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Prospective material and substance flow analysis of the end-of-life phase of crystalline silicon-based PV modules

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Abstract

The approaching end-of life phase of early installed PV modules gave rise to a variety of potential end-of-life strategies, ranging from basic generic waste management strategies to advanced case-specific recycling options. However, no comprehensive assessment on the full range of technological possibilities is available and only limited attention was given to the material recovery rates of these different technologies in light of circular economy. In addition, current material recovery rates are indifferent towards the material value and the value of their secondary applications. Based on an extensive literature review, ten end-of-life scenarios with potential learning effects are identified and their material flows are quantified using a combined material and substance flow analysis. Subsequently, material recovery rates from a mass, economic value and embodied energy perspective are calculated, incorporating the differences in secondary applications. The differences in the mass-based recovery rates of the seven end-of-life scenarios that did not have landfill or municipal waste incineration as the main destination were minimal, as 73-79% of the mass was recovered for the best-case learning scenario. For the economic value recovery rate (9-66%) and the embodied energy recovery rate (18-45%), more profound differences were found. The collection rate was identified as most crucial parameter for all end-of-life scenarios, learning scenarios and recycling indicators. The mass-based recovery rate might favor end-of-life scenarios that lead to dissipation of valuable materials in non-functional secondary applications. Additional targets are required to avoid cascading of valuable materials and to avoid the economic cost and environmental burden of virgin materials.

Keywords: Circular economy; Material flow analysis; Recycling indicators; Cascadability; Photovoltaic panels; Learning effects

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1. Introduction

By 2050, 60-78 million tonnes of cumulative photovoltaic (PV) module waste is expected on a global level (IRENA and IEA-PVPS, 2016). PV modules can be classified in three generations depending on the material used and the level of technological maturity. The first-generation PV modules uses crystalline silicon as a semiconductor, both in a monocrystalline as well as in a multicrystalline form. The second-generation PV modules are based on thin film cells, including semiconductors made from amorphous silicon, cadmium telluride or copper indium gallium diselenide. Third-generation PV modules are still mostly in a development phase and include PV modules with organic semiconductor materials (Sampaio and González, 2017). As the first-generation has a market share of 95%, it will constitute a major part of the first end-of-life (EoL) PV modules (Fraunhofer Insititute for Solar Energy Systems ISE, 2021). The main components of a typical first-generation PV module are illustrated in Figure 1.

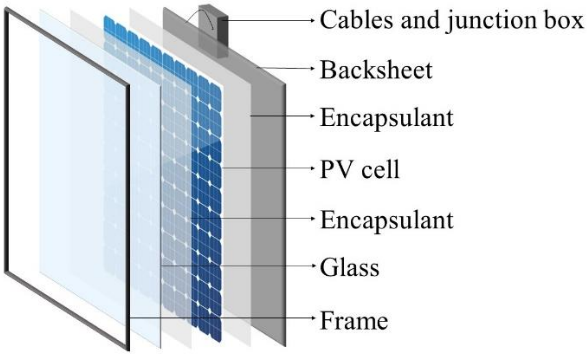

Figure 1. Components of a typical first generation PV module (Xu et al., 2018) *(single column)*

As only a limited number of PV modules has been recycled, the technology that will be used for the EoL phase remains uncertain and will be location and time dependent (Bracquene et al., 2018). Although the economic and environmental impacts of multiple EoL technologies have been assessed, most of these studies only focus on one or a few EoL possibilities, providing a fragmented perspective (e.g. Corcelli et al. (2017), Faircloth et al. (2019), Yu et al. (2017) and Athanailidis et al. (2018)). For a more comprehensive perspective, a broader range of possibilities needs to be included. This strategy was followed by Lunardi et al. (2018), who performed a life cycle assessment (LCA) for six EoL scenarios, including standard waste treatment options such as landfill and more advanced recycling technologies. They found that the advanced recycling technologies had a lower environmental impact. A more elaborated selection procedure was followed by Deng et al. (2019), who first performed an extensive review of EoL technologies and subsequently elaborated a techno-economic assessment (TEA). In this TEA, four mainstream EoL technologies were compared, being direct landfilling of the entire PV module, downcycling methods based on current glass recycling technologies, and two dedicated recycling methods based on mechanical and thermal recycling. The direct landfilling scenario was found to have the lowest net recycling cost, while the dedicated recycling methods had the highest costs. Similar to the study of Deng et al. (2019), this study will start from an extensive review of literature, but instead of selecting a limited set of technologies, a more comprehensive selection of potential EoL scenarios will be made wherein additional recovery processes are stepwise built in.

To assess these EoL scenarios, basic waste treatment technologies such as landfill and incineration will need to be compared with innovative recycling technologies. However, as these innovative technologies are still in a development phase, their mature configurations are unknown. Besides upscaling effects and further optimization of these processes, also learning effects will occur (van der Hulst et al., 2020). Learning effects are improvements in a specific practice when more experience in this practice is gained. These improvements can lead to cost or environmental impact reductions and should therefore be considered when comparing a new technology with a conventional technology (Caduff et al., 2012). To classify the maturity of a technology, technology readiness levels (TRL) can be used, ranging from the observation of basic principles at TRL0 to a commercial scale technology at TRL9 (Mankins, 2009). Although multiple studies have been found with comparisons of technologies on different TRLs, this issue was not further discussed or incorporated (i.e. Deng et al. (2019), Faircloth et al. (2019) and Zhang et al. (2017)). In the current study, learning effects will be included, following the guidelines of Thomassen et al. (2020).

The previously discussed studies focused mainly on the environmental impact and economic costs of the different processes. The material recovery rates of the specific processes were in general not studied in detail, leading to unspecified recovery rates (for example in the TEA of Deng et al. (2019), where references could be found to other studies but no overview of the used recovery rates was provided) or recovery rates of 100% (for example by Lunardi et al. (2018)). Although these studies provide important insights on economic and environmental considerations, most of the political targets in line with the Circular Economy action plan of the European Commission (2020a), focus on the quantification of recovered and recycled material streams. A study focusing on the material flows in different EoL scenarios has not been found in literature and this study aims to fill this gap.

To assess the material flows in the PV module EoL scenarios, a material flow analysis (MFA) can be used. An MFA is a systematic assessment of the material flows and stocks within a system, based on the law of conservation of matter (Brunner and Rechberger, 2004). MFAs have been used to assess the material flows from PV module waste in various regions, e.g. for Italy by Paiano (2015), for Mexico by Domínguez and Geyer (2017), for the USA by Domínguez and Geyer (2019), for Australia by Mahmoudi et al. (2019) and for India by Gautam et al. (2021). However, these studies do not specify the required recycling technologies, but assume perfect recycling or a combination of recycling rates from other technologies. As discussed by Mahmoudi et al. (2021), PV module waste can be classified in four levels, being products (e.g. crystalline-based silicon PV modules), components (e.g. frame, cell), materials (e.g. glass, metal) and substances (Ag, Si). While MFA assesses the material flows mostly on a product level, substance flow analysis (SFA) focusses on the material streams of the underlying substances, although the two terms are often used as synonyms (Brunner and Rechberger, 2004). To include both bulk recovery considerations and the economic and environmental properties of the individual substances, a combined MFA and SFA approach (M/SFA) was proposed to support decision making in waste management systems (Stanisavljevic and Brunner, 2014).

Based on this M/SFA, circular economy indicators can be calculated (Moraga et al., 2019). A Circular Economy monitoring framework was proposed by the European Commission to track the progress towards a circular economy, including ten indicators grouped into four stages (European Commission, 2018). These indicators are not only used to monitor progress, but also to formulate minimum requirements for different sectors. In practice, policy directives still use simple recycling rates. For example, the WEEE directive states that 80% of the PV module materials shall be prepared for re-use and recycled and 85% shall be recovered (European Parliament and Council, 2012). These indicators mostly focus on the quantity of material recovered, treating all materials the same without differentiating based on their economic and environmental importance. This way, small but important material fractions are overlooked as each material receives an equal weight when aggregating (Ardente et al., 2019; Nelen et al., 2014).

Instead of equal weights, the economic value can be used for aggregation into one recycling rate indicator (Di Maio et al., 2017). Linder et al. (2017) used this approach to introduce a product-level circularity metric, calculating the ratio of recirculated economic value to total product value. A similar metric that includes the environmental impact of the processes instead of the costs, is the circular economy performance indicator, introduced by Huysman et al. (2017). Although these metrics provide valuable information on the circularity of products, they are less useful for policy targets, as the required process cost and environmental impact calculations require detailed information that is often confidential and uncertain. The need for a simple metric has been advocated by Di Maio and Rem (2015), recommending that the indicator should be able to be calculated based on data from standard reports. The circular economy index as introduced by these authors calculates the ratio of material value produced by the recycler relative to the material value entering the recycling facility. A similar metric was used by Buechler et al. (2020) to quantify metal recovery. The only adaptation compared to the recycling rates used in the policy directives is the addition of material prices as weights. Therefore, this metric has been selected for the current study, extending it to incorporate the entire EoL phase instead of only the recycling facility. In addition to the economic value, also the embodied energy can be used as weighting factor to compare the different metrics and to include environmental considerations. The embodied energy represents the required energy that is needed to manufacture the component on the required purity level for PV module applications starting from virgin resources.

An additional flaw in the recycling rates used in policy directives is the disregard for the difference between closed-loop and open-loop recycling. In closed-loop recycling, the waste materials are recycled into the same products, while in open-loop recycling, the secondary application entails other kind of products (Nakatani, 2014). Without this differentiation, an unlikely one-to-one displacement of the secondary material for the primary material is envisioned (Zink et al., 2016). Open-loop recycling often entails downcycling where the material can be dispersed in non-functional applications, for example the use of metal containing ash in road infrastructure. This dissipation can lead to irreversible inaccessibility of valuable materials. The differentiation of the quality of the secondary application is typically not included in MFA, as MFA focusses primarily on quantity and not on quality (Dewulf et al., 2021). An exception was found in the MFA study of De Meester et al. (2019), where a differentiation was made between high-end secondary applications and low-end secondary applications, the latter typically replacing virgin construction materials. However, more than two secondary application levels can be identified. For example, besides the use in road construction, downcycling can also lead to the use of high-value materials in functional applications requiring a lower purity. This way, open-loop recycling can also be considered as cascading, where materials can be recycled to multiple cascading levels (Desing et al., 2021; Nakamura et al., 2014).

The main aim of this study is therefore to quantify the material recovery in the EoL phase of PV modules in light of the transition to a circular economy, considering not only the quantity but also the quality of material recovery according to a comprehensive approach. For this aim, the following novelties are introduced: 1) the M/SFA of an extensive range of PV module EoL scenarios consisting of different sets of treatment technologies; 2) the discussion of the learning effects for these PV module EoL technologies; 3) the analysis of recycling rates to include both the quality level of the second application and the different values of materials from a mass, economic and energy perspective.

2. Materials and methods

To provide a comprehensive overview of potential technologies and value-chains, an extensive literature review was performed, resulting in the definition of ten EoL scenarios. Subsequently, an M/SFA was conducted for each of these ten scenarios. The learning potential for all processes was discussed and quantified using multiple learning scenarios. As a last step, the recycling and recovery rates were assessed, both from a mass perspective and from an economic value and embodied energy perspective, differentiating between various secondary applications. As crystalline-silicon-based PV modules had the highest market share, this study will focus on this first generation (IRENA and IEA-PVPS, 2016).

2.1. Review of crystalline silicon PV recycling methods

To obtain a full overview of potential EoL technologies, both current practices and future practices were included by reviewing technical as well as economic and environmental assessments. This review resulted in 130 literature sources, encompassing in total 197 case studies. Key papers included Dias et al. (2017), Latunussa et al. (2016), Deng et al. (2019), Pagnanelli et al. (2017), Lunardi et al. (2018), Klugmann-Radziemska and Ostrowski (2010), Park et al. (2016), Duflou et al. (2018), Wambach (2017), Sander et al. (2007) and Farrell et al. (2020). A full overview can be found in Supplementary Information A. Resulting from the review, ten EoL scenarios were defined, summarized in Table 3 in Section 2.2. In each new EoL scenario, new processes are stepwise built in. In EoL scenario 1, the collected panels went directly to a landfill facility. In EoL scenario 2, the PV modules were first disassembled before going to a landfill, while in EoL scenario 3, the PV modules went to a municipal waste incineration after disassembly. In EoL scenario 4, the PV modules were shredded after disassembly and separated into different fractions. EoL scenarios 5-7 included an innovative delamination step after disassembly and shredding to separate the glass, semiconductor and PV cell itself. This delamination was based on a thermal, chemical and mechanical-thermal process for EoL scenarios 5-7, respectively. In EoL scenarios 8-10, the EoL scenarios 5-7 were extended with a dedicated metal recycling process to recover valuable materials such as silicon and silver.

