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Citation for the original published paper (version of record):
Marmy, C., Tazi, N., Orefice, M. et al (2026). A contribution to support circularity policy decision making on removal and separate recycling
of embedded electronics – methodology and applications in Switzerland and the EU. Resources, Conservation and Recycling, 226. http://dx.doi.org/10.1016/j.resconrec.2025.108672

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Resources, Conservation & Recycling 226 (2026) 108672

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling

Full length article

A contribution to support circularity policy decision making on removal and separate recycling of embedded electronics – methodology and applications in Switzerland and the EU

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ARTICLE INFO

Keywords:
Circular economy policy
End-of-life vehicles recycling
Proportionality assessment
Science for Policy
Critical Raw Materials
Electronic Devices in Vehicles

ABSTRACT

Scarce technology metals and critical raw materials (CRM) in electronic devices embedded in vehicles (EED) are often lost during end-of-life recycling. This study presents a methodology to assess the proportionality of mandatory removal and separate recycling policies. Combining material flow analysis (MFA), life cycle assessment (LCA), and economic evaluation, it quantifies environmental and economic trade-offs between baseline and policy scenarios. The approach was applied to Switzerland's revision of the ORDEE and the EU's update of the ELVD. In Switzerland, 41 EED types were benchmarked to define proportionality thresholds; in the EU, three were prioritized for CRM recovery. Results reflect contextual factors such as CRM criticality and economic feasibility, demonstrating the method's flexibility. Though limited to recycling in this work, the framework can be adapted to other circular strategies and allows coherent, comparative policy assessments and can be adapted to other sectors.

1. Introduction

The consumption of electric and electronic equipment has increased sharply over the last decades, both as standalone devices and embedded in other products, such as vehicles and buildings (Bel et al., 2019; EEA, 2020). For example, a modern passenger car contains 30 to 50 kg of embedded electronic devices (EED) (Marmy et al., 2023b). Like standalone electronics, vehicle EED are mostly composed of base metals and plastics, as well as amounts of non-base metals that are essential for advanced and strategic technologies such as renewable energy generation, electric mobility, or electronics. They include precious metals such as gold or silver, platinum group metals such as palladium or platinum or rare earth metals such as neodymium and dysprosium. They are described as Scarce Technology Metals in the Swiss Policy, a category of metals that are scarce in the earth's crust and necessary for high technology applications (Wäger et al., 2011; CH-ORDEE, 2022). Some of those metals are on the EU list of critical raw materials (CRM) as well as strategic CRM due to their high economic importance, and the vulnerability of their supply chains (CRMA, 2023). Moreover, the primary production of many Scarce Technology Metals and CRM generates significant environmental impacts (Takeda and Okabe, 2014). There are thus strong strategic, economic and environmental arguments to improve their circularity through recycling.

Waste management policies aiming to reduce environmental impacts by making additional activities or operations mandatory, thus generating additional cost for involved actors rely on the principle of proportionality to balance conflicting interests (TEU, 2016 Article 5). The proportionality framework is a methodology to assess whether a suggested policy measure delivers the expected benefits commensurate with its costs and burdens on the value chain actors (European Commission, 2023). It is based on quantification modules also including material, environmental and economic impacts, as well as feasibility (e.g. enforcement, technical, etc.).

The question is thus, what economic effort is worth what environmental gain in a competitive business model? To answer it, these aspects must be quantified. To achieve this task, a holistic assessment

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https://doi.org/10.1016/j.resconrec.2025.108672
Received 8 May 2025; Received in revised form 28 September 2025; Accepted 26 October 2025
Available online 10 November 2025

methodology is necessary to provide fact-based data. In particular, it must include environmental and economic evaluation methods that are based on common input parameters and data. Moreover, the fact that some products are embedded in other products is a constraint that must be considered.

Several approaches have been described in the scientific literature to evaluate the environmental benefits and socio-economic costs of waste management policies aiming to address circularity gaps of a specific product or sector (de Jesus and Mendonça, 2018; *EU - CEAA*, 2020; He et al., 2024; Kirchherr et al., 2018; Li et al., 2024; Marti and Puertas, 2021). However, those methodologies are often too specific to allow for a high-level, quantified and integrated model assessment linking material streams, environmental gains and socio-economic efforts required to evaluate the proportionality of such a policy (Deshpande et al., 2020; Islam and Huda, 2019; Kang et al., 2017; Papadopoulou et al., 2025; Teah and Onuki, 2017; Wang et al., 2020). From methodological perspective, circularity measures are also evaluated using integrated assessment models based on environmental, economic and social perspectives separately. Those assessments aren't usually realized based on common hypotheses, models, parameters or input data for each assessment, which compromises the generalizability and comparability of the results (Chenavaz and Dimitrov, 2024; D'Adamo et al., 2022; Hu et al., 2024; Korhonen et al., 2018). According to (Daly, 2023) or (Corona et al., 2019), an important challenge lies in the definition of a holistic benchmark to assess circularity in those three dimensions. Furthermore, according to the recent literature (Hertwich et al., 2019; Pauliuk et al., 2017) there is a weak representation of integrated system models and those often ignore specific material cycles, material efficiency and recycling, which make existing integrated models generating limited insights for detailed policy design. Thus, in our case, separate removal aiming at high quality recycling might be overlooked and policy-based recommendations might not be effective, leading to material, environmental and economic losses and burdens.

For example, In Switzerland and in the European Union, end-of-life vehicles recycling involves several operations, including a mandatory depollution, treatment in a car-shredder, and material recovery with a focus on base metals (EU-ELVD, 2000; CH-ADWO, 2016). Sometimes certain EED are removed prior to the shredding to be sold as used spare parts, however, most of them are still embedded in end-of-life vehicles when these are shredded (Marmy et al., 2023b, 2023a). scarce technology metals and CRM contained in EEDs are concentrated in the shredded light fraction (SLF), which is the waste output of the end-of-life vehicles shredding operation, and then often landfilled or incinerated (Widmer et al., 2015). Most of the scarce technology metals and CRM are generally lost or downcycled as alloying elements of within base metals (Andersson et al., 2016; Diaz et al., 2023; Mehr, 2021) during that process. To increase the recovery rates of those metals, EED can be removed from end-of-life vehicles and treated in Waste Electrical and Electronic Equipment (WEEE) recycling facilities. Those installations are optimized to also recover some CRM and scarce technology metals, in particular precious metals, besides base metals, and generate significantly less waste than end-of-life vehicles recycling facilities (Cui and Forssberg, 2003; Lee et al., 2007; Zhang and Xu, 2016). However, dismantling becomes extremely difficult (Liu et al., 2025), and those additional steps in the waste management system generate additional costs that might not be covered by the additional benefits. In consequence, for the recycling sector to remove, collect and recycle EED separately, incentives in the form of a financing system, established in the context of a policy or by the private sector might be necessary (Andersson et al., 2019).

