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Review

Recycling of Silicon-Based Photovoltaic Modules: Mediterranean Region Insight

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Abstract: The rapid expansion of photovoltaic (PV) installations across Mediterranean Europe since 2007 has resulted in a substantial increase in the need for end-of-life (EoL) management strategies for monocrystalline PV modules. This paper reviews the technical challenges and opportunities associated with the recycling of PV modules, focusing on the physical, chemical, and thermal processes currently employed. Despite advancements in recycling technology, significant gaps remain in infrastructure and regulatory enforcement, particularly in Mediterranean countries. The recovery of valuable materials such as silicon, silver, and glass presents both economic and environmental benefits, although the costs of recycling remain a key barrier to widespread adoption. Our analysis suggests that optimizing these recycling processes could improve their profitability and scalability, enabling more effective resource recovery. The paper concludes with recommendations for policy and infrastructure development to support the sustainable management of PV waste across the Mediterranean region.

Keywords: photovoltaic module recycling; silicon recovery; Mediterranean Europe; WEEE Directive; physical processes; chemical processes; thermal recycling

Citation: Diez-Suarez, A.-M.; Martínez-Benavides, M.; Manteca Donado, C.; Blanes-Peiró, J.-J.; Martínez Torres, E.J. Recycling of Silicon-Based Photovoltaic Modules: Mediterranean Region Insight. *Energies* **2024**, *17*, 6015. https://doi.org/10.3390/en17236015

Academic Editor: Anastassios M. Stamatelos

Received: 30 October 2024
Revised: 13 November 2024
Accepted: 22 November 2024
Published: 29 November 2024

1. Introduction

The Mediterranean region, with its abundant solar resources, has become a focal point for the deployment of photovoltaic (PV) module installation. This progress was driven by the European Union (EU) commitment to sustainability and decarbonization goals, reducing dependence on fossil fuels to address climate change. However, as the installed capacity of PV systems increases, the challenge of managing the waste generated by these systems at the end of their life cycle growths. The recycling of PV installations is therefore critical to ensuring that the environmental benefits of solar energy are not offset by the negative impacts of improper waste management [1,2].

Current methods of PV waste disposal, such as landfilling, are not sustainable and pose a significant environmental risk, such as the potential release of hazardous substances, water and soil pollution, and the loss of valuable materials that could be recovered and reused. The environmental impact of these practices needs the development of more sustainable waste management strategies. Future scenarios for PV waste management should focus on improving recycling processes, enhancing the recovery of critical materials, and reducing the environmental footprint of PV systems [3,4].

A photovoltaic (PV) module is a device that converts solar energy into electricity using materials such as silicon [5,6]. These modules are essential for the generation of renewable energy, as they allow the direct conversion of sunlight into electricity without emitting greenhouse gases during operation. Photovoltaic modules consist of multiple electrically connected cells that are encapsulated to protect them from environmental factors [7].

There are several types of photovoltaic modules, each with specific characteristics that affect their performance and applications, which are summarized in Table 1:

Table 1. Photovoltaic modules (adapted from [8]).

Technology	Cell Type
Silicon based	Monocrystalline Poly- or multicrystalline Ribbon a-Si (amorph/micromorph)
Thin-film based	Copper indium gallium (di)selenide (CIGS) Cadmium telluride (CdTe)
Other	Concentrating solar PV (CPV) Organic PV/dye-sensitised cells (OPV) Crystalline silicon (advanced c-Si) CIGS alternatives, heavy metals (e.g., perovskite), advanced III–V

Silicon technologies, such as monocrystalline modules, are noted for their high efficiency, which exceeds 20%, making them the optimal choice for installations where space is limited. This high efficiency and long-term durability are valued traits within the solar industry [9]. However, the production of monocrystalline modules involves energy-intensive processes, leading to higher manufacturing costs. Additionally, their performance can be diminished in arid climates [10].

Polycrystalline modules are cheaper to manufacture, making them economically attractive. Their efficiency ranges between 15% and 17%, which is considered adequate for many residential and commercial applications. However, they have lower efficiency compared with monocrystalline modules and lack a uniform appearance [11]. Ribbon silicon modules are known for using less silicon material during manufacturing, thereby reducing costs and environmental impact. Nonetheless, they have lower efficiency and face certain limitations in terms of durability and mechanical resistance [12].

Thin-film technologies, such as amorphous silicon (a-Si), offer greater flexibility and perform well under low-light conditions. However, their efficiency is lower, typically 6% to 10% less, and they often exhibit some degradation over time due to the Staebler–Wronsk effect [13]. CIGS (copper–indium–gallium–selenium) technology stands out for its high light absorption capacity and efficiency, which can reach up to 20% [14]. Nevertheless, the limited availability of elements such as indium and gallium, along with the complexity of the manufacturing process, can drive up costs and constrain large-scale production [15].

Cadmium telluride (CdTe) modules have low production costs and a reduced environmental impact in terms of energy used during manufacturing, making them competitive in terms of cost–benefit analysis. Their performance in warm climates is superior; however, the toxicity of cadmium and the limited availability of tellurium raise environmental and recycling concerns [16].

Other technologies include concentrator photovoltaic (CPV) systems and organic photovoltaic (OPV) cells. CPV systems can achieve efficiencies exceeding 40%, but they rely on solar tracking mechanisms and cooling systems, which increase the complexity of installation and maintenance. Additionally, their effectiveness is reduced in areas with high diffuse radiation or cloudy climates [17]. OPV cells are lightweight, flexible, and potentially cost-effective to produce, allowing their use in innovative applications such as curved surfaces and portable devices [18]. However, their efficiency remains low (around 10–15%) and they suffer from rapid degradation due to the instability of organic materials [19].

Perovskite modules offer high efficiency and low production costs. They can be manufactured using low-temperature processes, which reduce production expenses and allow lightweight and flexible configurations. However, their long-term stability remains an issue, as they are prone to degradation from environmental factors such as humidity, limiting their current durability and commercial application [20].

The typical structure of a photovoltaic module includes several components essential for its functionality and durability, as described in the Figure 1:

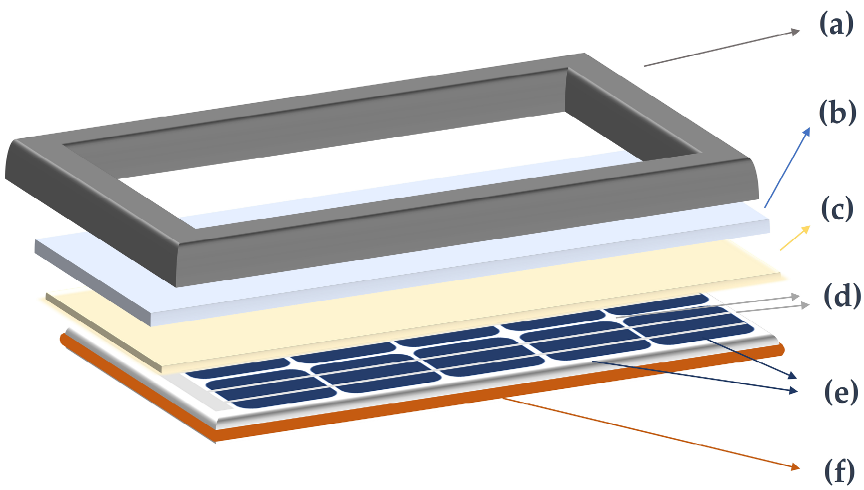

Figure 1. Typical structure of a photovoltaic module: (a) aluminum frame; (b) glass; (c) encapsulant (EVA); (d) silver collectors; (e) silicon PV cells, and (f) backsheet.

- The aluminum frame provides structural rigidity to the module, facilitating its installation and resistance to extreme weather conditions [7];
- Glass acts as a protective cover on the front of the module, providing protection against impact and weather, while allowing sunlight to enter with high optical transmission [21];
- Encapsulant (EVA—ethylene vinyl acetate) protects the cells from moisture and mechanical shocks, ensuring the longevity of the module by maintaining the integrity of the photovoltaic cells [22];
- Silver collectors are conductive lines on solar cells that collect and carry the generated electricity. Thanks to silver's high conductivity, they minimize electrical resistance and optimize current transfer, increasing the module's efficiency [23];
- Photovoltaic cells are the active components of the module, where the conversion of light into electricity occurs. The cells are connected in series and parallel to achieve the desired voltage and current [24];
- The backsheet acts as a moisture barrier and provides electrical insulation, typically being made of polymers such as polyvinyl fluoride (PVF) [25].

The configuration of photovoltaic modules varies considerably depending on the different absorber materials used. For instance, silicon-based modules, which include technologies such as monocrystalline and polycrystalline panels, are known for their high energy conversion efficiency and long durability. However, these modules require significant amounts of energy for their production [9]. In contrast, thin-film modules, such as those made of CIGS and perovskite, have different configurations and manufacturing processes that confer specific advantages and disadvantages. CIGS modules, for example, exhibit high capacity for light absorption and good performance under conditions of low radiation but face challenges due to the complexity of their manufacturing process and the limited availability of certain elements [14]. On the other hand, perovskite modules offer high efficiency and the potential for low production costs, but they still face long-term stability issues and the use of toxic materials such as lead [26].

The differences in configuration and composition of photovoltaic modules determine not only their efficiency and application but also the methods and feasibility of their recycling. Silicon-based modules, such as monocrystalline and polycrystalline types, have dominated the market for decades due to their high efficiency and durability. However, their recycling process involves the challenge of separating the silicon components from the encapsulation and backing materials [10]. Recycling these modules is crucial for recovering high-purity silicon and other valuable materials, contributing to reduced environmental impact and promoting a circular economy [16].

On the other hand, thin-film modules, such as CIGS and perovskite, have distinct configurations that pose unique challenges and opportunities in recycling. CIGS modules contain valuable metals like indium and gallium, whose recovery is essential due to their limited availability and high cost [14]. However, the recycling process for these modules is more complex and requires advanced techniques to effectively extract these metals without harming the environment.

Therefore, silicon modules can contribute to efficient recovery of valuable materials if managed properly, whereas thin-film modules, such as CIGS and perovskites, require a more specialized approach to avoid negative environmental impacts and maximize material recovery [27].

1.1. Analysis of the Recycling Potential

Data from the past decade reveal significant variations in installed PV capacity, waste generation projections, and manufacturing capacity across EU countries [28]. For example, countries with higher solar implementation rates are likely to face greater challenges in PV waste management. The Mediterranean region is expected to experience a substantial increase in quantities of end-of-life PV panels, highlighting the need for effective recycling infrastructure and policies. These data outline the importance of a coordinated approach to PV waste management that considers the specific needs and capacities of different regions [29].

By 2023, the total installed PV capacity in Europe reached 301,622 MW (see Table 2 and Figure 2a). Of this capacity, Mediterranean countries contributed 92,607 MW, representing approximately 30.70% of the total installed capacity in Europe (Figure 2b). This significant participation of Mediterranean countries underlines the importance of this region, characterized by high solar irradiation that facilitates the adoption of solar technologies for electricity generation.

Table 2. Total photovoltaic capacity installed in Europe (MW) (adapted from [30]).

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Albania	1	1	1	1	1	14	21	23	23	163
Andorra	0	0	0	0	1	2	3	4	4	4
Austria	785	937	1096	1269	1455	1702	2043	2783	3792	6832
Belarus	4	6	47	80	154	154	160	163	273	273
Belgium	3015	3132	3329	3621	4000	4637	5573	6012	6756	8549
Bosnia–Herzegovina	7	8	14	16	18	22	35	57	102	132
Bulgaria	1029	1028	1030	1031	1033	1044	1100	1275	1737	2937
Croatia	33	48	56	60	68	85	109	138	222	461
Cyprus	64	76	84	110	118	151	229	315	424	606
Czechia	2067	2075	2068	2075	2081	2111	2172	2246	2420	2499
Denmark	607	782	851	906	998	1080	1304	1704	3070	3529
Estonia	3	7	10	15	32	121	208	395	520	690
Faroe Islands	0	0	0	0	0	0	0	0	0	0
Finland	11	17	39	82	140	222	318	425	664	900
France	6034	7138	7702	8610	9629	10,729	11,917	14,603	17,341	20,542
Germany	37,898	39,222	40,677	42,291	45,156	48,912	53,669	60,036	67,477	81,737

Table 2. *Cont.*

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Greece	2596	2604	2604	2606	2651	2834	3288	4277	5430	7030
Hungary	89	172	235	344	728	1400	2131	2968	4235	5835
Iceland	1	3	4	4	5	7	7	7	7	7
Ireland	3	5	11	29	53	96	152	228	289	738
Italy	18,594	18,901	19,283	19,682	20,108	20,865	21,650	22,594	24,555	29,789
Kosovo	0	0	2	7	7	10	10	14	14	20
Latvia	0	0	1	1	2	3	5	7	113	353
Lithuania	69	69	70	74	82	103	164	255	572	1165
Luxembourg	110	116	122	128	131	160	187	277	317	432
Malta	55	75	94	112	132	155	188	205	222	231
Moldova Rep.	1	1	2	2	3	5	4	14	60	87
Montenegro	0	0	0	0	0	3	3	3	22	42
Netherlands	1007	1526	2135	2911	4608	7228	11,110	14,823	19,600	23,904
North Macedonia	15	17	17	17	17	17	85	91	190	535
Norway	13	15	27	45	68	120	160	205	358	616
Poland	27	108	187	287	562	1539	3955	7416	12,170	15,809
Portugal	415	447	513	579	667	901	1100	1646	2646	3876
Romania	1293	1326	1372	1374	1386	1398	1383	1394	1809	1917
Serbia	13	16	17	18	21	23	31	52	137	137
Slovakia	533	533	533	528	471	590	535	537	549	631
Slovenia	224	239	232	247	247	278	370	461	626	1034
Spain	4697	4704	4713	4723	4764	8807	10,136	13,715	23,311	28,712
Sweden	60	104	153	244	428	714	1107	1606	2388	3488
Switzerland	1061	1394	1664	1906	2173	2498	2973	3655	4340	5840
UK	5528	9601	11,914	12,760	13,060	13,345	13,551	13,915	14,651	15,657
Ukraine	819	841	955	1200	2003	5936	7331	8062	8062	8062
Albania	1	1	1	1	1	14	21	23	23	163
Andorra	0	0	0	0	1	2	3	4	4	4
Austria	785	937	1096	1269	1455	1702	2043	2783	3792	6832
Belarus	4	6	47	80	154	154	160	163	273	273
Belgium	3015	3132	3329	3621	4000	4637	5573	6012	6756	8549

The evolution of installed capacity in Europe has shown steady growth, driven by the rise of renewable energy and especially the expansion of solar PV technology in several countries in the region. Germany is the country with the largest installed capacity of photovoltaic energy in Europe, with 81,737 MW installed by 2023. Its leadership in this sector reflects the importance of policies supporting clean energy and the investment in solar infrastructure. This has been crucial to achieving climate and sustainability goals in the EU, as highlighted in the International Renewable Energy Agency (IRENA) reports [30].

During the period 2007–2008, part of the Mediterranean region of Europe (Spain, Italy, and Greece [31]) experienced a substantial growth in PV module installation, largely motivated by incentive policies such as feed-in tariffs and government subsidies. In Italy, for example, this massive increase led to the country becoming one of the top five contributors to global installed PV capacity in 2016, when it accounted for over 70% of installed solar capacity globally, sharing the lead with Germany, China, and Japan [32].

