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Article

The End of Life of PV Systems: is Europe Ready for it?

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Abstract: Like other plants, every PV power plant will one day reach the end of its service life. Calculations show that 20,400 tons of PV waste will be generated worldwide by 2030 and 60.2 million tons by 2050, not including the mass of the support structure. Such large amounts of waste pose a potential threat to the environment and people if not properly managed. The paper analysed the options for dealing with PV waste, namely reuse, recycling and landfilling. For recycling as the best option in terms of environmental protection and circular economy, an overview of recycling technologies and the percentage of achievable recycling for the materials contained in each PV system component is given. In addition, the current situation of legislation and recycling of PV modules in Europe was examined with special reference to the Balkan countries. There are a small number of factories for recycling 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 and consequently the economic unprofitability. For this reason, PV modules (after dismantling the aluminum frame and cables) are mostly disposed of as non-hazardous waste in landfills in these countries. Finally, the main barriers to faster implementation of PV module reuse and recycling are listed, along with guidelines for their removal. The cost of recycling Si modules is about ten times higher than the cost of disposal. To change this ratio in favor of recycling, cheaper recycling methods need to be developed and taxes on landfill disposal need to be increased.

Keywords: PV systems; end of life; recycling; re-use

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 decarbonising energy systems. Based on the data from [1] and [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, 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].

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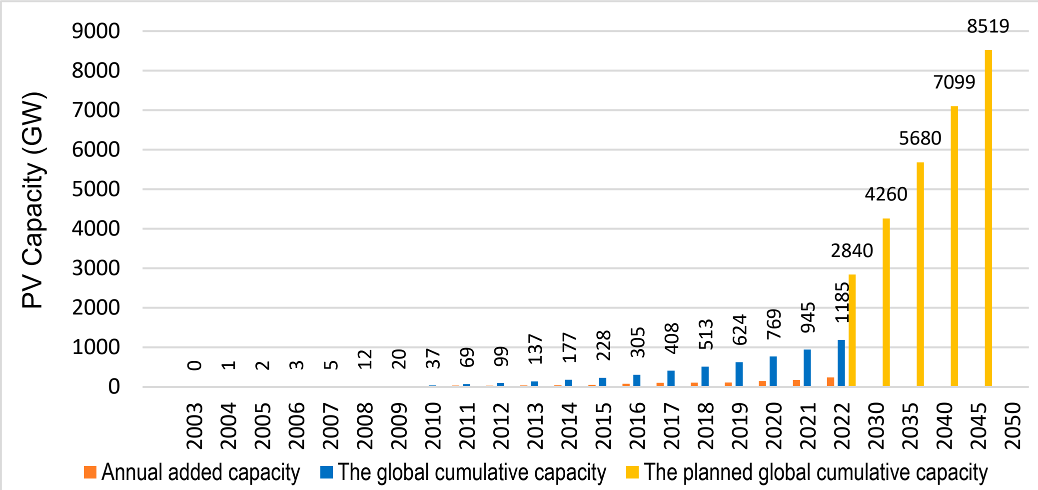

Figure 1. The Global PV capacity

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. Looking at the type of modules produced, it can be seen that the share of mono and poly- crystalline silica (c-Si) PV modules has steadily increased since 1988 (Figure 2). 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 of hazardous materials such as cadmium, tellurium, indium, gallium [4].

