Advances in Module Recycling - Literature Review and Update to Empirical Life Cycle Inventory Data and Patent Review

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Executive Summary

Introduction

Global cumulative installed solar photovoltaic (PV) capacity exceeded 1 TW in 2022, and deployment is expected to accelerate over the next decade. With PV industry scale-up there is increasing recognition that the volume of defective, damaged, and spent modules will expand rapidly in the decades ahead. Module management is becoming a pressing concern for owners and operators of solar generation systems. Development and optimization of collection, triage, repair, refurbishment, reuse, and recycling pathways are needed to convert PV materials into assets that contribute to the circular economy and improve environmental responsibility, rather than creating new waste streams.

PV modules that cannot be repaired or refurbished have reached end of life (EOL) and can often be recycled. A 2016-2017 IEA PVPS Task 12 study funded by the National Renewable Energy Laboratory (NREL) and EPRI reviewed PV recycling technologies in Europe, including four commercial glass and metal recyclers that process batches of PV modules on a periodic basis and one pilot-scale recycling process customized for PV modules.[1,2] Heath et al. showed that recovery of high-value materials like silicon and silver at high purity is needed to improve the economics of recycling[3]. New commercial and demonstration-scale recycling options for PV modules have emerged in the past few years, including some that claim to recover silicon and silver. Limited public data are available on recycling processes for pilot or commercial facilities.

The objective of this study was to identify advances in PV recycling technology that have the potential to be affordable, technically feasible, and environmentally responsible. A survey of recyclers, literature review, and patent search identified industry trends and advances in PV recycling processes. Additionally, leading recyclers supplied life cycle inventory (LCI) data and process flow diagrams for facilities that use advanced recycling treatments to separate PV materials with high quality and yield.

[1] Life Cycle Inventory of Current Photovoltaic Module Recycling Processes in Europe. IEA PVPS Task 12, IEA PV Power Systems Programme. Report IEA-PVPS Task 12-12:2017. ISBN 978-3-906042-67-1.
[2] Insights on Photovoltaic Recycling Processes in Europe: A Survey-Based Approach. EPRI, Palo Alto, CA: 2017. 3002008846.
[3] G.A. Heath, T.J. Silverman, M. Kempe, M. Deceglie, D. Ravikumar, T. Remo, H. Cui, P. Sinha, C. Libby, S. Shaw, K. Komoto, K. Wambach, E. Butler, T. Barnes, and A. Wade, "Research and development priorities for silicon photovoltaic module recycling supporting a circular economy." Nature Energy 5, 502-501 (2020).

Research Overview

The research team identified 177 recyclers and PV recycling equipment manufacturers globally through press releases, existing connections, past studies, and online search. Invitations to participate in the LCI survey were sent to 24 recyclers that are applying best available or new PV recycling technologies on a commercial or pilot scale. A questionnaire was developed to understand current practices and recycling treatments.

Six recyclers provided information and life cycle inventory data. A seventh LCI case was prepared based on a combination of a recycler LCI response and data previously published by Task 12[4]. Whereas only one of five recycling processes in the 2016-2017 IEA PVPS Task 12 report was customized for PV modules, all seven recycling facilities evaluated in the current study are dedicated to treating PV modules.

LCI data were analyzed across the respondents to compare material recovery rate and energy consumption. To facilitate comparison, a consistent system boundary was applied at the point in each process where a cell fraction (including metals) is separated from the glass and polymers. Subsequent steps to recover silicon and metals like silver, as well as purification steps were not included in the side-by-side analysis to facilitate comparison because not all recyclers responding to the LCI survey performed this function. The system boundary was slightly different for First Solar, as intermediate stage LCI data were not available prior to cadmium and tellurium recovery.

