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Editorial

End-of-Life Management and Recycling on PV Solar Energy Production

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Citation: Papamichael, I.; Voukkali, I.; Jeguirim, M.; Argirusis, N.; Jellali, S.; Sourkouni, G.; Argirusis, C.; Zorpas, A.A. End-of-Life Management and Recycling on PV Solar Energy Production. *Energies* **2022**, *15*, 6430. https://doi.org/10.3390/en15176430

Received: 16 August 2022
Accepted: 23 August 2022
Published: 2 September 2022

1. Introduction

The demand for clean energy is strongly related with many European and other global legislations and directives. At the same time, clean energy is a vital goal of the United Nations (UN), who proposed the sustainable development goals (SDG). Photovoltaic Panels (PV) are currently considered one of the most preferable renewable energy solutions across the globe as they contribute to the production of clean energy and the "production of clean air" and prevent several environmental issues deriving from the use of fossil fuels.

The issue of the end-of-life management of solar PV waste has been pointed out by several authors over the last 3 years [1–8]. The usage lifetime of each PV panel is approximately 30 years [9]. If end-of-life PV panels are not managed responsibly, their existence will result in massive global pollution (similar to plastics) across the terrestrial ecosystem.

2. End-of-Life PV Panels and Recycling

According to Markert et al. [7], the annual PV power capacity in 2019 was 114 GW with an observed year-to-year increase of 17.5%. Still, there has been a significant growth in the PV sector on a global level, as in 2016 solar power usage around the planet reached 310 GW and is expected to rise to 700 GW in 2025 and 4500 GW by 2050 [6]. At the same time, by the end of 2016, PV waste reached 250,000 tons worldwide; similarly, as PV panels reach the end of their life span, by 2030, these levels are expected to rise even further [6]. It is expected that the highest volumes will be projected in Asia with 3.5 Mt, Europe with 3 Mt, and the United States with 1 Mt. Lastly, between 2030 and 2050, a global accumulation of 60–89 Mt is expected.

Mathur et al., [6] mentioned that there is an oxymoronic push of encouragement for the use of renewable energy (especially PV systems), while at the same time there is a lack of clear policy for the efficient management of solar PV waste. The clear absence of a policy for the waste management and treatment of PV panels may also arise due to the crisis in leadership with an emphasis on global waste management, as mentioned by Zorpas et al. [10]. Considering that PV contain composite materials as well as cadmium, lead, selenium, tellurium, and encapsulated, chemically fixed, solidified, or polymerised waste, they should not be landfilled.

Through the Life Cycle Assessment (LCA) of solar-PV and solar-thermal systems, Parvez Mahmud et al. [8] indicated that a solar-thermal framework released four times more air emissions (100%) and three times that of soil and solid waste compared to solar-PV systems—23.26%, 27.48%, and 35.15%, respectively. At the same time, the findings indicated that solar panels are responsible for the biggest impact in the system under investigation. Furthermore, concerning the sensitivity and uncertainty analysis carried out for both frameworks of the study, Li-ion batteries as well as copper-indium-selenium (CIS)-solar collectors were found to perform better compared to others for most of the impact categories. Therefore, according to the study, through the calculated use of both systems and the careful selection of components, superior environmental performance could be achieved when taking into account aspects of toxicity and the minimization of solar panel-related impacts such as battery and heat storage. Among the sixteen impact types, the highest ones were climate change, ozone depletion, human toxicity, acidification, terrestrial eutrophication, ecotoxicity, water resource depletion, and solar collector land use.