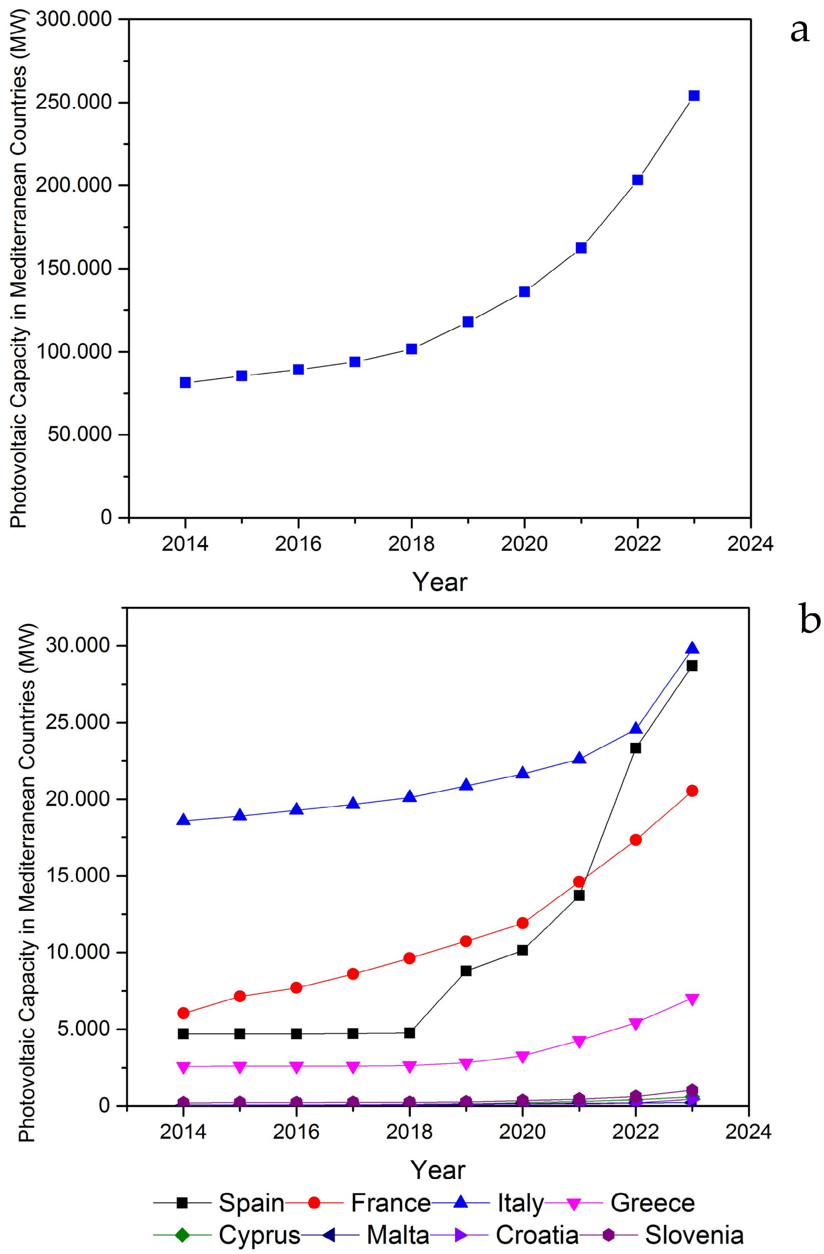

Figure 2. (**a**) Total photovoltaic capacity installed in EU and (**b**) total photovoltaic capacity installed in Mediterranean countries.

The efficiency of crystalline silicon modules installed in this region also varies considerably due to differences in solar radiation and ambient temperature. According to a study on the geographical variation in PV module efficiency, the Mediterranean region experiences a reduction of between 3% and 13% in annual module yield compared with standard test conditions, due to high average temperatures and intense solar radiation [33].

Monocrystalline photovoltaic modules have been and remain the most widely used type in solar installations due to their efficiency and long-term stability. This historical dominance in the European solar market, particularly during 2007 and 2008, has supported their large-scale adoption over other technologies and justifies the focus on their recycling, given their significant presence in the current photovoltaic landscape [34,35].

Furthermore, it is estimated that in 2009 alone, installed PV capacity in Europe reached an additional 7.2 GW, contributing to the global total of 22 GW. This growth was motivated by countries such as Spain and Italy, where generous incentive policies were implemented, helping to consolidate a large-scale PV installation base [36]. Despite their high solar potential, Mediterranean countries have not fully exploited their resources compared with less sunny nations, such as Germany, and this has led many researchers to propose the implementation of more effective policies to boost the harnessing of solar energy in these regions [37].

In terms of installed capacity, countries such as Spain are expected to manage more than 700,000 tons of photovoltaic waste by 2050, mainly from modules installed during 2007–2008. Since most monocrystalline silicon modules installed in the Mediterranean region have an estimated lifespan of 25 to 30 years, it is predicted that by 2030, there will be a considerable volume of modules that will need to be replaced and recycled [4,38].

Huge amounts of photovoltaic waste will require a robust approach to waste management and for this reason, recycling PV modules at the end of their useful life is going to be crucial to ensure the long-term sustainability of solar energy. This process is essential not only to avoid the accumulation of waste, but also to recover valuable materials such as silicon, glass, and precious metals, thus reducing the need to extract new raw materials [39].

The need to recycle rather than simply replace modules stems from the fact that without recycling, this PV waste could create a serious environmental problem. Accumulation in landfills not only involves the loss of valuable resources, but also the release of pollutants. Studies have shown that recycling PV modules can significantly reduce greenhouse gas emissions and other pollutants, contributing to the transition towards a circular economy in the Mediterranean region [40]. In the European context, regulations such as the WEEE Directive are expected to further boost recycling, setting clear targets for material recovery [32]. The PV industry must focus on creating and optimizing recycling systems to close the life cycle of these modules in a sustainable way [41].

1.2. Estimating the Useful Life of Facilities and Their Replacement Rate

The lifetime of PV modules has traditionally been estimated at 25 years, based on performance guarantees that ensure 80% of nominal power after that period. However, recent studies suggest that factors such as weather conditions, technological improvements, and economic decisions can influence the actual lifetime, accelerating module replacement [42]. As an example, the study by Lillo-Sánchez et al. [43] revealed significant power degradation, averaging 30.9% over 22 years, mainly due to defects such as discoloration, oxidation, and encapsulant delamination. The results were compared with similar studies to highlight the influence of prolonged exposure on the efficiency of photovoltaic systems. The work of Tan et al. [44] carried out in Australia indicates that in practice, the lifetime of modules can be between 15 and 20 years, due to these external factors, which underlines the need to adequately plan for waste management as installations reach their end of life.

The degradation of PV modules also plays a crucial role in determining their lifespan. In Europe, the performance of PV systems has been widely analyzed including in the studies by Golive et al. [45] and Linding et al. [46], finding annual degradation rates of between 0.74% and 0.86% from the collected data from over 8400 installed systems. These degradation levels mean that many systems may continue to operate beyond the 25 years expected, potentially delaying their replacement rates into the coming decades.

Deng et al. [6] consider performance degradation as one of the most critical factors for the removal of photovoltaic modules. When efficiency loss reaches between 70% and 80% of the original capacity, dismantling the system is considered. Maintenance becomes unfeasible, leading to the removal of the modules. Another important factor is physical damage and wear of the modules, which necessitates thorough evaluation. Electroluminescence, visual inspection, and infrared thermography are employed to detect faults, hot spots, cracks, delaminations, etc., facilitating module assessment [45]. Sica et al. [47] argue that these physical aspects not only impact efficiency but also pose safety risks, making them an additional key factor for module removal. Lillo-Sánchez et al. [43] demonstrated that combining electroluminescence tests with power loss analysis can provide an accurate assessment of when a module should be removed and processed for recycling.

The presence of loose connections or potential cable damage, which can compromise safety, is another factor that must be considered for the removal of modules [48]. New technologies provide substantial improvements in efficiency, which justifies the early removal of modules. This occurs because investment becomes favorable to optimize energy production and reduce operational costs [49].

From an economic perspective, Ravikumar et al. [50] argue that when cost–benefit analysis shows that maintenance costs exceed the benefits obtained, removing the modules becomes a reasonable option. According to Chowdhury et al. [51] circular economy policies can influence module removal decisions. The need to recover certain materials, such as silicon and precious metals, drives the early removal of modules [52].

The cost of critical components such as power converters and batteries is an aspect to consider in relation to the lifespan and replacement of PV installations. In residential installations with energy storage, it has been shown that the need to replace these components multiple times during the system's lifetime can reduce the profitability of the project. Therefore, it is essential to include a detailed analysis of the duration of these components in the economic evaluation of PV systems [53].

Extending the lifetime of photovoltaic modules has been identified as a key strategy to reduce both costs and environmental impact. The analysis by Peters et al. [54] suggested that increasing of the lifespan of modules from 30 to 50 years could reduce the demand for virgin materials by 3% and avoid the replacement of 62% of installed modules by 2050, which would contribute significantly to the circular economy.

The replacement rate of modules installed during 2007–2008 will be critical in the coming years, with large volumes of PV waste expected to reach end of life by 2030 and 2050 [55].

1.3. Importance of Recycling

The issue of recycling PV modules is directly linked to the exponential growth in the installation of these systems, determined by international commitments such as the Paris Agreement. The growth of solar energy has been significant, especially over the past decade, with an increase of more than 90% in global installed capacity between 2010 and 2020. This has raised concerns about the management of PV module waste, which is expected to reach between 1.7 and 8 million tons by 2030 and between 60 and 78 million tons by 2050 [56]. The massive growth in installations, especially in regions such as Europe and Asia, has generated the significant challenges, environmental and economic, of managing the waste derived from modules at the end of their useful life. Most of this growth in installations and waste is expected to occur in the next two decades, emphasizing the urgent need to improve recycling technologies for these modules to prevent them from ending up in landfills and to maximize the recovery of valuable materials [40,57].

Recycling of PV modules is not only essential for managing e-waste but also plays a crucial role in recovering critical raw materials such as silicon, aluminum, and precious metals. These materials can then be reused in the production of new modules or in other industries, reducing the dependence on resources and contributing to long-term sustainability in the context of the circular economy [47].

The purpose of this review was to consolidate existing knowledge on the recycling of PV installations in the Mediterranean, highlighting the importance of effective waste management strategies as the solar energy sector continues to expand. With the Mediterranean's substantial solar energy potential, this review emphasizes the need for robust recycling processes to ensure that the environmental benefits of solar energy are not compromised by the inappropriate disposal of decommissioned PV modules.

One of the primary differentiators of this review lies in its regional focus on the Mediterranean, a specificity often overlooked in broader studies on photovoltaic (PV) module recycling. While most reviews have addressed PV recycling within a general European or global context, they have not accounted for the unique environmental and infrastructural factors affecting the Mediterranean, where high solar irradiance, elevated temperatures, and regulatory variability present particular challenges for waste management. For instance, the review by Lunardi et al. (2018) provides a comprehensive survey of global PV recycling techniques but does not address regional adjustments necessary for effectiveness under Mediterranean conditions [58]. By contextualizing recommendations to suit Mediterranean infrastructure and regulatory frameworks, this review offers tailored insights that can enhance regional policy effectiveness and industry implementation, serving as a valuable localized resource for policymakers and industry stakeholders.

A further distinguishing aspect of this review is its exhaustive analysis of technical processes used in PV module recycling. Unlike previous studies that have focused narrowly on specific techniques, this review provides a comparative evaluation of physical, chemical, and thermal methods, each assessed for their effectiveness in reclaiming valuable materials like silicon and silver. The work of Isherwood (2022), for example, emphasizes crushing techniques but does not offer a comprehensive, side-by-side analysis of alternative methods [59]. Similarly, Dias et al. (2017) focus on pyrolysis without integrating this method into a broader comparison framework [60]. This review's holistic approach provides industry practitioners with a clearer, more strategic view of each method's viability under Mediterranean conditions, enabling the selection of recycling processes that are both effective and adaptable to local environmental and infrastructural constraints.

In addressing regulatory gaps and infrastructural needs, this review uniquely explores the differential implementation of the Waste Electrical and Electronic Equipment (WEEE) Directive across Mediterranean countries and its impact on PV recycling outcomes. Many existing studies, such as that by Savvilotidou et al. (2017), briefly mention regulatory challenges but lack in-depth analysis of how these disparities influence recycling efficacy across regions [61]. This review addresses this gap by providing an examination of the Mediterranean's specific regulatory landscape, identifying weaknesses in enforcement and infrastructure that hinder recycling efforts. Furthermore, we propose actionable recommendations to bolster local regulatory frameworks, enhancing the region's alignment with broader European objectives. This localized regulatory insight extends beyond the general observations found in the previous literature, offering concrete steps to improve recycling efficacy through policy adaptation.

Lastly, this review's approach to economic and sustainability considerations provides a regionally grounded perspective that broadens the understanding of PV recycling's financial feasibility within the Mediterranean context. While general studies on the economic viability of PV recycling, such as those by Choi and Fthenakis (2010) and Walzberg et al. (2021), offer valuable insights into recycling costs and benefits, they do so without regard to the unique financial pressures faced by the Mediterranean region [62,63]. This review addresses critical factors, such as high transportation costs and the limited local market for recycled materials, that uniquely affect the region. By analyzing these factors in the context of circular economy principles, we offer a tailored economic framework that clarifies the financial viability of recycling in this region and suggests pathways to improve profitability. This perspective complements the existing literature by equipping local decision makers with the knowledge needed to balance economic constraints with environmental sustainability goals.

In this context, the objective of this review was to explore the challenges and opportunities associated with the recycling of photovoltaic (PV) installations in the Mediterranean region. It aims to provide a comprehensive analysis of the technical, economic, and regulatory barriers affecting PV module recycling processes, focusing on their end-of-life (EoL) management.

2. Materials and Methods

This review was carried out with a semi-systematic approach by applying structured criteria for the selection of studies. The semi-systematic literature review combines elements of a systematic review with a narrative review, using a focused methodology [64].

In this work, information on technical, economic, and regulatory barriers, as well as opportunities for improvement, was analyzed, reviewing the challenges and opportunities related to the recycling of photovoltaic installations in the Mediterranean region.

To conduct a semi-systematic review, the steps of a systematic review including research questions, literature search, selection, study evolution, and data extraction were adapted [64].

2.1. Search Strategy

Planning was carried out at the beginning of the search following several steps: (1) defining the questions that the review aimed to answer, known as research questions; (2) specifying the keywords for conducting the search; (3) determining the sources used to retrieve scientific documents; (4) describing the quality assessment criteria.

2.2. Research Questions

What is the current state of technology regarding the recycling of photovoltaic modules?
What types of technologies are used for the recycling of modules?
What quantity of modules is being recycled?
What capacity do the infrastructures for photovoltaic modules have?
What future projects are being undertaken in the Mediterranean region?

2.3. Databases and Selection Criteria

Database searches were conducted in academic databases including Scopus, Web of Science, and Google Scholar, to ensure coverage of both scientific and policy-related literature.

Keywords used included "recycling of photovoltaic panels", "Mediterranean PV waste management", "challenges in PV recycling", and "circular economy solar energy".

The review focused on studies published between 2013 and 2024, covering a decade of recent advancements in the field.

For the selection of articles, keywords, titles, and abstracts were considered. In this way, only articles that met the inclusion criteria proceeded to the review phase (Figure 3).