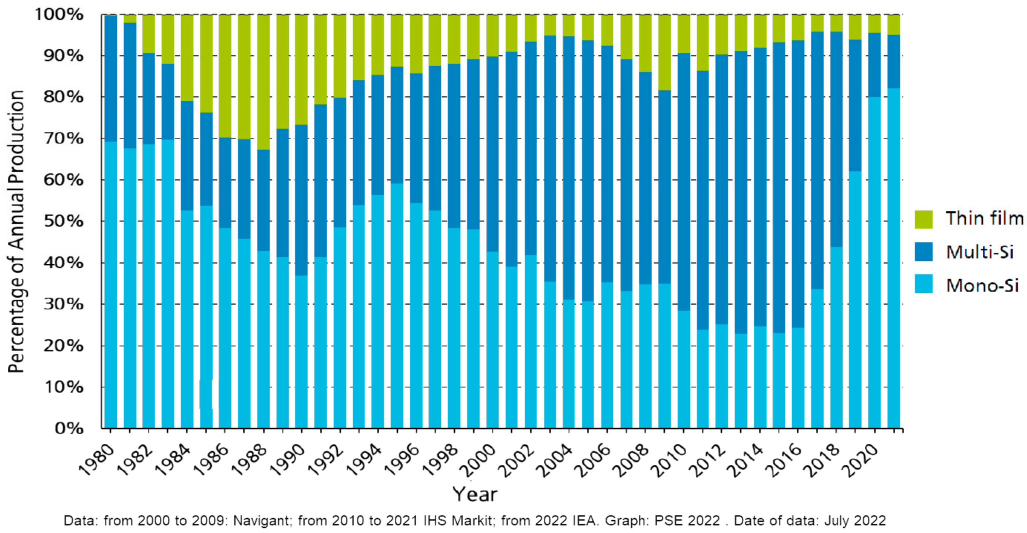

Figure 2. Percentage share of PV module production by year [4].

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

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 centres, 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 will take place in China, with the rest mainly in Europe and North America [4]. 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 the Europe with 17.7% and the North America with 12% [1]. Repowering is still relatively rare given the age of the oldest PV plants, but it is expected to increase in the near future. From this data, it appears that 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 [5], Germany, France, Italy and Japan are processed 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 [5] 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, could increase to 35% by 2030 and 70% by 2050 [6]. These projections include a 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 EOL. Extended producer responsibility (EPR), introduced by the European Directive on Waste Electrical and Electronic Equipment (WEEE) obliges producers and importers in each European member to organise 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 European Union. Although recycling is a viable option for PV panels, it is not the only option. According to 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 information that this is being implemented in practise.

In other regions of the world, 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 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. The costs of transporting photovoltaic modules to a recycling facility and high processing costs are cited as the main obstacles to recycling PV modules.

In South Korea, laws on EPR will come into force in 2023 and PV modules are classified as a separate product group. Based on the overall weight of the PV waste, recycling or reuse percentages should meet a need of over 80%. Even though there is now a lot of PV waste produced, most of it is landfilled [5].

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. First Solar, the world's largest PV recycler, has the largest capacity of 150 tons/day of thin-film CdTe PV modules. However, a recent analysis has shown that the limitations of current Si PV recycling technologies, the high cost

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of Si PV recycling and limited recycling capacity are the main barriers to PV waste management in the US [5].

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 innovation and development of intelligent photovoltaic industry (2021-2025) was published. During 2020, key equipment was developed for the mechanical and thermal-chemical method of recycling PV modules. The first PV module recycling demonstration line in China was built in 2021 with a overall recovery rate of more than 90% and an capacity of 110,000 modules per year.

1.1. Literature Review

When a power plant reaches EOL, the question arises of how to detreat its components in a way that minimises environmental impact, consumes the least energy, maximises recycling and is commercially viable at the same time. As more and more PV power plants reach 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 analyse 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 [7]. About 8 Mt of these modules could reach EOF by 2030, and about 80 Mt by 2050. He think that the available PV module recycling techniques are not efficient enough and are underutilized.

Dominguez and Geyer [8] assume that PV modules last average for 30 years and expect 9.8 million tons of PV waste in the US 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 22 billion dollars.

The most effective methods for recycling EOL modules were researched and proposed by Farreli et al. [9]. They focused on maximising 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 difficulties, opportunities, models and reasons for a critical review of closed-loop recycling.