This paper therefore highlights the research gap related to a systemic integrated methodology to assess the proportionality of removal and separate recycling of EED as CRM/scarce technology metals rich components while considering both environmental and economic trade-offs. The aim is therefore to suggest a new and replicable methodology addressing this research gap towards higher circularity of embedded components. The proposed approach builds on the circularity policy-ready proportionality assessment that is barely covered in literature. It is also intended to support both methodological and data gaps through respectively the combined assessment approach, as well as the lack of comprehensive information for scarce technology metals and CRM embedded in vehicle EEDs.

In this article, we present a methodology to assess the proportionality of mandatory removal and separate recycling used in two different contexts. The methodology combines the environmental and economic dimensions and is based on a multi-layered material flow analysis model that allows to consider end-of-life vehicles, EED embedded therein and the materials they contain as they flow through the waste management system.

The first application of the methodology took place in Switzerland in the frame of the implementation of the revised Swiss Ordinance on the Return, Taking Back and Disposal of Electrical and Electronic Equipment (ORDEE), which included an extension of the scope to cover electronic devices embedded in other products such as vehicles. The revised ORDEE, which was adopted on January 1, 2022, states that EED must be removed from end-of-life vehicles and recycled separately if the treatment is environmentally sound, and if it can be done for reasonable costs. To do so, the Federal Department of the Environment, Transport, Energy and Communications provides a list of EED that meet those conditions based on a methodology that has been developed by Empa and first applied for that purpose (Marmy et al., 2023b). The goal here was to provide fact-based data and recommendations to policy makers on which EED such a measure would be the most proportional.

The second application took place in the context of the revision of the End-of-Life Vehicles Directive into the End-of-Life Regulation in the European Union (*EU - Proposal ELVR*, 2023), with the objective of improving the circularity of critical raw materials and other materials in passenger cars, among other goals (*EU - CRMR*, 2024). The current proposal includes several possible policy measures, in particular the mandatory removal of some EED for reuse or recycling, also subject the proportionality condition. The methodology was adapted and used to select which EED should be concerned by this measure for the proposal, by quantifying the potential secondary materials, the environmental benefits and the economic impacts for each EED (Tazi et al., 2023).

2. Methodology

2.1. General approach

When vehicles have reached their end-of-life and become end-of-life vehicles, they enter the waste management system, which consists of a set of operations generating secondary raw materials, spare parts, waste and emissions, and which consume labor, energy and products such as chemicals. Considering the inputs and outputs of this system, as well as the material flows within it allows to evaluate the environmental impacts from generated waste and emissions, environmental benefits of EED reuse and produced secondary raw materials, and economic costs including costs of labor, energy and products entering the system, and the value of secondary raw materials and reusable EED.

In this methodology, at least two variants of the waste management system (i.e., scenarios) are modelled: the first to represent the existing situation (i.e., the baseline), and the second to reflect the expected consequences of the policy measure considered. The model combines a material flow analysis (MFA), an LCA-based environmental assessment, and an economic assessment for each scenario. It allows to evaluate the economic costs and environmental benefits of switching from one scenario to the other.

The three components of the model are interlinked in two main ways: firstly, the results of the MFA are the main data inputs to both the environmental and economic assessments, and secondly, all three components share external parameters, such as the material composition of the EED, the transport distances between each operation, or the ratio of different drive trains in the fleet of end-of-life vehicles entering the waste management system. Consequently, the results in terms of material flows, environmental benefit and economic cost for a given input of a waste management scenario are coherent by design, share input, and allow for comparisons, combinations and rankings. This also allows to observe the effects of varying external parameters on material, environmental and economic aspects.

The model operates on several interlinked levels. An end-of-life vehicle entering the waste management system contains a specific set of EED, each having a different mass and composition. This characteristic allows to put in relationship the output of the model (e.g. secondary raw materials, environmental benefit, economic cost) with the end-of-life vehicles at the input. The assessment is realized over one specific reference year.

The methodology follows four successive steps:

1. Definition of the scope
2. Definition of scenarios
3. Modelling and assessment of the scenarios (MFA, Economic assessment, environmental assessment)
4. Integration, analysis and interpretation of the results

2.2. Step 1: definition of the scope

The waste management system is represented as a set of operations linked by material flows that occur on three levels: end-of-life vehicles, EED and Material. A material flow on the material level describes the materials contained in EED once those have been shredded. A single material flow can occur at multiple superposed levels (e.g. end-of-life vehicles containing EED). Material flows on each level are characterized based on specific descriptors.

The descriptors are defined based on the goals and context of the study. The following descriptors were used in the applications described in this article:

- **Type of flow:** at the material level, the type of flow differentiates multiple recycling fractions (the intermediary outputs of recycling operations), secondary raw materials and waste. On EED level, the type differentiates the nature or destination of a flow of EED, such as "embedded", "for reuse" or "for separate recycling" for example.
- **Composition**: At material level, composition describes the mass fractions of elements and compounds composing the material flow. The composition can include pure elements, alloys, different types of plastics, possibly other compounds such as textiles, and the aggregated "rest".
- **EED Type**: EED sharing identical functions are considered of the same type. This descriptor is based on official nomenclature. Useful parameters of an EED type are average unitary mass and average composition. Types are mutually exclusive.
- **EED Category**: EED that generate similar types of material flows when recycled are defined as belonging to the same category. Each EED type belongs to one EED category.
- **Vehicle Category**: end-of-life vehicles of a given category contain similar sets of EED. An example of category would be the drive train. Each category is defined by the average number of each EED types it contains.

2.3. Step 2: definition of scenarios

Every operation of the waste management system has an input material flow, and at least one output material flow. These operations determine the level and characteristics of each of their output flows. The operations can generate environmental impacts and economic costs. The different types of operations are described in the following table (Table 1).

Table 1
List of operations addressed in scenarios of the end-of-life vehicles waste management system.

Operation	Description
EED removal	EED are removed from end-of-life vehicles to be reused, recycled or disposed of. This operation happens concurrently with the depollution of end-of-life vehicles. This work is typically realized manually.
Shredding and primary sorting	EED or end-of-life vehicles are shredded, and the output is sorted into several recycling fractions. Waste is also produced. End-of-life vehicles shredders focus on the recovery of base metals and a high throughput. WEEE shredders are optimized to better recover targeted metals (precious and/or CRM/scarce technology metals) and plastics, operate a lower through-put and typically generate less waste than end-of-life vehicles shredders.
Secondary sorting	Secondary sorting facilities allow to improve and segregate recycling fractions using various separation methods.
Logistics	Transport between the locations where operations take place.
Material recovery	Metal smelters and plastics recycling facilities produce secondary raw materials from recycling fractions, while also generating waste.
Waste Disposal	Disposal of operation waste in incinerators, landfills or other installations.