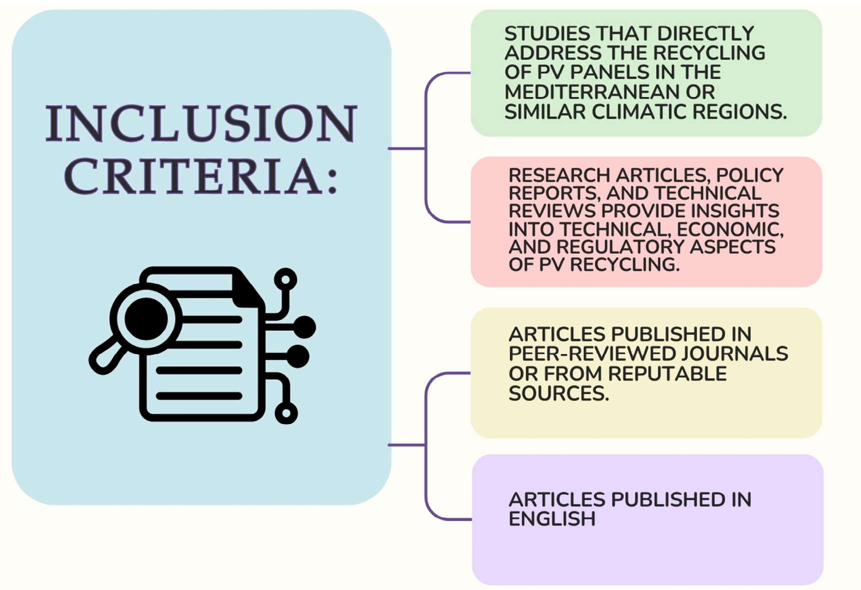

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Figure 3. *Cont.*

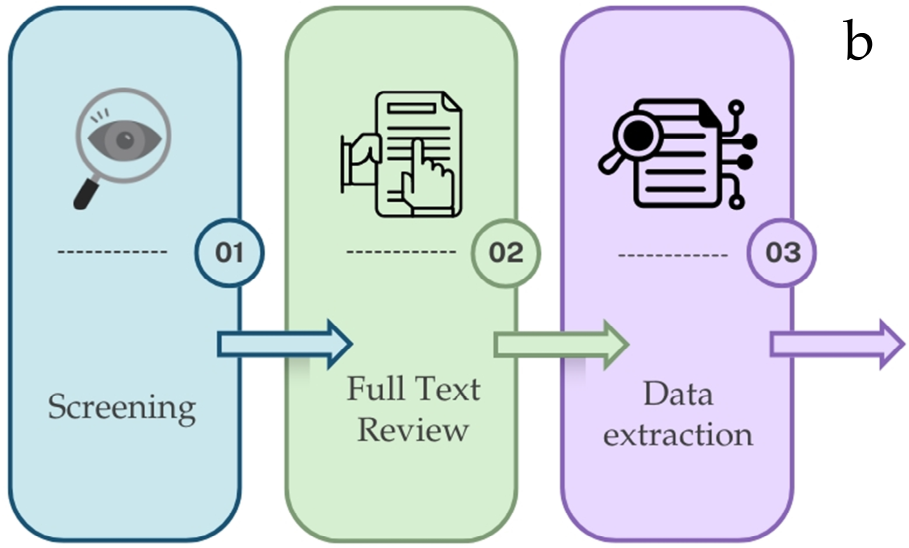

Figure 3. (**a**) Inclusion ariteria for the selection; (**b**) study selection process.

2.4. Study Selection Process

The selection study included the following stages:

Stage 1: Screening: Titles and abstracts were screened for relevance based on the inclusion and exclusion criteria;

Stage 2: Full-Text Review: Articles passing the initial screening were reviewed in full to ensure alignment with the review's objectives;

Stage 3: Data Extraction: Key data points extracted from the studies included types of recycling technologies, challenges faced, policy frameworks, and opportunities identified (see Figure 3).

Once the selection phase was completed, the articles were read in their entirety, and those that did not clearly address the following questions were excluded:

QC1: Are the research objectives clear?

QC2: Does the article present a well-founded research study, or is it merely a report based on expert opinions?

QC3: Does the study provide value for research or its practical application?

QC4: Was data collection conducted in a way that adequately addressed the research problem?

QC5: Was the research designed to effectively meet its objectives?

QC6: Is there a context explaining why the research was conducted?

QC7: Are future lines of work proposed for continuing the recycling of modules?

This checklist is an adaptation of the quality criteria analyzed by [65].

To extend this methodology to regions outside Mediterranean Europe, adjustments should include defining the context of the study to reflect local environmental, political, and market conditions, conducting a focused literature review to capture region-specific practices, assessing recycling technologies to determine their feasibility in the local context, identifying unique regional challenges and opportunities, and adapting the methodology to address the specific needs of the new area. This approach will ensure the flexibility and relevance of the methodology in diverse environmental, economic, and social contexts. Figure 4 illustrates these regional adaptations and contextual considerations.

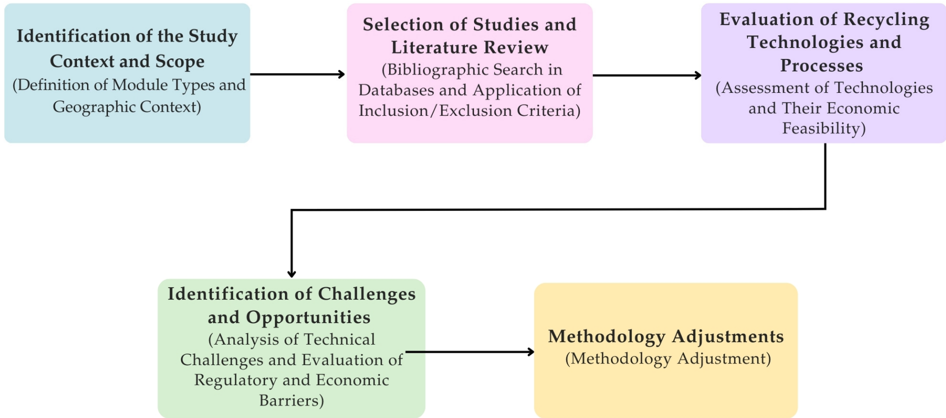

Figure 4. Research methodology flowchart.

2.5. Bibliometric Analysis

In this work, a bibliometric analysis was conducted using VOSviewer 1.6.20, creating a co-occurrence map of the keywords from the articles used for the manuscript.

Bibliometric analysis provides valuable insights for decision making, guiding institutions in research strategies and funding. Using quantitative indicators like publication and citation counts, it offers an objective overview of a field's evolution and current state. Its main objectives include assessing the impact of publications, identifying emerging trends, visualizing collaboration networks, and determining research gaps [66].

For this case, the references were analyzed in BibTeX format; the files were uploaded to the software to generate a map based on bibliographic data. The method used was fractional counting, as it is more accurate than full counting. A minimum of two keyword occurrences was set to obtain a representative sample of the words. This yielded 59 keywords, of which 20 were discarded for being prepositions, simple words that referred to the same concept in more complex terms, or those that were not relevant to the search.

3. Results

A narrative synthesis approach was used to organize and summarize the data, focusing on recurring themes such as technical difficulties, economic barriers, and regulatory gaps.

Qualitative coding was applied to categorize information into three primary themes: technical challenges, economic issues, and regulatory barriers, with additional categories for emerging opportunities and innovations.

In the following, Figure 5 details the number of articles reviewed from each database used, along with the quantity of papers that were considered of acceptable quality for the review.

A total of 415 articles were initially gathered from Scopus, Web of Science, and Google Scholar. Following a full-text review of 152 of these articles, ten additional relevant studies were identified and incorporated. Ultimately, 97 articles were selected as meeting the specific criteria for inclusion in this research.

The result of the bibliometric analysis is shown in Figure 6; the nodes represent key terms and the colors indicate the grouping of these terms into different thematic clusters, which can be interpreted as areas of interest within photovoltaic recycling research. The lines connecting the nodes represent the frequency with which terms co-appeared in the same documents, allowing the identification of relationships between topics and subtopics.

In the center of the map (Figure 6), the term "recycling" is the largest node and is shown in blue. This is because recycling was the central theme of the analyzed documents and frequently appeared in combination with other terms, although the use of fractional counting ensured that its size did not disproportionately overshadow other terms. Surrounding "recycling" are terms related to recycling process treatments, such as "chemical treatment" and "pyrolysis". These connections reflect specific methods investigated for treating photovoltaic modules at the end of their life cycle, indicating that the literature focuses on studying technical processes for material recovery.

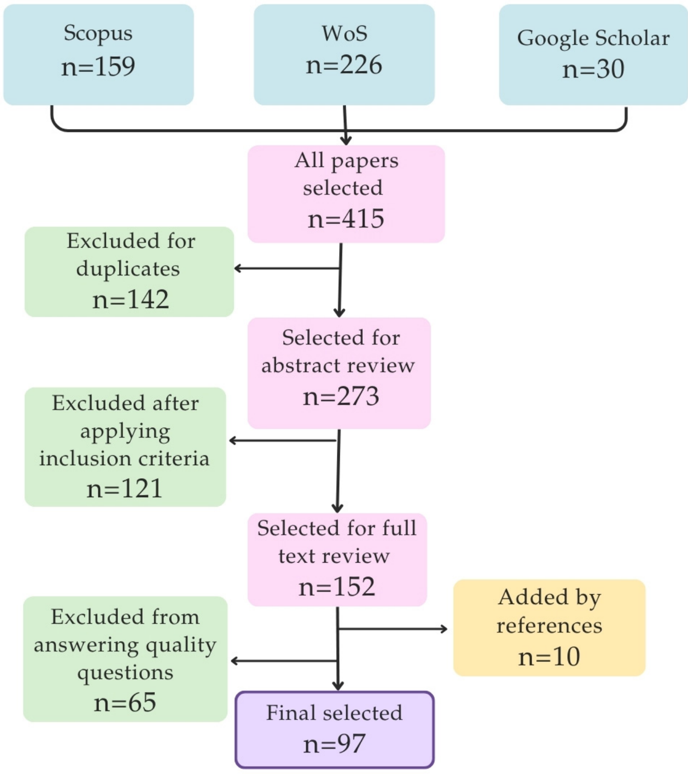

Figure 5. Number of articles reviewed from each database.

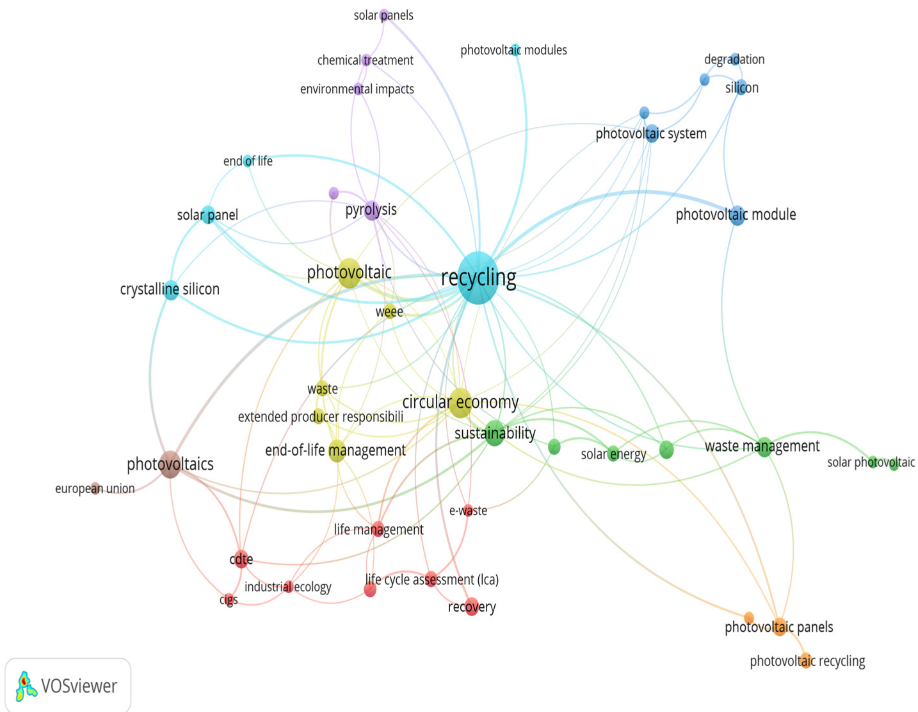

Figure 6. Results of bibliometric analysis (VOSviewer 1.6.20).

Another important cluster consists of terms associated with "circular economy" and "photovoltaic", both in yellow. The circular economy is a key concept connected to terms such as "end-of-life management", "waste electrical and electronic equipment (WEEE)", and "sustainable development". These connections suggest that a significant portion of the research focuses on the sustainability of photovoltaic module recycling and on how these modules can be managed to minimize environmental impact.

In the green area, there is another cluster centered on the term "sustainability", close to "circular economy". This group includes key concepts related to the sustainability of photovoltaic recycling and the circular economy and connects with other terms like "end-of-life" and "waste". These connections suggest that a significant part of the research has focused on sustainable practices for recycling photovoltaic modules and on how these processes can contribute to a circular economy that minimizes waste and environmental impact.

A light blue cluster includes terms related to the materials used in photovoltaic modules, such as "crystalline silicon" and "solar panel". This group suggests that there has been a focus on the study of specific materials that make up photovoltaic modules, as they present challenges for recycling and recovery. The presence of these terms indicates that the recycling of materials, such as crystalline silicon, is an important aspect of studying sustainability and waste management in the photovoltaic industry.

The cluster in red is associated with terms like "photovoltaics", "end-of-life management", and "industrial ecology". This group is related to the industrial aspects and lifecycle management of photovoltaic modules, suggesting that the research has also addressed how to manage modules from perspectives of industrial ecology and extended producer responsibility, with the aim of reducing environmental impacts at the end of product life.

The resulting semi-systematic review continues as follows.

3.1. Recycling Techniques

Monocrystalline photovoltaic modules have consistently been the most widely used in solar installations, largely due to their superior efficiency and long-term reliability. Their strong presence in the European solar market, especially in 2007 and 2008, has promoted their large-scale adoption over alternative technologies. This widespread use underscores the importance of focusing on their recycling, given their substantial role in the actual photovoltaic landscape [33,34].

Recycling of silicon PV modules involves a combination of physical techniques including mechanical processes such as crushing and separation, heat treatments to remove polymer layers, and chemical processes to dissolve certain components, facilitate material recovery, and retrieve important components such as glass, silicon, and valuable metals (see Figure 7). However, these techniques face economic and environmental challenges due to high cost and the generation of hazardous by-products and are continually being optimized to increase recovery rates and improve the economic viability of recycling [67].

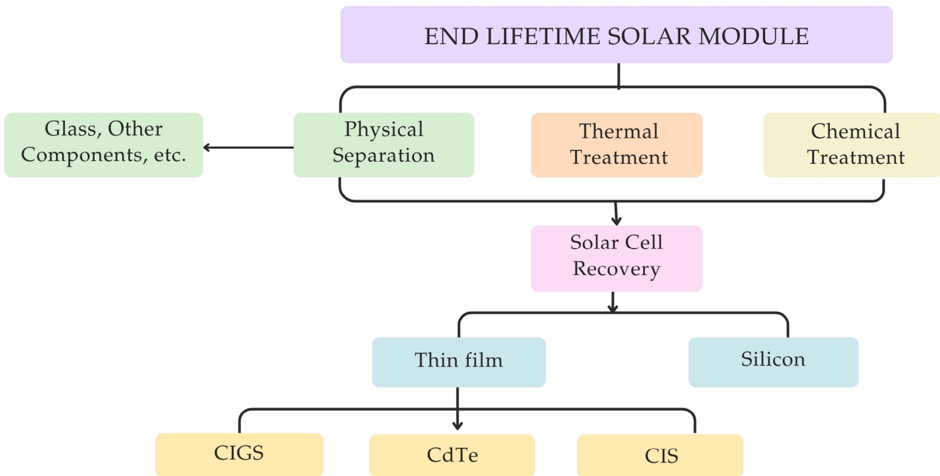

Figure 7. Different types of solar PV recycling processes.

