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Article

Sustainability Impacts Evaluation of the Recycling of End-of-Life Crystalline Silicon Solar Photovoltaic Panel Waste in South Korea

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Abstract: End-of-life (EoL) management of solar panel waste has emerged as an important issue related to first-generation solar panels in South Korea, which have already entered their retirement stage. In this study, the sustainability impacts of three scenarios for recycling EoL solar panels, namely, mechanical recycling (MR), chemical recycling (CR), and thermal recycling (TR) were investigated and their environmental and economic benefits were evaluated using the life cycle sustainability assessment (LCSA) method, with landfilling as the reference scenario. The results obtained showed a high global warming potential (GWP) as well as acidification for MR owing to the additional burden of transportation and industrial processes associated with MR. For CR, the use of chemicals and subsequent landfilling resulted in approximately 4.7 times higher terrestrial ecotoxicity than was observed for the landfilling scenario. Further, the GWP of TR was approximately 1.5 times higher than that of CR owing to its high energy consumption. However, its environmental burden was generally lower than those of MR and CR. The results of this study, which capture the current situation of EoL PV panels in South Korea, can be employed to facilitate the establishment of regulations that ensure sustainable management in this regard.

Keywords: crystalline silicon solar panels; end-of-life; life cycle sustainability assessment (LCSA); solar panel recycling; solar photovoltaics

1. Introduction

Solar photovoltaic (PV) energy has gained worldwide attention owing to its infinite availability and its provision of clean and sustainable energy, and the International Energy Agency (IEA) predicts that cumulative power generation using PV modules may increase to 14.5 TW by 2050 globally [1]. However, despite the advantages of solar PV energy, the rapid growth of the use of solar PV systems, primarily witnessed at the end of the 20th century, has resulted in an exponential increase in the amount of solar panel waste requiring disposal. Weckend et al. (2016) [2] estimated that the annual amount of end-of-life (EoL) PV waste will increase to approximately 68–78 million tons by 2050. Therefore, environmental issues related to the management of EoL PV waste are inevitable [3].

Recently, perovskite solar cells [4] have garnered significant attention due to their low manufacturing cost and applicability to flexible substrates. However, challenges related to long-term stability and environmental safety remain unresolved. Similarly, organic solar cells [5] face limitations in practical applications due to their low efficiency and short lifespan. Quantum-based solar cells [6] also hold great potential for achieving very high energy conversion efficiencies, but their commercialization is hindered by the complexity and high cost of manufacturing technologies. Despite the gradual increase in the proportion of third-generation solar modules over the years, the

solar panel market share is still significantly dominated by crystalline silicon (c-Si) solar modules, which accounted for 92% and 73.3% of the solar market in 2014 and 2020, respectively [7]. Further, given that the average lifespan of a c-Si PV module is approximately 25–30 years [8], a large number of first-generation c-Si PV modules, installed in the 1980s, have already entered their retirement stage [9]. Therefore, the reutilization of EoL PV panel waste could become an advanced field that requires further research and sustainable development.

In recent years, PV waste recycling policies have been implemented in several countries, in which solar power generation is highly prevalent. However, owing to the absence of economically viable and practical technologies, the waste modules are often neglected and discarded, leading not only to environmental pollution, but also the non-exploitation of a potential source of valuable resources [10]. The United Kingdom first officially adopted the European Union's (EU) revised Waste Electrical and Electronic Equipment (WEEE) directive on the disposal of waste solar PV panels in 2012. Germany has also implemented policies that enforce PV panel manufacturers and importers to take responsibility for EoL PV waste disposal [11,12]. Further, other EU countries, including Czech Republic, have initiated various joint ventures for the recycling and recovery of EoL solar panels in accordance with the WEEE directive [13]. Italy has also implemented legislation related to the collection and recycling of EoL panel waste [14]. Several non-EU countries have also implemented legislation to regulate solar panel waste management; however, the recycling of waste solar PV panels has not yet been considered in some developing nations, including India, North Korea, and Thailand [12]. Despite operating approximately twice as many solar panels as the United States, China still lacks recycling policies related to EoL PV panels, and it is only of recent that Chinese solar panel manufacturers and universities-initiated research on PV panel waste recycling [15]. In Japan, the New Energy Industrial Technology Development Organization (NEDO), in collaboration with solar panel manufacturers, encourages research on solar panel waste recycling [7]. Furthermore, in the United States, the California Department of Toxic Substances Control (DTSC) recently took up the responsibility to handle solar panel waste processing in anticipation of a decline in the processing capacity of European facilities [16].

