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The End of Life of PV Systems: Is Europe Ready for It?

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Abstract: Like other plants, every photovoltaic (PV) power plant will one day reach the end of its service life. Calculations show that 96,000 tons of PV module waste will be generated worldwide by 2030 and 86 million tons by 2050. Such large quantities of waste can endanger the environment and people if they are not disposed of properly. This paper investigated how photovoltaic waste is currently handled, how this problem is legally regulated and to what extent reuse, recycling and disposal are represented. As recycling is the best option in terms of environmental protection and a circular economy, an overview of recycling technologies and recovery rates for the materials contained in the PV system is given. Currently, there are a small number of recycling plants for PV modules in Europe, but none in the Balkan countries. The main reason for this is the small amount of PV waste in these countries, which is far below the profitability threshold for the recycling of 19,000 t/year, and even below the reduced threshold of 9000 t/year. The analysis shows that only seven EU member states will exceed this threshold by 2040, and more than half of the EU member states will not even reach this threshold by 2050. For this reason, PV modules (after dismantling the aluminum frame and cables) are mostly disposed of in landfills in these countries. This is an indication that this problem should be seriously addressed in the EU. In this context, the main obstacles to the reuse and recycling of PV modules are listed, together with guidelines for their removal.

Keywords: PV waste; end of life; recycling; reuse; environmental risk

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1. Introduction

In order to fulfill the Sustainable Development Goals, renewable energy systems are currently in the spotlight. The renewable energy market is dominated by solar and wind energy, while biomass and geothermal energy only make a small contribution [1]. In this study, we will focus on PV solar power plants because they are becoming one of the most economical and environmentally friendly technologies for electricity generation worldwide and therefore offer a sustainable solution for decarbonizing energy systems. Based on the data from the International Energy Agency (IEA) [1] and the International Renewable Energy Agency (IRENA) [2], a diagram of global PV capacities was created (Figure 1). Since 2010, there has been a significant increase in the annual capacity added, leading to an annual capacity of 240 GW in 2022 and bringing the total installed PV capacity worldwide to 1185 GW [1]. Global cumulative capacity is expected to reach 2840 GW in 2030, 5680 GW in 2040, 7099 GW in 2045 and 8519 GW in 2050 [2].

New projections from the IRENA [3] indicate that by 2050, there will be a total installed capacity of 14,000 GW worldwide, and it is likely that this amount will increase over time.

Three types of cells are generally used for PV systems. Monocrystalline PV cells are made of single-crystal silicon, which gives them a uniform and dark appearance. They have the highest efficiency and the longest lifetime among the three types of PV cells, but they are the most expensive [4]. Monocrystalline PV cells are used for areas with limited roof space or high electricity demand. Polycrystalline PV cells are made up of multiple silicon crystals, which give them a blue and speckled appearance. They have lower efficiency and a shorter lifetime than monocrystalline PV cells but are cheaper and easier to manufacture. Thin-film PV cells consist of thin layers of different materials, such as amorphous silicon, cadmium telluride or copper indium gallium selenide. They have the lowest efficiency and lifetime among the three types of PV cells, but they are also the most flexible and lightweight, so they can adapt to different shapes and surfaces.

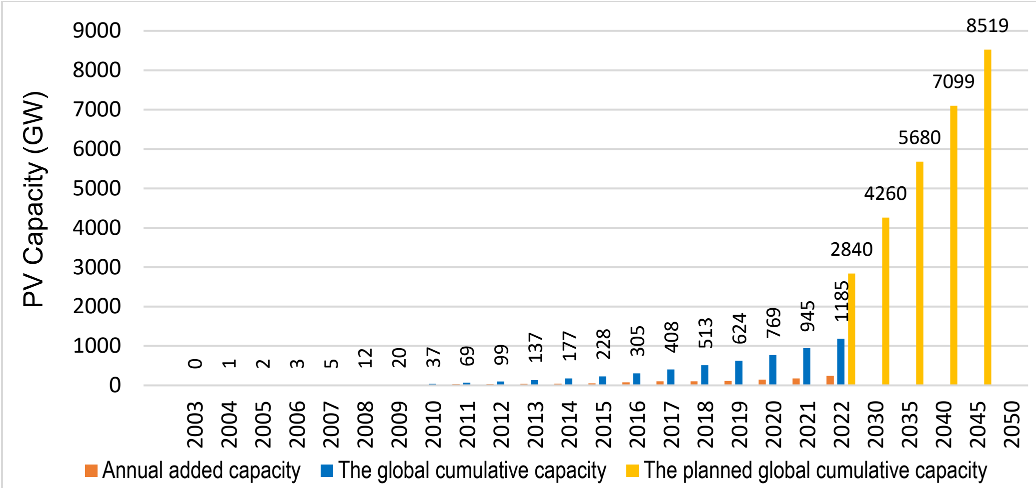

Figure 1. The global PV capacity.

Looking at the type of modules produced (Figure 2), it can be seen that the share of mono- and polycrystalline silica (c-Si) PV modules has steadily increased since 1988. Thus, the share of c-Si modules was about 68% in 1990 and about 95% in 2022. The remaining 5% of PV modules are thin-film modules (TFPV), some of which are made from hazardous materials such as cadmium, tellurium, indium and gallium [5].

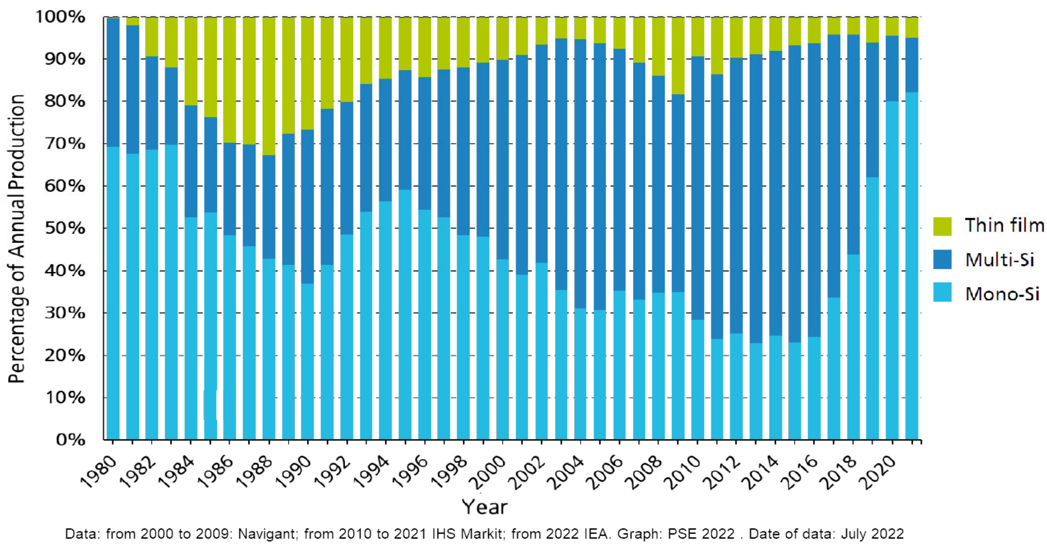

Figure 2. Share of production of individual types of PV modules by year [5].

PV systems produce neither waste nor emissions when generating electricity. However, the manufacture, installation and dismantling of PV system components at the end of life (EoL) represent a burden on the environment (see Section 3.1.4).

There are several EoL options such as reuse, recycling and landfilling. Landfilling is a simple option, but it is the least acceptable for the environment. Recycling is a more complex option that is environmentally sound, but its economic viability is questionable. PV technology has only been on the market for a relatively short time and the lifetime of PV systems is long, so the number of modules that are recycled is still small—only a few thousand tons per year in Europe. It is therefore not surprising that interest in this topic is still low in research centers, companies dealing with waste disposal and government institutions. The recycling of PV modules could become more important in view of the planned large capacities of PV plants and the increasing demand for silicon.