Module disassembly, ethylene-vinyl acetate (EVA) delamination, and recovery of valuable materials such as glass, silicon, and metals are the key stages in crystalline silicon module recycling processes. The goal is to develop more economical and environmentally friendly technologies that will improve the competitiveness of recycled materials [68] (Figure 8).

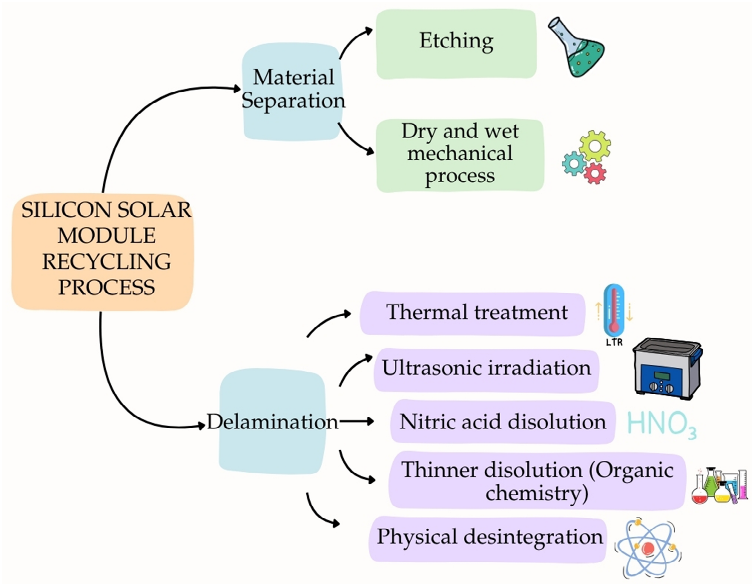

Figure 8. Silicon module recycling processes (adapted from [51]).

The main processes are described as follows.

3.1.1. Physical Processes

Physical recycling involves dismantling PV modules and separating materials such as aluminum frames, glass, and silicon wafers. In the physical process, PV modules are crushed to separate valuable materials such as glass and metals. This process can be followed by heat treatment to remove polymeric residues, allowing the recovery of clean glass in large quantities [63,69].

Physical mechanical separation processes used in recycling crystalline silicon (c-Si) photovoltaic modules include crushing the modules in different stages to separate the glass, aluminum, and solar cells. These processes are often combined with additional methods to maximize material recovery. High-voltage crushing is one of the most promising methods, allowing efficient separation of components without excessive damage, facilitating subsequent sorting and recycling [70]. Shredding facilitates the separation of materials such as glass and metals from solar cells. The combination with abrasion and laser cutting techniques, has proven effective in recovering materials such as glass and copper. New technologies such as laser-assisted methods are improving the efficiency of physical processes [71]. Furthermore, this type of process is considered essential in the first stage of recycling [68,72].

The recycling of kerf loss Si, is necessary to reduce waste, increase the value of the products, and make the process economically feasible. Kerf refers to the silicon waste produced during the wafer slicing process and is generated during silicon wafer cutting. This waste can be recycled by physical techniques involving filtration of the kerf sludge and conversion into dry pellets before being melted in an induction furnace. This process significantly reduces greenhouse gas emissions and energy consumption compared with primary silicon production [73].

The use of mechanical processes such as grinding enables the separation of basic components such as glass and metals, while thermal and chemical methods are necessary to delaminate and separate more complex layers such as encapsulants and backing materials containing fluoride polymers. However, each technique presents challenges in terms of cost, environmental impact, and efficiency. Mechanical separation can be difficult due to the complexity of the modules, while thermal methods can generate toxic emissions, and chemicals can produce secondary waste that must be managed properly [72].

Camargo et al. [74] applied a mechanical pretreatment to improve the recycling process to separate the silver, using a rotary micro-grinding tool to remove 10.32% of the polymer mass, primarily from the upper layer, complemented by thermal treatment and allowing the extraction of silver, glass, and a quantity of silicon during the process.

The work of Isherwood [59] proposed module recycling through crushing and mechanical separation. In crushing, the module is broken down, physically separating the bulkier materials. Thanks to the crushing, glass and some silicon fractions can be recovered. Silicon wafers can then be separated manually or automatically for recovery. To recover other materials, such as EVA, thermal treatments must be carried out.

On the other hand, for the separation of thin-film modules, Berger et al. [75], presented two strategies for recycling modules, based on mechanical methods and thermal combinations. First, a wet mechanical process was carried out on broken modules to separate components such as glass and semiconductors (indium and tellurium) using washing, sieving, and sedimentation techniques.

The EU recycling system uses physical processes such as shredding and optical sorting to separate glass and other materials from PV modules. While these methods are highly efficient for materials such as glass, they have limitations for the recovery of high-purity silicon [76].

3.1.2. Chemical Processes

Chemical processes are essential to separate valuable materials from photovoltaic modules, particularly in the case of components encapsulated in polymers, such as ethylene-vinyl acetate (EVA). The use of organic solvents has proven effective for delaminating encapsulation layers without damaging the solar cells. Solvent combinations such as toluene at 60 °C can be used to remove the encapsulation layers [77]. Chemical delamination methods have evolved significantly to enable the separation of encapsulants such as EVA by using more benign acids and organic solvents. These techniques not only improve process efficiency but also reduce recycling costs and associated pollutant emissions. This approach is particularly promising in regions such as Europe, where volumes of PV modules reaching end-of-life are rapidly increasing due to the implementation of renewable energy policies [78].

On the other hand, acids such as nitric (HNO_3) and hydrofluoric (HF) are also frequently used for chemical etching, allowing the removal of metallic coatings and the recovery of high-purity silicon wafers, with a recovery efficiency reaching up to 86% in recent studies [79].

The use of aqueous potassium hydroxide (KOH) solutions with a concentration of 30%, at temperatures between 60 and 80 °C, is another effective chemical approach for the removal of metallic coatings on PV modules. Subsequently, acid etching methods, for example, applying a mixture of nitric acid (HNO_3), hydrofluoric acid (HF), acetic acid, and bromine to remove metallic layers, anti-reflective coatings, and p-n junctions from solar cells, can achieve the recovery of high-purity silicon [57]. Despite their effectiveness, these processes have important challenges related to high operating costs and emissions of pollutants generated during chemical etching, which limits economic viability in some contexts [80].

The use of chemical methods such as acid leaching has been widely investigated for the recovery of precious metals and silicon from photovoltaic modules. Nitric acid is commonly used to dissolve metallic components and recover silver, while silicon purification is achieved by use of hydrofluoric acid, removing impurities such as titanium oxide. Recent optimizations in these processes have allowed a recovery efficiency of over 96%, minimizing the use of hazardous reagents and improving the sustainability of recycling methods [68,81].

Chemical stripping processes have been used to remove metallic coatings, diffusion layers, and anti-reflective materials from solar cells, improving recycling efficiency. These methods are often combined with thermal processes to maximize the recovery of valuable materials, such as silicon and precious metals, which can be reused in industrial applications [71,73].

The study by Zhang et al. [82] used a method to dissolve the EVA encapsulant with a solvent (isopropanol) to facilitate the separation of the layers of the photovoltaic module; the advantage of this method is that it is carried out at room temperature, and the solvent used is common and less aggressive than others typically used in recycling. In addition to EVA, glass is also recovered, as well as the plastics found in the module's rear side.

To dissolve impurities and unwanted materials on the surface of the cells, the work of Kang et al. [79] analyzed a chemical etching technique; with this technique, high-purity silicon was isolated. The method involved treating the photovoltaic module with an acidic chemical etching solution that, combined with a surfactant, improves the effectiveness of the process. After this etching, the silicon was processed, achieving recovery rates of 86% with silicon purity of 99.99%.

The investigation by Ko et al. [83] proposed a novel recycling method for photovoltaic modules, using a fluorine-doped tin oxide (FTO) sacrificial layer to separate the front glass from the EVA. Through voltage- and moisture-assisted corrosion, the FTO layer delaminates, allowing easy separation of components. This technique provides a more efficient alternative to traditional physical, chemical, and thermal methods, enhancing PV module recycling processes.

In the study by Savvilotidou et al. [61], the primary goal was to dissolve EVA and other materials from photovoltaic modules using mild sulfuric and lactic acid treatments. Once EVA was dissolved, key structural materials, including glass, silver collectors, and thin-film cells, were effectively recovered. Additionally, mechanical treatments were applied to further facilitate material recovery.

3.1.3. Thermal Processes

Thermal processes in PV module recycling involve the breakdown of polymers and other organic materials by applying high temperatures, facilitating the recovery of valuable materials such as silicon, copper, and glass. One of the most common methods is pyrolysis, where modules are heated to temperatures of approximately 500 °C, removing more than 99% of the polymers present in the modules [60]. Another method is heating treatment at temperatures above 600 °C, used to delaminate the modules and remove the polymer layers, facilitating the separation of key materials such as glass and solar cells. This process has been shown to be highly efficient, especially when combined with prior removal of the back layer of the module, maximizing the recovery of valuable materials [84].

Two-stage pyrolysis is a particularly promising approach for recycling PV modules, where in the first stage, the back layer is removed low temperature and in the second, at temperatures around 500–600 °C, valuable materials such as glass and silicon are separated without damaging them. This approach has proven to be efficient in recovering high-purity silicon and other components, while minimizing energy costs [57,85].

In recent studies, the use of pyrolysis has allowed the recovery of up to 91% of glass in fragments smaller than 1 mm. This thermal technique has been successfully combined with mechanical processes to optimize efficiency in the separation of valuable materials [86].

Thermal technologies use pyrolysis during the recycling process to effectively remove EVA and separate solar cells from glass [87]. Pyrolysis can be performed in two stages, so that the EVA can completely decompose. This technology, combined with mechanical treatment, is used to recover aluminum frames, previously separated along with connection boxes and cables [57].

In the work of Dias et al. [88] pyrolysis was used for EVA separation. The process was capable of removing 99% of the material, leaving inorganic materials for recovery and separating the silicon, which was released once the encapsulant had been removed and recovered without damage.

Different studies of EVA separation have been conducted using lower temperatures (between 167 °C and 260 °C) to separate glass and silicon once the EVA is removed, without oxidation of these components [89,90]. Another technique uses mechanical and thermal processes to recycle the silicon kerf generated during the silicon wafer cutting process. This material is collected and dried using natural gas before being melted in an induction furnace without the use of fossil reductants. This process not only reduces greenhouse gas emissions but also involves significant energy savings compared with primary metallurgical silicon production, with energy consumption reduced by up to 50% [73].

For copper–indium–gallium–selenide solar cell (CIGS) modules, pyrolysis can be used to decompose the polymers of the encapsulant. This treatment is carried out at high temperatures (600°C) in an argon gas atmosphere with a flow rate of 200 mL/min, enabling the removal of the EVA encapsulant. With this treatment, polymers are separated and there is no chemical oxidation affecting the metal components [91].

Despite their effectiveness, thermal processes also present significant challenges. Intensive energy use and emissions of toxic gases such as hydrogen fluoride (HF) raise environmental concerns. However, more advanced technologies such as controlled smelting make it possible to mitigate these effects by removing impurities and optimizing the purification of recycled silicon without the use of fossil reductants [73].

Thermal recycling has also been applied to processes such as silicon kerf pyrolysis, where high-purity metallurgical silicon (MG-Si) is recovered from waste generated in solar cell production. This approach, in addition to being energy efficient, significantly reduces the carbon footprint associated with the production of new silicon [47].

Photovoltaic modules come in four main types, each with distinct characteristics. Thin-film modules are made of materials like cadmium telluride (CdTe) or copper–indium–gallium–selenide (CIGS), offering flexibility and lightweight properties ideal for installations where weight is a limitation, although they generally have lower efficiency than crystalline silicon. Crystalline silicon (c-Si) modules, which include monocrystalline and polycrystalline types, dominate the market due to their high efficiency and durability. Monocrystalline silicon, made from a single crystal structure, provides higher efficiency, while polycrystalline silicon with multiple crystals is more affordable and produces less waste during manufacturing. Specifically, polycrystalline silicon solar cells are modules that use only polycrystalline silicon, which is slightly less efficient but is cost-effective for large-scale projects. Lastly, CIGS modules are a type of thin-film technology with higher efficiency than CdTe, thanks to their specific elemental composition. CIGS modules are lightweight and flexible, suitable for curved or weight-sensitive surfaces, though they require a more complex manufacturing process. Together, these technologies provide tailored solutions for a range of photovoltaic applications, balancing efficiency, cost, and flexibility. Table 3 summarizes the recycling methods applied to different PV modules.

Table 3. Recycling methods applied to different PV modules.

PV Panel's Type	Method Adopted	Recycled Products	Treatment Technology	Brief Description	References
Thin-film	Wet mechanical processing	Te, In	Mechanical	Vacuum blasting, attrition, and floating processes to recover Te and In.	[75]
c-Si	Mechanical crushing + triple crushing	Glass (85%), silver, silicon	Mechanical	Segregation of materials through two-blade rotor and hammer crushing, reducing mass of fractions undergoing thermal and hydrometallurgical treatment.	[25]
Thin-film	High-voltage pulse crushing (HVC)	Glass (80%), metals	Mechanical	Separation using high-voltage pulses; avoids fine dust generation and minimizes material wastage.	[25]
c-Si	Laser irradiation	Glass, solar, cells, backsheet	Physical	Non–destructive method with laser irradiation (1064 nm, 20 W).	[81]