Scenarios are different versions of the waste management systems, with identical scope and input of end-of-life vehicles containing EED, but differences in their operations, material flows networks, consumption of energy, labor and products, and production of reusable EED and secondary raw materials. At least two scenarios must be defined:

- The **Baseline Scenario** describes the existing waste management system where EED are typically not removed from end-of-life vehicles, and shredded while still being embedded.
- The **Alternative Scenario** reflects the waste management system if the recycling measure assessed in the study would be implemented, which means the removal of EED for separate recycling in the two applications described in this article. Compared to the Baseline scenario, operations can be added, modified or removed, also impacting the network of material flows.
- It can be useful to consider **additional alternative scenarios**, to represent variants of a proposed recycling measure, or its gradual implementation and effects over time.

2.4. Step 3: Modelling the scenarios

Modelling the scenarios consists of realizing a combined MFA, environmental assessment and economic assessment for each of them, and populating the models with data for each scenario. While doing so, ensuring the rationality of scenario assumptions is central. All assumptions used in modeling the operations in baseline and alternative scenarios should be explicitly defined. To evaluate the robustness of these assumptions, sensitivity analyses can be conducted, systematically varying key parameters within realistic ranges to assess their influence on material flows, environmental impacts, and economic costs. Methods such as Monte Carlo simulations can be used to explore uncertainty and identify which assumptions most significantly affect results.

The MFA allows to quantify the material flows in a scenario by assessing the material input of the waste management system in the year of reference for each treatment operation in order to model the quantities and characteristics of the secondary raw materials and waste produced for every scenario.

The material input of the system is defined as the quantity of EED of each type and category entering the waste management system in the reference year, measured in number and mass. Modelling the operations consists of defining transfer coefficients for each operation, in order to quantify and characterize its output flows in function of its input flows (Brunner and Rechberger, 2004). Those operations can be modelled based on experiments, data from the scientific literature, technical data from the industry, existing models or data from monitoring systems (Huisman et al., 2016; Løvik et al., 2021; Marmy et al., 2023b, 2023a; Nordelöf et al., 2019; "RMIS - JRC," 2022; Restrepo et al., 2020, 2019, 2018, 2017a, 2017b). Combining several approaches and making hypotheses is the way that was adopted in the two case-studies to tackle missing data.

The economic assessment of each waste management scenario is done by estimating difference in costs of the Alternative(s) scenario(s) compared to the Baseline scenario. Based on the hypothesis that all the scenarios use existing infrastructure and capacity; only operational costs are considered. All operations that are identical (in terms of transfer coefficients, inputs and outputs) both in the baseline and alternative scenarios do not have different costs and are thus not considered. Thus, only three operations generate additional costs in an Alternative Scenario: Removal of embedded EED, Logistics of the removed EED to WEEE recycling facilities, and shredding and primary sorting of EED in those facilities.

The environmental assessment is realized with an LCA-based approach to quantify environmental impact in environmental pollution points (UBP) or EF points (*EU - EF LCA*, 2021; "ISO 14040 LCA," 2006). The operations of each waste management scenario generate environmental impacts proportional to their throughput mass. Only the impact associated with the EED mass is considered, the impacts of treating end-of-life vehicles hulks being the same in all scenarios. This is done on a case-by-case basis using databases such as Ecoinvent (Wernet et al., 2016). Concurrently, secondary raw materials generated in each scenario are assumed to substitute primary raw materials. Consequently, the environmental impacts that the production of those primary raw materials would have generated is the environmental benefit of the waste management system, as with an "avoided burden" approach (Chen et al., 2010). Using the material flows estimated with the MFA, the environmental impact of each scenario can be assessed.

Comparing environmental impacts and benefits in a given scenario gives its environmental performance. Comparing the environmental performances of all the scenarios considered in the study allows to identify the best alternative according to the environmental assessment.

To ensure the reliability of the results, a structured approach to data quality control should be integrated into the methodology. Input data must be evaluated for accuracy, timeliness, and completeness. Accuracy can be enhanced by cross-verifying data against multiple sources, such as industry records, monitoring systems databases, and peer-reviewed literature, and by performing experiments on big and representative samples. Timeliness requires that datasets reflect current technologies, fleet compositions, and regulatory conditions. If the methodology is to be applied periodically, the data should periodically updated as well to capture changes in vehicle design or recycling practices. Completeness involves identifying gaps in the data, such as missing EED types or regional variations, and addressing them using estimation methods, surrogate data, or interpolation, while clearly documenting the assumptions made. Applying data quality indicators can help quantify uncertainty and provide transparency regarding the reliability of each dataset or the results of the models.

2.5. Step 4: Interpretation of the results

Step 3 can be done for all EED of a given type or category embedded in end-of-life vehicles in the reference year. Aggregating and comparing the results allows to compare secondary raw materials production, economic cost and environmental performance of EED removal and recycling along with WEEE for each EED type separately. This allows to classify each EED type based on the trade-off between additional burden and environmental benefits.

Those results can then be used to assess and compare possible recycling measures (e.g. in the context of a new policy) with the existing situation, in order to choose the best alternative. They can also be used to improve a proposed measure by selecting EED for which the trade-off is the most beneficial, and excluding the others. The results obtained through this methodology must be interpreted and combined in order to provide actionable insights on a case-by-case basis in the context of the specific recycling measure that is evaluated. Stakeholder inputs are also relevant in this step, and their active integration supports results robustness.

Transparency in reporting assumptions and data sources and quality is essential. Output should be presented taking those elements into consideration, by expressing uncertainties at least qualitatively and if possible, quantitatively, in order to allow stakeholders to understand the potential variability and implications for decision-making.

3. Application A: Mandatory separate recycling of EED in Switzerland

3.1. Context

The ORDEE was revised from 2016 to 2021, in order to extend its scope to electronic devices embedded in other products such as EED, and to improve the recovery of scarce technology metals. The revised version entered into force on 1 January 2022 (CH - ORDEE, 2022). It states that electronics falling under the scope of ORDEE must be collected separately from other waste, and recycled insofar as this is technically feasible, economically viable and ecologically sound. EED for which the removal and separate recycling respects the principle of proportionality submit to the same end-of-life requirements as stand-alone electronics, which include "Give-Back" and "Take-Back" obligations for the users and manufacturers respectively, as well as the recovery of a broad range of materials if possible, including scarce technology metals. In this case, the principle of proportionality is reflected in the two following conditions:

- EED removal from end-of-life vehicles is possible at a reasonable cost.
- EED separate recycling provides sufficient environmental benefits.

