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Initial analysis of selected measures to improve the circularity of critical raw materials and other materials in passenger cars

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Contents

Abstract

The European Commission is investigating several measures to reduce the supply risk of critical raw materials (CRMs) and increase their circularity. This is also investigated in the framework of the ongoing joint revision of the end-of-life (EoL) vehicles (ELV) directive (Directive 2000/53/EC, also known as the ELVD) and the directive on the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability (Directive 2005/64/EC, also known as the 3RTA). Investigated measures are also compliant with the objectives of EU strategic autonomy and the CRM act.

An initial analysis of measures is provided in this report, based on Joint Research Centre (JRC) and partners' consolidated data and knowledge on the composition of current and future critical and other materials in vehicles, to address market and/or circularity failures of targeted CRMs and other materials in passenger cars. These measures could be integrated into the ELVD or 3RTA to reach the common objective of increasing the circularity of CRMs and other materials in vehicles. Following this, a dedicated analysis of the impacts of shortlisted requirements from the assessed policy measures and the selected materials is provided.

The development of the impact assessment indicates that the investigated requirements could increase critical and other materials' circularity compared to a baseline scenario reflecting current EoL management practices. Overall, the investigated requirements could also generate additional socioeconomic benefits and improve the environmental performance of ELV management along with supporting innovation in the automotive value chain.

Other accompanying requirements and synergies that can be developed with ongoing investigated measures to increase the circularity of vehicles are also discussed.

Foreword

At the request of The European Commission's Directorate-General (DG) for Environment and DG Internal Market, Industry, Entrepreneurship and SMEs, this report was prepared to support the ongoing joint review of the end-of-life vehicles directive (ELVD) and the directive on the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability (3RTA). It assesses the impact of potential measures to increase the circularity of critical raw materials (CRMs), which are also covered by the CRM act. This report should not be interpreted in any way as a policy proposal from the European Commission that may be accompanied in due time by specific impact assessment material presented concomitantly with each proposal, as per the formal EU legislative procedure.

This report provides an initial analysis based on a number of modelling assumptions described in the report. Some requirements (coupling measures addressing targeted materials) addressed in this report are based on already existing ones addressing CRMs in other legislation. The formulation of requirements, their assumed timelines of implementation and the results of the preliminary impact assessment presented are an initial exploration, and further investigations are needed to fully cover all aspects of the assessed measures.

Acknowledgements

The production of this report was guided by Unit B.3 of DG Environment and Unit I.1 of DG Internal Market, Industry, Entrepreneurship and SMEs. We would like to thank Commission colleagues for the fruitful discussions and contributions to increase the quality of this work. We also acknowledge the exchanges, data and insights from targeted stakeholders, along with the review performed by Joint Research Centre (JRC) colleagues, which increasingly enhanced the quality of this report. Special thanks also to Pierre Gaudillat and Michaël Clairotte for the final review of this document. The graphical support was provided by Päivi Sund.

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Executive summary

The automotive value chain employs materials derived from over 60 raw materials, including critical raw materials (CRMs). In particular, the automotive sector consumes circa 50 % of the overall EU use share of some CRMs. However, at the current stage of end-of-life (EoL) vehicle (ELV) management, many of those materials, including CRMs with very high supply risks, are not recovered at all or not at their best.

- Policy context

  This *Initial analysis of selected measures to improve the circularity of critical raw materials and other materials in passenger cars* report, launched by the Joint Research Centre (JRC), is embedded in the activities of the current ongoing review of the ELV directive (ELVD) and the directive on the type-approval of motor vehicles with regards to their reusability, recyclability and recoverability (3RTA). It is also closely linked to the circularity objective of the CRM act. The latter is also related to the Versailles Declaration on CRMs and to the objective of achieving EU strategic autonomy, and an impact assessment of measures to increase the circularity of all materials targeted in the CRM act is being prepared.

- Objective and methodology

  The present study contributes to the abovementioned goals and provides an initial analysis of selected measures to improve the circularity of CRMs and other relevant materials in passenger cars.

  The report first addresses the state of play regarding relevant critical and other materials that present important market and/or circularity failures, which are then paired with measures to be potentially implemented in the revised ELVD and 3RTA. A group analysis by all partners involved in this study was carried out to assess each pair and shortlist the most relevant requirements to be further assessed.

- Main findings and expected benefits

  The four shortlisted requirements to be further assessed in this study are:

  — requirement 1 on mandatory removal of e-drive motors by authorised treatment facilities (ATFs);
  — requirement 2 on design provisions for e-drive motors;
  — requirement 3 on mandatory removal of selected electric and electronic components (EECs) by ATFs;
  — requirement 4 on information request for specific CRMs contained in vehicles and their labelling.

  The assessment of the impacts of the mentioned requirements covered the following dimensions:

  — material flows and secondary raw material (SRM) production;
  — environment-based assessment;
  — socioeconomic assessment, including impacts on innovation and administrative burdens.

  All of the assessed requirements contribute to the common objective defined in this report. The results of the preliminary impact assessment provide initial insights on the performance of each requirement. All four requirements provide added value to the quantity and quality of EU SRMs from ELV management. They contribute to reduce the environmental impact of vehicles and lead to extra revenues and additional job creation at the ATF level. None of the four requirements investigated hinder innovation, and all of them contribute to research and development (R & D) in the automotive value chain.

  Further expected benefits from the assessed requirements reside mainly in the contribution to the development of proper management of the EoL of e-drive motors, filling an important missing step in their value chain and promoting their circularity by establishing practices in the EU for reuse, remanufacturing and recycling. Another expected benefit would be the increased circularity of precious metals such as gold (Au) and silver (Ag) and of strategic metals such as copper (Cu), thus leading to the development of additional secondary markets in the EU and increasing its strategic autonomy.

- Related and future JRC work

  This report was jointly developed by the JRC and its partners as a first tentative step to investigate measures and initiatives to increase the circularity of CRMs and other materials in vehicles. It is embedded in the continuous assessments of the automotive value chain led by the JRC and it tackles several roadblocks and barriers in this sector to added circularity. Future research, in close partnership with directorates-general, should continue to investigate further measures, in the short and long term, to reduce the automotive value chain supply risk and increase its circularity.

- Quick guide

  Section 1 introduces the report and provides a succinct background of the project. Section 2 describes the project structure and introduces the experts and partners that jointly drafted this report and its assessment. It also presents the methodology used for the initial analysis of measures to increase the overall vehicle circularity. The analysis of knowledge on CRM and other materials used in vehicles and their EoL management is presented in Section 3. Following this, the investigated CRMs, measures and the methodology used to shortlist initial requirements (coupling measures applied to materials) are addressed in Section 4. Such requirements are then described in Section 5, providing a clear scope, timeline and objective for each requirement. Section 6 presents the results of the preliminary impact assessment of each requirement described in Section 5. It also provides recommendations on their deployment, along with potential synergies and accompanying measures to implement them efficiently. Conclusions and potential follow-up works are presented in Section 7.

1. Introduction

This introduction presents the background that led to the development of this work, the objectives of the study and the organisation of this *Science for Policy* report.

Vehicles put on the EU market are subject to the type-approval of motor vehicles with regards to their reusability, recyclability and recoverability ([1]) (referred to by Directive 2005/64/EC). The management of end-of-life vehicles (ELVs) is also regulated in the EU by Directive 2000/53/EC ([2]) (the ELVD), with the exception of the management of specific components such as batteries. However, both legislative instruments are not necessarily aligned with each other, and do not reflect the significant changes in the automotive value chain in recent decades. For instance, while the text for a new battery regulation proposal has been recently agreed on ([3]) to meet the large transformations in the market due to the spread of lithium-based batteries, the current ELVD does not yet reflect the similar transformations in the EU vehicle market and in particular the rising share of electric vehicles (EVs). Since EVs were just arriving on the EU market at the time when the ELVD was last revised, they were not mentioned explicitly in the ELVD itself, implying the potential imbroglio and risk of not being efficiently covered. The current ongoing review of both directives is thus an opportunity to increase their robustness and make them more future-proof in the face of technological and process advances.

Current practices in all steps of the automotive value chain have led to several market and circularity failures, namely inefficiencies in production and allocation, the uncompetitiveness of products put on the market, or incomplete information on the products leading to market outcomes that differ from those that would lead to the highest benefits for society. Generally speaking, circularity failures are observed when the circularity ([4]) of a material in a component is not maximised, for example because of technical limitations or market reasons (e.g. limited demand for secondary raw materials (SRMs)). This is observed in all types of drivetrains. There are, for instance, losses of valuable components and materials from EV parts, such as the example of electric drive (e-drive) motors containing (when present) rare-earth permanent magnets (REPMs). Even referring only to the more traditional internal combustion engine vehicles (ICEVs), those went through a remarkable and continuous electrification of their components with a higher share of precious and critical metals (e.g. gold (Au), palladium (Pd), gallium (Ga)) and strategic metals (e.g. copper (Cu)). Similarly to the REPMs, these materials are lost in current ELV management due to the lack of specific targets in the ELVD coupled with insufficient market drivers. To be specific, materials are considered lost not only when they are not recycled but also when they are downcycled into other materials, for instance ending up in steel recycling as impurities, because this also subtracts them from their value chain. The EU's overarching legislative packages aim to increase the sustainability and circularity of materials used in the EU. This is an explicit objective in the raw materials initiative ([5]), the circular economy action plan ([6]), the ecodesign for sustainable products regulation ([7]) and the European Green Deal ([8]). Circularity is also particularly targeted in several product-specific directives and regulations such as the waste electrical and electronic equipment (WEEE) directive, the next battery regulation and the ELVD. Indicators and monitoring instruments such as the raw materials scoreboard and the raw materials information system (RMIS) ([9]) are also deployed to ensure the implementation of the abovementioned packages. There is therefore a need to support the ongoing review of the ELVD and 3RTA with all necessary studies to achieve higher circularity of vehicles.

Lately, together with the increased supply risk and the global political context threatening the fair and sustainable supply of all the necessary materials to achieve the EU green transition, there is also a need to identify critical raw materials (CRMs) with high supply risk and economic importance to the EU value chain to achieve EU strategic autonomy. In the particular case of the automotive value chain, CRMs are used in various parts of

([1]) https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R0858.
([2]) https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex %3A32000L0053.
([3]) See COM(2020) 798.
([4]) A definition of circular economy is provided in the RMIS glossary (https://rmis.jrc.ec.europa.eu/uploads/A-B-C_Glossary_2020_09_08.pdf).
([5]) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52008DC0699.
([6]) https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en.
([7]) https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products_en.
([8]) https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.
([9]) https://rmis.jrc.ec.europa.eu/.

vehicles, and their supply risk is very high. In line with the objective of the Versailles Declaration ([10]) to reduce EU strategic dependencies, and in view of the CRM act defining CRMs for the EU economy ([11]), it was necessary to initiate further studies to investigate all the possible short- and long-term measures to reduce the criticality of materials and promote their circularity and resource efficiency.

The present study contributes to this effort by providing an initial analysis of selected measures and requirements to increase the circularity of selected materials in passenger cars.

([10]) https://www.consilium.europa.eu/media/54773/20220311-versailles-declaration-en.pdf.

([11]) https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en.

2. Project structure and methodology

2.1. Goal and scope of the study

In the context of the revision of the ELVD and 3RTA, the Commission is investigating measures to increase circularity in the value chain of road vehicles. This can be done at different stages of the vehicle life cycle, including at the design phase (related to type-approval legislation) and at the EoL stage (related to the ELVD). Several typical measures could involve, for example:

— recycled content, at the material level;
— recycling efficiency, at the material level;
— information request, at the material and/or part levels (targeting the investigated CRM/material);
— mandatory removal, at the part level (targeting the investigated CRM/material);
— mandatory dismantling for reuse and remanufacturing, at the part level (targeting the investigated CRM/material);
— ease of disassembly, at the part level (targeting the investigated CRM/material).

To support this effort of the European Commission, the present JRC work consists of: (1) a preliminary analysis to consolidate the Commission's data and knowledge of specific CRM content in vehicles ([12]), the current state of play and future trends; and (2) an initial assessment of the feasibility and of the costs/benefits of selected policy measures improving the circularity of key critical and non-critical materials in vehicles, to be implemented through ELVD and/or 3RTA. The assessment addresses the material flow analysis (MFA), socioeconomic analysis (including impacts on innovation and administrative burden) and environmental-based analysis of the potential benefits and burdens of each measure. The measures largely address embedded electric and electronic components (EECs), the quantity of which has been significantly increasing in new vehicles and which contain significant amounts of critical and precious metals, and electric drive motors used in hybrid electric vehicles (HEVs), plug-in HEVs (PHEVs) and battery electric vehicles (BEVs), collectively described as electric vehicles (EVs), which are expected to dominate the EU market for new vehicles, especially by the assumed time of implementation of the measures around 2030–2040.

2.2. Partners and organisation of the study

The JRC initiated and led the study, during the period from August 2022 to March 2023. A team of four partners was set up consisting of the JRC, Chalmers University of Technology, the Swiss Federal Laboratories for Materials Science and Technology (Empa) and the Oeko-Institute.

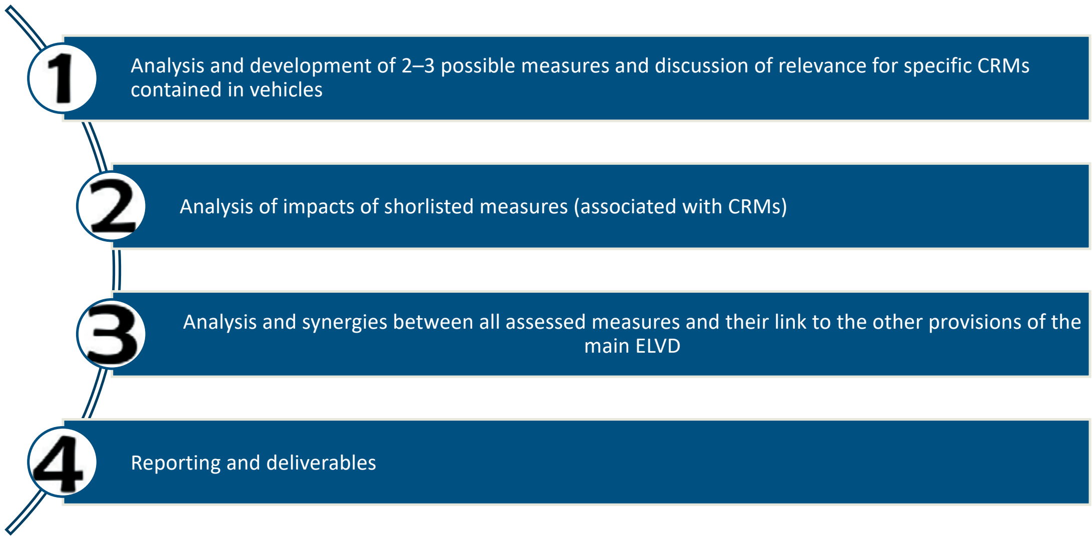
— Chalmers University of Technology (Sweden) already published several articles on the design and circularity of vehicles, with particular attention to CRMs, EVs and their electric drive (e-drive) motors (see for example Andersson et al. (2019); André & Ljunggren (2022); Tillman et al. (2020)).
— Similarly, Empa (Switzerland) has a deep knowledge of (circular) material flows (see for example Løvik et al. (2021); Marmy et al. (2023); Restrepo et al. (2018)) and has also worked with the Swiss Federal Office for the Environment (FOEN) on EoL vehicles provisions.
— The third expert partner is the Oeko-Institute (Germany), which the JRC is partnered with based on the joint review of the ELVD and the 3RTA. The institute also publishes policy briefs, reports and studies on the circularity of CRMs, including in the automotive sector (see for example Betz et al. (2021) and Mehlhart et al. (2016)).