Table 3. *Cont.*

PV Panel's Type	Method Adopted	Recycled Products	Treatment Technology	Brief Description	References
c-Si	Milled and electrostatic separation	Metals (95%)	Physical	Metal enrichment and separation via milling and electrostatic processes.	[88]
c-Si	High voltage pulse discharge	Copper (95%), silver (96%)	Physical	Energy-efficient separation using high-voltage pulse discharge (160 kV, 300 pulses).	[92]
c-Si	Shredding on knife mill + magnetic separator + heavy– medium separator	Crushed solar cells, glass and metals	Physical	Separation of solar panel materials using shredding, followed by magnetic and density separation methods.	[77]
c-Si	Milling and crushing with electronic separator.	Silicon solar cells and other metals	Physical	Materials are separated using an electrostatic separator after mechanical milling.	[88]
c-Si	High voltage pulse method	Silver, tin, copper, silicon, and aluminium	Physical	PV panel samples are cut into a small pieces, placed in a water-filled reactor, and subjected to 600 J shockwave impulses at a rate of one per second.	[93]
c-Si	High voltage pulse method in two different stages	Glass and solar cells	Physical		[57]
c-Si	High voltage fragmentation method	Copper, silver, aluminium, lead, silicon	Physical		[92]
c-Si	Laser irradiation method	Glass and solar cells	Physical	The EVA layer is recycled by using laser irradiation followed by mechanical peeling.	[81]
Polycrystalline silicon solar modules	Pyrolysis in Lenton tubular furnace	Silicon, glass	Thermal	A Lenton tubular furnace with a quartz tube with an inner diameter of 117 mm and a length of 900 mm was used.	[94]
c-Si	Pyrolysis	EVA	Thermal	Deacetylation and long-chain scission, requiring high energy.	[25]
c-SI	Pyrolysis	EVA, Cu, glass	Thermal	Thermal treatment of c-Si modules at 450 °C decomposes EVA, producing acetic acid and olefins. Copper strips, glass, and cells are separated through sieving post-treatment.	[95]
Polycrystallline silicon solar modules	1st stage: quartz halogen lamp; 2nd stage: 600 °C for 30 min.	Silicon, glass	Thermal	A two-stage thermal process uses a quartz halogen lamp and heat treatment to recover silicon and glass.	[96]
c-Si	Thermal decomposition	Glass, PV cells	Thermal	EVA is completely decomposed at 500 °C in air.	[94]
c-Si	Dielectric loss method	Glass and solar cells	Thermal	Low-temperature heating use alternating magnetic fields to separate glass from EVA.	[26]
c-Si	Organic solvent method	Silicon wafers	Chemical	Organic solvents are used to dissolve EVA.	[77]
c-Si	Supercritical CO_2 technology + organic solvent method	Glass, silicon wafers, metal solder tape, and backsheet	Chemical	Utilization of solvents at atmospheric pressure and supercritical CO_2 for delamination of a PV module.	[97]
c-Si	Organic solvent method	Silicon solar wafers	Chemical		[98]
c-Si	Microwave-enhanced organic solvent method	Silicon solar wafers	Chemical	A microwave-assisted organic solvent process to enhance separation of different layers of PV modules.	[99]
c-Si	Inorganic solvent method; KOH–ethanol, 200 °C in muffle furnace for 3 h	Silicon solar wafers	Chemical		[100]
CIGS photovoltaic modules	Hydrometallurgical	Cu^{2+}, In^{3+}, and Ga^{3+}	Chemical	Different reactions in the presence of a leaching agent lead to the dissolution or precipitation of metals.	[91]
CIGS photovoltaic modules	Electrodeposition	Copper and Indium	Chemical	Electrochemical process of reducing metal ions in an electrolyte, followed by the deposition of metal.	[91]
c-Si	Trichloroethylene + microwave	PV cells	Chemical	Complete separation within 2 h using trichloroethylene and a microwave field at 70 °C.	[99]

Table 3. *Cont.*

PV Panel's Type	Method Adopted	Recycled Products	Treatment Technology	Brief Description	References
c-Si	EDGA + ultrasonic power	PV cells	Chemical	Non-toxic reagent, reducing separation time by 3/4 through ultrasonic power.	[101]
c-Si	Organic solvents (toluene, D-limonene)	PV cells, EVA	Chemical	Immersion with toluene, tetrahydrofuran, or D-limonene, at 90 °C, 1 h.	[102]
c-Si	Batch leaching	Ag, Cu, Pb	Chemical	The method uses various lixiviants (HNO_3, MSA, H_2SO_4-H_2O_2) with a solid–liquid ratio of 1:50.	[95]
c-Si	Metal separation (catalyzed by Pt/AC)	Metals from leachates	Chemical	Pt/AC catalyst used to recover metals from leachates.	[95]

Focusing on the Mediterranean region, treatment information was available for only four countries: France, Italy, Spain, and Greece. While the first three have established infrastructures, Greece is still developing its large-scale recycling systems. However, since 2012, Greece has been adhering to the guidelines of the Waste Electrical and Electronic Equipment (WEEE) Directive [103].

Spain continues to prepare for the significant volume of waste expected by 2050, as it anticipates photovoltaic module waste to reach 100,000 tons between 2020 and 2030. Thus, the development of a national recycling industry is essential. According to the study by Santos and Alonso-García [38], by 2050, Spain will be equipped to recover 75% of the materials needed to manufacture new modules, representing a significant advancement for the country's circular economy. Spain, however, remains at a preliminary stage and lacks large facilities dedicated solely to the recycling of photovoltaic modules, as the collected tonnage has been low compared with other countries. Nevertheless, these quantities have been collected and processed by authorized treatment plants in collaboration with producer responsibility organizations (PROs) [104].

Meanwhile, Italy is developing facilities that facilitate the end-of-life management of modules, including the collection and processing of damaged panels, ensuring the sustainability of the entire module life cycle. Its infrastructures are linked to the WEEE and Legislative Decree No. 49 of 14 March 2014, which incorporated the provisions of this European Directive [105,106].

Italian recycling centers are characterized by their use of techniques for separating glass, polymers, and metals, recovering primarily valuable metals such as silicon, aluminum, and copper. These centers can achieve a high recovery rate (80% of materials) for crystalline silicon modules. However, the recovery rate for cadmium telluride modules is even better. They recover 90% of the glass and 95% of the semiconductor metals, significantly minimizing the environmental impact caused by cadmium release [105]. As an example, the Italian company Compton Industrial has developed a machine that recovers glass by delaminating it using steel tools, progressively recovering the materials from the photovoltaic module [107]. Table 4 shows the main treatments performed in Italian recycling centers.

Table 4. The main treatments performed in Italy (adapted from [99]).

Organization	Pyrolysis	Mechanical Treatment	Chemical Treatment
Eco Recycling (Italy), High-Tech Recycling Centre (Italy), Eco Power, Green Engineering	X	X	X
Sasil, S.p.A. (Italy), Stazione Sperimentale del Vetro (Italy), PV CYCLE (Belgium)	X	X	X
La Mia Energia (Italy), University of Florence, Department of Industrial Engineering (Italy), Leitat Technological Centre (Spain), PV CYCLE (Belgium)		X	

In addition to this, France has also demonstrated significant interest in recycling photovoltaic modules, showing notable progress in waste collection, with 4905 tons gathered in 2019. The company Veolia processed this waste, separating aluminum frames, connection boxes, and cables, and successfully recovering approximately 95% of the materials [104].

3.1.4. Leading Organizations in Photovoltaic Recycling Initiatives

The IEA–PVPS T12–28:2024 report [28] identifies 177 recyclers or recycling equipment manufacturers worldwide. As seen in Figure 9, within the Mediterranean region, Spain has only three recyclers, while France has six and Italy contains seven.

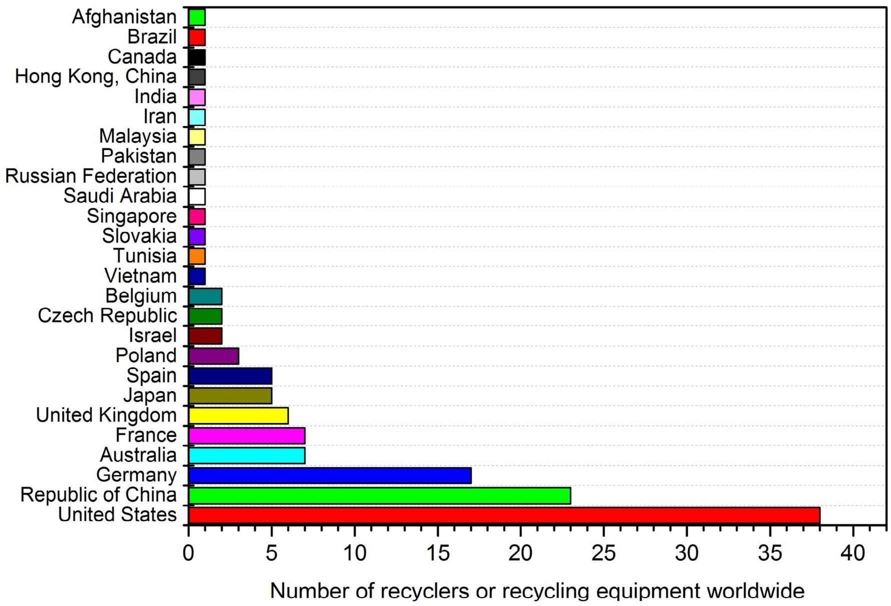

Figure 9. Recyclers or recycling equipment manufacturers worldwide.

Of the 177 recyclers, only 7 participated in the study, with two of them located in the Mediterranean region, as shown in Table 5, below [28].

Table 5. Recyclers included in the PVPS T12–28:2024 study report (adapted from [28]).

Recycler	Country	Technology	Comment
Reiling	Harsewilken, Germany	Mechanical	Commercial, new recycling center under construction.
Flaxres	Dresden, Germany	Light pulse	Pilot, subsequent steps not yet implemented.
LuxChemtech	Freiberg, Germany	Water jet, light pulse, chemical	Pilot, not all subsequent steps implemented yet.
First Solar Inc.	Frankfurt, Germany, Ohio, United States, Ho Chi Minh, Vietnam and Kulim, Malaysia	Mechanical, chemical	Recently upgraded recycling in progress in Germany, V4 under development; contact via First Solar Inc., USA.
ROSI SAS	Seyssins, France	Pyrolysis, mechanical, chemical	Pilot, under construction.
Tialpi	Mottalciata, Italy	Thermal, mechanical, chemical	Pilot plant in Italy handling 1000 tons per year.
NPC	Tokio, Japan	Mechanical, hot knife	Equipment manufacturer.

NPC is not a recycler per se, but it provided data on recycling equipment.

Within the study region, the companies focusing on photovoltaic module recycling were ROSI SAS, founded in 2017 in Grenoble, France, and Tialpi Srl, in the Piedmont region of Italy. Additionally, ROSI SAS operates a combined process with another French company, Envie 2E Aquitane [28].

The first company, ROSI SAS, focuses on silicon recovery, although it offers other recycling solutions. In this way, it adds value to photovoltaic industry products. They perform batch pyrolysis and a patented process to recover silicon and silver. This company can process any type of crystalline silicon photovoltaic module at the end of its life or those that have been separated [108].

The treatment process is carried out in several steps. Once the frame, junction box, and cables have been removed, the polymers undergo pyrolysis. A post-burner treats the gas from combustion, ensuring complete combustion occurs. The treated gases are then routed to a wet scrubbing system, where contaminants are removed, including acidic gases like hydrogen fluoride (HF) due to the presence of fluorine in the backsheet. Pyrolysis of the polymers allows efficient access to high-purity recoverable materials, such as glass, metals, and fragments of photovoltaic cells. The process produces high-quality, impurity-free glass. Copper interconnectors and fragments of photovoltaic cells are segregated using conventional mechanical separation techniques, such as screening and density classification. Additionally, ROSI has developed a specialized process for recovering the silver fingers and pads from broken cells, using a gentle chemical etching process, the details of which remain confidential [28].

ROSI SAS works with the company Envie 2E Aquitane, near Bordeaux. In October 2022, they launched a photovoltaic module recycling line, providing collection services for the company Soren. The modules they handle must be crystalline silicon with a single intact glass panel. Those with broken glass are sent directly to ROSI [109].

The Envie company processes 3000 tons of modules annually using equipment from Japan (NCP). Three classifications are made within the company, based on the condition of the modules. Those ready for reuse are distributed (approximately 5% of the modules). The second classification includes modules with intact glass and moderate deformation. The junction box, cables, and frames are removed from these modules using the NCP technique. The front glass is cut using hot knife technology. The module's laminate, which contains copper interconnectors and solar cells, is packaged and transported by truck to ROSI (approximately 15% of the module's total weight). The remaining products are sent to specialized recyclers for processing. Once the modules arrive at ROSI, they undergo the same treatment as described above [28].

Finally, the company Tialpi Srl, located in Piedmont, Italy, operates a pilot plant with a capacity of 300 tons per year, functioning continuously to produce high-quality glass with a waste size of 2 mm to 10 mm (60%). Aluminum recovery reaches 15%, while silicon, copper, and silver recovery are only 7%, through a process of acidic leaching and electrolysis that achieves 99% silicon purity. The recovery of these latter elements is still under development [110].

Table 6 summarizes the treatment capacity of each company and the recovery rates they achieve [28].

The nonprofit organization Soren (PV Cycle), headquartered in Brussels with operations in Italy and France, spearheaded photovoltaic waste management through Europe's first established recycling program. In 2016, Soren achieved a 96% recycling rate for crystalline silicon photovoltaic modules, surpassing current WEEE standards. This milestone underscores their commitment to advancing sustainable photovoltaic waste solutions across Europe. The activity begins with the removal of the module's junction box, cables, and frame. Next, the module undergoes a mechanical crushing process, after which is the materials are classified and separated. This separation allows the materials to be sent for other specific recycling processes [64].

Additionally, according to the IEA–PVPS T12–28:2024 report [28], a total of 456 related patents have been registered globally, with approximately 80% focused on c-Si modules and around 6% on CdTe modules. For c-Si module recycling, most patents involve mechanical methods, followed by combined methods. In the Mediterranean, four patents have been developed: three in Italy and one in France, as detailed in Table 7.

Table 6. The treatment capacity of each company and the recovery rates they achieve (adapted from [28]).

	ROSI	Envie and ROSI	Tialpi
Capacity (tons/year)	3000	3000	3000
Module	c-Si	c-Si	c-Si
% Recovery	90.6	91.3	100
% Cables	0.85	0.89	1
% Frame	7.79	7.79	15
% Junction boxes	4.3	4.3	1
% Ferrous metals	0	0	0
% Non-ferrous metals	0.87	4.27	0
% Polymers/sheets	0	0	14
% Glass waste	71.4	72.1	65
% Ground glass mix, sheets, and metals	3.4	0	3
% Dust	0	0	0
% Other	2	2	1
Recover Silicon	Yes	-	Yes
Recover Silver	Yes	Yes	Yes

Table 7. Patents developed in Mediterranean countries (adapted from [28]).

Patent Name	Country	Date	User
Method for fabricating a composite structure to be separated by exfoliation	France	18 July 2012	Figuet Christophe, Gourdel Christophe, Soitec Silicon on Insulator
A method and machine to assist recycling of photovoltaic panels	Italy	11 October 2012	Compton S.R.L and Pasin Andrea
Process for treating spent photovoltaic panels	Italy	9 May 2014	Eco Recycling S.R.L.
Method and apparatus for detaching glass from a mono- or polycrystalline silicon photovoltaic panel	Italy	16 September 2015	Sasil S.p.A.
Method and plant for recycling photovoltaic panels	Italy	31 October 2018	University of Padua

In this line, the European Union has for several years been funding projects for the recycling of photovoltaic modules. As the IEA–PVPS T12–28:2024 report describes [28], numerous companies and organizations have actively participated, completing several initiatives. The Mediterranean region has been involved in two significant projects on this topic.

The LIFE12 ENV/IT/000904 project [111] was funded by the European Union's Life program. Its main objective was to develop innovative technology to recover materials from photovoltaic modules at the end of their useful life. To achieve this, a combination of chemical and mechanical treatments was used, which, in addition to recovering glass and metals, reduced the environmental impact generated by photovoltaic waste.

This project managed to design and build a pilot plant that processed unused photovoltaic modules and separated their components. Glass, which represented 80% of the panel's weight, was recovered in high quality. The same occurred with silicon and silver, both recovered with high purity levels. For this, the modules were dismantled with mechanical technology, separating their main components. Next, a thermal and chemical treatment was conducted to recover the glass and metals without affecting quality, and finally, refinement technologies were used to repurpose the materials into new products or for other industries.

The developed process consisted of several stages to dismantle and recover the different components of photovoltaic modules (see Figure 10).

