Solar Energy Materials & Solar Cells 306 (2026) 114521

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Material recovery and characterization from end-of-life photovoltaic modules using water-jet delamination[☆,☆☆]

Berhane Darsene Dimd[a,*], Wolfram Palitzsch[b], Yijiang Xu[a], Birgit Ryningen[a], Nagarajan Somi Ganesan[a], Martin Bellmann[a]

[a] Department of Sustainable Energy Technology, SINTEF Industry, Alfred Getz Vei 2, Trondheim, 7034, Norway
[b] LuxChemtech GmbH, Alfred-Lange-Straße 18, Freiberg, 09599, Germany

ARTICLE INFO

Keywords:
EoL PV recycling
Water-jet delamination
Material recovery
Critical raw materials
Circular economy

ABSTRACT

The rapid deployment of photovoltaic (PV) systems is projected to generate significant volumes of end-of-life (EoL) modules, necessitating efficient recycling strategies that enable high-value material recovery and reintegration into PV value chain and other high end applications. This study presents an assessment of high-pressure water-jet delamination recycling technology, developed to improve the quality of material recovered from crystalline silicon PV modules. The approach was evaluated at pilot scale for the recovery of high purity silver (Ag), copper (Cu), silicon (Si), glass, and polymer. Material characterization was performed using ICP-MS, XRF, and SEM-EDS to determine elemental composition, morphology, and impurity profiles. The results show that the water-jet approach results in recovery of less cross-contaminated material streams, including Ag-rich fractions that reached up to 97 wt% purity after downstream purification. The recovered silicon from this process contains residual metallization, indicating the need for further refining. This study provides an evaluation of advanced delamination-based recycling route, highlighting the potential to improve material recovery and support the development of circular recycling pathways for PV modules, while indicating the need for further process optimization toward further industrial implementation.

1. Introduction

The transition toward clean and low-carbon energy systems has accelerated the global deployment of photovoltaic (PV) systems. Crystalline silicon (c-Si) modules dominate the market due to their technological maturity and cost competitiveness, resulting in rapidly expanding installed capacities worldwide. This growth is accompanied by increasing demand for critical raw materials and precious metals required for PV ingot and module manufacturing, including silicon, silver, aluminum and copper. Within the European Union (EU), domestic availability of several of these materials is limited, leading to significant dependence on international supply chains that are vulnerable to price volatility and geopolitical constraints. Sustainable material management strategies, including end-of-life (EoL) PV module recycling, are required to ensure long-term resilience and competitiveness of the European PV sector.

The scale of the forthcoming EoL PV waste volume also underscores this necessity. According to the World Energy Transitions Outlook by the International Renewable Energy Agency [1], the projected volume of EoL PV modules from global cumulative PV installations is expected to increase to approximately 4 Mt by 2030, 50 Mt by 2040, and more than 200 Mt by 2050 under IRENA's 1.5 °C Scenario.[1] From this waste stream, more than 17.7 Mt of raw materials could potentially be recovered by 2050, generating an estimated USD 8.8 billion in material value. In the EU, EoL PV waste streams are also expected to increase significantly over the coming decades. Estimates from the European Commission Joint Research Centre suggest that cumulative PV waste in Europe could reach several million tonnes by 2050 as early deployment waves approach the end of their operational lifetimes. These projections highlight PV recycling not only as a waste mitigation strategy, but as a strategic instrument for resource security and industrial sustainability.

Despite the substantial recovery potential, recycling of EoL PV modules remains technically and economically challenging [2]. PV

☆ This article is part of a Special issue entitled: 'Recycling of PV modules' published in Solar Energy Materials and Solar Cells.

☆☆ This work is part of the QUASAR project funded by the European Union's Horizon Europe research and innovation programme under grant agreement number 101122298.

* Corresponding author.
E-mail address: berhane.dimd@sintef.no (B.D. Dimd).