About 93% of the total global production of PV modules in 2021 took place in China, with the rest mainly in Europe and North America [5]. Due to the high concentration of PV production capacity in China, the policy of supporting local production is visible all over the world.

China (44%) and India (30%) also account for most of the additional PV capacity in 2022, while Europe accounts for only 16%. In terms of cumulative capacity, China leads with 35%, followed by Europe with 17.7% and North America with 12% [1]. Significant solar capacities are also being built in other parts of the world. For example, the planned production capacity of the solar project in Seih Al-Dahal, south of Dubai, is 5 GW by 2030 [6].

Repowering is still relatively rare given the age of the oldest PV plants, but it is expected to increase in the near future. From these data, it appears that the recycling of PV modules will be most important in China, followed by Europe and the USA.

In the present, there is no global monitoring or reporting of the recycling rate of PV modules, hence it is impossible to determine it precisely. However, there are some estimations and examples in the literature. According to the IEA [7], Germany, France, Italy and Japan process a few thousand tons of PV waste annually. In Spain and South Korea, the amount of waste PV modules is still less than 1000 tons per year.

According to the IEA [7], 211,142 tons of PV modules were placed on the market in Germany in 2018. The amount of collected waste PV modules was 7865 tons (3.7% compared to newly installed modules). Of this quantity, 87.6% was recycled and 12.4% was destined for reuse.

According to one estimate, the average global recycling rate for PV modules was 14% in 2019, and on the assumption of a high recycling scenario, this could increase to 35% by 2030 and 70% by 2050 [8]. These projections include certain assumptions and uncertainties and may change depending on the type of modules, the rate of degradation, the cost and accessibility of recycling infrastructure, the demand for and price of recovered materials, and the impact on the environment. Furthermore, there is no international standard for recycling PV modules, and various states and regions may have different laws and practice.

For instance, the European Union has created particular policies and instructions for the management of PV modules at the EoL. Extended producer responsibility (EPR), introduced by the European Directive on Waste Electrical and Electronic Equipment (WEEE), has obliged producers and importers in each European member state to organize the collection, transport, recycling and financing of these operations for their PV equipment since 2014. Following its publication in 2012, the WEEE Directive is being transposed into national regulations by each member state of the European Union. Although recycling is a viable option for PV panels, it is not the only option. According to the WEEE Directive, EU member states must ensure 85% collection and 80% recycling of materials used in PV modules. All EU member states should carry out adequate inspection controls and monitoring of the work of companies that recover PV modules in accordance with the provisions of the WEEE Directive. In addition, all countries should report regularly on the amount of PV waste processed during the year. However, so far there is very little evidence that this is being implemented in practice.

In other regions of the world, the EoL of PV systems is generally managed according to each state's legal and regulatory framework for the treatment and disposal of general waste. However, several countries have launched or are developing legislative initiatives to accelerate the EoL management of PV systems, including funding for technology research and development.

In Australia, EoL management is still in its infancy, so only a tiny number of EoL PV modules are recycled. In South Korea, laws on EPR will come into force in 2023 and PV modules are classified as a separate product group. Even though there is now a lot of PV waste produced, most of it is landfilled [7].

In the USA, some states have laws that specifically address the EoL of PV systems. PV module recycling companies in the US have varying levels of capacity and experience. A recent analysis has shown that the limitations of current Si PV recycling technologies, the high cost of Si PV recycling and the limited recycling capacity are the main barriers to PV waste management in the USA [7].

In China, the development of equipment and legislation related to the recycling of PV equipment is being rapidly developed. Technical standards for the green design of PV modules supported by the Chinese Ministry of Industry and Information Technology were published until 2020, and in 2022, the Action Plan for the innovation and development of an intelligent photovoltaic industry (2021–2025) was published. The first PV module recycling demonstration line in China was built in 2021.

When a power plant reaches its EoL, the question arises of how to detreat its components in a way that minimizes environmental impact, consumes the least energy, maximizes recycling and is commercially viable at the same time. As more and more PV power plants reach their EoL and generate more waste, this problem will become even more important in the future. To achieve the main objective of this investigation, the first step is to analyze the available literature in order to understand more deeply the topic of PV module dismantling, especially c-Si modules, which make up the largest market share.

More than 90% of PV modules are made of c-Si and have an average lifetime of 30 years, according to Peplow [9]. About 8 Mt of these modules could reach EoL by 2030 and about 80 Mt by 2050. It is thought that the available PV module recycling techniques are not efficient enough and are underutilized.

Dominguez and Geyer [10] assume that PV modules last on average for 30 years and expect there to be 9.8 million tons of PV waste in the USA between 2030 and 2060. They estimate that 9.2 Mt of metal can be recovered from PV systems. The material value of these metals is estimated at USD 22 billion.

The most effective methods for recycling EoL modules were researched and proposed by Farrell et al. [11]. They focused on maximizing the recycling of module components, respecting design constraints. They provided information on some of the latest industrial and academic recycling techniques. Alternative cascade options for open-loop recycling are presented, as well as the difficulties, opportunities, models and reasons for a critical review of closed-loop recycling.

Dias and Veit [12] assessed the potential hazards of first generation modules. PV modules contain both hazardous and valuable materials. They investigated mechanical, thermal and hydrometallurgical recycling processes and evaluated different recovery options and their results.

Ko et al. [13] pointed out that effective procedures for the management of PV waste are needed to reduce its impact on the environment and facilitate the transition to a sustainable circular economy. In their study, they provided a comprehensive overview of the separation process of the c-Si modules and analyzed attempts to develop modules for easy recycling. In addition to the environmental impacts of PV systems, Sica et al. [14] also considered the possibilities of recycling PV modules. They promoted a method known as the circular economy, which reduces waste and improves resource efficiency.

Jing Tao et al. [15] investigated three different methods of recycling PV modules: recycling production waste, processing and reusing discarded modules, and recycling EoL modules. For each route, the current technology and the advantages and disadvantages were examined. The advantages and difficulties of recycling PV modules from an economic and environmental perspective were also addressed.

A summary of the recycling methods and difficulties in recycling PV modules from first and second generation was presented by Gahlot et al. [16]. They focused on the application of different pretreatment and extraction processes to recover metals and essential elements from different types of PV modules. Additionally, they evaluated the economic worth, environmental effect, and global trends of recycling PV modules. They provided a projection for the future path of the recycling industry and proposed a comprehensive strategy for metal recovery.

The recycling of photovoltaic modules is important from an economic and environmental point of view, according to Wang [17], who noted that solar energy produces a lot of waste. There are differences between recycling PV modules and recycling electronics, and the components used in PV modules can be recycled both mechanically and chemically.

A novel technique for recycling silicon photovoltaic modules was presented by Dias et al. [18] and involves deframing, shredding and electrostatic separation. This technique yields a valuable mixture of metal and silicon, while a mixture of glass, silicon and polymer is of lesser value. The technological, environmental and economic advantages of the proposed technique were compared in the article with those of a full recycling system and landfilling. They suggested that the proposed method can be more profitable than full recycling and is superior to landfilling in certain cases.

Lin et al. [19] discussed the development trend of the c-Si solar cell market and analyzed its physical structure and composition. They also discussed recycling technologies for c-Si solar cells. They analyzed manual disassembly, dissolution with inorganic acid, a combination of thermal and chemical methods, and dissolution with an organic solvent, and they list the shortcomings of each processing method.

The economic viability of recycling PV modules was assessed by D'Adamo et al. [20] under different market conditions and costs. They showed that without avoiding landfill expenses, it is not economical, but when a high value is given, it becomes lucrative. They recommended that decision makers link the costs of PV module disposal with the benefits of recycling.