Solar power generation in South Korea, which began in the early 2000s, has grown explosively in recent years. The growth rate of the cumulative installed capacity of solar power generation in South Korea between 2019 and 2020 was approximately 36.2%, indicating that a considerable number of solar panels were installed in just one year [17]. Further, according to the Korea Environment Institute [18], the cumulative amount of waste solar panels generated up to 2023 was approximately 12,690 tons, and it has been predicted that this amount will increase exponentially in the coming years, possibly reaching 87,124 tons by 2030 and 820,029 tons by 2040. Additionally, since 2023, after which significant generation and disposal of solar panels is anticipated, the government of South Korea adopted the Extended Producer Responsibility (EPR) system as a strategy for managing EoL solar panels, and under this regulation, the government aims to increase the recycling and reuse rates of discarded solar panels within three years to over 80%, aligning with the EU standard [19].

In this study, the environmental benefits of recycling EoL c-Si solar PV panel waste in South Korea were comprehensively analyzed. Given that three waste PV panel recycling processes, i.e., mechanical recycling (MR) [20–24], chemical recycling (CR) [25–27], and thermal recycling (TR) [28–30], have been extensively used to extract reusable components from waste PV panels, in this study, scenario-based comparison analysis for these three recycling processes was performed, using ISO-14040-based life cycle assessment (LCA) [31], which has been extensively used to assess EoL solar panels, particularly, to quantify their environmental impacts [32–35]. Given that the reutilization of EoL PV waste is intricate, not only from an environmental protection perspective, but also in terms of economic and social factors, it is expected that the results of this study will provide insights that can facilitate policy making regarding the sustainable recycling of EoL c-Si solar PV modules.

2. Scenario and Methodology

2.1. Description of Recycling Scenarios

Figure 1 shows a schematic representation of the system boundary involving the collection, transportation, dismantling, and disposal of waste PV modules simplified from Li et al. (2023) [15]. The masses of the materials shown in Figure 1 were estimated based on a single solar panel weighing 18 kg, and the proportions of each material were determined using the ratios of the solar panels derived from data reported by Li et al. (2023) [15]. Further, the recycling of waste solar panels was primarily processed according to the following order: waste collection, separation of parts, such as junction boxes and frames, removal of ethylene vinyl acetate (EVA), extraction of reusable metals, and separation of the back sheet. The recycling process began with the manual separation of the aluminum alloy frame and junction box from the module. The junction box contains wires as well as plastics, which are highly recyclable; however, in recycling scenarios in the present study, it was assumed that the junction box can be directly reused in new solar products. Further, depending on the method used to remove the EVA film attached to both sides of the silicon cells, the separation process could be divided into the MR, CR, and TR processes. Approximately 70 wt.% of a solar panel is composed of glass, and MR involves crushing the glass and sorting materials for recycling, while CR and TR involve recycling the glass without destruction.

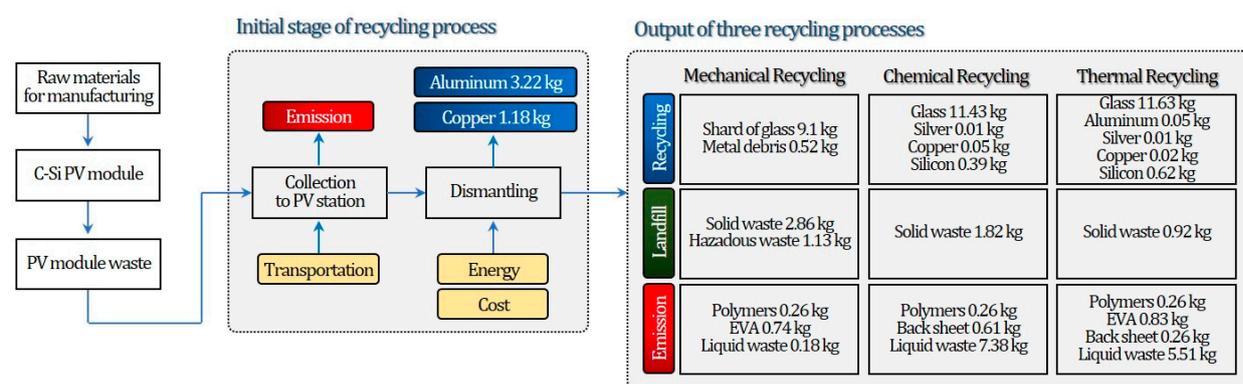


Figure 1. Schematic representation of the system boundary for three different recycling scenarios.