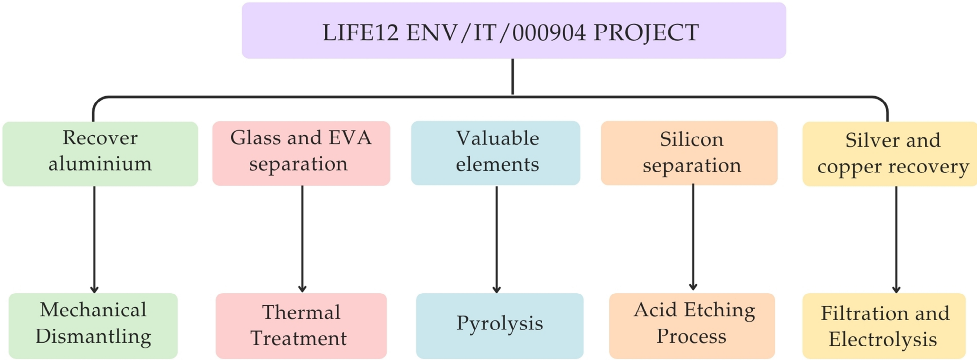

Figure 10. Processes at LIFE12 ENV/IT/000904 project.

The project concluded in 2016, with the Italian company Sasil S.p.A. coordinating the entire process [111].

Another key project, Photolife (LIFE+ 2023) [112], concluded in August 2015, was funded by the European Union's LIFE+ program to advance recycling through specialized treatment methods. To achieve this, a pilot plant with an annual processing capacity of 200 tons was established, managed by Eco-Recycling, a spin-off of the Inter-University Research Centre of Rome.

Figure 11 shows the several project stages designed to maximize the recovery of materials from modules at the end of their life.

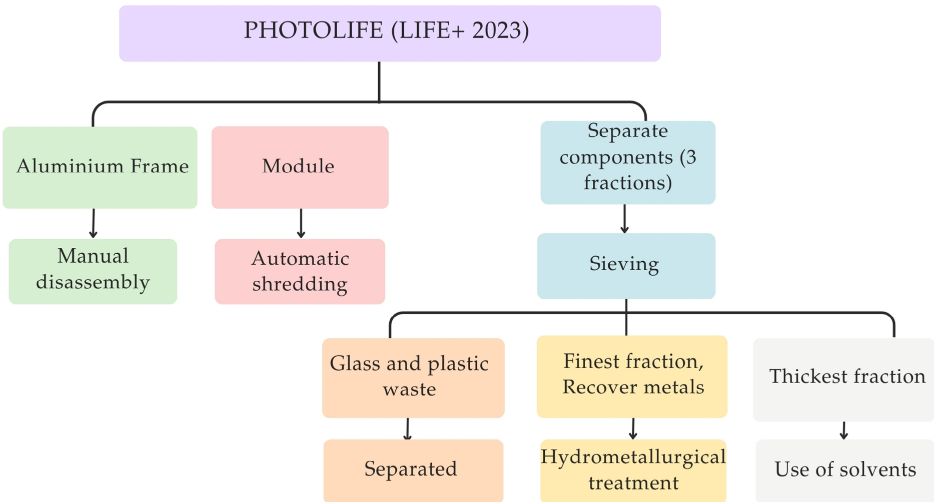

Figure 11. Stages of the Photolife (LIFE+ 2023) project.

Currently, there are several active projects focusing on photovoltaic module recycling, with the Mediterranean region prominently involved in PHOTORAMA, a European project funded by Horizon 2020. Its main goal is to develop new technologies to recover valuable materials like silver, silicon, indium, and gallium once a module has reached the end of its useful life. This project aims to achieve the recycling of both crystalline silicon and inorganic silicon modules. For this, different European Union countries collaborate, led by France, with Spain and Italy also participating [113].

Table 8 presents projects developed in Mediterranean countries to advance photovoltaic waste recycling. The PHOTORAMA project, led by France, aims to recover valuable materials such as silver, silicon, indium, and gallium through a multinational collaborative process, achieving 50% progress in technology development. The ongoing PV4INK project focuses on improving photovoltaic waste management to comply with EU circular economy strategies, optimizing recycling infrastructure and implementing collection systems. Both projects reflect the Mediterranean region's commitment to advancing PV recycling technologies and adhering to European environmental policies [114].

Table 8. Projects developed in Mediterranean countries.

Project	Objectives	Timeline	Technical Details	Expected Results	Progress Metrics
PHOTORAMA	Develop technologies to recover valuable materials (silver, silicon, indium, gallium)	2021–2025	Multi-stage collaborative process with several EU countries, led by France	Increase the recycling rate of crystalline silicon and inorganic modules	50% progress in the development of advanced technologies, multinational collaboration
Spanish Initiative (PV4INK)	Address the challenges of photovoltaic waste management with a projected increase in waste volume	Ongoing	Focused on compliance with EU circular economy strategies and improving recycling infrastructure	Optimize waste management and comply with European environmental policies	Implementation of collection systems, assessment of recycling infrastructure

The project began in 2021 and is expected to conclude in 2025. For recycling, the company follows a multi-stage technological process (Figure 12):

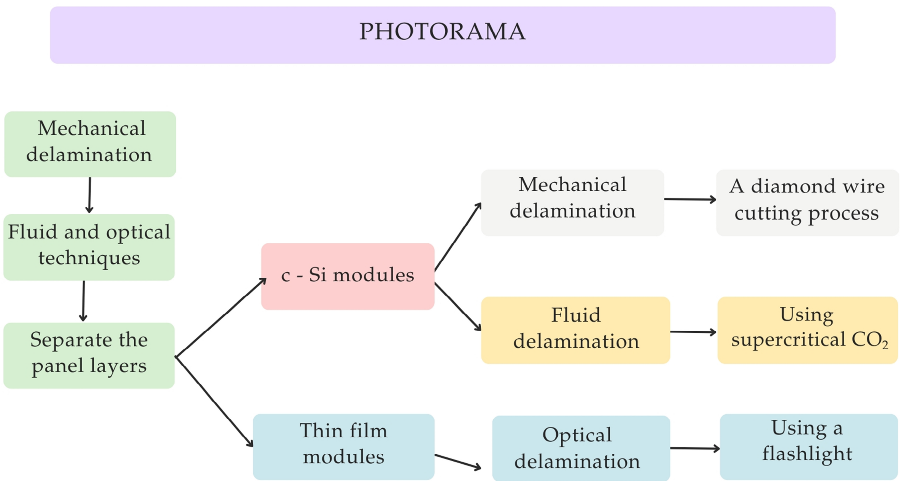

Figure 12. Stages involved in the PHOTORAMA project.

3.2. Technical Challenges in PV Recycling

Recycling photovoltaic (PV) modules presents numerous technical challenges that impact both economic and environmental feasibility. As the solar industry has rapidly expanded, so too has waste from end-of-life modules. However, limited recycling infrastructure and high associated costs remain substantial barriers. The main challenges include the efficient recovery of valuable materials, safe handling of hazardous substances, and the lack of recycling-oriented designs from the manufacturing stage. The overarching goal is to develop recycling methods that are both environmentally sustainable and economically viable at a large scale [115].

One of the biggest technical challenges is the structural complexity of photovoltaic modules. These comprise a combination of materials, such as glass, silicon, precious metals, and polymers, which are tightly integrated. Separating these components efficiently without damaging valuable materials, such as silicon solar cells, is difficult. In addition, low demand for recovered materials limits incentives to invest in more advanced recycling technologies [6].

Another obstacle is the lack of standardization in PV module designs, which complicates the recycling process. Most modules have not been designed with disassembly or recycling in mind, resulting in greater difficulty in separating them into useful components. Furthermore, current recycling processes, which include mechanical, chemical, and thermal techniques, generate hazardous byproducts such as chemical residues and toxic emissions, which require proper handling [116]. This situation underscores the need for stricter regulations that incentivize manufacturers to design modules that are easier to recycle, thus improving both the efficiency of the process and its long-term sustainability [47].

3.2.1. Material Recovery

Recovering materials from end-of-life PV modules is one of the most significant technical challenges in the solar recycling industry, essential for ensuring the sustainability and economic viability of solar energy. However, efficient separation of these components remains a technological challenge due to the complexity of the modules' multilayer structures and polymer encapsulants such as ethylene-vinyl acetate (EVA) [6,117].

One of the main challenges is the recovery of silicon, a key component in the manufacture of new modules. Current techniques such as chemical etching and thermal processes have been optimized to improve recovery rates. Recently, an approach based on the use of phosphoric acid as a single reagent has shown promise, achieving a silicon recovery rate of 98.9%. This process simplifies recycling, eliminating the need for multiple reagents and reducing operating costs, while decreasing the generation of toxic waste [118]. Additionally, recovered silicon has been shown to be reusable in advanced applications such as anodes for lithium-ion batteries, presenting new opportunities for its reuse in industries beyond solar [118].

Glass, which makes up more than 70% of the weight of PV modules, also presents significant challenges. Mechanical processes such as crushing combined with optical separation techniques make it possible to recover up to 95% of the glass without compromising its quality. This glass can then be reused in the manufacture of new modules or in other industrial applications, contributing to the circular economy and reducing the demand for virgin natural resources [3,6].

Finally, the recovery of precious metals, such as silver and copper, is also critical. Techniques such as chemical leaching with mild acids have been perfected to maximize the extraction of these metals, achieving recovery rates of over 90% in some cases. These metals are crucial not only for their economic value but also for their essential role in the internal electrical connections of modules [3,47].

Advances in these processes are vital to increasing the efficiency and economic viability of PV module recycling, allowing the industry to remain competitive and sustainable in the long term.

3.2.2. Hazardous Materials Handling

Recycling of photovoltaic modules involves not only the recovery of valuable materials but also the proper handling of hazardous substances present in the modules, such as lead, cadmium, and selenium. These elements, mainly used in the connections and conductive layers of the modules, are highly toxic and can pose serious environmental risks if not handled correctly. An important challenge in this process is the need to develop recycling techniques that allow these materials to be extracted without causing the release of hazardous substances into the environment [55,68].

One of the main environmental risks is the handling of lead, used in the soldering of photovoltaic cells. During the recycling process, if lead is not extracted and managed properly, it can leak into the soil and water bodies, causing serious pollution. In Europe, the WEEE Directive establishes strict protocols for the handling of these materials, which has driven the development of advanced technologies for their safe disposal [1,77]. However, in many regions, adequate infrastructures to manage this waste are still lacking, limiting the capacity for safe recycling.

Cadmium telluride (CdTe) modules are highly toxic. Exposure to cadmium can have severe effects on human health, causing kidney and bone damage as well as damage to the ecosystem if released into the environment. Current recycling methods such as pyrolysis and chemical treatments have proven effective in capturing cadmium, although these processes require rigorous control to avoid toxic emissions [79,119].

Selenium, used in some layers of PV modules, also poses challenges in terms of recycling. Its extraction often involves harsh chemical treatments that can generate additional hazardous waste. As the PV industry expands, it is critical that recycling technologies evolve to reduce the risks associated with handling selenium and other hazardous materials. Current research is focused on improving leaching processes to minimize environmental impacts while maximizing recovery rates for this element [57].

A recurring problem in PV module recycling is the emission of toxic gases, such as hydrogen fluoride (HF), during the incineration of fluorinated polymers found in module encapsulants. These emissions can cause air pollution and pose a serious risk to workers at recycling plants. To mitigate these risks, some facilities have implemented gas treatment systems such as scrubbers, which capture and neutralize these compounds before they are released into the environment [40].

Another critical aspect is the development of stricter regulations to govern the handling of these hazardous materials during recycling. In countries such as Germany and Italy, recycling programs based on extended producer responsibility (EPR) have been implemented, requiring manufacturers to finance the safe recycling of the modules they sell. These programs have proven effective in improving the management of hazardous materials, but their application is not yet uniform across Europe [76,84].

Finally, advancing recycling technologies aimed at reducing the impact of hazardous materials is essential for ensuring the sustainability of solar energy. Technologies such as chemical delamination and advanced pyrolysis are being improved to reduce the generation of toxic waste, which will allow safer and more efficient recycling in the future [60,78].

3.2.3. Inadequate Recycling Design

The design of current photovoltaic (PV) modules presents several obstacles that hinder their recycling at the end of their useful life. One of the main problems is the lack of consideration for efficient disassembly and separation of materials during the design stage, which makes recycling processes more expensive and complicated.

Iakovou et al. proposed improvements in module design, including the use of intermediate layers that are easier to separate and technologies that facilitate automated disassembly. These changes would allow the efficient recovery of key materials, such as glass and silicon, reducing the environmental impact and costs associated with recycling [120].

One of the main areas identified for improvement is the replacement of difficult-to-handle encapsulation materials, such as ethylene-vinyl acetate (EVA), with more easily removable and recyclable alternatives. Schoden et al. suggested that the development of new reversible encapsulants and adhesives could significantly improve recycling efficiency by reducing the generation of hazardous waste and facilitating the separation of module layers [121].

Another critical aspect is the lack of standardization in the materials and manufacturing methods of photovoltaic modules. Farrell et al. [122] proposed using uniform materials and standardized components to simplify future recycling efforts. Additionally, a modular design is recommended to facilitate material recovery, allowing greater automation and cost efficiency in the recycling process.

Automation is also a significant challenge in PV module recycling. Lu et al. highlighted that current modules were not designed to be efficiently processed by automated machinery. To address this problem, they proposed the use of adhesives that lose their properties at certain temperatures, which would allow automated disassembly without compromising valuable module components [123].

The eco-design approach has also gained importance in the discussion on how to improve the recyclability of PV modules. Heath et al. [124] suggested that module components should be designed to facilitate their disassembly and recovery, prioritizing materials that are not only recyclable but also have a lower ecological footprint throughout the module's life cycle. This approach is essential for reducing environmental impact and improving the sustainability of recycling.

Furthermore, an optimized design that facilitates access to valuable materials can significantly reduce recycling costs, as discussed in the study by Calì et al. [125], who proposed simplifying disassembly processes and eliminating difficult-to-separate materials as a key strategy to make recycling more profitable.

Finally, the study by Mariotti et al. [126] highlights the importance of integrating materials that can be easily disassembled, such as reversible adhesives, and of eliminating components that require complex chemical processes for their separation. This research points to the need for continued innovation in the development of materials to improve the efficiency and economic viability of recycling photovoltaic modules at the end of their useful life.

These proposals highlight the urgent need to redesign current photovoltaic modules to facilitate recycling, reduce costs, and minimize environmental impact, which will be key to meeting future recycling challenges in the solar industry.

3.3. Economic Barriers: High Recycling Costs vs. Disposal

Recycling costs for PV modules can be significantly higher than landfill disposal, ranging from USD 15 to USD 45 per module compared with USD 1 to USD 5 for landfilling. This makes recycling economically less attractive, especially without external incentives [116]. The lack of adequate infrastructure for recycling PV modules also exacerbates this situation, as the limited availability of recycling facilities makes the process even more expensive compared with the cheaper alternative of landfill disposal [52]. However, recent studies suggest that the implementation of regulatory policies and the optimization of recovery processes for valuable materials such as silicon and silver could improve the economic viability of recycling [127].

Economic feasibility analysis of silicon photovoltaic (c-Si) module recycling technology has revealed significant challenges, primarily due to the associated costs and variability in the economic models employed. Several studies have indicated considerable financial losses. For instance, a centralized recycling plant for frameless modules was estimated to incur a deficit of EUR 27/module [128]. More detailed analysis that considered the economic loss of high-value rare metals highlighted even greater deficits of up to EUR 96/module [129]. A manual pilot study reported a loss of approximately EUR 43/module, while projections for full-scale pilot and automated plants indicated a range from a loss of EUR 5.3/module to marginal gains of EUR 3.1/module [32,130]. These findings demonstrate that profitability is highly dependent on the scale and degree of automation within the recycling process.