The research team also identified relevant patents and literature on the topic of PV recycling. The global patent search identified 456 relevant patents on recycling PV components, processing methods, and recovered materials. The search relied on DEPATISnet[5] and a 2018 IEA PVPS Task 12 report that used the Worldwide Intellectual Property Service (WIPS). The literature search revealed 569 relevant results identified through Scopus, SciFinder, Google, and ResearchGate. Statistical evaluations were carried out to identify trends in patents and literature by year, country, recycling treatment method, organization, author, and so on.

Results

Five European recyclers and First Solar (US) shared data for recycling capacities between 1 000 t/yr to 50 000 t/yr. A seventh LCI case was modelled based on a combination of a recycler LCI response and previously published data.4

- First Solar Inc., Tempe, U.S.
- Reiling Glas Recycling GmbH & Co. KG, Marienfeld, Germany
- LuxChemtech GmbH, Freiberg, Germany
- Flaxres GmbH, Dresden, Germany
- ROSI SAS, Grenoble, France
- Envie 2E Aquitane, Saint-Loubès, France and ROSI SAS, Grenoble, France, combined processes (modelled using ROSI LCI response and previously published data4)
- Tialpi S.r.l., Mottalciata, Italy

Most of the LCI survey results rely on input from companies that are scaling up new technologies. Many data gaps still exist that could not be fully resolved by the data provided or information from the expert interviews. For example, each LCI assumes a significantly different input mix (module type), making

[4] R. Frischknecht, K. Komoto, T. Doi 2023, Life Cycle Assessment of Crystalline Silicon Photovoltaic Module Delamination with Hot Knife Technology, IEA PVPS Task 12, International Energy Agency (IEA) PVPS Task 12, Report T12-25:2023. ISBN 978-3-907281-41-3.
[5] DEPATISNET is an online service of the German patent agency (DPMA): https://depatisnet.dpma.de/DepatisNet/depatisnet?window=1&space=main&content=basis&action=basis

direct comparisons challenging. The capacity of the processes varies from 1 000 t/yr (LuxChemtech) to 50 000 t/yr (Reiling), and the amount of material processed annually varies from a test batch size of 7.5 t for Flaxres' pilot line to 41 921 t/yr for First Solar's commercial facilities. Some of the data are projections of expected values for facilities under construction, such as for ROSI's pilot plant in Grenoble, whereas data for established facilities represent actual data. One of the LCI cases (Envie & ROSI) is a modelling result based on preliminary data.

Despite these challenges, the results provide useful insights for a variety of recycling approaches at different levels of development and the associated recovery rates and energy consumption.

Material Recovery

Material output was normalized to 100% for each recycler, such that the cumulative material fractions sum to the weight of one module or one ton of input. The percentages for cables, frames, junction boxes, and non-ferrous metals differ between the respondents largely because of differences in the types of modules that were processed. One main difference is glass recovery rates. Tialpi, Reiling, and Flaxres recover similar percentages of glass, and LuxChemtech and ROSI, with and without Envie, can achieve slightly higher glass outputs. First Solar modules are glass-glass construction, resulting in a higher percentage of glass output. There are also differences in the mixed fractions and dust produced in each process. Mechanical processes (such as Reiling's crushing step, Tialpi's use of a blade to remove the glass, and ROSI's mechanical sortation) tend to produce more dust than water-jet and thermal processes. Pyrolysis fully removes the foil fraction, effectively increasing the relative amounts of the other outputs in the two ROSI LCI cases.

Energy Consumption

Energy consumption data were not yet available for the ROSI LCI cases. Reiling and Flaxres are the most efficient in terms of energy consumption. The chemical and water-jet processes developed by LuxChemtech consume a moderate amount of electricity, but it is still more than twice the consumption of Reiling's facility. Tialpi results are in the same energy consumption range as the LuxChemtech process. First Solar's LCI data include recovery of cadmium and tellurium, resulting in higher electricity consumption than the other LCI cases presented.

