unit market value of second-hand PV modules (approximately EUR 0.10/W) indicates that only limited resources, in terms of both time and cost, can be allocated to preparing these modules for reuse [70].

The manufacture of silicon (Si)- and cadmium telluride (CdTe)-based modules is a process requiring careful environmental consideration owing to high energy demand, intensive use of raw materials, and the presence of toxic elements. Silicon mining increases fossil fuel consumption due to its energy-intensive nature and poses occupational health risks associated with dust emissions. In particular, the conversion of metallurgical-grade (MG) silicon into solar-grade (SoG) silicon in crystalline silicon (c-Si) module technologies requires a substantial amount of energy. This underscores the significant advantages that second-life application methods offer in photovoltaic systems, both in reducing manufacturing-related environmental impacts and in strengthening economic sustainability [22].

Many decommissioned PV modules, despite a certain degree of performance loss, have not entirely lost their functionality and retain reuse potential. However, the circulation of these modules in the secondary market is not yet governed by a clear legal framework or standardized quality control mechanisms. This gives rise to considerable variation in the quality and price range of second-hand PV modules available in the market. The number of PV modules reaching the end of their service life is projected to increase substantially in the coming years. From the perspective of the circular economy, reuse practices contribute to extending the service life of these modules and enhancing resource efficiency by preventing their premature entry into the waste stream [87].

2.3.2. Challenges of the Second-Hand PV Market

Studies in the literature indicate that one of the greatest barriers to the adoption of second-hand PV panels lies in market uncertainties. In this market, deficiencies in supply and demand reinforce one another, and consumer trust remains low owing to the absence of a proven track record. Furthermore, the ongoing trend toward new panels becoming both more efficient and less expensive further constrains the development of the second-hand market. Safety concerns and a lack of aesthetic integrity constitute additional limiting factors [67].

Another significant barrier limiting the reuse of PV modules is the absence of clearly defined technical criteria and legal frameworks for assessing module suitability for reuse. This gap becomes even more pronounced when combined with the lack of comprehensive global policies governing PV waste management. Addressing this gap is critical for improving economic feasibility, achieving high recovery rates, and enhancing environmental performance [14]. In this context, the "IEC TR 63525 ED1: Reuse of PV modules and circular economy" working committee is developing a standardized protocol for assessing the characteristics of reusable PV modules, with the aim of supporting the emergence of a reliable and sustainable market structure for reuse [87,88].

2.3.3. Direct Second-Life Application of PV Modules (Without Repair)

Existing studies indicate that the direct reuse of modules requires considerably less processing than material extraction during recycling and therefore yields the highest economic return [89]. In most cases, reusing a panel is regarded as a more feasible and cost-effective option, since no additional processing is required [90].

Nevertheless, panels intended for direct reuse must still meet essential performance standards in terms of safety, efficiency, and durability. Indeed, the lower efficiency and shorter remaining service life of decommissioned panels compared with new-generation modules can render such modules economically less viable in certain applications [70].

According to a study conducted in Algeria in 2019, supplying energy to remote areas via diesel generators can double transportation-related costs, with unit energy costs reaching approximately USD 0.38/kWh. In contrast, since a second-life PV panel cannot generate the same power output as a new panel within the same surface area, a larger panel surface is required to meet a given power demand; at the three sites examined (Adrar, Annaba, and Setif), the normalized performance ratios measured after 10, 16, and 22 years of operation, respectively, were found to be 0.86, 0.808, and 0.824. Based on these findings, it was proposed that panels retired from PV plants concentrated in the Sahara region be redirected toward second-life applications in agricultural pumping systems, and this option was compared with the same pumping service provided by diesel generators [50].

As an example, panels sourced from a PV plant in Adrar were, after approximately ten years of use in electricity generation during their first life cycle, sold at one-fifth of their original purchase price and redirected to a second life of approximately eight years in pumping systems. This extended the panels' total service life from 10 to 18 years and postponed panel waste processing from 2026 to 2034. In economic terms, pumping 1 kWh costs approximately USD 3.04 using a diesel generator, compared with only USD 0.96 using reused PV panels, yielding an economic benefit of approximately USD 2.08 per kWh. Assuming a 20% nominal power loss, the panel continues to generate energy, with only a moderate reduction in the water flow rate delivered; under these conditions, the second-life service period can be extended from 8 to 15 years, and panel waste processing can be postponed until 2041. A further advantage of this approach is that approximately 20% of the initial investment made in the PV plant's panel procurement can be recovered [50,91].