The research by Choi and Fthenakis [62] introduced a mathematical framework to evaluate profitability, emphasizing the importance of operational scale. Another study demonstrated that module recycling could become profitable if the waste volume reached 19,000 tons per year, which would enable operational cost reductions through economies of scale [130]. Other analyses, such as that by Cucchiella et al. [71], have highlighted that industrial recycling plants face losses ranging from EUR 38/module to EUR 15/module. However, it was observed that recycling complete photovoltaic energy systems that include structural steel and copper wiring could offer economic incentives due to their higher recovery value [131].

Compared with other electronic products, silicon photovoltaic modules have a low cost in EUR/kg, making recycling less attractive [132,133]. In contrast, products such as mobile phones exhibit much higher recovery potential due to the concentration and value of recoverable materials [132]. Additionally, the price of recovered materials, such as glass and polysilicon, varies significantly based on purity levels, impacting total revenue [8]. For instance, glass can range from EUR 2.7–67/ton and polysilicon from EUR 10.8–36/kg, depending on quality [134]. This underscores the importance of considering the quality and purity of recovered materials in economic models, for a more accurate representation of economic feasibility [134].

Net present value (NPV) is a critical metric for assessing the economic feasibility of recycling projects, as it reflects the difference between the present value of future cash flows and the initial investment. A positive NPV indicates a profitable venture. Choi and Fthenakis emphasize that recycling projects achieve economic feasibility only when processing volumes exceed 19,000 tons annually, due to cost reductions from economies of scale [130]. Additionally, incorporating asset depreciation and maintenance costs is essential for a more accurate long-term NPV evaluation. Granata et al. found that adopting advanced recycling technologies, such as thermal separation, enhanced the NPV due to improved material recovery efficiency [88].

Return on investment (ROI) is a key indicator that measures the profitability of a project relative to the initial investment, expressed as a percentage. In the context of photovoltaic module recycling, ROI can vary significantly depending on factors such as the value of recovered materials and operational costs involved.

Cucchiella et al. demonstrated that recycling can yield a positive ROI when high-value components such as silver and copper are recovered, enhancing the net revenue of the operation [71]. Liu et al. conducted a cost–benefit analysis in China and found that, under certain market conditions, recycling modules could result in economic benefits. They noted that policies such as tax incentives and optimization in material recovery significantly improved ROI, making the project economically viable [135].

Processing costs and the efficiency of recovery technologies directly impact the ROI of photovoltaic module recycling. Advanced methods of separation and purification can significantly enhance the recovery of high-purity materials, translating to higher revenues and a stronger ROI. Rubino et al. [136], conducted a techno–economic analysis demonstrating that the incorporation of advanced recycling processes, including polymer separation and the recovery of silver and silicon, was able to achieve a 94% recovery rate and 75% recoverable value, highlighting the economic feasibility of recycling when such technologies are optimized. This underscores the importance of investing in advanced recovery technologies to maximize the economic return of photovoltaic module recycling [136]. Moreover, governmental support and environmental policies promoting recycling can contribute to improving ROI by reducing operational costs and ensuring the economic sustainability of recycling plants [56].

Wade et al. noted that government regulations, including tax credits and subsidies, can substantially boost ROI by offsetting operational costs and encouraging investment in recycling infrastructure [131]. These policies help mitigate financial risks and support the development of economically sustainable recycling operations. Implementing efficient technologies and leveraging supportive regulations can create a favorable environment where recycling projects not only break even but generate significant profits.

In conclusion, achieving a positive ROI in photovoltaic module recycling depends on a combination of efficient technologies, the recovery of high-value materials, and supportive policies that incentivize the process. These strategies not only drive profitability but also secure the long-term economic feasibility of recycling efforts.

A cost–benefit analysis (CBA) compares total investment and operational expenses against expected benefits to determine the economic feasibility of a project. In the context of photovoltaic module recycling, Fthenakis highlighted that initial costs associated with collection and transport pose significant challenges that can be mitigated through the recovery of high-value, high-purity materials [134]. D'Adamo et al. argued that employing advanced purification technologies could shift the CBA toward profitability, provided that high recovery rates are maintained [32]. Marwede and Reller emphasized the importance of considering factors such as fluctuations in silicon prices and energy efficiency improvements in recycling processes, which could positively impact the CBA [137]. Furthermore, Dominguez and Geyer contended that environmental benefits such as emissions reductions should be quantified alongside financial metrics to achieve a comprehensive CBA [138]. This comprehensive approach integrates both economic and environmental aspects, providing a holistic view of the viability and potential benefits of photovoltaic module recycling.

The expanded analysis including multiple references confirms that the financial viability of photovoltaic module recycling depends on factors such as operational scale, material purity, and regulatory incentives. Financial indicators like NPV and ROI, supported by a positive CBA, are critical to ensuring project profitability. Implementing efficient technologies and leveraging public policy incentives are essential strategies for making photovoltaic module recycling economically viable.

The economic feasibility of photovoltaic (PV) module recycling varies significantly depending on the technology employed, with each method involving distinct operational costs and material recovery efficiencies. Physical recycling methods, including crushing and mechanical separation, generally entail moderate operational costs due to their reliance on standard mechanical equipment. However, these processes demand considerable energy to operate the crushing and separation machinery. For example, high-energy pulse crushing or laser cutting, although more advanced, increase operational expenses due to the specialized equipment and maintenance required. Studies indicate that conventional crushing methods cost approximately EUR 10 to 20/module, while the use of sophisticated approaches such as laser cutting can elevate costs to around EUR 30/module [60]. Despite being more economical, physical processes may not achieve the same levels if purity in material recovery as more complex recycling methods.

Chemical recycling processes often incur higher costs due to the necessity of specific reagents, such as nitric and hydrofluoric acids, which dissolve metallic components and separate encapsulants. These processes also require robust waste treatment systems to manage hazardous chemical byproducts, adding significantly to operational expenses. Although highly effective at recovering valuable materials like silver and silicon, the costs associated with chemical waste management and effluent treatment are substantial, with estimated costs ranging from EUR 25 to 50/module, depending on the quantity of reagents used and the specific waste management infrastructure required [61]. Methods utilizing less hazardous reagents may marginally reduce costs, although this comes at the expense of lower recovery efficiency, potentially impacting the economic value of the recycled materials.

Thermal processes, such as pyrolysis and high-temperature treatments, also carry considerable operational costs due to their high energy requirements. These methods effectively remove encapsulants like ethylene-vinyl acetate (EVA) and facilitate material recovery without chemical reagents; however, energy consumption and the need for emission controls for hazardous gases such as hydrofluoric acid (HF) substantially increase expenses. The estimated cost of pyrolysis processes varies between EUR 35 and 60/module, depending on the specific temperature requirements and emissions management systems in place [139]. Double-stage pyrolysis, designed to enhance the purity of recovered materials, raises costs further toward the upper end of this range, making it a less economical option unless high-purity material recovery is prioritized.

Finally, combined methods that integrate physical, thermal, and chemical steps represent the most expensive approaches due to the complexity and number of stages involved. However, these methods offer the highest efficiency in recovering high-value materials like high-purity silicon and silver, and they also enable the reuse of other components such as glass. By employing a phased approach, combined methods balance recovery efficiency with cost optimization, achieving optimal material recovery at the expense of higher operational costs. The cost of combined recycling methods ranges from EUR 45 to

75/module, varying according to the number of stages and the specialized equipment used in each phase. Advanced separation techniques, such as selective solvent application and controlled pyrolysis, increase expenses but enhance material purity, potentially offsetting operational costs through the sale of high-demand, pure materials [62,63].

Table 9 provides a comparative analysis of the recycling costs, key cost factors, efficiency levels, and references for various photovoltaic (PV) module recycling technologies.

Table 9. Recycling Technology Cost Analysis.

Recycling Technology	Cost per Module (€)	Key Cost Factors	Efficiency	References
Physical Processes (e.g., Crushing, Laser Cutting)	10–30	Energy for machinery, maintenance of advanced equipment like laser cutters.	Moderate; lower-purity recovery.	[60] Dias et al., 2017
Chemical Processes (e.g., Nitric and Hydrofluoric Acids)	25–50	Cost of reagents, waste treatment for hazardous byproducts.	High for valuable materials (e.g., silver), but costly.	[61] Savvilotidou et al., 2017
Thermal Processes (e.g., Pyrolysis)	35–60	High energy consumption, emission controls for hazardous gases.	Effective for removing encapsulants; high material purity.	[139] Ravikumar et al., 2020
Combined Methods (Physical, Thermal, and Chemical)	45–75	Complexity of stages, specialized equipment for multi-step recovery.	Highest; optimal recovery of high-value materials.	[62,63] Choi & Fthenakis, 2010; [62,63] Walzberg et al., 2021

3.3.1. Low Market Demand for Recovered Materials

Low market demand for recovered materials from photovoltaic (PV) modules is a crucial factor affecting the economic viability of recycling. One of the main problems is that recovered materials such as glass, aluminum, and silicon are typically of lower purity and value than virgin materials, making them less attractive for reuse in the manufacture of new modules or industrial products. According to the study by Deng et al. [140], the current demand for recycled materials from silicon modules is insufficient to stimulate a robust market, leading to financial losses in recycling operations, especially due to competition from virgin materials and the low price of recycled materials.

The International Energy Agency (IEA) report [28] highlights that high recycling costs combined with limited revenues from the sale of recycled materials make it difficult to create a lucrative market for these products. Without sufficient technological development and stricter incentive policies, the recycling market remains economically unattractive. Furthermore, an analysis by the National Renewable Energy Laboratory (NREL) notes that without government intervention in terms of research and development, it will be difficult to overcome barriers relating to demand in the market for recycled PV materials, limiting progress towards a circular economy in the solar sector [141].

3.3.2. Transportation Costs

The need to transport PV modules to specialized recycling facilities adds another layer of expense, particularly in regions where such facilities are scarce.

Transporting PV modules to specialized recycling facilities adds a significant layer of cost to the process. This challenge is accentuated in regions where recycling infrastructure is limited, requiring long journeys to reach the appropriate treatment plants. Optimizing transport routes presents a viable solution to reduce both the costs and emissions associated with recycling. Recent studies have shown that proper logistics planning can reduce these costs by more than 50%. However, the shortage of specialized facilities in some areas remains a major obstacle to the economic viability of PV module recycling. Furthermore, transport becomes one of the most critical factors when distances are considerable, significantly increasing costs and therefore affecting the profitability of the process [142,143].

Research by Fthenakis et al. [134] highlights that reverse logistics costs, which include the collection of modules and their transportation to recycling centers, represent a significant portion of total recycling expenses, particularly in regions with dispersed infrastructure. These expenses can vary depending on the distance traveled and the number of modules transported per trip, as long distances increase operational costs due to higher fuel consumption and vehicle wear.

Chiquillo Molano et al. [144] presented a reverse logistics plan designed to optimize the collection of end-of-life modules, aiming to reduce transportation costs and environmental impact. Their study emphasized that transportation represents one of the most significant costs in the recycling cycle due to the need to move panels from dispersed collection points to centralized recycling facilities. Transport efficiency not only leads to cost reductions but also plays a critical role in reducing the carbon emissions associated with the process. Optimizing transportation infrastructure is essential for minimizing these costs. Key strategies include reducing travel distances and maximizing the number of modules transported per load to improve the economic feasibility of recycling. These practices not only decrease costs but also reduce the carbon footprint associated with photovoltaic module recycling, contributing to a more sustainable waste management approach [50].

A study conducted in Australia demonstrated that strategic planning, including forecasting waste flow and considering the locations of collection centers, enables the design of shorter and more efficient transport routes. This results in reduced operational and capital costs. That study aimed to find an optimal location for a collection center based on the location of waste generation sites, thereby minimizing transportation distances [144].

In the study by Celik et al. [143], transportation costs exceeded processing costs in recycling plants when distances surpassed 2000 km, as observed in some countries where plants are in remote industrial areas. In such cases, road transport by trucks is typically the most viable option but poses significant environmental and economic costs. This situation led to considerations of alternatives such as route optimization and an increase in collection centers near photovoltaic installation areas.

Subsidies and support policies can play a crucial role in the economic viability of photovoltaic module recycling. Yu et al. [145] explored the impact of different collection and transportation strategies in Zhejiang Province, China, an area with a high volume of distributed photovoltaic installations. Two distinct approaches were compared: one led by the local government, and another based on producer cooperation under the principle of extended producer responsibility (EPR). The government-led approach proved effective in establishing infrastructure but faced challenges due to bureaucracy and limited resources. Integrating producers' sales and service networks leveraged existing transportation routes, optimizing collection and reducing logistics costs by nearly 10% during periods of high waste generation. However, this model requires a robust regulatory framework and close collaboration between producers and local authorities to ensure a steady and coordinated flow of materials from collection points to recycling facilities.

Another factor influencing transportation costs is the number of damaged or defective modules generated during the service life of photovoltaic systems, as outlined in the study by D'Adamo et al. [32]. These damaged modules require special handling and are sometimes classified as hazardous waste under certain regulations, which raises transportation costs due to the safety and regulatory requirements that must be met. These restrictions increase logistics costs and can limit the profitability of module recycling systems.

Technological advances in transportation and logistics methods, such as the use of electric trucks to reduce fuel costs and environmental impact, are considered emerging strategies according to recent studies in sustainability and photovoltaic waste recycling [146]. Implementing these technologies would not only contribute to lowering transportation costs but also enhance the sustainability of the life cycle of photovoltaic modules.

3.4. Regulatory Challenges

In Europe, recycling of PV modules is regulated under the Waste Electrical and Electronic Equipment (WEEE) Directive, which requires producers to take responsibility for recycling the modules they sell. This directive was introduced in 2003 and revised in 2012 (2012/19/EU) to include PV panels, imposing targets of 80% recycling and 75% recovery by 2018, and 85% and 80% by 2020, respectively [60].

Despite the implementation of these regulations, recycling rates for PV modules in Europe are still relatively low. In 2016, between 0.1% and 0.6% of the total installed modules were recycled, equating to approximately 43,500 to 250,000 metric tons of PV waste. By 2030, the amount of PV waste being recycled is expected to have increased significantly, reaching up to 4% of the total installed capacity. Countries such as Germany, Italy, and Spain have started to develop more efficient models for collection and recycling; however, substantial challenges persist relating to the economic viability of these processes [58,147].

The European Union has implemented advanced regulations such as the WEEE Directive, which sets ambitious targets for recycling photovoltaic modules, with recycling and recovery rates of up to 85%. This has positioned Europe as a leader in photovoltaic waste management worldwide, especially countries such as Germany and France, which lead in terms of technological capacity for recycling [148,149].

Despite these advances, significant challenges remain in optimizing recycling processes, particularly in the separation of multilayer materials, which contain polymers and other toxic compounds such as fluorine. Correct extraction and treatment of these materials prior to incineration is key to minimizing toxic emissions [68].

3.4.1. Inconsistent Regulatory Frameworks

The lack of uniform regulations at a global level represents a major challenge to the recycling of PV modules. While the European Union has made progress with the WEEE Directive, other countries lack robust regulatory frameworks that ensure proper management of PV waste. This disparity affects the efficiency of recycling processes and limits the development of a coherent and efficient global recycling industry. It is crucial that greater regulatory harmonization between regions is promoted to facilitate a smooth transition towards a circular economy in the PV sector [150].

