Beyond the Surface: Environmental Depth of Photovoltaic Recycling Methods

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https://doi.org/10.52202/077496-0009

Abstract

This study delved into the Life Cycle Assessment (LCA) literature review findings regarding photovoltaic (PV) recycling methodologies. LCAs' boundaries significantly influence environmental impact categories such as functional units, electricity consumption, material flows. Regardless of system scale functional unit values of literature studies are given to compare different system boundaries. This paper highlights PV module types and LCA tools, noting thermal methods in both c-Si and CdTe PV technologies yield lower environmental impacts than chemical and mechanical approaches. Additionally, a delamination process was conducted and LCA results were analyzed at the laboratory scale using hexane. The delamination success is 99%. Notably, recycling significantly diminishes environmental footprints compared to landfilling, with a fraction of Global Warming Potential (GWP) values.

Keywords: Global Warming Potential (GWP), photovoltaic recycling, Life Cycle Assessment (LCA), environmental Impact, sustainability

Introduction

The increasing diversity in photovoltaic (PV) panel technologies, along with widespread efforts to enhance existing technologies in terms of efficiency, durability, power, and other technical specifications, has raised concerns about the environmental sustainability of solar energy production (Ghosh & Yadav, 2021; Smith et al., 2021).

PV modules play a significant role in promoting renewable energy and reducing the use of fossil fuels. Additionally, the management of end-of-life modules and the formulation of necessary policies are crucial factors for ensuring the sustainability of evolving technologies (Ghosh & Yadav, 2021). Therefore, research is being conducted on PV module recycling methods and their environmental impacts, especially after their average 30-year lifespan or in case of premature failures. Environmental impact categories considered by LCA studies offer quantitative assessment opportunities in this context. Generally, SimaPro, GaBi, and OpenLCA tools stand out in research (Dias et al., 2021; Klugmann-Radziemska & Kuczyńska-Łażewska, 2020; Lim et al., 2022a).

A report published by the IEA and IRENA states that by the year 2050, the world will face 78 million tons of PV-module waste. Making measures obligatory through legal regulations by countries will ensure the regulation of increasing waste management problems in the future (IRENA and IEA, 2016). European Union countries have served as role models for other countries in terms of setting collection and recycling targets for PV modules. Although comprehensive legislation is yet to be established, the inclusion of PV recycling in the EU's Waste Electrical and Electronic Equipment (WEEE) Directive is seen as a pioneering step. The directive limits recycling responsibility to panel manufacturers (Chowdhury et al., 2020; Council of the European Union, 2019).

In the United States, there is no comprehensive PV recycling regulation covering all states (Urbina, 2022). However, California has issued a regulation (Senate Bill 489) stating that PV module waste is included in universal waste management (Chowdhury et al., 2020; State of California, 2015). Senate Bill 5939, published by the state of Washington, discusses tax incentives for recycling renewable energy production

https://doi.org/10.52202/077496-0009

technologies and the collection of modules. It is noted that reusing materials obtained from the recycling of PV modules requires less cost than directly using raw materials and can potentially provide economic returns to countries where recycling is practiced (Washington State, 2019). However, factors such as waste collection, transportation to recycling facilities, and the economic and political structures of countries result in varying levels of economic return. Therefore, there is a need for LCA and feasibility studies to be diversified through country-specific research.

Literature Review on LCA of PV Recycling

This study delved into the LCA results of PV recycling methods, with a focus on environmental-impact categories. The boundaries of LCAs, including functional units (given in Table 1), electricity consumption, material inputs and outputs, directly influence the environmental impact assessment (Table 1). Irrespective of whether recycling research is conducted at the laboratory or industrial scale, functional unit values serve as a crucial reference. Furthermore, the study outlines PV module types and specifies the LCA tools used.

