Ongoing Waste Issue Towards the Development of Photovoltaic Module Recycling Regulations

Aslı Birtürk[1[0000-0002-3637-2821]*] and Melih Soner Çeliktaş[1[0000-0003-0597-5133]]

[1] Ege University, Solar Energy Institute, 35100, Bornova, İzmir, Turkey

Abstract. In this paper, solar photovoltaic (PV) systems, that play an essential role in reducing fossil energy resources, are considered from a sustainability perspective. Solar PV systems, accounting for a significant capacity share among renewable energy sources, will have environmental and economic repercussions in the future. Despite photovoltaic (PV) modules contributing to the production of renewable energy for an average of 25 to 30 years, they pose a threat to the global environment. Policies should support the significance of initiatives. This will ensure that PV manufacturers, users, governments, and R&D researchers assume responsibility for PV module waste, which is expected to be encountered more frequently and rapidly in the near future. Prioritizing global awareness and policy development in the field of solar PV recycling will inspire future work. Furthermore, the prospect of other solar PV technologies consolidating their market position in the future will necessitate a solar PV recycling industry. This industry should encompass all developing PV technologies.
Keywords: energy policy, energy resources, clean energy, PV recycling

1 Introduction

In spite of the fact that photovoltaic recycling is a worldwide issue, no country has enacted regulations on the matter. The primary focus for countries not enacting regulations is to increase the capacity of solar PV facilities, rather than addressing the future of photovoltaic panels after their 25- to 30-year lifespan. The increasing popularity of solar energy has driven up the demand for PV panels. Over the period from 2012 to 2022, the global PV capacity soared from 100 GW to 1 TW [1]. By 2026, all new public and commercial structures with a floor area of more than 250 m^2 constructed in the European Union must have solar panels installed on the roofs. By 2027, all previously constructed commercial and public buildings with a floor area greater than 250 m^2 must comply. By 2029, all new residential buildings will be required to install rooftop PV systems [2].

On one hand, the escalating demand for natural material resources places these resources at risk for the future. In the context of photovoltaic modules, silicon modules utilizing newer technologies exhibit a lifespan of 25 to 30 years, while their older counterparts deployed in the field have a shorter lifespan of 20 to 25 years. Consequently, the implementation of a recycling system for panels within a specific lifecycle can mitigate

* Corresponding author: birturkasli@gmail.com

both the present and future waste issues, thereby significantly reducing the rate of resource depletion through the reintegration of essential minerals.

Global PV panel waste is expected to reach 78 million tons by 2050. Within the context of the Green Transformation, the European Union is required to strengthen efforts in parallel with the gradual reduction in dependency on fossil fuels and the fight against climate change [3–5]. In alignment with the determined action plan, the Solar Energy Strategy has been published to double the deployed capacity of PV systems by 2025, aiming to reach an approximate capacity of 600 GW by 2030. Evaluating the economic feasibility of PV systems within the scope of these strategies, revisions to the Eco-Design and Energy Labeling regulations are scheduled for 2023. These revisions will specifically address PV module efficacy, durability, repairability, and recyclability. Since 2012, the legislation of the European Commission has given priority to the recycling of photovoltaic (PV) modules. It is emphasized that the largest volume of PV module waste is projected to arise in 2025, with waste quantities anticipated to increase over time. This necessitates the establishment of the PV module recycling industry within a relatively short timeframe. This underscores the imperative for recycling to adopt more innovative approaches, which is a critical aspect. Given this context, it is anticipated that substantial measures will be enacted for PV module recycling in Europe during the 2023 revision [2,5].

As the solar industry gains prominence, the conditions for expanding the capacity of PV facilities will steadily improve. Nevertheless, the increasing demand for PV modules also translates to a higher demand for the valuable minerals necessary for their production [6]. To systematically address these challenges, it is imperative to establish the necessary policies. Recycling processes should provide clarity on transport, storage, processing, and transportation to industrial production for utilization. In this context, the National Renewable Energy Laboratory (NREL) emphasizes the impact of PV recycling on the circular economy. Future projections suggest that the reclamation of valuable minerals through photovoltaic panel recycling could amount to $60 million by 2030 and potentially reach two billion euros by 2050. However, in the United States, recycling incentives are currently absent. An alternative approach involves transferring waste PV modules to recycling nations, but this strategy necessitates international agreement provisions [7].

2 Policy Impact on PV module recycling

While there are no regulations regarding the recycling of PV modules in Europe, the Waste Electrical and Electronic Equipment (WEEE) Directive underlines the requirement for manufacturers to regulate the recycling of PV modules. [8].

It is anticipated that PV recycling industries will be established by 2030, with numerous countries already taking proactive measures in this regard. The current juncture demands a collaborative effort among R&D researchers, industry stakeholders, and policymakers. To optimize material recycling, a priority must be placed on energy-efficient, effective, and cost-efficient techniques, ensuring the restoration of minerals from PV modules to the highest possible production quality. A symbiotic partnership between module manufacturers and researchers is indispensable to achieve this objective.