All three partners have also been involved in EU projects and studies on the recovery of secondary raw materials (SRMs), such as 'Prospecting secondary raw materials in the urban mine and mining wastes', 'Optimising quality of information in raw material data collection across Europe', 'Future availability of secondary raw materials' (FutuRaM) or 'Voluntary certification scheme for waste treatment'.

The study was divided into four main tasks (see Figure 1), and each task into several subtasks. The partners were involved all together or individually on specific tasks, depending on the type of task and the expertise of each partner. The JRC supervised all the tasks.

([12]) Although this term is more generic and refers to other vehicles categories, it will be used in this report to refer to passenger cars.

Figure 1. Structure of the study

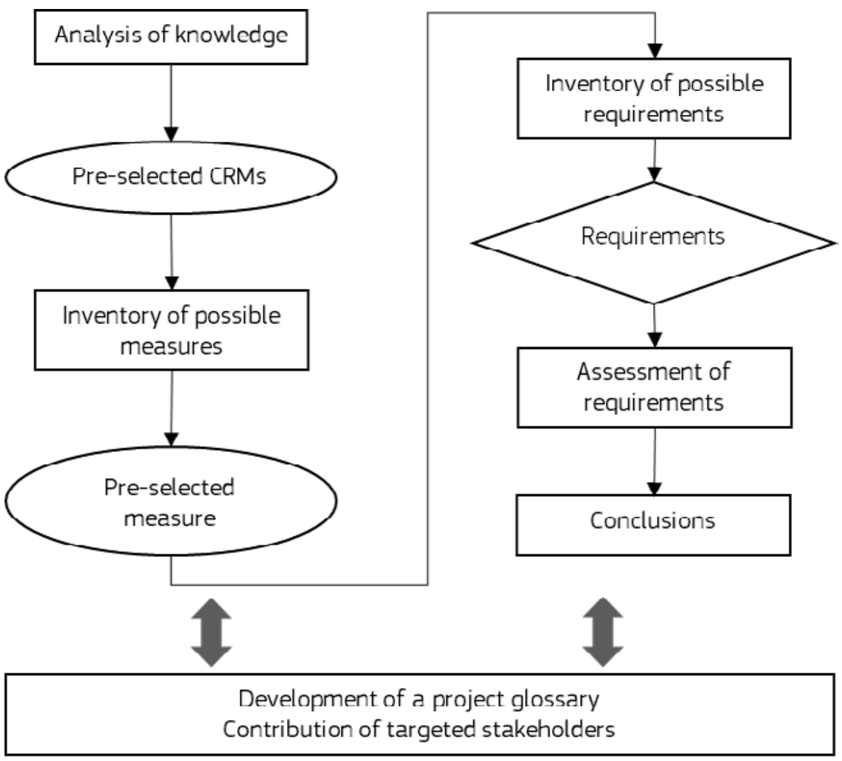


Source: JRC own elaboration.

2.3. Methodology deployed

The methodology used for the study included the review of scientific and technical literature, analysis of practices of a few selected stakeholders (original equipment manufacturers (OEMs) and waste management operators) and analysis and assessment performed by the project team. Despite the short period during which the study was conducted, a methodology was defined according to the process flow diagram in Figure 2.

Figure 2. Process flow diagram describing the project methodology. The square boxes represent the actions, the circle boxes the outcomes and the diamond box the milestones.



Source: JRC own elaboration.

The analysis of knowledge consisted of the study of the latest information about CRMs in vehicles and of management practices of ELVs and the current status of the main EU policies relating to new vehicles (Section 3), namely the 3RTA (a product policy) and the ELVD (a waste policy). Thus, measures both at the EoL and at the design and manufacture stage were considered. The outcome of this first analysis was a pre-selection of CRMs to be targeted with appropriate measures and opened to the second stage of the study, i.e. joint discussion and decision-making by the partners of the study to pre-select the possible measures (Section 4) and translate them into material-specific requirements (Section 5). Agreeing on an unambiguous glossary for the project was an important part of the project itself (see glossary). In particular, the following terms were defined.

— Component type or category: constituting an element of a larger product (e.g. a vehicle), made up of one or more parts, all necessary to a specific function.
— Measure: a policy instrument, at the product or waste level, with the purpose of producing a specific impact to tackle a specific failure (e.g market and/or circularity failures).
— Requirement: a combination of a measure and the targeted material(s) or component(s) to which it is applied. A requirement has a specific timeline, formulation and stakeholder target (e.g. recyclers, OEMs, end users).

Another element developed during multiple stages of the project is the contribution of targeted stakeholders. Since the study was carried out in a very limited amount of time, it was not possible to initiate a large and systematic data collection engaging a wide range of stakeholders. Nevertheless, the study team was able to consult a few experienced operators from the EoL phase: one expert in the EoL management of the automotive value chain (based in Belgium), one ELV and e-ELV dismantler (based in Italy), one metal recycler dealing also with fractions from the abovementioned dismantler, and targeted feedback from the European Steel Association. Additional collected data and feedback concerned car depollution, dismantling, shredding, sorting (also using post-shredding technologies (PSTs)) and recycling of SRMs from ELVs. Data and feedback were collected through a phone call with the Belgian operator and a visit to the plants of Italian operators.

The study also benefited from the experience, knowledge and network of the partners. In particular, the study team got feedback/input from selected OEMs or car repairers to discuss, mainly, information on the weight, bill-of-materials and ease of disassembly of parts such as e-drive motors and/or actuators.

It was necessary to target a selection of CRMs, measures and requirements to investigate because of the limited time and resources of the project, so two kinds of feasibility were considered: technical feasibility, i.e. the readiness of a requirement to be implemented; and project management feasibility, i.e. the ability of the team to address the task within the study. The shortlisted requirements were finally assessed in terms of MFA, environmental-based impact and socioeconomic impact (Section 6). This last stage of the project also included recommendations from the impact assessments and an analysis of possible synergies among requirements and of parameters to further analyse.

At the end of this report, you will find conclusions on the development of the study, on its results and on the possible impacts, together with ideas for a possible continuation of the study.

3. Analysis of knowledge on CRMs in vehicles and ELV management

3.1. CRMs in vehicles

The automotive value chain employs materials derived from over 60 raw materials, to be used in ICEVs and EVs, although > 95 % of the weight of the vehicles (Parchomenko et al., 2021) is made up of only 11 materials for ICEVs (iron (Fe), steel, plastic, copper (Cu), cast and wrought aluminium (Al), lead, carbon black, glass, paint and rubber) and only 14 materials for EVs (Fe, steel, plastic, Cu, wrought Al, neodymium (Nd) for permanent magnets (PMs), cathode active materials, graphite, ethylene carbonate, electrolyte, carbon black, glass, paint and rubber).

From a material flow perspective, most of the value of an ELV is in the base metals (steel, Al and Cu), CRM flows are scarce compared to the base metals, and their content differs significantly between ICEVs and EVs (Løvik et al., 2021). ICEVs in particular contain cerium, lanthanum, palladium (Pd), platinum (Pt) and rhodium in the catalytic converter, whereas EVs contain many CRMs in the electric power train, namely Nd ([13]) and dysprosium (Dy), mainly in the REPMs of the e-drive motor, and lithium, cobalt, manganese (Mn), and nickel in the battery. A trend applicable to both ICEVs and EVs is the increase in electrics and electronics which corresponds to a higher content of silver (Ag), gold (Au), Dy, Nd and Pd (Bobba et al., 2020). The future spread of fuel cells vehicles will also require large amounts of Pt and Pd. As for most used metals, larger demand for Cu and Al is observed due to the transition from ICEVs towards EVs ([14]). On the other hand, the shift towards EVs increases the use of wrought Al over cast Al; the former contain CRMs: 4xxx and 5xxx Al-alloys contain silicon (Si) and magnesium (Mg) respectively, alongside other metals such as Cu and Mn, while silicon steel (Si-steel) contains up to 3.5 weight percent (%wt) of Si metal (see also Glossary), and high-strength steel is relevant for its Niobium content, along with Mn and Si.

Similarly, Mg alloys are also made up of Al and Mn and, in general, the automotive sector corresponds to 50 % of the Mg demand in the EU (European Commission, 2020). Finally, it is supposed that vehicles also have significant amounts of Ga, in integrated circuits, sensors and microchips, and of titanium (Ti), but little to no data are available for these two elements. In Annex I a summary of (critical) materials in vehicles and their main use is reported.

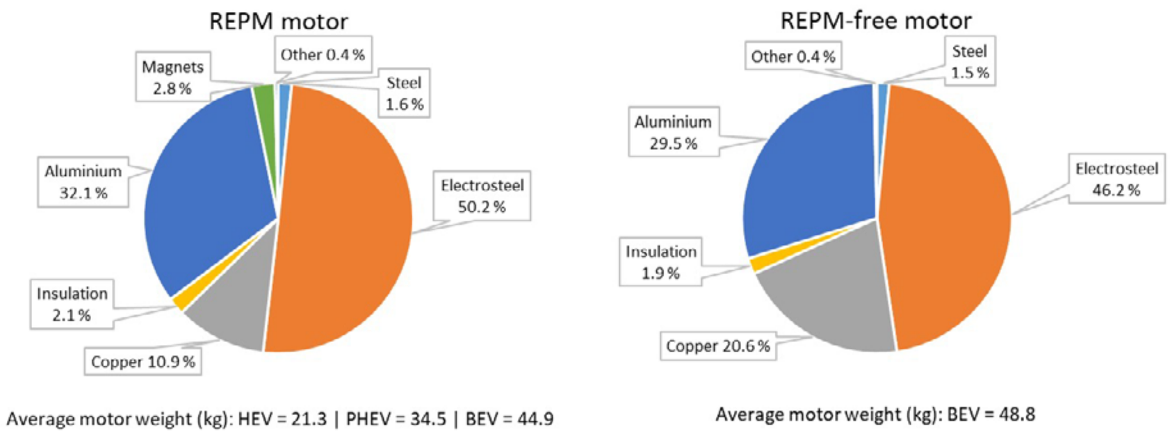
Despite their relevance, materials in EV batteries are not included in the scope of this report because they are specifically covered by other EU policies; neither are materials in catalytic converters, since their high economic value provides a significant incentive to recycle them. Nonetheless, platinum group metals (PGMs) such as Pd in electronics were considered in the analysis and selection in this study. Rare-earth element (REE) mining and smelting has tremendous environmental impacts (Takeda & Okabe, 2014), and REE recovery from ELVs is null. REEs are present in several components of both ICEVs and EVs: for instance, glass windows and catalytic converters have lanthanum and cerium (albeit not recovered); electronics, actuators and small motors do have REPMs even if they belong to ICEVs, as found from indirect evidence of shredded ICEVs. However, undoubtedly, the largest consumption of REPMs is in e-drive motors. It is worth noting that REPMs in e-drive motors and small motors are not the same with regards to composition – the former have a higher content of light and heavy REEs, while the latter are mainly based on ferrite magnets – and also differ in terms of recyclability, as discussed in Section 3.2.2. A second type of e-drive motors do not have REPMs but only Cu induction coils (REPM-free e-drive motors, see Glossary), however they have a significantly lower market share and contain almost no CRMs. It has been reported (in Munoz (2022) and Løvik et al. (2021)) that PHEVs and HEVs exclusively use REPM e-drive motors, while circa. 23 % of BEVs sold in Europe in 2021–2022 use REPM-free e-drive motors.

In this study it is assumed that such market share distributions will remain constant for EVs until 2040. In Figure 3 the bills of materials of REPMs and REPM-free e-drive motors are reported (Tillman et al., 2020). Although some recent OEM announcements reported the decreasing use of rare-earth elements, especially Dy, REPM material demand is unlikely to change in the coming years. The increasing global electrification of vehicles is also leading to an overall increased long-term demand for REPM materials. As for REPM-free motors, OEMs are to date relying on Cu rotor winding, and a major switch to other materials (such as Al) is unlikely to be seen in the next years, as Cu offers the best performance.

([13]) Although it is mainly neodymium-praseodymium Nd(Pr) alloy, it will be referred to as Nd in this report.

([14]) See https://rmis.jrc.ec.europa.eu/veh#/p/intro.

Figure 3. Bill of main materials (%wt) of e-drive motors and average weight (kg)

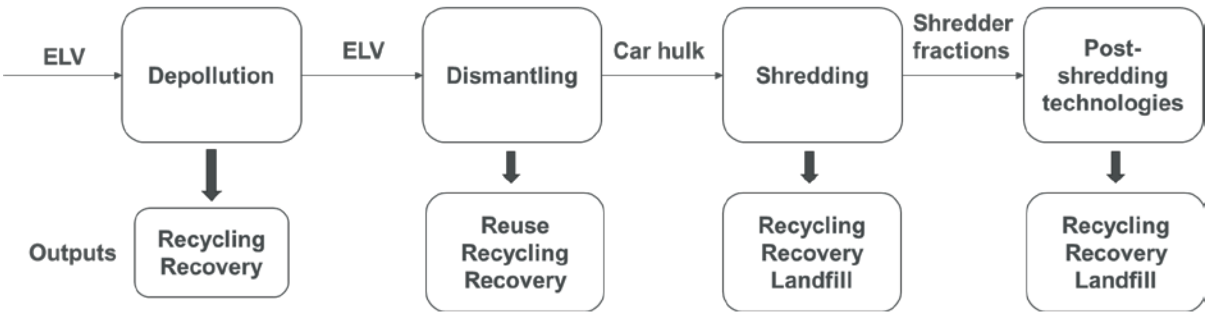


Source: JRC own elaboration, based on (Tillman et al., 2020).

3.2. ELV treatment and recovery chain

The EoL management of vehicles is currently regulated by the ELVD, although practices can change at the local level from country to country. In Figure 4, a generic scheme on ELV treatment is shown.

Figure 4. Generic scheme of ELV management.



Source: JRC own elaboration.

* Recovery is meant either as incineration (with or without energy recovery) or as defined in Annex II to Directive 2008/98/EC ([15]) and is different per each fraction.

Depollution and dismantling are usually carried out by authorised treatment facilities (ATFs). Depollution of a vehicle includes the removal of all the fluids, battery and explosive components (airbags), along with other components, as required by the current the current Annex I(3) to the ELVD. Dismantling (destructive and reversible) includes the removal of components such as bumpers, catalysts and tyres in order to promote recycling or energy recovery. Some of these are addressed in Annex I(4) to the ELVD, while other components are removed for reuse/remanufacturing purposes. The remaining car body is sent to a shredder facility generating automotive shredded residues that are sorted to separate the ferrous and non-ferrous fractions, which contain several materials. These fractions, together with other shredder residues, might eventually be further sorted with PSTs to improve the purity of the obtained fractions and consequently the quality of recycling at the recycler's facility. The remaining non-recycled flows are generally diverted to incineration (with and without energy recovery) and landfill.