Wang et al. [21] analyzed the barriers to recycling PV modules. According to the study's results, the main barriers to PV module recycling are the difficulty of implementing serial recycling processes, large investments, lack of incentives and a small market. It is expected that after about ten years, the price of the initial investment will decrease and the market will grow, but the impact of insufficient infrastructure will increase.

Isherwood [22] pointed out that with the rapidly growing market for solar modules, it is crucial to prepare for the extensive recycling of used PV modules. PV cell material separation and extraction can be carried out manually, mechanically, chemically (dry or wet) or by a combination of these approaches.

Tembo and Subramanian [23] described in their paper the operations carried out in the high-value recycling process and products as a result of recycling. The paper also addressed the environmental impacts associated with the recycling of PV panels. Finally, the paper presented the status of global photovoltaic waste management policies with a focus on major markets.

The recovery of silver and indium from old CIGS PV modules using various concentrations of nitric acid was investigated by Teknetzi et al. [24]. They also investigated whether it was possible to remove zinc as an impurity and what influence the acid concentration had on the purity of the leached metals. They discovered that although the recovery of silver and indium increased with a higher pH and surface/liquid ratio, the impurity also increased. They suggested that the purity of silver could be improved by selectively removing zinc with a low acid concentration.

The manufacture of PV system components and their recycling at EoL may use or generate toxic materials harmful to human health and the environment. The literature has sufficiently addressed this problem as well.

For subgroups of children and adults, Nain et al. [25] assessed the risks to the environment and human health from dermal exposure and ingestion of the likely fate and transport of leached metal contents from solar arrays. The results showed that children are at the greatest risk of lead poisoning. Metals such as cadmium, lead, indium, molybdenum and tellurium, if they come into contact with the skin, can adversely affect children and adults. Exposure to polluted soil leads to an overall hazard index of more than one. Exposure to lead leads to a significant cancer risk every time, while other metals expose people to a manageable non-cancer risk. Piasecka et al. [26], by applying the Life cycle Analysis (LCA) approach, analyzed the materials used in PV power plants from an environmental and energy point of view.

The most damaging to the environment are solar panels that are discarded in landfills after usage. The metals PA6, cadmium, nickel, copper, lead and silver are the most hazardous to human health and the environment.

Recycling processes could reduce the environmental damage they cause. Guidelines for the environmentally acceptable reuse of solar power plant parts and materials have been proposed. The proposed model based on the entire recycling process at the EoL of a PV system was applied by Mulazzani et al. [27] to analyze the energy consumption of different recycling technologies. The conclusion of their analysis was that c-Si modules can be recycled with a low energy consumption of 130–300 kWh/tons of PV module, with an estimated total recycling rate of about 84%.

In this paper, the authors make projections for the amount of waste in Europe in the original scenario, assuming an average lifespan of PV systems of 27 years, based on data on installed PV capacity from 2000 to 2022. In addition to a summary of the current status of available technologies for recycling, the economic and environmental aspects of the problem of PV module recycling are presented, as well as the related current status and perspectives in some Balkan countries. The aim of this paper is to give warning of the current economic unprofitability of PV module recycling and the need to take appropriate measures to prevent PV waste from ending up in landfills.

2. Materials and Methods

In the introductory part of this work, the significance of the topic was presented on the basis of information from various literary sources. These literary sources were searched for in the scientific databases Web of Science and Scopus using the keywords "recycling of PV systems" and "end of life of PV systems". Other databases such as Google Academic, Wiley Online Library and PubMed were also searched. In addition to the data published in academic journals, important data from IRENA, IEA and official documents of the European Union (EU directives and EU solar strategy) were collected. In the introductory part, it was shown that PV waste can pose a significant risk to the environment if not properly treated and that recycling is a necessary option in this sense.

In the second step, the importance of the analyzed topic was underpinned by numerical indicators for the amount of PV waste that will be generated in the coming period. These numerical indicators were calculated based on the assumption of an average lifetime of PV modules of 27 years [28], the data on installed PV capacities from 2000 to 2022 and the average PV mass ratio per unit of power (t/MW) for the period from 1980 to 2050. The report by IRENA [29] shows that the mass of the module decreases exponentially over time, from 145 kg/kW in 1990 to 45 kg/kW in 2050. The authors also calculated the average mass of modules per unit of power for the year 2023 based on the mass of representative standard types of photovoltaic modules from leading manufacturers of PV systems and obtained a value of 51 kg/kW [30]. By combining the above data and comparing the calculation of waste for the actual unit mass for individual years and the average unit mass for the entire observed period, data on the average unit mass of the module of 60 kg/kW were obtained.

In the third step, the components of the PV module and their mass fractions (%) in the module are shown to see which materials are most represented in the PV module. If the proportions of each material in the PV module and the average mass of the module per unit capacity are known, it is easy to calculate the mass of each material for the installed capacity.

The fourth step describes the approaches to disassembling the module into its components and the possibility of recycling individual components. Also, if the recycling rate (which changes as technology improves) is known, the mass of materials that can be recycled and returned to the PV module manufacturing process can be calculated.

In the fifth step, the economic aspect of recycling is reviewed, and other barriers to the efficient recycling of PV modules are also listed.

In the sixth step, an overview is given of the current state of PV waste management in Europe and the available infrastructure for recycling, with a particular focus on the Balkan countries. In order to obtain information on the current situation of PV module recycling in neighboring countries, an interview was conducted with waste management companies in Croatia and with representatives of the university community in Slovenia, Serbia and Hungary.

3. Results and Discussion

The typical predicted life of a PV module is about 25–30 years. This time frame may be shortened due to damage during transport and installation, early failures following commissioning, technical and physical failures during operation brought on by adverse environmental conditions [31] and unanticipated outside influences, such as natural catastrophes [32]. The question arises as to what happens to the components of the PV plant when they reach the EoL.

EoL management for PV systems implies the processes that are used when PV modules and other system parts are retired. The decommissioning, dismantling, disposal or recycling are some of these operations. In view of the planned large capacities of PV plants, it is logical that huge amounts of waste will be generated from PV systems at the EoL. With PV waste rising from 0.1% of new installations in 2016 (43,500 tons of waste) to over 80% in 2050 (about 60 Mt of waste), there will be a greater demand for efficient EoL solutions [7,29].

But first, we will take a look at the main components of a PV system:

- Photovoltaic module;
- Assembly (support structure);
- Inverter;
- Electrical conductors—wiring;
- Junction boxes/protection devices;
- Batteries (stand-alone PV systems);
- Electricity meter (systems connected to the grid).

The EoL of PV modules is usually defined by a 20% drop in performance compared to the original. This means that the modules are still functional. After this period, they are replaced by new ones, or not at all, depending on the financial possibilities of the owner, government incentives, economic viability, energy prices and other factors.

Since it is difficult to calculate the amount of waste that will be generated in the coming period based on the previous definition, the data from Figure 1 on annually installed PV capacity and the assumption of an average PV system lifetime of 27 years were used for the calculation. Assuming that the mass of the module for the observed period is an average of 60 kg/kW, this results in a waste quantity of 60 tons per MW of installed capacity. The calculation shows that 96,000 tons of waste from PV modules will be generated worldwide by 2030 and about 86 Mt by 2050 (Figure 3).

Based on data from IRENA [33], by 2030, Europe will cumulatively generate about 35.5 thousand tons of waste from c-Si modules and 1.9 thousand tons of waste from thin-film modules. By 2050, there will be about 15.3 million tons of waste from c-Si modules and 0.6 million tons of waste from thin-film modules. Figure 4 shows the estimated mass of PV modules in Europe that will reach their EoL in certain years.

