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Life Cycle Inventory of Current Photovoltaic Module Recycling Processes in Europe

PVPS

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

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Abbreviations:

BOS	Balance of system
EVA	ethylene-vinyl-acetate
FE	ferrous
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
NF	non-ferrous
PET	polyethylene-terephtalate
PIB	polyisobutylene
TPT	Tedlar®-polyester-Tedlar®

Executive Summary

Introduction

Solar photovoltaic (PV) installations must be properly dismantled and any waste treated and disposed at the end of project life. However, because most of the world's nearly 400 GW of PV systems have been built in the past decade – each expected to operate for between 20 and 30 years – current PV module waste volumes do not yet justify widespread operation of PV recycling facilities. The necessary policies and technolo¬gies for recycling PV systems are currently under rapid development. With modifications to the European waste electrical and electronic equipment directive (WEEE 2012/19/EU) in 2012, take back and recycling of PV modules is, in fact, already mandatory in Europe. There, take back and recycling is currently performed in small but annually-increasing quantities. Even though waste treatment is considered part of a module's life cycle, only a few life cycle inventories (LCI) of energy and materials flows are available for the industrial recycling processes that are used today to recycle crystalline silicon-based (c-Si) PV modules. LCI are the data inputs that inform life-cycle assessments which quantify the environmental impacts across the full life cycle of PV modules—from manufacturing and use to end of life. To help progress the industry forward, a survey of European recyclers was performed to characterize existing commercial recycling processes and share associated life cycle inventory data

System Boundaries

The reference unit, or "functional unit" in the vocabulary of life cycle assessment, is defined as the processing of one metric ton of crystalline silicon PV modules in recycling lines for laminated glass, metals, and electronic wastes. Today, all modules are processed in discrete batches, yet not metered at that scale. Thus the process energy for a batch is estimated based on scaled annual production data as well as on input and output streams. All the recyclers that participated indicated that the recycled output materials were processed further downstream; these were not included in the study as they are outside of the control and knowledge of the respondents. Direct emissions (e.g., dust and water emissions) were also not accounted for in the recycling processes.

Results

Sixteen recyclers were contacted worldwide between 2015 and 2016, of which five European companies (one in Belgium, two in Italy, and two in Germany) provided LCI data. Survey responses indicate that the participating companies are fully compliant with the WEEE directive. The companies' practices often even exceed the current demands set by the WEEE directive, though future WEEE requirements may become more stringent. In all cases, the batches of PV modules processed to date represent a small share of the total recycling capacity of the plants. Four of five recyclers incorporated the module recycling processes into their preexisting lines without any modifications except for some new parameter settings and optimizations.

Table ES-1**:** Summary of Recyclers that Participated in the Study

Respondent	Company	Country	Process	Type of Recycler	PV Volume (t/yr)
#1	Anonymous	Germany	Mechanical	Glass	1,200
#2	Exner Trenntechnik GmbH	Germany	Mechanical	Metal	100-250
#3	Maltha	Belgium	Mechanical	Glass	1,000
#4	Nike	Italy	Mechanical	Glass	600
#5	Sasil S.r.l.	Italy	Combination of mechanical, thermal, and chemical	Prototype PV recycling system	(1t/hr tests)

Four respondents (#1, #2, #3 and #4) use mechanical processes to separate the module materials; processes include crushing, sieving, and metal separation. The obtained glass cullet feedstock can be used for foam or fiberglass production, while the metals extracted during the process can be sold to metal recyclers and smelters. In addition, the foils coated with metal and solar cell residues can be eliminated in energy-generating waste-incineration (waste-to-energy) plants or be landfilled. However, it should be noted that the materials recovered in the recycling process are of varying quality which may or may not be suitable for all secondary markets.

Respondent #5 has advanced a new dedicated PV recycling process to the demonstration stage. The process provides useful output streams and a high yield with a higher materials recovery fraction than the processes currently used. In this process, the foils are first separated from the glass via a thermo-mechanical approach. The foil is then incinerated and the resultant ash is dissolved in a leaching process. The leached silicon can subsequently be used for ferro-silicon production, while metals can be recovered from the leachate in an electrolysis process. (Note: this pilot facility was put on hold in April 2016 due to insufficient supply of waste modules and for other commercial reasons.) Despite its pre-commercial status, the demonstrated process was included in this study because it shows that modern recycling processes dedicated to PV modules can provide higher recovery fractions – especially for metals and silicon – as compared to the more general processes at other recycling facilities. Thus, the environmental footprint of PV modules can be further optimized.

Across the five respondents, electricity consumption of the recycling processes was reported to be in the range of 50 to 100 kWh per ton (t) of module input for the mechanical processes (Respondents #1, 3, 4 and 5) and 494 kWh/t for the metal recycler (Respondent #2), which uses fine milling of the material to increase glass and metal yields. For the demonstration-scale, dedicated PV recycling facility (Respondent #5), the electrical energy consumption was reported to be about 50 kWh/t for the mechanical processes plus about 76 kWh-equivalent of natural gas per ton of module input for the thermal and incineration processes. All respondents used some diesel fuel for front-end loaders although they did not always report the specific amount of fuel use, and where reported it was small.

The outputs of the recycling processes (given as percentages by weight of the input modules) also vary across all five respondents. The glass yields vary between 59% and 75%. Nonferrous metals were recovered in the range of 13.5% to 21.8%; the higher end of this range is achievable by incinerating the foils and recovering the silicon and metals from the bottom ash, as was demonstrated by one of the respondents (#5) through a new dedicated PV module recycling process.

The polymer fraction, also known as the foil fraction, is another output stream for the majority of the assessed recycling processes. It is essentially a mix of module encapsulant and backsheet waste materials that the mechanical processes cannot further separate into recoverable materials. Often precious metals such as silver are found in this fraction. For the processes surveyed, this waste is usually either incinerated for (low grade) energy recovery or is landfilled.

Better results in the sense of a reduced impurity of the foil fraction can be achieved if greater efforts are made to separate the components, as can be seen in the results achieved by Respondent #2 and Respondent #5 using two different approaches. Respondent #2 uses a more intensive mechanical process to crush and mill the modules down to finer particles, as compared to Respondents #1, #3, and #4. Respondent #5 uses a thermo-mechanical process that can remove polymers and thus separate the other components to a higher level of purity. As expected, there is a tradeoff for greater materials recovery in the form of increased energy needs for these two processes, though there is likely room for further optimization as PV waste streams grow and experiential learning accrues.

Conclusions

Very little public information is available regarding the environmental effects of PV module recycling processes and, more generally, options for decommissioning and disposal of PV systems. This research is valuable for understanding current recycling processes employed in Europe where PV module recycling is already mandatory according to the WEEE Directive. As such systems for the collection of modules have been implemented and commercial recyclers have started to recycle waste modules in full compliance with the laws—mostly by using excess capacity in existing recycling facilities designed to treat laminated glass, metal, or e-waste. The current WEEE mandates do not require a high enough recovery fraction of the mass of input modules to necessitate specialized module recycling processes to recover more minor constituents. However, that seems likely to change in the near future. By contrast, there is currently no regulatory framework for PV recycling in the U.S., but state-level legislation and initiatives are under consideration.

This study also helps to inform the direction of future research. As indicated in the results reported by the five respondents of our survey, better recovery yields seem to require more process steps and greater energy consumption. To minimize the life cycle environmental impact of PV generated electricity (considering from the manufacture of the PV modules to their use and end-of-life management) and also to increase the value of module recycling, recovery of valuable but trace constituents like silver will be necessary. This will require both greater waste streams to justify dedicated recycling facilities and further research and development. Development of dedicated PV module recycling facilities that offer higher yields, recovery of valuable materials, and optimization of electricity consumption can offer environmental and economic benefits to all stakeholders involved.

Introduction

Photovoltaic (PV) module recycling is mandatory in Europe. Several commercial recycling facilities were identified in Germany, Belgium and Italy. Besides providing service to their own countries, these facilities also serve most other European countries. New facilities are expected to be built when the waste stream grows sufficiently to justify the economics. Commercial recycling operations appear to be rare in non-European countries, perhaps due to the lack of regulations, no formal take-back or recycling policies, and small quantities of PV-module waste.

Information on pilot-scale PV-recycling activities has been published in China, Japan, Australia, and several European countries. Research into PV-recycling technologies and processes is ongoing in all major PV countries and regions, including Europe, Japan, China, Korea, Singapore, India, Australia, and the United States. For more information, interested readers can review a companion Task 12 report entitled "End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies", available by searching "Most Recent Publications" on the PVPS Task 12 homepage (http://iea-pvps.org/index.php?id=56).

This report describes results of a survey-based study focused on crystalline-silicon (c-Si) PV-module recycling technologies that currently are operated at the commercial or demonstration scale. An initial survey was conducted for the National Renewable Energy Laboratory (NREL) in 2015 (referred to herein as the "first study"), and a second survey was conducted with support from the Electric Power Research Institute (EPRI) in 2016 (referred to herein as the "current study"). To maintain compliance with the prevailing laws in Europe (e.g., European WEEE directive 2012/19/EU; Directive 2008/98/EC on waste), current commercial-scale crystalline-silicon PV–recycling facilities in Europe must recover bulk materials, such as glass, aluminum (Al), and copper (Cu), but do not yet have to recover minor constituents. For this reason, bulk recycling processes for c-Si modules are the focus of this study which aimed to document data regarding the energy and material flows in a life-cycle inventory (LCI). This study fills a gap in publicly available data regarding the LCI of c-Si module recycling, which can then be used to evaluate full life cycle impacts of PV technologies using internationally accepted life cycle assessment (LCA) methods (Frischknecht et al. 2016).

Approach

Sixteen international recyclers known for their interest and activities in c-Si PV-module recycling were identified through a review of recent press releases about demonstration and pilot projects, scientific publications, presentations at conferences, personal contacts, and participant lists from recent PV-recycling conferences organized by the PV CYCLE Association in Europe. The major stakeholders were asked to agree to terms and conditions before supplying LCI data for this study. A questionnaire was developed to collect LCI data and ascertain the status of recycling activities at each facility.

Recyclers accepted the following terms and conditions.

- The dataset will be anonymized and confidentiality agreements will be signed on request.
- A general recycling process description will be given without sharing any proprietary information.

- The whole recycling process will be treated as a black box with inputs and outputs. The consumption of materials and energy will represent the sum of all subprocesses.
- If PV-module recycling is carried out in discrete batches (which was the case for all recyclers contacted) and material and energy consumption cannot be measured on a per-batch basis, then data can be provided on an average annual level with correction factors for the capacity share of the batches and to adjust for different settings of the machinery and for the materials processed.
- If downstream product treatments within the recycling process cannot be fully disclosed, then general information on industrial consumers of the different output materials and likely further treatment and utilization of the materials will be provided.