[1] Energy transition pathway consistent with limiting global warming to 1.5 °C above pre-industrial levels in line with the Paris Agreement.

https://doi.org/10.1016/j.solmat.2026.114521
Received 31 March 2026; Received in revised form 4 June 2026; Accepted 15 June 2026
Available online 23 June 2026

modules are heterogeneous with respect to size, technological generation, material composition, and degradation state, and they were not originally designed with recyclability as a primary objective. Their laminated multi-layer architecture, including glass, encapsulant, silicon cells, metallic interconnects, and backsheet materials, challenges efficient separation and limits the recovery of high value components. Current industrial recycling routes primarily focus on bulk material recovery, typically focusing on aluminum frames and glass. They have limited recovery efficiency or insufficient purity when it comes to valuable materials such as silicon, silver, and copper. In addition to these technical barriers, economic factors further restrict large-scale operation of PV recycling technologies. In some regions, landfill disposal remains less expensive than dedicated recycling processes where recycling operations typically incur higher operational cost. These combined technical and economic constraints highlight the need for more efficient and scalable separation technologies, particularly improved delamination processes that enable the recovery of high-value materials from PV modules.

2. EoL PV recycling

Recycling strategies for c-Si PV modules have evolved over the past decade, largely due to increasing volume of EoL PV waste and the development of regulatory frameworks for electronic waste management [3]. Early approaches mainly relied on mechanical dismantling and shredding processes, which enable efficient removal and recovery of aluminum frames and partial glass fractions [4,5]. However, bulk shredding often leads to cross-contamination between silicon wafers, encapsulant residues, and metallic interconnects, thereby limiting the recovery of high-value materials and their purity.

To address these limitations, thermal delamination techniques have been developed to separate laminated PV module layers [6,7]. These approaches typically involve pyrolysis-based decomposition of encapsulant materials and back sheet polymers, allowing improved access to silicon cells and metallic contacts. While thermal processes can improve material separation and facilitate downstream recovery steps, they are associated with high energy demand and potential gaseous emissions, which may require additional treatment and raise concerns regarding environmental impacts [8,9].

Chemical delamination methods have also been investigated as an alternative route for selective removal of encapsulant layers [10–12]. By dissolving or degrading polymer components, these processes can preserve the structural integrity of silicon wafers and metallic fractions, thereby improving recovery potential for high-value materials. However, large-scale implementation of chemical approaches remains constrained by reagent consumption, wastewater treatment requirements, and challenges related to process throughput and operational costs [9,13].

More recently, delamination technologies such as laser processing and high-pressure water-jet systems have emerged as promising alternatives [14–16]. These approaches separate module layers while minimizing mechanical damage and cross-contamination between materials. Despite these technological developments, comprehensive assessment of delamination-based EoL PV recycling methods for recovery of valuable materials and metals remain limited in the literature. In particular, systematic evaluation that consider material purity of recovered critical materials such as silicon and silver are scarce.

Therefore, this study through the QUASAR project,[2] was initiated to investigate and upscale advanced delamination-based recycling pathways for c-Si PV modules. This work evaluates high-pressure water-jet delamination based recycling that mechanically separates laminated module layers while minimizing cross-contamination between material fractions. This work aims to contribute to the development of scalable EoL PV recycling solutions by addressing important gaps in the current literature. Specifically, the study:

- Examines the effectiveness of the process in recovering high-value material, with particular attention to the purity of critical fractions such as silicon and silver.
- Evaluates pilot scale implementation of water-jet delamination route.

3. Materials and methods

This section describes the experimental framework, pilot-scale delamination processes and analytical methods used to evaluate material recovery from EoL PV modules. It covers the pilot-scale delamination process, as well as the characterization techniques applied to assess the quality and purity of the recovered fractions.

3.1. Study framework

The experimental work presented in this study was conducted within the QUASAR Horizon Europe project, which aims to advance circular solutions for EoL PV modules through the development and demonstration of two recycling technologies. The project brings together multiple European research and industrial partners to improve the recovery of valuable materials from EoL PV modules and to enable their reintegration into the PV value chain and other high end applications. Key objectives include increasing recycling efficiency and producing high purity material suitable for further industrial use. Within this framework, a high-pressure water-jet delamination approach was investigated as an advanced separation route for recovery of valuable materials from EoL PV modules.. This recycling technology represents separation route aimed at improving material recovery compared with conventional mechanical recycling processes. This study focuses only on evaluating the performance of the water-jet delamination route with respect to the quality and purity of recovered materials. The analyzed material fractions in this study originated from pilot-scale processing of multiple EoL PV modules manufactured by a single company and belonging to the same module generation. The characterized silver, silicon, glass, and polymer samples therefore represent aggregated process outputs rather than individual module-specific samples. It is important to note that EoL modules used in this study were commercial PV modules that had been removed from service prematurely before reaching their standard service lifetime (25–30 years). The modules were decommissioned due to premature failure and subsequently entered the EoL PV stream. Therefore, in the context of this work, the term EoL module refers to modules that have entered the recycling pathway, rather than modules that have necessarily completed a conventional 25-year field lifetime. Exact manufacturing dates, installation dates, and service durations cannot be disclosed due to confidentiality restrictions.

