End-of-Life Waste from Photovoltaic Systems: Current Practices, Challenges, and Opportunities

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***Abstract*—The rapid growth of photovoltaic (PV) solar energy has introduced significant challenges related to the management of End-of-Life (EoL) panel waste. Projections estimate that by 2050, global PV waste could exceed 60 million tons. The absence of specific regulatory frameworks and the limited development of recycling infrastructure further aggravate the situation, underscoring the urgent need for sustainable waste management practices and the integration of circular economy principles within the solar industry. This paper discusses existing regulatory policies across various countries, along with recent technological advances in recycling processes. Furthermore, it emphasizes the importance of implementing a circular economy-based waste management model to enable the recovery of valuable materials, reduce reliance on virgin raw materials, and mitigate the environmental impact of the PV sector.**

Keywords — Photovoltaic waste, recycling, circular economy, sustainability.

I. INTRODUCTION

In recent years, solar photovoltaic (PV) energy has emerged as one of the leading renewable energy sources worldwide. Driven by technological advancements, significant cost reductions, and the increasing demand for sustainable energy solutions, the installed capacity of PV systems has expanded rapidly across numerous countries [1]. According to the International Renewable Energy Agency (IRENA), global installed PV capacity reached 1 419 GW by the end of 2023, with continued growth expected, particularly in countries such as China, India, the United States, Japan, and Germany [2].

However, the rapid advancement of photovoltaic technology also presents new challenges—particularly concerning the end-of-life (EoL) management of solar panels. By 2050, it is estimated that over 60 million tons of photovoltaic waste will be generated worldwide [3]. This growing volume represents a significant environmental concern, as PV panels contain valuable materials such as silver, which can be recovered and reused, provided that appropriate policies and technologies are in place to support efficient recycling and resource recovery [4].

Currently, most of the leading solar energy-producing countries lack specific regulations for photovoltaic waste, often categorizing it under general classifications such as electro-electronic or industrial waste. The absence of a standardized legal framework, coupled with limited infrastructure for collection and recycling, underscores the urgent need for effective waste management strategies. In this context, the adoption of a circular economy model becomes essential to ensure the sustainable handling of EoL photovoltaic panels [5].

In this context, the present study aims to assess the global landscape of waste generation in the solar photovoltaic (PV) industry, identifying key challenges in waste management, as well as recent technological and regulatory advances related to environmentally responsible disposal. The paper outlines the three generations of PV modules and reviews current recycling methods, while also introducing pioneering initiatives identified through the literature. In doing so, it offers an overview intended to support future research efforts and inform policy development in this evolving field.

The structure of this paper is as follows: Section 2 provides an overview of photovoltaic panel technologies; Section 3 discusses projections and the environmental impacts of waste from the solar industry. Section 4 outlines regulatory policies in different countries, while Section 5 presents recycling strategies and sustainable management approaches aligned with circular economy principles. Finally, Section 6 concludes the paper.

II. PHOTOVOLTAIC TECHNOLOGIES

Photovoltaic technologies have evolved across multiple generations, distinguished by the materials and manufacturing techniques employed. Three main generations are typically identified, each with unique characteristics. The first generation, based on crystalline silicon (c-Si), continues to dominate the market due to its high efficiency and long-term durability [3]. The second generation involves thin-film technologies, which offer advantages such as reduced weight, flexibility, and competitive efficiency levels [6]. The third generation comprises emerging technologies—including perovskite solar cells and concentrating solar photovoltaics (CPV), which show promising improvements in efficiency and the use of novel materials [7]. This ongoing technological evolution is essential for improving both the sustainability and economic viability of solar energy, paving the way for more advanced and efficient energy conversion systems.

The categorization of the most common photovoltaic modules on the market is exemplified in Fig. 1.

Fig. 1. Categorization of first, second and third generations of photovoltaic technologies [9, 10, 11].

A. *First generation - Crystalline silicon (c-Si)*

The first generation cells, made of crystalline silicon (c-Si), represent the most widely used technology in the solar

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energy sector, and are recognized for their high efficiency and long durability [3]. These panels can be classified as monocrystalline or polycrystalline, depending on the manufacturing process used. Structurally, they are composed predominantly of glass, polymer and aluminum, materials that account for more than 90% of the module's composition, and are classified as non-hazardous waste. These panels are characterized by the use of thin sheets, known as semiconductor wafers [7]. This technology is recognized for its high reliability and consolidated performance. It continues to be the most prevalent on the market, accounting for 95% of global photovoltaic power generation capacity in 2020 [8].