Only a few commercial PV module recycling facilities exist today, mostly located in Europe. Moreover, they typically only run on a periodic basis to process batches of modules. In anticipation of increasing demand, several recycling companies are, however, evaluating the PV waste market to assess waste-volume growth. Others are pursuing research- and pilot-stage PV module recycling activities. New PV-specific commercial recycling technology investments have not yet been made due to the currently small volume of PV waste.

Sixteen recycling companies were emailed a questionnaire in 2016, of which nine indicated interest in collaboration and potential participation in future assessments. Five companies responded with the requested LCI input or updated responses provided in the first study (performed in 2015). Based on information known about the universe of potential respondents, the responses contained herein are considered representative of current recycling operations in Europe. None of the companies previously had collected data at the level of detail requested in the questionnaire. Because the participating plant operators collect very little process data on a machine level, aggregate data on the consumption of energy, materials, and other consumables was instead supplied. To clarify the data received, all participating companies were interviewed by phone, and in-person meetings were held with two of the companies.

Review of Prior Published Literature: Life-Cycle Assessment of Commercial PV-Recycling Processes

A review of available literature on commercial recycling processes was conducted prior to beginning the data-collection effort. Several life-cycle assessment (LCA) studies that focused on PV recycling were identified.

Maltha is a laminated-glass recycler in Belgium that services the PV CYCLE Association. An LCA study of its c-Si PV-module recycling process was conducted by Michael Held (Fraunhofer IBP, Germany) in cooperation with PV CYCLE in 2012 (Held 2012; Held 2013). PV CYCLE and Held were contacted to obtain the LCI data from the study, but the data were bound by nondisclosure agreements and thus could not be provided the first time it was requested. Maltha, however, subsequently agreed to provide data. The process used by Maltha is described in the “Respondent #3 Data” section of this report. The results of the study mentioned above were used to estimate electrical-energy consumption.

The Italian company Sasil S.r.l. developed an innovative recycling process in a recent European Commission–funded project called, “Full Recovery End of Life Photovoltaics” (FRELP) (conducted from July 1, 2013 to April 30, 2016).[1] Life-cycle inventory data were collected in the pilot phase of the project and a life-cycle assessment was published by the

[1] www.frelp.info/

partner Joint Research Centre (JRC), Ispra, Italy (FRELP 2016). Sasil provided data for the current study, and its process is described in the "Respondent #5 Data" section of this report.

Another LCA was carried out by bifa Umweltinstitut (Seitz 2013) in 2013, but for confidentiality reasons only the aggregated final results were presented and, again, no LCI data were available to share. This LCA was based on data for SolarWorld's c-Si recycling process. In the SolarWorld process, the foils were pyrolized and the residues were separated using mechanical sorting. This process allows the recovery of very pure materials: glass, aluminum, copper, and solar cells. Yields of about 100% were achieved for copper and aluminum; the solar cell yield was 72.8% with 99.999% purity; and glass yields were 94.3% with 99.99% purity. A fine fraction (2% to 4%) containing glass, inorganic filler materials from the polymers, and small solar-cell fragments had to be landfilled. Solar silicon could be obtained by subsequent selective etching of the solar cells. SolarWorld published several LCA studies on c-Si recycling using the company's proprietary processes (Wambach et al. 2009; Bombach et al. 2006; Schlenker et al. 2006). Unfortunately, in those LCAs the LCI data were not disclosed, and recycling activities stopped in 2012 for economic reasons. Thus, the SolarWorld LCA is not included in this study because its information is not relevant to current recycling processes.

Characterization of Input to the Recycling Process: Crystalline-Silicon PV-Module Waste

No detailed statistics are currently available regarding the type and vintage of modules processed in recycling facilities. It seems that there is little interest in detailed assessments of recycling process inputs, likely because such additional efforts are currently neither mandatory nor remunerated. To facilitate comparison of the different recycling processes in this study, it is assumed that the input to the commercial recycling facilities is standard c-Si modules manufactured in 2013. These are used as a reference—or "typical"—module to enable calculation of the inputs and outputs for the different materials as presented in IEA-PVPS 2016. This is a simplifying assumption because, in practice, recycling facilities receive a mix of different module types.

Because c-Si modules are subject to rapid technical development, more than 50,000 different c-Si module types are already are on the market, with different specifications and compositions according to the module database available from the magazine *Photon*.[2]

It is expected that the composition of the input batches (e.g., module size, technology, power, materials, frames, junction boxes) will vary depending on age and type of module waste. Until the beginning of the twenty-first century, most modules were built with 32 to 40 cells (about 10 cm x 10 cm cell size) connected in series, such that they were suitable for battery charging applications (12 V_{DC}). A modern standard module is assembled with 60 cells (15.6 cm x 15.6 cm cell size) in series and designed predominantly for grid connection (Table 2).

Although there might be some benefit for recycling plants to adjust plant settings for the actual modules treated, the data required to calibrate such adjustments are generally are not available. Thus, average data are used by the plant operators to adjust settings to

[2] http://www.photon.info/en/photon-databases; accessed October 15, 2016; the database is currently offline but can be purchased.

accommodate periodic batches of c-Si PV modules. Likewise, generic methods to adjust the LCI for different module input parameters and manufacture years were developed.

Some of the metals used in modules are precious (e.g., silver) or otherwise valuable (e.g., solar-grade silicon due to high embedded energy), some could be scarce (e.g., indium), and some are toxic (e.g., lead). Precious, valuable, scarce, and toxic materials usually only are present in small quantities.

In previous LCI data-collection efforts, module data were presented per nominal peak power (W_p) or module area (m^2). This is not useful in waste-treatment scenarios because the input and output are measured by mass (metric tons).

Table 2. Material Composition of a Modern Standard c-Si Module with 60 Cells for Year 2013 Presented as an Example (Sources: Raithel 2014, Wambach 2015)

C-Si Module with 60 Cells		**Year 2013**	
Weight/Power*		78.6 g/W_p	
Efficiency		15.8%	
Cell Thickness		170 µm	
	Material	**g/W_p**	**%**
Glass	Glass	59.9	76.22
Encapsulant	EVA	4.5	5.75
Backsheet	PET	3.0	3.77
Frame	Al	6.1	7.82
Cells and Ribbon	Si	3.7	4.70
	Ag	0.032	0.04
	Cu	0.58	0.74
	Sn	0.056	0.07
	Pb	0.033	0.04
Sealant, Potting Compound	PIB, TPT, silicone, other	0.67	0.85
* Without junction box			

System Boundary and Functional Unit

The system boundaries set for the first study and the current study are presented below. The LCI data of 5 crystalline-silicon PV-module recycling plants are described in the “Respondent #1 Data” to “Respondent #5 Data” included in this report. All the plants are located in Europe—the only region where PV module recycling is already mandatory and included in the laws regarding electronic waste.

Based on discussions with experts on PV module recycling, technology providers, and others in related industries, the set of input parameters for an example c-Si module–recycling process was developed. These parameters track or influence the set and the amounts of material, energy, and water used, recycled, and consumed in the recycling process, as well as the waste sent to landfills or incineration sites, and the emissions to air and water. A schematic of the process flow for the proposed generic LCI was produced to reflect the selected recycling process to be inventoried in an electronic format (see Figure 1).

The PV-module waste stream is still is very small, and these amounts are not expected to increase substantially before the year 2020. Thus, most of the current recycling processes are performed in recycling plants designed for laminated glass (which can be assumed to be the best technology available today for recycling PV modules). Other recyclers use their facilities for electronic waste, television and CRT recycling, and metal recycling. The modules are mostly recycled in batches and in time slots of several hours or days, because the PV waste amounts are not sufficient to fill the plant's operating capacity. After accumulating sufficient PV waste to ensure economic processing, the batches are processed—within a year of receipt, as required by law. The LCI data are not measured individually and thus must be correlated with the total production of the plant. This correlation leverages data that are measured over longer periods—such as fuel consumption, water, and electricity—based on the proportion of total weight processed.

In current commercial-scale c-Si PV recycling, bulk materials (glass, aluminum, copper) are recovered and the bulk-recycling process is the focus of this life-cycle inventory. All the processes and the results obtained and described here are in full compliance with the prevailing laws in Europe (e.g., European WEEE Directive *2012/19/EU*; the Directive 2008/98/EC on waste).

The functional unit is defined per unit mass, so all input flows are correlated with mass. This was accomplished in the following sequence, applied to each of the respondent's processes (Table 3).

1. Characterization of c-Si module inputs to the recycling process and correlation with input weight, using averaged module data (Table 2). The same materials content was assumed to apply to the waste module input for each recycling process included in this LCI.
2. Definition of the process flow of recycling for each respondent with full balance of materials, energy, media, consumables, and all outputs.
3. Characterization of output materials and correlation with input weight.
4. Quantification of emissions to air and water.
5. Indirect effects such as buildings, machinery, maintenance, etc.* are not included
6. Indirect effects of offices, such as commuting, are ignored. *

* Effects that are not part of the process but are necessary for the operation, such as infrastructure, and auxiliary equipment. Even commuting, business trips, and coffee machines can contribute to the resource and energy consumption of an activity, but are typically minor or outside of the system boundary and thus not considered here.

Missing data were added from literature and interviews with experts if possible, and reasonable assumptions were made and documented. Because the different processes in recycling plants vary, the LCI data-collection questionnaire was modified to the needs of the individual respondents (see the LCI tables below).

Table 3. System Boundaries for this Life-Cycle Inventory Study

Included	Not Included
Module Input, at Recycling Plant Gate	
	Dismantling of the PV power plant, balance of system components (BOS) (support structures, racks, foundations fences, buildings at PV plant)
c-Si modules (mono- and multi-crystalline)	Non-c-Si module designs
Module cables	PV plant cabling
Packing material arriving at recycling plant (e.g., crates, pallets, cardboard, plastics)	Inverters, batteries, transformers
Junction boxes	Connection boxes at PV plant
Internal transport (e.g., fork lift, wheel loader) within the plant area	All transport up to arrival at gate of recycling plant including pick up, pre-processing, inter-mediate storage before the gate of recycling plant.
Processing	
Consumables	e.g., Filters, sealings, lubricants
Electricity consumption (including that used for compressed air)	
Water (if used)	
Fuels (diesel, oil, gas)	
Output at gate (of varying quality) • Glass (with/without blending) • Metals (Al, Cu) • Polymers (for energetic use) • Other: o Emissions to air and water o Wastes to incineration and landfill	External post-processing (assumed to be available in commercial LCI databases), for example: • Transport, refinery, melting • Foam or fiberglass manufacturing • Energetic use of polymers • Landfill disposal of slags/ashes of waste-to-energy plants Additional processing and landfill disposal of collected dusts and wastes will not be analyzed.
Recycling Plant Infrastructure	
Recycling machinery, wheel loader	Buildings, commuting of employees, cafeteria etc.
Relative size and number of batches (aggregated).	Maintenance and depreciation time (to account for indirect material and energy use of the machinery) were not disclosed.