2.2. M/SFA

All M/SFAs started from the same PV panel composition. This composition was classified in six components, consisting out of twelve materials or substances, that could be grouped in seven substance groups. To define a representative composition for the silicon photovoltaic panels, the information gathered in the literature review was used. The resulting representative composition is provided in Table 1.

Table 1. Representative composition of silicon PV modules (Latunussa et al., 2016; Peeters et al., 2017; Strachala et al., 2017)

Silicon photovoltaic component	Material/Substance	Substance group	Composition %(w/w)
Frame	Aluminum	Aluminum alloy	17.80
	Magnesium	Aluminium alloy	0.07
	Silicon	Aluminium alloy	0.13
Cables and junction box	Undefined polymer	Plastics	0.67
	Copper	Copper	0.33
Backsheet	PET/PVF	Plastics	1.50
Glass	Glass	Glass	70.00
Encapsulant	EVA	Plastics	5.10
Cell	Silver	Silver	0.22
	Aluminum	Aluminum	0.53
	Silicon	Silicon	3.34
	Copper	Copper	0.11
	Tin	Other non-ferrous metals	0.10
	Lead	Other non-ferrous metals	0.05
	Zinc	Other non-ferrous metals	0.05

PET: polyethylene terephthalate; PVF: polyvinyl fluoride (Tedlar); EVA: ethylene vinyl acetate

To differentiate between the quality of the secondary products, different cascading levels (CL) were introduced to classify the destinations of the different materials. As the difference between what can be considered high-end, medium-end and low-end is subjective, specific CLs should be defined if a further differentiation is desirable. The CLs as used in this study are explained in Table 2, with a specific example for the secondary application of glass. CL6 refers to the 'unknown destination' and is used if no data could be found on the destination of the materials, for example due to hoarding of the PV modules at home or due to illegal collection and reselling. The explanation of the CLs for the other materials can be found in Table A1.

Table 2. Definition and glass example for the different cascading levels as defined for this study.

	Cascading level	Secondary application of glass
CL0	Closed-loop recycling	Glass for PV modules
CL1	Open-loop recycling to high-end application	Bottle glass
CL2	Open-loop recycling to medium-end application	Glass for insulation material
CL3	Open-loop recycling to low-end application	Glass used as road construction material
CL4	Energy recovery	Not applicable
CL5	Lost in landfill	Glass in landfill
CL6	Unknown destination	Unknown destination

An overview of all processes and destinations considered in the different EoL scenarios is provided in Table 3. A detailed description of the different scenarios, including all used data for all analyses can be found in Supplementary Information B. The mass balances were calculated based on primary data received from PV Cycle, the organization responsible for the EoL of PV modules in Flanders (Belgium), current recycling facilities and literature.

Table 3. Included processes and destinations in the ten EoL scenarios (the underlined processes are not yet at TRL 9)

EoL scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Processes										
Collection	x	x	x	x	x	x	x	x	x	x
Disassembly		x	x	x	x	x	x	x	x	x
Aluminium smelter		x	x	x	x	x	x	x	x	x
Cable separation		x	x	x	x	x	x	x	x	x
Plastic recycling		x	x	x	x	x	x	x	x	x
Copper smelter		x	x	x	x	x	x	x	x	x
Incineration of plastic from the cables		x	x	x	x	x	x	x	x	x
Bottom ash treatment		x	x	x	x	x	x			
Incineration of the PV cell			x							
Generic shredder				x						
Further processing non-ferrous fraction				x						
Glass recycling to glass foam				x						
Incineration of the waste from glass recycling				x	x	x	x	x	x	x
Shredder specific for PV panel applications					x	x		x	x	
Hot knife (mechanical delamination)							x			x
Glass recycling to bottle glass					x	x	x	x	x	x
Glass recycling to solar glass					x		x	x		x
Thermal delamination					x		x	x		x

Chemical delamination						x			x	
Dedicated metal recovery								x	x	x
Secondary material application or destination										
Landfill (CL5)	x	x	x	x	x	x	x	x	x	x
Unknown destination (CL6)	x	x	x	x	x	x	x	x	x	x
Aluminium, metallurgical grade (CL0)		x	x	x	x	x	x	x	x	x
Copper, metallurgical grade (CL0)		x	x	x	x	x	x	x	x	x
Plastics (CL1)		x	x	x	x	x	x	x	x	x
Construction materials (CL3)		x	x	x	x	x	x	x	x	x
Emissions with energy recovery (CL4)		x	x	x	x	x	x	x	x	x
Glass for insulation material (CL2)				x						
Glass for PV modules (CL0)					x	x	x	x	x	x
Bottle glass (CL1)					x		x	x		x
Silicon, metallurgical grade (CL0)								x	x	x
Silver, metallurgical grade (CL0)								x	x	x

The main differences between the ten EoL scenarios according to these CLs are provided in Table A2. For the different EoL scenarios, also learning effect ranges were included. According to the guidelines published by Thomassen et al. (2020), these learning effects should be estimated by combining the extrapolation of historical effects and expert estimates. However, the technologies included in the EoL scenarios are either mature technologies from other industries, e.g. copper smelting, or novel technologies that are still in the development stage. The mature technologies were assumed to be at the end of their learning path. Therefore, no learning effects were included for these technologies. The innovative processes are not on the market yet or have only been on the market for a very short time, resulting in a lack of historical data that could be extrapolated. To include the learning effect of these technologies, expert estimates, combined with literature estimates and proxy data from similar processes were therefore used to calculate a maximum achievable value (MAV). However, as concluded from the expert consultations, most values reported in literature were already based on the theoretically MAV. Therefore, these reported values have been considered as the maximum learning scenarios and lower values have been included in the assessment to correct for the expected lower values in the first years of commercialization. This led to four learning scenarios (L1-L4) for the material yields in the various new processes as discussed in more detail in Appendix B. For all EoL and learning scenarios, corresponding Sankey diagrams were constructed using the e!Sankey software (iPoint, 2021).

2.3. Recycling and recovery rates

Based on the M/SFAs, recycling and recovery rates were calculated for each of the EoL scenarios and each of the learning scenarios, covering the mass recovery, economic value recovery and embodied energy recovery. Figure 2 illustrates the composition of a PV module from a material, economic value and embodied energy perspective. To quantify the embodied energy, the cumulative energy demand of the virgin materials was used.

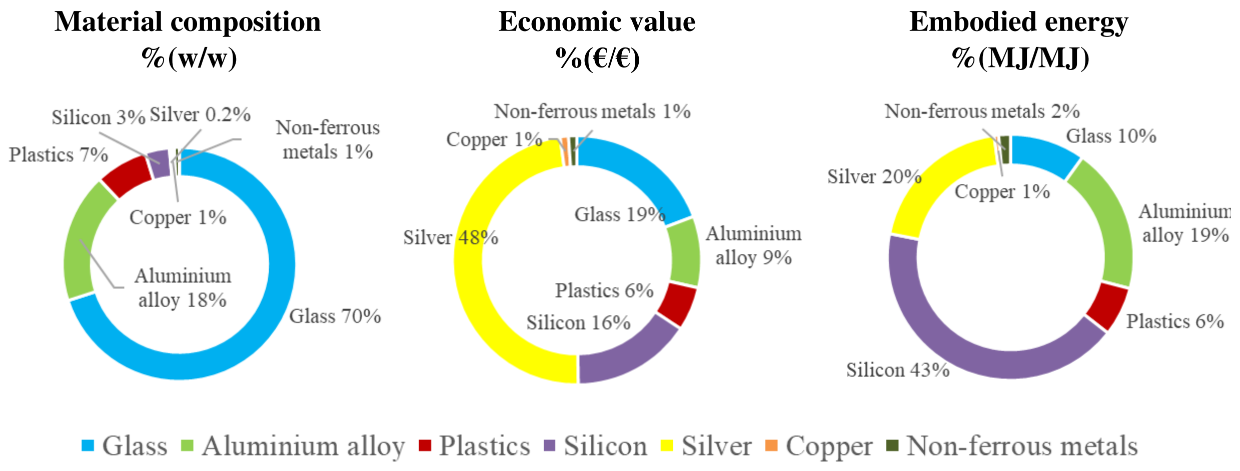

Figure 2. Composition of crystalline silicon-based PV modules *(2-column)*

2.3.1. Mass-based recovery rate

The mass-based recovery rate (Equation 1) calculates the mass of recovered materials compared to the initial mass in the waste PV modules. The metric is expressed in % and can be calculated for each of the substance flows, for each of the CLs, for each of the EoL scenarios and for each of the learning scenarios. The overall recycling rate as often used in policies, is based on the mass-based recovery rate$_{CL0\text{-}3}$, without differentiation amongst the CLs or substance flows. The mass-based recovery rate can also include energy recovery (CL4). To calculate the mass-based recovery rates, the results from the M/SFA were used.

$$Mass\text{-}based\ recovery\ rate_{i,j,CL0-k} = \frac{\sum_{m=0}^{k}\sum_{l=1}^{7} M_{i,j,l,m}}{\sum_{l=1}^{7} M_{l,waste\ solar\ panels}},$$

$$\forall\, i \in EoL, j \in LS, k \in CL, l \in SF, m \in \{0-k\}, \qquad (1)$$

with EoL= set of ten end-of-life scenarios, indexed by i; LS= set of four learning scenarios, indexed by j; SF= set of seven substance flows, indexed by l; CL=set of five cascading levels, indexed by k; $M_{i,j,l,k}$ = the recovered mass of substance flow l at cascading level k in end-of-life scenario i at learning scenario j [tonne]; $M_{l,\text{ waste PV modules}}$ the mass of substance flow l in the waste PV modules [tonne].

2.3.2. Economic value recovery rate

Besides recovering the mass of the materials, also the economic value of the materials can be recovered. The economic value recovery rate (Equation 2), based on the circular economy index (Di Maio and Rem, 2015), calculates the recovered economic value of the materials relative to the potential maximum recoverable economic value expressed in %. While equation 2 illustrates the economic value recovery rate of the sum of the substance flows, this metric can also be calculated for the individual substance flows. To calculate the economic value recovery rate, the results from the M/SFA were supplemented with economic prices for all materials at all CLs.

$$Economic\ Value\ Recovery\ Rate_{i,j,CL0-k} = \frac{\sum_{m=0}^{k}\sum_{l=1}^{7}(M_{i,j,l,m} * EV_{l,m})}{\sum_{l=1}^{7}(M_{l,waste\ solar\ panels} * EV_{l,k=0})},$$

$$\forall\, i \in EoL, j \in LS, k \in CL, l \in SF, m \in \{0-k\}, \qquad (2)$$

with EoL= set of ten end-of-life scenarios, indexed by i; LS= set of four learning scenarios, indexed by j; SF=set of seven substance flows, indexed by l; CL=set of five cascading levels, indexed by k; $M_{i,j,l,k}$ = the recovered mass of substance flow l at cascading level k in end-of-life scenario i at learning scenario j [tonne]; $M_{l,\ \text{waste PV modules}}$ the mass of substance flow l in the waste PV modules [tonne]; $EV_{l,k}$ = the economic value of substance flow l at cascade level k [€ per tonne].

2.3.3. Embodied energy recovery rate

Equation 3 illustrates the embodied energy recovery rate for EoL scenario i and learning scenario j. Similar as for the previously introduced recovery rates, the embodied energy recovery rate can also be calculated for the individual substance flows. To calculate the embodied energy recovery rate, the results from the M/SFA were supplemented with the embodied energy values for all materials at all CLs, following the avoided burden approach.

$$Emdobied\ Energy\ Recovery\ Rate_{i,j,CL0-k} = \frac{\sum_{m=0}^{k}\sum_{l=1}^{7} M_{i,j,l,m} * EE_{l,m}}{\sum_{l=1}^{7} M_{l,waste\ solar\ panels} * EE_{l,k=0}},$$

$$\forall\ i \in EoL, j \in LS, k \in CL, l \in SF, m \in \{0-k\} \qquad (3)$$

with EoL= set of ten end-of-life scenarios, indexed by i; LS= set of four learning scenarios, indexed by j; SF=set of seven substance flows, indexed by l; CL=set of five cascading levels, indexed by k; $M_{i,j,l,k}$ = the recovered mass of substance flow l at cascading level k in end-of-life scenario i at learning scenario j [tonne]; $M_{l,\ \text{waste PV modules}}$ the mass of substance flow l in the waste PV modules [tonne]; $EE_{l,k}$ = the embodied energy of substance flow l at cascade level k [MJ per tonne].