Recycling Survey and LCI Key Findings

- Mechanical recycling is still the benchmark. Mechanical recycling is optimized for costs, capacity, and output but frequently includes some downgrading of material quality. Reiling's improved, pure-mechanical process for silicon-based modules represents a fully commercial, best available technology that sets a benchmark for maturity, cost, and low energy consumption. However, it does not allow recovery of silicon and silver.
- Innovative technologies offer improved recycling quality. New technologies in pilot-stage demonstrations offer excellent recycling quality in terms of yield and purity of the fraction and economic value opportunities. Innovative approaches include light pulse treatment, water-jet cleaning, pyrolysis, and chemical treatment. Recyclers have demonstrated full recovery of aluminium frames, cables, junction boxes, interconnectors, silicon, and silver. Envie & ROSI, ROSI, LuxChemtech, Tialpi and Flaxres separate a glass fraction that can offer the flat glass industry a future source of usable cullet as a secondary raw material, saving melting energy. Improving the quality of recovered materials offers upcycling opportunities that can offset the cost of recycling and advance PV circularity.
- Strong thin-film recycling experience. First Solar operates a proprietary recycling system for its own thin-film module technology that has achieved over 90% material recovery through continuous process improvements in recent years. Some emerging recycling technologies are expected to be applicable to thin-film modules of any kind, as well as silicon-based modules, though some additional special treatment might need to be added.
- Facilities dedicated to PV recycling. There has been a dramatic shift since the 2016-2017 IEA PVPS Task 12 study in terms of the number of recyclers that accept PV modules and in terms

of the development and demonstration of recycling treatments and processes customized for PV modules. The first commercial PV module recycling plants with advanced treatments to separate materials with high quality and yield are being planned and constructed to support the growing supply of end-of-life modules.

Patent and Literature Review Key Findings

Global interest in PV recycling is rising as evidenced by steep increases in publications, patents, and research. The number of publications and patent applications coincides with growth in the global PV market and the introduction of PV waste policies in several regions.

Nearly 80% of patents target recycling processes for silicon-based modules, cell metals, polymers, glass, or devices. Thin-film and emerging technologies comprise the remaining patent space. Patents typically focus on recovering valuable material, toxic materials, or semiconductor materials, though some address glass and polymers. Technical approaches include mechanical, chemical, and thermal treatments, or combinations of treatment methods.

Patent filings and ownership correlate with major production locations and major PV installation markets. Top regions for patent applications are People's Republic of China, United States, South Korea, Japan, and Europe. People's Republic of China owns the most patents with 141, followed by 85 in Japan, 79 in South Korea, 54 in the U.S., and 33 in Germany. Most patents are filed by universities, research institutions, and module manufacturers. There are few applications by recyclers, professional waste treatment companies, and equipment manufacturers because the current waste stream in most regions is still too small to justify significant investments in dedicated recycling technologies.

Published literature is primarily comprised of journal articles and conference papers. PV recycling is viewed as an important topic globally. The U.S. has the most publications, followed by Italy and People's Republic of China, but developing countries and emerging markets like Ghana, South Africa, and Mexico are also publishing papers about PV recycling. Most studies are authored by research institutions and universities, frequently in collaboration with PV manufacturers, equipment providers, and recycling companies. Of the top 25 publishing organizations, only one was a recycler, First Solar. Results for individual leading authors show that U.S. authors hold the most publications, followed by authors in Italy and People's Republic of China. This result follows the same trend as the total number of publications by country.

How to Apply Results

Solar PV system asset owners and operators, as well as utility integrated resource planners can use the knowledge and perspectives in this study to inform module management strategies and enable a circular economy for energy materials as an integral part of the clean energy transition in cooperation with authorities, take back systems and recyclers. Commercial recyclers and researchers within the international solar PV community and related disciplines can use the LCI data to support work that further improves recycling quality and improves economic value. LCI data for PV module recycling can be used by researchers in full life cycle assessments for PV. Identifying gaps in treatment technologies and operating experience also helps in shaping research and development (R&D) priorities.

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