Reference Recycling Process

Today, the mechanical treatment in laminated glass recycling plants (e.g., the processes of Respondent #1 presented in Figure 1, and of Respondent #3 presented in Figure 3) represents a state-of-the-art process for recycling c-Si modules that sets a cost benchmark. It is frequently employed in discrete batches to allow for the adjustment of process parameters and account for the small processed quantities. There is almost no additional investment required to separate the module into its main components: glass (>75% by weight), aluminum (about 8%), and polymers (about 10%). While the equipment and process steps, as well as the yield and output quality, can vary slightly at different recycling plants, the mechanical treatment process can be viewed as the reference process for this LCI study.

State-of-the-art laminated-glass recycling plants are typically equipped with crushers, magnets, sieves, eddy-current devices, inductive sorters, optical sorters, and dust collection systems. Plant capacities are often on the order of 200,000 tons per year. For reference, PV module recycling represents approximately 0.5% of a recycling plant's total capacity, based on current volumes.

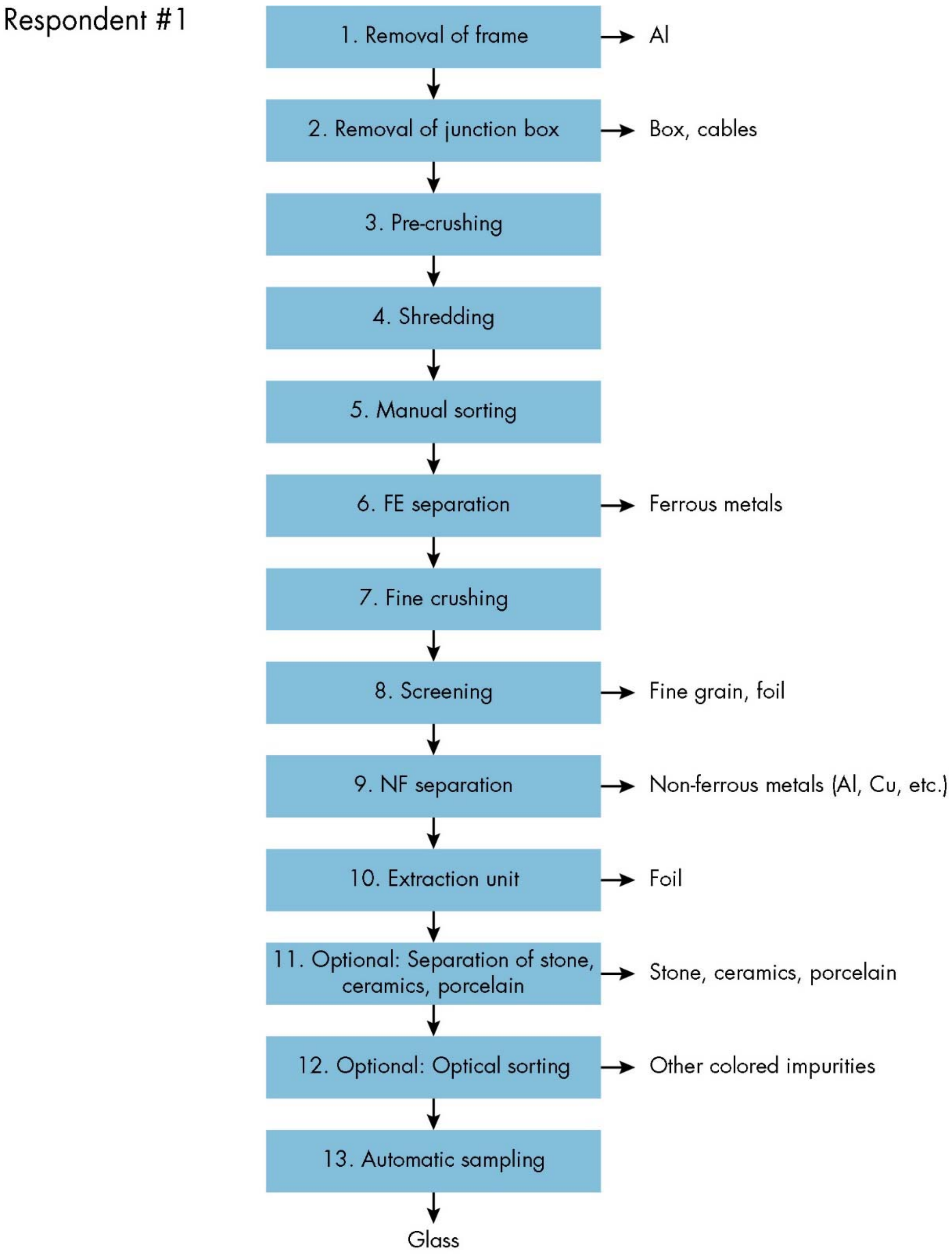

Figure 1. Example of a PV-module recycling process performed as a batch run in a laminated-glass recycling plant, which is considered the reference process of this study since it sets a cost benchmark for PV module recycling in Europe today. This process flow represents the process of Respondent #1.

The process in a laminated-glass recycling line as described as a reference process is carried out by Respondent #1 and Maltha (Respondent #3). Other laminated-glass recycling companies—not included in this study because they were unable to provide any data—also use a similar process. A more-detailed description of the steps of this process is provided in the summary of Respondent #1, below.

The PV-module recyclers whose primary business is laminated-glass recycling are very experienced in the recycling of laminated glass from automotive and building applications, but have processed relatively small amounts of PV modules until now. This could explain the lack of available data. Because the construction of a solar module (containing mainly glass, aluminum, EVA, and PET) differs from the double-glass laminate of automotive and building applications, the energy consumption, auxiliary material usage, and wear of the machinery can be different when PV modules are recycled. The leading PV-module recyclers interviewed reported that they even must reduce the throughput slightly to account for the greater complexity of PV modules versus automotive and building laminated glass (Held 2012; Held 2013).

The large nominal capacities of the laminated-glass recycling plants will accommodate increases in the number and sizes of the discrete batches of waste PV modules as volumes grow, by replacing other laminated-glass streams and using free capacities. Thus, the potential nominal capacity of the plant is given in the tables as an indicative number of current scales. The utilization of the plant for PV-module recycling might reduce the capacity for the established glass recycling and the operators most probably will adjust the product mix for optimum economic results. Nonetheless, based on interviews conducted across the industry, there is no evidence of a PV-recycling capacity bottleneck today.

The typical output materials of the recycling process of a laminated-glass recycling plant (Figure 1) are listed below.

Aluminum Frame (Step 1)

The aluminum frames are removed either in a manual process (sometimes also at pre-treatment companies) prior to the automatic separation of the module components or are removed by nonferrous metal separators (eddy-current devices) after initial shredding or crushing. The material might contain some iron screws, cast aluminum edge connectors, and some glue and sealant residues such as acrylic foam, silicones, and polyisobutylene (PIB). The aluminum will be sold for re-melting. This latter process is not included in the LCI, but the downstream usage of the output material is indicated as far it was disclosed by the respondents (recyclers).

Cables and Junction Boxes (Step 2)

Cables and junction boxes are frequently removed manually or automatically before the process, sometimes even at a pre-treatment company. In some cases, cables are removed manually after the first crushing and are separated in the impurity removal step. The junction box also sometimes is recovered in the polymer and mixed-metal fraction (Step 10).

Cables and junction boxes are collected and sold to appropriate electronic-waste recyclers for further processing. Further processing by the electronic-waste recyclers is not included in this LCI.

Mixed Metals (Step 6 and Step 9)

Mixed metals are separated after subsequent crushing and sieving processes with nonferrous metal separators. This fraction can contain metals including aluminum (interconnectors, frame parts), copper (interconnectors), and some solar cell fragments, all with contaminants of polymers and glass. Additionally, some metallic contact materials (junction boxes) might be present if the junction boxes are automatically separated. The metals are sold to metal recyclers. In most cases, some additional cleaning steps are performed to remove potential impurities such as polymer (glue) residues and screws prior to re-melting of the metals. The external metal recycling process is not part of the LCI.

Polymer/Foil (Step 8 and Step 10)

The polymer fraction (or foil fraction) is another output of this recycling process and consists mainly of the encapsulant and backsheet materials. The separation can be done by aeraulic sorting in which compressed air is used to provide the energy for separation of glass and foil. Most of the solar cells and interconnectors are collected in this fraction as well. This output is frequently forwarded en masse to waste-to-energy plants, if it meets the input specifications of the plants with respect to heavy-metal concentrations and halogen concentrations, which must be less than 1% measured as chlorine in Europe (IED 2010; European Commission 2006; Joint Research Centre 2017). If the halogen content is too great, then incineration in a specialized hazardous-waste plant must be carried out. It can be assumed that the input specifications can be met in most cases.

It is not typically possible to separate the solar cells and the silver metallization on them with current technologies. It is theoretically possible for the metals of this mixed-material fraction to be partly extracted from the bottom ash of the incineration process. Depending on the degree and success of efforts applied in prior process steps, this fraction still could contain significant amounts of glass, partly sticking to the polymers. The share of glass in this fraction can be derived from the (theoretical) module material composition and the percentage of the fraction given in the LCI tables.

The polymers are used for energetic recovery in waste-to-energy plants in compliance with European laws. In other countries the polymer fraction may be landfilled. The energetic recovery process is not part of the LCI.

Stones, Ceramic, Porcelain (Step 11)

Step 11 is implemented in most glass-recycling plants because these impurities might not melt properly and can cause defects in the glass. If the PV modules are collected properly and are free of impurities then this step can be skipped.

Other Impurities (Step 12)

Other impurities that show a different color as compared to the glass cullet can be removed by optical sorting. In module-recycling, solar-cell fragments might be detected and blown out, for example, by using compressed air.

Glass (After Step 13)

In Step 13, samples are taken automatically as a quality control of the final glass cullet to avoid potential complaints of the downstream users for not meeting specifications for maximum allowed impurity concentrations.

The resulting crushed glass fraction still could be heavily contaminated with polymers, silicon, and metals, although it still can be used. After blending with other recycled glass in the glass foam or glass fiber industry, for example, it can be used to manufacture thermal insulating materials. A blend of 15% to 20% of PV-module glass within thermal insulating materials seems to be achievable according to experts. With increasing waste streams, this market could become saturated in the future, consequently requiring investments in new recycling technologies and output markets. Additionally, the impure fractions obtained from the purely mechanical separation process currently used suffer from low selling prices. The foam glass or fiberglass process is not part of this LCI, however additional information on those processes can be found in Busto et al. (2011) and Blengini et al. (2011).