Dias and Veit [10] assess 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. [11] point 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 provide a comprehensive overview of separation process of the c-Si modules and analyse attempts to develop modules for easy recycling. In addition to the environmental impacts of PV systems, Sica et al. [12] also considered the possibilities of recycling PV modules. They promote a method known as the circular economy, which reduces waste and improves resource efficiency.

Jing Tao et al. [13] investigate 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 are examined. The advantages and difficulties of recycling PV modules from an economic and environmental perspective are also addressed.

A summary of recycling methods and difficulties in recycling PV modules from first and second generation was presented by Gahlot et al. [14]. They focused on the application of different pre-treatment 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.

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Recycling of photovoltaic modules is important from an economic and environmental point of view, according to Wang [15], 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. [16] 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 are compared in the article with those of a full recycling system and a landfill. They suggest that the proposed method can be more profitable than full recycling and is superior to landfilling in certain cases.

Lin et al. [17] discuss the development trend of the c-Si solar cell market and analyse its physical structure and composition. They also discuss recycling technologies for c-Si solar cells. They analyse manual disassembly, dissolution with inorganic acid, a combination of thermal and chemical methods, and dissolution with an organic solvent, and list the shortcomings of each processing method.

The economic viability of recycling PV modules was assessed by D'Adamo et al. [18] under different market conditions and costs. They showed that without avoided 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. [19] analysed 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 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 [20] points out that with the rapidly growing market for solar modules, it is crucial to prepare for the extensive recycling of used PV modules. PV cells material separation and extraction can be carried out manually, mechanically, chemically (dry or wet), or by a combination of these approaches.

Tembo and Subramanian [21] describe in their paper the operations carried out in the high-value recycling process and products as a result of recycling. The paper also addresses the environmental impacts associated with the recycling of PV panels. Finally, the paper presents 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. [22]. 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 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 processed this problem as well.

For subgroups of children and adults, Nain et al. [23] 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 pose the greatest lead hazard. 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. [24], applying the 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.

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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 EOL of a PV system was applied by Mulazzani et al. [25] to analyse the energy consumption of different recycling technologies. The conclusion of their analysis is 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%.

2. Materials and Methods

The aim of this investigation is to analyse the existing techniques for dealing with components of PV systems at EOL and the problems associated with them.

The chapters and restrictions of the research were defined in light of the established study objective. Key questions, or keywords that may start a database search to get the needed answers, were identified for each content unit. The first step was to search scholarly databases including Web of Science, Scopus, Google Academic, Wiley Online Library and PubMed.

A large portion of the data was gathered from papers that were published in academic journals by publishers like MDPI, Taylor & Francis, Elsevier, and others, as well as from IEEE, relevant book titles, papers presented at international conferences, and specific scientific literature. The International Renewable Energy Agency, the European Environment Agency, and official European Union documents (EU Directives and EU Solar Strategy) all provided information to varying degrees.

Most of the data used in the analysis comes from articles issued in the last five years. The missing data comes from somewhat older but still accessible documents. Additionally, a technique called "snowballing" was utilized to find other publications based on the reference lists of research works that were discovered. In general, the research results are conducted and assessed according to available literature sources that have been published in the last seven years.

In this research, it was estimated that inverters would last between 10 and 15 years and PV modules would last an average of 27 years [26]. However, it should be mentioned that improvements in solar technology are increasing the lifespan of PV modules and decreasing their rate of deterioration over time.

The calculation method was also used in the part of the paper that analyse the total amount of waste from the PV system that will be generated by 2050 and also to determine the amount of particular materials that could be obtained by recycling the PV system.

To obtain information on the current situation of PV module recycling in the surrounding countries, an interview was conducted with waste management companies in Croatia, 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 and unanticipated outside influences, such as natural catastrophes [27]. The question arises as to what happens to the components of the PV plant when they reach 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 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 [5,28].