Hazardous substances in solar PV waste, such as lead, nickel, chromium, and cadmium, contaminate air, water, and soil when EoL PV modules are incinerated [35]. Solar PV panels also contain conventional materials, such as aluminum, glass, copper, and critical metals, such as silver [36], the reuse of which can reduce resource exhaustion, conserve energy, and sustain the growing number of solar installations [37]. In this study, a transportation distance for the waste PV panels of 100 km was assumed given that the government of South Korea recently planned to expand the two existing recycling centers to seven nationwide.

2.2. Methodology

2.2.1. Environmental Sustainability and Indicator

To evaluate the environmental sustainability of the EoL solar PV modules, a weighted factor, E_i was proposed with respect to the mass of the components and environmental factors, such that [38]:

$$E_i = E_i^{mat}(m_i) + E_i^{pro}(m_i) + E_i^{use}(m_i) + E_i^{EoL}(m_i) \quad (1)$$

where E_i represents the weighted factor for environmental impact along the product life-cycle and m_i represents the mass of the material. Further, the superscripts mat, pro, use, and EoL represent the material extraction, production, use, and EoL stages, respectively. In this paper, E_i^{EoL} represents environmental impact from recycling processes shown in Figure 1.

2.2.2. Economic Sustainability and Indicator

Economic sustainability is directly affected by the costs of materials and energy usage. In this study, economic sustainability was analyzed considering life cycle costs (LCCs) as economic indicators. Specifically, the LCC analysis included four stages of the product lifecycle. The LCC of the i th component (LCC_i) was calculated as follows:

$$LCC_i = C_i^{mat} + C_i^{pro} + C_i^{use} + C_i^{EoL} \quad (2)$$

with

$$C_i^{mat} = \alpha_i^{mat} N_i m_i \quad (3)$$

$$C_i^{pro} = \alpha_i^{pro} N_i \quad (4)$$

$$C_i^{use} = f_i (\alpha_i^{use} + \alpha_i^{disassy} + \alpha_i^{assy}) \quad (5)$$

$$C_i^{EoL} = \alpha_i^{disposal} n_i - \beta_i^{recovery} (N_i - n_i) + C_i^{disassy} \quad (6)$$

where C_i^{mat} represents the material cost of the i th component, α_i^{mat} and N_i represent the unit cost and number of the materials, respectively, and C_i^{use} includes service costs related to disassembling failed components and installing new components [39]. Further, f_i represents the service frequency of the i th component. C_i^{EoL} includes reuse, recycling, and disposal options. Additionally, the model comprised the number of disposed components, n_i , and the reuse/recycling factor, $\beta_i^{recovery}$. Finally, the LCC of the c-Si solar PV module composed of i components was calculated as follows:

$$LCC_{PV} = \sum_{i=1}^i C_i^{mat} + C_i^{pro} + C_i^{use} + C_i^{EoL} \quad (7)$$

3. Results and Discussion

3.1. Environmental Impacts

In this study, modelling to analyze and compare the environmental impacts of three EoL PV panel recycling scenarios was performed using openLCA software version 2.2.0. Environmental impact was calculated based on Ecoinvent database [40], which provide environmental impact data when producing or treating materials. Typical LCA modeling is developed based on product lifecycle that has five stages: material extraction, manufacturing, transportation, usage, and end-of-life stages. However, in this study, developing openLCA model is focused on environmental impacts of each recycling processes at the end-of-life stage. Accordingly, openLCA model are developed based on the three different recycling processes as shown in Figure 1. The environmental impacts considered included: terrestrial eco-toxicity (kg 1.4-DB-eq), photochemical oxidation (kg C₂H₂-eq), freshwater eco-toxicity (kg 1.4-DB-eq), eutrophication (kg PO₄-eq), acidification potential (kg SO₂-eq), human toxicity (kg 1.4-DB-eq), global warming potential (GWP; kg CO₂-eq), ozone depletion potential (ODP; kg CFC-11-eq), and marine aquatic eco-toxicity (kg 1.4-DB-eq). The environmental benefits obtained for the three recycling scenarios relative to the environmental burden of complete PV waste landfilling are presented in Table 1. Further, Figure 2 shows the absolute values of the environmental impacts of the three recycling methods relative to the case of landfills.