The purity and quality of the glass and the polymer fractions are sufficient to fulfill the obligatory recycling quota by general acceptance of a severe loss of quality of the recycled materials compared to the original new materials. The main components (glass, aluminum, copper) are recovered at cumulative yields of more than 85% by weight, and fully comply with current European legal requirements such as the European WEEE Directive *2012/19/EU* or the Directive 2008/98/EC on waste.

The separation of glass and polymers also can be achieved by physical and chemical processing in solvents (maceration), acids, bases, and other substances. Examples of physical/chemical separation processes are presented in Sander (2007). Other waste-treatment companies might use their mechanical separation lines for e-waste or metals (e.g., Exner, Nike). The process steps are similar. Details are included in the flow charts of the different recyclers (below).

Results of the Survey

The current study focuses on recycling technologies that are operated on a commercial level with standard crystalline-silicon modules of the year 2015/16 and also includes a new demonstration-scale process.

According to interviews conducted with international collection and logistic service providers, there are no other commercial recycling activities known in Europe apart from the ones mentioned in this study. Even Spanish modules might be recycled in Belgium or Germany. Responses to the questionnaires were collected via email, and complemented by several phone interviews. A couple in-person meetings complemented the written data.

The LCI tables show that the annual quantities of processed modules increased at the established recyclers as compared to the 2015 study. According to the interview results, however, only minor technical changes were made – except for some process optimizations – at all respondents. Details were not provided.

The results of the current (2016) survey of the same recyclers contacted in 2015 and newly contacted recyclers are summarized below. The previous survey collected data from operations in 2014 and 2015. The survey in 2016 collected data from operations in 2015. If these new results supersede an estimate that was reported in 2015, the prior estimate is indicated in brackets.

A major change occurring since the 2015 survey was conducted is that the new waste electrical and electronic equipment directive (WEEE Directive *2012/19/EU*) that includes PV modules was put into force in nearly all of Europe. It is now mandatory that modules be collected and recycled. For this reason, it is assumed that several new recycling facilities will be up and running in Europe in the future.

The PV-module waste stream is presently still very small; greater amounts aren't expected until after the year 2020 (IEA-PVPS 2016). Thus, most of the recycling processes today are carried out in general recycling plants, mainly for laminated glass, e-waste, or metals. The modules are usually processed in discrete recycling batches.

The current study focused on recycling technologies that are operated on a commercial level or published applied research and development activities with plans to at least build a pilot line in the short-to-medium term; that is, in the next few years. The questionnaire (Excel spreadsheet, see Appendix 1) was slightly modified for more clarity through structure and content versus the 2015 questionnaire. The negotiation results on the terms and conditions to provide data did not change significantly, but the interest in the work and the overall willingness for further cooperation clearly improved due to better personal relationships with the recyclers that were successfully established previously.

In 2015, the questionnaire was sent out to 7 recyclers (6 in Germany, 1 in Belgium) known for performing PV-module recycling in a state-of-the-art process in 2015. In 2016, the same companies were contacted to request an update. Eleven newly identified recyclers were also contacted to collect additional data. The recyclers were identified by expert interviews, press releases, and an online survey. Additionally, some (European) collection systems and reverse logistic providers such as Take-E-Way (www.take-e-way.de), PV CYCLE (www.pvcycle.org), and SENS eRecycling (www.erecycling.ch), were interviewed but they did not disclose information on the collected amounts and recycling results. Stiftung EAR (www.stiftung-ear.de)—the national register for waste electric equipment—was founded by producers as their clearinghouse for the purposes of the Electrical and Electronic Equipment Act (ElektroG). Entrusted with sovereign rights by the Federal Environment Agency (UBA), Stiftung Ear registers the producers of electrical and electronic equipment and coordinates the provision of containers and the pickup of electrical and electronic waste equipment at the public-waste disposal authorities in the entire Federal Republic of Germany. Stiftung EAR reported that there were only 104 container pickups of PV modules in the municipal collection system in 2016 (Stiftung Elektro-Altgeräte Register 2016; Stiftung Elektro-Altgeräte Register 2017).

Responses to the questionnaires were collected via email and interviews conducted both on the phone and in person. Statistics on the data-collection process are shown in Table 4.

Table 4. Results of Inquiries to PV-Module Recyclers

	2015	**2016**
Contacts	8 recyclers (1 of them rejected upfront)	16 recyclers (7 rejected)
Locations	6 recyclers in Germany, 1 recycler in Belgium	8 recyclers in Germany, 1 recycler in Belgium, 1 recycler in France, 1 recycler in Switzerland, 3 recyclers in Italy, 1 recycler in Australia, 1 recycler in Japan
Technologies	6 laminated-glass recyclers, 2 e-waste recyclers	5 laminated-glass recyclers, 2 e-waste recyclers, 2 metal recyclers, 5 PV-module recyclers (pilot stages), 2 general waste-treatment companies
Questionnaires Sent to Recyclers	7	9
Respondent Feedback on Questionnaires Sent	7	7
Face-to-face Negotiations	3	2
Data Sets Received	1 (anonymized), Germany 1 Exner Trenntechnik	5 1 Respondent #1 (anonymized), Germany 1 Exner Trenntechnik, Germany 1 Maltha, Belgium 1 Nike, Italy 1 Sasil, Italy

Description of Life-Cycle Inventory Data Provided in Response to the Questionnaire

Respondent #1 Data

The first survey respondent is an experienced laminated-glass recycler that performs crystalline-silicon PV-module recycling activities of approximately 1,200 tons per year within a total laminated-glass recycling capacity of about 200,000 tons per year. The general process carried out is presented in Figure 1. All output products will be further treated by other, external, specialized waste-treatment companies or be sent to a landfill. This state-of-the-art process is very similar to that published about Maltha in Belgium (Held 2012).

The recycling company (Respondent #1) that responded prefers to not be named and requested that the data be anonymized. The respondent provided only general information about the recycling process. Further description of the recycling process is added here by the author of this report and the most probable usage of the output material is presented based on the author's best knowledge of typical downstream processes in Germany, and on insights gained through expert interviews. Examples are shown in Table 5 and are included in the discussion of the assumed recycling process included below.

Table 5. Possible Downstream Processes and Author's Assumptions of Possible Usage of the Outputs

Output	Possible downstream (external processing)
Cables	Cable recycler (stripping of polymers; recycling of polymers, if possible, otherwise incineration; recycling of copper; use in copper production)
Junction boxes	Electronic-scrap recycler (usage is material dependent, but typically most of the metal is recovered; the polymers can be recycled partly or are incinerated)
Ferrous metals (magnetic)	Metal recycler (use in metal production)
Non-ferrous metals	Metal recycler (use in metal production)
Polymers/foils for energetic use	Incineration (treatment of bottom ashes to extract metals, mineral part used as construction or backfill material)
Glass cullet	Foam-glass manufacturer (glass fiber)
Mixture of glass cullet, foil and metals	Output is about 10%, the possible utilization is 9% lower value foam glass, fiber, or mineral, about 1% landfill
Other	Other residues (e.g., packing materials, other impurities, dust) (landfill or incineration)

The recycling process (based on reported and assumed information) is described in Figure 1. The first processing step is usually a coarse crushing of the modules followed by a visual inspection process and manual removal of large extraneous material (e.g. cardboard, cables). After that, magnetic (ferrous) material is separated; for example, magnetic steel (impurities), screws, and steel parts of junction boxes. The module fragments are then typically fine-crushed to prepare the laminates for the separation into three different fractions: glass (cullet), fines (mainly fine glass particles), and foils, together with most of the encapsulated interconnectors and solar cells. This is often done using screens to remove fine grains and foils from the main glass stream. Afterwards, the nonferrous metals (e.g., aluminum frame parts, copper interconnectors, metal parts of the junction box, solar cell fragments) are removed via nonferrous metal (NF) separators. In most cases eddy-current separator devices are used here. This fraction of nonferrous metals commonly is further refined by specialized metal recyclers, which usually combine sorting by density with sensor-based sorting processes.

In the extraction unit (*see* Figure 1) more foil fragments are collected, and these could either be added to the other foil fraction or could form a mixed-waste fraction of fine glass particles, metals, and foils. Next, other impurities such as solar cell residues and interconnectors can be removed by optical sorting. This is usually done if the quality inspection results from the automatic sampling of the cullet stream do not meet the specification required for the output. It can be assumed that the customer of the output cullet is a foam-glass or glass-fiber producer.

Respondent #1 provided only general information on further treatment or utilization of the outputs. As stated, the author provides additional detail based on professional judgement. The questionnaire response received is shown in Table 6.

According to Respondent #1, the foil fraction (*see* Table 6) is used energetically in waste-to-energy plants, and the metal and solar cell residues currently end up in the incineration bottom ash. Due to European laws (e.g., 2000/76/EG, 2010/75/EU), it can be assumed that metals will be recovered from this ash in several subsequent treatment steps, and that the mineral part will be used as, for instance, construction material, back-fill material, and landfill construction material. The fines (these typically are grain sizes of less than about 3 mm; some recyclers might require other sizes) are most frequently put in landfills. In this scenario, silicon and silver on the cells are not recovered.

After the foil extraction, the remaining material (mostly glass cullet that is larger than 3 mm) can be optically sorted if further purification of the glass cullet is required, but this is an optional step. The impurities (small pieces such as solar-cell fragments) are usually blown out using compressed air at the position detected by the optical sensor. Several nozzles are fixed in a row and can be controlled individually to ensure the local removal of any impurity detected. The resolution of the system is limited to some square centimeters, and usually a mixture of glass, metals, and solar cells is blown out—which can be further purified if it is economically feasible, or can be used in a low-quality foam-glass or recycled-mineral material application. In some cases, the whole fraction is landfilled.

The respondent did not disclose the identity of recipients of the output materials nor the further treatment processes. It is known, however, that the use of the outputs depends on local conditions and price structures within the relevant legal framework, and can change.

The downstream processes (recycling steps that do not occur on site, but rather are performed by other companies) are indicated in a quite general way because the company is not able to disclose its business relationships, or does not know the details of the follow-up processes. Based on review of conference presentations and interview results, it can be assumed that follow-up processing is done with state-of-the-art mechanical- and sensor-based recycling technology. Examples of possible treatments and utilizations are shown in Table 6.