The Swiss Federal Department of the Environment, Transport, Energy and Communications is in charge of defining a list of EED that fulfill those criteria and thus fall in the scope of the ORDEE. The Swiss Federal Laboratory for Materials Science and Technology (Empa) was mandated to develop and implement the methodology presented in this article to provide fact-based data allowing to establish this list. Detailed explanations on this applications, including regarding the sources of the data used and detailed results are given in the final report of the study published by the Swiss Federal Office for the Environment "Projekt EVA II: Synthesebericht (Projektbericht)" (Marmy et al., 2023b).

3.2. Step 1: Definition of the scope

The recycling measure to be assessed for each type of EED is the removal of EED from end-of-life vehicles and their recycling with WEEE in Switzerland. The reference year of the study is 2021. Batteries do not fall within the scope of the ORDEE and are as such not considered in this study. Moreover, sensors, a category of EED, are also excluded due to their small individual mass and high embeddedness, which makes them hard to remove effectively.

The descriptors of the material flows in this application of the methodology are defined as the following:

- **Type of flow**: 10 recycling fractions, 3 types of waste, 10 secondary raw materials, and 3 EED destinations
- **Composition**: 3 base metals (Fe, Al, Cu), 3 precious metals (Au, Ag, Pd), 4 types of plastics (PP, PMMA, ABS, PC-ABS), and aggregated rest.
- **EED Type**: 43 distinct types of EED

- **EED Category**: 4 different categories (Controllers, Actuators, Headlights, Cables)
- **Vehicle Category**: 4 different drive trains – Internal Combustion Engine Vehicle (ICEV), Hybrid Electric Vehicle (HEV), Plug-In Hybrid Electric Vehicles (PHEV), Battery Electric Vehicle (BEV)

3.3. Step 2: Definition of scenarios

Two waste management scenarios were defined as following and represented in the figures below.

The Baseline Scenario represents the waste management system for EED in its current form. This scenario is a simplified representation the waste management system for EED in Switzerland. A certain proportion of some EED are removed to be reused as spare parts. Those are typically parts that are easy to remove and for which there is a high demand for spare parts, such as actuators for windows or the trunk, or easy to replace electronics such as infotainment modules, as well as parts that often get damaged during the use of vehicles such as headlights. The removed ratio for each EED types can be consulted in the source references (Marmy et al., 2023b, 2023a). The rest of the EED remains embedded in end-of-life vehicles as they undergo shredding and primary sorting in a car shredder, generating multiple recycling fractions and waste. The recycling fractions are sent to smelters to recover mostly base metals, with or without secondary sorting (Fig. 1).

The Alternative Scenario (Figs. 1 and 2) represents the waste management system for EED if all of them have to be removed and recycled along with WEEE. This scenario is based on a practical experiment in collaboration with E-waste recyclers and experts of the sector. As in the baseline scenario, some EED are removed to be reused as spare parts. The remaining EED are also removed and undergo shredding and primary sorting in a WEEE recycling facility. Additional recycling fractions are produced, and less waste is generated compared to the Baseline scenario. Base metals, but also some plastics and precious metals/scarce technology metals are recovered in smelters and recycling installations (Marmy et al., 2023b).

3.4. Step 3: Modelling the scenarios

The input of the waste management scenarios was quantified based on the number of end-of-life vehicles treated in Switzerland in

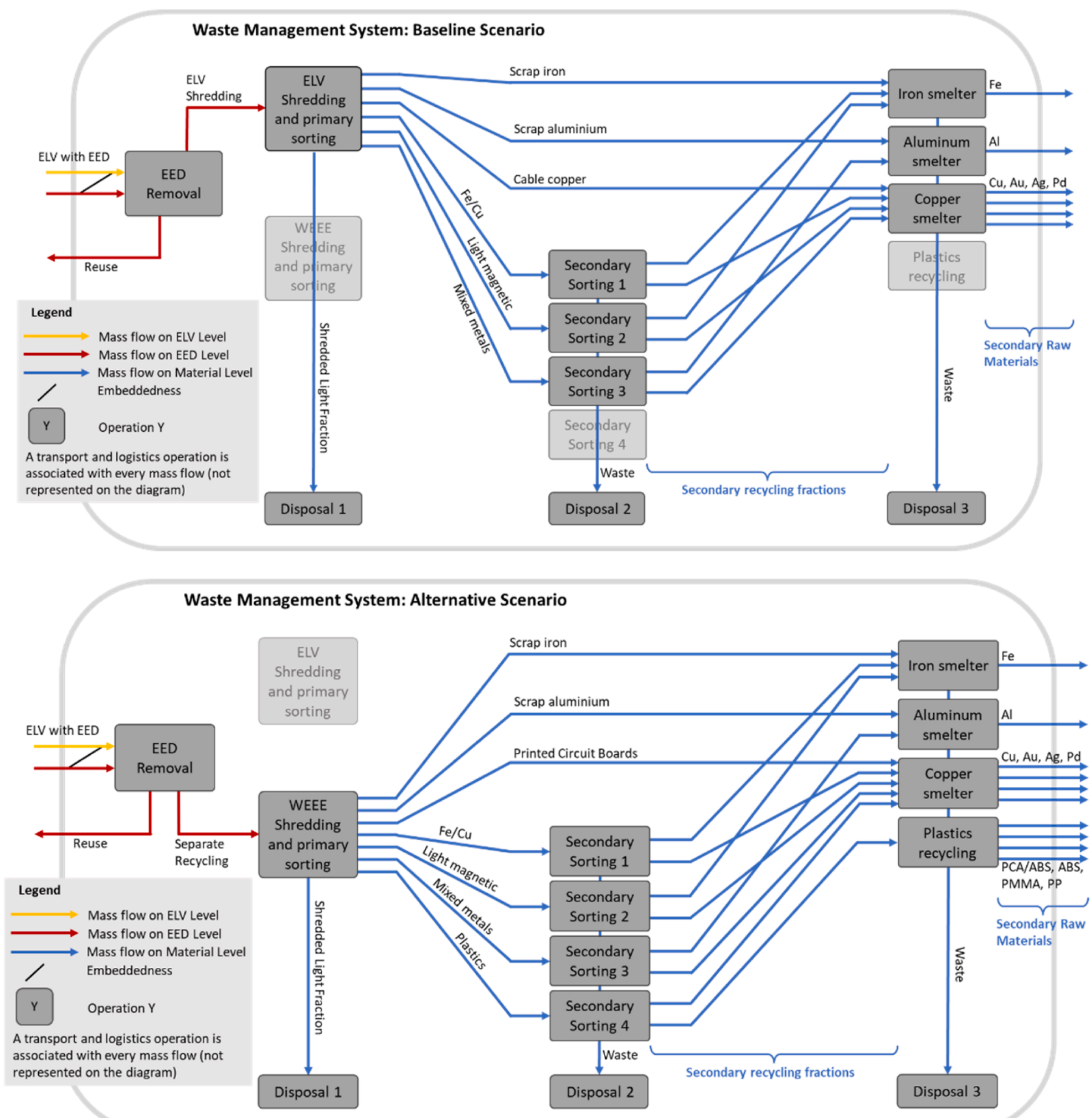

Fig. 1. Diagrams representing the baseline scenario and the alternative of the waste management system for EED.