But first let's take a look at the main components of a PV system (Figure 3):

- Photovoltaic module
- Assembly (support structure)
- Inverter
- Electrical conductors – wiring

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- Junction boxes/protection devices
- Batteries (stand-alone PV systems)
- Electricity meter (systems connected to the grid)

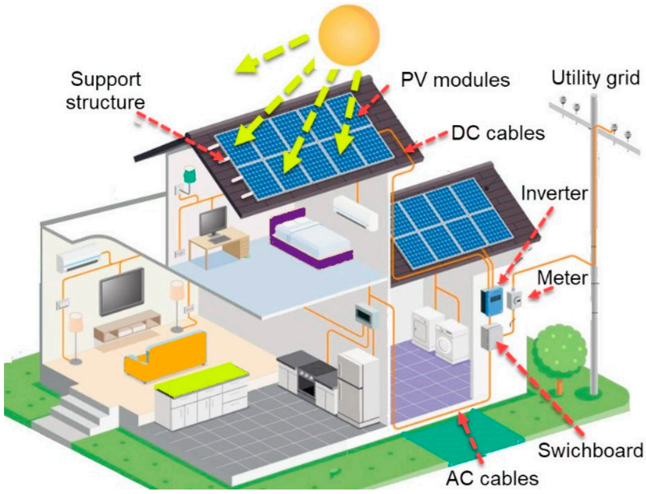

Figure 3. The major components of the PV system.

The results of the calculation of PV waste until 2050 are presented below. In doing so, the authors chose the average lifetime value of a PV power plant of 27 years, which is slightly more than the currently most commonly declared 25 years.

The rest of the article analyses the issue related to each of the listed components of the PV system when it reaches EOL.

Based on the data from Figure 1 on annual installed PV capacities, a projection of PV capacities that will reach EOL in the coming period was made. 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 which period they are replaced by new ones, or not at all, depends on the financial possibilities of the owner, government incentives, economic viability, energy prices and other factors.

In this study, an average lifetime of a PV power plant of 27 years was assumed. In Figure 4, the grey line shows the installed cumulative capacities of PV power plants reaching their EOL Assuming the average mass of the modules of 51 kg/kW [29], this results in a waste quantity of 50.9 tons per MW of installed capacity. The calculation shows that 20,400 tons of waste from PV modules will be generated worldwide by 2030 and 60.3 Mt by 2050 (Figure 4). The indicated amount of waste does not include the mass of the support structure. Literature mentions a similar amount of 60 to 80 Mt by 2050 [30–32].

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 [33], 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.

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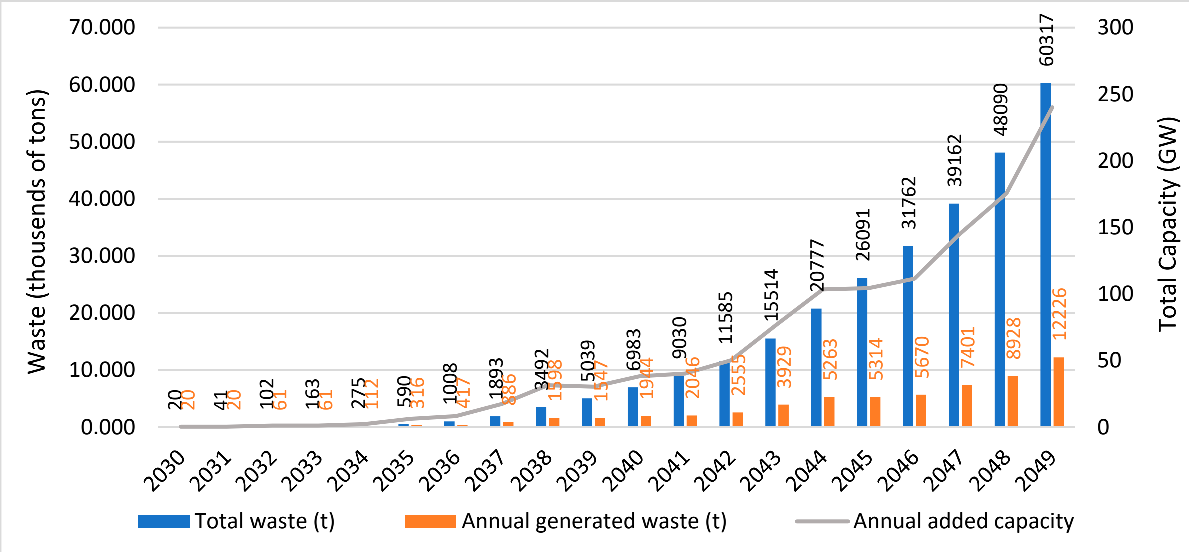