Table 6. LCI Data Provided by a Laminated-Glass Recycler (Respondent #1)

Name		Respondant #1: Anonymous	
Time Period		2015/16	
Geography		Europe, Germany	
Technology		Mechanical processing	
Representativeness		Individual real processes in discrete batches	
Date of Study		October 2016	
Collection Method		Data from anonymous recycler	
Comment		German electricity mix	
Plant			**Comment / Reference**
Capacity		200,000 t/yr	Total capacity laminated glass
Type of Plant		Glass recycling plant	
Location		Germany	
Time Period		2015/2016 and (2014)	
Modules Processed			
Total Input		1200 t/yr (1000)	2014 numbers in brackets
Components / Fuels			
Electricity Consumption	kWh/t	60	
Diesel/Oil Consumption	l/t	2.5	
Output	% weight		
Cables	%	0.75	Cable recycler
Junction boxes	%	0.52	Electronic scrap recycler
Ferrous Metals			
Magnetic	%	0.02	Metal recycler
Non-Ferrous Metals	%	16.05	Metal recycler
Polymers / Foils for Energetic Use	%	12.31	Incineration
Glass Cullet	%	58.99	Foam glass, glass fiber
Mixture of Glass Cullet, Foil and Metals	%	10.4	9% other utilization, 1% landfill
Other	%	0.96	Other residues, landfill or incineration
Total Output	%	100	

The data provided are based on June 2015 and 2016 deliveries, reflecting recycling that was carried out in discrete batches. Different types of crystalline-silicon modules—such as mono- or multi-crystalline silicon, and glass-Tedlar and glass-glass laminates—were mixed in the recycling line (or across different batches) but are not further distinguished in the data provided. The company did not present a detailed breakdown of energy consumption at a tool/process step level because it is considered proprietary information and is not measured in detail.

Energy consumed in the module recycling process is electricity for the processing plant (e.g., for compressing air) and oil (diesel) for internal transport with four-wheel loaders. Other consumables either are not used or statistics of their use were not provided in the questionnaire response.

Information about emissions to the atmosphere was not provided. Emissions potentially can be estimated independently, at least for combustion of diesel by the four-wheel loaders, by using emission factors. No information was given about dust emissions from the facility, yet those can be assumed to be quite small because dust is collected at the processing line by an emission-control device. The dust collected is usually landfilled.

Some LCI data on foam-glass production—which is the major purchaser of the glass cullet—was published by Busto et al. (2011).

Respondent #2 Data

Exner Trenntechnik GmbH is an experienced metal recycler who performs crystalline-silicon PV-module recycling activities equaling approximately 100 to 250 tons per year, within a total recycling capacity of about 52,000 tons per year (*see* www.exner.de). The process description and LCI data are based on 2015 deliveries reflecting recycling that was carried out in discrete batches. Different types of crystalline-silicon modules—such as mono- and multi-crystalline silicon, and glass-Tedlar and glass-glass laminates—were mixed in the recycling line (or across different batches), but are not further distinguished in the data provided.

Exner’s recycling process is described in Figure 2, for which only general information was provided. The first processing step is a coarse crushing of the modules (Step 1) without initial removal of cables, frames, and junction boxes—in contrast to the process of Respondent #1. Next, the materials are sorted manually to remove, for example, packaging material and other impurities (Step 2). Then the module fragments are fine-crushed in a mill (Step 3) to prepare the laminates for the separation into three different fractions: glass fines, metals, and foils, together with most of the encapsulated interconnectors and solar cells. In a multistep screening process, the glass particles are classified by grain size (Step 4), the foils and the metals are separated with a nonferrous-metal separator (Step 5), and the metal fraction is further processed to separate aluminum and copper (Step 6). Due to the crushing and milling processes, the metals from the cables and junction boxes also are collected during these steps. The polymer parts together with the foils are collected in Step 3 through Step 5.

Exner provided only general information on further treatment or utilization of the outputs. Aluminum is used in the steel industry and the copper fraction is recycled at a precious metal smelter works. The foil fraction is incinerated for energetic use; silicon and silver are not yet recovered. The main fraction is classified by size. According to the quality, the glass is used for foam glass or fiber glass production, concrete manufacturing or may be even disposed of in the case of the dust. According to limited processed amounts no stable output paths are established yet. The downstream processes (recycling steps that do not occur on-site, but rather by subsequent companies) are indicated in a quite general way because the company is not able to disclose their business relationships or does not have knowledge about the details of the follow-up processes.

The author of the present report assumes that the most probable usage of the output materials is similar to the assumptions made for Respondent #1. The author further assumes that approximately 90% of the mineral and metal parts of a module can be recycled if the process is optimized beyond current practice.

The LCI data provided is reported in Table 7. Respondent #2 did not present a detailed breakdown of energy consumptions at a tool/process step level because it considers that to be proprietary information and it is not measured in detail. Due to the small batch size in relation to the total capacity and the significant number of different running processes for other wastes, the energy consumption is estimated by Exner.

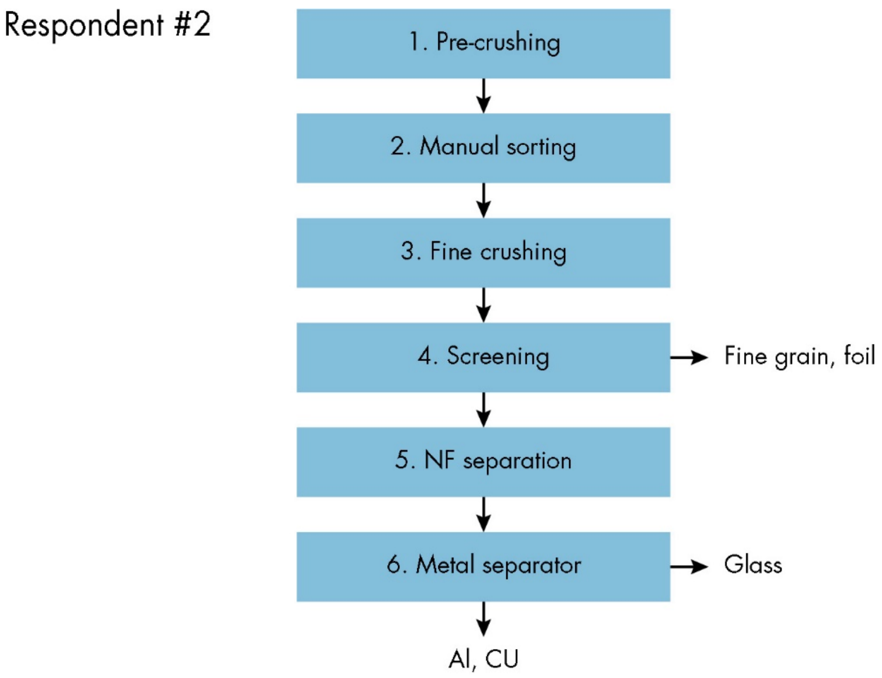

Figure 2. Schematic drawing of c-Si module recycling process used by Respondent #2. All output products are further treated by other external specialized waste-treatment companies or are put in a landfill. Note that there is not a separate process step for frame separation.

Energy consumed in the module-recycling process includes electricity for the processing plant (e.g., for compressing air, and for sensors, sieves, and conveyors), and oil (diesel) for internal transport with four-wheel loaders or for heating. The fuel consumption was considered to be very low but was not measured. Other consumables were not reported, possibly because they were not used.

Emissions to the atmosphere were not provided. Potentially, they can be estimated independently using emission factors based on combustion of diesel by the four-wheel loaders. No information was given on dust emissions, yet those can be assumed to be quite small because dust is collected at the processing line by a dust-collection and filter system. The collected dust is usually landfilled but no information was provided about this process.

Table 7. LCI Data Provided by Exner Trenntechnik GmbH (Respondent #2)

Name		Respondent #2: Exner Trenntechnik GmbH	
Time Period		2016	
Geography		Europe, Germany	
Technology		Mechanical processing in metal recycling plant	
Representativeness		Individual real processes in discrete batches	
Date of Study		October 2016	
Collection Method		Data from Exner Trenntechnik GmbH	
Comment		German electricity mix	
Plant			**Comment / Reference**
Capacity		52,000 t/yr	Capacity can be increased by variation of total product mix; total recycling capacity 52,000 t/yr, modules 250 t/yr
Type of Plant		Mechanical treatment of metals	
Location		Langelsheim, Germany	
Time Period		2015 (2014)	
Modules Processed			
Total Input		250 t/yr (100 in 2014)	2014 numbers in brackets
Components / Fuels			
Electricity Consumption	kWh/t	494	Estimation based on annual plant consumption, estimated by respondant, process energy only
Diesel/Oil Consumption	l/t		Internal transport, no information provided, assumed as negligible
Output	% weight		
Cables	%		Not separated
Junction Boxes	%		Not separated
Ferrous Metals			Steel works, neglected
Magnetic	%		
Non-ferrous Metals	%	15	Aluminium (10%), non-ferrous metals (NE) (5%); separation of Al and Cu after NE separation in a subsequent process; Al used in steel industry; Cu further recycled at precious metal smelter
Polymers / Foils for Energetic Use	%	10	Separated in sifting process from non ferrous metals; energetic use of foils; incineration in waste to energy plant
Glass Cullet	%	75	Use in foam or fiber glass industry, different grain size fractions, different utilizations, mostly foam and fiber glass applications
Mixture of Glass Cullet, Foil and Metals	%		No information provided
Other	%		No information provided (e.g. emissions, collected dust)
Total Output	%	100	

Respondent #3 Data

Maltha (www.maltha.nl) is a large laminated glass recycler with plants in Belgium, The Netherlands, and Portugal. Its module-recycling process was modified recently versus the LCA process published in 2012 by Held and PV CYCLE (Held 2012).

Maltha intensified the cooperation with the WEEE recycler and sister company Coolrec in Belgium (both owned by the van Gansewinkel Group). Now Coolrec removes the electronic components such as cables, junction boxes, and frames. This is indicated in Figure 3, Step 1 and Step 2. Subsequently, the pretreated modules are transported to the Maltha plant in Lommel (Step 3). The process of Maltha in Belgium is similar to the process used by Respondent #1. The bare laminates are shredded (Step 4), impurities are manually sorted out (Step 5), the material is then crushed (Step 6), and separated into metals (Step 5 separation). Next is the extraction of metals (Step 6); separation of nonferrous metals (Step 9); removal of glass, porcelain, and ceramics (of which the latter two might be introduced in waste PV module collection bins) (Step 10); and removal of foil with interconnector and solar cells (Step 11) by sieving it from the final output, which is glass cullet. For the current study, Maltha for the first time agreed to provide LCI data with terms and conditions similar to those of the other companies.