Table 1. Environmental benefits of the three recycling processes relative to landfilling.

| Impact category | Mechanical Recycling (MR) | Chemical Recycling (CR) | Thermal Recycling (TR) |
|----------------------------------|---------------------------|-------------------------|------------------------|
| Terrestrial eco-toxicity | -2.56131 | 15.1943 | -2.83348 |
| Photochemical oxidation | -0.59974 | -0.72082 | -0.66353 |
| Fresh water aquatic eco-toxicity | -3.2206 | -4.12505 | -3.56289 |
| Eutrophication | -0.49645 | -0.65664 | -0.54938 |
| Acidification potential | -34142.8 | -58912.65674 | -37772.2 |
| Human toxicity | -798.36438 | -981.34784 | -883.2034 |
| Global warming potential (GWP) | -2442.57795 | -3107.68639 | -2702.17943 |
| Ozone layer depletion (ODP) | -0.00022 | -0.00024 | -0.00024 |
| Marine aquatic eco-toxicity | -2689640 | -2953250 | -2975450 |

Note: The positive values represent a higher environmental burden, while the negative values represent an environmental benefit, compared with the case of landfills.

MR involves removing aluminum and copper from solar panels, followed by cutting and shredding the panels to recover the materials [41,42]. This process primarily utilizes physical treatment to break down the PV panel waste, thereby allowing the separation of glass, metals, and other materials. However, some of the challenges associated with this process include the high transportation costs and the resulting increase in greenhouse gas emissions. Transporting waste panels to processing facilities consumes large amounts of energy, resulting in further increases greenhouse gas emissions. A considerable amount of energy is also required to separate glass fragments and metal pieces during processing, further increasing fossil fuel consumption as well as greenhouse gas emissions. Moreover, our analysis showed that the MR process results in relatively higher GWP and acidification levels than the other recycling methods owing to the increased use of fossil fuels. Specifically, the GWP of the MR process was 1467.9 kg CO₂-eq, the highest among the three recycling methods. However, this value represents only approximately 37% of the GWP observed landfilling. Regardless, the air pollution and release of harmful chemicals during this process can negatively affect human health and also result in freshwater aquatic ecotoxicity.

CR involves the use of various chemicals, e.g., HNO₃ [43,44], H₂SO₄ [45], HCl [46], HF [47] to remove EVA layers from solar panels and recover valuable materials, such as precious metals. This process is advantageous in that it allows the recycling of materials, such as glass without damaging them. It also offers economic benefits associated with the recovery of precious metals, such as silver. However, the chemicals used in the CR process lead to an increase in liquid waste and are associated with a high environmental burden. For example, the chemicals used to remove EVA significantly increase acidification in environmental media to levels similar to that observed for the MR process (approximately 36.38 kg SO₂-eq). Further, many liquid chemicals used in CR are non-recyclable and require landfilling, which significantly increases terrestrial ecotoxicity. Our analysis showed that the terrestrial ecotoxicity level of CR was 4.7-fold higher than that of landfilling, indicating a serious environmental impact.

TR process primarily involves melting the EVA layer in solar panels to separate the glass and solar cells from the panel waste at moderate temperatures [34,48]. This process facilitates glass recycling and offers economic benefits associated with the recovery of small quantities of precious metals. Additionally, this method has lower transportation and industrial process burdens than MR

and also avoids the burden of chemical landfilling associated with CR. However, it imposes an environmental burden owing to its high energy consumption. In particular, the GWP of TR was determined to approximately 1.5 times higher than that of CR, primarily because of the greenhouse gases emitted during the thermal treatment process. Consequently, for efficient recycling of waste solar panels, it is necessary to adopt an approach that maximizes the advantages of each recycling process while mitigating their drawbacks. For example, advanced sorting and processing technologies should be introduced to reduce the amount of solid waste generated during MR. The development of eco-friendly chemicals is also essential. Further, technological improvements to enhance the energy efficiency of TR should also be considered. Such an integrated approach will help minimize the environmental impact of recycling waste solar panel wastes and promote efficient resource utilization.