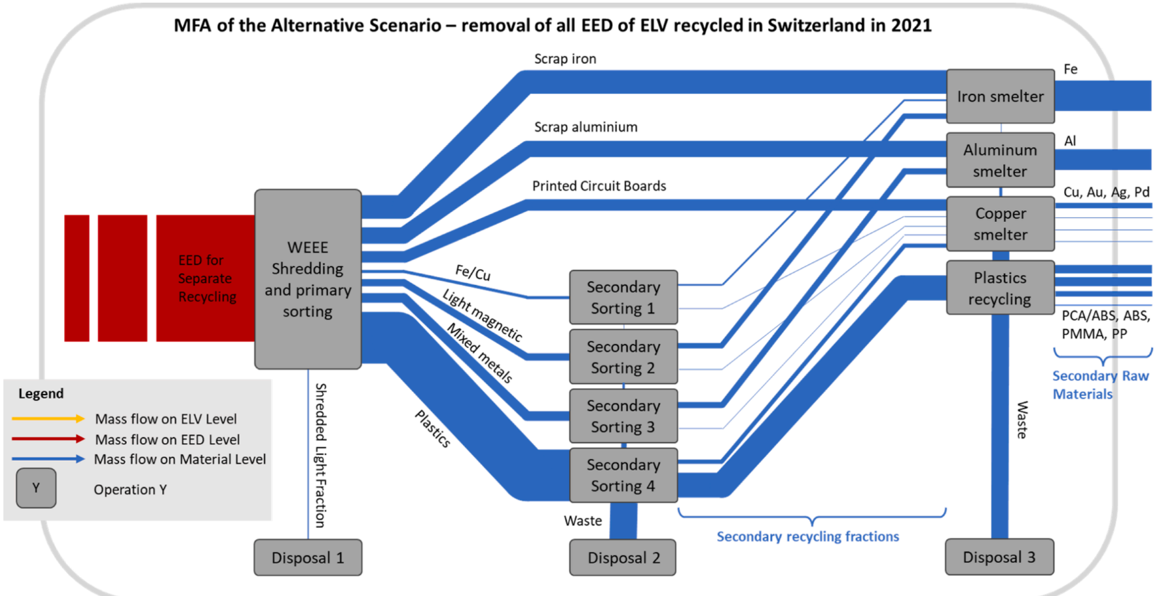

Fig. 2. Material flows in the alternative scenario if all EED of all types are removed from end-of-life vehicles being recycled in Switzerland in 2021. EED for separate recycling at input: 2′501'107 kg. Primary recycling fractions: Plastics: 1′017'406 kg, Scrap iron 466′445 kg, Scrap Aluminum 322′239, Printed Circuit Boards 222′299 kg, mixed metals 195′898 kg, Light magnetic 141′267 kg, Fe/Cu 106′008 kg. Total Waste: 1′258'437 kg. Total Secondary fractions 876′009 kg, Secondary Raw Materials generated: Fe 594′495 kg – Al 408′996 kg – Cu 101′808 kg – Ag 164 kg – Au 40 kg – Pd 6 kg – PC/ABS 168′748 kg – ABS 183′846 kg – PMMA 111′950 kg – PP 25′312 kg (Marmy et al., 2023b).

2021 (around 68′000 vehicles), the proportion of each drive-train of those end-of-life vehicless, the number of EED of each type in an average end-of-life vehicles of each drive-train, and the average mass of a EED of each type. This data was obtained from a fleet model, experiments, literature and official statistics of the year 2021 and can be found in Annex D of the report *Projekt EVA II: Synthesebericht (Projektbericht)* (Marmy et al., 2023b; Restrepo et al., 2018).

The operations of the waste management scenarios were modelled based on different sources, such as official statistics, surveys of the reuse rate of each EED type, data from experiments on removal time for each type and production of recycling fractions from car-embedded electronics in an E-waste recycling facility, technical data from a car-shredding facility, and scientific literature (Marmy et al., 2023b).

On that basis, an **MFA** was realized for both waste management scenarios, which allows to quantify the size and composition of the material flows between every operation, as well as the secondary raw material produced for a given input mass of each EED category in the reference year. Combining those results with the total input mass and category of each EED type for the reference year of 2021, the material flows of the scenario, including the secondary raw materials generated were quantified for each EED type in the reference year. The MFA of the alternative scenario is illustrated in Fig. 2 showing the material flows for all EED by category in 2021.

Based on those results, and using additional data on average removal time of each EED type (Restrepo et al., 2017a), market data for logistics services and for the financing system for electronic recycling in Switzerland (Marmy et al., 2023c), **an economic assessment** of the Alternative Scenario in 2021 for each EED type was realized. This allows to quantify the additional cost compared to the Baseline Scenario if all EED have to be removed and recycled separately in an WEEE recycling facility, for each EED type (see Table 2. Those results can then be aggregated by category of EED, and for an average end-of-life vehicle. The relative cost of removal is high compared to recycling and logistics. However, the total cost of removing all EED of all categories from an end-of-life vehicles is about 190 CHF per end-of-life vehicles. This represents about 0.5 % of the price of an average new car in Switzerland in 2021 (Marmy et al., 2023b, 2023c).

Table 2
Economic, environmental and overall scores of the five EED types with the highest overall scores.