B. *Second generation - Thin film technology*

The second generation of photovoltaic modules is mainly defined by the use of thin film technology, which can be broadly divided into two main types: copper-indium-gallium-selenium (CIGS) and cadmium telluride (CdTe). CIGS panels incorporate a semiconductor layer composed of elements such as copper, indium, gallium and selenium, providing excellent light absorption properties [7]. Due to their high absorption efficiency, CIGS modules require significantly thinner semiconductor layers than crystalline silicon (c-Si) panels to achieve comparable performance—hence the designation “thin film” [3]. CdTe panels, by contrast, utilize cadmium telluride as the semiconductor material. This compound is more effective than silicon at absorbing sunlight under certain conditions, offering performance advantages in low-light or high-temperature environments. However, CdTe panels typically exhibit lower overall efficiency compared to c-Si modules [6], although they benefit from lower production costs, making them a cost-effective alternative for large-scale installations [12].

C. *Third generation – Emerging tecnhologies*

Third generation photovoltaic cells are based on emerging technologies that incorporate novel materials—such as organic compounds—with the aim of overcoming the limitations of previous generations by enhancing efficiency and reducing production costs. This category includes technologies such as concentrating photovoltaics (CPV), organic semiconductors, and perovskite solar cells [3]. Multi-junction cells, by stacking materials with different bandgaps, enable more efficient capture of solar spectrum. Perovskites, meanwhile, offer high light absorption and low-manufacturing costs, making them a promising complement or alternative to silicon-based cells. These innovations represent a significant step forward in the pursuit of more efficient and cost-effective solar energy solutions. However, challenges related to stability, durability, and commercial scalability must still be addressed before widespread adoption is possible [6]. Despite their potential, third-generation technologies currently account for only about 1% of global photovoltaic power generation capacity.

III. SOLAR INDUSTRY WASTE PROJECTIONS

Although photovoltaic technologies offer the environmental advantage of zero emissions during operation, the presence of heavy metals in PV modules raises significant environmental and public health concerns at EoL stage [13]. Given an average lifespan of approximately 30 years, and with global PV waste projected to exceed 60 million tonnes by 2050 [3], the current regulatory gap, particularly regarding the responsibilities of manufacturers, distributors, and end-users in managing PV waste, is a critical issue. According to data from the International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems [3] and [4], the cumulative waste volumes of PV panels by 2025 by country is as shown in Fig. 2.

Fig. 2. Cumulative waste volumes (in million tonnes) of PV panels by 2050, by country (Adapted from [3] and [4]).

Furthermore, the rapid expansion of the photovoltaic market and the lack of specific regulations increase the urgency of developing efficient management and recycling strategies, ensuring environmentally responsible disposal and the recovery of high-value materials.

A. *Environmental impact of PV panels*

The categorization of photovoltaic panels into first, second and third generation is also reflected in the distribution of photovoltaic waste, and it is estimated that 90%, 7% and 3% of future waste will correspond to each of these generations of panels, respectively [3]. Crystalline silicon panels (first generation), predominant in the market due to their low cost and technological maturity, will represent the largest share of the first group of photovoltaic panel waste, reaching 85-90% of the total [15]. This scenario reflects the widespread adoption of this technology over the last three decades, consolidating it as the main waste generator in the solar sector. The crystalline silicon panels, predominant in the market due to their technological maturity, will represent the largest share of the first group of photovoltaic panel waste, reaching 85-90% of the total [15]. This scenario reflects the widespread adoption of this technology over the last three decades, consolidating it as the main waste generator in the solar sector. With regard to thin-film technologies (second generation) and solar panels from emerging technologies market share, the proportion of waste from these categories is expected to grow progressively, requiring effective management and recycling strategies for different types of photovoltaic materials [16]. Furthermore, third generation photovoltaic panels feature rare materials, which makes the recycling process essential for recovering critical elements and reducing dependence on new extractions from the environment [3].

Under a hazardous materials approach, one of the main concerns regarding the treatment and disposal of PV panels is the emission of toxic gases, such as hydrofluoric acid, which can be released into the environment if special requirements are not adopted for their handling and disposal [17]. However, the urgent need to develop new recycling technologies cannot ignore a rigorous assessment of their environmental sustainability [18]. The recovery and reuse of photovoltaic panel materials can reduce environmental concerns and supply chain steps in the solar energy sector, boosting new business opportunities and promoting a circular economy model in this type of industry.

B. *Impact of solar market growth on waste generation*

Even though it has been in research since the late 1990s and had its first patent registered for recycling c-Si photovoltaic panels in 1995, academic knowledge of the supply chain for photovoltaic panels is scarce [19]. Furthermore, the global panel recycling infrastructure is still in its infancy, with reuse rates estimated at 14% [38], lower than in major solar energy markets such as the United States and China, where recycling rates are often below 10% [39]. Despite this, most countries globally still do not have specific regulations to deal with panels at the end of their useful life. As a result, panels are disposed of more economically and inappropriately, including disposal in landfills and even illegal export to developing countries [19]. The technical challenges of recycling panels include the efficient separation of their components and materials. Although the recycling of thin film panels has advanced due to the presence of heavy and rare metals, the recycling of crystalline silicon panels still faces economic and logistical limitations [17].