A field study conducted on decommissioned modules from five different solar power plants in Thailand aimed to assess the reuse potential of end-of-life panels. The study examined 258 modules of multicrystalline silicon (c-Si), amorphous silicon (a-Si), and copper indium diselenide (CIS) types, with operational histories ranging from 7 to 10 years. The modules were assessed for performance, safety, and functionality through visual inspection, insulation testing, and field-based I-V measurements. The findings indicate that approximately 74% of the modules exhibited a normalized power output above 70%, rendering them technically suitable for second-life application. These results demonstrate that reuse can extend the service life of photovoltaic modules, thereby increasing their economic value and reducing the growth rate of PV waste volumes [87].

2.3.4. Second-Life Application of PV Modules Through Repair

Repairing PV panels can be a preferred option, particularly for high-value or rare modules. The efficient identification and functional restoration of faulty but repairable modules is regarded as an important approach that can contribute to the development of a more profitable and sustainable second-life sector [17].

Nevertheless, repair and refurbishment processes have not yet been established on a systematic basis within the PV industry. These tasks are largely carried out by independent private companies, without support from original manufacturers. The absence of formal testing and certification mechanisms reduces consumer confidence in the reliability of repaired panels. Furthermore, existing gaps in research and development (R&D) constitute a significant limitation, particularly with respect to the standardization of repair techniques and the assurance of long-term performance [17,90].

Although the ongoing performance of modules over time requires regular monitoring (assessments of this kind are already being conducted), findings by Dobra et al. indicate that repair processes—whether or not they involve module replacement—are nearly always environmentally beneficial and economically feasible compared with disposal [88], a conclusion corroborated by other studies. Indeed, a separate study demonstrated that PV panel refurbishment is approximately one hundred times more effective than panel replacement in terms of carbon footprint [92].

Rosillo et al. report that approximately 10% of failures observed in PV modules result from ribbon busbar interruptions. In most cases, these failures are addressed by system owners through module replacement, since purchasing a new module is often more economical than repair. In this context, the study under review developed a low-cost and practical repair method specifically targeting ribbon busbar interruptions [93].

The proposed method begins with a series of tests aimed at identifying faulty modules. These include dry and wet insulation testing, indoor I-V curve measurements, and electroluminescence (EL) imaging. These tests can be performed using simple measurement instruments such as voltmeters, enabling rapid and low-cost fault characterization. Once the fault location has been identified, a limited access area is opened on the rear surface of the module to reach the interrupted busbar, and the repair is carried out.

Following the repair procedure, the initial tests are repeated to verify the module's functionality. The study's findings indicate that ribbon busbar interruptions can be effectively resolved using this method, thereby contributing to the second-life application of PV modules. Although such approaches are not always more economically advantageous than procuring new modules, they offer considerable potential in terms of waste management and environmental sustainability [93].

Various methods have been developed for in situ PV panel refurbishment, one of which employs a polydimethylsiloxane (PDMS) layer approximately 0.1 mm thick applied directly in the field. PDMS is a hydrophobic polymer known for its 150 °C Relative Thermal Index (RTI) and high thermal stability and is also used in PV module lamination. Field tests have shown that panels treated with a PDMS layer exhibited substantially improved ground impedance values following repair, with this improvement remaining stable over a five-year monitoring period. These findings indicate that the method can extend the service life of PV modules by at least five years and, owing to its low-cost nature, offers a solution that can be repeated at intervals of five to seven years. In contrast, panels that did not undergo refurbishment exhibited pronounced performance losses and permanent failures over a comparable period. Comparative analyses show that PDMS-based refurbishment is approximately 11 times less costly and has a carbon footprint approximately 120 times lower than panel replacement. In addition, PDMS coating was found to effectively restore the electrical insulation properties of the modules [92].

According to Tsanakas et al., the repair of PV modules is currently a largely manual, labour-intensive process. This process comprises fault detection, module disassembly, replacement or repair of the faulty component, and reassembly of the multilayer module structure. However, this procedure is both time-consuming and requires skilled technicians. Given the high labour costs and lengthy repair times involved, replacing the module with a new one is, in many cases, considered a more economically viable option [18].

2.3.5. Second-Life Application of PV Modules in Agrivoltaic Systems

One of the widespread applications of PV panels is in agrivoltaic systems, which combine energy generation with agricultural activities (see Figure 16). By casting shade on the ground surface, solar panels reduce the rate of water evaporation and thereby lower irrigation requirements [94]. In addition, they provide a protective microclimate against

climatic conditions that can adversely affect plant growth—such as extreme temperatures, strong winds, frost, and hail—contributing to increased crop yield and improved quality [95–97]. Plants growing beneath PV arrays generate a natural cooling effect through evapotranspiration, thereby lowering module temperature and potentially enhancing the efficiency of PV systems [98,99].