The modules are processed in discrete batches to allow for the adjustment of the process parameters, and to account for the small quantities to be processed. There is almost no additional investment required to separate the different components of the modules. The recycling is carried out using magnets, crushers, sieves, eddy-current devices, optical sorters, inductive sorters, and exhausting systems. The resulting crushed glass fraction still could be heavily contaminated with polymers, silicon, and metals, and can be used with other recycled glass in the glass-foam or glass-fiber industry as thermal insulating material.

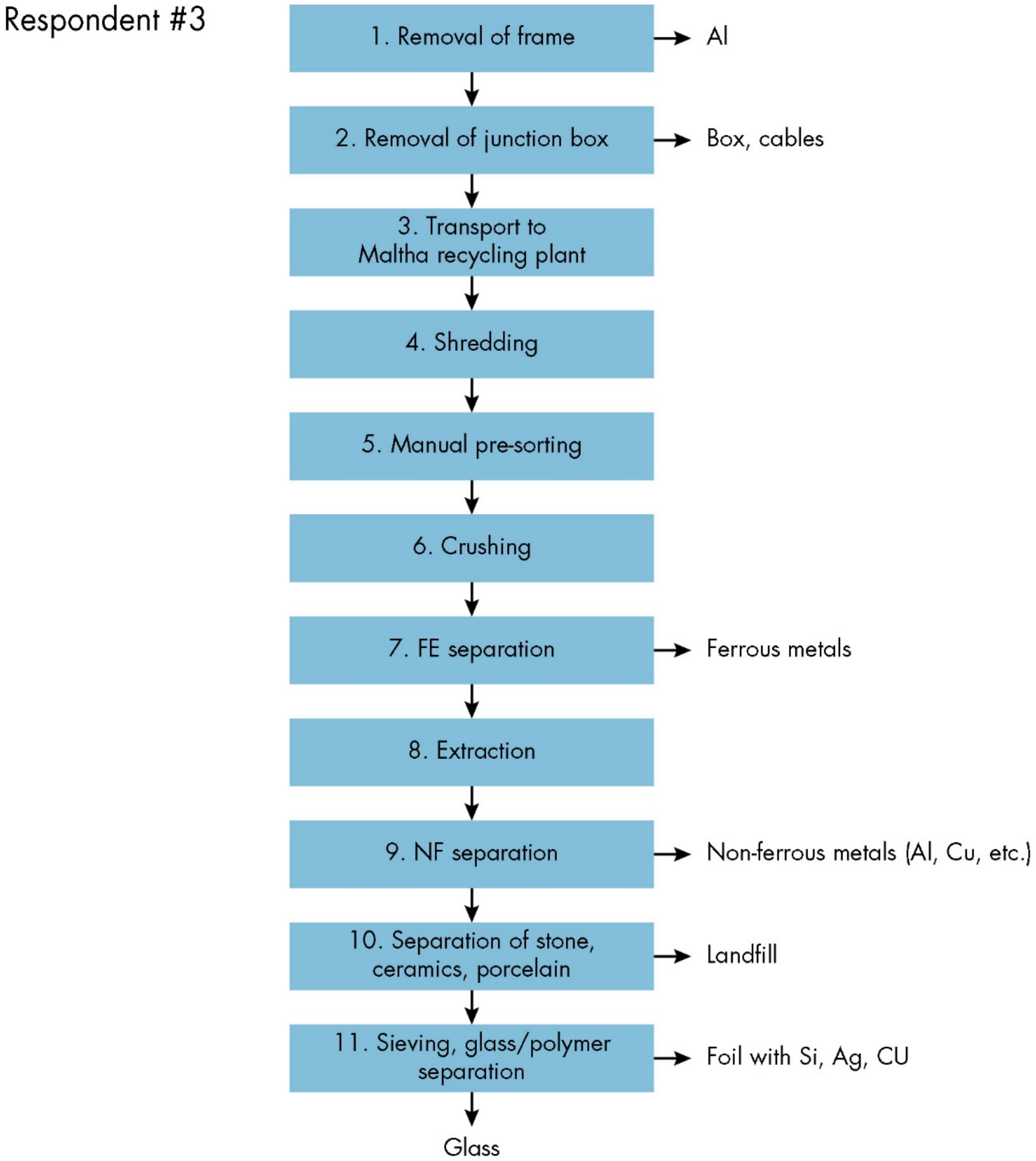

Figure 3. Schematic recycling process of Respondent #3. Note that transport to Maltha is not included in the LCI data for this respondent.

The transport from Coolrec to Maltha (Step 3) is not included in the LCI data (Table 8). The energy consumption is not measured (or even measurable) on a batch level, thus reasonably justified estimates were provided including Step 1 and Step 2 which previously were carried out at Maltha. There appears to be variability in plant throughput, however; thus, normalized energy consumption, as seen in the two LCAs performed by Held (Held 2012; Held 2013), is based on two different assumptions of the plant throughput. The author used these data to estimate the range of the energy consumption shown in Table 8. The greater energy consumption (84 kWh/t) is correlated to the smaller throughput as compared to standard laminated-glass recycling, and it is assumed that this described the status. The reduced energy consumption is correlated to a potentially greater throughput that seems to be achievable according to the publications mentioned herein.

The main components—glass, aluminum, and copper—are recovered at cumulative yields of more than 85%, that fully comply with current European legal requirements. The polymer fraction is landfilled or incinerated in waste-to-energy plants.

*Table 8. LCI Data Provided by Maltha with Additional Information by Held (2012) and Held (2013)**

Name		Respondent #3: Maltha BE	
Time Period		2015/2016	
Geography		Europe, Belgium	
Technology		Mechanical treatment in laminated glass recycling plant with pretreatment in WEEE recycling plant	
Representativeness		Individual real processes in discrete batches	
Date of Study		October 2016	
Collection Method		Data from Maltha BE	
Comment		Belgian electricity mix with 50% PV use *	
Plant			**Comment / Reference**
Capacity		200,000 t/yr	http://www.maltha-glassrecycling.com/holglas-vlakglas/vlakglas.aspx
Type of Plant		Glass recycling plant	Cooperation with WEEE recycler Coolrec (BE) for pretreatment
Location		Belgium, Lommel	
Time Period		2015	
Modules Processed			
Total Input		1000 t/yr	Estimation 2016 > 1000 t
Components / Fuels			
Electricity Consumption	kWh/t	46 - 84	Throughputs 10t/h and 3.4 t/h respectively; 3.4 h/t seems to be currrent state of the art (own estimation based on publications of Held and PVCYCLE *)
Diesel/Oil Consumption	l/t	2.5	Internal traffic, own estimation
Other			
Output	% weight		
Cables	%	0.6	Cable recycler
Junction Boxes	%	0.9	WEEE recycler
Ferrous Metals			Metal industry
Magnetic	%		
Non-ferrous Metals	%	13.5	Al
Polymers / Foils for Energetic Use	%	15	Landfill, to be replaced by waste incineration
Glass Cullet	%	64	Foam and fiber glass production; future potential for container and float glass
Mixture of Glass Cullet, Foil and Metals	%	6	Landfill
Other	%	0	
Total Output	%	100	

*According to Held, 50% of the energy need is supplied by a PV generator, 50% from the Belgian energy mix.

Respondent #4 Data

The general process of the glass recycler Nike (www.nikesrl.com) is quite similar to the previously discussed processes of Respondent #1, Respondent #2, and Respondent #3.

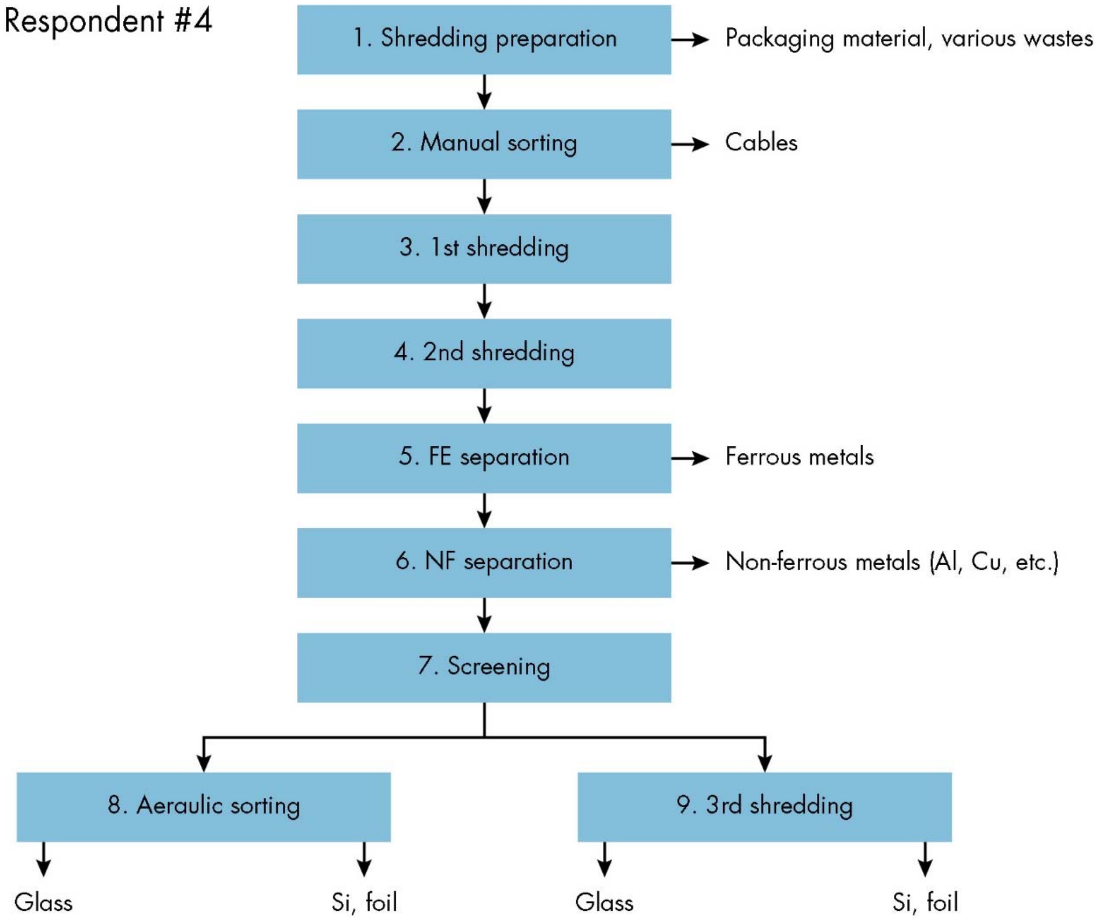

Figure 4 describes the process (graph provided by Nike). Different types of crystalline-silicon modules—such as mono- and multi-crystalline silicon, and glass-Tedlar and glass-glass laminates—were processed in the recycling line (or across different batches) but are not further distinguished in the data provided. Nike processes modules in discrete batches in the recycling plant. The company did not present a detailed breakdown of energy consumptions at a tool/process step level because it is considered proprietary information and is not measured in detail.