Ravikumar et al., (2020) compared two scenarios for PV module recycling, highlighting combination methods as environmentally preferable due to lower impacts in various categories. Deng, Dias, Lunardi, and Ji (2021) developed a chemical process for recycling silver from silicon plates and solar panels, assessing environmental impact categories such as ecotoxicity and climate change. Singh, Powar, and Dhar (2023) analyzed the LCA of framed c-Si and frameless CdTe modules, emphasizing the environmental benefits of recycling materials from end-of-life panels. The FRELP recycling technology, referenced in multiple studies, especially for c-Si modules, achieves nearly 100% recycling efficiency and is discussed along with its environmental impacts and transportation logistics (Ganesan & Valderrama, 2022; Dias et al., 2021; Latunussa, Ardente, Blengini, & Mancini, 2016; Mathur, Singh, & Sutherland, 2020a).

Table 1. Classification of GWP Results of PV Recycling Methods

No	Reference	Scale	Method(s)	PV Type	GWP ($kgCO_2$ eq)	Database	Functional Unit
1	(Ravikumar et al., 2020)	Lab scale	Chemical, Thermal, and Mechanical (Probe sonicator, bath sonication)	CdTe	4.70E+00	SimaPro Ecoinvent	1 m^2
2	(Deng et al., 2021)	Lab scale	Mechanical, Chemical (Alkaline, KOH etching, HNO3 leaching, and electrowinning)	c-Si	-1.60E+00	OpenLCA Ecoinvent 3.2 ReCiPe2016 Midpoint (H)	1000 g
3	(Latunussa et al., 2016)	Large Scale	Chemical, Thermal, and Mechanical (Electrolysis, acid leaching, incineration)	c-Si	3.70E+02	SimaPro	1000 kg

4	(Mathur, Singh, & Sutherland, 2020a)	Large Scale	Chemical, Thermal, and Mechanical (Incineration, electrolysis)	c-Si	2.75E+03	SimaPro	1 ton
5	(Singh et al., 2023)	Lab Scale	Chemical, Thermal, and Mechanical (Burning, chemical solvent)	c-Si and CdTe	4.14E-01 and 5.29E-01	SimaPro	1 kg
6	(Ansanelli, Fiorentino, Tammaro, & Zucaro, 2021)	Large Scale	Mechanical, Chemical, and Thermal Methods	c-Si	3.36	SimaPro	24 tons
7	(Oteng, Zuo, & Sharifi 2023)	Large Scale	Mechanical, Chemical, and Thermal Methods (İncineration, leaching, electrolysis)	Conventional Mono c-Si	1 E+05	SimaPro	1000 kg
				Policy Option A Mono c-Si	−298.64		
				Policy Option B Mono c-Si	-1 E+06		
8	(Ganesan & Valderram, 2022)	Lab and Large Scale	Mechanical (Cutting)	Centralized bulk recycling (c-Si)	−3021	OpenLCA	1 ton
			Mechanical (Cutting)	Decentralized bulk recycling (c-Si)	−3040		
			Mechanical, Chemical, and Thermal Methods (İncineration, leaching, electrolysis)	High-Value Recycling (FRELP) (c-Si)	−3539		
9	(Lim et al., 2022b)	Lab and Large Scale	Mechanical, Chemical, and Thermal Methods (İncineration, leaching, electrolysis)	c-Si	25	GaBi	1000 waste panels, each with 400 mm × 200 mm

Experimental PV Delamination Method

Tembo et al. used both acidified and non-acidified hexane for the recovery of PV modules. The PV sample was exposed to hexane at 25°C for 24 hours, resulting in a delamination rate of 66%. Brenes et al. in 2023, observed that when samples were exposed to hexane at 55°C for 30 minutes, the EVA layer swelled slightly, but the c-Si wafer was not delaminated from the EVA layers.

In this study, c-Si sample was placed in an Erlenmeyer flask containing 100 ml of hexane as the solvent, and the flask was covered with aluminum foil to prevent vapor escape. The experiment was conducted in a shaking incubator at 150 rpm for 24 hours. After 24 hours of exposure to hexane, the sample was filtered, and the separated parts were cleansed of the chemical. The details of the experimental study are provided in Table 2.