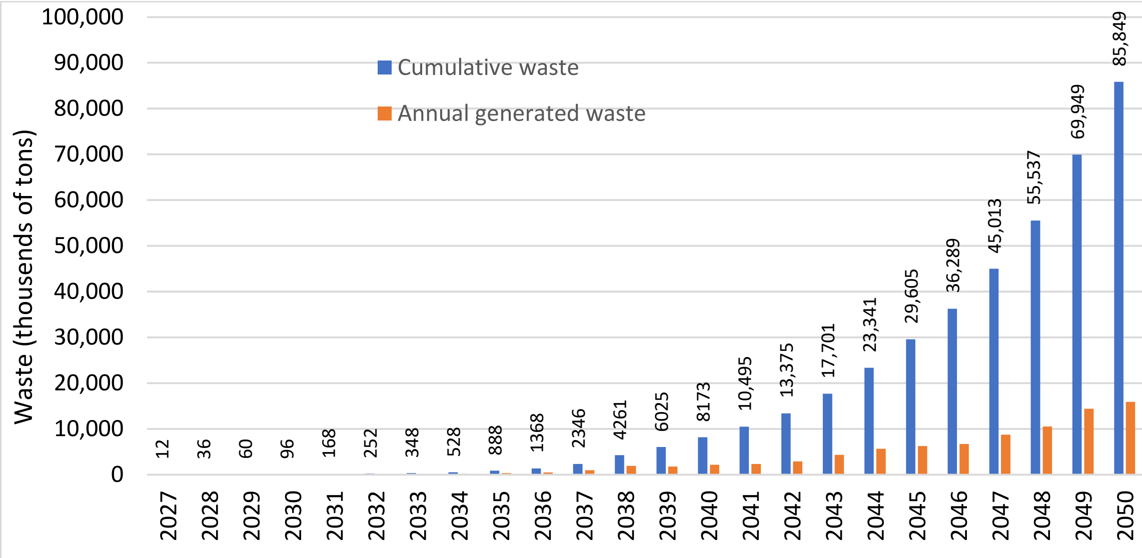

Figure 3. Estimated amount of global PV waste.

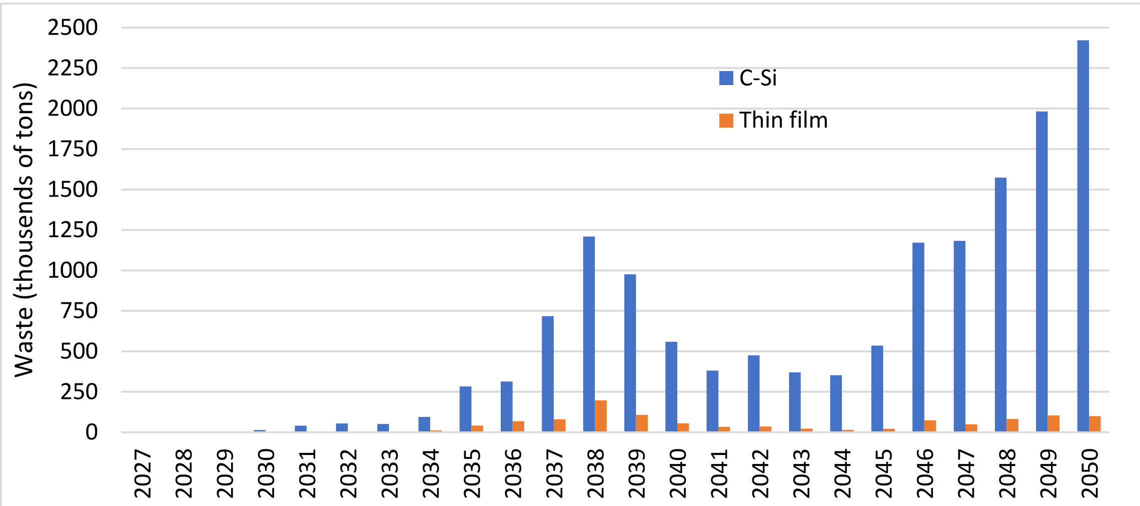

Figure 4. Estimated yearly amount of PV waste in Europe (based on data from Fraunhofer Institute for Solar Energy Systems [5] and data from IRENA [33]).

The indicated amount of waste does not include the mass of the support structure. The literature mentions a similar amount of 60 to 80 Mt by 2050 [34–36]. The quantity of waste increases significantly if the inverter's and wires' bulk are included. This can support the sustainability of the long-term supply chain [37], promote the recovery of energy and embedded materials, reduce CO_2 emissions and shorten the energy payback time by releasing about 78 Mt of raw materials and other essential components globally by 2050.

If we analyze the data for Europe in more detail, we come to the following conclusions. By 2030, most PV waste will be generated in Germany (26,100 t), the Netherlands (2760 t), Italy (1560 t), Austria (1380 t), Spain (1320 t) and Switzerland (1320 t). There will be an enormous increase in PV waste in the periods 2031 and 2040, as well as 2041 and 2049 (Figure 5).

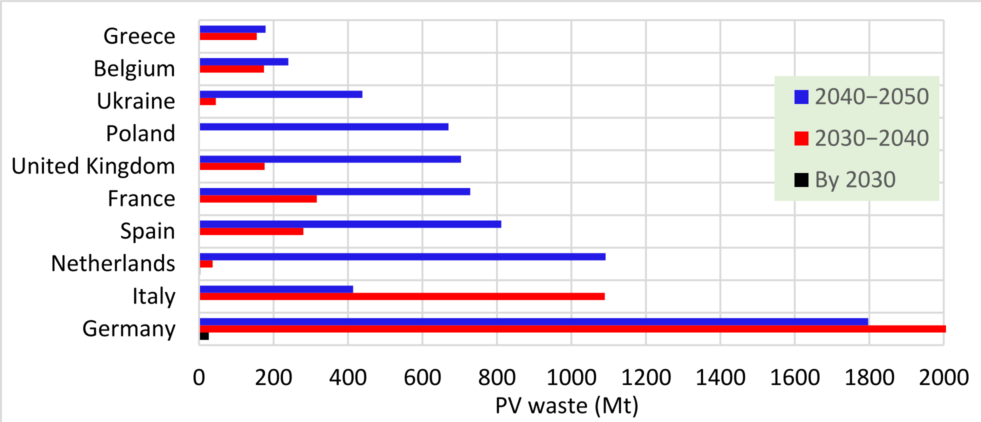

Figure 5. Estimated amount of PV waste for selected countries (based on [5,33]).

The EU-27 member states that will generate the least PV waste by 2049 are Latvia (3369 t), Ireland (8116 t), Croatia (10,938 t), Malta (13,260 t), Luxembourg (19,150 t) and Cyprus (25,860 t). Of the other countries in Europe that are not members of the EU 27, these are Iceland (420 t), Montenegro (1332 t), Albania (1716 t), Northern Macedonia (5096 t), Bosnia and Herzegovina (6448 t), Serbia (8220 t) and Norway (19,280 t).

PV modules can occasionally be reused or refurbished to have a "second life" as power producers after operating for around 27 years. It is known that the annual efficiency of c-Si modules decreases by about 0.56–2.96%/year during their lifetime [38]. For many PV cell applications, high efficiency is not important, so in this case, reusing old but still functional modules is fully acceptable. This approach includes thoroughly cleaning the module, checking for defects or damage, repairing or replacing damaged components and testing the module for functionality. If they pass the test, the modules can be recertified before being sold for reuse [39]. How much calculated waste is sent for reuse is difficult to estimate.

All PV systems, however, ultimately approach the end of their useful lives. While weather damage and improper installation account for the majority of end-of-life issues, some customers and system operators elect to replace PV modules before the warranty expires or take advantage of technological advancements.