Targeted actions prior to shredding such as disassembly operations instead of dismantling (the extent to which the disassembly process is performed, including the number of steps required to disassemble selective parts from the component) might increase the amount and reusability of recovered components: for instance, disas-

([15]) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32008L0098.

sembly for reuse is mainly triggered by market needs and demand, as it is also confirmed by ATF managers. It mainly targets ELVs that had a short use phase. Last year a report by the French Agency for Ecological Transition estimated that around 82 kg of material per ELV was extracted for reuse (Deprouw et al., 2022). Disassembly requires more efforts and time at ATF level to remove the component from the vehicle without destructive operations. Systematic removal of large and heavy components (containing a mix of materials such as metals and plastics) from the ELV is advocated for and is technically feasible (Potrykus et al., 2020) ([16]).

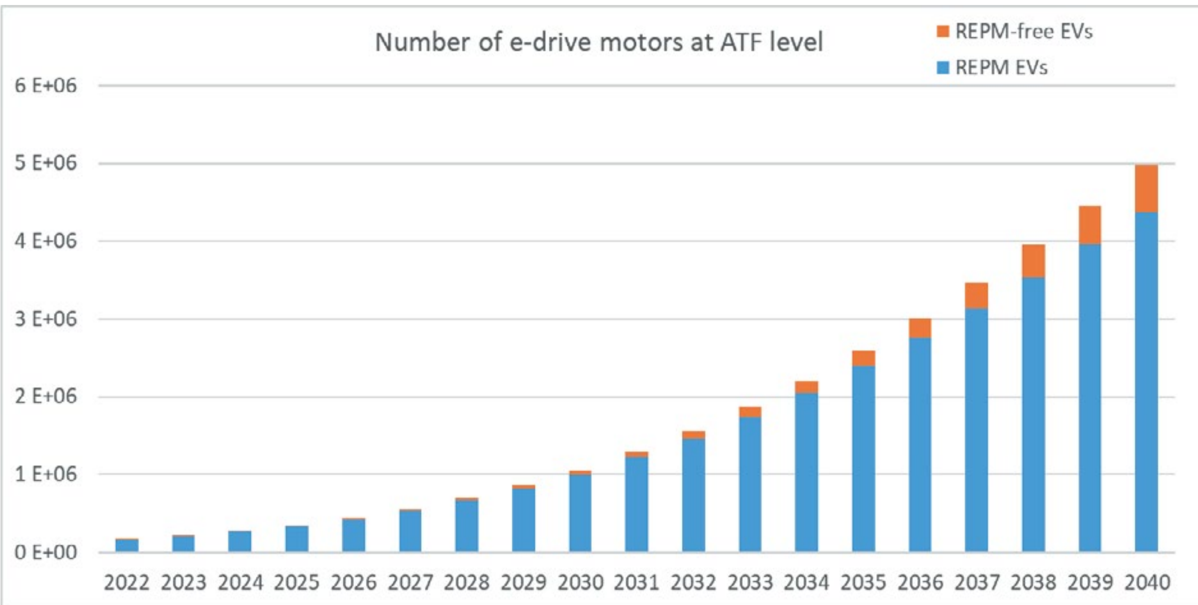
What remains of the car bodies afterwards is shredded as it is, or mixed with other waste flows such as white goods (e.g. fridges or other large household appliances). The variability of the input flow at the shredder and the variability of the granularity of the shredded parts make the quality of the shredded fractions heterogeneous. The deployment of PSTs throughout the EU varies as well, even at the Member State level. One example is the glass fraction which is not recovered and ends up in the inert material phase at the shredder facility, but the European Association for National Associations of Automotive Recyclers in Europe reported that ATFs in Italy also recover the glass to preserve the health of the shredding machines. In fact, the ELVD gives no indication on the implementation of PSTs, while these are increasingly reaching a level of efficiency that makes it possible to also recover minor fractions or to separate different Al alloys. The main obstacles to the deployment of common PSTs at the EU level are the inhomogeneous quality of the upstream shredded fractions and the cost of all the technologies.

Two cases can be illustrated as circularity failures: the recycling of e-drive motors and the recycling of EEC group. The main reason is that these components are not disassembled. The next two sections describe the current state of play of their EoL management.

3.2.1. Case study of e-drive motors

The majority of e-drive motors contain REEs, which are lost in the shredding operations and for which the EU has an import reliance of 100 %. The baseline scenario for these and the REPM-free e-motors is that they are not disassembled. In Figure 5, the forecasted amounts (in number per year) of e-motors collected at the ATF level are presented.

Figure 5. Forecasted (number of) e-drive motors from EVs at the ATF level



Source: JRC own elaboration. Forecast based on Euro 7 forecast data. Passenger cars lifetime based on Weibull distribution. All HEV and PHEV e-drive motors are REPM motors. 23 % of BEVs have REPM-free motors. Collection rates for EVs at the ATF level match with collection rates of EV batteries.

([16]) Also based on the statement of an ELV and eELV dismantler based in Italy, in 2022.

This means that the potential collected and disassembled REPM e-motors would contain a deposit of about 0.7 kilotons (kt) of REPMs in 2030 and 4.2 kt in 2040, whereas the same total number of e-motors would contain circa 15 kt of Si-steel in 2030 and 89 kt in 2040. Cumulated Cu content in the collected ELVs would be up to 3.5 kt of Cu in 2030 and 22 kt in 2040. A baseline scenario on the recycling output rates of the materials in e-motors is reported in Table 1, based on the support study for the ELVD review study (Baron et al., 2022) and on expert feedback on circular economy for e-drive motors (Tillman et al., 2020).

Table 1. Recycling rates assumed for the e-drive motor baseline scenario in 2022, 2030 and 2040 (e-motor shredded within the car hulk)

Material	Baseline recycling rate %
Steel (including Si-steel)	87 %
Al	82 %
Cu	3 %
Magnets (Neodymium (NdFeB))	0 %

Source: JRC own elaboration. Baseline recycling rates are the same for 2022, until 2040. Si-steel is assumed to be recycled along with other steel grades.

For the sake of convenience, one baseline scenario is assumed for the years 2022, 2030, 2035 and 2040, meaning that no changes in the recycling rates are expected without in-force policy measures such as the motor disassembly. Moreover, the recycling output rates for materials contained in both REPM and REPM-free e-motors are assumed to be the same. It can be noted that Si-steel is assumed to be recycled along with other steel grades. In contrast, Si-metal is a CRM and is assumed to not be functionally recycled as such. This means that at the material level, Si-steel is recycled within other metal streams, but at the elemental level, Si-metal is lost and not recycled. Given the concentration of Si in Si-steel of up to 3.5 %wt, the baseline scenario would correspond to a loss of Si-metal corresponding to up to 2.7 kt in 2040. Similarly, 4.2 kt of REPMs (including Nd and Dy) would be lost in 2040. As for Cu, only 0.5 kt would be recovered in 2040 from the e-drive motors allocated flows, according to the baseline.

In conclusion, it is evident that the lack of policy interventions contributes to losses of the CRMs Si, Nd and Dy in the e-motors and a very low recovery of Cu, a strategic material for the transition to e-mobility. Also, the recovery of base metals such as steel and Al, although already high, might benefit from the right policy measures, since creating a separate recycling flow of Si-steel and Cu might also increase the quality of recycled steel and Al, where usually these materials are contaminants (see Section 6.1).

3.2.2. Case of EECs

The baseline scenario for EECs is extracted from the EVA II report (Marmy et al., 2023 – see Section 3.2.3).

There is a large variety of EECs that belong to three main categories.

- Controllers: components that perform control tasks in the vehicle, by using data provided by sensors and sending instructions to actuators. Controllers typically contain printed circuit boards (PCBs). Most of the precious metals present in vehicles are concentrated in this category.
- Actuators: components that perform motion functions with the help of components such as small electric motors. They rely on PMs that can contain Nd or Dy.
- Sensors: components that measure physical parameters in or around the vehicle. The dimension of sensors is very small; they contain only small quantities of precious metals and CRMs, and they are commonly distributed to many locations in the vehicle. As a consequence, this category of devices was not considered in this study due to their lack of potential in terms of material recovery.

Some specific devices cannot univocally be classified in any of those categories, and therefore constitute distinct categories of their own.

- Headlights: modern models contain actuators, sensors and controllers, in order to perform functions such as detecting the intensity of ambient luminosity, orienting the light beam and controlling those actuators.

Therefore, they share the characteristics of controllers and actuators, and contain valuable plastics such as poly(methyl methacrylate) (PMMA).

— Cables: vehicles depend on cables to link all components together and provide them with electricity, data and instructions. They contain mostly Cu and plastics.

As for the case of e-drive motors, the baseline scenario is considered the same for the years 2022, 2030, 2035 and 2040 and, more precisely, no removal of the components for separate recycling is considered to occur. However, the current disassembly for reuse still takes place. Hence, the EECs are either disassembled for reuse or sent for shredding with the rest of the car hulk, where only (part of) the base metals composing them will be recovered, as also reported in Table 2.

Table 2. Baseline material recovery from the stream of the four categories sent to recycling, as assessed in the EVA II report

	Recovered materials from embedded electronics (%wt/component)										
	Fe	**Al**	**Cu**	**Au**	**Ag**	**Pd**	**PP**	**PMMA**	**ABS**	**PC/ABS**	**Losses**
Headlights	7.2	8.3	0.3	0	0	0	0	0	0	0	84.2
Actuators	25.2	20.2	1.3	0	0	0	0	0	0	0	53.3
Controllers	38.8	18.1	1.2	0	0	0	0	0	0	0	41.9
Cables	0	0	37.5	0	0	0	0	0	0	0	62.5

Source: EVA II report (Marmy et al., 2023). This table excluded the portion of each component category that is removed (prior to shredding) from the ELV and used as spare parts. Polymers are defined in the glossary.

The table does not only include base metals and precious and critical metals, but also plastics (mainly polypropylene (PP), acrylonitrile butadiene styrene (ABS), polycarbonate-ABS (PC/ABS), and PMMA). In the EVA II report (Marmy et al., 2023), to estimate the recovery rate of the baseline scenario (production of SRMs from EECs still embedded in cars in an ELV recycling facility), it is assumed that the treatment processes are equivalent to those in a typical electronic waste (e-waste) recycling for the base metals. However, since ELV recycling facilities are not generally designed to sort PCBs and plastics in specific fractions, those materials and the elements they contain end up in a waste output called shredded light fraction (SLF) that is then incinerated. Thus, materials that would end up in those fractions in an e-waste recycling facility are considered as lost in the baseline scenario. As a consequence, Al and Fe are recovered very well in all scenarios, Cu is partially recovered in the baseline scenario compared to the others, and precious metals are completely lost without a separated recycling flow of EECs. The scenario and its consequences are very similar to those for e-motors, with the only difference being that a minimum flow of disassembly for reuse (second sale) is carried out for components such as headlights or actuators but not for e-motors. Similarly, removing the embedded electronic components prior to shredding will also result in a higher quality of recycled steel and Al. Therefore, an intervention to introduce mandatory disassembly of EECs seems necessary and is evaluated in the following sections.

3.2.3. Recent review of the Swiss ordinance on e-waste

The Swiss ordinance on e-waste (OREA) ([17]) was revised from 2016 to 2021 and entered into force on 1 January 2022. This legal text addresses all kinds of electrical and electronic equipment (EEE), including devices embedded in other products or buildings. It provides the disposal requirements applicable to any EEE in its scope. In particular, e-waste falling under the OREA must be collected separately from other waste, and recycled insofar as this is technically feasible, economically viable and ecologically sound. Recyclable materials contained in those EEE, such as Fe, Al, Cu, some plastics and glass, must be appropriately recovered. Moreover, the so-called scarce technology metals (STMs) ([18]), such as Au, Ag, indium, Ga, germanium, Nd or Dy, must also be recovered when possible. Any material that cannot be recycled must be incinerated.

([17]) Swiss ordinance on the return, take-back and disposal of electrical and electronic equipment, originally in French: *Ordonnance sur la restitution, la reprise et l'élimination des appareils électriques et électroniques* (https://www.fedlex.admin.ch/eli/cc/2021/633/fr#lvl_d867e23).

([18]) STMs consist of precious metals, rare-earth metals and other special metals, that are scarce in the earth's crust, and have specific physical properties that make them essential in various technologies, especially in electronics (FOEN, 2022; Wäger et al., 2011).

The OREA also provides that the EEE embedded in vehicles ([19]) falling under its scope must be removed and recycled separately, in accordance with the disposal requirements applicable to regular e-waste (Article 10). For those EEE, the manufacturers are subject to a free take-back and disposal obligation (Articles 6 and 9). The Swiss Federal Department of the Environment, Transport, Energy and Communications is in charge of defining a list of EEE embedded in vehicles that fall under the OREA if they respect the principle of proportionality, which in this case corresponds to the following two conditions:

— their removal from vehicles is possible at a reasonable cost;
— their recycling with the latest technology provides sufficient environmental benefits.

The FOEN commissioned Empa to realise the EVA II project, which aimed to evaluate car-embedded EEE in view of those two conditions. Using dynamic MFA, economic and life cycle assessment (LCA) models, the cost and environmental benefits of removing and recycling each car-embedded EEE separately was assessed. 43 embedded EEE types, distributed in four main categories (referred to in this report as the EEC group) – cables, headlights, actuators and controllers – were evaluated. The results of this study are detailed in a series of unpublished but accessible-on-demand reports, and also summarised in a published final report (Marmy et al., 2023). The elaboration of a list of components to be mandatorily removed and recycled separately, based on the results of the EVA II project, should be completed in 2023.

([19]) also defined as EEC in the previous sections.

4. List of pre-selected materials and corresponding measures

In this section, target materials relevant in ELV management are selected, at the component or vehicle level. Afterwards, a list of investigated measures is presented, followed by the methodology to select the most feasible ones according to the perspectives of the ELVD/3RTA, and in view of the limited project timeline. Finally, the requirements, i.e. coupling each measure with a targeted material or part, are assessed and a shortlist of those to be further investigated is created.

4.1. List of pre-selected materials and measures

As explained in Section 2.3, it was necessary to select materials to investigate. The reasons for selection were either to improve the circularity of materials at the vehicle level or to address a potential lack of information previously highlighted by (Løvik et al., 2021). The results are presented in Table 3, where it is also indicated if the material is associated with one or more specific components or is considered at the vehicle level.

Table 3. Pre-selected CRMs for further assessment in this report

Pre-selected material	Component or vehicle level	Remark
REEs (Nd and Dy in REPMs)	e-drive motor	Possible synergistic effects also on base metals (incl. Cu) and Si-steel
Precious metals (Ag, Au, Pd)	EEC group (headlight, controllers and actuators)	Possible synergistic effects also on base metals (incl. Cu) and PMMA
Mg	Vehicle body, die cast parts	
Ti	Vehicle body	
Ga	Electronics	EEC group also contain Ga

Source: JRC own elaboration.

REEs and in particular Nd and Dy are mainly in e-drive motors, making up to 33 %wt of the REPM and up to 4 %wt of an e-drive motor. It is expected that Dy demand will double by 2030 and will be six times higher by 2050, while Nd demand is also expected to increase 11-fold by 2032 ([20]), due to the electrification of the EU fleet. However, in the current EoL management of ELVs, these CRMs are lost through dispersion in other recovered material fractions (Andersson et al., 2017). E-drive motors are usually not dismantled from ELVs prior to shredding (see Section 3.2.1) and thus REEs in REPMs are lost during the shredding: a share goes into ferrous fractions, another into fines or stuck to shredder walls (Deubzer et al., 2019). The EU-estimated EoL recycling input rates for Nd and Dy are below 1 % ([21]).