Table 2. Combination of Chemical and Thermal PV Delamination Method at Lab-Scale

Parameter	**Value**
Chemical	Hexane
Chemical Amount	100 ml
PV Sample Weight	6.280 g
Temperature	58°C
Duration	24 hours
Energy Consumption	3.618 kWh
Separated Glass	5.061 g
Glass Separation	Observed
Front EVA Separation	Observed
c-Si Wafer	Not separated from back EVA
Back EVA	Not separated from c-Si Wafer
Backsheet Separation	Observed

Results and Discussion

In this experimental study, the laminated glass and front EVA layer were easily separated from each other. The c-Si wafer remained laminated to the back EVA layer (Figure 1). Under these experimental conditions, the recovery of the glass, front EVA, and backsheet layers from the c-Si wafer was achieved (Table 3). Therefore, considering the remaining laminated back EVA weighing 0.287 g, the delamination success rate over the total mass of 6.28 g was 99%.

Table 3. Mass Distribution of the PV Sample after Delamination

Solution	Chemical Quantity (ml)	PV Quantity (g)	Energy Consumption (kWh)	Glass (g)	EVA(s) (g)	c-Si Layer (g)	Backsheet (g)
Hexane	100	6,280	3,618	5,061	0.574	0.52	0.125

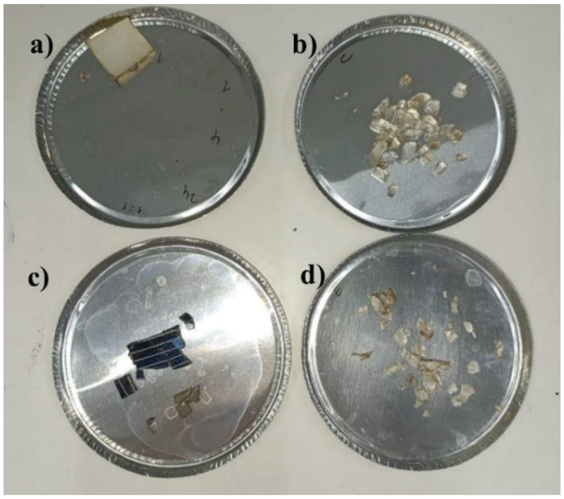

Fig. 1. A PV sample that has been exposed to hexane at 58°C for 24 hours a) Backsheet b) Glass c) c-Si Wafer + Back EVA d) Front EVA

Considering the 10 studies listed in Table 1, the chemical solvents and energy consumption employed in the delamination methods for the recycling of CdTe and c-Si modules directly influence the LCA results. It is understood that CdTe modules entail a lesser environmental impact compared to c-Si modules from similar chemical applications.

In this study's assessment, the use of strong chemical hexane resulted (compared to other landfilling parameters, EVA and PET) in higher environmental impact in categories such as terrestrial acidification, terrestrial ecotoxicity, and land use comparing to other categories given in Table 4. The prolonged 24-hour processing time to increase the success of delamination has led to high environmental impact in categories such as stratospheric ozone depletion, land use, mineral resource scarcity, and water consumption. The significant reduction in environmental impact resulting from the recycling of solar glass and multi-Si wafers is particularly notable in categories such as global warming potential, terrestrial acidification, stratospheric ozone depletion, ozone formation, and human health.