EED Type	Env^{EED}_{score}	Eco^{EED}_{score}	$Overall^{EED}_{score}$	Data quality
Headlights	1.00	0.58	0.79	+++
Amplifier	0.19	0.93	0.56	+
Controller automatic gearbox	0.19	0.91	0.55	++
DCDC converter	0.07	0.97	0.52	+
Inverter (for xEVs)	0.01	1.00	0.50	+

An environmental assessment of both scenarios was realized based on the results of the MFA, the unitary environmental impact of each operation, and the avoided burden of secondary raw material production. This allowed to quantify the environmental impacts and benefits associated with each type of EED in both waste management scenarios (see Table 2). The avoided burden of producing secondary raw materials outweighs the environmental impacts or the waste management system for all EED in all scenarios. Summing up the avoided burden and the environmental impacts allows to determine the performance of each scenario. Moreover, the alternative scenario is environmentally more performant than the baseline scenario for all EED categories except cables. The difference between the two scenarios is particularly high for controllers and headlights (Haarman et al., 2018; Marmy et al., 2023b, 2023d). The environmental assessment assessed factors and categories under the Environmental footprint EF 3.0. The environmental module is well defined and characterized in the author's previous report (Marmy et al., 2023d), and only the Global Warming Potential was used as comparative basis, together with the environmental pollution points (UBPs) of the ecological scarcity method in the context of the Swiss analysis (*Swiss Eco-Factors 2021 according to the Ecological Scarcity Method*, 2021).

3.5. Step 4: Interpretation of the results

The goal was to provide fact-based data to support the policymaker on defining the list of EED for which removal and recycling a WEEE recycling installation respects the principle of proportionality. To do that, it is necessary to combine both the environmental benefits and economic cost in a single indicator. This was realized by following a procedure with the following steps:

1. The environmental performance is calculated by summing the avoided burden (positive value) and environmental impact (negative value) for a given type of EED in a scenario.
2. An environmental score for each EED is calculated by scaling the environmental performance between 0 and 1, with the highest score meaning the highest environmental benefit of separate recycling.
3. The economic score is calculated by scaling the costs of the alternative scenario for each EED type between 0 and 1, with the highest score meaning the lowest economic cost of separate recycling.
4. Environmental (ρ_{env}) and economical (ρ_{eco}) weights are determined and a weighted average for each type of EED in an average end-of-life vehicle allows to determine an overall score. The weights correspond to the perceived importance of each dimension (by the decision makers). In this example, both weights are set to 0.5.
5. The quality of the data was qualitatively assessed by the authors of the study. Factors considered include the number of data points on dismantling time, recycling output, and material composition, as well as other parameters listed earlier. The source of the data was also taken into account (e.g., own experiments, literature, industry standards, system monitoring data, or assumptions based on comparable EEDs). Data quality tends to be lower for less common EEDs in the car fleet, such as amplifiers or devices used in xEVs, since fewer data points are available. As a result, assumptions must be made more frequently in these cases.

Table 2 shows the five EED with the highest overall score, with equal weights for the environmental and economic dimension. An additional qualitative evaluation of the data quality was also included.

4. Application B: Mandatory separate recycling of EED in the EU

4.1. Context

The methodology described above was also used in the European context of the joint revision of the end-of-life vehicle directive (*EU - Proposal ELVR*, 2023), and the directive on the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability (*EU - TAMV*, 2005). Among the goals of the European Commission was to investigate measures to increase circularity of vehicles, reduce the supply risk of CRMs, and assess the potential benefits of removal and separate recycling of components and materials from end-of-life vehicles. A dedicated impact assessment study was supported by the study led by Baron et al. (Baron et al., 2023), as well as a JRC study on recycled plastic content targets for vehicles (Maury et al., 2023). Besides, the trend towards the electrification of the EU fleet, the development of the so-called software defined vehicles and the high CRM content of EED shifted the focus on EED as key elements in this development (Carrara et al., 2023; Hu et al., 2024). For this reason, a JRC study was conducted to assess the benefits of removing different types of EED from end-of-life vehicles and recycling them in WEEE recycling facilities in the EU (Tazi et al., 2023). The principle of proportionality used in the Swiss policy is also fundamental at EU level. Consequently, the model described in application A was adapted for the European context and used to determine a list of EED for which separate recycling would be mandatory. Detailed explanations on this applications, including regarding the sources of the data used and detailed results are given in the final report of the study published by the Publications Office of the European Union "Initial analysis of selected measures to improve the circularity of critical raw materials and other materials in passenger cars" (Tazi et al., 2023).

4.2. Step 1: Definition of the scope

As in application A, the recycling measure to be assessed is the removal of EED from end-of-life vehicles and their recycling with WEEE. The reference year of the study is also 2021. The types of EED considered are also identical. However, end-of-life vehicles recycled in the geographical scope of the EU-27 are considered, instead of in Switzerland. In this application, the assessment is based on the recovery of four materials (Cu, Au, Ag and Pd), the economic cost and environmental benefits of removal and separate recycling.

The descriptors used in application B are also identical to application A (see above).

4.3. Step 2: Definition of scenarios

end-of-life vehicles and WEEE waste management systems in the EU and Switzerland are similar, as well as the proposed measures to be assessed. In consequence, the baseline and the alternative scenarios are also identical as in application A. EED types shortlisted in step 4 are evaluated in the alternative scenario for 2030 and 2040, based on projection of future end-of-life vehicles and EED flows in Europe (see Table 3) (Baron et al., 2023).

4.4. Step 3: Modelling the scenarios

The scenarios are modelled based on results from application A. The input flow of EED is calculated based on all end-of-life vehicles recycled in the EU in the reference year, and the average EED content of each vehicle category. The MFA of application A provides the potential SRM production by EED category in both scenarios as a fraction of EED input (see Table 3). This allows to quantify the production of the targeted materials (Cu, Au, Ag, Pd) in the EU for both scenarios, by EED category.

The economic assessment is similar to application A, with a converted (CHF/€) hourly wage for EED removal. As shown in Table 3 and Table 4, the separate recycling of controllers separate recycling increase slightly the total additional costs per average end-of-life vehicle compared to the overall burdens.

The environmental assessment is also similar to application A, but is based on the calculation of global warming potential (GWP) in [kg eq CO_2] based on EF.3, instead of ecological scarcity methodology used for the section above (*EU - EF LCA*, 2021).

4.5. Step 4: Interpretation of the results

In this application, the results are used to define a shortlist of EED types for which removal and separate recycling (i.e. the alternative scenario) is considered to be proportional, instead of just ranking benchmarking them as in application A. The following inclusion and exclusion criteria were used for this purpose:

1. Only EED types with the highest CRM content should be integrated on the list. In consequence, only EED belonging to the category of

Table 3
SRM produced as a fraction of the recycling inputs, focusing only on the targeted materials (Cu, Au, Ag and Pd) at EU level.

Scenario	EED category	SRM produced as a fraction of the recycling input			
		Cu	Au	Ag	Pd
Baseline	Headlights	3.10^{-3}	0	0	0
	Actuators	13.10^{-3}	0	0	0
	Controllers	12.10^{-3}	0	0	0
	Cables	375.10^{-3}	0	0	0
Alternative scenario	Headlights	50.10^{-3}	2.10^{-5}	1.10^{-4}	4.10^{-6}
	Actuators	21.10^{-3}	5.10^{-6}	4.10^{-5}	6.10^{-7}
	Controllers	27.10^{-3}	4.10^{-5}	8.10^{-5}	5.10^{-6}
	Cables	375.10^{-3}	0	0	0

Table 4
Potential additional benefits of separately removing and recycling the three shortlisted components, calculated at EU level.