It is estimated that the recovery of materials from photovoltaic waste could generate 2 billion new panels and an economic value of approximately US$ 15 billion by 2050 [3]. Thus, the sustainability of the solar sector will depend directly on the development of efficient supply chains for the waste management, reducing environmental impacts and optimizing the use of natural resources.

In view of the above, it can be seen that due to the accelerated growth of solar energy and the projected increase in plant waste, it is essential to adopt solid and strict regulatory policies that promote the emergence of new recycling technologies and the reuse of photovoltaic panels at the end of their useful life.

IV. REGULATORY POLICIES FOR SOLAR PHOTOVOLTAIC WASTE MANAGEMENT

The lack of uniform global standards represents a significant obstacle to the implementation of efficient recycling practices and environmentally responsible disposal of this waste [14].

In this respect, the European Union stands out as a benchmark for integrating photovoltaic waste management into the Waste Electrical and Electronic Equipment (WEEE) European Directive [20], the so-called WEEE Recast of 4 July 2012, giving manufacturers responsibility for the proper management of these material and establishing minimum mandatory targets for collection (65%), recycling (80%) and recovery (85%) [4]. The adoption of extended producer responsibility (EPR) has been consolidated as an efficient model for transferring the obligation to manage waste to manufacturers, encouraging the development of solar panels that are easier to recycle and more sustainable production processes [14]. Moreover, the WEEE Directive [20] imposes the take-back, treatment, and recycling of end-of-life PV panels, obliging producers to finance recycling programs, allowing them to internalize the cost of recycling in the product's price structure, and ensuring compliance with strict environmental standards [24].

Fig. 3 depicts the recycling flow of PV panels in a circular economy. The process begins at the design stage, where manufacturers can prioritize the use of recyclable materials, modular designs, and non-toxic components to facilitate disassembly and recovery at the end of the product's life. The panels then move through the stages of production and distribution, eventually reaching the consumer, who installs and uses them typically over a service life of 20 to 30 years.

At the end of life, panels are collected through specialized take-back schemes and they are then sent to recycling facilities, where valuable materials such as glass, aluminum, silicon, copper, and silver are recovered.

These recycled materials can be reintroduced into the production chain to manufacture new panels or other products, thus closing the loop and minimizing environmental impact, raw material extraction, and waste.

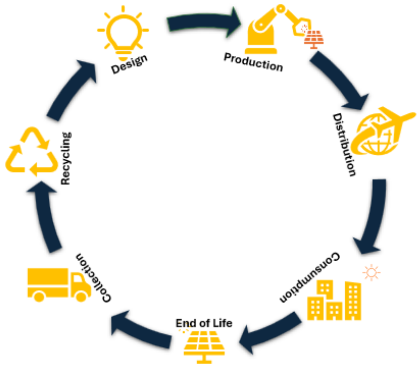

Fig. 3. Circular economy flow applied to photovoltaic (PV) panels.

A. *Comparison of regulatory policies in different countries*

This section explores the different approaches adopted by countries in regulating the disposal and recycling of solar panels at the end of their useful life.

China, the world's largest producer and consumer of solar panels [21], faces significant challenges in regulating photovoltaic waste. The management of the panels in their EoL is still in its infancy, as there is a lack of regulation for the recycling of solar panels [18]. Recent efforts seek to develop a regulatory framework to boost recycling and mitigate environmental impacts [24].

Japan has developed innovative technologies such as hot knife technology, a mechanical cutting technology used in solar panel recycling [22]. It should be added that the country invests in national policies that encourage research and development projects aimed at recycling solar panels in order to achieve sustainability in the photovoltaic sector [23].

In the United States, regulations vary by state, with Washington, California and North Carolina being the pioneers in creating specific laws for recycling solar panels [24], while most of the country still lacks unified federal guidelines to boost the recycling of photovoltaic panels, with investments in infrastructure and awareness programs. As a result, more than 90% of panels are disposed of as ordinary waste, without specific recovery processes [25].

Australia has begun to implement policies for recycling solar panels through state programs, most notably in the states of Victoria and South Australia, which have banned the disposal of photovoltaic panels in landfills. However, there is still no comprehensive national policy for managing this waste [26].

India, with the growth in the adoption of solar energy, has sought to integrate environmental guidelines for the sector with regulations for the management of photovoltaic waste. The country is in the process of developing specific guidelines for the disposal and recycling of solar panels, with the aim of reducing environmental impact and recovering valuable materials [27]. It is even ensuring that the processing of waste other than photovoltaic solar panels, boards or cells is done in accordance with the applicable rules or guidelines in force [28].

