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Review

End-of-Life Photovoltaic Modules

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Abstract: More than 78 million tons of photovoltaic modules (PVMs) will reach their end of life (EOL) by 2050. If they are not responsibly managed, they can (a) pollute our terrestrial ecosystem, (b) indirectly encourage continuous mining and extraction of Earth's finite resources, and (c) diminish the net environmental benefit of harvesting solar energy. Conversely, successfully recovering them could reduce resource extraction and waste and generate sufficient economic return and value to finance the production of another 2 billion PVMs by 2050. Therefore, EOL PVMs must participate in the circular economy, and business and political leaders are actively devising strategies to enable their participation. This article aims to facilitate and expedite their efforts by comprehensively reviewing and presenting the latest progress and developments in EOL PVM recovery methods and processes. It also identifies and thoroughly discusses several interrelated observations that impede or accelerate their efforts. Overall, our approach to this article differs but synergistically complements and builds upon existing life cycle assessment-based (LCA-based) contributions.

Keywords: life cycle; circular economy; circularity; end-of-life; solar energy; photovoltaics; energy decarbonization; energy systems; photovoltaic modules; sustainability

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Citation: Tan, J.; Jia, S.; Ramakrishna, S. End-of-Life Photovoltaic Modules. *Energies* **2022**, *15*, 5113. https://doi.org/10.3390/en15145113

Academic Editor: Gianpiero Colangelo

Received: 14 June 2022
Accepted: 12 July 2022
Published: 13 July 2022

1. Introduction

Renewable energy will be the future as the push for energy decarbonization accelerates. These energy sources are virtually inexhaustible and replenish naturally. They also do not pollute the air or emit harmful greenhouse gases. The total renewable energy produced worldwide grew by more than 75% in the preceding decade, from 4196.94 to 7443.81 Terawatt-hours (TWh) [1]. The International Energy Agency [2] projects that renewable energy systems will account for almost 95% of the increase in the global power capacity over the next 5 years. Such accelerated growth is expected, with a more significant and concerted push towards net-zero emissions. By 2050, renewable energy systems will likely replace fossil fuel-based energy systems as the dominant energy source [3,4].

1.1. Current State and Prospects of Solar Energy Systems

Among all, harvesting solar energy is one of the fastest-growing avenues and most favored [5]. Solar energy systems accounted for over half of all renewable power expansion in 2021 [2]. It experienced the most growth in the preceding decade among all renewable energy systems. Its global output grew at a 38.8% compounded average growth rate, implying that annual solar power generation doubled every few years. If solar energy systems continued to grow at this rate, they would become the most significant contributor to power generation growth [1,2,4,6].

Solar energy is one of the safest forms of energy on Earth [7]. Sunlight, the richest and most abundant resource that reaches all parts of Earth's surface [8], can be converted into electricity using photovoltaics, solar heating and cooling, and concentrating solar power [9].

efficiently extract high-purity recyclates from EOL PVMs without producing additional waste and carbon emissions. The lesson learned is that planning for the EOL of the next-generation PVMs should not be an afterthought. Hence, taking a step further, we encourage scholars to explore the development of tools and frameworks to enable next-generation PVMs to be designed for participation in the circular economy.

Our second observation relates to the scale of published works. We observed that most works were conducted at a laboratory scale or trialed on a small scale. We speculate that scholars might have limited opportunities to conduct large-scale investigations due to the global lack of established PVM recovery facilities to collaborate. Similar to the discontinuation of the FRELP project, the insufficient and inconsistent volume of EOL PVMs could be the primary reason behind the lack of industrial-scale facilities. Nevertheless, we believe this problem is transient and will gradually be resolved when annual EOL PVM generation exceeds 130,000 tons, the estimated level by the "European Association for the Recovery of PV Modules" required for PVM recovery activities to be sustainable [83]. In the meantime, the lack of access to realistic field tests remains a severe limitation to advancing further research. Without empirical data and evidence, it is difficult for scholars to continuously improve and propose readily adoptable solutions. Nevertheless, scholars should creatively devise means to conduct realistic simulations and prepare for upcoming field testing opportunities.