	2030	2040
SRM (Cu, Au, Ag, Pd) production in t	3355.4	3644.8
Estimated separate recycling costs, per vehicle, in EUR	5.9	5.9
Estimated net additional environmental benefits, per fleet, in tCO2eq	67,807	73,651

controllers are included, based on the results of application A and additional stakeholders and literature statements and feedback (Cucchiella et al., 2016; Marmy et al., 2023b).

Results regarding economic costs and environmental benefits of removal from end-of-life vehicles and separate recycling need to be robust. This data quality parameter was qualitatively assessed in application A, with score ranging from “+” to “+++” (see Table 2).

The additional cost of the alternative scenario for an EED type must be low, both per unit of EED mass and per end-of-life vehicles. This puts the focus on bigger, heavier EED that are easier and cost-effective to identify and remove.

The environmental benefit of the alternative scenario for an EED type must be high. This ensures that the EED types for which the cost of removal and separate recycling is considered acceptable are worth the effort.

Consequently, out of the 41 different types of EED identified in the study, only the three following EED types fulfilled the proportionality criteria to be included in the list of EED for the EU context:

- Inverter (for xEVs).
- Control module / valve box automatic transmission.
- Infotainment control unit (sound, navigation and multimedia).

Based on the average mass and number of those EED types per end-of-life vehicles, and combining such information with the expected end-of-life vehicles fleet collected at EU level (Tazi et al., 2023), the production of SRM, the additional cost and the environmental benefits of the alternative scenario can be calculated for 2030 and 2040 (see Table 3 and Table 4) highlights the potential additional benefits at EU level. Estimates were calculated for 2030 and 2040.

5. Discussion

The methodology described in this article was applied to two distinct policy contexts and scopes. The first application (application A) referred to the Swiss revision of the ORDEE, which makes separate recycling of embedded electronics mandatory if the principle of proportionality is met, meaning that separate recycling would have to be “environmentally sound” and “economically viable”. The goal was to define a list of EED types respecting these criteria, and the methodology was developed to provide a scientifically sound foundation to perform this assessment.

The second application referred to the EU revision of the ELVD, which aimed to improve the performance of ELV recycling and minimize the loss of CRM and other important materials for the EU (Cu, Pd, Au and Ag). Separated EED recycling in WEEE recycling facilities was evaluated as one potential policy measure to overcome circularity gaps. The policy objective was to provide a shortlist of EED for which the principle of proportionality is met. For this purpose, the methodology used in application A was adapted to the EU context, and complemented with a set of criteria to select EED types meeting the conditions of proportionality.

Application A led to the benchmarking of 41 EED types, in order to allow policy makers and actors of the automotive sector to define the limit of proportionality together and select the threshold above which removal and separate recycling of EED is proportional. The process of establishing the list is still underway. In application B, the definition of the threshold was integrated in the methodology, and 3 EED types were selected for the list for mandatory removal and separate recycling. The full list is provided in the Annex VII part C of the new vehicle regulation proposal (*EU - Proposal ELVR,* 2023). Interestingly, the 3 EED types selected in application B (inverter for xEVs, control module / valve box automatic transmission and infotainment control unit (sound, navigation and multimedia) are not the same as the top 3 EED types having the highest overall score in application A (headlights, amplifier and ccontrol module / valve box automatic transmission). However, all those EED types were highly ranked in both studies, due to their ease of dismantling, high mass and high content in valuable materials such as precious metals.

Both applications use the same data for the composition and distribution of EEDs, as well as for dismantling time, since the same vehicle models and brands are present in both Switzerland and the EU. Moreover, ELV recycling and e-waste recycling are carried out using similar technologies and achieve comparable yields in both contexts. Consequently, the waste management system modeling applied in both cases is identical. However, differences exist in the vehicle fleet composition and in labor costs. The data used to quantify these parameters therefore differs between the two applications.

The difference between the results of applications A and B illustrates how the same methodology applied in a very similar way can be interpreted differently depending on policy context and objectives (e.g. the importance of CRM in EU Policy, which differs from the concept of “Scarce Technology Metals” used in Switzerland), the definition of proportionality (e.g. more importance is given to the economic cost in the EU context,), and role distribution between policy decision makers and science-for-policy actors.

In Switzerland, for example, the final EED list is defined by policymakers in consultation with industry stakeholders, based on fact-based data provided by researchers. In their conclusions, the researchers suggested that policymakers should determine the relative weighting of environmental and economic dimensions in the analysis. As an illustration, they presented results with equal weights assigned to both dimensions. In the EU, however, the researchers went a step further by providing a concrete proposal for an EED list, effectively indicating where they considered the balance between economic costs and environmental benefits should be struck. Policymakers receiving this proposal can then choose to adopt it as is or adjust it according to their priorities.

If mandatory removal of EEDs from ELVs for separate recycling is implemented, the recycling yield of precious and critical metals will increase in both the EU and Switzerland. If only Switzerland was to adopt such measures, however, this could create an incentive to export ELVs abroad for treatment. By contrast, if the EU alone were to introduce such measures, Switzerland would face strong incentives to align its regulations to maintain compatibility with the EU market. The methodology presented in this study can also be applied to anticipate yield increases for specific materials, as well as to monitor the impacts of policy changes and assess the overall efficiency of the ELV recycling sector. The two applications demonstrate how this methodology was useful for policy makers designing or assessing new recycling measures. Indeed, in order to evaluate the proportionality of a measure, combining environmental and economic assessments into an integrated and coherent model based on a material flow analysis is a necessity. Moreover, taking advantage of the similarities between different markets (in this case EU and Switzerland) allows to use similar approaches and base data to model the results of a change in recycling policies.

Nevertheless, the methodology in its current form has several limitations.

The methodology was designed to assess policy measures on recycling, which is only one of several possible circular economy strategies (Kirchherr et al., 2017). It can be difficult to integrate and compare other circular economic measures such as reducing the number of vehicles, repairing or refurbishing the EED. As the objectives and outputs of the three assessed dimensions need to be adapted for the new context. In application A, a share of EED is removed from ELV to be reused, and this is accounted for in the MFA. However, there is no assessment of the environmental benefits or economic cost of reuse compared to separate recycling. Extended system boundaries and adapted assessment approaches considering life-time extensions through reuse of EED, for example, might allow to compare the costs and benefits of other circularity strategies such as reuse, repair, refurbish, with recycling.