Reuse and recycling provide benefits over disposal in landfills or incinerators from an economic and environmental standpoint. The primary goals of recycling PV modules are to minimize remaining waste, increase recovered material for future manufacturing, and reduce associated energy use and emissions. This is especially crucial in light of worries about probable shortages of materials needed to achieve worldwide decarburization and electrification [40–44]. Reuse is the process of utilizing modules or pieces of modules for new applications, such as construction materials, creative endeavors or educational assets [45]. Furthermore, recycling and reuse may both lead to the development of new sectors and jobs in the circular economy. While recycling involves many more processing stages and yields lower income, module reuse provides more money with fewer processing steps [46]. Finding a market that is large enough and sufficiently sustainable to accommodate the huge amount of modules that are being retired is the primary barrier for module reuse. In Sweden, for example, the promotion of reuse and repair centers and tax relief for repair shops have been proposed. Social behaviors could be a crucial role in the development of secondary PV markets and the management of EoL PV, as psychological and behavioral characteristics often undermine the viability of technical solutions [47].

It should also be noted that about 99% of the photovoltaic modules collected today have been damaged in some way during their operation or during transport at the end of their life. In most cases, the glass panel is broken and cannot be economically repaired or replaced.

3.1. Photovoltaic Module

Solar modules are the most significant component in the context of PV system end of life. In a PV module, several photovoltaic cells are connected together with copper wires soldered with tin and lead to form modules. These modules are encapsulated in adhesive-like layers of EVA, the back is covered with polyethylene terephthalate and polyvinyl fluoride, then a cover glass is added and everything is placed in an aluminum frame (Figure 6).

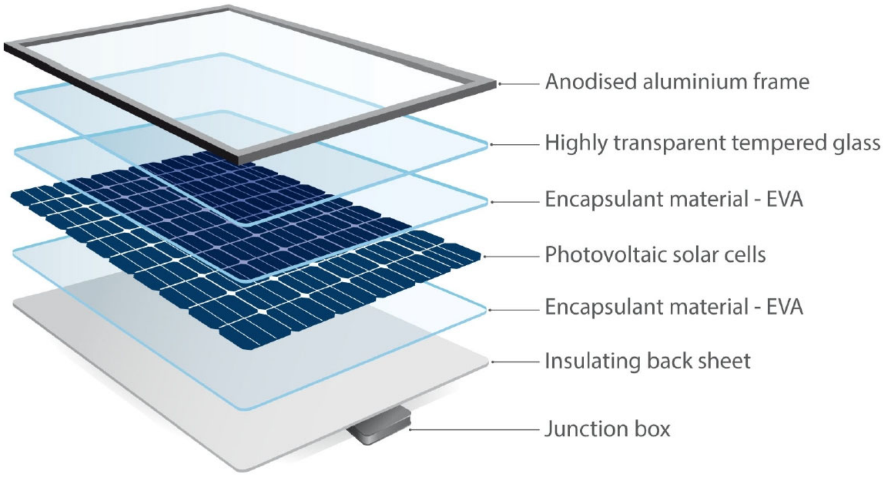

Figure 6. Assembly view of solar PV module. (With permission of GSES [48]).

Data on the type, quantity and percentage of materials that make up the components of the PV system are necessary to obtain a complete picture of the recovery of the photovoltaic module (Table 1). In addition to silver, aluminum is another component of metallizing pastes that has not yet been addressed. For a 166 × 166 mm^2 monofacial cell, about 750 mg of aluminum are needed [49]. Since the backside grid layout only needs around 25% of the analogous monofacial cell with full-surface aluminum metallization, bifacial cells contain substantially less backside aluminum. For thin-layer modules, the mass fraction of glass and aluminum is over 95% [50].

Table 1. Components of c-Si solar module [32,51].

Item/Material	Content (kg/kWp)	Mass Fraction (%)	Remark
Frame—Al	12.771	18	Al scrap suitable for producing secondary Al
Poly c-Si chips—Si	3.101	4	Recovery rate of silicon ~95%
Silver bar line—Ag	0.03	0.05	Electrolysis or leaching solution deposition is applied
Cu busbar and tabbing	0.451	2	Recovery from cable scrap (~97%)
Top surface—tempered glass	54.721	70	Glass cullet for glass production
Backsheet layer—polyvinyl fluoride	17.091	1.5	Energy recovery from incineration process
Encapsulation layer—ethylene vinyl acetate (EVA)		5	Energy recovery from incineration process

There are several ways to recycle solar panels. Most of them involve some or all of the following listed processes [52,53]:

- Separating the junction box and frame from module;
- Separating the encapsulant from the laminated construction
- Separation of the glass panel and c-Si cells via thermal, mechanical or chemical processes;
- Extraction and purification of c-Si cells and important metals (e.g., silver, copper, tin, Al and lead) via electrical and chemical processes.

Recycling technologies are mature for mono or multi c-Si modules. PV modules that are not based on silicon require the use of various recycling technologies. PV modules based on cadmium telluride (CdTe) are first shredded into different fractions, and then chemical baths are applied to separate the different semiconductor materials, enabling the recovery of 95% of the components. The technologies for recycling this type of PV module have made great progress in recent years, but for other thin-film types, there are opportunities for further improvements [45].

After processing at the first recycling facility, the materials recovered from the PV modules are transferred to another destination like smelters, processing factories and secondary markets for further recycling or processing.

3.1.1. Mechanical Approach

The mechanical approach for deconstructing modules involves processes of crushing and/or pulverization, resulting in larger or smaller granules. In addition, thermal processes can be used to separate individual materials contained in the grains obtained. In crushing and/or shredding, the modules are processed into gravel using suitable machines such as hammer mills and crushers [54], with the aluminum frame and junction box being removed first (Figure 7).

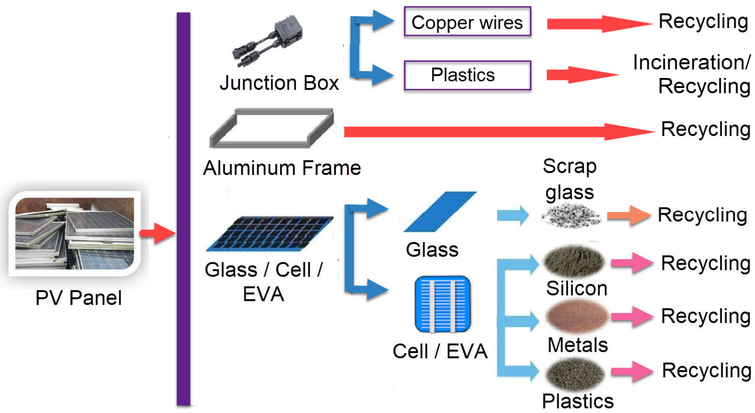

Figure 7. Mechanical approach to recycling.

The module frame can be easily and completely recycled with very little energy input (8 MJ/kg) [50]. This is important considering that the energy consumption in the primary production of aluminum is very high (about 200 MJ/kg Al) [55].

After mechanical grinding, the resulting granules can be sorted with an electrostatic separator. In electrostatic separation, materials are classified on the basis of their electrical conductivity. Contrary to hydrometallurgical and chemical processes, the electrostatic separation is viewed as an effective, efficient mechanical method that uses less power than thermal processes and generates no waste [56]. Electrostatic separation requires a high degree of control and calibration of the electric field and power supply characteristics. Even small variations in voltage, humidity, temperature or composition of the source material will affect the performance and quality of the separation. An eddy current separation method that uses an electrical vortex to separate crushed material can also be used. The particles are separated according to their conductivity and shape [57].