The separation process mainly consists of three shredding processes with ferrous and nonferrous metal separation and screening. The different fractions are used in a manner similar to the outputs of the other PV recyclers.

In a pretreatment Step 1, all extraneous material (i.e., cardboard, plastics) is removed. In Step 2, the cables are manually collected separately. No information about a separation of the junction boxes was provided. Step 3 and Step 4 are shredding steps, intended to achieve the desired particle sizes for Step 5, which is ferrous material separation via magnetic sorting, and Step 6, which is nonferrous material separation using an eddy current. In this step the Al of the frames is separated. After a screening process (Step 7), glass and foils with solar-cell residues are separated either by aeraulic sorting (Step 8) or after shredding (Step 9).

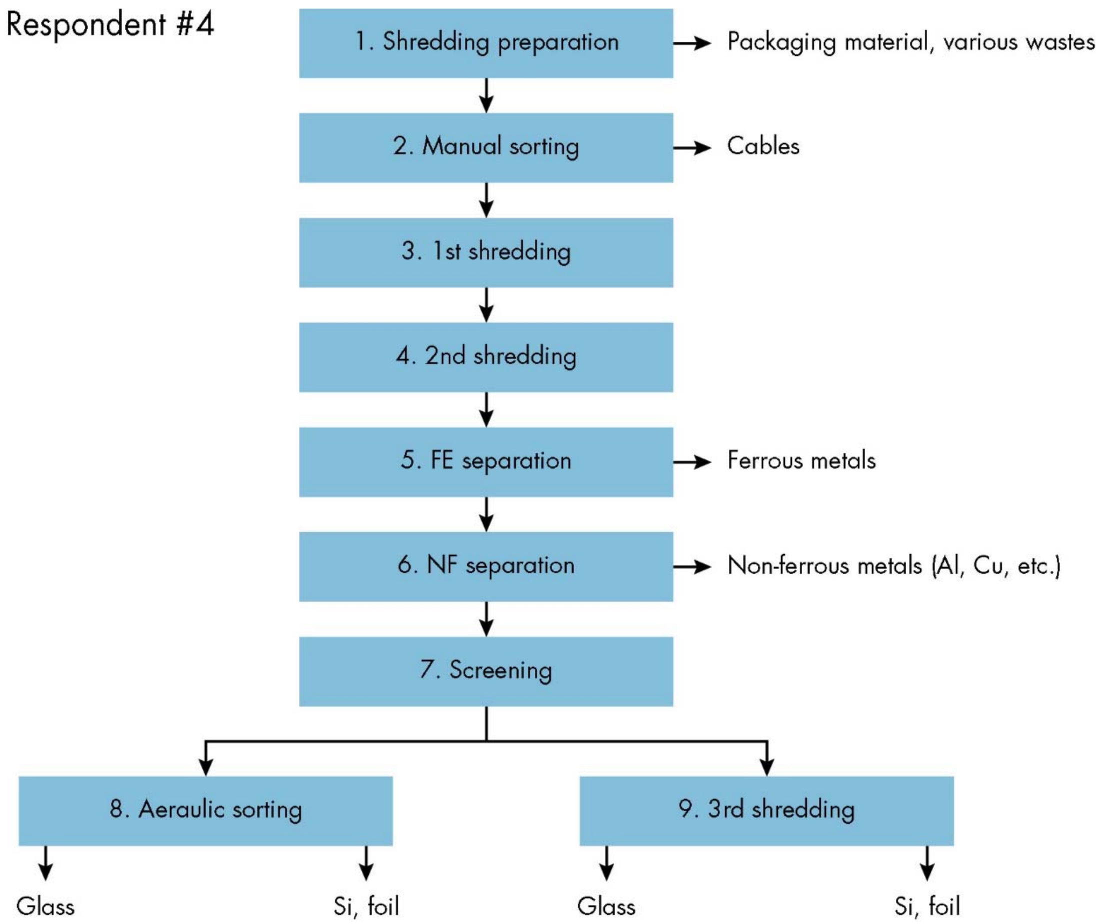

Figure 4. Schematic recycling process at Nike S.r.l.

Energy consumed in the module-recycling process includes electricity for the processing plant (e.g., for compressing air; powering motors, conveyors, sensors) and oil (diesel) for internal transport with four-wheel loaders. Other consumables are either not used or the statistics of use were not provided in the questionnaire responses.

The LCI data are shown in Table 9. Emissions to the atmosphere were not provided. Potentially, emissions can be estimated independently using emission factors based on combustion of diesel by the four-wheel loaders. No information was given on dust emissions, yet those can be assumed to be quite minimal because dust is collected at the processing line by a dust-collection and filter system. The dust is collected usually landfilled.

Table 9. LCI Data for Nike S.r.l.

Name		Respondent #4: Nike SRL	
Time Period		2015/2016	
Geography		Europe, Germany	
Technology			
Representativeness		Individual real processes in discrete batches	
Date of Study		October 2016	
Collection Method		Data from Nike SRL, Rome	
Comment		Italian electricity mix	
Plant			**Comment / Reference**
Capacity			No information provided
Type of Plant		Glass Recycling Plant	
Location		Italy, Rome	
Time Period		2016	
Modules Processed			
Total Input		600 t/yr	
Components / Fuels			
Electricity Consumption	kWh/t	100	
Diesel/Oil Consumption	l/t		Not provided
Output	% weight		Specify and indicate utilization, subsequent treatment
Cables	%	1.2	Cable recycler
Junction Boxes	%		Polymer, WEEE recycler
Ferrous Metals			Metal industry
Magnetic	%	0.5	
Non-ferrous Metals	%	19.3	Metal industry
Polymers / Foils for Energetic Use	%		Waste incineration, see mixed fraction
Glass Cullet	%	62	Foam glass production
Mixture of Glass Cullet, Foil and Metals	%	17	Waste incineration
Other	%	0	
Total Output	%	100	

Respondent #5 Data

The Italian company Sasil S.r.l. developed a more complex recycling process enabling the high-quality recovery of components. A schematic drawing is shown in Figure 5. The process was conducted at a demonstration-scale facility. It includes the separation of glass and foil, incineration of the foil with recovery of the silicon and the metals, leaching of the incineration residues, filtration, and electrolysis (to recover silver and copper to be further processed by metal recyclers). This process seems to represent the high-yield and high-quality process mentioned by PV CYCLE in its 2016 press release (PV CYCLE 2016). More details of the process can be found in (FRELP 2016). The pilot process was stopped at the end of the FRELP project in spring 2016 for commercial reasons, and because of the short supply of modules. An LCA was conducted by the Joint Research Centre (JRC), Ispra, at the end of the project (Latunussa et al. 2016). Major results from the JRC LCA also can be found on the project website (FRELP 2016).

The Sasil process is quite different from the processes described for Respondent #1, Respondent #2, Respondent #3, and Respondent #4 (*see* Figure 5). The main targets of the research projects were the recovery of high-quality extra-clear glass and metallurgical-grade silicon for ferro-silicon production. Silver and copper also were recovered and purified by electrolysis. After removal of the frames (Step1), junction box, and cables (Step 2), the module glass is broken and the broken laminate is heated to (at minimum) the softening temperature of the polymers to separate the polymer from the glass (cullet) (Step 3) (e.g., using a vibrating knife). An optical-sorting step (Step 4) is included to obtain a high-quality glass suitable for flat- or container-glass manufacturing. The polymer (foil) fraction is cut to pieces (Step 5) and incinerated (Step 6) to separate the polymers from the metals and solar cells. Metals and solar cells are ground to a size of about 0.5 mm before sieving (Step 7). Next, leaching (Step 8) is performed using nitrous acid, and the metals are completely dissolved; the solution is separated from the silicon of the solar cells by filtration (Step 9). The silicon can be used for ferro-silicon production. The solution of the metals then is electrolyzed to recover silver and copper (Step 10). The residual sludge from the final treatment of the chemicals (oxidation, neutralization, precipitation) is landfilled.

Respondent #5

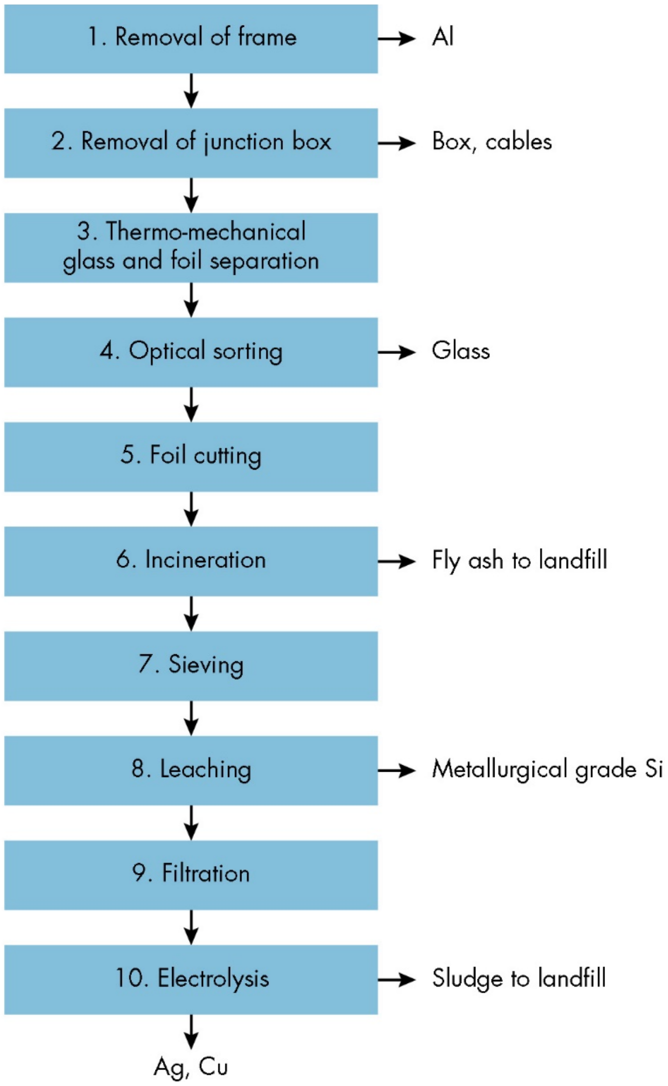

Figure 5. Schematic process flow of Sasil

Using this process, about 88% of the input material and up to 95% of the glass was recovered in good quality (the polymers incinerated represent about 7% of the input mass). If the sludge of metal hydroxides (0.2%) is neglected, the output results can be directly compared to the output results of the other respondents within the precision of the data collected. Like the Solarworld process mentioned in “Review of Prior Published Literature: Life-Cycle Assessment of Commercial PV-Recycling,” the Sasil process enables the full recovery of glass, metals (including silver), and silicon in greater yields and of high purity. The energy consumption of the designated PV-module recycling process was reported as about 50 kWh per ton for the mechanical, and about 76 kWh-equivalent per ton of natural gas for the thermal and incineration process. The LCI data are provided in Table 10.