Much like in Europe, the United States lacks a PV-specific law. However, several states have taken the initiative to shoulder this responsibility themselves. For instance, the Washington State Senate has passed a resolution endorsing the reclamation and recycling of obsolete PV modules. In California, ongoing initiatives seek to categorize PV module waste and institute corresponding regulatory measures [9]. The Ministry of Economy, Trade and Industry (METI) in Japan, along with METI's collaboration with the Japan Photovoltaic Energy Association (JPEA), has devised a roadmap for the collection, recycling, and processing of end-of-life PV modules. This roadmap incorporates recommendations from JPEA concerning the advancement of recycling technologies [10].

The WEEE directive explicitly places the responsibility of waste management on module manufacturers across all EU nations. Notably, First Solar's commitment to Europe sets the precedent for manufacturers accumulating PV modules for recycling, a practice that could lead to the introduction of more rigorous regulations. Participating in waste collection and facilitating transportation to suitable recycling facilities can yield a significant impact, particularly given that not every manufacturer may undertake the establishment of dedicated recycling facilities. In such cases, the collaboration of state institutions becomes imperative, as variations in country policies may result in disparities.

For instance, the establishment of PV CYCLE by key stakeholders in the PV industry highlights a significant initiative. This organization has assumed the responsibility of coordinating the transportation of waste modules to over 300 waste collection centers throughout Europe. Consequently, the importance of incentive mechanisms to enhance stakeholder involvement in the resolution of potential issues becomes evident [3].

It is imperative to recognize that one of the foremost policy actions nations will undertake in this context is the prohibition of used PV module disposal. In the absence of enforceable regulations, uncontrolled disposal of PV modules has the potential to trigger environmental chaos in numerous countries. European nations have addressed photovoltaic module recycling through a comprehensive directive known as WEEE (Waste Electrical and Electronic Equipment). Recognizing the exponential increase in installations of photovoltaic module systems, significant bodies like the International Energy Agency emphasize the necessity of introducing a specialized directive to ensure the sustainability of such systems.

Within this framework, paramount attention has been given to critical minerals embedded within photovoltaic modules. Forecasts indicating that the depletion of valuable mineral resources will outpace projections until 2050 due to heightened production demands underscore the imminent requirement for recycling photovoltaic modules from both economic and environmental standpoints in Europe [10–12].

3 Solar PV module Recycling

Ninety-five percent of solar PV facilities are outfitted with crystalline silicon (c-Si) PV technology. On average, a c-Si PV panel is composed of approximately 76% glass, 10% polymer, 8% aluminum, 5% silicon, 1% copper, and less than 0.1% silver and other metals. Across various PV module systems, the regulated separation of hazardous components like lead, cadmium, and selenium is imperative. Moreover, rare elements such as silver, indium, and tellurium should undergo extensive reprocessing.

The identification of reuse opportunities should be grounded in the recycling potential of materials with high embodied energy, such as silicon and glass. Critical Raw Materials encompass components of paramount importance to the EU economy, and their production entails significant risks. The International Energy Agency's report forecasts a twofold increase in demand for precious minerals in photovoltaic modules by 2040. Notably, copper's demand is projected to triple, whereas silver and silicon are anticipated to rise by 18% and 45% respectively [3,11].

Hence, reprocessing photovoltaic modules assumes paramount importance in the context of sustainability. The preservation of essential material resources, the integration of waste into production, the enduring feasibility of renewable energy systems, economic advantages, and environmental conservation collectively underscore the significance of PV recycling.

Although solar PV modules can be subjected to recycling processes, the presence of polymer layers presents challenges that can impact environmental integrity and purity levels. Notably, ethylene-vinyl acetate (EVA) poses a notable obstacle to achieving high-purity recycling due to its strong adherence to tempered glass, solar cells, and the back sheet. Addressing EVA requires high-temperature thermal treatments, given its corrosion-resistant nature. However, these treatments can potentially inflict damage upon the solar cells due to their adhesive link with glass. This, in turn, hampers the high-purity recycling of valuable metals like silver and copper. Successful solutions entail the dissolution of EVA's resin structure through controlled swelling and delicate detachment from adjacent layers [13,14].

The backsheet layer in solar PV modules comprises polyethylene terephthalate (PET) and polyvinyl fluoride (PVDF). While non-fluorine-based backsheets offer more favorable environmental outcomes, their fluorine-based counterparts tend to be more environmentally detrimental. The PET/PVDF structure is laminated onto the EVA layer, a design that mitigates adhesion-related issues and potential solar cell damage during delamination processes. For effective recycling, the removal of the aluminum frame and junction box is a requisite step.