Figure 4. Estimated amount of global cumulative PV waste in thousands of tons

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 [34]. 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 [35].

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 material shortages needed to achieve worldwide decarburization and electrification [36–40]. Reuse is the process of utilizing modules or pieces of modules for new applications, such as construction materials, creative endeavors, or educational assets [41]. 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 higher money with fewer processing steps [42]. Finding a market that is large enough and 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 [43].

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

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is covered with polyethylene terephthalate and polyvinyl fluoride, then a cover glass is added and everything is placed in an aluminum frame (Figure 5).

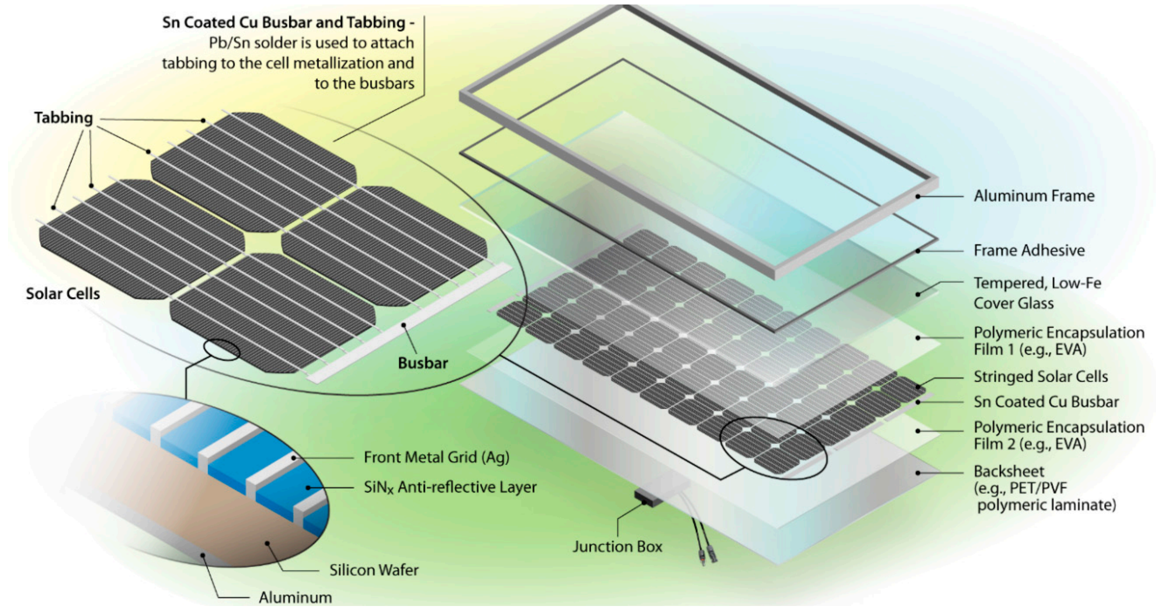

Figure 5. Assembly view of Solar PV module [44].

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). Besides silver, aluminum is another component of metallizing pastes that has not yet been addressed. For a 166 x 166 mm² monofacial cell, about 750 milligrams of aluminium are needed [46]. 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 aluminium is over 95% [47].