Markert et al. [7] described the main issues arising with the complications of the end-of-life management of PV panels. Since the large-scale use of PV technologies is relatively new, there is still insufficient or even no infrastructure for recycling solar panels, displaying the lack of regard for future needs when it comes to solar panels' capacity for being recycled. The cost and benefits of recycling are largely unknown. According to Market et al. [7], the private cost of end-of-life management of c-Si PV is USD 6.7/m^2, mostly generated from transportation (USD 3.3/m^2) and landfilling (USD 3.1/m^2), while the actual cost (i.e., consumed materials, electricity, and investment) of the recycling process is very small (USD 0.3/m^2). Furthermore, the economic value of recycled materials from c-Si PV waste is USD 13.6/m^2. Consequently, when excluding the external costs, the net benefit from recycling is USD 6.7/m^2, while when including the external costs, the net benefit is still USD 1.19/m^2. This paper provides technological solutions for c-Si PV treatment by translating the data into technical and economic industrial process designs.

Herceg et al., [5] indicated that due to the increasing amount of waste PV, waste management will gain proportionally increasing traction in the upcoming decades. In their paper, LCA methodology was used to analyse the environmental performance of PV-systems and their respective waste management methods that have been developed. Their research highlights how recycling has the potential to improve the environmental impact of PV electricity but also how there is room for improvement. In their work, it was shown how landfilling/incineration and landfilling/pyrolysis were the best potential technologies for improving the environmental footprint of the production of electricity via PV.

Considering that PV play a fundamental role in the transition towards more sustainable energy production compared to traditional fossil fuel-based energy production, Rubino et al. [11] indicated that as PV panels are involved in the European Directive as WEEE (waste of electric and electronic equipment), in terms of the recycling and recovery index, this should be 80% and 85%, respectively; additionally, a separate collection scheme should be implemented. Generally, local governments are responsible for the collection and management of WEEE; they are the contact between residents and the waste management processes. There is a clear opportunity for the development of a strategy to manage or recycle the end-of-life PV panels as they are mainly composed of high-quality solar glass (70–90%); however, metals are also present in the frames (Al), the cell (Si), and the metallic contacts (Cu and Ag). Rubino et al. [11] mentioned that around USD 72 per 100 kg of PV panels can be recovered by entirely recycling the panels' metal content. For that reason, Rubino et al. [11] proposed "*The PhotoLife process*" for the treatment of end-of-life PV panels in order to recover high value glass, Al, and Cu scraps, as well as an upgrade process enabling polymer separation and Ag and Si recycling. Using the *PhotoLife process*, an 82% recycling rate, a 94% recovery rate, and 75% recoverable value were attained. The economic feasibility of the process according to the simulations was demonstrated to be 30,000 metric tons per year.

Furthermore, Zieminska-Stolarska et al. [12] analysed the possible waste management scenarios of PV panels through LCA and they have used several key performance indicators such as the energy payback time, CO_2 footprint, and GHG emissions. In their research, two types of PV-systems were used: high-concentration PV (HCPV) and low-concentration PV (LCPV). As mentioned above, an important issue for the environment is the development of recycling and recovery methods for solar cells composed of III–V semiconductors, which are currently disposed of as hazardous waste.

Similarly, in Australia, Daljit Singh, et al. [13] presented the LCA of end-of-Life PV panels. The research team used a functional unit of 1 kWh of electricity production across a 30-year PV system lifespan and they have compared three different waste management practices: (a) direct to landfill, (b) recycling by laminated-glass-recycling facility (LGRF), and (c) recycling by the full recovery of end-of-life photovoltaics (FRELP). They found that recycling technologies reduced the overall impact score of the cradle-to-grave PV systems from 0.00706 to 0.00657 (for LGRF) and 0.00523 (for FRELP), as measured using the LCA ReCiPe endpoint single score. The CO_2 emissions decreased slightly from 0.059 kg CO_2 per kWh (landfill) to 0.054 kg CO_2 per kWh (for LGRF) and 0.046 kg CO_2 per kWh (for FRELP). The authors also pointed out the necessity for the careful evaluation of PV recycling technologies and steps before implementing them. In addition, they highlighted the importance of considering a circular design during the process of evaluation, such as utility and longevity principles. In addition, the authors concluded that recycling approaches minimized the environmental impact of the end-of-life PV panels and that new circular eco-designs should be applied.