2.4. Sensitivity analysis of all scenarios

A sensitivity analysis was conducted for each of the different learning and EoL scenarios. In this sensitivity analysis, the most influencing parameters were defined for each of the following indicators: mass-based recovery rate$_{CL0}$, mass-based recovery rate$_{CL0-1,}$ mass-based recovery rate$_{CL0-2,}$ mass-based recovery rate$_{CL0-3,}$ economic value recovery rate$_{CL0-4,}$ embodied energy recovery rate$_{CL0-4}$. By including six indicators for ten EoL scenarios and four learning scenarios, in total 240 sensitivity analyses were conducted. Each of these sensitivity analyses was conducted with the Crystal Ball software from Oracle. For each of the mass yields included in the model, a triangular distribution between -10% and +10% was selected. This distribution was chosen to enable an identical variation on all mass yields and has been selected before for similar sensitivity analyses (Thomassen et al., 2019; Van Dael et al., 2013). All analyses were conducted using 10.000 iterations.

3. Results and discussion

3.1. M/SFA

The M/SFAs of the ten EoL scenarios in the best-case learning scenario (L4) are illustrated in Figure 3 (and Figure S1 in Supplementary Information C). The M/SFAs of the other learning scenarios can be found in Appendix C, together with the other results of these learning scenarios. The color of the recovered materials indicates their CL, ranging from light grey (CL0) to black (CL>4). As the main component, glass dominates the Sankey diagrams, although its destination differs. The recycling path of the aluminium alloy to CL0 is also clearly visible.

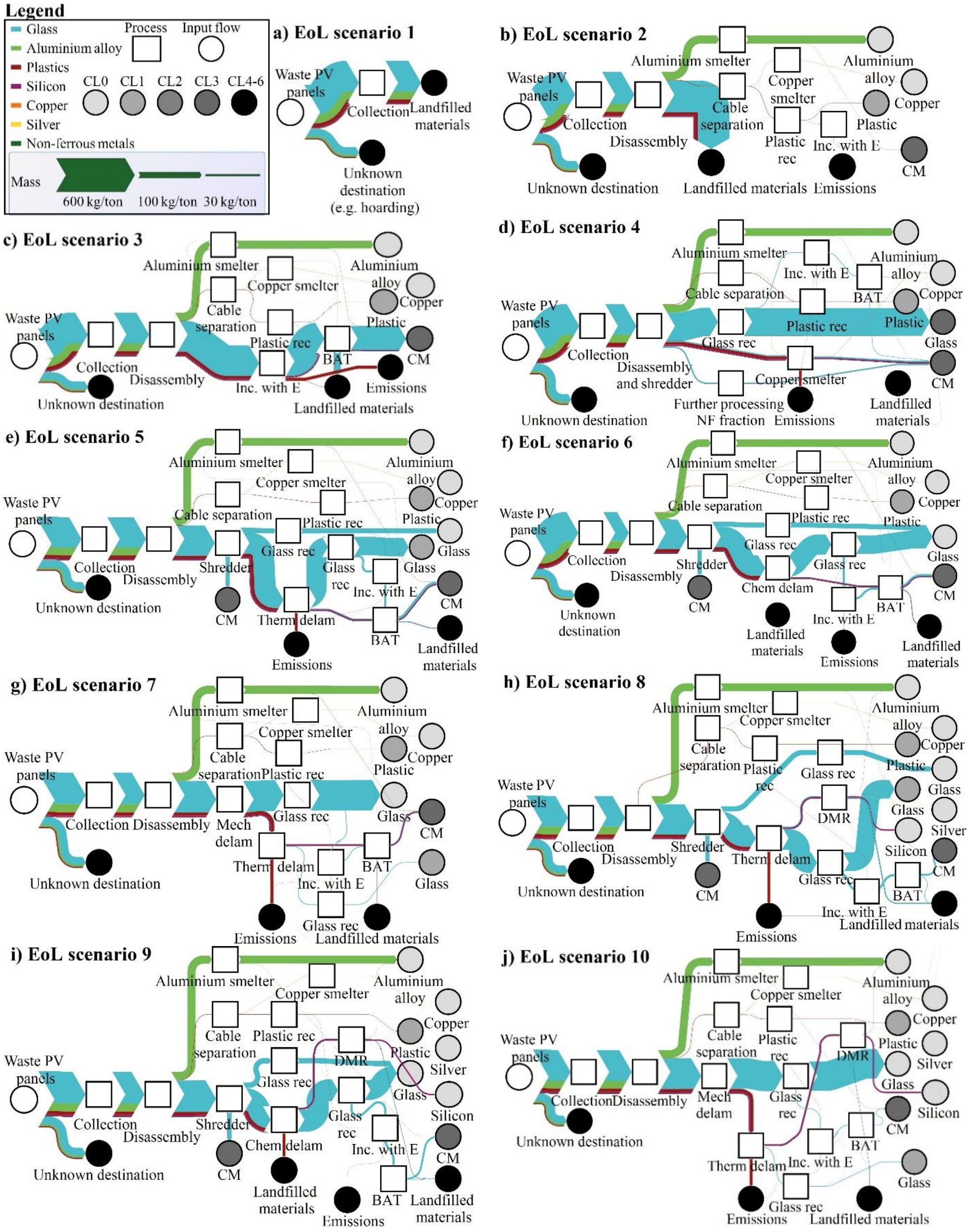

Figure 3. M/SFAs of different EoL scenarios for the best-case learning scenario (L4) (DMR: dedicated metal recycling; Inc. with E: Incineration with energy recovery; BAT: bottom ash treatment; CM: construction materials; Mech: Mechanical; Therm: Thermal; Chem: Chemical; Delam: Delamination; Rec: Recycling) *(2-column)*

3.2. Recycling and recovery rate

3.2.1. Mass-based recovery rate

Figure 4 illustrates the mass-based recovery rate$_{CL0-4}$ for the various EoL scenarios in L4. The difference between the mass-based recovery rate$_{CL0-4}$ for EoL scenario 3-10 is small (ranging between 67-79%), if no further material or CL considerations are included. Although 67% of the mass is recovered in EoL scenario 3, 46% goes to low-value applications (CL3). In the more advanced EoL scenarios, more mass is recovered in CL1 and CL0, with a maximum mass-based recovery rate$_{CL0}$ of 68% in EoL scenario 10. As the metals in the solar cell itself only constitute a small mass fraction, their recovery has a minor influence on the mass-based recovery rate$_{CL0-4}$. This results in only small differences between EoL scenario 5 and 8, 6 and 9, and 7 and 10. To calculate if the recovery and recycling or reuse targets are met (80%/85%), the losses due to non-collection and the losses in the recycling facilities (smelter, glass recycling) could be excluded (European Commission, 2019). This way, EoL scenario 3 meets the recovery target and EoL scenarios 4-10 meet both targets (Figure C5).

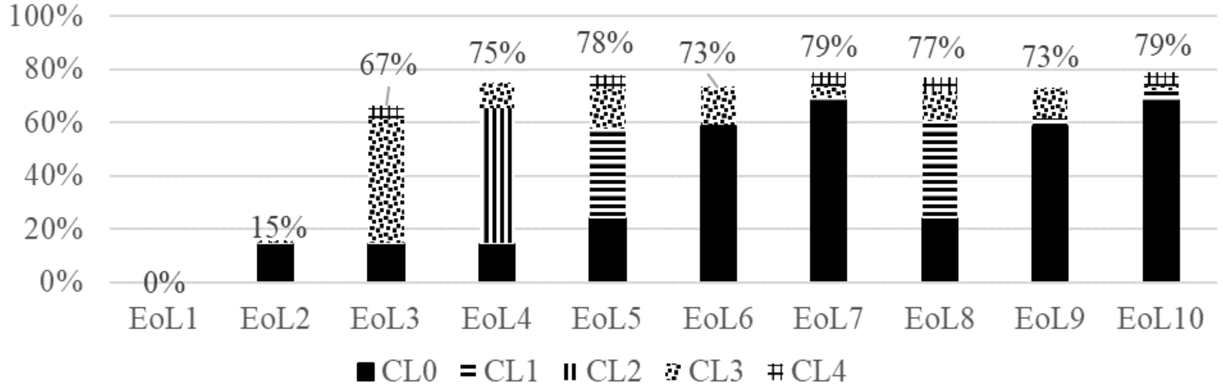

Figure 4. Mass-based recovery rate$_{CL0-4}$ for total mass in L4 (numbers indicate mass-based recovery rate$_{CL0-4}$) *(2-column)*

In Figure 5, the various learning scenarios and substance flows are illustrated. Glass is already recovered in EoL scenario 3, however, only at low quality (CL3). In EoL scenario 4, the main glass recovery occurs at CL2, while for EoL scenario 5 and 8, this occurs at CL1. In EoL scenarios 6,7,9 and 10, glass is mainly recovered at CL0. Aluminium is recovered to a similar extent in EoL scenarios 2-10. Although EoL scenarios 3 and 4 are based on current practices and have therefore fewer learning opportunities, the total difference between the mass-based recovery rate$_{CL0-4}$ for the various learning scenarios is similar compared to the EoL scenarios 5-10. The mass-based recovery rate$_{CL0-4}$ of learning scenario 4 for EoL scenarios 3-10 is 58-70% higher than the mass-based recovery rate$_{CL0-4}$ for learning scenario 1. In EoL scenario 2, the difference was less pronounced.

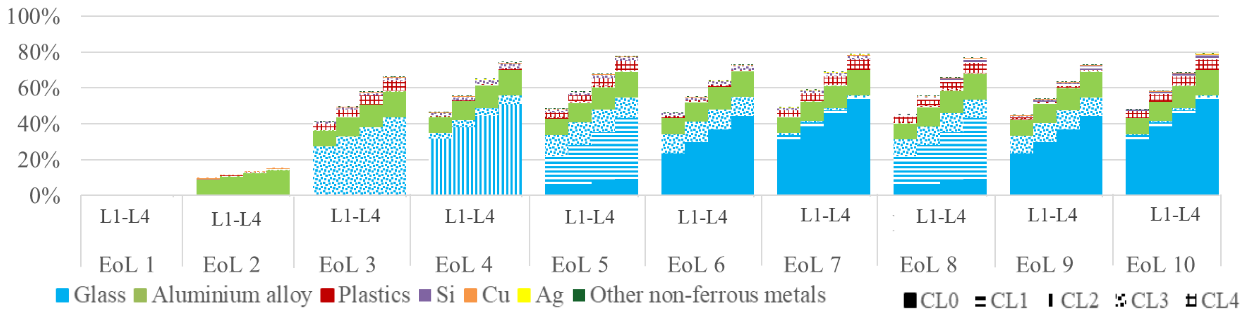

Figure 5. Mass-based recovery rate$_{CL0\text{-}4}$ of the ten EoL scenarios, including various substance flows (L1-4=learning scenario 1-4; EoL 1-10= EoL scenario 1-10; CL0-4=Cascading levels 0-4) *(2-column)*

3.2.2. Economic value recovery rate

While for EoL scenario 3-10 for the last three learning scenarios at least half of the total mass is recovered, half of the economic value is only recovered in learning scenario 4 of EoL scenario 8-10 and learning scenario 3 of EoL scenario 10 (Figure 6). The economic value recovery rate$_{CL0\text{-}4}$ of EoL scenarios 8-10 (52-66% in L4) is also much higher than for the less advanced EoL scenarios (0-23% in L4). This can be explained by the high economic value of silver, which is only recovered in these last three EoL scenarios. The four learning scenarios indicate the large uncertainty on the last three end-of-life scenarios compared to the earlier EoL scenarios, where the difference between the learning scenarios is smaller. The differences between the learning scenarios for EoL scenarios 8-10 are much larger compared to the differences identified for the mass-based recovery rate$_{CL0\text{-}4}$. This can be explained by the included lower TRL technologies in EoL scenario 8-10, which focus on the recovery of higher value substance flows, such as silver.