Figure 16. Agrivoltaic system combining PV modules with agricultural land use (illustrative diagram).

Agrivoltaic systems offer a dual-function structure that enables the integration of sustainable energy generation with agricultural activities, while also presenting a significant opportunity from the standpoint of circular economy principles. In this context, the second-life application of decommissioned yet still functional PV modules within agrivoltaic installations delivers both environmental and economic benefits. Deploying second-hand modules in such systems supports resource efficiency by reducing the demand for new raw materials, while also contributing to a reduction in PV waste volumes and an extension of overall system service life. Agrivoltaic applications thus represent a strategic solution not only for sustainable energy generation but also for the practical implementation of second-life scenarios for PV panels. Recent studies show that second-hand PV modules can be repaired using appropriate methods and reused, thereby enabling their integration into new installations and substantially extending overall system service life [93]. This approach is regarded as an effective strategy supporting the transition toward a circular economy within the photovoltaic industry. Research conducted by Nieto Morone et al. similarly demonstrated that partially repaired or second-hand PV modules, despite exhibiting a certain degree of electrical degradation, can still deliver adequate performance [71].

The study employed 15 new JNMM144-450L modules, each rated at 450 Wp, alongside 15 repaired TopSolar TSM 160M modules with a peak power of 170 Wp. The second-hand modules, which had approximately 12 years of operational history, underwent repair and preliminary assessment procedures to restore their functionality. Prior to reuse, the modules were subjected to a series of electrical and visual tests, conducted in accordance with characterization procedures established in previous studies [71,100].

The results obtained indicate performance differences between the new and reused modules. For instance, in the May measurements, correlation coefficients were calculated at

0.987 for new panels and 0.943 for reused panels, indicating that both panel groups exhibited a stable irradiance response under favourable climatic conditions. However, the consistently higher correlation values observed for new panels suggest that the performance gap becomes more pronounced over time [71,100].

Consistent with this finding, the monthly performance ratio data presented in Figure 17 show that both panel groups followed a similar seasonal trend, with a peak observed in July and a marked decline in August for both groups. The performance gap between new and reused panels remained generally stable within the range of 0.10–0.11, widening slightly to approximately 0.13 in August; this may indicate that high summer temperatures have a comparatively more pronounced effect on older modules [100].

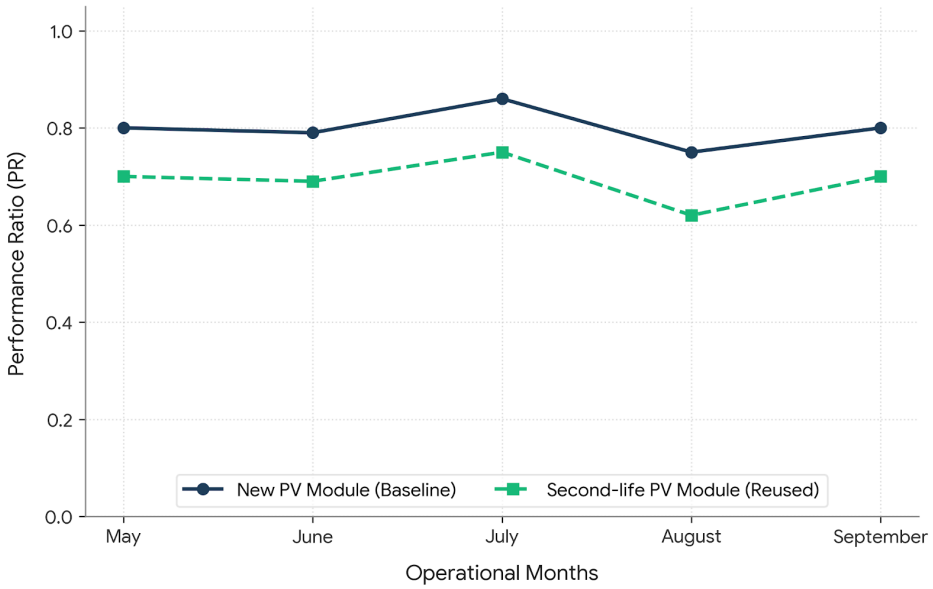


Figure 17. Performance of new and second-life PV modules used in the study [100].

Nevertheless, the overall results indicate that second-hand modules remain operationally viable. The reuse of photovoltaic modules in agrivoltaic systems or in installations with low power requirements enhances resource efficiency in line with circular economy principles and reduces carbon emissions associated with manufacturing and disposal. From an economic standpoint, reused modules lower the initial investment costs of new system installations, offering a financially sustainable alternative [87,100].