Delamination is a critical step in EoL PV recycling, as the strong adhesion between glass, encapsulant, cells, and back-sheet complicates the recovery of high-value materials. The water-jet approach separate the laminated layers using a high-pressure water and enables the separation of the glass plate while maintaining its structural integrity. As a result, the process yields highly pure glass. This recycling technology is applicable for modules with glass/back sheet arrangement. The detached polymer material, which consist of the back sheet and encapsulant layers, is subsequently separated from the process water through filtration, after which the water is recirculated within the system. The simplified process diagram of this approach is shown in Fig. 1. Following delamination, additional separation steps are applied to recover valuable materials from the mixed fraction.

This study focuses on characterization of recovered material fractions and evaluation of achievable material quality from the water-jet delamination route. Quantitative assessment of full process recovery efficiencies and mass balances is outside the scope of the present work and will be addressed in future studies.

[2] https://quasar-project.eu/

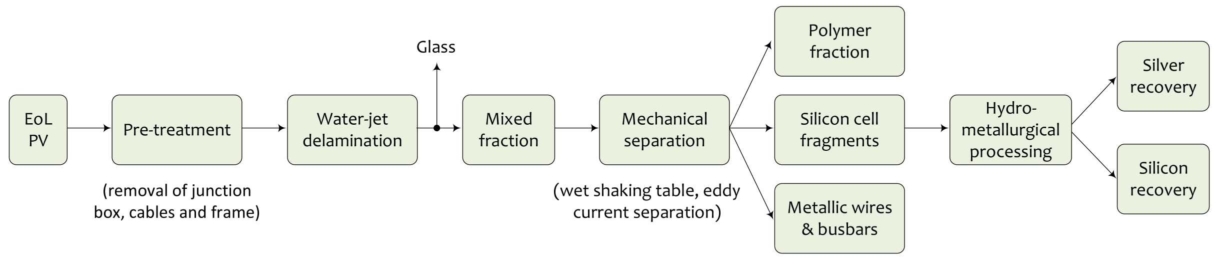

Fig. 1. Simplified process flow of water-jet delamination based processing of EoL PV modules.

3.2. Material recovery and process outputs

Following water-jet delamination, the process yields two primary outputs: intact glass and a mixed fraction containing polymer materials, silicon cell fragments, and metallic interconnectors. The mixed fraction was subsequently processed using established density-based mechanical separation methods, including wet shaking table separation for heavy and light fractions. Metallic wires and busbars were further separated using eddy-current separation methods. The silicon-rich cell fragment fraction was then processed using hydrometallurgical treatment to recover silver. Silver was recovered through electrochemical deposition, followed by melting and formation into spherical particles. The recovered materials were then subjected to analytical characterization. The recovered glass and polymer fractions were characterized after physical separation without additional purification treatment.

3.3. Material characterization techniques

The recovered materials were analyzed for elemental composition and morphological characteristics to determine their quality and purity. Elemental analyses were performed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and X-ray Fluorescence (XRF), while Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS) was used for morphological examination and localized elemental analysis. ICP-MS is mainly important to quantify trace and major elements in the recovered material fractions due to its high sensitivity for detecting metals at low concentrations. ICP-MS analyses were performed three times on representative recovered samples. Reported concentrations correspond to average values, and relative standard deviation (RSD) values were used to evaluate analytical repeatability. XRF analysis was used as a non-destructive method to determine the bulk elemental composition of the samples. SEM-EDS was employed to investigate the surface morphology of recovered materials and to assess the spatial distribution of elements within the analyzed samples. These techniques are important for the evaluation of material composition and the quality of recovered fractions from the delamination process.