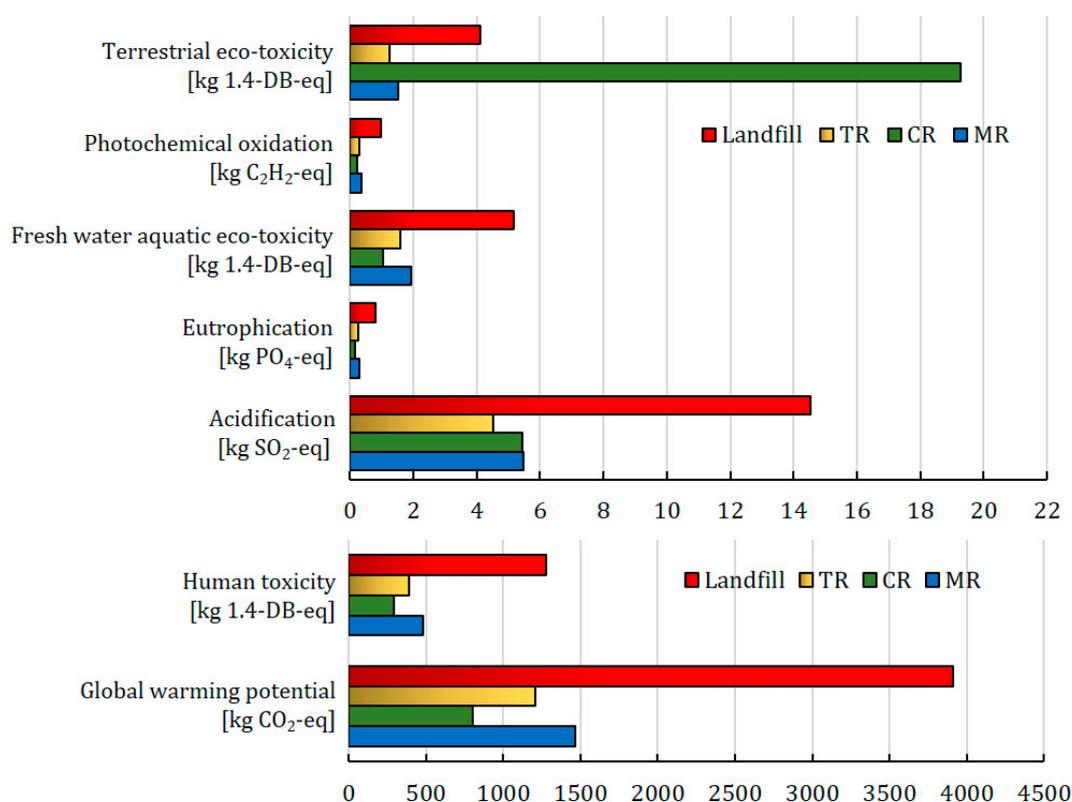


Figure 2. Environmental impacts of three presented recycling methods and landfilling.

3.2. Economic Impacts

The economic analysis of the three waste solar panel disposal methods revealed higher costs for MR, CR, and TR than for landfilling, as shown in Table 2. This observation could be attributed to the technical characteristics of each process and the cost associated with the facilities required for these treatment processes. The MR process involves physical crushing and separating waste panels to recover useful materials. Although this method is relatively simple, the purity of the materials obtained after crushing is low, i.e., the associated impurities reduce the value of recycled materials. Additionally, the cost of maintaining the crushing machinery is high, and additional energy and costs are incurred to further refine the crushed materials. Thus, the total cost of MR for 75 waste PV modules was determined to be \$11,140, which is significantly higher than those associated with the other treatment methods. CR involves immersing the waste panels in chemical solvents to selectively dissolve and separate the constituent materials. This method improves the purity of the recovered materials, thereby increasing the value of the recycled materials. However, the chemical solvents

used as well as the process of disposing of the chemical wastes generated after treatment are considerably costly. Furthermore, additional facilities are needed to control the associated chemical reactions and minimize the environmental impact of the waste, leading to an increase in overall costs. Specifically, the cost associated with CR of 75 waste PV modules was determined to be \$7,080. The TR process involves heating waste panels at high temperatures to recover valuable materials. This process is effective for recovering useful metals or semiconductor materials but is highly energy intensive. Further, it is associated with additional costs related to managing harmful gases or the waste generated during the thermal treatment process. Owing to the complexity of the process and the high cost of energy consumption, the total cost of the TR was \$6,190. Conversely, landfilling, the simplest treatment method, involves disposing of waste panels without recycling, and thus, requires no specific technical process. It only involves transporting the waste to a landfill site for disposal and the payment of the landfill usage fee. Thus, the cost associated with landfilling 75 waste PV modules was the lowest at \$5,880. However, the long-term negative environmental impact of landfilling and the associated additional social costs were not reflected in this estimate.

Expanding South Korea's solar panel recycling market offers substantial indirect benefits. It has the potential to create jobs in facility operations, material recovery, and logistics, contributing to economic revitalization [49]. Moreover, it reduces social compensation costs by mitigating environmental and public health damages caused by landfilling. Additionally, recycling efforts decrease carbon emissions associated with raw material extraction and production, which positively impacts carbon trading markets and generates economic value through carbon credit sales [7,50]. This observation suggests that while the economic cost associated with landfilling may be low in the short term, the accumulated environmental costs could lead to significant long-term economic burdens. Further, the different recycling method varied with respect to economic feasibility based on their associated technical characteristics and costs. Even though landfilling may appear more economical in the short term, recycling has become increasingly important from an environmental sustainability point of view.