Table 10. LCI Data Provided by Sasil S.r.l. (Respondent #5)

Name		Respondent #5: Sasil S.r.l.	
Time Period		2013/2016	
Geography		Europe, Italy	
Technology		Detachment of glass by patented technology, burning of EVA sandwich, recovery of silicon by leaching, recovery of silver and copper by electrolysis	
Representativeness		Individual real processes in discreet batches	
Date of Study		October 2016	
Collection Method		Data from Sasil S.r.l.	
Comment		Italian electricity mix	
Plant			**Comment / Reference**
Capacity		8,000 t/yr	1 t/h of Si PV modules (50 panels per hour) test
Type of Plant		Recycling plant	Prototype and laboratory equipment
Location		Brusnengo (Biella), North West Italy	
Time Period		2013-2016	Realized only the prototype to detach the glass
Modules Processed			Specify
Total Input			Only silicon PV panels, test operation
Components / Fuels			
Electricity Consumption	kWh/t	50	E.g. estimation based on plant electricity consumption
Diesel/Oil Consumption	l/t	0.5	Internal traffic
Gas	m3/t	10	Gas for burning sandwich for external incinerator
Output	% weight		Specify and indicate utilization, subsequent treatment, e.g.
Cables	%	0.5	Cable recycler
Junction Boxes	%	0.5	WEEE recycler
Aluminium	%	18	Aluminum for recycle
Silicon	%	3.64	Silicon for iron-silicon alloy by acid leaching and filtration
Silver + Copper	%	0.16	Silver 0.05%, copper 0.165%, by electrolysis
Polymers / Foils for Energetic Use	%	7	Incineration and recovery energy
Glass Cullet	%	70	Float glass
Mixture of Metal Hydroxide	%	0.2	Landfill
Other	%		
Total Output	%	100	

Discussion and Conclusions

Market

A great number of research activities were identified in Europe, concentrated in Germany, Austria, Italy, France, Spain, and Poland. A very high global interest was observed in recycling research, reflected by an increasing number of patents and publications that were produced mainly by research institutes (Komoto et al. 2017). Several new international research projects seem to be in the queue.

In contrast, the number of commercial activities is far less, owing to the small number of waste modules on the market. The interviews revealed that several recyclers have already studied the new business cases, but seem to be very reluctant to start commercial recycling activities at this stage, instead preferring to continue to observe the market for now.

Despite the scientific interest, and the mandatory systems already in place in Europe, the number of waste PV modules is presently still rather small because most PV plants were built in the last 10 years and have not yet exceeded their lifetimes. Thus, there presently is little commercial interest in investing into PV-module recycling technologies because the waste streams are too small to justify it. Several pilot and commercial projects have been stopped or put on hold until the market increases (*e.g.,* FRELP 2016).

PV Materials

Some of the metals used in a module are precious or valuable, some are scarce, and some are toxic. Precious, scarce, and toxic materials are usually present in small quantities only, and might be replaced as substitutes are found that can reduce the price of modules and module environmental impact. Changes in module composition can affect the design of recycling systems, especially systems that achieve higher recovery fractions beyond the bulk materials, and also the value of the materials recovered from recycling modules. Thus, it will be important for the emerging module recycling market not only to be aware of changes in module composition but also to initiate discussions with manufacturers both for information exchange and to explore the potential for module design to consider ease of material recovery.

Summary of LCI Results

Respondent #1, Respondent #2, Respondent #3, and Respondent #4 use mechanical processes to separate the components of the PV modules. Depending on the efforts made and the equipment used, the yields and the energy consumption can vary. The downstream processes are similar: the glass and the metals recovered are further treated at downstream processors. The foil fraction is used for energy generation (i.e., incinerated) or landfilled, and the metal and solar-cell residues are not (yet) recovered. All of these companies process the modules in discrete batches within an existing recycling plant designed for a different commodity (glass or metals). The recovery rates vary between about 75 and 92% depending on the yields of the main targeted materials and the desired quality levels preset by the different recyclers (Figure 6).

Across the five respondents, electricity consumption of the recycling processes was reported to be in the range of 50 to 100 kWh per ton (t) of module input for the mechanical processes (Respondents #1, 3, 4 and 5) and 494 kWh/t for the metal recycler (Respondent #2), which uses fine milling of the material to increase glass and metal yields. For the demonstration-scale, dedicated PV recycling facility (Respondent #5), the electrical energy consumption was reported to be about 50 kWh/t for the mechanical processes plus about 76 kWh-equivalent of natural gas per ton of module input for the thermal and incineration processes. All respondents used some diesel fuel for front-end loaders although they did not always report the specific amount of fuel use, and where reported it was small.

The processes of laminated-glass recyclers—Respondent #1 and Respondent #3—are very similar, but differ slightly in yields of materials and energy consumption, as it could be expected from the process descriptions. Figure 6 compares the recycling outputs (given as percentages by weight of the input modules) of all respondents. Across all five respondents, the glass yields vary between 59% and 75%, where Respondent #1 had the lowest yield and Respondent #2 had the highest. Nonferrous metals (including Al of the frames) were recovered in the range of 13.5% to 21.8%; the higher end of this range is achievable through incineration of the foils followed by recovery of silicon and metals from the bottom ash, as was demonstrated by Respondent #5 using a dedicated module-recycling process.

Note especially that the foil fraction for the processes of Respondents #1, 2, 3 and 4 is essentially a fraction of materials that was so contaminated that the mechanical processes could not further separate and recover valuable materials, i.e., it is a mixed waste, although some precious metals such as silver are found in this fraction. For these respondents, this waste is either incinerated for (low grade) energy recovery or is landfilled.

Better results in the sense of a reduced impurity of the foil fraction can be achieved if greater efforts are made to separate the components, as can be seen in the results achieved by Respondent #2 and Respondent #5 using two different approaches. Respondent #2 uses a more intensive mechanical process to crush and mill the modules down to finer particles, as compared to Respondents #1, #3, and #4. Respondent #5 uses a thermal process in combination with mechanical to remove the polymers and thus can separate the other components to a higher level of purity. As can be expected, there is a tradeoff for greater materials recovery in the form of increased energy needs for these two processes, though there is likely room for further optimization as PV waste streams grow and more experience and experimentation is had.

The results clearly show that with improved technology a better yield and quality can be achieved by the improved and new processes. To encourage investments into new advanced processes and scale them up to a commercial level, a sufficient input stream is necessary. This can be expected to be established within the next 10 to 15 years in major PV markets based on the most recent forecast (IEA PVPS, 2016).

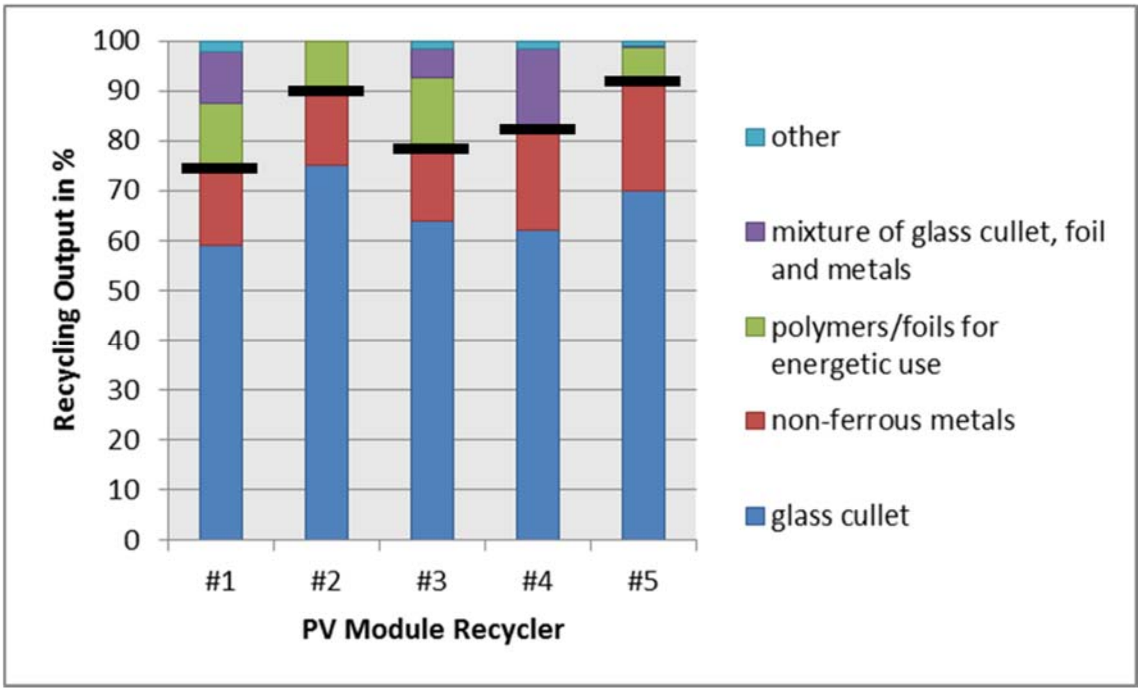

Figure 6. Fraction of recycling output (percent of total output mass) by material category for each of the five respondents. (Polymers are included in mixture for respondent #4.) The bold black lines indicate the total material recovery rate of the process.

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Appendix 1

Life-cycle inventory (LCI) questionnaire distributed to the recyclers.

Name		LCI of cryst. Si PV module recycling	
Time period		2015	
Geography		Europe, Germany	
Technology			
Representativeness		Individual real processes in discreet batches	
Date			
Collection method		Data from (name recycler or anonymized)	
Comment		Country Electricity mix	
Plant		1	comment/reference
capacity	t/yr		
Type of plant		Glass Recycling Plant	
Location		country	
time period		2015/16	
Modules processed			specify
total input	t/yr		
Components/fuels			
electricity consumption	kWh/t		
Diesel/oil consumption	l/t		
Output with examples			specify and indicate utilisation, subsequent treatment
cables	%		
junction boxes	%		
ferrous metals			
magnetic	%		
non-ferrous metals	%		
polymers/foils for energetic use	%		
glass cullet	%		
mixture of glass cullet, foil and metals	%		
other	%		
total output	%		

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