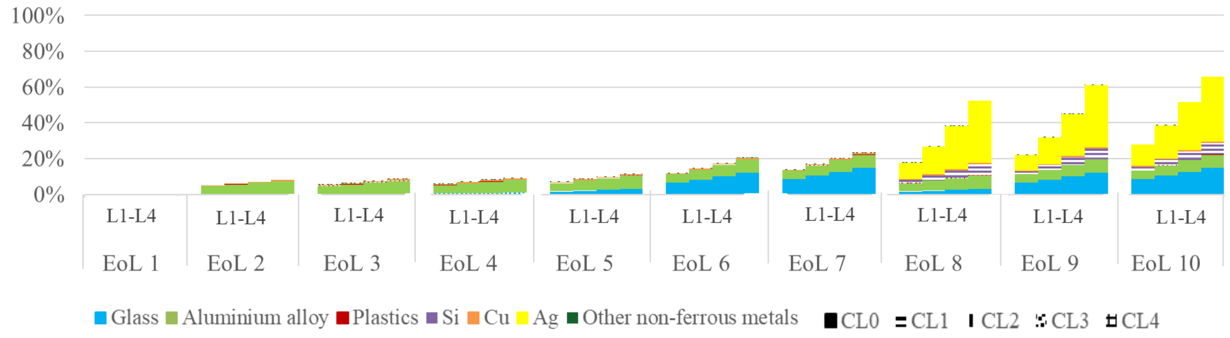

Figure 6. Economic value recovery rate$_{CL0\text{-}4}$ of the ten EoL scenarios, including various substance flows *(2-column)*

3.2.3. Embodied energy recovery rate

None of the defined EoL scenarios in the various learning scenario exceeds an embodied energy recovery rate$_{CL0\text{-}4}$ of 50% (Figure 7). However, the differences in the embodied energy recovery rate$_{CL0\text{-}4}$ are smaller than for the economic value recovery rate$_{CL0\text{-}4}$. Similar as for the economic value, most of the embodied energy is recovered in closed-loop recycling (CL0). The smaller difference between the EoL scenarios can be explained by the large amount of embodied energy in aluminium that is mainly present in the frame. As the frame is already recycled in EoL scenario 2, the additional gain in more advanced EoL scenarios is smaller. The incineration and thermal delamination of the plastic fraction also induces a recovery in embodied energy, which does not occur in EoL scenario 6 and EoL scenario 9 that include only chemical delamination. In EoL scenarios 8-10, where also the metals in the cell are recycled, an additional recovery of embodied energy due to the potential closed-loop recycling of silver is obtained.

As the aluminium recovery plays a vital role for the embodied energy recovery rate$_{CL0\text{-}4}$, the differences between the results of the various learning rate scenarios are less profound than for the economic value recovery rate$_{CL0\text{-}4}$, leading to an improvement of 60-130% of the embodied energy recovery rate$_{CL0\text{-}4}$ for learning scenario 4 in comparison to the embodied energy recovery rate$_{CL0\text{-}4}$ for learning scenario 1.

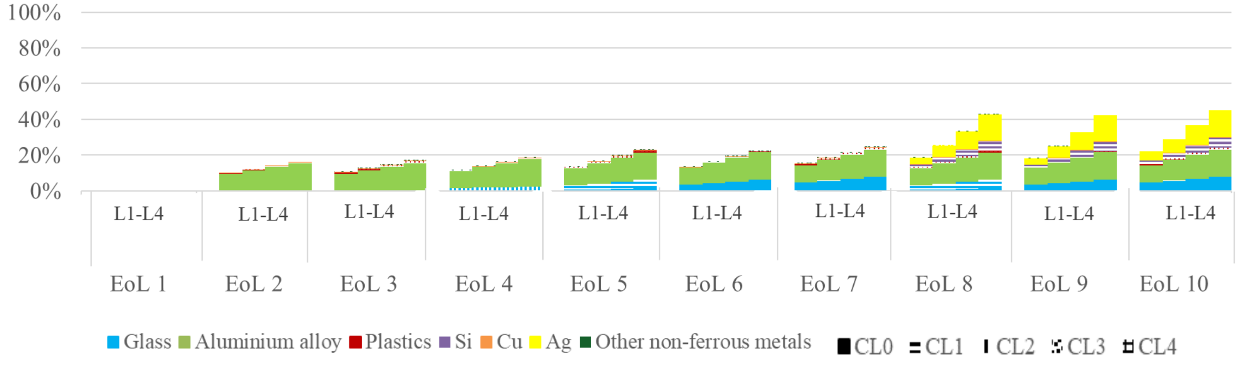

Figure 7. Embodied energy recovery rate$_{CL0\text{-}4}$ of the ten EoL scenarios, including various material categories *(2-column)*

3.3. Sensitivity analysis of all the scenarios

The results of the sensitivity analysis for the best-case learning scenario are provided in Figure 8, including all parameters that have an influence of more than 10% on the variance of the indicators. The collection rate is the most influencing parameter for all indicators and all EoL scenarios. A rate of 50 and 80% in the worst-case and best-case learning scenario, respectively, was assumed. If the worst-case learning scenario would have included this 80% collection rate, all recovery rates for all scenarios would have improved with 60%.

A second important parameter is the mass yield of aluminium in the aluminium smelter. As aluminium is an important component in mass, economic value and embodied energy, this parameter also influences all indicators. A third group of parameters that has a high influence are the glass recovery rates for the various processes. The silver recovery in the dedicated metal recycling process, and the processes before aiming to maximize the fraction ending up in the dedicated metal recovery have only a high influence on the economic value recovery rate$_{CL0\text{-}4}$. The embodied energy recovery rate$_{CL0\text{-}4}$ is mainly influenced by the aluminium recovery, which can only be improved by improving the collection rate and minimizing the amount of aluminium that ends up as unrecovered slag. This also explains why only two parameters have an influence of more than 10% on the variance of the embodied energy recovery rate$_{CL0\text{-}4}$. The higher number of parameters with an impact of more than 10% on the variance of the economic value recovery rate$_{CL0\text{-}4}$ can be explained by the larger number of processes prior to the silver recovery process. In addition, also the parameters influencing glass CL0 recovery are much more important for the economic value recovery rate$_{CL0\text{-}4}$ then for the embodied energy recovery rate$_{CL0\text{-}4}$.

The sensitivity analysis illustrates that the chosen indicator has a large effect on which parameters are identified as important. This means that depending on what the target is, different improvement processes will receive priority. In addition, also the learning assumptions influence which parameters have a large influence.

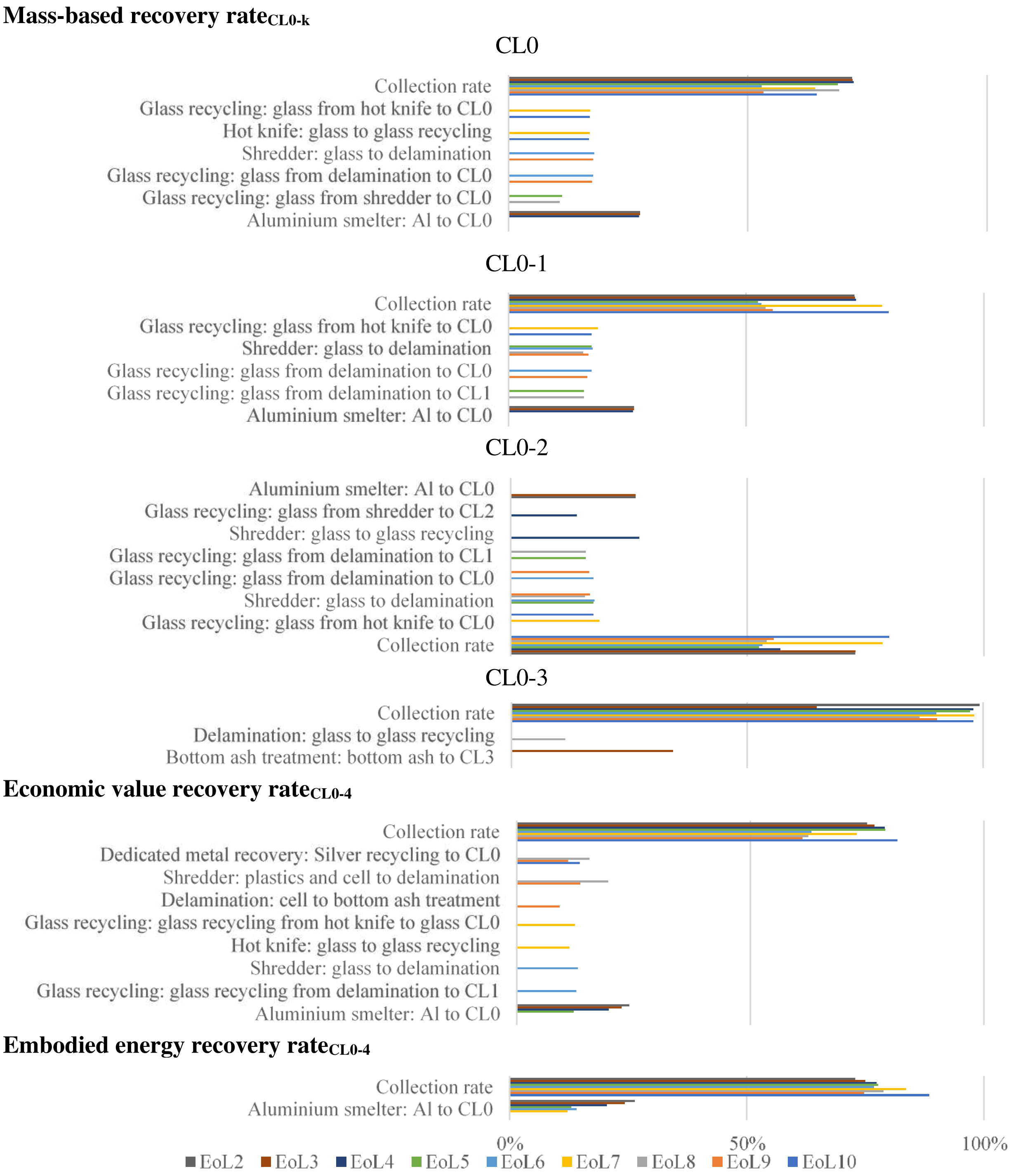

Figure 8. Sensitivity analysis results for the different recovery rates in the best-case learning scenario (the percentages indicate the influence of a change in the parameter on the variance of the indicator; a negative percentage indicates that an increase in the parameter leads to a decrease in the indicator) *(2-column)*

3.4. Limitations and recommendations

Due to the large number of technologies, the selected EoL scenarios cannot provide an exhaustive overview. For example, electric delamination methods were excluded as the differences between these technologies and the included delamination technologies were assumed to be small (Song et al., 2020). For a more extensive discussion on the technical challenges and opportunities and research priorities of current recycling technologies, Farrell et al. (2020) and Heath et al. (2020) can be consulted.

The M/SFA requires the specification of the material composition of the waste stream. However, this is time dependent (Peeters et al., 2017). Labels stating the exact material content of the installed PV modules would help taking this variability into account (Norgren et al., 2020).

By adding the process-specific cost and energy requirements, the net recovered economic value and embodied energy can be calculated for all EoL scenarios. As this would require a detailed TEA and LCA of all the included processes, reporting these targets would be data intensive. As the current study focused on the material perspective, this was considered out of scope. Nevertheless, multiple studies focusing on LCA and TEA studies are available and can be consulted for this purpose (e.g. Deng et al. (2019), Faircloth et al. (2019) and Lunardi et al. (2018)). In addition, this study has mainly focused on recycling and recovery. Other circular economy strategies such as reuse, repair and remanufacturing have been excluded, but can also play a major role (Deng et al., 2020). For example, Tao et al. (2020) found higher revenues for PV module component reuse compared to material extraction from these modules. Although the M/SFA in this study focused on a specific technology, it can also be used to study the material flows on a regional or system level. This way, also other circular strategies could be visualized in Sankey diagrams. Additional circularity indicators could be useful to assess these strategies. For example, the in-use occupation of materials indicators as introduced by Moraga et al. (2021) quantifies the maintenance of the materials in a useful state in products, covering multiple product lifetimes.

The PV module collection rate is identified as the most important parameter. As it depends on the location, data from the region of Flanders was used. In Flanders, the collection of PV modules is arranged by PV Cycle, who has setup 58 collection spots in the region. In addition, PV modules can be picked up by request. The collection in other regions is often organized in a different way. In Germany, the government has initiated public collection points for private PV modules and additionally, business-to-business e-waste compliance schemes have been set up. In the USA, the only specific PV EoL regulation was found in Washington, where a stewardship and takeback program is required (Washington State Legislature, 2020). In Japan, China and India (other important PV module waste producing countries according to IRENA and IEA-PVPS (2016)) currently no specific regulations for the EoL of PV modules exist yet (Heath et al., 2020). A more extended discussion on the PV module EoL management systems in these countries can be found in IRENA and IEA-PVPS (2016), Heath et al. (2020) and Majewski et al. (2021).

The economic value recovery rate$_{\mathrm{CL0\text{-}4}}$ was based on market prices. However, prices are volatile, which means that the economic value recovery rate$_{\mathrm{CL0\text{-}4}}$ can vary on a daily basis. Although this complicates comparison, this does mirror economic reality as market and demand influences the importance of the different materials. To facilitate comparisons, transparency on the used prices (and overall data) is crucial.

The cascading levels indicate the highest potential CL, however, additional purity processes can always lead to a higher CL**.** In this case, additional raw material might be required to dilute impurities or dedicated additional purity processes may lead to additional material losses. The defined CLs are therefore specific for each case and can change when the system boundaries of the M/SFA change.