Moreover, dos Santos Martins Padoan et al. [4] proposed a quantitative assessment of material flux from pilot treatment plants for PV waste. The process focused, among other steps, on the dismantling of aluminium frames and mechanical size reduction as well as the physical treatment of the milled fragments to release coarse glass from encapsulant polymers.

According to Tan et al. [2], there will be more than 78 million tons of PV panels that will reach their end-of-life by 2050. Inappropriate waste management practices will lead to extremely negative environmental issues such as pollution of the ecosystem, the encouragement of mining and the extraction of raw materials, and the degradation of the environmental benefits of harvesting solar energy. Considering the circular economy strategy and the proposed targets, Loizia et al. [14] and Tan et al. [2] mentioned that a new eco-friendly design for the next-generation PV panels should be applied with innovative and optimized existing methods. Those are divided into physical and chemical methods. Physical methods cover the mechanical recovery, which includes the manual dismasting and removal of the junction box and aluminium frame, followed by crushing, while the ethylene-vinyl acetate small particles are sieved using a vibratory separator at low temperatures. This recovery stage produces low purity recyclates that need further sorting into their elements. Other separation steps may include flotation (the division of the glass sizes between 45 and 850 nm), electrostatic separation (separating each substance by its electrical conductivity), eddy current separation (separating the crushed recyclable material), and mechanical screening (sorting the recyclates by size, shape, thickness, and other differences). Additional high-voltage pulse crushing separates copper, aluminium, lead, silver, and tin. Pyrolysis is another physical end-of-life PV recovery technique with a required temperature above to 400 °C in order to gain clean PV cells. Pyrolysis aims to decompose ethylene-vinyl acetate at an optimized temperature. In general, pyrolysis divides glasses, cells, and backplanes and produces pyrolysis oil, which according to Antoniou and Zorpas [15] needs further attention.

Chemical methods are considered simpler and require less energy. The inorganic solvent dissolution methods require end-of-life PV panels to be immersed in acid or alkali solution. The process removes metal impurities using nitric acid and hydrofluoric acid.

Another method to remove metal impurities from the cell's surface is the use of organic solvents, which dissolve ethylene-vinyl acetate. While soaked, the various components are exposed and separated, allowing the PV cell sheet to be extracted. The expansion process, which corresponds to the crosslinked and non-crosslinked parts of the films, widens the gap between the tempered glass and the silicon panel, while the dissolution process dissolves the ethylene-vinyl acetate film into liquid. Similar studies indicated that ethylene-vinyl acetate solubility in organic reagents increased with an increasing temperature. Other studies indicated that the solvent could overcome ethylene-vinyl acetate adhesion and allow end-of-life PV panels to be recycled. In addition, PV panels contain valuable metals such as silver; therefore, silver powder could be extracted by dissolving it in nitric acid, precipitate silver chloride, a sodium hydroxide treatment, or a hydrazine hydrate reduction [2].

3. Conclusions

There are vast research opportunities and research fields available for the next generation scientist (in the era of chemical engineering, environmental engineering, energy engineering, process engineering, material science, etc.) that would like to invent in this area. Moreover, there is an increased necessity for the new technological development and optimization of PV recycling facilities, as due to the rising use and disposal of PV panels, their handling at their end-of-life stage will become an increasing matter of interest and a huge pressure point on the environment, society, and economy. Furthermore, *energies* and MDPI will have a significant and vital role to play as they intend to be the leading publisher in these areas. The research areas of main interest include end-of-waste criteria and quality protocols' development, which are at the core of the reuse and recycling of PV panels; the assessment through multicriterial analysis of all the existing methods [16,17] to define and choose the best available and sustainable method to manage end-of-life PV panels; the assessment via LCA of several approaches related to the management of PV panels at the end of their lifetime; and to categorize composite materials [18] and determine how they can be reused.

Funding: This research received no external funding.

Acknowledgments: This editorial's authors would like to thank the authors for submitting their excellent contributions to the journal.

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

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