4. Results and discussion

This section presents the characterization of the material recovered from the water-jet delamination route. The analysis focuses on the purity of recovered materials, with particular emphasis on the economically valuable metals silver (Ag) and copper (Cu), as well as the silicon (Si) fractions. Elemental composition and morphological characteristics of these recovered materials were evaluated using ICP-MS, XRF, and SEM-EDS as described in Section 3.3. In addition to the metallic and silicon fractions, this section also examines the properties of glass cullet and polymer recovered from the water-jet delamination process. The results provide a detailed assessment of the water-jet delamination route in terms of its ability to produce material streams with high purity and potential for further refining or recycling.

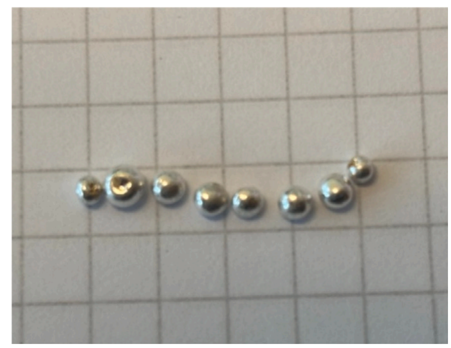

Fig. 2. Silver beads recovered from the water-jet delamination route after purification.

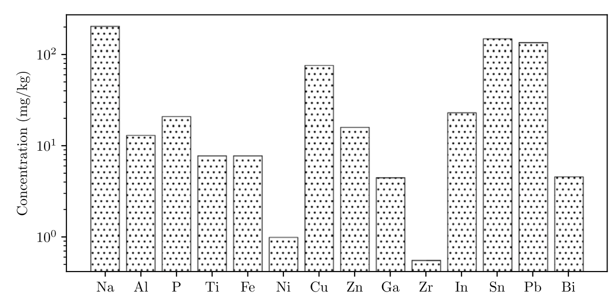

Fig. 3. Trace elemental impurities in the recovered Ag determined by ICP-MS for water-jet delamination route. Concentrations are shown on a logarithmic scale. The relative standard deviation (RSD) values for the major impurities were below 1.3%.

4.1. Recovered silver

Fig. 2 shows sample of the silver fractions recovered after processing through the water-jet delamination route. The silver shown in the figure corresponds to material recovered after downstream hydrometallurgical purification and electrochemical deposition of the Ag-rich fraction obtained from the water-jet delamination route.

The purity of the recovered silver fraction was determined using XRF, which indicated an average Ag content of 97 wt%. To further characterize the impurity content and profile, ICP-MS analysis was conducted to quantify trace elements present in the recovered Ag (Fig. 3).

The results show high concentrations of metallic impurities, Sn (148 mg/kg), Pb (135 mg/kg), and Cu (76 mg/kg). These elements are consistent with materials commonly associated with PV cell metallization and soldering. Overall,it can be concluded that the water-jet delamination route yield Ag-rich fraction with high Ag purity but still contains impurities associated with metallization and soldering.

Fig. 4. Recovered smart wire from water-jet delamination route.

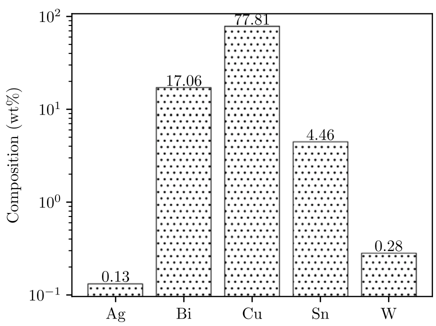

Fig. 5. Elemental composition of the recovered smart wire determined by XRF analysis for the water-jet delamination route.

Fig. 6. Recovered silicon powder from water-jet delamination route.

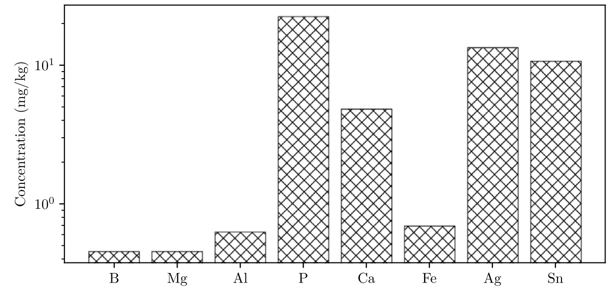

Fig. 7. Trace elemental impurities in the recovered silicon powder determined by ICP-MS for water-jet delamination route. Only major selected concentrations are shown on a logarithmic scale. The relative standard deviation (RSD) values were less than 1.0%.