3.5. Policy implications

The M/SFA approach enables the identification of data gaps and can provide important recommendations for monitoring and policy purposes. In practice, the recycling rate is often measured at the entrance of a recycling plant, without a full overview of the value chain. M/SFAs are therefore recommended as a standard method for monitoring policy targets as they require a full inventory of material flows.

Policy directives, such as the WEEE directive (European Parliament and Council, 2012) and the directive on packaging and packaging waste (European Parliament and Council, 2018), state the mass-based recovery rates as major targets to boost the circular economy. However, when this indicator is used to compare basic waste management technologies such as incineration with more innovative recycling schemes, only limited improvement can be made by the innovative technologies. If all forms of material recovery, including non-functional recovery as construction materials, are treated equally, no incentive is provided to further develop technologies focusing on material recovery to high-value applications. This could be observed from the similar mass-based recovery rates$_{\mathrm{CL0\text{-}3}}$ of EoL scenario 4 and 10. However, the advantage of these innovative technologies becomes clear when the recycling rate only includes the higher value-applications (mass-based recovery rate$_{\mathrm{CL0\text{-}1}}$), or alternatively, when the economic value recovery rate$_{\mathrm{CL0\text{-}4}}$ or embodied energy recovery rate$_{\mathrm{CL0\text{-}4}}$ is used for comparisons. Besides the quantity, also the quality of recycling is important. In the Circular Economy action plan of the European Commission (2020a), the need for high-quality recycling is stated, however, how this high-quality is defined is not further elaborated. The use of CLs as proposed in this study could enable the differentiation between different quality levels of recycling, avoiding downcycling of materials, which can lead to the inaccessibility of materials for further functional applications (Dewulf et al., 2021).

Besides the quantity and the secondary application of the material, also the sort of material is important. The mass-based recovery rates were dominated by glass recycling as glass constitutes the highest fraction of a PV panel. Other materials such as precious metals (silver) or critical raw materials as defined by the European Commission (2020b) (silicon) constitute a limited fraction of the total mass. Efforts to improve their material specific recycling rate did not have an important impact on the mass-based recovery rates. Therefore, specific targets for these material groups may be required to promote their recycling to higher cascading levels. For the classification of other material groups, the categorization of raw materials as provided by Dewulf et al. (2015) can be used. In the economic value recovery rate$_{\mathrm{CL0\text{-}4}}$ and the embodied energy recovery rate$_{\mathrm{CL0\text{-}4}}$, the various materials are weighted according to their economic value and embodied energy. In addition, these two indicators also account for the different CLs, as in CL3, the replaced virgin materials will have a lower economic value and embodied energy than in CL0. Recovering materials with a high economic value and embodied energy is crucial as the avoided economic cost and environmental burden of not having to supply the virgin materials is high. The embodied energy serves here as a proxy for a broader environmental impact, a correlation which has been previously identified by Huijbregts et al. (2010).

Currently, the term ‘recycling’ covers almost all cascading levels, which can lead to very high recycling rates (e.g. 93.5% (PV Cycle, 2021)). This is a much higher value than the values found by the current study. Multiple explanations exist, being differing system boundaries, where for example the collection step is excluded, the inclusion of processes that are not yet operating on a commercial level and the inclusion of all forms of secondary applications. The differences in how these recycling rates are calculated makes it impossible to compare various numbers from various studies. To enable a more specific definition of what the recycling target should include, also a stricter monitoring is required to make the required data available. In addition, standards, such as the under development ISO TC 323, could be useful to harmonize circularity calculations (Perissinotti Bisoni et al., 2020). Ideally, the definitions and the monitoring are internationally agreed, and implemented and maintained by public policy bodies.

The transition to renewable energy is an important condition to tackle environment problems such as climate change (Edenhofer et al., 2012). However, this increased use of renewable energy leads to an additional material demand, which can have detrimental effect on the environment as well. The transition to renewable energy and the transition to a circular economy are therefore inherently linked (Carrara et al., 2020). Recycling PV modules is an important step to limit the loss and additional demand of materials, which is required to sustain these transitions on a long term.

The transition to a circular economy does also contribute to the sustainable development goals (SDGs), although no specific SDG for ‘circular economy’ exists (UN General Assembly, 2015). As discussed by Farrell et al. (2020), ten out of the seventeen SDG could be targeted when improving the recycling of PV modules, making it a very relevant topic on a global level.

4. Conclusions

As currently only limited amounts of PV module waste are available, only basic waste management technologies are applied. More specific technologies are under development, but have not yet reached TRL 9. To encourage the recycling of PV modules, targets have been introduced. However, the recycling rates used by these targets are not able to distinguish between the difference in value of the recycled materials and the difference in the secondary application. In this study, these differences have been analyzed, illustrating a clear advantage of more innovative recycling technologies, but also indicating the insufficiency of the current targets to promote these innovative recycling technologies. While current recycling processes focus on recovering the bulk glass fraction, smaller but more valuable fractions such as silver and silicon are not recovered. Although the technologies for this recovery are available, the right incentives are still lacking. A more specific definition of ‘recycling rates’ could assist in providing these incentives. In general, the main parameter influencing the recovery of materials from PV modules is the collection rate. Therefore, it is crucial to get a clear view on what happens with PV modules after their useful lifetime. This monitoring is also crucial for the other recycling steps to enable a more harmonized way of assessing recycling processes.

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Appendix A: Cascading levels for the different materials

Table A1. Cascading levels for the different materials (N/A: not applicable; N/I: not included)

	CL0	CL1	CL2	CL3	CL4	CL5	CL6
Glass	PV modules	Bottle glass	Insulation material	Road construction	N/A	Landfill	Unknown
Silicon	PV modules	Metallurgical grade	N/I	Road construction	N/A	Landfill	Unknown
Aluminium alloy	PV modules	N/I	N/I	Road construction	N/A	Landfill	Unknown
Copper	PV modules	N/I	N/I	Road construction	N/A	Landfill	Unknown
Plastics	PV modules	Mixed plastics	N/I	Road construction	Energy	Landfill	Unknown
Silver	PV modules	N/I	N/I	Road construction	N/A	Landfill	Unknown
Other non-ferrous metals	PV modules	N/I	N/I	Road construction	N/A	Landfill	Unknown

Table A2. The main differences between the ten EoL scenarios (CL1,5 indicates that a part of the material flow is recovered in CL1 and the other part is recovered in CL5; The CLs in bold indicate a major change compared to the previous EoL scenario)

EoL scenario	Glass	Frame and cables (metals)	Frame and cables (plastics)	Backsheet and encapsulant	Cell (Ag)	Cell (Si)	Cell (Cu)	Cell (Al)	Cell (Other metals)
1	CL5	CL5	CL5	CL5	CL5	CL5	CL5	CL5	CL5
2	CL5	**CL0**	**CL1,5**	CL5	CL5	CL5	CL5	CL5	CL5
3	CL5	CL0	CL1,5	**CL4**	**CL3**	**CL3**	**CL0,3**	**CL3**	**CL3**
4	**CL2,3**	CL0	CL1,5	CL4	CL3	CL3	CL0,3	CL3	CL3
5	**CL1**	CL0	CL1,5	CL4	CL3	CL3	CL0,3	CL3	CL3
6	**CL0**	CL0	CL1,5	CL5	CL3	CL3	CL0,3	CL3	CL3
7	CL0	CL0	CL1,5	**CL4**	CL3	CL3	CL0,3	CL3	CL3
8	CL1	CL0	CL1,5	CL4	**CL0,3**	**CL1,3**	**CL0,3**	**CL0,3**	**CL3**
9	**CL0**	CL0	CL1,5	CL5	CL0,3	CL1,3	CL0,3	CL0,3	CL3
10	CL0	CL0	CL1,5	**CL4**	CL0,3	CL1,3	CL0,3	CL0,3	CL3

Appendix B: Learning effect assumptions

Table B1. Learning rate assumptions material yields in four learning scenarios (%)

Process	Parameter	L1*	L2*	L3*	L4*
Collection	Collection rate	50.00	60.00	70.00	80.00
Shredder (EoL 5,6,8,9)	Glass to glass recycling	15.00	15.67	16.33	17.00
	Glass to delamination	62.00	64.67	67.33	70.00
	Glass to construction materials	23.00	19.67	16.33	13.00
	Cell fraction to delamination	77.00	83.33	89.67	96.00
	Cell fraction to construction materials	23.00	16.67	10.33	4.00
Hot knife	Glass fraction to glass recycling	90.00	92.67	95.33	98.00
	Glass fraction to delamination	10.00	7.33	4.67	2.00
	EVA fraction glass recycling	10.00	6.67	3.33	0.00
	EVA fraction to delamination	90.00	93.33	96.67	100.00
Thermal delamination	Glass to glass recycling	85.00	88.67	92.33	96.00
	Glass to metal recovery	15.00	11.33	7.67	4.00
Chemical delamination	Cell fraction to glass recovery	0.50	0.37	0.23	0.10
	Cell fraction to metal recovery	94.50	96.13	97.77	99.40
	Cell fraction to landfill	5.00	3.50	2.00	0.50
	Plastics to metal recovery	10.00	6.67	3.33	0.00
	Plastics to landfill	90.00	93.33	96.67	100.00
	Glass to glass recycling	94.50	96.03	97.47	98.90
	Glass to metal recovery	5.00	3.67	2.33	1.00
	Glass to landfill	0.50	0.37	0.23	0.10
Dedicated metal recovery	Copper recovery	50.00	65.00	80.00	95.00
	Copper to landfill	50.00	35.00	20.00	5.00
	Silicon recovery	50.00	65.00	80.00	95.00
	Silicon to landfill	50.00	35.00	20.00	5.00
	Silver recovery	50.00	65.00	80.00	95.00
	Silver to landfill	50.00	35.00	20.00	5.00

*0: worst-case; -: lower intermediate case; -+: higher intermediate case; += best-case

For the collection rate, a best-case assumption of 80% was assumed, based on discussions with PV Cycle. For the worst-case learning scenario, a collection rate of 50% was used, similar to the 51.4% collection rate of electric and electronic appliances in Flanders in 2019 (BeWEEE, 2021). The shredder process, which was based on the work of Pagnanelli et al. (2017), was varied according to the different experimental results reported in the mass balances. For the glass separation yield in the hot knife process (mechanical delamination), the 98% yield assumed by Latunussa et al. (2016) and Ardente et al. (2019) was used. After personal communication with the authors, this yield was identified as the best-case value. As no worst-case value was available, a loss of 10% leading to a yield of 90% was assumed, similar to the yield in the glass recycling process itself. This loss could for example be induced by broken glass. The hot knife scrapes the encapsulant layer from the glass layer. In the best-case scenario, 100% of the encapsulant is removed. As concluded by the experimental results in the study of Terryn (2018), the encapsulant is able to reach the required temperature to enable processing 150 panels per hour and could thus be removed completely. In the worst-case, only 90% of the encapsulant is removed.

The data for the thermal delamination process were based on the work of Pagnanelli et al. (2019) where the different reported results for the glass yield were used as best-case and worst-case. It was assumed that this process did not allow for improvement possibilities to reduce the 0.5% of metals ending up in the glass fraction. To enable a fair comparison between the thermal and chemical delamination, also the assumptions from the chemical delamination process were based on the study of Pagnanelli et al. (2019). As they reported that the metal fraction in the glass was five times lower after chemical delamination compared to thermal delamination, 0.1% of the metal fraction was assumed to end up in the glass fraction. This was assumed to be the best-case. In the worst-case, the same assumption, being 0.5%, as for the thermal delamination was used. After the chemical delamination, the plastic fraction is landfilled. This fraction is assumed not to contain any metals in the best-case learning scenario. In the worst-case learning scenario, 5% of the metals is assumed to be lost in this landfilled fraction.

The chemical delamination assumes that the glass fraction does not contain any plastic anymore. In the best-case scenario, all the plastic is landfilled. However, in the worst-case scenario, the plastic and cell fraction (including the metals) are not separated in an efficient way and 10% of the plastics ends up in the metal fraction. This 10% was selected as it is preferable that plastic ends up in the metal fraction compared to metal ending up in the plastic fraction and thus being landfilled. For the glass fraction, 98.9% of the glass is recovered, following the mass balances from Pagnanelli et al. (2019). The glass fraction ending up with the metal fraction constitutes 1% of the total glass fraction, while 0.1% of the glass ends up in the plastic fraction. In the worst-case scenario, a fivefold higher loss was included for both parameters, similar as for the assumption of 0.5% cell fraction lost in the glass fraction.