Shredding the module and using it as mixed glass cullet is now the most popular method for recycling photovoltaic modules. Scrap glass can be used as raw material in the glass industry. When applying the module crushing process, various techniques can be used to separate the different components after the granules have been obtained. These include separation processes based on particle size, such as screening, flotation and froth flotation processes analogous to those used in mining processes, wear-based delamination, chemical washing processes, which may also include additional treatment and filtration processes, thermal processes, such as pyrolysis of polymers, or a combination of the aforementioned processes [53,54]. In the mechanical screening method, granules are sorted by size, shape and thickness, and in the case of silicon, a yield of more than 85% can be achieved. The method is practical because it requires the least amount of energy and does not require chemical reagents [58].

Another option is to use the cells as silicon waste and feed them into the silicon manufacturing process. Alternately, they may be put through a succession of chemical etching procedures to create "virgin" wafers that could be used to create fresh cells [59–61].

There is also a method that uses infrared heaters and a vibrating knife to cut the panel glass. This recycling method is used by the Italian recycling company, Tialpi [9]. As much as 98% of the glass can be extracted, and the rest of the EVA/solar cell/back panel sandwich is incinerated [62].

3.1.2. Thermal Approach

Unlike the mechanical approach, there is no crushing involved. In thermal delamination, the components are separated from the panel with the intention of reducing damage to the key parts, especially the cells. Delamination of modules is mainly applied to c-Si modules. After the module has been layered, the glass pane and the aluminum frame are fed into the further recycling stream and the undamaged silicon wafers are further processed. The separated cells can be cleaned, tested for functionality and efficiency and used directly for the production of new modules. However, over the last decade, PV cells have become much thinner [5] and therefore have less strength, making them more susceptible to damage and cracking. Consequently, more modern modules are unlikely to produce a large quantity of undamaged cells, especially since even the most careful deconstruction of the module leads to further cell damage [15].

Since EVA is used as an encapsulation material, its separation is key to delaminating the module. This can be achieved via heat treatment (pyrolytically decomposing of EVA) and sometimes via the burning of the EVA and the back wall material. Delamination can also be carried out with a cryogenic process, as described in the study by Dassisti et al. [63].

The thermal process consists of heating the PV module in a suitable oven to a temperature of 420 °C to 500 °C, with the temperature rising by about 20 °C/min. The process usually takes about 30 min. The plastic evaporates and the PV cells detach from the glass [50]. This can be conducted in the open air or in an inert atmosphere [15,60,64]. Pyrolytic delamination can also be performed in fluidized bed reactors and muffle furnaces with heat recovery of collected combustible gases [62].

Although the recycling process uses energy, up to 85% of the recovered cells can be reused, which reduces energy consumption by up to 70% for the production of new PV modules. This process can be utilized for commercial PV module recycling, with better outcomes than the chemical method due to its simplicity and high efficiency. The duration of the thermal process is significantly shorter compared to chemical processing. In addition, there are no problems with solvents. The production of hazardous gases during the thermal evaporation of the EVA polymer is a drawback of thermal recycling. These are mainly hydrogen fluoride (HF) produced by the fluorinated compounds typically used in backsheet polymers [46,65].

3.1.3. Chemical Approach

Typical chemical techniques for dissolving EVA include employing nitric acid, solvents, or solvents in combination with ultrasonic irradiation [46,61]. The main problem is choosing the right composition of etching solutions, their concentration and the optimal process temperature. The price of the chemical compounds used is high, both because of their nature and their quantity. The additional cost of disposing of the waste solution must also be taken into account in chemical treatment. The excessively long time needed to achieve satisfactory results, combined with the relatively high price of the solvent used and the need to dispose of the spent solvent, do not suggest that the chemical method would be suitable for the commercial recycling of PV modules.

Accordingly, the recycling process requires mechanical, thermal or electrical energy to separate the individual parts of the module. It also needs the use of specific chemicals and water, which results in certain kinds of gas emissions. However, the burning of non-recyclable parts beyond a certain amount of energy also emits dangerous gases. The removal of EVA and the extraction of metals with the least amount of formation of harmful gases and waste water are the key challenges in recycling PV modules [66].

High value recycling aims to recycle not only the glass and Al frames but also the more valuable materials contained in the cells such as Ag, Si, Al and Cu. After a solution leaching or etching process, this can be achieved via electrolysis, metal replacement or chemical deposition. With the last mentioned method, the highest utilization rate of 99.5% can be obtained [67].

Materials for which no efficient recycling process is recommended are polymers, especially the encapsulation of the board (usually EVA) and the backsheet foils (polyethylene terephthalate). The lack of interest in recycling these materials is due to the fact that they are difficult to recycle and economically unviable [12].

3.1.4. Environmental Impacts of Recycling PV Modules

PV module disposal in landfills can take up a lot of space and limit the amount of land available for other uses. Landfilling may also contaminate the soil and allow harmful compounds like cadmium, lead and selenium to leak out of PV materials [68]. By recovering valuable materials and lowering the demand for raw material extraction, recycling may have a positive influence on land usage.

Water can be used in large quantities in the washing, rinsing and material separation processes during the recycling of PV modules. Especially in areas with limited water supplies, water consumption affects the quantity and quality of water resources. The use of closed loops, water-saving technologies and alternative solutions can reduce the amount of water consumed. The recycling or disposal of PV modules can result in the production of a variety of pollutants, including noise, wastewater, solid waste and gas emissions. CO_2, methane, nitrogen oxides, sulfur oxides and volatile organic compounds are some of the gases emitted. There is also particulate matter. Wastewater can contain contaminants such as metals, acids, bases, organic solvents and others.

The greenhouse gas emissions associated with PV installations can also change depending on whether the PV modules are recycled or sent to landfill. Recycling can reduce emissions by saving energy and resources that would otherwise be used to manufacture new PV modules. According to Muller et al. [69], an energy reduction of 70% is possible when recycled Si is returned to primary production. By causing the organic elements in the PV modules to break down and release methane, landfilling can increase emissions. When compared to alternative end-of-life choices, CO_2 emissions from recycling PV panels are generally low and depend on the kind of panel. If recycling is powered by renewable energy sources, they can be decreased even further.

Glass, metals, plastics and other materials that are not recovered or repurposed might be considered as solid wastes. If not treated appropriately, the PV modules may contain dangerous substances that endanger both human health and the environment. Lead (Pb), antimony (Sb), copper indium gallium selenide (CIGS) and cadmium telluride (CdTe) are a few examples. When ingested, breathed in or absorbed via the skin, these substances have the potential to be harmful, carcinogenic, mutagenic or teratogenic. By using less harmful or more recyclable materials and technology, hazardous materials can be avoided.

When PV modules are landfilled or burned, they can release harmful elements like lead and cadmium into the groundwater and soil. Workers handling the panels during recycling are at danger from these metals, especially if they are exposed to dust or fumes.

It is important to emphasize the positive effects of recycling PV modules. A cradle-to-grave study shows that recycling PV modules at the end of their lifecycle can reduce terrestrial ecotoxicity by 74%, human toxicity potential by 26%, global warming potential by 24% and acidification by 37% [70].

3.1.5. Economical Aspects

The cost of recycling PV modules depends on several factors, such as the following:

- The type and composition of the PV module, which affects the complexity and efficiency of the recycling process and the value of the recovered materials;
- Recovery rates;
- The location and availability of the recycling facility, which affects transport and logistics costs as well as environmental regulations and standards;
- Annual amount of PV waste processed in the recycling plant;
- Market conditions and demand for recycled materials which affect the turnover and profitability of the recycling business;
- Silver (Ag) concentration in PVs and Ag prices.

In most recycling plants, the actual processing volume is less than 100 tons per year. Some plants accumulate PV modules until they have collected a sufficient amount for processing [7]. As the capacity of these plants is currently low, the processing cost per unit is likely to be high. Furthermore, the materials that make up the module are usually difficult to separate and are of little value. At the same time, silver accounts for 47% the value of the material but less than 1% of the mass of the module [9]. As far as recycled glass is concerned (75% by mass, 8% by value in PV module), its use is usually limited to less valuable products where high transport costs are a major problem. Therefore, currently, in most countries, the costs of recycling are higher than the revenues for the recovered materials.