— While targeting the e-drive motor, there is also the opportunity for higher-quantity and -quality recycling routes for steel, Si-steel, Al alloys and Cu (see Section 3.1 for e-motor composition). Compared to ICEV, EVs are expected to require more Al, up to 199 kg by 2025 ([22]), and Cu, from the current 30 kg to up to 73 kg in the level-4 autonomous vehicles (IDTechEx, 2022). There is also a potential significant shift from cast Al to wrought Al alloys in new vehicles, and their improved sorting and recycling would avoid the loss and dilution of CRMs contained within. Targeting a higher sorting and recycling of Cu from this component will also lead to the reduction of so-called ‘meatballs’ generated from the shredding of the e-drive motor within the car hulk, with a consequent decrease of its contamination of other materials such as steel and Al.

— Precious metals and other relevant materials in the EEC group (see Section 3.2.2), such as electronics, controllers, actuators, headlights and cables, are not systematically dismantled from cars prior to shredding. For instance, PCBs could be recovered by density sorting and other PSTs and sent to special recyclers (e.g. Umicore treating from 25 to 100 tonnes of flows from shredded e-scrap ([23]). However, PCBs and

([20]) https://www.idtechex.com/en/research-article/rare-earths-in-evs-problems-solutions-and-what-is-actually-happening/25071.

([21]) See for Dysprosium raw material profile, in RMIS https://rmis.jrc.ec.europa.eu/.

([22]) DuckerFrontier, *Aluminium content in European Passenger Cars*, prepared for European Aluminium, public summary, 10 October 2019.

([23]) https://pmr.umicore.com/en/recyclables/e-scrap#tabs.

other lighter parts usually end up in the SLF directly during the shredding, a fraction generated directly at the shredding step through cyclone process (strong ventilation to evacuate the lighter parts). SLF is difficult to sort because of its fibrous properties. Moreover, the shredding of PCBs causes a lot of friction, which removes precious metals in the form of microscopic particles that then cannot be recovered. It is, then, more advantageous to dismantle and treat PCBs separately in smaller, more specialised installations that do not generate so much SLF (< 2 % of the mass for e-waste recycling, vs 15–20 % of the mass for car recycling). The PMMA can also be recovered if lighting is extracted prior to shredding, although it might only be worth it for headlights with transparent PMMA and backlights. Further economic analysis might be required to assess the economic benefits of recovering PMMA from lighting.

— Among the materials that might be targeted at the vehicle level are Mg, Ga and Ti. Mg content is expected to increase because of its lightweighting properties (Weiler, 2019). Mg die cast parts can be dismantled prior to shredding ([24]). In principle, Mg material can also be sorted using PSTs such as density sorting. It was reported in the International Magnesium Association report (Bell et al., 2015) that 80 % of the Mg (both die cast and Al alloys) will not be sorted and will be lost, ending up, after shredding, in non-ferrous fractions or plastics (Mg die cast having a density close to polyvinyl chloride). The most recent stakeholder consultation also reported that some recyclers are rapidly investing in PSTs (density sorting, laser-induced breakdown spectroscopy ([25]), etc.) to sort Al scrap by alloy type. Yet due to low market demand, it is unlikely that such practices would be generalised for all recyclers, although the technical feasibility of such techniques is proven ([26]). Ga is an important element used in semiconductors by the automotive sector, found in integrated circuits and sensors. Calvo and Valero (2022) estimated a use between 0.4 and 1.1 g of Ga in EVs. The Ga-containing parts are usually neither separated prior to nor post shredding, and Ga is therefore lost in the non-ferrous fraction. Another roadblock for Ga, as stated in a previous JRC report, is the lack of robust data to estimate its stocks and flows use in automotive parts (Løvik et al., 2021). Ti is also used in small quantities in vehicles. It is mainly used in alloys (see Table 28 in Annex I). As with Ga, it was stated also for Ti in a previous JRC report that the lack of robust Ti data prevents from estimating its stocks and flows use in automotive parts (Løvik et al., 2021).

In Table 4, pre-selected measures are reported. There are of two types of targeted measures: those focusing on products put on the market and those for waste-management operators. Both types can be applied within the ELVD/3RTA. Reported measures resulted from the analysis of market and/or circularity failures highlighted in previous sections, and were also investigated in other instruments (e.g. the Swiss ordinance on e-waste (OREA)) and based on lessons learnt from previous policy experiences. For instance, the mandatory declaration of content, specifically targeting some CRMs, and design measures to ease disassembly have been derived from the previous ecodesign regulation for servers and data storage products ([27]). The measures on recycled content and on material recovery level and recycling efficiency have been introduced in the recent battery regulation ([28]) to increase the level of circularity of the main battery metals. Similar measures were also investigated for other materials in vehicles, such as plastics, in the support studies to the revision of the ELV and 3RTA.

All the investigated measures tackle market and/or circularity failures in some way. For instance, lack or unavailability of market outcomes for secondary materials which have been produced but are still not yet cost efficient is a market failure that can be tackled by recycled content measures. By doing so for plastics in vehicles, or lithium in batteries, the EU provides the legal certainty for market players to invest in order to reach cost-efficient processes. Furthermore, information failure (included within market failure), is generated when not all market players have the same available information, preventing them from making informed choices. The battery and ecodesign regulations pointed out such failures, highlighting the difficulty for waste management operators to remove batteries or some components from servers because it was unclear where components are located. In this case, an information request measure can be introduced to tackle such a failure. Afterwards, materials and products put on the market can be mismanaged at their EoL, leading to low circularity at material or product level. Such a failure can be minimised by introducing proper measures dealing with collection or recycling efficiency. All the abovementioned failures are considered to fall under the scope of circularity failure.

([24]) As stated in the ELVD, Annex I (4).

([25]) Laser-induced breakdown spectroscopy is used for instance to sort aluminium by alloy type.

([26]) Based on stakeholders' statements on the feasibility of sorting aluminium scrap by alloy types using available PST.

([27]) Commission Regulation (EU) 2019/424.

([28]) COM(2020)798.

All these measures have been pre-selected by the working team based on past analysis of several circularity issues and of policy, however they also have to be properly coupled with the preselected materials and components in order to have the highest possible benefits for the circularity of targeted CRMs from ELV management, while still keeping costs and the burden limited. In Section 4.2, the methodology used to shortlist requirements; i.e. coupling pre-selected materials and measures, is presented together with the results of the shortlisting. The measures presented in Table 4 addressed different types of circularity failures (e.g. market, information, or technical failures, etc.).

Table 4. List of investigated measures in the current report

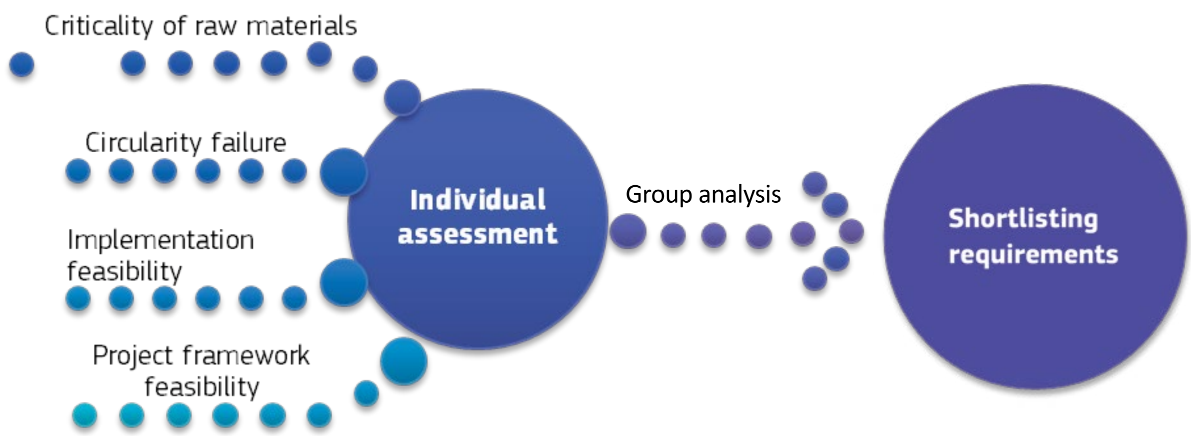
Measures in product policy – 3RTA	Measures in waste policy – ELVD
Mandatory declaration of content, including possible labelling of components containing specific CRMs	Mandatory removal prior to shredding to promote recycling
Design of provisions to ease disassembly	Mandatory removal prior to shredding to promote reuse, refurbishment and remanufacturing
Recycled content	Material recovery level and recycling efficiency

Source: JRC own elaboration.

4.2. Shortlisting of pairs of materials and measures for further assessment

Materials and measures were paired specific requirements. The requirements were then individually assessed by the study partners to pre-select the most suitable ones for further investigation. Figure 6 below shows the methodology used in this stage of the study.

Figure 6. Methodology used to shortlist requirements (pairs) for further assessment



Source: JRC own elaboration.

The project partners used the following five criteria to develop their assessments:

- criticality of the raw materials, already presented in Section 3.;
- market failures (see Section 1) in the value chain of components and of primary and secondary materials, such as the prevention of the creation of secondary markets;
- circularity failures (see Section 1) in ELV management, such as loss of material;
- feasibility of the implementation of the requirements, i.e. the feasibility from several perspectives such as the technical, legislative or administrative feasibility;
- feasibility of the analysis in the frame of the current project, i.e. the possibility for the study partners to provide a well-structured assessment within the time constraints of the project.

Afterwards, the results were merged into a shortlist of requirements, through a group analysis of all partners of the study. The resulting shortlisted requirements are listed in Table 5 and will be described in the next sections, followed by the assessments from material flow, environmental and socioeconomic perspectives, including impacts on innovation and administrative burden.

Table 5. Shortlisted requirements to improve circularity in the ELV management

Product policy – 3RTA	Waste policy – ELVD
Ease of disassembly of e-drive motor	Mandatory removal prior to shredding of e-drive motor
Mandatory declaration of REE content in vehicles, with possible labelling	Mandatory removal prior to shredding of EEC group
Mandatory declaration of content of Ga used in vehicle	

Source: JRC own elaboration.

The non-shortlisted requirements are reported in Table 29 (see Annex II) together with more details on why they were discarded, which can be attributed to one or more of the following reasons:

— relevant failure criteria to be further considered;
— prerequisites to set up the requirement;
— project readiness / ability to properly investigate the requirement within this project;
— lack or absence of relevant information to investigate the measure for the targeted CRMs/materials within this project.

5. Proposals of requirements to be assessed

In order to assess the possible measures shortlisted, it is necessary to clearly specify them. The general objective of the policy interventions is to improve the circularity of CRMs in vehicles in all life cycle stages. Each of the four policy measures analysed in this study is presented in the four following sections: (i) clearly defining the scope and the suggested timeline for the measure; (ii) formalising the exact formulation of the measure; and (iii) explaining how the proposed measure should contribute to improve the situation. An assumed timeline of application is set for each measure after the entry into force of the respective regulation.

5.1. Requirement 1: Mandatory removal of e-drive motor by ATFs

— What is the current (or projected) situation and how can this requirement improve the situation?

- Problem – current situation: current waste management practices do not lead to the recycling of sufficient quantities and/or qualities of e-drive motor flows (circularity failure), but rather to losses of CRMs and other materials (e.g. Cu), and investment in CRM targeted recycling facilities in Europe is lacking. The lifespan of the component is in principle very long, potentially longer than the vehicle lifespan, but this is not reflected in the current EoL management of the e-drive motor.
- Objective – improved situation: create the opportunity for circularity through e-motor dismantling (reuse/refurbishment/remanufacturing/recycling) at the EoL phase; incentivise investments in circularity infrastructure; create a positive impact on the quantity and quality of SRMs; increase the EU's strategic autonomy and reduce supply vulnerabilities, especially those relating to REEs.

— Scope and timeline.

- The component scope includes all e-drive motors, when existing in the ELV, the REPM and the REPM-free motors (see 3.1).
- The proposed timeline for the measure to be implemented is 3 years after the entry into force of the relevant regulation (hence assumed to be on 1 January 2029). The timeline suggested provides, in principle, sufficient lead time for those involved in the value chain to adapt. However, the proposed timeline can also be reduced, as removal requirements do not in principle imply significant technological development and investments. Further investigations would assess the appropriate timeline of implementation.

— Requirement.

- The mandatory requirement (formulated as follows) is to be included in the ELVD part of the regulation, in particular in the current version of Annex I, Section 4, to the ELVD:

Requirement (1) on mandatory removal of e-drive motor by authorised treatment facilities:

"

By 2029, removal, when present, prior to shredding process to enhance reuse or high-quality recycling of the additional component:

– e-drive motor.

"

5.2. Requirement 2: Design provisions for e-drive motors

This requirement is adapted from the existing material efficiency requirement contained in the ecodesign regulation on servers and data storage products (see Section 1.2.1 of Annex II to Regulation 2019/424 ([29]) and is, hence, likely to be enforceable. This requirement is more effective for e-drive motors as current practices at waste management facilities do not allow the recovery of REPM materials or Cu from the e-drive motor. These REPM materials, if not properly removed before shredding, are likely to be shredded and diluted in the ferrous

([29]) Regulation 2019/424 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R0424.

fraction. Thus, a better design that would ensure cost-effective removal of the e-drive motors would enhance the creation of a separate waste flow and is likely to develop REPM recycling from e-drive motors. An improved design can also be complemented with a set of information to ensure that all involved in the value chain have accurate information on the sequences to safely disassemble the motor. Further information on software control and safety firmware to allow its normal functioning after repair and/or reuse operations should also be provided. The unavailability of or incomplete information on software and firmware for those involved in repair and reuse does not only impact components' normal functioning, but also jeopardise the safety of operators and the security of the system hosting these components (Polverini et al., 2018).

This requirement can also lead the way for a more elaborate future version that improves the design for circularity of e-drive motors and promotes the reuse and repair of the components and its parts. Improvement could address, for instance, interfering elements with the disassembly of e-drive motor. It could also lead to the development of quantitative metrics/targets to be fulfilled by OEMs, building on the ongoing review of the ecodesign regulation for servers, available scientific metrics (e.g. based on ease-of-disassembly metrics (Peeters et al., 2018; Vanegas et al., 2018)) and on available standards on material efficiency, including those developed under CEN/CLC/JTC 10 ([30]). This also includes the possibility to develop new specific standards on e-drive motor design for dismantling and disassembly.

— What is the current (or projected) situation and how can the requirement improve the situation?

  ° Problem – current situation: absence of design for circularity practices; current design does not facilitate disassembly of the component; current practice is leading to the loss or dilution of REPM materials in ferrous streams.
  ° Objective – improved situation: incentivise design for circularity of e-drive motors and make it verifiable; make requirement 1 more efficient and economically profitable; and enhance ease of disassembly measures and prepare possible further requirements (e.g. in review clause) on further disassembly (disassembly depth and disassembly sequences, see definitions in glossary) of e-drive motor parts (to easily extract and recycle the REPM, for example).

— Scope and timeline.

  ° The component scope for vehicles includes all e-drive motors, when existing in the vehicle, the REPM and the REPM-free motors.
  ° The targeted timeline is 5 years after the entry into force of the relevant regulation (for vehicles newly type approved after this date, assumed to be on 1 January 2031).

— Requirement.