Table 1. Components of c-Si solar module [27,45].

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 bushbar and tabbing	0.451	2	Recovery from cable scrap (~97%)
Top surface - tempered glass	54.721	70	Glass cullet for glass production
Back-sheet layer - Polyvinyl fluoride	17.091	1.5	Energy recovery using 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 listed processes [48]:

- Separating the junction box and frame from module;
- Separating the encapsulant from the laminated construction

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- Separation of the glass panel and c-Si cells by thermal, mechanical or chemical processes;
- Extraction and purification of c-Si cells and important metals (e.g., silver, copper, tin, Al, lead) by 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 [41].

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

3.1.1. Mechanical Approach

The processes for deconstructing modules can be divided into two groups: Delamination and crushing and/or shredding procedures. In crushing and/or shredding, the modules are processed into gravel using suitable machines such as hammer mills and crushers [49], with the aluminium frame and junction box being removed first (Figure 6).

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 [50].

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. Module frame can be easily and completely recycled with very little energy input (8 MJ/kg) [47]. This is important considering that the energy consumption in the primary production of aluminium is very high (about 200 MJ/kg Al) [51].

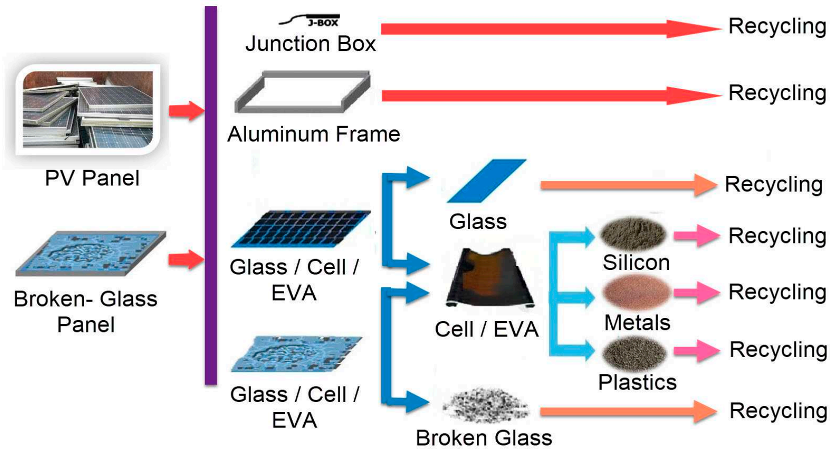

Figure 6. Mechanical approach to recycling.

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 [52,53].

In delamination, the components are separated from the panel with the intention of reducing damage to key parts, especially the cells. Delamination of modules is mainly applied to c-Si modules.

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After separating the Al frame and junction boxes, delamination of the module begins by thermal or chemical treatment, destruction or removal of the encapsulation [53].

After the module has been layered, the glass pane and the aluminium 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 [4] 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 [13].

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 [54–56].

3.1.2. Thermal Approach

Since EVA is used as an encapsulation material, its separation is key to delaminating the module. This can be achieved by heat treatment which leads to thermal decomposition and, sometimes, burning of the EVA and the back wall material.

The thermal process consists of heating the PV module in a suitable oven to a temperature above 420 °C, with the temperature rising by about 20 °C/min. The process takes about 25 minutes. The plastic evaporate and the PV cells detach from the glass. [47]. This can be done in the open air or in an inert atmosphere [13,55].

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.

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 [57].

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 [42,58].

3.1.3. Chemical Approach

Typical chemical techniques for dissolving EVA include employing nitric acid, solvents, or solvents in combination with ultrasonic irradiation [42,56]. 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 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 [59].

Materials for which no efficient recycling process is recommended are polymers, especially the encapsulation of the board (usually EVA) and the backing layer. The lack of interest in recycling these materials is due to the fact that they are difficult to recycle and economically unviable [10].