Table 2. Operational costs of the three presented recycling methods and landfilling for 75 waste PV modules.

| Recycling process | Operational cost [US\$] |
|----------------------------------|--------------------------------|
| Mechanical Recycling (MR) | 11,140 |
| Chemical Recycling (CR) | 7,080 |
| Thermal Recycling (TR) | 6,190 |
| Landfill | 5,880 |

3.3. Regulation Related to EoL Solar Panel in South Korea

The government of South Korea recently adopted the Extended Producer Responsibility (EPR) system to enhance the efficiency of waste solar panel recycling and establish a technological foundation for sustainable energy transition. This system mandates producers to take responsibility for the collection and recycling of EoL solar panels to the end of minimizing the environmental impacts of these solar panels throughout their lifecycle. Previously, South Korea's recycling policies primarily imposed recycling responsibilities on producers for specific waste types, such as household appliances and electronic devices, with fees collected from producers used to establish and operate recycling facilities. However, solar panels represent a new category of materials characterized by a high level technical complexity and significant recycling costs, which make adequate recycling under the existing system challenging. Further, solar panels are composed of various materials that are difficult to separate.

To address these challenges, the South Korean government has expanded its efforts by developing recycling infrastructure and advancing related technologies. This includes increasing the number of recycling facilities from two to seven, strategically located across five major regions to

facilitate efficient collection and processing. Additionally, innovative recycling technologies have been developed, such as processes that reduce energy consumption to one-third of conventional methods while recovering high-purity materials. The government also provides regulatory exemptions to support pilot recycling initiatives and has introduced economic incentives for improved recycling performance. Through these measures, the government aims to achieve an 80% recycling and reuse rate for waste solar panels by 2025, aligning with international standards.

The new EPR system is expected to promote the development and application of specialized technologies for the efficient separation and recycling of these materials. Such an approach will encourage producers to consider recyclability during the initial product-design stage, leading to more efficient waste management and resource circulation. Furthermore, in conjunction with the EPR system, the implementation of EoL PV module recycling policies is necessary to mandate the use of eco-friendly and recyclable materials in solar panel manufacturing, enforce the collection of EoL panels, establish regional recycling centers, and provide incentives to producers based on recycling performance, thereby improving the efficiency of South Korea's solar panel recycling system.

4. Conclusions

In this study, the environmental impacts of recycling end-of-life solar panels in South Korea were examined. The LCSA method was employed, and three recycling scenarios, namely, MR, CR, and TR, were analyzed and compared with landfilling. Based on the results obtained, the main conclusions of this study are summarized as follows:

- In MR, after removing aluminum and copper from the waste panels, additional transportation and industrial processes are required during the cutting, grinding, and screening stages. The extensive use of fossil fuels and the resulting emissions during these processes lead to a higher GWP as well as higher acidification levels. In the CR scenario, the use of chemicals and subsequent landfilling significantly increase terrestrial ecotoxicity level, resulting in an environmental burden that is 4.7 times higher than that of landfilling. In the TR scenario, the use of thermal energy to melt the EVA layer results in an environmental burden owing to greenhouse gas emissions. However, the environmental burden of TR was generally lower than those of the two other recycling processes.
- The government of South Korea introduced an Extended Producer Responsibility (EPR) system to promote the recycling of EoL solar panels, placing responsibility on producers for the collection and recycling of these PV materials. This system aims to reduce the environmental impacts of solar panels, encourage the development of recycling technologies, and establish an efficient waste management system in this regard. In addition to the EPR system, the use of eco-friendly materials in solar panel manufacturing and the mandatory use of recyclable materials should be enforced. The mandatory collection of EoL panels, the establishment of regional recycling centers, and the provision of incentives based on recycling performance will pave the way for an efficient future for solar panel recycling in South Korea.

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References

1. International Energy Agency, Net zero by 2050: a roadmap for the global energy sector, Int. Energy Agency, <https://www.iea.org/reports/net-zero-by-2050>, 2021, 224.