  ° The mandatory requirement (formulated as follows) is to be included in the 3RTA part of the regulation:

Requirement (2) on design provisions for e-drive motors:

"

From 1 January 2031, manufacturers shall ensure that the design of the vehicle and joining, fastening or sealing techniques do not prevent disassembly operations for repair and reuse purposes of e-drive motor, when present. Manufacturers shall also ensure that any software component controlling the operation of the e-drive motor does not impede its normal functioning after repair and reuse operations.

This should be ensured by manufacturers by providing instructions on the disassembly operations that include:

– the type of operations to be performed;

– the type and number of fastening technique(s) to be unlocked;

– the tool(s) required.

"

([30]) https://standards.cencenelec.eu/dyn/www/f?p=205:7:0::::FSP_ORG_ID:2240017&cs=18A65BEA4289B745403E9407952618CE3.

5.3. Requirement 3: Mandatory removal of selected EEC group by ATFs

The list of vehicle EECs mentioned in this requirement is shortlisted based on the results of the EVA II study (Marmy et al., 2023) assessing the feasibility of increasing circularity through the mandatory dismantling and separate recycling of components prior to shredding. The original list of the study assessed 43 components. The rational for shortlisting only three components is described in Section 6.3.

— What is the current (or projected) situation and how can the requirement improve the situation?
  - Problem – current situation: insufficient circularity of EoL flows of CRM-rich components; inadequate current sorting and recycling practices lead to the loss of precious metals, CRMs and relevant strategic materials (e.g. Cu) from the targeted components category.
  - Objective – improved situation: improve circularity at EoL phase, notably of EECs from vehicles; increase circularity rates of key materials (e.g. Pd, Cu and precious metals); increase reuse, refurbishment, re-manufacturing and recycling rates; increase EU strategic autonomy and reduce supply vulnerabilities.

— Scope and timeline.
  - The components scope for the EEC group is focused on the controllers' category and applies to the following, when existing in the ELV:
    - infotainment control units containing sound, navigation and multimedia;
    - control modules or valve boxes for the automatic transmission;
    - inverters of the EVs.
  - The targeted timeline is 3 years after entry into force of the relevant regulation (hence assumed to be on 1 January 2029).

— Requirement.
  - The mandatory requirement (formulated as follows) is to be included in the ELVD part of the regulation, in particular in the current version of Annex I, Section 4, to the ELVD:

Requirement (3) on mandatory removal of selected EEC group by authorised treatment facilities:

"

By 2029, removal, when present, prior to shredding process to enhance reuse or recycling of the selected components:

– infotainment control unit containing sound, navigation and multimedia;

– control module or the valve box for the automatic transmission;

– inverter of the EVs.

"

5.4. Requirement 4: Request for information from OEMs on specific CRMs contained in vehicles, and targeted labelling requirements

This requirement is adapted from the existing material efficiency requirement contained in the ecodesign regulation on servers and data storage products (see Section 3.3 of Annex II of Regulation (EU) 2019/424 ([31]) and is hence likely to be enforceable. The available standards on material efficiency, including those developed under CEN/CLC/JTC 10 ([32]) (e.g. EN 45558 – General method to declare the use of critical raw materials in energy-related products) could also be used to facilitate the enforcement of this requirement at e-drive motor level.

The labelling of the REPM e-drive motors is based on the JRC report supporting the ecodesign requirement for electronics displays. This requirement is more effective for e-drive motors, as the current state of play reports

([31]) https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1553786820621&uri=CELEX %3A32019R0424.

([32]) https://standards.cencenelec.eu/dyn/www/f?p=205:7:0::::FSP_ORG_ID:2240017&cs=18A65BEA4289B745403E9407952618CE3.

information failure at waste management system level; the actors of the waste management system do not have sufficient information on e-drive motors, nor on the presence of REPMs within, preventing them from making informed choices. Labelling parts or products with specific material content (to ease its identification) would in principle incentivise the dismantling and separate collection of the e-drive motor at ATFs.

— What is the current (or projected) situation and how can the requirement improve the situation?

  ° Problem – current situation: very little information on CRMs contained in vehicles; ATFs are often not aware of the existence of REPMs in the vehicle composition.
  ° Objective – improved situation: improving ATFs' knowledge on vehicle composition; clear distinction of labelled components for better sorting of the targeted CRM.

— Scope and timeline.

  ° The components scope is focused on: Nd and Dy contained in REPM e-drive motors, when present, in new vehicles; Ga contained in controllers (larger than 10 cm^2) and sensors used in new vehicles. The Ga scope also includes integrated circuits used in vehicles.
  ° The targeted timeline foreseen is 3 years after the entry into force of the relevant regulation (hence assumed to be on 1 January 2029).

— Requirement.

  ° The mandatory requirement (formulated as follows) is to be included in the 3RTA part of the regulation:

Requirement (4) on information request from OEMs on specific CRMs contained in vehicles, and targeted labelling requirements

"

From 2029, the following information content shall be made available on the components, when present, from the time the vehicle is placed on the market, free of charge by manufacturers, their authorised representatives and importers, upon registration by the interested third party on a website that provides:

– indicative weight, at e-drive motor level, of the following CRMs:

 – neodymium,

 – dysprosium;

– number of rare-earth permanent magnets, at e-drive motor level;

– use of glue in the assembly of the permanent magnet within the e-drive motor;

– coating used on permanent magnets, at e-drive motor level;

– indicative weight, in controllers (e.g. printed circuit boards with surface area larger than 10 cm^2) and sensors, of gallium.

Manufacturers shall also ensure that rare earth permanent magnets (REPM), when present in the e-drive motor, and exceeding a total magnet weight of 0.8 kg, are labelled, as indicated below.

REPM

The logo shall be clearly visible, durable, legible and indelible.

"

6. Assessment of the shortlisted requirements

The requirements shortlisted in the previous section are translated into various scenarios and then assessed below. Three dimensions were used, when possible, to assess the performance of each requirement:

— material flows and SRM production;
— environment-based assessment;
— socioeconomic assessment, including impacts on innovation and administrative burden.

6.1. Requirement 1: E-drive motor requirement for ATFs

Scenarios are constructed against the current baseline and then assessed considering the 2030–2035–2040 timeline. While the baseline scenario of the e-drive motor is described in Section 3.2.1, two scenarios were constructed to assess the performance of this requirement (Table 6). Scenarios (Sc.) 2.1 and 2.2 presented below are two steps of one single scenario, but occurring in successive points in time (from 2030 to 2040 respectively), representing a gradual implementation of the measure.

Table 6. Constructed scenarios for the assessment of the e-drive motor requirement for recyclers

Scenario	Description of the scenario	Year of assessment
Sc.1	Removal of the e-drive motor, prior to shredding, for 100 % recycling purposes	2030, 2035 and 2040
Sc.2.1	Removal of the e-drive motor, prior to shredding, for 80 % recycling purposes and 20 % reuse purposes	2030
Sc.2.2	Removal of the e-drive motor, prior to shredding, for 70 % recycling purposes and 30 % reuse purposes	2040

Source: JRC own elaboration.

6.1.1. Material flows and SRM production

The current baseline scenario of e-drive motor treatment is described in Section 3.2.1. In that scenario, the e-drive motor would not be dismantled nor sent to a separate recycling process and would be shredded within the ELV. Based on this, the main recovered materials from the e-drive motor fraction would be the base metals (Al, steel and Cu partially); see Section 3.2.1 for more specific data. The present section assesses the new scenarios developed for the e-drive motor requirement for waste management operators and compares the results against the baseline scenario defined above.

In order to map all the flows and ensure consistency of analysis with the ongoing works on the analysis of measures for ELVD review (e.g. Baron et al. (2022) Maury et al., (2022)), the following data and assumptions were considered.

— EU fleet data are based on the ongoing impact assessment of the ELVD review. Fleet data include Euro 7 updates. The future supply and material content of e-drive motors were based on the high/low demand scenarios (HDS/LDS) constructed in Carrara et al. (2023). While both future scenarios envisage stability in base metals and Si-steel intensities used in e-drive motors, the reduction of REE content is considered from 2030 to 2050 and is presented in Table 7. Nd and Dy consumption reduction are then adapted for the assessed periods.

Table 7. Consumption reduction of Nd and Dy in magnets in e-drive motors, assumed in both HDS and LDS

	HDS		LDS	
Reduction (–) compared to the baseline scenario	Nd	Dy	Nd	Dy
By 2030	– 10 %	– 10 %	– 30 %	– 66 %
By 2050	– 15 %	– 15 %	– 40 %	– 75 %

Source: (Carrara et al., 2023).

— The e-drive motor average market share and the material compositions of the main technologies (REPM and REPM-free motors) are described in Section 3.2.1. It is assumed that the material composition trends would remain the same in the assessed future (compared to actual material compositions), and materials used for future e-drive motors (including REEs) would be similar to actual bill of materials, as long as magnet price volatility remained acceptable. Such a trend in Nd prices has also been confirmed in the latest IDTechEx report (Edmondson et al., 2022), which observes a consistent Nd price over the years.
— 2030, 2035 and 2040 EoL scenarios, drafted in order to estimate the future SRM production from e-drive motors, are provided in Table 8. It is assumed that the already high recycling of steel and Al will increase even further, but more slowly compared to the recycling rate of Cu. For the latter, the impact is to be allocated as an effect of the disassembly measure that facilitates the creation of a separate flow of the currently lost Cu (via the improvement of PSTs and thus of recycling quality).

Table 8. Recycling rates assumed for the e-drive motor 2030, 2035 and 2040 scenarios (e-motor separate recycling)

Material	2030 recycling rate, %	2035 recycling rate, %	2040 recycling rate, %
Steel	90 %	91 %	92.5 %
Al	90 %	91 %	92.5 %
Copper	80 %	83 %	85 %
Si-metal (*)	0 %	18 %	35 %
Magnets (NdFeB)	0 %	18 %	35 %

Source: JRC own elaboration.

(*) See Section 3.2.1 for notes on the Si-steel. Here, we assumed that Si-metal would be targeted for recycling after 2030 as more Si-steel became available, creating a secondary market opportunity. Further investigation on the relevancy of Si-steel functional recycling to recover Si-steel or silicon metal is ongoing.

— For the sake of simplicity, it is assumed that all EVs would be equipped with one single e-drive motor, and that the ELVs reaching the ATF would still be equipped with their corresponding e-drive motors, if they exist in the drivetrain.
— E-drive motors that would be disassembled for reuse in Sc.2 can also be diverted back to recycling for several reasons (e.g. failures, higher material prices), and it was thus assumed that this diversion rate would be 10 % of disassembled e-motors for reuse purposes.

The assessed requirement for e-drive motors is thus targeting circa 1 million ELVs, reaching EU ATFs in 2030, 2.5 million ELVs in 2035, and circa. 5 million ELVs at ATF level in 2040 (cf. Figure 5). It is forecasted that 1 million, 2.4 million and 4.3 million REPM e-motors from ELVs will be separately collected from ATFs in 2030, 2035 and 2040 respectively.

Based on the scenarios constructed and their corresponding recycling rates in 2030, 2035 and 2040, the overall expected SRM production is reported in Table 9. The latter is also used to assess the potential ability to feed the estimated demand for e-drive motor materials in 2030, 2035 and 2040. This is presented in Figure 7, where the secondary base metals and secondary Si-steel production are compared with the potential e-drive motor expected material demand. Based on Sc.1, the potential SRM coverage of future e-drive motor materials supply are 3 %, 7 % and 18 % in 2030, 2035 and 2040 respectively. This scenario would also lead to the development of a dedicated recycling value chain of e-drive motors to recycle magnet materials and potentially Si-steel (33). Reused flows (34) can also benefit from such a value chain in further loops, where disassembled e-drive motors for reuse purposes would be diverted to recycling routes. In general, both Sc.1 and Sc.2 would contribute to the development of recycling and reuse practices for e-motors. As for SRMs from REPM recycling, the potential corresponding flows available for recycling thanks to Sc.1 are up to 0.774 kt in 2030, 2 kt in 2035 and 4.2 kt in 2040. Since the assumed 2035 and 2040 recycling rates for magnet materials would be 18 % and 35 % re-

(33) Although Si-steel contains silicon metal (a CRM), statements from targeted stakeholders and expert feedback did not identify the recycling of this CRM from e-drive motors as relevant. It was also reported that Si-steel flow may be a disruptive element in steel recycling.

(34) Reused flows of e-drive motors can be injected to cover demand for new vehicles (e.g. through reuse or remanufacturing), or can be diverted to other value chains.

spectively, the magnet materials (secondary rare-earth oxides) produced would be up to 0.35 kt in 2035 and up to 1.4 kt in 2040. Such flows would in principle cover, in closed loop perspective, circa 12 % to 13 % of the expected REEs e-drive motor demand, based on 2040 LDS and HDS respectively, with significant contributions to the reduction of supply disruptions and to European strategic autonomy.

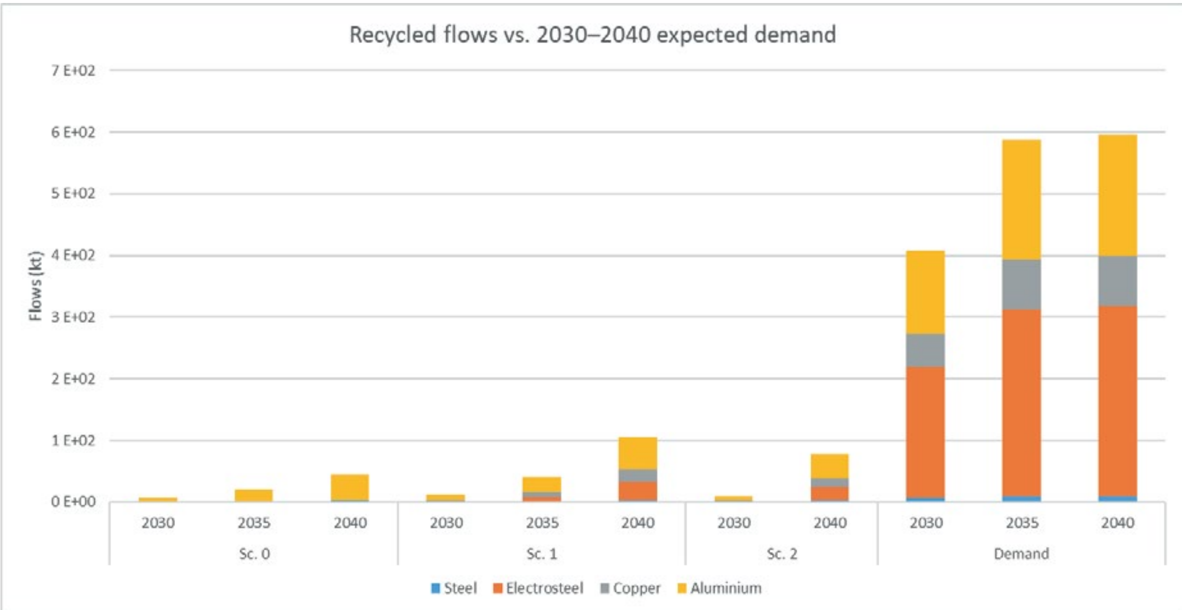
Table 9. 2030, 2035 and 2040 SRM production from Sc.1 – 100 % removal scenarios for recycling (units in kt)

Material	Sc.1 – 2030	Sc.1 – 2035	Sc.1 – 2040
Magnet materials	0	0.3	1.4
Si-metal (*)	0	7.1	31.2
Copper	2.8	8.1	19.1
Al	8.6	23.8	52.7

Source: JRC own elaboration.

(*) Further investigations to assess the feasibility of recycling Si-metal are ongoing (see 3.2.1).