2.4. Disposal of PV Modules

Despite the technical maturity of the recycling and second-life options discussed in the preceding sections, disposal practices continue to account for the majority of the global PV waste stream—a finding that clearly illustrates the gap between technical potential and actual field-level practice. Although recycling is regarded as one of the most environmentally sustainable waste management methods, the economic feasibility of photovoltaic panel recycling processes remains limited under current conditions. Recent studies indicate that recycling, particularly for silicon-based PV modules, does not yet constitute a cost-effective solution. The principal reasons for this include the low market value of recoverable materials, the high operational costs of recycling processes, the relatively limited volume of waste generated to date, and the still-underdeveloped recycling infrastructure specific to the PV industry [29,31,101].

Under these conditions, a substantial proportion of PV panels reaching the end of their service life is directed to, or buried in, landfills, the most common disposal method

worldwide; in many countries, this practice takes place alongside other household waste, within the framework of existing legal regulations [29,34,102,103]. It is difficult, however, to characterize this approach as an environmentally or economically sustainable solution: landfilling leads to the permanent loss of valuable, recoverable materials such as glass, aluminium, and silicon, while also increasing the risk of releasing potentially hazardous chemical components contained within the module structure into the environment [16,104]. It is therefore critical to develop economically viable recycling technologies for PV waste management and to increase dedicated infrastructure investment in this area.

Indeed, the deterioration of module component integrity over time can lead to the leaching of toxic elements such as cadmium (Cd), lead (Pb), and selenium (Se) into soil and groundwater [14,27,105]. Given that such leaching poses serious environmental risks to ecosystem and human health, the disposal of PV modules via landfilling is not regarded as a sustainable waste management approach.

2.5. Economic Feasibility of PV End-of-Life Management Pathways

Economic feasibility is discussed throughout this review alongside the technical assessment of each pathway; given its central role in determining which end-of-life route becomes viable at scale, this section synthesizes the recycling, second-life, and disposal literature into a focused comparative assessment.

The fundamental economic barrier to recycling is the persistent cost gap between recycling and landfilling: in the United States, recycling a silicon PV module costs approximately USD 15–45, compared with only USD 1–5 to landfill it [21]. This gap explains why landfilling remains the default pathway in the absence of regulatory or market intervention (see Section 2.4). Threshold-based analyses indicate the conditions under which this gap can be closed: recycling glass components becomes profitable once end-of-life modules can be collected at a cost below USD 150 per tonne, and recycling becomes favourable relative to landfilling whenever landfill disposal fees exceed USD 100 per tonne and transport costs remain below USD 200 per tonne [16]. Country-level estimates of recoverable value vary substantially with local material composition, labour costs, and commodity prices: assessments for China estimate an average economic gain of USD 340 per tonne of recycled material [46], while the corrected, mass-balance-consistent estimate for India indicates approximately USD 452 billion in recoverable material value out of a total commodity value of USD 645 billion for cumulative PV and BOS waste through 2047 (see Section 2.2.1) [41]. A recent techno-economic review further confirms that, while mechanical recycling is currently the most commercially mature and cost-effective route for bulk materials (glass and aluminium), achieving cost-competitive recovery of higher-value materials (silver; high-purity silicon) continues to depend on advances in low-energy separation processes and harmonized policy support [57].

Second-life application offers a distinct economic profile: because it avoids the material-separation and reprocessing costs inherent to recycling, direct reuse typically yields a higher economic return per module than recycling [89], provided that panels meet minimum safety and performance thresholds. Field-level economic evidence supports this: in an off-grid agricultural pumping application in Algeria, second-life PV modules reduced the levelized cost of pumped water to USD 0.96/kWh, compared with USD 3.04/kWh for diesel generation, while also recovering approximately 20% of the original PV plant's panel investment [50]. Similarly, second-life modules deployed in agrivoltaic systems lower the initial investment cost of new installations relative to new modules, offering a financially accessible pathway to circular reuse [100]. However, the addressable volume of the second-life market remains constrained by the relatively low unit market value of second-hand PV

modules (approximately EUR 0.10/W), which limits the time and cost that can economically be allocated to qualification and repair [70].

Taken together, these findings indicate that no single pathway is economically preferable under all conditions: second-life application offers the most favourable economics where technically feasible, given its minimal reprocessing requirements; recycling economics remain highly sensitive to collection costs, landfill fees, and local commodity prices, becoming favourable primarily where these thresholds are met or where regulation (e.g., EPR schemes; landfill restrictions) internalizes the cost of disposal; and disposal, while currently the cheapest option in the absence of such regulation, imposes environmental and resource costs that are excluded from its direct economic comparison. This underscores the importance of the four-axis comparative framework introduced at the beginning of Section 2, within which economic feasibility must be weighed jointly with environmental performance, technical maturity, and material recovery potential rather than assessed in isolation.