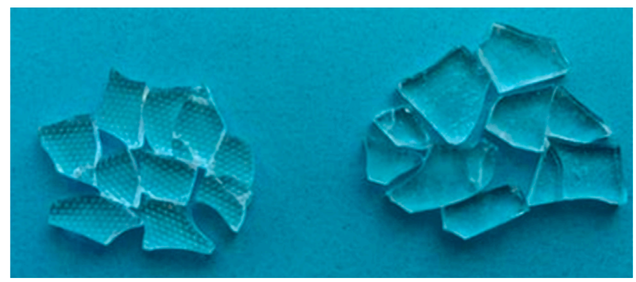

Fig. 8. Glass cullet recovered from water-jet delamination. Left: patterned glass. Right: flat glass.

Fig. 9. Recovered polymer sample from water-jet delamination route.

4.2. Recovered smart wire

Fig. 4 shows sample of smart wire recovered from the water-jet delamination process. The elemental composition of the recovered sample, by XRF (see Fig. 5), indicates that Cu is the dominant component, accounting for 78 wt%. In addition to Cu, the recovered fractions contains low melting soldering alloy such as Bi (17 wt%) and Sn (4.5 wt%). Bismuth is used as part of a Sn-Bi or Bi-rich solder coating on the copper wires that makes contact to the cell fingers.

4.3. Recovered silicon

Fig. 6 shows silicon cell powder recovered from the water-jet delamination process. The ICP-MS analysis of this silicon powder shows that (Fig. 7) P is present at relatively high concentrations in the recovered silicon (22.33 mg/kg). This is due to the presence of phosphorus doped emitter layers in the recovered fraction. Similarly, the high Ag concentration (13.33 mg/kg) in the recovered silicon powder is related to incomplete removal of front side Ag metallization and the presence of fine metallic residues. In addition, relatively smaller concentrations of Sn (10.67 mg/kg) and Ca (4.83 mg/kg) are also detected. Overall, the delamination process recover silicon with doping and residual surface coatings and metallization derived impurities.

4.4. Recovered glass cullet

Samples of glass cullet recovered from the water-jet delamination process are shown in Fig. 8. The elemental composition of the recovered glass cullet was determined by XRF analysis for two different sources (Table 1). Both samples show compositions typical of soda-lime silicate glass, with SiO_2, Na_2O, and CaO as the dominant constituents. An important difference between the two samples is the higher Sb_2O_3 content in the patterned glass (0.453 wt%) compared to the flat glass (0.052 wt%). Antimony is commonly used as a fining agent in glass production and its presence challenges recycling in conventional float glass production. A key limitation for large-scale recycling is the variability and uncertainty in glass compositions, particularly for modules manufactured outside the EU. This lack of compositional transparency challenges the integration of recovered cullet into existing glass production streams and may necessitate additional sorting or purification steps.

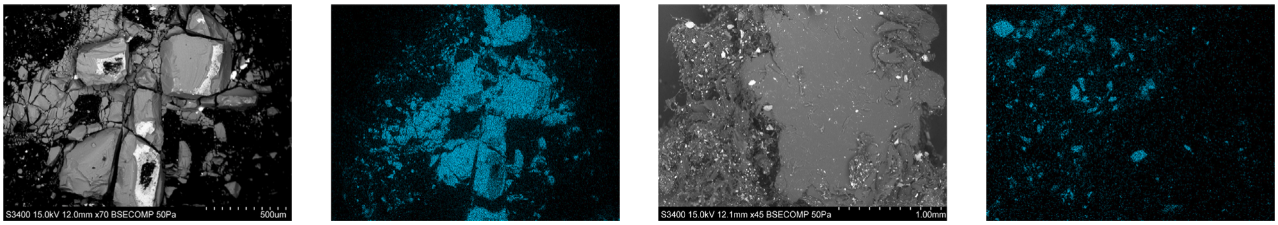

Fig. 10. SEM-EDS silicon mapping on random polymer flakes from water-jet delamination. The blue color in the above images represent the SEM-EDS signal for silicon.

Table 1
Elemental composition of recovered patterned and flat PV glass samples determined by XRF.