Despite the improvements introduced by the WEEE Directive in Europe, significant challenges remain in relation to the lack of a globally coherent regulatory framework for recycling PV modules. Significant differences in national regulations hinder the effective implementation of recycling strategies, slowing down progress towards a circular economy. The need for a global regulatory approach is clear, and its lack of implementation creates significant obstacles to the sustainable management of PV waste [151].

3.4.2. Extended Producer Responsibility

The European Union's regulatory framework, through the WEEE Directive, has also driven the implementation of extended producer responsibility (EPR). This regulation requires photovoltaic module manufacturers to ensure the collection and recycling of products at the end of their useful life, promoting the development of recycling infrastructure throughout the region [71]. However, although the regulations are clear, the adoption and infrastructure for recycling have not advanced uniformly across all European countries, presenting standardization challenges [47,76].

Producers are responsible for recycling the photovoltaic panels they put on the market, which includes the cost of collection and treatment at the end of their useful life [57].

In countries such as Germany and Italy, additional measures have been implemented. In Germany, since 2015, the "Elektroaltgerategesetz" (ElektroG) regulation has obliged manufacturers to finance the recycling of each module sold, ensuring a complete recycling treatment. In Italy, photovoltaic modules have been classified as WEEE since 2014, and manufacturers must join a national register to manage the collection and recycling of modules [57,152].

Finally, several reports have highlighted Europe's role as a pioneer in recycling photovoltaic modules. Companies such as Reiling in Germany are already expanding their recycling capacities, reaching up to 50,000 tons of recycled modules per year [76,153]. In this respect, Europe remains the most advanced region in the implementation of infrastructure for recycling photovoltaic modules, with Germany and France at the forefront [71].

3.5. Benefits and Opportunities for Improvement

Recycling of PV modules enables the recovery of valuable materials such as silicon, silver, copper, and aluminum, which has significant economic implications. The value of these materials varies depending on the type of module and the recycling methods used. For example, recovering high-purity silicon (over 99.9%) can yield a value of approximately USD 95 per kW in crystalline-type modules, which equates to a recovery of more than 50% of the silicon needed to produce new modules by 2040 and 2050 [154]. However, the costs associated with the recycling process can be high. A cost–benefit analysis conducted in China estimated the recycling cost per kilowatt (kW) to be approximately USD 25.11, with a net benefit of USD 0.57 per kW [135]. Other studies have suggested that although complete recycling of PV modules is environmentally beneficial, it is not always economically viable [56].

Economic benefits are increased by recovering high-value materials such as silver, present in the internal connections of the modules. Studies indicate that it is possible to recover between 85% and 95% of the silver using advanced chemical and thermal recovery techniques [63]. In addition, some recent processes have managed to recover up to 90% of the aluminum and more than 95% of the glass in reusable form. The recovery of these materials not only reduces the need for virgin resources but also decreases the environmental impact associated with the production of new solar modules. However, the economic cost of the recycling process still poses challenges, especially in the management of waste generated by polymers and other composite materials, which may require additional treatments that increase total costs [155].

The value of materials recovered from PV waste could reach USD 2.7 billion by 2030 and up to USD 80 billion by 2050, highlighting the economic potential of recycling these modules. This is particularly relevant given the increasing number of PV modules that will reach the end of their useful life in the coming decades [156].

Silver recovery from photovoltaic modules is crucial, due to the material's high demand and projected scarcity by 2075. For every ton of end-of-life photovoltaic panels, it is possible to recover approximately 600 g of silver, representing significant economic value. Furthermore, it is estimated that recycled silicon can reduce the cost of manufacturing photovoltaic cells by 65%, decreasing greenhouse gas emissions by 42% during the production of new modules [55].

Thermal recycling of photovoltaic modules can recover up to 79.7% of the glass and 3.9% of the silicon. This glass can then be reused in the manufacture of new modules or in innovative applications, for example, as a filler in polymer composites. Recycled silicon with a purity close to 98% can be reused in the production of electronic components, reducing production costs and greenhouse gas emissions associated with the manufacture of new modules [68].

In addition, technologies have been developed for the recovery of titanium dioxide (TiO_2) and other valuable compounds during heat treatment. These innovations not only increase the profitability of recycling but also reduce dependence on new raw materials [68].

Recycling valuable materials such as silver, copper, and silicon is crucial, although high costs of initial investment and continued operation limit their profitability. More efficient methods are being developed to improve the economic viability of recycling photovoltaic modules [68].

3.5.1. Advancements in Recycling Technologies

The development of low-impact recycling processes is crucial to improving the sustainability of thin-film PV modules. One example of this is the "Double-Green Process" (DGP), a method designed for the efficient recycling of CdTe, a-Si, and CIS/CIGS PV panels. This process mainly uses mechanical treatments with minimal use of chemicals, which significantly reduces its environmental footprint. Furthermore, the DGP is characterized by a high level of automation and flexibility in production capacity, making it a viable solution both from a technical and economic point of view. Through lifecycle analysis (LCA) and discounted cash flow (DCF), it has been shown that this process is capable not only of recovering valuable materials but also of doing so cost-effectively under certain conditions. This advancement represents an important step towards the implementation of more sustainable recycling systems for thin-film PV technologies, contributing to the reduction in the environmental impact of PV waste [157].

New technologies applied to the recycling of photovoltaic modules have experienced rapid advancement in recent years. Recent innovations have enabled improved recovery of critical materials such as silicon and glass through the use of advanced separation techniques and more efficient dismantling processes. These methods not only improve the profitability of recycling by maximizing the quantities of reusable materials but also decrease the environmental impact associated with traditional waste management processes. In addition, solutions have been introduced that allow a higher degree of automation in recycling, reducing dependence on manual labor and minimizing human errors in component sorting. These technologies are contributing significantly to the economic and environmental viability of photovoltaic module recycling [158].

Recent developments in process automation are transforming PV module recycling. The use of robotic systems and artificial intelligence has enabled more accurate and faster sorting of recovered materials, increasing recycling efficiency by reducing processing time and improving the quality of the separated materials. These innovations have also enabled the scaling up of recycling, making the treatment of large volumes of modules at the end of their useful life more viable. Automated systems have proven crucial in reducing operating costs and increasing the sustainability of processes, making recycling more accessible at an industrial level [159].

3.5.2. Policy Recommendations

A key approach to advancing towards a circular economy in the photovoltaic sector is the international implementation of extended producer responsibility (EPR). According to Cimadomo et al. [160], although EPR has been effective within the European Union's borders, its application to exported products is limited. Strengthening the traceability of exported photovoltaic modules for reuse is recommended, as well as improving international cooperation to ensure proper waste management in countries like Nigeria and Ghana. These measures could mitigate the negative environmental and social impacts in receiving countries and ensure that economic incentives flow to the places where this waste is managed.

Another important recommendation comes from the studies by Ali et al. [161], who emphasized the need for a clear and uniform regulatory framework for management of photovoltaic waste in regions like Saudi Arabia. The lack of coherent guidelines and the absence of adequate recycling infrastructure results in many modules ending up in landfills, leading to a waste of valuable materials. The proposal is that policies should not only incentivize recycling but also encourage the creation of an industry capable of reusing and recycling materials at a competitive cost.

Finally, Su et al. [162] suggest that advancements in photovoltaic module recycling technologies, including the use of organic solvents and advanced recovery processes, can significantly transform the economic viability of recycling. Policies should encourage research in emerging technologies and provide grants or tax incentives for companies to adopt these processes more widely.

This comprehensive policy approach can ensure that both producers and recyclers are incentivized to close the life cycles of photovoltaic modules in a way that is both environmentally and economically sustainable.

3.5.3. Circular Economy Initiatives

The use of circular economy principles in the manufacturing and remanufacturing of perovskite solar cells has significantly improved the sustainability of the photovoltaic module life cycle. This approach focuses on optimizing recycling processes to minimize waste generation and maximize the reuse of valuable materials, thus contributing to a more efficient and circular system within the solar energy industry [163].

Eco-friendly pretreatment processes have proven effective for the recovery of high-purity silicon from end-of-life photovoltaic modules. These processes are aligned with the principles of the circular economy, as they enable the efficient reuse of key materials, promoting sustainability and reducing the environmental impact of discarded solar modules [164].

The implementation of improvements in photovoltaic module recycling, such as the recovery of silicon wafers from damaged panels, is key to promoting a circular economy. Optimizing these recovery processes not only reduces the need for extracting new resources but also ensures better reuse of critical materials, contributing to long-term sustainability [165].

The recovery of valuable elements from solar panels is essential for adding value to waste and closing the circular economy loop. Utilizing these materials in construction or industrial applications not only reduces the demand for virgin resources but also drives sustainability by maximizing the use of recovered components in new life cycles [166].

The recycling of electronic devices, including photovoltaic modules, can be significantly optimized using circular practices in electronic waste management. Initiatives such as optimized transportation and improved waste management help maximize material recovery, contributing to global sustainability and reducing environmental impact [167].

The adoption of circular economy-based operational strategies in photovoltaic waste management has shown promising results. These strategies, focused on a multi-stakeholder perspective, enable more efficient recovery of valuable materials and promote sustainability in the end-of-life management of modules [168].

3.6. Future Perspectives in Mediterranean Countries

In Spain, the evolution of photovoltaic capacity has not followed a linear pattern, which is a key factor to consider when estimating future waste volumes. It is worth noting the significant increase in installed photovoltaic capacity during 2019 and 2020 compared with previous years, representing a change in response to new initiatives aimed at achieving climate neutrality [104].

Currently, the amount of photovoltaic waste in Spain is low, but a significant increase is expected in the short and medium term due to the end of life of the first installed plants. In the long term, this increase will be driven by the aging of more recent plants and new installations projected for the coming years.

However, there are individual systems that contribute to photovoltaic waste generation and which have not been considered in these estimates. The Energy Plan 2030 projects an increase in renewable energy capacity, targeting 39 GW of installed photovoltaic capacity by 2030 [169]

Some scientific studies have forecasted photovoltaic waste in Spain using different projections. The latest update provides new scenarios based on two approaches, including one that estimates a photovoltaic capacity of 47 GW by 2030 [104].

Estimated projections for photovoltaic waste in France indicate that it is expected to exceed 43,000 tons annually by 2030 and reach 118,000 tons by 2040 [169]. To address this significant increase, in February 2021, Soren launched a new tender process to establish three facilities dedicated to recycling photovoltaic panels in the country. Two of these plants have been operational since June 2021: one managed by Galloo in Halluin, northern France, and another operated by ENVIE 2E Midi-Pyrénées in Portet-sur-Garonne [104].

In Italy, according to the IRENA/IEA PVPS Task 12 report on end-of-life photovoltaic panels published in 2016, ref. [170] the accumulated waste volume nationally, depending on the estimated average lifespan of photovoltaic modules, is projected to range between 140,000 and 500,000 tons by 2030, with an expected increase to 2.2 million tons by 2050.

In March 2021, Spain's Integrated National Energy and Climate Plan (PNIEC) 2021 was finalized. This plan includes a projection that considers a scenario of 26 GW of installed photovoltaic capacity by 2030, aligned with PNIEC goals. Based on these projections, several photovoltaic waste generation scenarios were calculated, considering both regular and early losses until 2050 [104].

3.7. Future Trends and Forecasts About PV Recycling

In the coming years, the number of PV modules reaching the end of their useful life is expected to increase significantly, generating large volumes of waste. By 2050, it is estimated that the global volume of PV module waste could reach between 60 and 78 million tons. One of the main challenges will be the economic viability of recycling, with current costs ranging between USD 600 and 1000 per ton of modules. However, these costs are expected to decrease as recycling technologies are optimized. In this context, recycling will play a key role in mitigating environmental impact and fostering a circular economy, especially in Europe, where a strong regulatory framework is already in place. Projections indicate continued growth in recycling capacity, driven by the development of new technologies and stricter policies, thus avoiding the dumping of PV waste in landfills [58,171].

Future research should be focused on improving the efficiency of recycling processes, especially using cleaner thermal and chemical technologies. Advances such as electrostatic separators, which are more environmentally friendly and cost-effective, and the replacement of strong acids with less polluting solutions, will be key in optimizing material recovery. New recycling technologies, such as the use of supercritical water, which employs wastewater instead of clean water, are being investigated to further reduce environmental impact [63].

The concept of extended producer responsibility (EPR) will continue to play a central role in promoting recycling. This policy places responsibility on manufacturers for managing products at the end of their life, covering the costs of collection, treatment, and recycling. A recent study in Zhejiang Province, China, showed that EPR-based models can significantly reduce logistics costs in the long term, proving to be more efficient than other government-run schemes [145].

PV waste management will remain a major challenge in the coming decades. The adoption of more efficient recycling technologies, together with the development of appropriate infrastructure, is expected to be key to coping with the exponential growth of waste, especially in Europe, leading to installed solar energy capacity. The implementation of EPR policy will remain crucial to improving large-scale collection and recycling [67].

In Europe, regulations such as the WEEE Directive will continue to drive the development of PV module recycling technologies. Innovations in techniques such as pyrolysis and other thermal delamination methods are expected to optimize material recovery. However, countries such as India and China, which are beginning to introduce similar regulations, will face greater challenges in implementing recycling systems comparable to those in Europe [85,89].

With recycling demand increasing, advanced thermal and chemical separation technologies are projected to be key to improving efficiency and reducing the cost of recycling. New large-scale recycling plants and innovative business models will be key to overcoming current barriers and ensuring the long-term sustainability of the photovoltaic industry [68,72].

In the future, the need for large-scale recycling plants is expected to become imperative to deal with increasing volumes of PV waste. The economic viability of these plants will be greater than that of pilot plants, due to economies of scale, which will facilitate the implementation of more sustainable infrastructures [71].

4. Conclusions

The Mediterranean region faces significant hurdles in photovoltaic (PV) module recycling, with challenges spanning technical, economic, and regulatory areas. Technical complexities, such as the separation of hazardous and valuable materials, combined with high recycling costs, limit economic viability. Additionally, regulatory gaps, especially the lack of uniform guidelines, further hinder efficient PV recycling practices across Mediterranean countries. These findings underscore the necessity for integrated solutions that streamline module design for easier disassembly, incentivize recycling, and ensure a cohesive policy framework.

To advance PV recycling in the Mediterranean, it is necessary to develop regional policies that align with EU standards, investing in advanced recycling technologies to improve recovery efficiency and fostering stronger collaborations among stakeholders, including manufacturers, governments, and recycling facilities. These actions will not only enhance material recovery but also reduce environmental impact and recycling costs. Emphasizing modular design and adopting uniform materials will facilitate recycling processes, reduce economic barriers, and promote a circular economy.

Author Contributions: Conceptualization, A.-M.D.-S. and E.J.M.T.; methodology, M.M.-B.; software, C.M.D.; validation, M.M.-B. and A.-M.D.-S.; formal analysis, A.-M.D.-S., E.J.M.T. and M.M.-B.; investigation, C.M.D. and M.M.-B.; resources, A.-M.D.-S.; data curation, E.J.M.T. and J.-J.B.-P.; writing—original draft preparation, A.-M.D.-S. and M.M.-B.; writing—review and editing, E.J.M.T.; visualization, J.-J.B.-P.; supervision, E.J.M.T. and J.-J.B.-P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: Marta Martínez Benavides would like to thank the University of León for her research support technician contract (TE-2023), granted by the Regional Government of Castilla y León and co-financed by the European Union (Code: 701117).

Conflicts of Interest: The authors declare no conflicts of interest.

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