Figure 7. Recycled flows vs 2030–2035–2040 expected material demand. The targeted e-drive motor materials and SRMs are steel, Si-steel, Cu and Al (units in kt)



Source: JRC own elaboration. Sc.1 was assessed for 2030, 2035 and 2040, whereas Sc.2 was assessed for 2030 and 2040.

From the reuse perspective, Sc.2.1 and Sc.2.2 contribute up to 5 kt and 46 kt of e-drive motors to the reuse market (as a whole) in 2030 and 2040 respectively. Such flows are up from 1 % to 8 % compared to the expected demand of base metals (steel, Al and Cu) and Si-steel used for e-drive motors. However, the magnet shares available for reuse purposes, if compared in a closed loop perspective against future scenarios, are from 7 % in 2030 to 48 % in 2040 for LDS, while they are 1 % in 2030 and 9 % in 2040 for HDS. The potential of the reuse of REPMs is relevant for e-drive motors and other markets, and can also contribute to remanufacturing strategies. The resistance to demagnetisation of the REPMs is thanks to the properties of Dy, which allow a higher useful lifetime product under high Curie temperature. The latter is significant for the REPM composition.

Overall, the introduction of the mandatory removal of e-drive motors prior to shredding provides significant flows available for higher recycling and reuse. When we look at the contribution to recycling and SRM production, Sc.1 (Table 10) ensures a higher SRM production for 2030, 2035 and 2040 and could contribute to meeting the expected demand of e-drive motor materials (up to 0.3 kt and 1.4 kt of recycled rare-earth oxides in 2035 and 2040 respectively). This scenario is also relevant for the increase of CRM and PM recycling from ELV and acts as a prerequisite step for more circularity of e-drive motors and their materials. It contributes towards creating an EoL flow from ELV to be sent to further recycling and processing steps. Sc.2 contributes to the development of a secondary market by providing e-drive motor reused flows, which are at a higher level than recycling. Besides, reused flows would end up in recycling eventually. It is unclear if reused flows from Sc.2 would reduce the material dependency of e-drive motors, as secondary reuse can also be diverted for alternative applications requiring less performance constraints.

In general, although both scenarios contribute equally to recycling and to the production of SRMs, Sc.1 would be better performing from a short-term MFA than Sc.2. Both scenarios contribute to the development of secondary markets (SRM and reused e-drive motors) in Europe.

Table 10. Potential of SRM production of the assessed scenarios of the e-drive requirement for recyclers

	Sc.0	Sc.1	Sc.2
Material flows and SRM production	Baseline	Best performance	Good performance

Source: JRC own elaboration

6.1.2. Environmental-based assessment

The assessment of the environmental impacts of changing the EoL handling of e-drive motors is based on a review of LCAs on e-drive motors and REPMs. Despite the fact that the increasing adoption of e-drive motors is considered as one of the drivers of supply risk for resources such as Nd and Dy, there are few LCAs investigating e-drive motors and REPMs. Some LCAs compare production of REPMs using primary or recycled raw materials (e.g. Ciacci et al. (2019); Jin et al. (2016, 2018)), however these do not specifically address such magnets used in e-drive motors, but rather address, for example, those used in hard disk drives, which involves other magnet properties and composition, quantities and dismantling processes. The only LCA comparing several recycling alternatives and the remanufacturing of full e-drive motors is Tillman et al. (2020). Even if these alternatives do not exactly correspond to the scenarios Sc.0, Sc.1 and Sc.2, Tillman et al. (2020) is deemed the most relevant study for the assessment.

Tillman et al. (2020) reports on the attributional cradle-to-grave LCA of three different motor designs. For this assessment, the results for the design of the so-called reference motor, an REPM motor with Cu windings, are used. Four alternatives for EoL can be distinguished:

— alternative (alt.) 1: recycling of the e-drive motor as part of the car hulk, with shredding followed by post treatment and recovery primarily of steel scrap, Al scrap, Cu rich fraction and mixed metals orso-called ‘meatballs’ (no recycling of REPMs);
— alt. 2: dismantling of the e-drive motor followed by recycling of REPMs ([35]) and by pure fractions of steel scrap, Al scrap and Cu windings so that less processing of these metals is needed in comparison to alt. 1 and slightly higher quantities are recovered;
— alt. 3: remanufacturing of the e-drive motor (only replacing the motor shaft and bearings) so that the motor’s lifetime is increased by 50 % (in terms of driving distance) before being recycled according to alt. 1;
— alt. 4: remanufacturing of the e-drive motor (only replacing the motor shaft and bearings) so that the motor’s lifetime is increased by 50 % (in terms of driving distance) before being recycled according to alt. 2.

Compared to alt. 1 (baseline), the other alternatives increasingly reduce climate change impacts (Table 11).

([35]) According to Tillman et al. (2020), REPM materials are shredded and found mainly in steel scrap, Cu-rich fraction and shredded residues. Additional information on dismantling steps for passenger car e-drive motors can be found in Section 5.2 of the same reference.

Table 11. Comparison of climate change impacts of handling one e-drive motor, compared to alt. 1 in grams CO_2 equivalent and percentage reduction)

	Reduction of climate change impact compared to alt. 1, results per e-drive motor	
	%	**grams CO_2 equivalent**
Changing from alt. 1 to alt. 2	4	0.15
Changing from alt. 1 to alt. 3	9	0.30
Changing from alt. 1 to alt. 4	15	0.50

Source: (Tillman et al., 2020).

The reduction of climate change impacts when dismantling the e-drive motor (alt. 2) instead of shredding it with the car hulk (alt. 1) is relatively small (see Table 11) and mainly due to somewhat lower processing requirements and higher recovery of the motor's main constituents, namely steel, Al and Cu. Together, these materials make up more than 90 % of the total mass of the motor. The contribution of recycling magnets (alt. 2 corresponding to less than 3 % of the total mass) is of little importance. In this study, magnet recycling represents recovery to properties similar to metals from primary production, which is regarded as the most expensive alternative in terms of both costs and environmental impacts (Elwert et al., 2016). With other recycling processes, the impacts could be somewhat reduced, but the main benefit of changing from alt. 1 to alt. 2 would still depend on increased recovery of steel, Al and Cu. In addition to climate change impacts, resource scarcity impacts are assessed (Tillman et al., 2020). The reduction of resource scarcity impacts is larger than those of climate change (16 % lower than alt. 1), mainly due to the higher yield of Cu since its crustal scarcity potential is over 1 800 and 2 900 times larger than that of Fe and Al respectively. The recovery of Nd and Dy contributes to some extent to this reduction due to larger crustal scarcity potentials – 1.4 times and 7.9 times higher than that of Cu respectively. Thus, increased recovery of Nd and Dy contributes little to the reduction of climate change impacts and contributes somewhat to reducing resource scarcity impacts when comparing the LCA results of changing from alt. 1 to alt. 2.

Impacts are further reduced when remanufacturing the motor (alt. 3 and 4) and extending its use before recycling instead of directly shredding it with the hulk (alt. 1) (see Table 11). This of course depends on the fact that its use is increased by 50 %. However, the benefit of this extension is relatively small since the materials that contribute most to the environmental impacts are recovered at high rates. Climate change impacts compared to alt. 1 are reduced by 9 and 15 % respectively (see Table 11) and resource scarcity impacts are reduced by 10 and 25 % respectively compared to alt. 1. If other materials that were not recovered at similarly high rates in recycling had contributed more to the impacts of producing the motor, the crediting of recycled materials would be lower and, thus, the benefit of use extension higher. Thus, highly efficient recycling of the materials that have the highest impact when producing the motor (steel, Al and Cu) limits the benefit of extending the use of the motor through remanufacturing.

The results from Tillman et al. (2020) cannot be directly used to quantify the impacts of the scenarios, but can be used to discuss the environmental impacts of an e-drive motor in Sc.0, Sc.1 and Sc.2 (see overview in Table 12). Sc.0 is relatively close to alt. 1 and Sc.1 to alt. 2, and Sc.2 is a combination of alt. 2 and 4. Thus, in terms of both climate change and resource scarcity, the handling of one motor in Sc.0 would result in the highest impacts, followed by Sc.1 and Sc.2, in 2030, 2035 and 2040. The scenarios include a combination of REPM and REPM-free motors and a higher content of Cu, whereas Tillman et al. (2020) only study the former. However, the ranking of the alternatives would be the same if LCAs were to address induction motors and no significant changes were assumed. This is because the ranking depends on the efficiency of how the main materials – steel, Al and Cu – are used, while REPMs have a very limited contribution to the ranking. Note that this statement concerns the ranking of the alternatives per motor type and not between the motor types.

Table 12. Climate change performance of the assessed scenarios of the e-drive requirement for waste management operators (reduction of impact of handling one e-drive motor compared to the baseline scenario)

	Sc.0	Sc.1	Sc.2
Climate change	Baseline	Better performance	Best performance

Source: JRC own elaboration

6.1.3. Socioeconomic assessment

To assess the socioeconomic impacts of the e-drive motor requirements, each of the scenarios was looked at in terms of the economic impacts and social impacts for waste management operators (ATFs and recyclers).

Based on the quantification of the MFA detailed in Section 6.1.1, for each scenario the number of e-drive motors and their related composition were used to consider the costs of dismantling/disassembling the affected motors, the revenues returned from their recycling or reuse and how the time needed for removal activities translates into a change in employment. For each of these stages, the following methodology was applied.

— Based on the number of motors dismantled or disassembled, the time needed for removal activities was calculated as a proxy for calculating impacts on employment and related costs: using information provided by an ATF ([36]), it was assumed that 10 minutes will be needed for the process of dismantling a motor when it is intended to be sent for recycling, and 20 minutes when disassembled for reuse. Dismantling is assumed to take less time as it is not necessary for the e-drive motor to remain intact so that it can be reused. The dismantling may be done manually or with the use of heavy equipment, meaning that in some cases a motor may be removed within less than a minute ([37]). However, 10 minutes is assumed to be an average, also covering the time needed to position the vehicle for removal, bring relevant equipment for the process and transfer the motor to where it will be stored until transport. The time for removal for reuse is longer due to the assumption that care must be taken to ensure that the e-drive motor remains functional and can be reused or remanufactured. Nonetheless, it is possible that in some cases the motor will be unsuitable for reuse or remanufacturing and will be resent to recycling. In such cases the time needed for removal would be assumed based on the intention of reuse, whereas the difference in treatment route will affect other economic impacts related to the chosen route (i.e. related revenues, see the following points).

— The time needed for dismantling and disassembling all e-drive motors was used to consider impacts on employment. For this purpose, the time in minutes was converted into units of 200 days, assuming that a day of labour consists of 8 hours of work, and 200 days of work were considered to represent one additional job.

— To look at the costs for the ATF associated with the time spent on removal of e-drive motors, it was assumed that the cost of each additional hour of labour was EUR 35. This cost was assumed based on the 'Optimization of the separation of components and materials from end-of-life vehicles for the recovery of critical metals' (ORKAM) study (Groke et al., 2017). Furthermore, based on information provided by an ATF ([38]), additional time was taken into consideration to cover further logistics costs related to dismantling (assumed to require approximately an additional EUR 19 per motor) and disassembly (assumed to require approximately an additional EUR 129 per motor). These costs were derived based on the total logistics costs, and their relation to the time specified by the ATF for logistics related to the treatment of a vehicle when the e-drive motor remains in the vehicle (sent to shredder) or when it is dismantled or disassembled (recycled or reused respectively) was not specified. However, it is considered that, though referred to in minutes, this time actually does not represent the specific allocation of the removal actions but is rather a broader proxy including the related overhead, logistic equipment and other logistic actions involved. For example, costs of storage of removed e-drive motors (rent for space, container), or costs of processing

([36]) Based on field data collected from an ELV and e-ELVs dismantler (based in Italy), in 2022.

([37]) See for example this video, where heavy duty machinery is used to remove an ICE motor within less than a minute: https://www.youtube.com/watch?v=3Ji8XZQn0tQ, last accessed 31 January 2023.

([38]) See footnote 39.

for e-drive motors to be sold for reuse (software [39]), updates, maintenance, etc.). For this reason, the data is used to estimate additional ATF costs beyond those related to the removal activities.

— To calculate revenues for both ATFs and recyclers, cost data was used from various sources (see the following subpoint). These values were used to calculate costs for each scenario in relation to the weights of reused e-drive motors or in relation to the amount of material expected to be sent to recycling by the ATFs or sold as secondary material by the recycler. In this case, revenues were calculated for the baseline and then subtracted from the revenues of the respective year and scenario to derive the difference in revenues.

  ° To calculate revenues for ATFs, cost data were taken from the ORKAM study (Groke et al., 2017) as to revenues for ATFs from sales of different materials and of e-drive motors. Cost data were given in this study per kg, and revenues were thus calculated based on the expected weight of motors (or motor materials) to be sold for reuse or for recycling. It is not clear if the cost for the e-drive motor given in this study would apply for the e-drive motor or only for smaller motors, however in the absence of other data it has been applied. The data used is specified in Table 13. As in the case of the baseline, the material contained in a motor is sent to the shredder as part of the hulk; in this case, the revenue is calculated for the ATF based on what they receive from shredders per tonne of vehicle hulk. This is also displayed in Table 13. In the case of Si-steel, it is not clear if such scrap would retrieve a different revenue as that retrieved for Fe/steel [40]. Thus, for Si-steel scrap sold by the ATF, the same revenue per kg is assumed as for Fe/steel. In the case of magnets removed from e-drive motors, the revenue is calculated based on the expected weight of Nd within the motor, i.e. 26 %, and not in relation to the complete weight of the magnet.
  ° To calculate the revenues for recyclers from sales of recycled material, data were taken (in alignment with the ELV impact assessment main study (Baron et al., 2022)) from https://www.letsrecycle.com, calculated as an annual average value for 2021. Here too, seeing as data could not be found for Si-steel, revenues for that material were assumed to be the same as for Fe/steel. As it is not completely clear whether such fractions would be recycled separately from steel, the recycling efficiency has also been assumed to be the same for both steel types. This fraction is however referred to individually to indicate, that, should the demand for such steel justify separate recycling in the future, the e-drive motor removal could be expected to be beneficial in this respect. The data used are specified in Table 13 below.

Table 13. Revenues retrieved, assumed for calculation of ATF and recycler revenues

ATF revenues for components/materials	EUR/tonne	Source
E-motor	370	ORKAM study (Groke et al., 2017)
Fe/steel	130	
Al	850	
Cu	4 200	
Brass	3 000	
Nd	69 360	
Plastic	400	
Vehicle hulk	110	(Zimmermann et al., 2022)
Recycler revenues for components/materials	EUR/tonne	Source

([39]) Some ATFs use digital platforms for the sale of components that they have removed for reuse. See, for example, https://vagparts.ie/product-category/used-car-parts/ or https://store.eurolineparts.com/.

([40]) Stakeholders consulted stated that 'If more electrical steel were to become available then it is not possible to speculate on the price effect or if there would be a price differentiation for this type of scrap'. As Si was deemed to affect the process of steel recycling, it could not be concluded if its recycling would be more or less costly and thus also whether Si-steel scrap would retrieve a higher or a lower revenue.