3. Conclusions

This study addresses the end-of-life (EoL) waste problem that is expected to grow considerably alongside the increasing deployment of photovoltaic modules, driven by rising global energy demand. Within this framework, recycling, second-life applications, and disposal methods were examined on a literature-based basis. Drawing on 105 selected sources identified through a structured, keyword-based Google Scholar search complemented by backward reference screening, this study provides an integrated assessment of PV module structures, waste management processes, material recovery potential, and the limitations of current practices.

The literature reviewed indicates that landfilling is not a sustainable option for PV waste management, owing to both the loss of valuable materials and the risk of toxic component leaching into the environment. Recycling is an environmentally preferable approach, as it mitigates the environmental impacts of harmful components such as lead and enables the recovery of important materials, including glass, aluminium, and silicon, as well as Ag, In, Ga, Cd, and Te. Nevertheless, the multilayer laminated structure of crystalline silicon (c-Si) modules in particular, together with delamination processes and operational costs, emerge as key factors constraining the economic feasibility of recycling. Accordingly, the broader adoption of recycling practices under current conditions depends on the establishment of efficient collection and logistics infrastructure, improvements in process efficiency and the development of appropriate economic incentive mechanisms.

Second-life application offers an approach more closely aligned with circular economy objectives by preventing the premature entry of PV modules that have not entirely lost their functionality into the waste stream. The literature reviewed indicates that the concept of an "end-of-life PV module" is often defined by reference to the 25-year service life associated with manufacturer warranties; however, this time-based approach does not always reflect the actual technical condition of the module. Indeed, many PV modules have been shown to continue generating energy at the end of this period, retaining a substantial proportion of their nominal power output. In this context, the point at which modules enter the waste stream is not determined by service duration alone but rather through the combined consideration of multiple factors, including technical performance, field conditions, safety status, economic expectations, and the operator's replacement decisions. The literature further indicates that, in several field studies, a substantial proportion of modules were found suitable for reuse following specific testing and classification procedures, and that this approach is particularly applicable in contexts such as off-grid applications, low-power-demand systems, and agrivoltaic installations.

Disposal practices, despite the technical maturity of recycling and second-life applications, continue to account for the majority of the global PV waste stream, revealing a pronounced gap between technical potential and actual field-level implementation. The literature indicates that disposal via landfilling prevents the economic recovery of valuable materials such as glass, aluminium, and silicon, while increasing the risk that toxic elements such as cadmium, lead, and selenium will leach into soil and groundwater over time. For this reason, although disposal remains widely practised under current conditions, it is not regarded as a sustainable waste management strategy.

In conclusion, the literature indicates that recycling constitutes a strong option from an environmental standpoint, although its economic feasibility remains limited in many scenarios, primarily owing to process costs. In this context, second-life application emerges as a complementary approach that enhances resource efficiency by delaying the premature entry of modules retaining residual functionality into the waste stream; disposal, by contrast, continues to dominate under current conditions but does not align with long-term sustainability objectives. The large-scale implementation of these approaches depends not only on technical suitability assessments but also on strengthened traceability and reliability mechanisms. Emerging international standards such as IEC TR 63525 represent concrete steps in this direction and may contribute to the future maturation of the second-life market in terms of reliability and transparency.

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Abbreviations

The following abbreviations are used in this manuscript:

PV	Photovoltaic
EoL	End-of-Life
c-Si	Crystalline Silicon
multi-Si	Multicrystalline Silicon
a-Si	Amorphous Silicon
CdTe	Cadmium Telluride
CIGS	Copper–Indium–Gallium–(Di)Selenide
CIS	Copper Indium Diselenide
EVA	Ethylene-Vinyl Acetate
BOS	Balance of System
WEEE	Waste Electrical and Electronic Equipment
LCA	Life Cycle Assessment
CPV	Concentrated Photovoltaic
OPV	Organic Photovoltaic

DSSC	Dye-Sensitized Solar Cell
PDMS	Polydimethylsiloxane
RTI	Relative Thermal Index
ATR	Attenuated Total Reflectance
EDS	Energy-Dispersive X-ray Spectroscopy
EL	Electroluminescence
IEC	International Electrotechnical Commission
EPR	Extended Producer Responsibility
C2C	Cradle-to-Cradle
MG	Metallurgical-Grade
SoG	Solar-Grade
R&D	Research and Development

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