2. Weckend, Stephanie, Andreas Wade, and Garvin A. Heath. End of life management: solar photovoltaic panels. No. NREL/TP-6A20-73852. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2016.
3. Mahmoudi, Sajjad, Nazmul Huda, and Masud Behnia. "Critical assessment of renewable energy waste generation in OECD countries: decommissioned PV panels." *Resources, Conservation and Recycling* 164 (2021): 105145.
4. Qi, Xingnan, et al. "Bidirectional targeted therapy enables efficient, stable, and eco-friendly perovskite solar cells." *Advanced Functional Materials* 33.19 (2023): 2214714.
5. Gao, Yueyue, et al. "Asymmetric Π -bridge engineering enables high-permittivity benzo [1, 2-B: 4, 5-B'] difuran-conjugated polymer for efficient organic solar cells." *Advanced Materials* 36.9 (2024): 2306373.
6. Huang, Xiufang, et al. "Efficient and Stable Z907-Based Dye-Sensitized Solar Cells Enabled by Suppressed Charge Recombination and Photocatalytic Activity." *ACS Sustainable Chemistry & Engineering* 12.34 (2024): 13007-13016.
7. Xu, Yan, et al. "Global status of recycling waste solar panels: A review." *Waste Management* 75 (2018): 450-458.
8. Mahmoudi, Sajjad, et al. "End-of-life photovoltaic modules: A systematic quantitative literature review." *Resources, Conservation and Recycling* 146 (2019): 1-16.
9. Aman, M. M., et al. "A review of Safety, Health and Environmental (SHE) issues of solar energy system." *Renewable and Sustainable Energy Reviews* 41 (2015): 1190-1204.
10. Cho, et al. "Current Status and Utilization Technology of End-of-Life Photovoltaic Modules." 29.4 (2020): 15-30, doi.org/10.7844/kirr.2020.29.4.15
11. Sharma, Arvind, Suneel Pandey, and Mohan Kolhe. "Global review of policies & guidelines for recycling of solar PV modules." *International Journal of Smart Grid and Clean Energy* 8.5 (2019): 597-610.
12. Chowdhury, Md Shahariar, et al. "An overview of solar photovoltaic panels' end-of-life material recycling." *Energy Strategy Reviews* 27 (2020): 100431.
13. Divya, A., et al. "Review on recycling of solar modules/panels." *Solar Energy Materials and Solar Cells* 253 (2023): 112151.
14. Paiano, Annarita. "Photovoltaic waste assessment in Italy." *Renewable and Sustainable Energy Reviews* 41 (2015): 99-112.
15. Li, Jing, et al. "Life cycle analysis of the economic costs and environmental benefits of photovoltaic module waste recycling in China." *Resources, Conservation and Recycling* 196 (2023): 107027.
16. Ali, Amjad, et al. "Policies and regulations for solar photovoltaic end-of-life waste management: Insights from China and the USA." *Chemosphere* 340 (2023): 139840.
17. Korea Energy Agency, "2020 New and Renewable Energy Supply Statistic" (2021) <https://www.knrec.or.kr/biz/pds/statistic/view.do?no=120>
18. Jo, J. H., S. Seo-won, and K. Yu-seon. "Management status and improvement plans of waste solar panels." Korea Environmental Research Institute (2018).
19. Lee, Su-Hee, and Yong-Chul Jang. "Analysis for End-of-Life Solar Panel Generations by Renewable Energy Supply towards Carbon Neutrality in South Korea." *Energies* 16.24 (2023): 8039.
20. Strachala, David, et al. "Mechanical Recycling of Photovoltaic Modules." *ECS Transactions* 81.1 (2017): 199.
21. Del Pero, Francesco, et al. "Innovative device for mechanical treatment of End of Life photovoltaic panels: Technical and environmental analysis." *Waste Management* 95 (2019): 535-548.
22. Camargo, Priscila Silva Silveira, et al. "c-Si PV module recycling: Analysis of the use of a mechanical pre-treatment to reduce the environmental impact of thermal treatment and enhance materials recovery." *Waste Management & Research* 41.11 (2023): 1661-1673.
23. Fiandra, Valeria, Lucio Sannino, and Concetta Andreozzi. "Photovoltaic waste as source of valuable materials: A new recovery mechanical approach." *Journal of Cleaner Production* 385 (2023): 135702.
24. Li, Jiayan, et al. "Recycling Si in waste crystalline silicon photovoltaic panels after mechanical crushing by electrostatic separation." *Journal of Cleaner Production* 415 (2023): 137908.
25. Azeumo, Maurianne Flore, et al. "Photovoltaic module recycling, a physical and a chemical recovery process." *Solar Energy Materials and Solar Cells* 193 (2019): 314-319.