ATF revenues for components/materials	EUR/tonne	Source
Fe/steel	187	Prices for most materials are taken from https://www.letsrecycle.com data for 2021, calculated averages converted to EUR. Price for Nd is given in EUR/ounce for 22 December 2022, taken from Nd: https://www.dailymetalprice.com/metalpricescurr.php
Al cast	967	
Al wrought	1 161	
Cu	6 286	
Plastic	400	
Nd	132 773	

Source: Oeko-Institute compilation, based on (Baron et al. (2022)

The analysis was performed by looking at the difference in impacts incurred in relation to the baseline scenario.

As for the baseline scenario, it has been assumed that the e-drive motor is not removed for reuse nor recycling. Thus, the point of comparison for other scenarios is 0 costs for the various players and 0 impacts on employment (related to the removal of the e-drive motor). For revenues, the difference between revenues incurring in the baseline from shredding the motor together with the hulk and between removal and separate recycling have been calculated.

In relation to jobs, Table 14 presents the expected impacts incurred should the e-drive motor requirement be applied as prescribed in the various scenarios. Though the scenarios do show differences when looking at the total amount of jobs to be created, the order of magnitude remains similar and is related to the additional time needed for disassembly of motors; as most e-drive motors will not be required to be disassembled, the difference between Sc.1 and Sc.2 remains modest in comparison to the differences between them and the baseline.

Table 14. Employment impacts of the assessed scenarios of the e-drive requirement for ATFs (difference in impact as compared to baseline scenario) (scope is EU-27)

Jobs	2030		2035	2040	
Position	**Sc.1 100 % removal for recycling 2030**	**Sc.2.1 80 % removal for recycling 2030**	**Sc.1 100 % removal for recycling 2035**	**Sc.1 100 % removal for recycling 2040**	**Sc.2.2 70 % removal for recycling 2040**
ATF disassembly	0	40	0	0	310
ATF dismantling	110	90	270	520	360
Total new jobs in scenario	**110**	**130**	**270**	**520**	**670**

Source: Oeko-Institute compilation

Employment impacts are not considered for recyclers. This has to do on the one hand with the lack of data, and on the other hand with the expectation that the impacts would be less significant. Though there will be changes in the amounts of materials available for recycling, it is understood that these will be marginal in most cases, whereas changes in quality are expected to be reflected in changes in revenue and not in jobs. For the base materials –steel, Al and Cu–, existing capacities are expected to cover benefits to be incurred in terms of additional scrap available for recycling. Where this may differ is for the recycling of Nd and REPMs when these are recycled from e-drive motors. This recycling currently does not exist in the EU, and it is unclear if, without policy intervention, it will develop by 2035–2040 or if additional time would be needed to allow for the development of regional capacities. Should such capacities be lacking, magnets could be exported for recycling – the first facilities for this are understood to exist in Asia for example. In this case, any change in jobs would be outside the EU. Should capacities develop, some job development would be expected in the EU, however this cannot be quantified at present. As explained above, separate recycling of Si-steel could also be a benefit of this requirement, however as there are uncertainties as to whether such recycling would occur, it is not considered in relation to jobs as explained above.

Looking at costs for ATFs (see Table 15), two aspects have been considered – costs related to the removal activities of e-drive motors and the accompanying logistical costs. As explained above, there could be some overlap between these cost items. However, to remain conservative, both have been calculated and will be discussed further after the expected revenues are presented. A first glance clarifies that the differences between the scenarios are much more significant, with Sc. 2 resulting in costs that are twice as high as those of Sc.1 in 2030 and almost three times as high in 2040. The difference between years is related to the significant increase in the amount of vehicles with e-drive motors which will arrive at EoL in this period and undergo ELV treatment.

Table 15. ATF costs related to the assessed scenarios of the e-drive requirement for ATFs (difference in impact as compared to baseline scenario) (figures in EUR)

ATF costs	2030		2035	2040	
	Sc.1 100 % removal for recycling 2030	**Sc.2.1 80 % removal for recycling 2030**	**Sc.1 100 % removal for recycling 2035**	**Sc.1 100 % removal for recycling 2040**	**Sc.2.2 70 % removal for recycling 2040**
Disassembly costs	0	2.5 million	0	0	17.4 million
Dismantling costs	6.2 million	4.9 million	15.1 million	29 million	20.4 million
Logistic disassembly costs	0	27.1 million	0	0	192.4 million
Logistic dismantling costs	20.3 million	16.2 million	49.8 million	96 million	67.1 million
Total additional ATF costs	**26.5 million**	**50.8 million**	**64.8 million**	**125 million**	**297.3 million**

Source: Oeko-Institute compilation.

Finally, revenues were calculated both for ATFs and for recyclers and are presented in Table 16. Here too, the significant increase in the number of ELVs containing an e-drive motor and arriving at EoL treatment makes for a large increase in impacts when comparing the results for 2030 and 2040. A second factor is the assumption that in 2040 it will be possible to remove the magnets from the e-drive motors and send them for separate recycling. The impacts in this case only reflect the revenues that will be retrieved for the Nd in the magnets, which may have a partial impact. Though it is imprecise to sum up the impacts on ATFs and recyclers, given that the cost items calculated may not reflect the complete situation, looking at the numbers, it can be concluded that the benefits (in this case benefits from material and component sales) are higher in Sc.1 than in Sc.2. Upon comparing the various revenues with the costs for ATFs (again an incomplete picture), it becomes obvious that here again, Sc. 1 has a better performance in terms of the monetary costs compared to Sc.2. This is related to the revenues for sales of the e-drive motor for reuse being significantly lower than most revenues that ATFs receive for sorted materials sold (only for steel is the revenue higher).

Table 16. ATF and recycler revenues related to the assessed scenarios of the e-drive requirement for ATFs (difference in impact as compared to baseline scenario) (figures in EUR)

Revenues	2030		2035	2040	
	Sc.1 100 % removal for recycling 2030	**Sc.2.1 80 % removal for recycling 2030**	**Sc.1 100 % removal for recycling 2035**	**Sc.1 100 % removal for recycling 2040**	**Sc.2.2 70 % removal for recycling 2040**
ATF disassembly revenues	0	2.2 million	0	0	20 million
ATF dismantling revenues	22.2 million	17.7 million	98.4 million	214.5 million	152.1 million
Total for ATFs	**22.2 million**	**19.9 million**	**98.4 million**	**214.5 million**	**172.1 million**
Recycler dismantling revenues	19.2 million	14.0 million	68.0 million	181.3 million	117 million

Source: Oeko-Institute compilation.

Looking at the proportion of costs for ATFs and their expected benefits suggests that in Sc.1 benefits will offset costs with time (by 2040), but that in Sc.2 ATFs may need some compensation to ensure feasibility as costs remain higher than benefits. This will not always be the case, as in some Member States the labour costs may be lower and in some ATFs a one-time investment in equipment may allow a significant reduction in the time needed for dismantling and thus also in the cost. Though the relations differ (see Table 17), an order of magnitude of between EUR 3 and EUR 30 per vehicle could need compensation (or allocation of benefits throughout the waste-management value chain where recycler revenues are high). This could be achieved for instance via extended producer responsibility (EPR).

Table 17. Average ATF costs and benefits per assessed vehicles

ATF impacts per vehicle	2030		2035	2040	
	Sc.1 100 % removal for recycling 2030	**Sc.2.1 80 % removal for recycling 2030**	**Sc.1 100 % removal for recycling 2035**	**Sc.1 100 % removal for recycling 2040**	**Sc.2.2 70 % removal for recycling 2040**
ATF costs EUR/e-vehicle	25	48	25	25	60
ATF benefits EUR/e-vehicle	21	19	38	43	35
ATF costs EUR/vehicle	3	5	7	12	30
ATF benefits EUR/vehicle	2	2	10	21	17

Source: Oeko-Institute compilation. ATF costs and benefits were calculated per e-vehicle, but also per average vehicle (regardless of its powertrain) in order to perform calculation and cost-benefit assessment at EU fleet level. Thus, ATF costs and benefits per vehicle would be lower, compared to the ones per e-vehicle, since they also integrate non-EVs' share.

Finally, this measure would also have a positive impact on innovation and R & D devolvement in the EU. The available e-drive motor flows would foster research, innovation and the development of new recycling technologies to increase the recovery of SRMs from these flows. It is unlikely that such a measure would hinder advances in performance and new technology approaches. Furthermore, this requirement is intended to be applied in the form of a Commission regulation, leading to no costs in transposing it into Member State legislation. However, additional administrative costs would be expected for public authorities and waste management operators, mainly linked to the reporting of e-drive motors sent for recycling or reuse. In such case, as stated in Baron et al. (2022), administrative costs would be higher for waste management operators than for public authorities. Overall, administrative cost would be moderate, as already existing schemes could also be used to report on e-drive motors. Administrative burden would be higher for Sc.2 than Sc.1, as the former also requires reporting on e-drive motors sent for reuse.

To conclude on the impacts that could be quantified, Table 18 presents the partial socioeconomic performance, using colour coding to distinguish between the levels of performance of the scenarios in each of the cost items.

Though all scenarios lead to the development of jobs, when looking at costs, Sc. 1 performs better than Sc.2 (i.e. it has lower costs). Though not reflecting all cost items, comparing the costs and the revenues further supports that the requirements specified for Sc.2 would be more ambitious in terms of costs. It should not be understood that such costs would not be justified, in particular as this section still does not look at the performance presented in the sections above. A benefit in terms of social and environmental impacts can come at an economic cost, whereas the final comparison involves considering if this cost is proportionate to the expected benefits. This shall be discussed later in this section. It could be considered whether to refer to reuse requirements as voluntary, at least at initial stages, should a demand for reuse of such motors in vehicles be negligible and should reprocessing alternatives still need time for developing. However, once REPM recycling capacities have developed in the EU, this may lead to pressure on ATFs to send material for recycling, undermining the assumed higher environmental benefit that is to be incurred when e-drive motors are reused or remanufactured. This is also to be kept in mind in light of the understanding that an e-drive motor sent for reuse will eventually reach EoL and will then probably be recycled in a further loop. Such benefits have not been included in the model (they incur at a later time, and when the e-drive motor is not reused in vehicles the benefit will be further incurred for other actors), and could change the relation between the two scenarios.

Table 18. Socioeconomic performance of the assessed scenarios of the e-drive requirement for recyclers (average variation compared to the baseline scenario)

	Sc.0 – baseline	Sc.1	Sc.2.2
Costs assessment	No impacts expected as removal not performed	Moderate	High
Additional revenues	No impacts expected as removal not performed	Best performance	Good performance
Potential job creation (only ATFs)	No impacts expected as removal not performed	Good performance	Best performance
Impacts on innovation	No impacts expected as removal not performed	Positive	Positive
Administrative burden	No impacts expected as removal not performed	Limited to moderate for waste management operators and public authorities	Moderate for waste management operators and public authorities

Source: JRC own elaboration

6.2. Requirement 2: E-drive motor design requirement for OEMs

6.2.1. Impact assessment

This requirement would be applied for new types of e-drive motor put on the EU market and would enhance the ecodesign of e-drive motors in future vehicles. The core of the requirement is defining constraints on the OEM to provide clear and succinct instructions on the disassembly operations. Such instructions should include a list of interfering components and parts to be taken out to reach the e-drive motor, the different tools required and the number and types of fastening techniques to unlock and extract the e-drive motor. Tools should be of a type available on the market and not proprietary or uniquely developed for vehicles of a specific OEM, to avoid the development of unfair competition and the generation of extra burdens for waste management operators. The second part of the requirement encourages the OEM to ensure that all the disassembly operations and the fastening techniques are minimised, while using available tools, to ensure that the e-drive motor disassembly operation is optimised. This would in principle also ensure that the e-drive motor is not locked by a chip or other software preventing its free standalone reuse without pay access monitored by the OEM after dismantling it from the vehicle or the ELV.

While this requirement would not markedly influence the potential SRM production from e-drive motor recycling, nor their environmental impacts, the estimated reporting and design costs might be slightly impacted (see Table 19). The impacts of this requirement on the previous one for ATFs (see Section 6.1) are tackled in the subsequent section. This requirement is drafted to be technology neutral and performance neutral. It should also increase R & D projects in order to achieve higher ecodesign performance of future e-drive motors. A previous stakeholder consultation conducted during the review process of the original requirement in the ecodesign regulation on servers and data storage products mentioned that an ecodesign requirement could promote innovation ([41]). This requirement might also lead to an increased administrative burden. However, it is not expected to be a heavy burden on OEMs, as already existing data channels could be used to ensure the implementation of this requirement, such as the international dismantling information system ([42]) or already available repair and maintenance information channels. Besides, at the Member State or EU level, this requirement could generate limited additional administrative burden, mainly linked to type-approval authorities that need to ensure that OEMs are fulfilling additional design requirements. Additional administrative costs for requirements for vehicle design were also investigated in the study to support the impact assessment for the review of the ELVD (Baron et al., 2022).

([41]) SWD(2019) 106 final.

([42]) https://www.idis2.com/.

6.2.2. Updated impacts of requirement 1

The application of this requirement targets the process of extracting the e-drive motor from the ELV and would thus not influence the material recovery from e-drive motor recycling and reuse (compared to results of Section 6.1.1). It would also not lead to potential environmental impacts compared with the e-drive motor requirement for recyclers (see Section 6.1.2).

As for the socioeconomic impacts, the assessed requirement would require OEM investments in the reporting of instructions and reports to be provided to ATF to ease the disassembly of the e-drive motor. Besides, in order to minimise disassembly operations and the use of non-generic tools at ATF level to extract the e-drive motor, R & D costs would need to be generated at OEM level to enable the development and implementation of new technologies and processes. Such costs are aligned with the five strategic R & D areas identified by the European Council for Automotive R & D ([43]). However, it is expected that these R & D costs allocated to the ease of disassembly designs would be distributed over the next decade and are also aligned with most of the OEMs' perspective on the development of sustainable vehicles and improved mobility see for example the BMW I vision circular ([44]) or Renault Re-factory ([45]). Furthermore, the World Economic Forum, in partnership with the World Business Council for Sustainable Development, the European Institute for Innovation and Technology's Climate-KIC, Systemiq, Accenture and McKinsey are leading the circular cars initiative, which aims to increase the circularity of the automotive industry ([46]). For example, the requirement for ease of disassembly of the e-drive motor for maintenance and repair could go hand in hand with the ease of disassembly for recycling. Note that this refers to the disassembly of the motor from the vehicle, whereas thorough disassembly into individual parts (not a part of this requirement) needs further consideration.

From the ATF perspective, the requirement aims to facilitate disassembly operations of the e-drive motor when present in the ELV. It is thus subsequently expected that the requirement would, over time, lead to a decrease in removal (destructive dismantling) and disassembly times and to the optimisation of ATF costs. Looking at the costs estimated for the dismantling and disassembly of e-drive motors in Table 15, and given that the time needed for disassembly is double the time needed for dismantling, it is not surprising that the costs for disassembly are close to those for dismantling in 2030 and are almost as high in 2040, despite the still modest shares of e-drive motors to be disassembled (20 % and 30 % respectively). In other words, any design changes that would reduce the time and effort needed for disassembly (or dismantling for that matter) could be expected to have a positive effect on waste management operators, and thus improve the impacts of requirement 1 (see Section 6.1).