For the dedicated chemical metal recovery, a recovery of 95% was assumed for copper, silver and silicon and a recovery of 50% was assumed for aluminium, based on the work of Latunussa et al. (2016) and Ardente et al. (2019). This was categorized as the best-case assumptions after communication with the authors. As a worst-case assumption, a recovery of 50% was used for copper, silver and silicon as well. For all parameters, intermediate values were selected for the intermediate scenarios.

Appendix C: Additional results

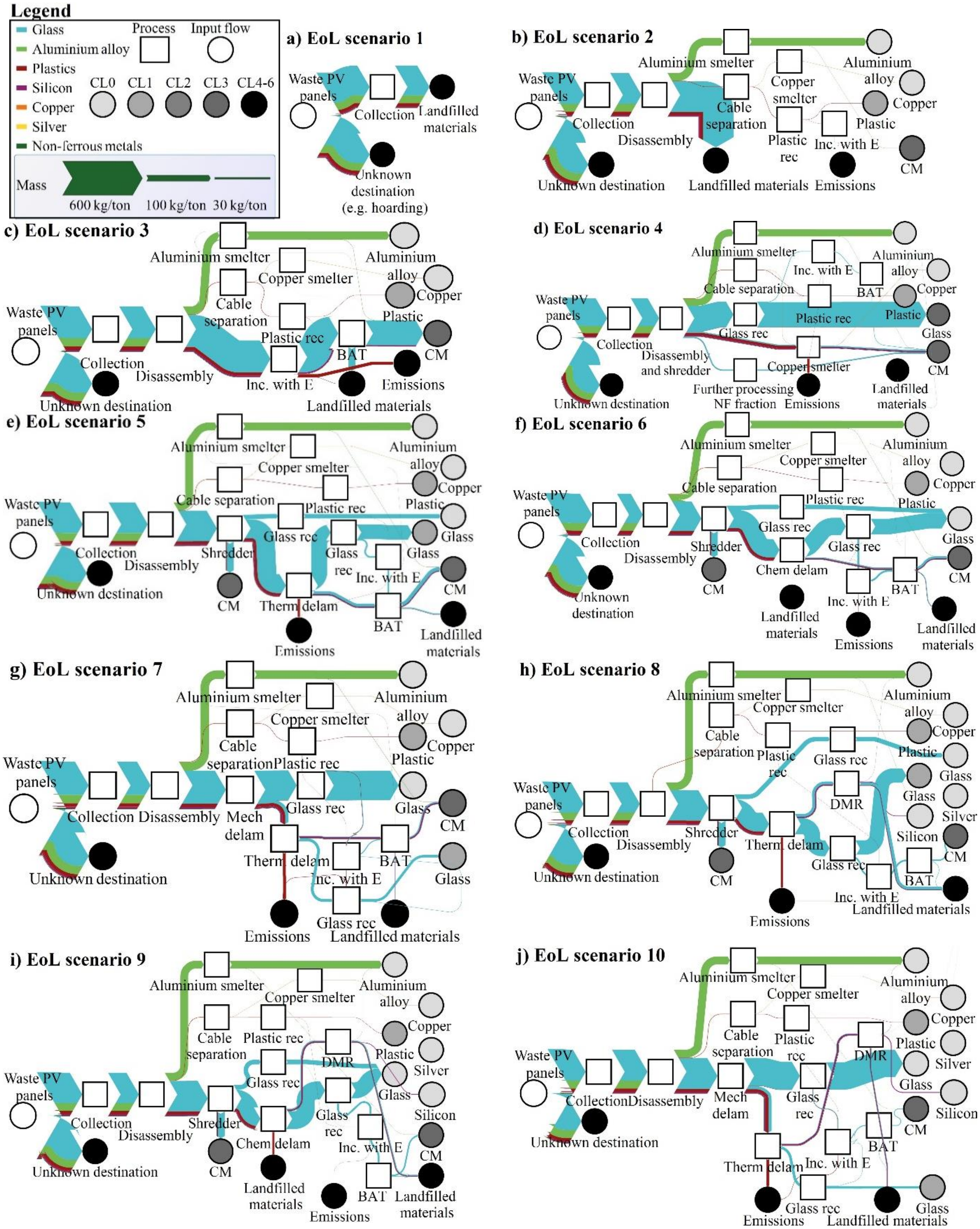


Figure C1. M/SFAs of different EoL scenarios for learning scenario (L1) (DMR: dedicated metal recycling; Inc. with E: Incineration with energy recovery; BAT: bottom ash treatment; CM: construction materials; Mech: Mechanical; Therm: Thermal; Chem: Chemical; Delam: Delamination; Rec: Recycling)

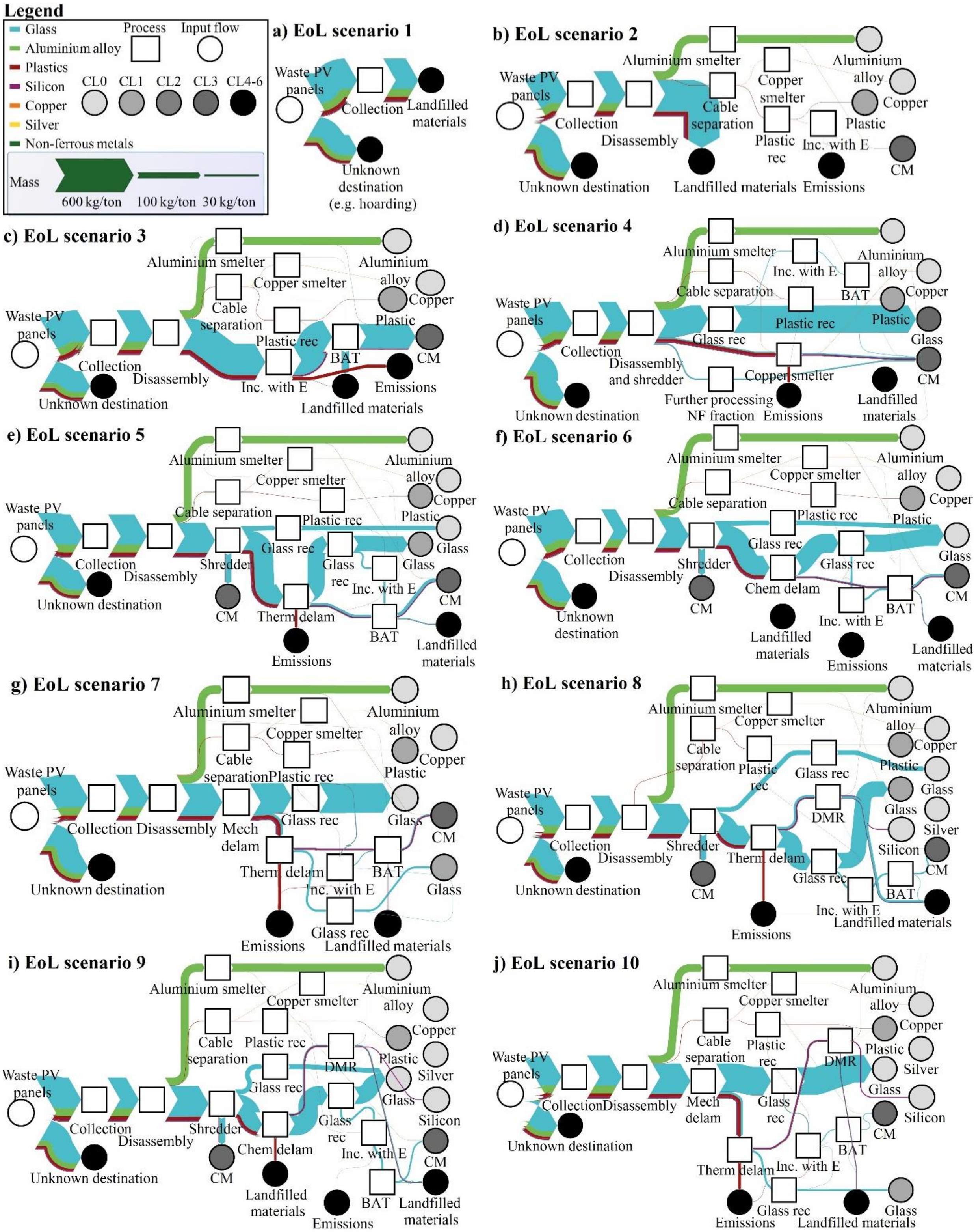


Figure C2. M/SFAs of different EoL scenarios for learning scenario (L2) (DMR: dedicated metal recycling; Inc. with E: Incineration with energy recovery; BAT: bottom ash treatment; CM: construction materials; Mech: Mechanical; Therm: Thermal; Chem: Chemical; Delam: Delamination; Rec: Recycling)

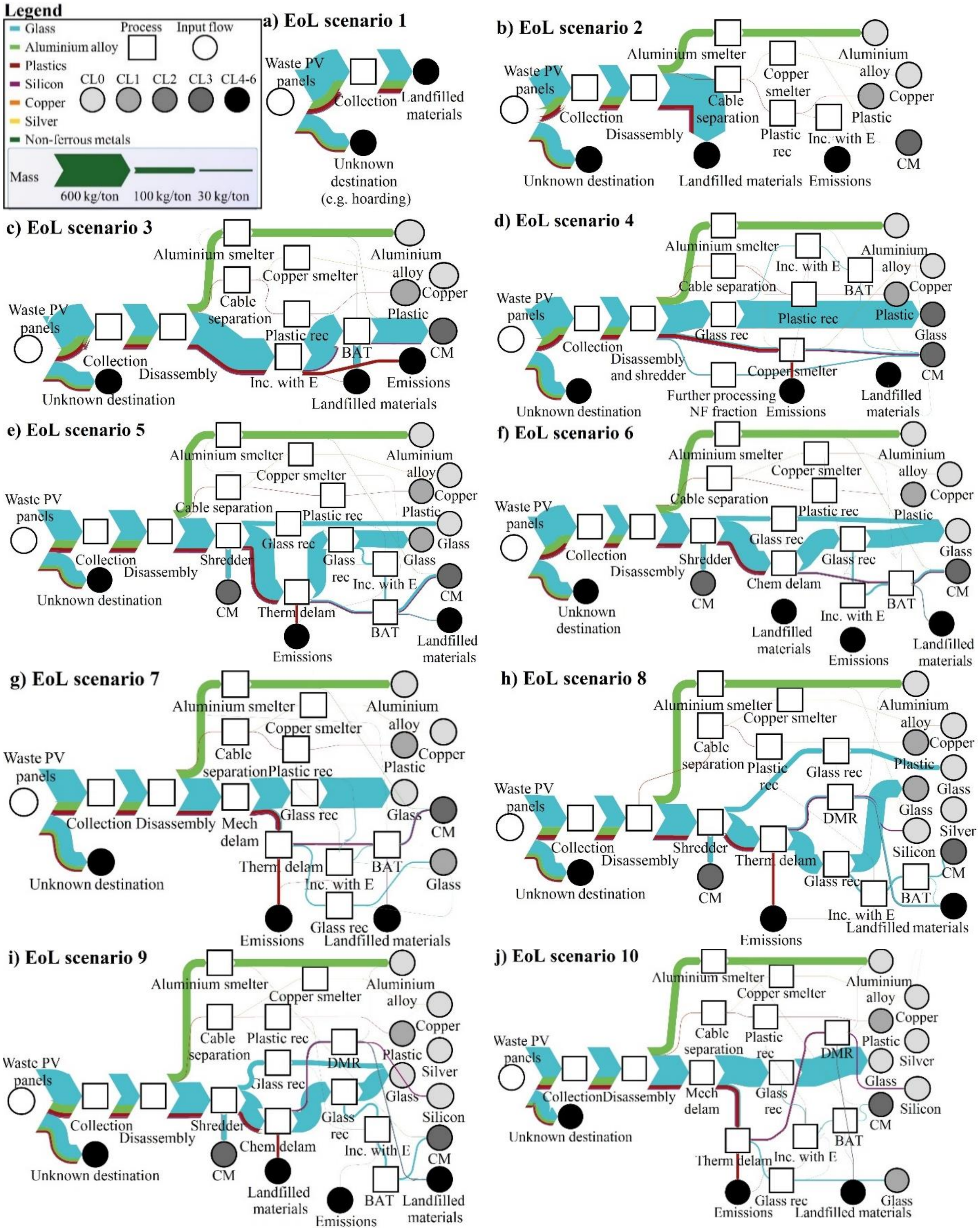


Figure C3. M/SFAs of different EoL scenarios for learning scenario (L3) (DMR: dedicated metal recycling; Inc. with E: Incineration with energy recovery; BAT: bottom ash treatment; CM: construction materials; Mech: Mechanical; Therm: Thermal; Chem: Chemical; Delam: Delamination; Rec: Recycling)