3.1.4. Environmental Impacts of Recycling PV Modules

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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. 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, sulphur 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 linked to PV systems may also change depending on whether or not PV modules are recycled or disposed in landfills. Recycling can lower emissions by saving the energy and resources that would otherwise be used to create new photovoltaic modules. 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 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, 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.

3.1.5. Economical Aspects

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

- 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.
- The location and availability of the recycling facility, which affects transport and logistics costs as well as environmental regulations and standards.
- Market conditions and demand for recycled materials, which affect the turnover and profitability of the recycling business.

In most 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 [5]. 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 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 [57]. 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 is some data on the level of recycling costs. According to one source [60], the average cost of recycling PV modules in 2020 is $28 per module. The cost of recycling a silicon PV module in the US is about $15-$45, while landfilling costs only $1-$5. To shift this ratio in favors of recycling, cheaper recycling methods need to be developed and taxes on waste disposal increased [57].

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3.2. Assembly (Support Structure)

According to [61], for utility-scale PV systems with a capacity of 20 MW and more, the amount of material (mainly steel) used for the supporting structure is about 62 t/ MW of installed capacity. Figure 7 shows a typical supporting structure.

Figure 7 The supporting structure for utility scale PV system (Slavonski Brod, Croatia).

Assuming that 53% of the installed capacity is utility-scale PV power plants [29], about 39 Mt of PV waste have been 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.

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. Recycling of the inverters is a difficult process that takes into account a number of technical, financial, and environmental factors. 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 [62] (Table 2).

Table 2. Materials used in the inverter and their treatment methods [62,63].

Material	Material share (%)	Method of treatment
Plastic	0.44	60% recycling, 40% incineration
Metal	59.39	90% recycling, 10% disposal
PCBA	38.93	65% recycling, 10% incineration and 25% disposal
Wiring	1.05	
Rubber	0.19	100% incineration

According to the above, 79.70% of inverters can be recycled, 4.37% can be disposed of by incineration, and 15.93% can be safely disposed of in a landfill [62]. Recycling inverters can lessen the environmental effect of mining and producing new materials by recovering valuable resources like copper, aluminum, steel, and plastics.

3.4. Electrical Conductors – Wiring

Recycling cable wires is a proven process [64]. The cable wire raw material first goes into the shredder and then into the crusher to get the small wire pieces. 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

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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 [27]. The crushed wires are usually sold in the form of copper shot.

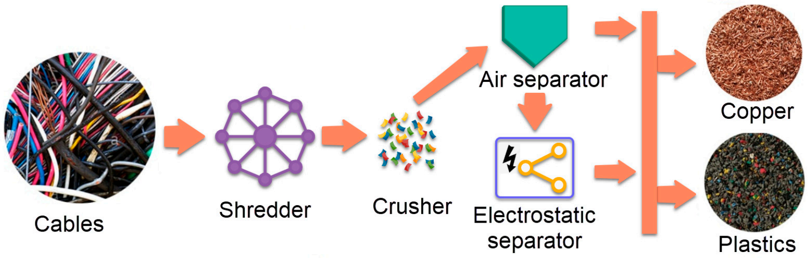

Figure 8. Recycling of wiring.

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 of plastic, the most popular technique is to burn it, preferably with energy recovery [65]. The junction box's wires have a copper conductor inside that is separated from the plastic in recycling process.