Recycling methods involve the chemical and thermal removal of the EVA resin layer, with the utilization of potent chemicals often resulting in successful outcomes [15–18].

The challenge of recycling the EVA layer is substantial, primarily due to its constrained applicability arising from costly methods and limited research regarding decomposition and other techniques (traditional and innovative methods) for photovoltaic panel recycling (Table 1). An essential aspect to scrutinize in conventional recycling approaches is their environmental footprint. Within the literature, innovative strategies have been explored, ranging from the application of diverse organic solvents to decomposition, to the utilization of technologies from disparate fields, all aimed at decomposing or recycling photovoltaic panels [13,14].

Table 1. Traditional and Innovative PV Recycling Methods

Mechanical Recycling		**Chemical Recycling**		**Thermal Recycling**	
Traditional	Innovative	Traditional	Innovative	Traditional	Innovative
Crushing	High Voltage Crushing	Strong Chemicals	Mild extracting technology	Incineration	Pyro - metallurgical technology
Shredding	Electro-hydraulic Fragmentation	Leaching	Chemical + hydrometallurgical treatment	Thermal treatment	Supercritical Technology
Milling	Irradiation by laser	Solvent usage	Biometallurgical Technology	Combined Heat treatment	Vacuum metallurgical technology

Integrated thermal and chemical methods, which neither harm the environment nor cause significant damage, occupy a pivotal position among innovative approaches. An essential consideration pertains to the efficient separation of polymer layers with decreased high-temperature resistance, emphasizing heightened efficacy and reduced energy consumption [19].

- Utilization of organic solvents at elevated temperatures (typically exceeding 180 °C) contingent upon method combinations.
- Diminishing energy consumption by expediting the degradation of polymer layers through elevated temperature and pressure.

– Amplifying the impairing impact of mechanical techniques, particularly on tempered glass, thereby abbreviating the duration of subsequent experimental phases.

In the context of the Life Cycle Assessment (LCA) for the energy-efficient recycling of photovoltaic modules, electricity consumption emerges as a significant output.

– Achieving a high recycling rate and optimizing energy consumption efficiency through the utilization of Life Cycle Assessment (LCA) outcomes.

The assessment of the environmental impact potential stemming from polymer degradation stands as a significant challenge in the recycling of photovoltaic modules

– While toluene demonstrates high efficacy in polymer degradation, there is a pressing need for the development of studies focusing on environmentally friendly solvents.

4 Results and Discussion

Global installations of photovoltaic systems have exhibited an annual average growth of 100 GW since 2016. In 2016, the total installed capacity reached 290 GW, a benchmark that has been surpassed, exceeding 1 TW as of 2023. Simultaneously, while global installations are expanding at a rapid pace, there is a concurrent surge in demand for minerals necessary for production.

The report on the end-of-life strategy for photovoltaic solar panels, published by the International Energy Agency, projects the quantity of waste generated by photovoltaic modules from 2016 to 2050. The report anticipates a global waste volume of 78 million tons of solar panels by 2050. As this projection was formulated in 2016, an assessment of the present increase in installations becomes imperative. Taking into account the yearly growth of global installed capacity, consisting of panels averaging 300 W and 18 kg in weight, alongside an average yearly increase of 100 GW, the current annual waste accumulation surpasses 6 million tons. Accordingly, this trajectory is poised to escalate to 10 million tons per annum by 2050.

The widespread belief in increasing renewable energy sources and diminishing reliance on fossil fuels is evident. However, it is essential, within the framework of the UN Sustainable Development Goals (SDGs), to illuminate both the implications of capacity expansion and the prospective environmental ramifications associated with the generation of debris from PV modules in the future.

Organizations should adhere to an evaluative framework rooted in the classification of materials within PV modules. To avert potential environmental harm stemming from recycling processes, a comprehensive assessment of material properties such as solubility, flammability, and toxicity is indispensable. Without such evaluation, the emergence of hazardous waste capable of infiltrating soil, water, and air could counteract the very essence of recycling's intent. Within this context, it becomes imperative to disclose significant environmental analyses and address potential hazards within regulatory frameworks.

Due to the continuous development of photovoltaic panel technologies and the rapid increase in installations, the emergence of photovoltaic panel waste as a global problem is undeniable. This issue is projected to further escalate in the future. Despite the scarcity of existing studies on this matter, the acceleration in the development of innovative methods aligns with the ongoing expansion of global installations. In this context, the forthcoming commercial viability of photovoltaic panel recycling techniques nurtured stands as a pivotal facet of future development. Recycling promotes sustainable mineral utilization, resource conservation, supply security, and the mitigation of environmental impact through effective methods and infrastructure.

To achieve thorough management and methodical execution of PV recycling strategies, the entities responsible for state policies will encounter the most formidable challenge.

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