By extension of our second observation, our third observation relates to unit economics. Today's unit economic calculations for EOL PVM recovery processes are primarily estimated and may not accurately represent future operations. Hence, similar to testing and reporting the technical and sustainability performances of the proposed solutions, the unit economics must be critically evaluated in a representative operational environment. More importantly, the unit economics must be financially attractive for industry players to participate. Presently, economic incentives for recovering EOL PVMs are severely limited as there is much uncertainty about the dominant recovery process, related investments required, and profitability. We believe that deriving representative unit economics will be an emerging research area that directly affects the future direction of EOL PVM recovery research.

In sum, for future works to add significant value, scholars must consider how their proposed solutions can be integrated into a more extensive industrial-scale system. At the same time, they must also consider its overall sustainability, operational feasibility, and economic viability. We recommend that scholars adopt tools such as LCA and techno-economic assessment to evaluate their technologies' environmental and economic aspects thoroughly. We firmly believe harmonizing these aspects is critical for any solution to scale beyond laboratory scale and achieve widespread adoption. Scholars should also lead the way in redesigning PVMs with their EOL in mind if given the opportunity.

7. Conclusions

In conclusion, we discussed the urgent need for energy decarbonization and how it accelerates the world's transition to adopting renewable energy sources. Solar energy is highly favored and widely adopted. Silicon-based PVMs, the most used instrument to capture and convert solar energy to electricity today, will continue to be rapidly deployed.

As all PVMs will eventually reach their end of life, this will create an abundance of incoming EOL PVMs. We discussed the consequences of mismanagement of EOL PVMs. This can result in (a) pollution across our terrestrial ecosystem, (b) indirectly encourage continuous mining and extraction of Earth's finite resources, and (c) diminish the net environmental benefit of harvesting solar energy. On the other hand, the successful recovery of EOL PVMs could reduce resource extraction and waste and generate sufficient economic return and value to finance the production of another 2 billion PVMs by 2050.

Despite several proposed EOL PVM recovery methods (physical, chemical, and mixed) and processes (FRELP and ASU), none seemed to be a proven, effective, and responsible industrial-scale solution to manage the incoming EOL PVMs and reclaim their valuable materials. While the current state-of-the-art demonstrated the technical and financial possibility of EOL PVMs being responsibly and effectively recovered, more needs to be done to ensure the desired outcome can be achieved at an industrial scale. To this end, accessing realistic field testing opportunities is critical for scholars to evaluate the practicality and implications of their proposals. Other critical variables such as its overall sustainability, operational feasibility, and economic viability must also be considered. Regardless, our review firmly suggests that scholars, the industry, and relevant stakeholders have recognized the imperative for EOL PVMs to participate in the circular economy. They also agree that ineffective EOL PVM management will become a black eye for the supposedly clean industry.

Author Contributions: J.T.: Conceptualization, methodology, formal analysis, investigation, resources, writing—original and revision draft preparations, S.J.: Conceptualization, methodology, formal analysis, investigation, resources, writing—original draft, S.R.: Resources, supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Acknowledgments: J.T. would like to acknowledge the support provided by the NUS Research Scholarship (GRSUR5000001 Res Sch (PhD) SERIS SC) during his study.

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

Abbreviations

The following abbreviations are used in this manuscript:

ARL	Anti-Reflective Layer
ASU	Arizona State University
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
EOL	End-of-Life
EU	European Union
EVA	Ethylene-Vinyl Acetate
FRELP	Full Recovery End of Life Photovoltaics
GaAs	Gallium Arsenide
InP	Indium Phosphide
LCA	Life Cycle Assessment
PV	Photovoltaics
PVM	Photovoltaics Modules
TPT	Tedlar Polyester Tedlar
TWh	Terawatt-hours
WEEE	Waste Electrical and Electronic Equipment

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