Oxide	Patterned wt%	Flat wt%	Oxide	Patterned wt%	Flat wt%
SiO_2	69.539	72.863	Fe_2O_3	0.015	0.032
Na_2O	15.617	13.900	Cl	0.022	0.008
CaO	9.446	8.315	ZrO_2	0.011	0.012
MgO	2.469	4.132	SrO	0.004	0.004
Al_2O_3	1.924	0.495	Ag_2O	0.003	0.000
Sb_2O_3	0.453	0.052	TeO_2	0.001	0.002
SO_3	0.331	0.156	MnO	0.001	0.000
TiO_2	0.162	0.026	Y_2O_3	0.000	0.001
PbO	0.001	0.000	Bi_2O_3	0.000	0.001

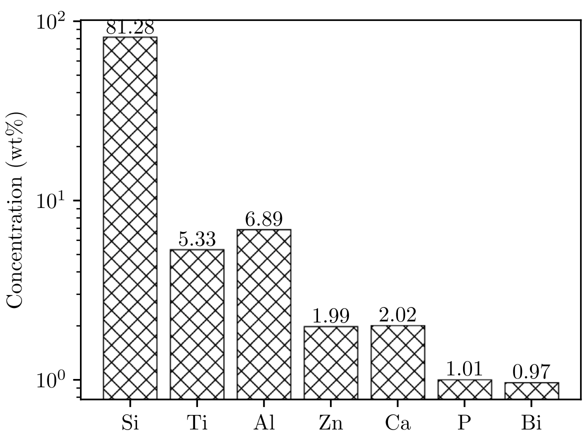

Fig. 11. XRF analysis of the recovered polymer from water-jet delamination.

4.5. Recovered polymer

Fig. 9 shows the polymer sample recovered from the water-jet treatment of EoL PV modules. It can be seen that it consists of polymer flakes with residues, including silicon fragments, as confirmed by SEM-EDS mapping as well (Fig. 10). These observations indicate incomplete separation of fine inorganic particles during the delamination.

The elemental composition of the polymer sample was analyzed by XRF and the results are presented in Fig. 11. This analysis focuses on metallic elements, while elements below F are not detected by XRF. Consequently, the reported values are normalized to 100 wt% based on the measured metal content, excluding oxygen and other light elements. The XRF results indicate that the recovered polymer contains substantial inorganic contamination, dominated by Si (81 wt%), with additional Al (6.8 wt%) and Ti (5.3 wt%). The presence of metallic elements within the polymer shows residual cell and interconnection materials, indicating possible limitations in the current separation approach and the need for additional purification steps.

It is important to note that the present study focuses on characterization of representative recovered fractions obtained from pilot-scale processing of a consistent module population and does not provide a comparative statistical analysis across different PV manufacturers or module generations.

5. Conclusions

This study provides a comprehensive evaluation of water-jet delamination technology, for the recovery of valuable materials from EoL PV modules, addressing an important gap in the literature related to assessment of recovery performance and material purity. The results show that the recycling approach enable the recovery of Ag, Cu, Si, and glass fractions, but with different level of contamination.

The water-jet delamination route has good performance in preserving material integrity and minimizing cross-contamination, resulting highly pure silver (up to 97 wt%) and intact glass suitable for potential closed-loop recycling. The recovery of Cu was effective, with small impurity content. For silicon, the recycling route recovered material with residual metallization and coatings, indicating the need for further refining for high value reuse. The impurity contents and profiles underline the importance of process selection depending on downstream purification strategies and end use. The water-jet delamination route also proved to be effective in recovering high quality glass as well as polymer fractions that can be used as secondary raw materials for backsheet production and other waterproofing agent applications.

Overall, this work demonstrates that advanced delamination routes can improve material separation and facilitate generation of higher-purity recovered fractions compared with conventional bulk mechanical recycling approaches. This study contributes to the development of more efficient and circular EoL PV recycling pathways, supporting the transition toward higher recovery rates, higher purity and improved reintegration of critical and valuable materials into the PV value chain.

CRediT authorship contribution statement

Berhane Darsene Dimd: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Wolfram Palitzsch:** Writing – review & editing, Methodology, Conceptualization. **Yijiang Xu:** Writing – review & editing, Writing – original draft, Conceptualization. **Birgit Ryningen:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Nagarajan Somi Ganesan:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Martin Bellmann:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT in order to improve the language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing 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.