In both applications, the economic assessment considers only additional operational costs of the alternative scenario. However, other potentially significant costs, linked for example to the administration and management of a financing system, to research and development or recycling technologies, or to investment in new infrastructure could also be the consequence of a new recycling policy measure. Moreover, the base hypothesis that any additional recycling measure will lead to an increase in costs can be debated. For example, if the new recycling policy makes a more efficient but capital-intensive technological or technical innovation mandatory in order to improve the economic performance of recycling, the alternative scenario can in fact become less costly than the base scenario in the long term. In both applications, the new policy aims at overcoming some barriers to a new economical optimum, such as access to capital, removal of the competitive advantage of not investing, willingness to take risks, awareness of the potential, strategic clarity, availability of technology or existence to a secondary market for output materials. The recycling of rare earths from permanent magnets could be one such example.

The environmental assessment doesn't consider the effect of improving or worsening the management of hazardous substances that a new recycling policy could have. For example, some headlights used diodes that contain mercury. In the current system, those are shredded with vehicles containing them. However, if headlights are removed to be recycled separately, they need to undergo a depollution operation, where such diodes are removed and disposed of in hazardous waste treatment facilities, which is an improvement in terms of hazardous materials segregation and disposal. This potential benefit is not considered in this methodology.

Furthermore, active stakeholder engagement, seen as relevant criteria to enhance the quality of environmental policy decisions, and effects were not fully assessed within this framework and might need further investigation. Stakeholder participation should be in principle considered as early as possible within this integrated methodology, engaging with relevant stakeholders systematically towards robust exploitation in policy-studies (Fæhn and Stoknes, 2023; Gregory et al., 2020; Reed, 2008).

From a general perspective, this methodology depends on large amounts of data, parameters, hypotheses and projections. The initial uncertainties of all those variables are propagated and exacerbated in the calculations of the model, which must be managed in a transparent manner. For example, it would be helpful to assess the robustness of the assumptions considered for each scenario by doing sensitivity analyses of its parameters.

Identifying those limitations allows to interpret the results of this methodology properly. Addressing them would make the methodology more precise, accurate and flexible to other contexts and products. Still, as demonstrated in the applications, the general approach and results of the methodology in its current form provides critical information and a lot of value for policy makers.

6. Conclusion

The methodology outlined in this study is designed to aid policymakers in evaluating a recycling policy measure mandating separate recycling for EED within WEEE recycling facilities. Using results obtained through this methodology, policymakers can assess if the environmental benefit of separate recycling is worth the economic cost for each EED type, a trade-off often expressed by the principle of proportionality in legal texts.

The methodology models at least two scenarios for each the Swiss and the EU waste management system: the baseline scenario representing the current situation, and an alternative scenario reflecting the expected outcomes of a proposed policy measure. It integrates an MFA, an LCA-based environmental assessment, and an economic assessment, enabling the evaluation of the economic and environmental implications of the alternative scenario.

The three model components are interlinked: MFA results provide key data inputs for the environmental and economic assessments, and all components share external parameters such as EED material composition, transport distances, and the ratio of different drive trains in the ELV fleet. This interconnected approach ensures coherent results in terms of material flows, environmental benefits, and economic costs, facilitating comparisons and analyses across different scenarios.

This methodology was used in two distinct policy contexts. Initially developed and applied in Switzerland, it informed the revision of the ORDEE, which mandated separate recycling of EED if deemed both environmentally beneficial and economically viable. This involved scientifically evaluating various EED types to establish criteria for their separate recycling.

In the second application, the methodology was adapted for use in the context of the revision of the ELVD in the EU. The goal was to improve recycling of ELV components in order to minimize the CRM losses. Evaluating separate EED recycling within WEEE facilities was explored as a policy measure to address circularity gaps. The objective of this application was to identify which EED types were meeting the principle of proportionality.

In the Swiss application, 41 EED types were benchmarked to provide a fact-based foundation for policy makers to establish thresholds for proportionality. In contrast, in the EU application, these thresholds were integrated into the methodology, resulting in the selection of three EED types. Notably, the top three EED types identified in application A (headlights, amplifier and control module for automatic transmission) differed from those selected in application B, illustrating how contextual factors such as CRM importance and economic considerations influence the interpretation of similar raw results.

These applications underscore the methodology's utility for policymakers in developing and assessing recycling measures. By modelling the potential impacts of policy interventions and comparing them with current practices, the methodology supports informed decision-making. Crucially, integrating environmental and economic assessments through material flow analysis ensures a comprehensive evaluation of policy proportionality.

Future research could build on this methodology in several directions. Proportionality could be reframed beyond a binary threshold towards multi-criteria optimization problem, enabling policymakers to explore trade-offs of environmental, economic, and social dimensions. Additional sustainability aspects, such as labor conditions, regional employment effects, innovation, and risk management, could also be integrated. Methodologically, the approach could use a dynamic MFA that reflects vehicle fleet evolution and technological change, while also incorporating circular economy strategies beyond recycling, including reuse, repair, and remanufacturing. Finally, refined cost modelling that incorporates capital investments, financing schemes, economies of scale, and technology learning curves would allow for a more realistic assessment of the long-term implications of policy measures.

Beyond ELVs, the framework could be adapted to other waste streams and policy contexts, such as small electronics (such as mobile phones, laptops, etc.), renewable energy technologies (PV inverters, wind turbine electronics), or battery systems. In these applications, the methodology could support policymakers in evaluating proportionality across diverse circular economy measures, thereby enhancing its relevance and robustness.

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CRediT authorship contribution statement

Charles Marmy: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nacef Tazi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martina Orefice:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation. **Maria Ljunggren:** Writing – review & editing, Validation, Formal analysis. **Yifaat Baron:** Writing – review & editing, Validation, Formal analysis. **Manuele Capelli:** Methodology, Investigation, Formal analysis, Data curation. **Fabrice Mathieux:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition. **Patrick Wäger:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

Patrick Waeger reports financial support was provided by Stiftung Auto Recycling Schweiz. Patrick Waeger reports financial support was provided by Federal Office for the Environment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The research on which this paper is based was carried out with financial support from the Swiss Federal Office for the Environment (FOEN), Stiftung Auto Recycling Schweiz (SARS), and Chalmers University of Technology via the Area of Advance Production.

The author would like to express sincere gratitude to Isabelle Baudin (formerly FOEN), Daniel Christen (SARS), Rolf Widmer, Amund Loevik, Eliette Restrepo, Lorena Toledo and Heinz Böni (formerly Empa) for their valuable guidance, support, and the stimulating exchanges that contributed to the development of this paper.

Data availability

Data will be made available on request.

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