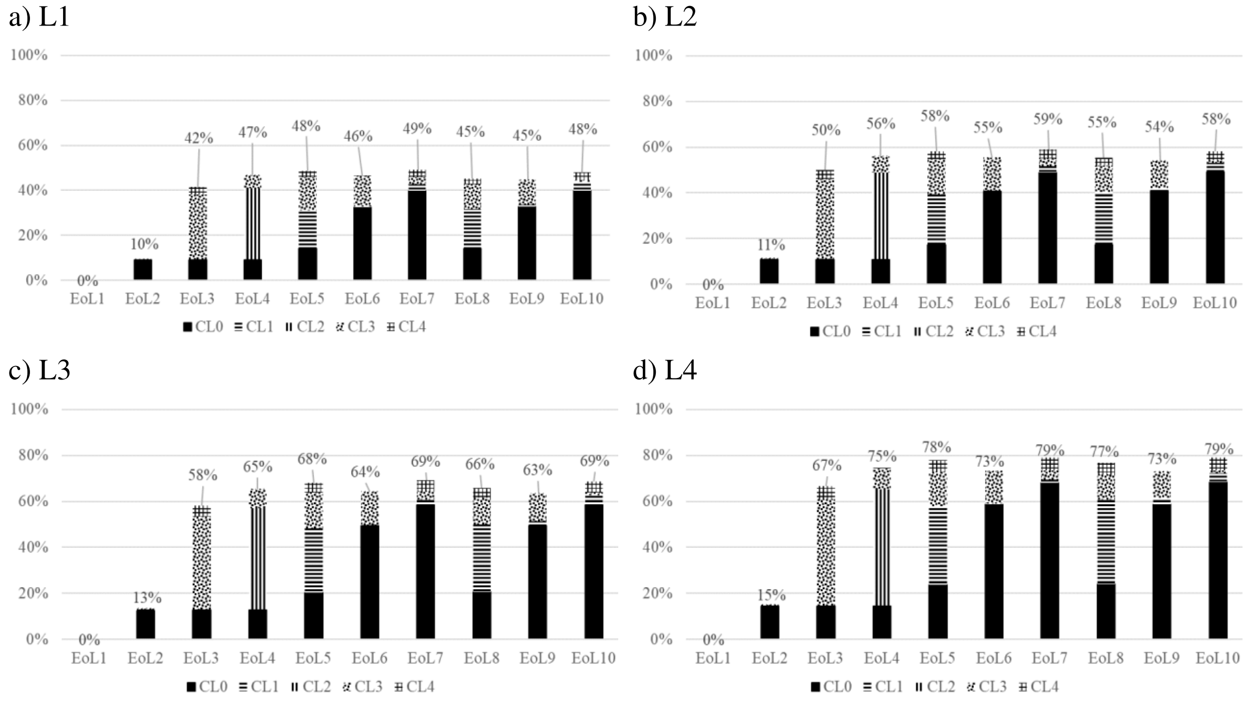


Figure C4. Mass-based recovery rate for total mass at the different CLs in L1-4 (number indicates mass-based recovery rate$_{0\text{-}4}$)

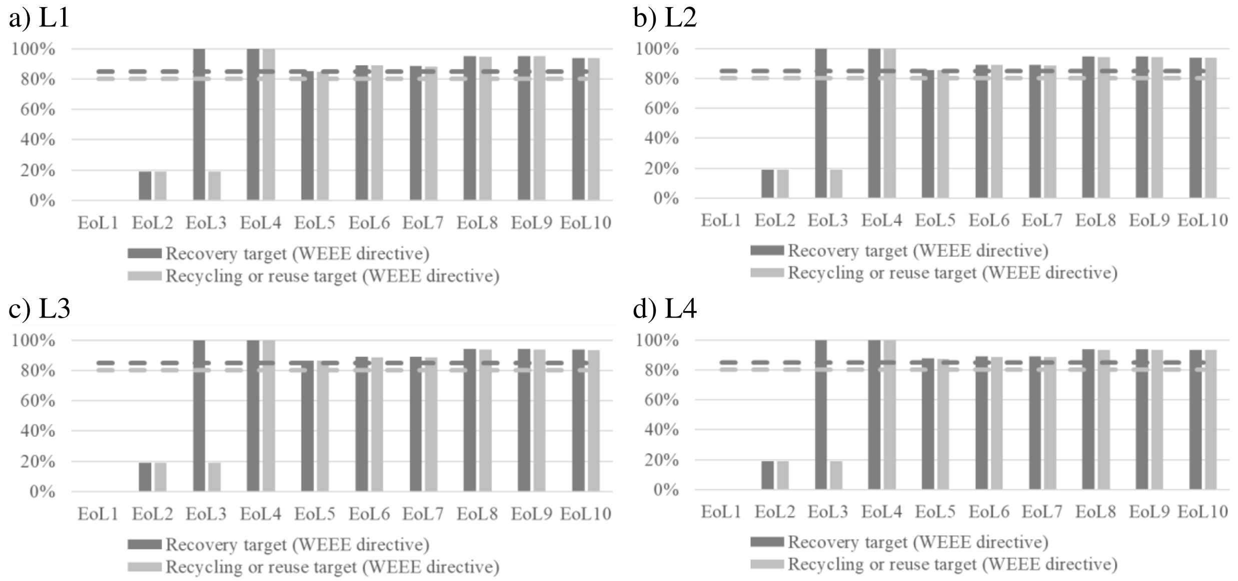


Figure C5. Recycling and reuse targets of the WEEE directive for L1-4

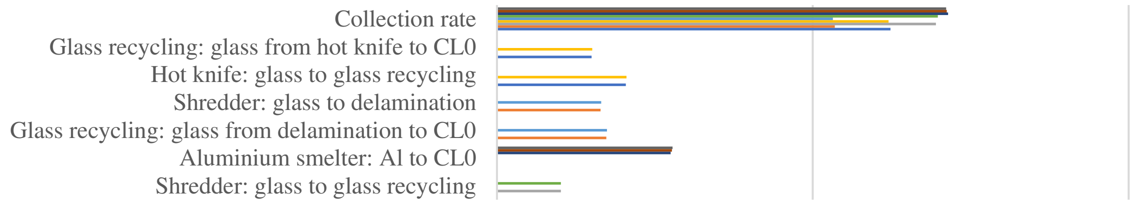
Table C1. Mass-based recovery rates per material in learning scenario 1-4

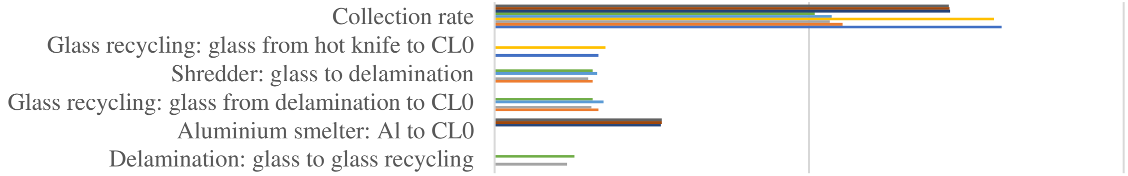
L1	CL	EoL1	EoL2	EoL3	EoL4	EoL5	EoL6	EoL7	EoL8	EoL9	EoL10
Glass	0	0	0	0	0	7	34	44	7	34	44
	0-1	0	0	0	0	31	34	48	31	34	48
	0-2	0	0	0	45	31	34	48	31	34	48

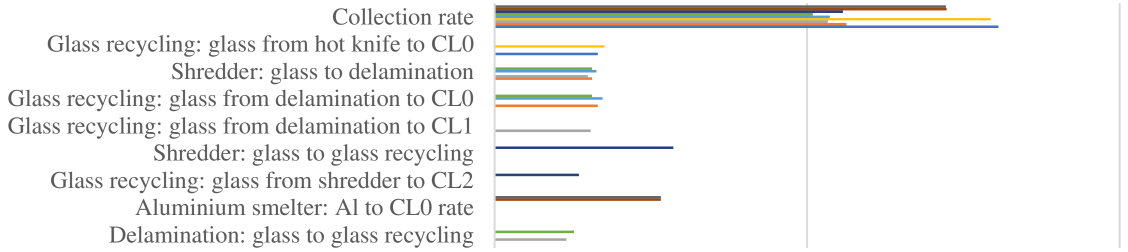
	0-3	0	0	39	50	48	49	50	45	48	49
Aluminium alloy	0-0	0	49	49	49	49	49	49	49	49	49
	0-3	0	50	50	50	50	50	50	50	50	50
Plastics	0-1	0	3	3	3	3	3	3	3	3	3
	0-3	0	3	3	5	14	16	3	14	14	3
	0-4	0	5	50	6	50	18	50	50	15	50
Silicon	0-1	0	0	0	0	0	0	0	19	18	25
	0-3	0	0	33	48	42	40	39	31	30	25
Copper	0	0	35	37	47	37	37	38	40	40	42
	0-3	0	37	46	49	48	48	48	45	45	44
Silver	0	0	0	0	0	0	0	0	19	18	25
	0-3	0	0	34	48	42	40	40	31	30	25
NF metals	0-3	0	0	35	48	43	42	41	12	12	0
L2	CL	EoL1	EoL2	EoL3	EoL4	EoL5	EoL6	EoL7	EoL8	EoL9	EoL10
Glass	0	0	0	0	0	9	43	54	9	43	54
	0-1	0	0	0	0	40	43	58	40	43	58
	0-2	0	0	0	54	40	43	58	40	43	58
	0-3	0	0	47	60	58	59	60	55	58	59
Aluminium alloy	0-0	0	59	59	59	59	59	59	59	59	59
	0-3	0	60	60	60	60	60	60	60	60	60
Plastics	0-1	0	4	4	4	4	4	4	4	4	4
	0-3	0	4	4	6	13	15	4	13	13	4
	0-4	0	6	60	8	60	17	60	60	15	60
Silicon	0-1	0	0	0	0	0	0	0	32	31	39
	0-3	0	0	40	58	49	48	47	43	41	39
Copper	0	0	42	45	56	45	45	45	51	50	52
	0-3	0	45	55	59	58	57	57	56	55	55
Silver	0	0	0	0	0	0	0	0	32	31	39
	0-3	0	0	40	58	50	48	47	43	41	39
NF metals	0-3	0	0	42	58	51	50	50	10	10	0
L3	CL	EoL1	EoL2	EoL3	EoL4	EoL5	EoL6	EoL7	EoL8	EoL9	EoL10
Glass	0	0	0	0	0	11	52	65	11	52	65
	0-1	0	0	0	0	50	52	68	50	52	68
	0-2	0	0	0	63	50	52	68	50	52	68
	0-3	0	0	55	70	68	69	70	65	68	69
Aluminium alloy	0-0	0	69	69	69	69	69	69	69	69	69
	0-3	0	70	70	70	70	70	70	70	70	70
Plastics	0-1	0	5	5	5	5	5	5	5	5	5
	0-3	0	5	5	7	11	13	5	11	11	5
	0-4	0	6	70	9	70	14	70	70	13	70
Silicon	0-1	0	0	0	0	0	0	0	50	49	56
	0-3	0	0	46	67	56	55	55	57	56	56
Copper	0	0	49	52	66	52	52	53	62	62	64
	0-3	0	52	65	69	67	67	67	67	67	66
Silver	0	0	0	0	0	0	0	0	50	49	56
	0-3	0	0	47	67	57	56	55	57	56	56
NF metals	0-3	0	0	49	67	59	58	58	7	7	0
L4	CL	EoL1	EoL2	EoL3	EoL4	EoL5	EoL6	EoL7	EoL8	EoL9	EoL10
Glass	0	0	0	0	0	13	63	77	13	63	77

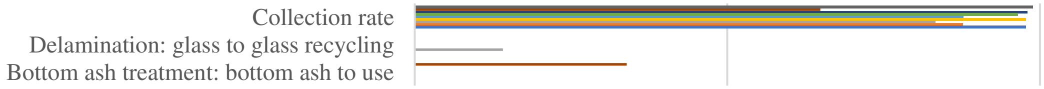
	0-1	0	0	0	0	62	63	78	62	63	78
	0-2	0	0	0	72	62	63	78	62	63	78
	0-3	0	0	62	80	78	79	80	77	78	80
Aluminium alloy	0-0	0	79	79	79	79	79	79	79	79	79
	0-3	0	80	80	80	80	80	80	80	80	80
Plastics	0-1	0	5	5	5	5	5	5	5	5	5
	0-3	0	5	5	8	8	8	5	8	8	5
	0-4	0	7	80	10	80	10	80	80	10	80
Silicon	0-1	0	0	0	0	0	0	0	73	73	76
	0-3	0	0	53	77	63	63	62	76	76	76
Copper	0	0	56	60	75	60	60	60	75	75	76
	0-3	0	59	74	79	77	76	76	79	79	79
Silver	0	0	0	0	0	0	0	0	73	73	76
	0-3	0	0	54	77	64	64	63	76	76	76
NF metals	0-3	0	0	56	77	67	66	66	3	3	0