Data availability

Data will be made available on request.

References

[1] International Renewable Energy Agency, World Energy Transitions Outlook 2022: 1.5° C Pathway, International Renewable Energy Agency IRENA, 2022, OCLC: 1515478216. URL: https://www.irena.org/publications.
[2] P. Chowdhury, H. Chowdhury, T. Chowdhury, R. Corkish, Standardization as a pathway to a circular PV industry: Addressing material recovery and design challenges, Sol. Energy Mater. Sol. Cells 296 (2026) 114067.
[3] J. Ramírez-Cantero, S. Pérez-Huertas, M.J. Muñoz-Batista, A. Pérez, M. Calero, G. Blázquez, State of the art of end-of-life silicon-based solar panels recycling with a bibliometric perspective, Sol. Energy Mater. Sol. Cells 281 (2025) 113312.
[4] R. Deng, N.L. Chang, Z. Ouyang, C.M. Chong, A techno-economic review of silicon photovoltaic module recycling, Renew. Sustain. Energy Rev. 109 (2019) 532–550.
[5] M.F. Azeumo, C. Germana, N.M. Ippolito, M. Franco, P. Luigi, S. Settimio, Photovoltaic module recycling, a physical and a chemical recovery process, Sol. Energy Mater. Sol. Cells 193 (2019) 314–319.
[6] M. Calero, J. Ramírez-Cantero, S. Pérez-Huertas, A. Pérez, M. Mateos, G. Blázquez, Recycling end-of-life solar panels: A comparative study of thermal and solvent delamination techniques, Sol. Energy Mater. Sol. Cells 295 (2026) 113990.
[7] T. Dobra, D. Vollprecht, R. Pomberger, Thermal delamination of end-of-life crystalline silicon photovoltaic modules, Waste Manag. Res. 40 (1) (2022) 96–103.
[8] Y. Xu, J. Li, Q. Tan, A.L. Peters, C. Yang, Global status of recycling waste solar panels: A review, Waste Manage. 75 (2018) 450–458.
[9] J. Tao, S. Yu, Review on feasible recycling pathways and technologies of solar photovoltaic modules, Sol. Energy Mater. Sol. Cells 141 (2015) 108–124.
[10] J. Lee, N. Duffy, J. Petesic, T. Witheridge, J. Allen, Comparative assessment of solvent chemical delamination of end-of-life solar panels, Waste Manage. 190 (2024) 122–130.
[11] P. Dias, L. Schmidt, M. Monteiro Lunardi, N.L. Chang, G. Spier, R. Corkish, H. Veit, Comprehensive recycling of silicon photovoltaic modules incorporating organic solvent delamination – technical, environmental and economic analyses, Resour. Conserv. Recycl. 165 (2021) 105241.
[12] J. Vaněk, K. Jandova, P. Vanýsek, P. Maule, Chemical Delamination Applicable to a Low-Energy Recycling Process of Photovoltaic Modules, Processes 11 (11) (2023) Publisher: Multidisciplinary Digital Publishing Institute.
[13] S.D. Singh, P. Anand, M. Di Nardo, A.K. Singh, S. Pandey, Challenges and Opportunities in Recycling Technology of Silicon-Based Photovoltaic Solar Panels: A Systematic Review, Circ. Econ. Sustain. 5 (8) (2025) 7283–7328.
[14] R. Aninat, M. van der Vleuten, J. Scraigne, H. Fledderus, A. Biezemans, J. Bosman, J. Gomes, A. Kuypers, M. Theelen, Laser-assisted delamination for high-value recycling of solar panels, Prog. Photovolt., Res. Appl. 34 (3) (2026) 297–309, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/pip.70041.
[15] A. Ali, M. Shahid, S.A. Qadir, M.T. Islam, M.W. Khan, S. Ahmed, Solar PV end-of-life waste recycling: An assessment of mechanical recycling methods and proposed hybrid laser and high voltage pulse crushing method, Resources 13 (12) (2024) Publisher: Multidisciplinary Digital Publishing Institute.
[16] R. Deng, Y. Zhuo, Y. Shen, Recent progress in silicon photovoltaic module recycling processes, Resour. Conserv. Recycl. 187 (2022) 106612.