There are some data on the level of recycling costs. According to one source [71], the average cost of recycling PV modules in 2020 was USD 28 per module. The cost of recycling a silicon PV module in the USA is about USD 15–45, while landfilling costs are only USD 1–5. To shift this ratio in favor of recycling, cheaper recycling methods need to be developed and taxes on waste disposal increased [9].

Granata et al. [72] states that the profitability threshold of a PV waste module recycling plant is 19,000 t/year. According to the aforementioned data from IRENA [33], the threshold of 19,000 t/year will be reached first by Germany (2031), then by Spain (2034), Italy (2035), Belgium (2036), the Czech Republic (2036), France (2037) and the United Kingdom (2038). If higher co-financing of recycling and higher recycling efficiency is assumed, the profitability limits of plant operation can be reduced to 9000 t/year PV waste. But even in this case, the results do not differ significantly; Germany reaches this threshold in 2030, France in 2036, Greece in 2037 and Austria in 2039.

What should be highlighted, in any case, are the countries that will not reach the threshold of 9000 t/year of PV waste at all (or only after 2047), and these are Bulgaria, Romania, Slovenia, Finland and Slovakia, in addition to the listed countries that generate the least PV waste.

This shows that most countries in Europe will have a problem with the economic viability of recycling PV waste. Therefore, in these countries, recycling PV waste will require much more funding from producers and distributors (and perhaps also from the government). As a possible solution to this problem, it is proposed to establish recycling facilities in certain areas of Europe, covering several countries and/or regions.

3.2. Assembly (Support Structure)

According to Huang [73], the amount of material (mainly steel) used for the support structure is about 62 t/MW for PV systems with a capacity of 20 MW or more. Figure 8 shows a typical supporting structure. Assuming that 53% of the installed capacity is utility-scale PV power plants [30], about 39 Mt of PV waste will be produced by 2050.

The mounting structure for rooftop PV power plants consists mainly of Al profiles. The mass of these profiles is about 4.4 kg/kW. Assuming that rooftop PV power plants account for 47% of the installed capacity, about 2.45 Mt of waste from the mounting structure will be generated by 2050.

Figure 8. The supporting structure for utility-scale PV systems (Slavonski Brod, Croatia).

3.3. Inverters

The second most crucial component of the PV system is the inverter. Since solar inverters typically last 15 years, most systems need to replace their inverters at least once throughout their lifespan. By 2050, this will result in a significant amount of end-of-life inverters. The recycling of the inverters is a difficult process that takes into account a number of technical, financial and environmental factors. A lack of uniform inverter design and labeling is one issue with inverter recycling that makes it challenging to distinguish and separate the various parts and materials.

Printed circuit boards (PCBs) account for 40% of the inverter's mass and are 65% recyclable, while metals account for 60% of the inverter's mass and are 90% recyclable [74] (Table 2).

Table 2. Materials used in the inverter and their treatment methods [74,75].

Material	Material Share (%)	Method of Treatment
Plastic	0.44	60% recycling, 40% incineration
Metal	59.39	90% recycling, 10% disposal
PCBs	38.93	65% recycling, 10% incineration, 25% disposal
Wiring	1.05	
Rubber	0.19	100% incineration

According to Table 2, 79.70% of inverters can be recycled, 4.37% can be incinerated and 15.93% can be safely disposed of in a landfill [74]. Recycling inverters can lessen the environmental effect of mining and produce new materials by recovering valuable resources like copper, aluminum, steel and plastics.

3.4. Electrical Conductors—Wiring

According de Araújo et al. [76], recycling cable wires is a proven process. The cable wire raw material first goes into the shredder and then into the crusher to obtain the small wire pieces (Figure 9). Then, the copper is separated from the plastic in the air classifier using weights and the force of friction or by sieving in screens. To improve purity and capacity, the remaining material is fed into a high-voltage electrostatic separator.

The entire process of recovery is covered by the dust collection system. By recycling electrical conductors, approximately 97% of the material invested can be recovered, and by burning the polymer, additional energy of 2.87 MJ/kg can be obtained [32]. The crushed wires are usually sold in the form of copper shot.

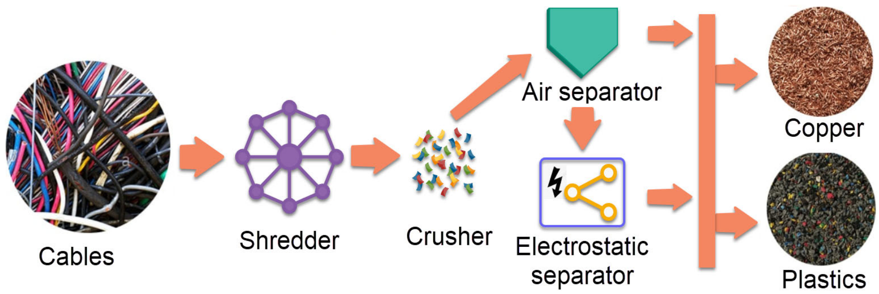

Figure 9. Recycling of wiring.

3.5. Junction Boxes/Protection Devices

The PV module junction box contains the electrical connections of the module, including the connections of the PV array and the bypass diodes. The PV modules' junction boxes are typically manually disconnected in most cases. They are then dismantled and the materials recycled according to the usual procedures for electronic scrap. The box is made of thermoplastic filled with hardening silicone (for insulation). It is possible to separate the components, but this is usually not economical. In order to eliminate the plastic, the most popular technique is to burn it, preferably with energy recovery [77]. The junction box's wires have a copper conductor inside that is separated from the plastic in the recycling process.

4. The Situation in Europe Regarding the Recovery of PV Waste

In Europe, there is a website (http://www.solarwaste.eu/, accessed on 20 September 2023) that explains the legal implications of the WEEE Directive for the PV sector and provides a wealth of information and resources for anyone interested in the disposal and recycling of PV modules in the European Union. This website is managed by PV CYCLE, a European non-profit association.

The problem in Europe is the annual amount of PV waste, which, in most countries, is far below the threshold for economically viable recycling. Consequently, there are few plants that can recycle modules. However, there are PV panel recycling companies in Europe that operate according to recycling standards set by national regulations. For example, the companies Veolia and PV CYCLE opened the first European facility for recycling EoL PV modules in Rousset (France) in 2018. The facility aims to process 4000 tons of PV waste per year, which represents around 65% of all PV waste in Europe [78]. Reiling GmbH & Co. KG in Marienfeld, Germany offers a comprehensive recycling service for waste PV modules. The non-profit organization PV CYCLE offers a network of collection points and recycling facilities for PV modules throughout Europe. There are also a number of companies in the rest of the world involved in recycling PV waste. Some of these companies are as follows:

- First Solar, founded in 1999, Tempe, AZ, USA;
- Silcontel, founded in 2008, Haifa, Israel;
- Hanwha Group Co. Ltd., founded in 2010, Seoul, Republic of Korea;
- Suzhou Shangyunda, founded in 2010, Kunshan, China;
- SUNY GROUP, founded in 2011, Zhengzhou, China;
- Recycle Solar Technologies, founded in 2017, Scunthorpe, UK;
- Suzhou Bocai E-energy, founded in 2019, Kunshan, China;
- RECLAIM PV RECYCLING PTY LTD., founded 2014, Torrens Park, Australia.