26. Padoan, Flavia CSM, Pietro Altimari, and Francesca Pagnanelli. "Recycling of end of life photovoltaic panels: A chemical prospective on process development." *Solar Energy* 177 (2019): 746-761.
27. Deng, Rong, et al. "A sustainable chemical process to recycle end-of-life silicon solar cells." *Green Chemistry* 23.24 (2021): 10157-10167.
28. Shin, Jeongeun, Jongsung Park, and Nochang Park. "A method to recycle silicon wafer from end-of-life photovoltaic module and solar panels by using recycled silicon wafers." *Solar Energy Materials and Solar Cells* 162 (2017): 1-6.
29. Maani, Thomas, et al. "Environmental impacts of recycling crystalline silicon (c-Si) and cadmium telluride (CDTE) solar panels." *Science of The Total Environment* 735 (2020): 138827.
30. Hua, Matthew, and Ramy Imam. "Concept for Solar Panel Recycling based on High-Temperature Density Separation." *Journal of Student Research* 11.4 (2022).
31. Finkbeiner, Matthias, et al. "The new international standards for life cycle assessment: ISO 14040 and ISO 14044." *The international journal of life cycle assessment* 11 (2006): 80-85.
32. Latunussa, Cynthia EL, et al. "Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels." *Solar energy materials and solar cells* 156 (2016): 101-111.
33. Lisperguer, Rubén Contreras, et al. "Environmental Impact Assessment of crystalline solar photovoltaic panels' End-of-Life phase: Open and Closed-Loop Material Flow scenarios." *Sustainable Production and Consumption* 23 (2020): 157-173.
34. Maani, Thomas, et al. "Environmental impacts of recycling crystalline silicon (c-Si) and cadmium telluride (CDTE) solar panels." *Science of The Total Environment* 735 (2020): 138827.
35. Ansanelli, G., et al. "A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels." *Applied Energy* 290 (2021): 116727.
36. Deng, Rong, et al. "A techno-economic review of silicon photovoltaic module recycling." *Renewable and Sustainable Energy Reviews* 109 (2019): 532-550.
37. Aryan, Venkat, Mercè Font-Brucart, and Daniel Maga. "A comparative life cycle assessment of end-of-life treatment pathways for photovoltaic backsheets." *Progress in Photovoltaics: Research and Applications* 26.7 (2018): 443-459.
38. Kim, Samyeon, and Seung Ki Moon. "Sustainable platform identification for product family design." *Journal of cleaner production* 143 (2017): 567-581.
39. Chung, Wu-Hsun, Gül E. Okudan Kremer, and Richard A. Wusk. "Life cycle implications of product modular architectures in closed-loop supply chains." *The International Journal of Advanced Manufacturing Technology* 70 (2014): 2013-2028.
40. Wernet, Gregor and Bauer, Christian and Steubing, Bernhard, et al. "The ecoinvent database version 3 (Part I): Overview and methodology." *The International Journal of Life Cycle Assessment* 21 (2016): 1-13.
41. Ali, Amjad, et al. "Recycling and Material Extraction from End-of-Life Photovoltaic Modules Waste: Exploring Physical Recovery Techniques." 2024 IEEE 1st Karachi Section Humanitarian Technology Conference (KHI-HTC). IEEE, 2024.
42. Niekurzak, Mariusz, et al. "Conceptual design of a semi-automatic process line for recycling photovoltaic panels as a way to ecological sustainable production." *Sustainability* 15.3 (2023): 2822.
43. Šleiniūtė, Agnė, et al. "Feasibilities for silicon recovery from solar cells waste by treatment with nitric acid." *Chemija* 31.3 (2020).
44. Wongnaree, Natcha, et al. "Recovery of silver from solar panel waste: an experimental study." *Materials Science Forum*. Vol. 1009. Trans Tech Publications Ltd., 2020.
45. Click, Natalie, et al. "Innovative recycling of high purity silver from silicon solar cells by acid leaching and ultrasonication." *Solar Energy Materials and Solar Cells* 270 (2024): 112834.
46. Kavousi, Maryam, and Eskandar Keshavarz Alamdari. "Comprehensive and Sustainable Recycling Process for Blended Different Types of End-of-Life Solar Panels: Leaching and Recovery of Valuable Base and Precious Metals." (2023).
47. Prasad, D. S., et al. "A unique sustainable chemical method for the recovery of pure silicon from waste crystalline silicon solar panels." *Sustainable Materials and Technologies* 37 (2023): e00671.

48. Klugmann-Radziemska, Ewa, et al. "Experimental validation of crystalline silicon solar cells recycling by thermal and chemical methods." *Solar energy materials and solar cells* 94.12 (2010): 2275-2282.
49. Ferrão, Paulo, et al. "Environmental, economic and social costs and benefits of a packaging waste management system: A Portuguese case study." *Resources, Conservation and Recycling* 85 (2014): 67-78.
50. An, Miaorui, and Xinlu Sun. "Carbon footprints of solar panels in China provinces based on different production and waste treatment scenarios." *Journal of Cleaner Production* 435 (2024): 140453.

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