3.6. The situation in Europe Regarding the Recovery of PV Waste

In Europe, there is a website (http://www.solarwaste.eu/) 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 small number of 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 solar modules in Rousset (France) in 2018. The facility aims to process 4,000 tons of PV waste per year, which represents around 65% of all PV waste in Europe [66]. Reiling GmbH & Co. KG in Germany offers a comprehensive recycling service for waste PV modules. The non-profit organisation 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:

- First Solar, founded in 1999, USA
- Silcontel, founded in 2008, Israel
- Hanwha Group Co. Ltd., founded in 2010, South Korea
- Suzhou Shangyunda, founded in 2010, China
- SUNY GROUP, founded in 2011, China
- Recycle Solar Technologies, founded in 2017, United Kingdom
- Suzhou Bocai E-energy, founded in 2019, China
- RECLAIM PV RECYCLING PTY LTD, founded 2014, 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 recycling centers accept one or two PV panels. If it 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 €1/kg of PV

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modules. The company separates the aluminium frame and wiring from the panel, 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 cable and plastic recycling, where only certain types of plastics are recycled and the rest is burned in a furnace at roughly 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 get 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. Moreover, there is no recycling plant for PV modules in Serbia and Bosnia and Herzegovina. Besides landfilling, Serbia also exports end-of-life modules to Germany and Africa. A similar situation is likely in other countries that have not installed large PV capacities.

3.7. Challenges and barriers in PV recycling

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

- 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
- A deficit of recycling infrastructure and technologies
- Insufficient demand on the market for recycled or used PV modules
- Consumers and stakeholders are not enough informed and 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 practise 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 series.

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 re-use, should be carried out with an approach that focuses on the protection of the environment and human health and on the 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.

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- 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 [67].
- Appropriate rules and incentives are required to motivate participants along the supply chain to behave pro-actively 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 the like [43]. For example, SOREN is 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 is collected about 15,000 tons of PV waste in the period from January 2015 to August 2020 [66].

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.

4. Conclusion

Since 2010, there has been a significant continuous increase in annually installed PV capacities worldwide, so that by 2050 total PV capacities of 8512 GW and more are planned. The assumed lifetime of PV systems is 25 to 30 years. It follows that a large number of PV plants will reach EOL from 2035 onwards. In Europe, the number of plants reaching the end of their service life is several tens of thousands of tons per year.

EOL systems need to be disposed of, with reuse, recycling or landfill being the worst option from an environmental point of view. Reuse is the best option as it reduces the amount of waste over time, but the problem is finding a market for such a large amount of PV equipment. The recycling technology depends on the type of PV module. 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 there are well-established recycling processes. The removal of EVA and the recovery of metals while minimising the formation of harmful gases and effluents are the main challenges in recycling PV modules.

In case of thin-film PV cell technology, the content of hazardous components in PV modules is the main concern in the waste management phase.

Recycling technologies are based on mechanical, thermal or chemical approaches. Each of these approaches has its limitations, advantages and disadvantages.

Although there is a legal obligation in some countries to recycle PV modules at the end of their life (in Europe, the basic law is the WEEE Directive), in practise the recycling rate is not satisfactory. In 2019, for example, it was only 14%, which means that most of the mass of modules ends up in landfill. Economic unprofitability and the lack of recycling infrastructure are cited as reasons for the low recycling rate. In order to remove the barriers to more efficient recycling, certain measures should be taken, such as the construction of regional recycling centres, the use of advanced techniques in the design of PV systems that facilitate recycling (e.g., "design for recycling"). In addition, regulations and laws for PV waste management should be developed and harmonised at global level.

Improving the collection, treatment and recycling of PV modules at EOL can improve the sustainability of production and consumption, increase resource efficiency and contribute to the circular economy. Furthermore, the economic and environmental trade-offs between repair/reuse of modules and alternative circular economy strategies (e.g., recycling) need to be robustly assessed and compared. Circular economy approaches to PV EOL may provide chances for employment and safer management of hazardous materials, as well as environmental justice and benefits for society.

In many countries, the cost of recycling Si modules is ten times higher than the cost of landfilling. To change this ratio in favour of recycling, cheaper recycling methods need to be developed and taxes on PV waste disposal need to be increased. In this context, PV waste should be defined as a separate category in legislation.

EOL is an essential aspect of a PV system's environmental sustainability that shouldn't 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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