Mass-based recovery rate$_{\text{CL0-k}}$

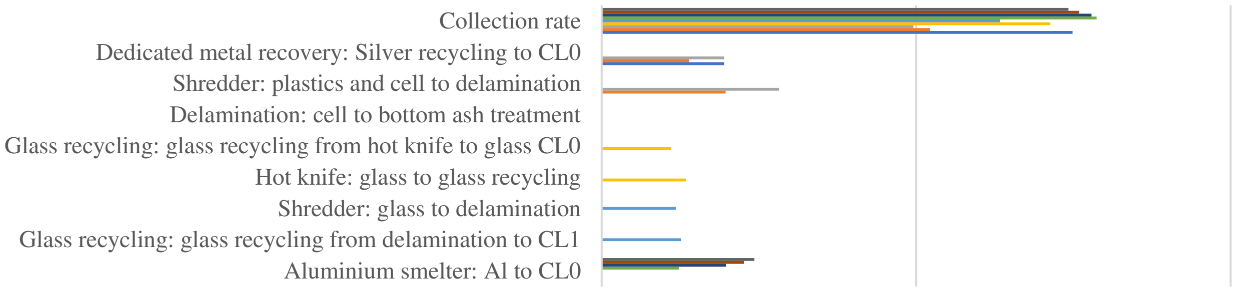

CL0


CL0-1


CL0-2


CL0-3

Economic value recovery rate$_{\text{CL0-4}}$



Embodied energy recovery rate$_{CL0-4}$

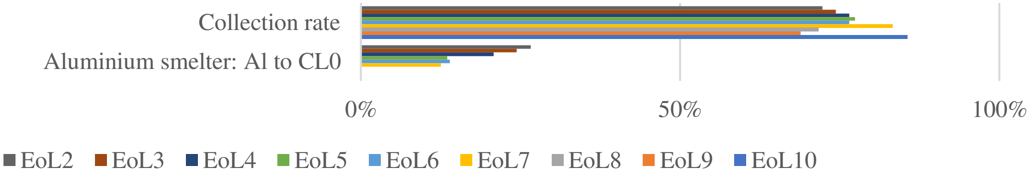
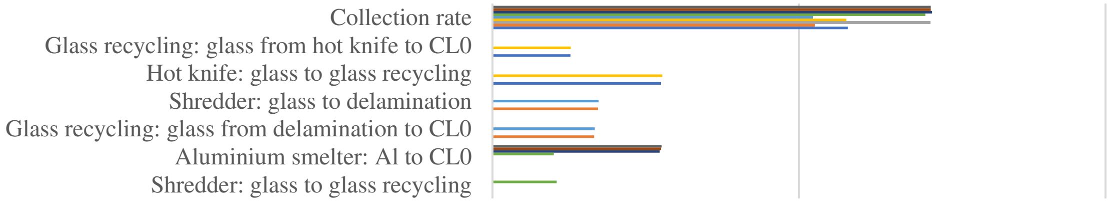


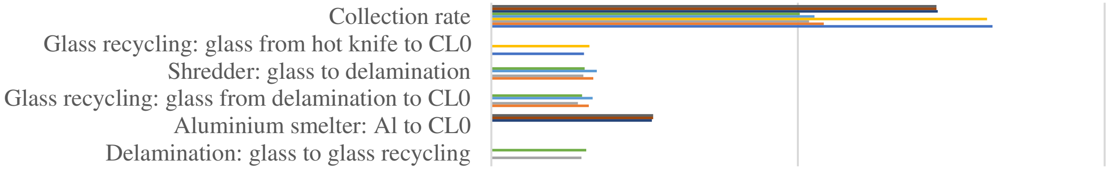
Figure C6. Sensitivity analysis results for mass-based recovery$_{CL0}$, mass-based recovery$_{CL0-1}$, mass-based recovery$_{CL0-2}$, mass-based recovery$_{CL0-3}$, economic value recovery rate$_{CL0-4}$ and embodied energy recovery rate$_{CL0-4}$ in L3 (the percentages indicate the influence of a change in the parameter on the variance of the indicator; a negative percentage indicates that an increase in the parameter leads to a decrease in the indicator)

Mass-based recovery rate$_{CL0-k}$

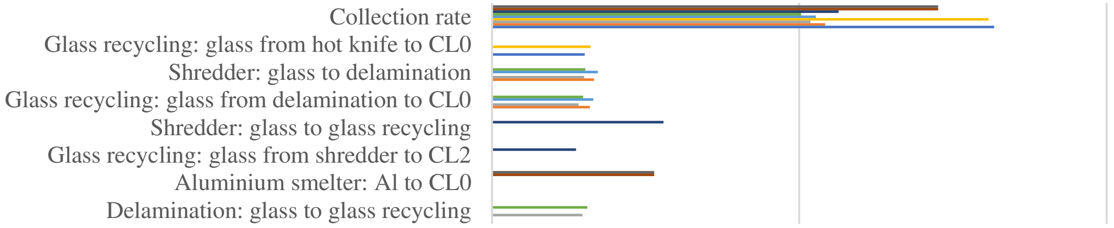
CL0



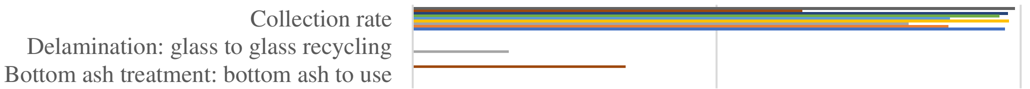
CL0-1



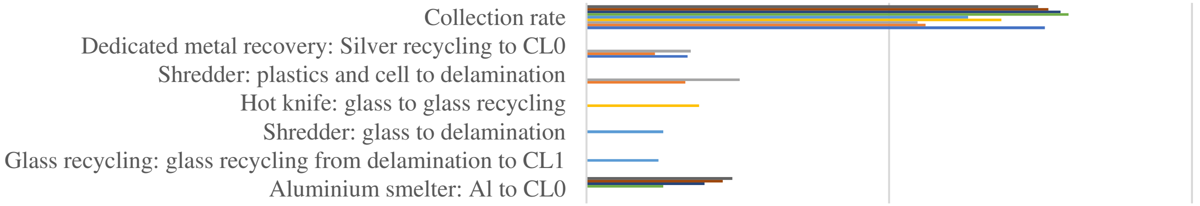
CL0-2



CL0-3



Economic value recovery rate$_{\mathrm{CL0\text{-}4}}$



Embodied energy recovery rate$_{\mathrm{CL0\text{-}4}}$

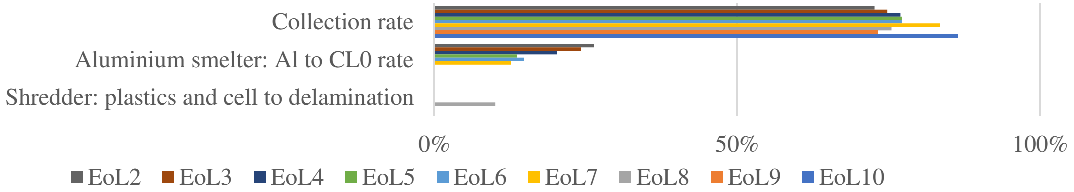
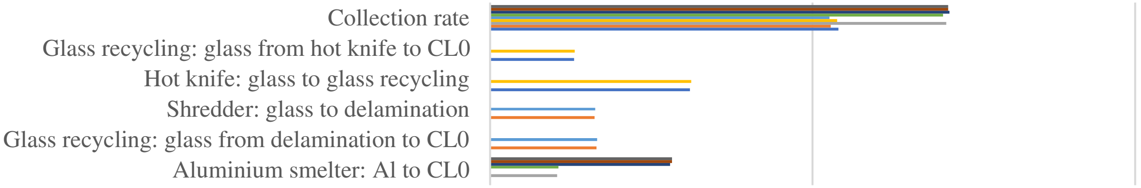


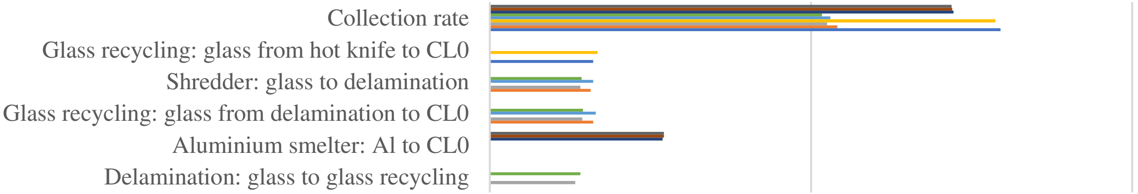
Figure C7. Sensitivity analysis results for mass-based recovery$_{\mathrm{CL0}}$, mass-based recovery$_{\mathrm{CL0\text{-}1}}$, mass-based recovery$_{\mathrm{CL0\text{-}2}}$, mass-based recovery$_{\mathrm{CL0\text{-}3}}$, economic value recovery rate$_{\mathrm{CL0\text{-}4}}$ and embodied energy recovery rate$_{\mathrm{CL0\text{-}4}}$ in L2 (the percentages indicate the influence of a change in the parameter on the variance of the indicator; a negative percentage indicates that an increase in the parameter leads to a decrease in the indicator)

Mass-based recovery rate$_{\mathrm{CL0\text{-}k}}$

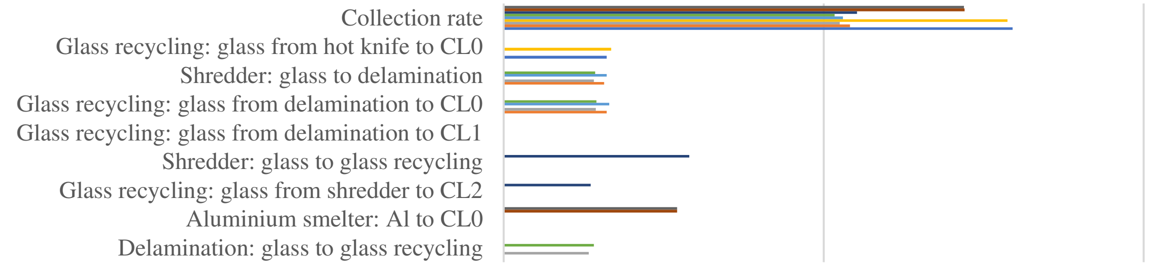
CL0



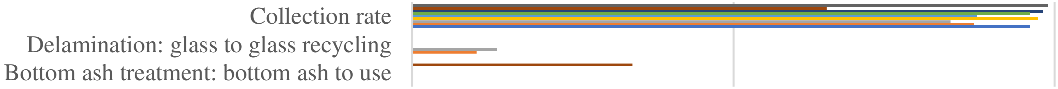
CL0-1



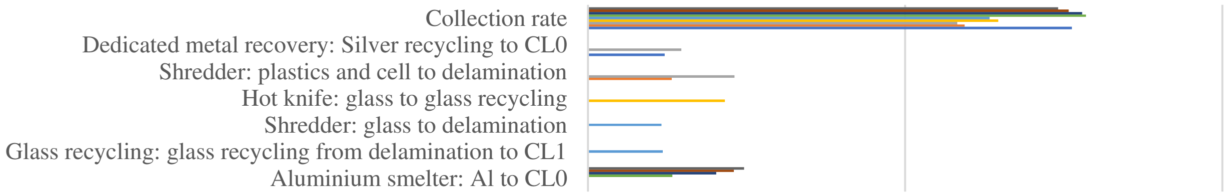
CL0-2



CL0-3



Economic value recovery rate$_{CL0-4}$



Embodied energy recovery rate$_{CL0-4}$

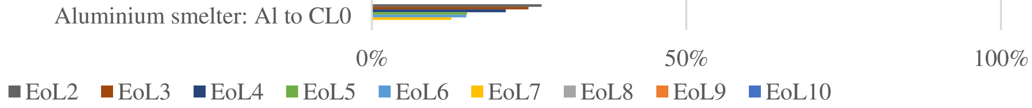


Figure C8. Sensitivity analysis results for mass-based recovery$_{CL0}$, mass-based recovery$_{CL0-1}$, mass-based recovery$_{CL0-2}$, mass-based recovery$_{CL0-3}$, economic value recovery rate$_{CL0-4}$ and embodied energy recovery rate$_{CL0-4}$ in L1 (the percentages indicate the influence of a change in the parameter on the variance of the indicator; a negative percentage indicates that an increase in the parameter leads to a decrease in the indicator)

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