The authors were interested in the situation of recycling in neighboring countries and contacted companies and institutions involved in waste management. In Croatia, the collection yards accept one or two PV panels. If there is a larger number of panels, then the disposal is taken over by companies that have a license for electronic waste. At the same time, they charge a disposal fee of EUR 1/kg of PV modules. The company separates the aluminum frame and wiring from the panel, the rest of the panel is crushed and ground, and the granulate is disposed of as non-hazardous waste. There is no company in Croatia that recycles panels and there are no short-term plans for recycling. There is aluminum frame, cable and plastic recycling, where only certain types of plastic are recycled and the rest are incinerated in a furnace at around 500 °C. The reasons given are the high investments in the plants, the low number of modules to be recycled and the lack of market for recycled raw materials, which leads to economic unprofitability. The situation is similar in Slovenia, where the possibility of receiving incentives from EU funds to start the recycling process is being explored. In Hungary, the government has tried in recent years to encourage certain companies to recycle PV panels, but without success. We have not found out what happens to the panels at the EoL, but it is assumed that most of them end up in landfills. In Serbia and Bosnia and Herzegovina, very little PV capacity is installed [79], so the amount of PV waste generated is very small. Therefore, these countries do not have facilities for recycling PV waste and it is questionable when they will have any. In addition to landfilling, Serbia also exports PV waste to Germany and Africa. A similar situation is likely in other countries that have not installed large PV capacities.

5. Challenges and Barriers in PV Recycling

We also need to be aware of the difficulties and issues associated with recycling PV modules. Some of them are as follows:

- The absence of a standardized and effective PV module collecting mechanism. There is no international law or incentive for PV module owners to recycle their equipment. Due to this, there is a low rate of recycling and a significant danger of illegally dumping PV modules.
- There is a deficit in recycling infrastructure and technologies.
- There is insufficient demand on the market for recycled or used PV modules.
- Consumers and stakeholders are not sufficiently informed and are not aware of the issue.
- The complexity and variety of materials and designs used in PV module designs. Due to the differences in each material's characteristics, several recycling techniques are needed. Because of this, it is challenging to separate and collect the PV modules' precious elements.
- The expensive and unprofitable practice of recycling PV modules. Recycling PV modules is often laborious, energy-intensive and technically challenging. Recycling costs can be higher than the value of the recovered materials.
- Regarding the potential market for PV module reuse after reaching their technical EoL, the biggest obstacle is the lack of regulations. For example, old modules may not comply with the new standards, warranty conditions usually do not exist and the government does not offer incentives for such modules. If a larger number of modules is needed, there is also the problem of how to find modules with similar performance that can be connected in a series.
- There is a great danger that in many countries, for economic reasons, PV waste will be disposed of in landfills instead of being recycled, thus polluting the environment.
- To overcome these obstacles, the following is recommended:
- Establish and harmonize laws and regulations for the recovery of PV modules.
- The establishment of producer responsibility schemes is one of the means to promote the development and production of electrical and electronic devices that fully considers and facilitates its repair, possible upgrading, reuse, dismantling and recycling.
- Encourage the study and creation of cutting-edge techniques and technology for recycling and reusing.
- Legislation should be adopted requiring PV manufacturers to take full responsibility for the collection of PV waste, in particular, by financing the collection of PV waste throughout the waste chain, including waste from private households, in order to avoid separately collected waste continuing to be subjected to suboptimal processing and illegal export. The producer should have the option of either fulfilling this commitment on their own or as a member of a collective scheme.

- The collection, storage, transport, processing and recycling of PV waste, as well as its preparation for reuse, should be carried out with an approach that focuses on the protection of the environment and human health and on a circular economy.
- The European Union should finance the construction of regional centers for the collection and recycling of PV modules through various projects. We should examine whether it is a good solution for each country to have its own recovery center.
- Encourage market growth and value generation for used PV modules.
- Inform the public about the advantages and possibilities of PV module EoL management.
- Improve the design of PV systems for easier recycling by applying the approach of "Design for Recycling" (DfR) and "Design for the Environment". It is essential for product designers to be aware of possibly relevant recycling techniques in order to maintain a high level of recyclability. This facilitates the implementation of DfR in cases where the manufacturer is also a recycler for its own products [80].
- Appropriate rules and incentives are required to motivate participants along the supply chain to behave proactively and cooperatively in order to shift the PV supply chain from a linear to a circular economy. Some new circular business models for PV installations need to be applied, such as take-back, deposit–refund, product–service and others [47]. For example, SOREN is an accredited PV take-back scheme founded in 2014 by the French photovoltaic industry in order to fulfill its waste management obligations under the directive 2012/19/EU. It has collected about 15,000 tons of PV waste in the period from January 2015 to August 2020 [78].
- Significantly increase the fees for landfilling PV waste or ban it (Victoria in Australia, for example, has already banned the landfilling of PV waste). In this context, PV waste should be defined as a separate category in legislation.

By taking these steps, the whole community may ensure that PV modules provide clean energy during their useful lives as well as value and sustainability once they are retired.

6. Conclusions

Renewable energy sources have recently become more and more important, and in this sense the installed capacities of PV power plants have increased exponentially since 2010. Assuming a lifetime of PV plants of 27 years, capacities will reach the end of their lifetime in the period from 2027 to 2050. Proportionally to the increase in installed capacities, the amount of PV waste will also increase. Thus, by 2050, 15.3 million tons of waste from c-Si modules and 0.6 million tons of waste from thin-film modules will be generated in the EU. This huge amount of waste needs to be treated in an appropriate way so that it does not become a problem for the environment. This paper identifies three options for handling the waste generated: reuse, recycling and landfill. For each option, the advantages, disadvantages and associated problems have been listed. The recycling option have been analyzed in detail.

The recycling technology depends on the type of PV module. Recycling technologies are based on mechanical, thermal or chemical processes. Each of these approaches has its limitations, advantages and disadvantages. The most developed recycling technology is for c-SI modules, while recycling technologies for CIGS and CdTe modules can still be developed.

The least problematic is the recycling of the Al frame, support structure and wiring, for which well-established recycling processes already exist. Removing EVA and recovering metals while minimizing the formation of harmful gases and effluents are the biggest challenges in recycling PV modules. In thin-film PV cell technology, the content of hazardous components in the PV modules is the main problem in the waste management phase.

Although there is a legal obligation to recycle PV modules at the end of their life (in Europe, the basic law is the WEEE Directive), in practice, the recycling rate is not satisfactory. In many countries, the vast majority of PV waste is disposed of, as the presented analysis of the situation in some Balkan countries shows. Economic unprofitability and the lack of recycling infrastructure are cited as reasons for the low recycling rate.

In the literature, the profitability threshold of the PV module recycling plant is given as 19,000 t/year. In Europe, this threshold will be reached first by Germany (2031), followed by Spain (2034) and Italy (2035). It should be noted that some countries will not reach the viability threshold at all before 2050 (or only after 2047), namely, Bulgaria, Romania, Slovenia, Finland and Slovakia, in addition to the already mentioned countries that generate the least PV waste. This suggests that most countries in Europe will have a problem with the economic viability of recycling PV waste, which will require additional funding from producers and distributors (and possibly from the government). Additionally, a significant increase in PV waste disposal fees would also help.

In order to remove the barriers to more efficient recycling, certain measures should be taken, such as the establishment of regional recycling centers and the use of advanced techniques in the design of PV systems that facilitate recycling (e.g., "design for recycling"), and cheaper recycling methods need to be developed. In addition, regulations and laws for PV waste management should be developed and harmonized at the global level. Circular economy approaches to PV EoL are proposed that may provide chances to employ a safer management of hazardous materials, as well as environmental justice and benefits for society.

EoL is an essential aspect of a PV system's environmental sustainability that should not be disregarded. The environmental impact at that stage can be minimized and the positive aspects of PV systems can be increased by putting in place the proper waste management and recycling strategies and practices.

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