Examples of the successful implementation of the circular economy approach at the end of the useful life of panels can be found in European Union countries, Vietnam, Malaysia, the USA (Ohio), India, among others, where there is an advanced infrastructure for recycling and where specialized companies have been developed in the country to deal with the recycling process with the aim of recovering materials used in panels [29].

B. Barriers and opportunities for new policies

The first barrier to overcome is the implementation of effective regulations governing the environmentally correct final disposal of panels at the end of their useful life. Furthermore, one of the main challenges is the lack of recycling infrastructure and the absence of financial incentives for manufacturers to invest in material recovery technologies [3]. Another challenge to be overcome is the cost involved in the process of recycling panels, as the interested parties - manufacturers, collectors and recyclers - prioritize economic impacts more than environmental impacts [30]. Furthermore, the lack of awareness about the environmental impacts of improper disposal makes it difficult to adopt best practices [29].

However, there are significant opportunities for regulatory progress. The adoption of EPR policies could stimulate the development of new recycling processes, as well as encouraging the design of panels that are easier to dismantle and reuse [3]. Global standardization of strict standards for solar panel recycling could increase the efficiency of the sector and reduce operating costs required for environmentally friendly compliance with the closed-loop supply chain.

The application of the circular economy is an opportunity that is emerging as a promising approach for the solar photovoltaic sector, promoting the reuse of materials and reducing the extraction of natural resources [31]. Collaborative initiatives between governments, industries and research institutions can accelerate the implementation of more effective regulations and guarantee a sustainable future in the solar energy sector.

V. SOLAR PHOTOVOLTAIC WASTE MANAGEMENT

In order to deal with the growing number of solar panels in EoL, it is necessary to address the management of materials from the decommissioning of photovoltaic plants. To this end, pilot projects have been developed by private companies with the aim of disposing of the panels in a sustainable way [17].

In this way, approaching waste management following the principle of the 3 R's (reduce, reuse and recycle) turns the central idea into action, as this methodology promotes conscious consumption and responsible waste management, with the aim of minimizing the amount of waste sent to landfills and optimizing the use of natural resources, promoting the circular economy [32].

The recycling of solar panels, especially crystalline silicon (c-Si) panels, which dominate the global market, has become a priority in the sustainable management of the EoL of this equipment [5][34]. The main recycling methods are mechanical, thermal and chemical. The mechanical process, which is widely applied, involves manual disassembly, crushing and physical separation of materials such as glass, plastic, aluminum and copper, allowing for a high rate of reuse, especially glass, which can be recycled up to 99.5% [33][35]. It is considered to be an energy-efficient method with low toxic waste generation, although it has limitations when it comes to recovering high-value materials [36].

The thermal method involves exposing the panels to temperatures between 450 °C and 600 °C, degrading polymers such as EVA and allowing the separation of components such as glass and silicon, as well as the recovery of precious metals such as silver and copper [5][23][34]. Chemical recycling uses reagents such as hydrofluoric acid and trichloroethylene to dissolve the protective layers and selectively extract silicon and valuable metals with high purity [34]. Although effective, this method requires strict control of toxic waste and higher operating costs [4][17].

There is also the combination of mechanical, thermal and chemical methods that has been increasingly applied to maximize the recovery of materials and strengthen the adoption of the circular economy in the photovoltaic sector [33]. This advance in the sustainable management of EoL panel waste has been driven by private initiatives. Some companies have stood out by offering specialized solutions for the final disposal of these materials in line with the requirements of current environmental regulations.

One of the main ways of reusing materials after the recycling process is to recover them to make new products. One example is the recovery of glass from photovoltaic modules, which is then used in the production of new glass packaging [1]. There is also the use of metallic material, such as aluminum from the support structure of the modules, to create new products, and laminated material that is reused to produce new rubber items [37].

In this context, it is important to complement the study by presenting examples of technological innovation and pioneering already existing in the sector, addressing in more depth the recycling methods and successful waste management models currently implemented worldwide.

VI. CONCLUSIONS

The rapid expansion of solar photovoltaic (PV) energy has been a key driver of the global transition toward sustainable energy systems.

However, the resulting growth in end-of-life (EoL) photovoltaic waste poses significant environmental, economic, and regulatory challenges. As this study has shown, the current lack of standardized frameworks and dedicated recycling infrastructure could undermine the long-term sustainability of the solar industry if not urgently addressed.

Embracing circular economy principles is crucial to promote the efficient recovery of valuable materials, minimize environmental impacts, and foster the development of new business models around PV recycling.

Advances in recycling technologies, coupled with the implementation of comprehensive regulatory policies, will be instrumental in ensuring that the solar energy sector continues to support global decarbonization goals without creating new waste-related burdens.

Future research and coordinated international action are essential to scale up sustainable EoL management practices and to unlock the full environmental and economic potential of photovoltaic energy.

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