https://doi.org/10.52202/077496-0009

Table 4. LCA results of the Experimental Delamination Method

Impact category	Landfilling			Emission	Recovery		
	EVA	PET	Hexane	Electricity	Solar glass	Multi-Si wafer	Total
Global warming (kg CO_2 eq)	2.56E-07	2.71E-08	1.05E-05	2.59E-04	-6.84E-07	-7.36E-06	2.62E-04
Stratospheric ozone depletion (kg CFC11 eq)	6.62E-09	9.18E-10	3.01E-07	9.80E-06	-8.16E-09	-3.00E-07	9.80E-06
Ozone formation, Human health (kg NOx eq)	1.95E-07	2.31E-08	1.59E-05	2.44E-04	-1.08E-06	-6.28E-06	2.53E-04
Terrestrial acidification (kg SO_2 eq)	1.13E-07	1.31E-08	6.08E-06	2.20E-04	-8.62E-07	-4.29E-06	2.21E-04
Freshwater eutrophication (kg P eq)	2.30E-07	1.28E-08	2.11E-05	3.43E-04	-1.50E-07	-4.79E-06	3.59E-04
Marine eutrophication (kg N eq)	7.59E-09	3.52E-09	3.34E-07	1.29E-06	-1.71E-08	-4.77E-07	1.14E-06
Terrestrial ecotoxicity (kg 1,4-DCB)	9.20E-07	1.36E-07	5.76E-05	3.30E-04	-1.62E-06	-4.90E-05	3.38E-04
Freshwater ecotoxicity (kg 1,4-DCB)	7.31E-08	1.14E-08	2.86E-06	2.27E-05	-1.12E-07	-1.84E-06	2.37E-05
Land use (m^{2}a crop eq)	8.03E-09	1.00E-09	4.94E-07	5.24E-06	-2.23E-08	-2.56E-07	5.46E-06
Mineral resource scarcity (kg Cu eq)	5.12E-11	4.81E-12	2.61E-09	8.91E-09	-1.07E-10	-5.54E-10	1.09E-08
Water consumption (m^3)	5.22E-08	3.26E-09	3.44E-06	7.53E-05	-1.12E-07	-9.37E-06	6.93E-05

The environmental impact of recycling is significantly lower than landfilling, as explained through the Global Warming Potential (GWP) value in the study by (Lim et al., 2022b). While landfilling has an environmental GWP impact of 121 kg CO_2-eq, the impact of recycling is nearly one-fifth of this value. Mathur et al., (2020b) report positive environmental benefits in the recovery of Al, Cu, and Ag metals across all impact categories such as Ozone depletion, Global warming potential, Acidification, Eutrophication, Carcinogenics, Non-carcinogenics, and Ecotoxicity excluding ozone depletion.

Conclusion

In conclusion, this research underscored the critical role of LCA in evaluating PV recycling methods. It elucidated the varied environmental impacts associated with different recycling techniques and PV module types, emphasizing the necessity of maximizing environmental benefits through material reuse. Thermal methods emerge as more environmentally benign compared to chemical and mechanical approaches. Metal recovery processes present challenges due to their ozone-depleting potential, contrasting with the relatively lower impact of mechanical disassembly. Notably, recycling markedly reduces environmental burdens compared to landfilling, as specifically shown by Global Warming Potential (GWP) values. Insights from long-term studies, particularly regarding CdTe PV technology, elucidate emission patterns and address concerns about cadmium leakage. Moving forward, holistic approaches to PV recycling that consider lifecycle impacts and material flows will be instrumental in fostering sustainable energy practices and mitigating environmental footprints.

Authorship Statement

Asli Birturk: Conceptualization, Methodology, Investigation, Visualization, Writing – Original draft, Formal Analysis

Betul Aksoy: Conceptualization, Methodology, Formal Analysis, Investigation, Validation

Melih Soner Celiktas: Conceptualization, Project Administration, Supervision, Methodology, Review, Editing

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors would like to thank Ege University Scientific Research Projects Coordination Unit for project support (Project number: 29603), Turkish Scientific and Technological Council for financial support of ARDEB project (Project number: 121Y515) and both for the national and international doctoral scholarships to Asli Birtürk under the framework of BIDEB 2211-C (Grant number:1649B032203727) and BIDEB 2214-A (Grant number: 1059B142300626). Special thanks to the American Solar Energy Society for the JEDI (Justice, Equity, Diversity, and Inclusion) conference scholarship (ASES SOLAR 2024) received by Asli Birtürk. We would also like to express our gratitude to everyone in the past who provided us with these opportunities for our research.

https://doi.org/10.52202/077496-0009

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https://doi.org/10.52202/077496-0009