Table 19. Potential impacts of the assessed requirement 2 (average variation compared to the baseline scenario)

	Sc.0	Sc.1	Sc.1 (combination of requirement 1 and requirement 2)
Material flows and SRM production	Baseline	Very limited additional benefits	Better performance
Environmental benefits	Baseline	Very limited additional benefits	Better performance
Costs for suppliers and OEMs	Baseline	Low to medium(*)	Low to medium(*)
Costs for ATFs and recyclers	Baseline	Very low	Very low
Potential job creation	Baseline	Very low(*)	Very low(*)
Additional revenues and likelihood of increasing recycling/ reuse/remanufacturing	Baseline	Increased revenues	Increased revenues
Impacts on innovation	Baseline	Positive	Positive
Administrative burden	Baseline	Limited for OEMs, moderate for public authorities	Limited for OEMs, moderate for public authorities

Source: JRC own elaboration.

(*) Low to medium could roughly be quantified as one additional job linked to reporting at OEM level.

([43]) https://www.eucar.be/strategic-pill %E2 %80 %8Bars/.
([44]) https://www.press.bmwgroup.com/global/article/detail/T0341253EN/the-bmw-i-vision-circular?language=en.
([45]) https://www.renaultgroup.com/en/news-on-air/news/station-flins-re-factorys-incubator-opens-its-doors/.
([46]) https://www.weforum.org/projects/the-circular-cars-initiative.

6.3. Requirement 3: EEC group requirement for ATFs

The assessment presented in this section is mainly based on methodologies and results from the recent EVA II project, carried out by Empa for FOEN (see Section 3.2.3 for more information on the Swiss context). The main results are summarised in the *Projekt EVA II* report (Marmy et al., 2023). Additional information and data are reported in Annex III.

This requirement would apply to EECs embedded in vehicles (main categories defined in Section 3.2.2). The key characteristic of those components is that they require electricity to function, either from an external source through a cable or with the help of an internal battery. Most of the precious metals contained in vehicles are concentrated in those components but are lost in the current ELV management (see Sections 3.1 and 3.2). To improve the performance of ELV recycling, the solution promoted by this measure is to remove the EECs from vehicles and recycle them separately in e-waste recycling facilities, which are optimised for CRM and precious metals recovery.

In the EVA II project (Marmy et al., 2023), 43 types of EECs were identified, excluding sensors and including two types of e-drive motors that are addressed specifically in Section 6.1. Based on results from EVA II, this study assesses the socioeconomic and environmental impact of removing and separately recycling 41 types of devices of the four categories (controllers, actuators, headlights and cables) from vehicles. This is done by comparing the 'scenario baseline', which represents the current situation, and Sc. 1' (see Table 20 below), where components are removed to be recycled, in a mass flow analysis model of separate component recycling combined with economic and LCA assessment tools. The goal is to identify key components for which removal and separate recycling has the most positive environmental and socioeconomic impact. Recycling yields for Sc.1 are assumed to be the same for the assessed year 2030. Results are calculated per vehicle and then per EU fleet in 2030, 2035 and 2040.

Table 20. Constructed scenarios for the assessment of the e-drive motor requirement for recyclers

Scenario	Description of the scenario	Year of assessment
Baseline	Current situation – no removal of components for separate recycling prior to car shredding; for each component type, a proportion of components are removed to be sold as used spare parts (described in detail in Section 3.2.2)	
Sc.1	Removal of the targeted category of components, prior to shredding, for 100 % recycling purposes (excluding the components to be sold as used spare parts)	Suggested timeline by 2029–2030

Source: JRC own elaboration, based on EVA II project (Marmy et al., 2023).

6.3.1. Material flow and SRM production

As discussed in Section 3.2, ELVs recycled in Europe undergo depollution and dismantling steps prior to their shredding. During those processes, some EECs are removed to be sold as used spare parts.

The goal of the measure examined in the current section is not to hamper the reuse of EECs as spare parts, which can be considered as a circular economy practice, but to complement it by improving recycling. In consequence, the following hypotheses are made in Sc.1.

— Only the components that are not sold as used spare parts are removed and recycled in dedicated facilities. In other words, only additional environmental benefits and costs for the current situation (scenario baseline) are considered.

— The overabundance of used spare parts of some components could influence the reuse market, for example by reducing selling prices which could make the removal costs for recycling less affordable. Those dynamics have contradicting effects, until a new equilibrium is reached. However, modelling this kind of interaction is not in the scope of the current study, in which it is assumed that the systematic removal of components from vehicles does not influence the market of used spare parts.

In order to estimate the proportion of components removed to be sold as used spare parts for each component type, data from the EVA II project are used (see Table 31 in Annex III). Those data were collected in Switzerland in 2018, but they are nevertheless a good indicator of the situation in the EU due to the strong similarities between the Swiss and the EU vehicle fleet, and the international nature of the automotive industry and spare part market.

In Sc. 1, all the components removed from vehicles that are not sold as used spare parts are treated in dedicated e-waste recycling facilities. In order to evaluate the quantities of SRMs generated that way, the methodology and results of the *Materialverwertungsmodul* (material recovery module in German), developed in the frame of the EVA II project (see Table 30 in Annex III), were used.

The material recovery module models the outputs in terms of quantity and material content generated by the recycling of the four categories of components addressed in this study listed in Section 6.3. Components belonging to the same category are considered to be equivalent by unit of mass in the material recovery module, because they have similar compositions and produce similar output when recycled. The development of the module is mainly based on the results of an experiment where about 10 tonnes of vehicle EECs were collected, sorted according to those categories, and then treated in an e-waste recycling facility in Switzerland. The output fractions of that process were then characterised, quantified and chemically analysed. Once this primary mechanical treatment is carried out, its output fractions can undergo a secondary sorting treatment. In the end, all the material flows reach material recovery facilities, namely Cu smelters (that also recover precious metals), Al smelters, Fe smelters or plastics recycling facilities, where SRMs are produced. Waste is also produced in each process. In order to model secondary sorting and material recovery, data from scientific literature, monitoring tools from the industry and interviews with experts were used (see Table 30 in Annex III; the structure of the material recovery module is also represented in Figure 15 in Annex III).

The elements and materials considered in the model are the metals Fe, Al, Cu, Ag, Au and Pd and the recyclable plastics PP, PMMA, ABS and PC/ABS. The quantities of each of those materials that can be produced as an SRM are represented in Table 21 as a proportion of the recycling input mass for each component category.

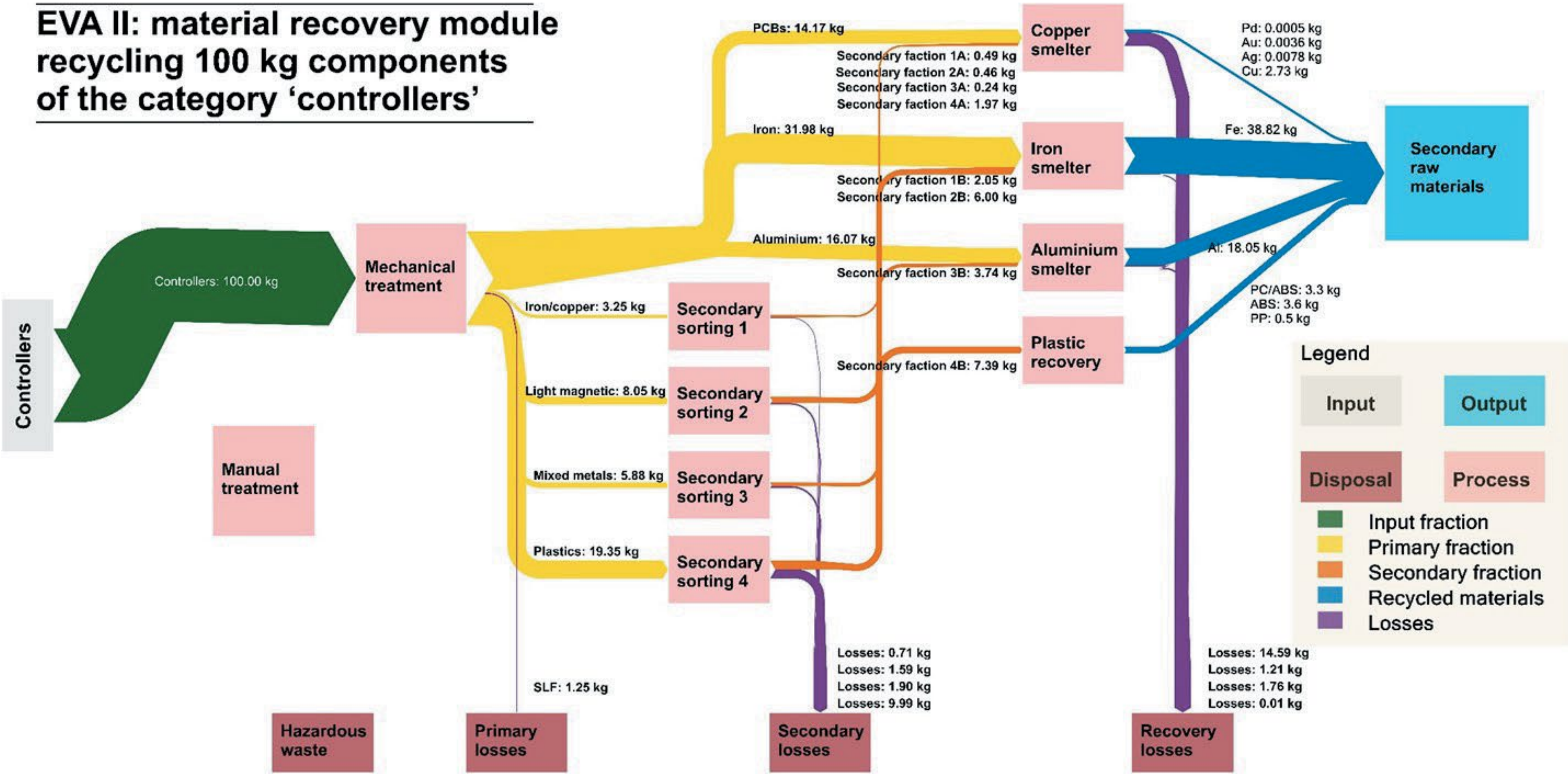
The results show that recycling components from the categories 'controllers' and 'headlights' facilitate the recovery of significantly more precious metals than those from 'cables' and 'actuators'. Moreover, about 50 % of the input mass of headlights can be recovered as plastics. Acrylic glass (i.e. PMMA) is considered as being particularly valuable. Figure 8 represents the mass flow diagram of the recycling of 'controllers', as modelled in the material recovery module of EVA II.

Table 21. SRM produced as a fraction of the recycling input for each scenario, component category and material considered in the material recovery model

Scenario	Category of component	SRM produced as fraction of the recycling input										
		Fe	Al	Cu	Au	Ag	Pd	PP	PMMA	ABS	PC/ABS	Losses
Baseline	Headlights	0.072	0.083	0.003	0	0	0	0	0	0	0	0.842
	Actuators	0.252	0.202	0.013	0	0	0	0	0	0	0	0.533
	Controllers	0.388	0.181	0.012	0	0	0	0	0	0	0	0.419
	Cables	0	0	0.375	0	0	0	0	0	0	0	0.625
Sc. 1	**Headlights**	**0.072**	**0.083**	**0.050**	**2E-05**	**1E-04**	**4E-06**	**0.018**	**0.201**	**0.133**	**0.122**	**0.321**
	Actuators	0.252	0.202	0.021	5E-06	4E-05	6E-07	0.010	0.000	0.071	0.065	0.380
	Controllers	**0.388**	**0.181**	**0.027**	**4E-05**	**8E-05**	**5E-06**	**0.005**	**0.000**	**0.036**	**0.033**	**0.330**
	Cables	0.000	0.000	0.375	0E+00	0E+00	0E+00	0.000	0.000	0.000	0.000	0.625
Difference	**Headlights**	**0**	**0**	**0.047**	**2E-05**	**1E-04**	**4E-06**	**0.018**	**0.201**	**0.133**	**0.122**	**−0.521**
	Actuators	0	0	0.008	5E-06	4E-05	6E-07	0.010	0	0.071	0.065	−0.153
	Controllers	**0**	**0**	**0.015**	**4E-05**	**8E-05**	**5E-06**	**0.005**	**0**	**0.036**	**0.033**	**−0.089**
	Cables	0	0	0	0	0	0	0	0	0	0	0

Source: EVA II project (Marmy et al., 2023)

Figure 8. Sankey diagram of the recycling of 100 kg of components of the category 'controllers' in an e-waste recycling facility, as modelled in the material recovery module of the EVA II project



Source: JRC elaboration, adapted from EVA II project (Marmy et al., 2023). PCBs in this figure refer to printed wiring boards.

6.3.2. Environmental assessment

In order to assess the environmental impact of the proposed measure, results from the *Ökobilanzmodul* (LCA module in German, see Table 30 in Annex III), developed in the frame work of the EVA II project, were used. The LCA module facilitates the estimation of the environmental impacts of the baseline scenario and Sc. 1 for each identified component category, using the methodology of the EU's product environmental footprint (European Commission, 2021), the ecological scarcity methodology (developed by Switzerland), and global warming potential (quantified in kg CO_2 equivalents). Components belonging to the same category are considered to be equivalent by unit of mass from an LCA perspective, because they undergo the same treatment processes, have similar compositions and produce similar output when recycled.

The boundaries of the considered system go from car dismantling to the production of SRMs, including elimination of the waste produced during the different processes. The functional unit is 1 kg of components of each considered category. On the one hand, recycling involves a certain number of processes (such as transport, shredding, sorting, incineration, material recovery, etc.) that generate all kinds of environmental negative impacts, estimated in the LCA module. On the other hand, recycling facilitates the production of SRMs (see Section 6.3.1), which are considered to substitute for primary raw materials in the market. Since those primary raw materials are not produced, the negative environmental impacts associated with their primary production, also estimated in the LCA module, are avoided. This 'avoided burden' constitutes the environmental benefit of recycling. Comparing the negative environmental impacts and avoided burdens in a given scenario (baseline or Sc. 1) allows the net environmental benefit of this scenario to be estimated. The difference in net environmental benefit of both scenarios allows the environmental benefit of switching from one (baseline) to the other to be estimated (Sc. 1). The final results of the LCA module for each component category are presented in Table 22.

Table 22. Environmental benefit of each scenario, and from switching from the baseline to Sc. 1, for each method and component category considered in the study.

Scenario	Component category	Global warming potential (kg CO_2eq)	Ecological scarcity methodology 21	Environmental Footprint 3.0
Baseline	Headlights	– 0.67	5.33E + 02	1.51E-04
	Actuators	2.81	6.57E + 03	6.40E-04
	Controllers	2.85	6.14E + 03	5.47E-04
	Cables	– 0.08	1.97E + 04	6.42E-03
Sc. 1	Headlights	4.96	1.61E + 04	3.19E-03
	Actuators	4.38	1.01E + 04	1.24E-03
	Controllers	5.23	2.02E + 04	4.16E-03
	Cables	– 0.08	1.97E + 04	6.42E-03
Baseline to Sc. 1	Headlights	5.65	1.56E + 04	3.04E-03
	Actuators	1.58	3.50E + 03	5.97E-04
	Controllers	2.39	1.41E + 04	3.62E-03
	Cables	0.00	0.00E + 00	0.00E+00

Source: EVA II project (Marmy et al., 2023). The functional unit is 1 kg of components of each considered category.

The results show that applying the proposed measure to 'controllers' and 'headlights' generates the most environmental value, because it allows the recovery of precious metals that both categories of devices contain. Moreover, recycling the important quantities of plastics contained in headlights has the twofold environmental benefit of reducing the amount of material incinerated and the associated impacts, and generating SRMs that can substitute for the production of primary plastics.

6.3.3. Socioeconomic assessment

In order to assess the (economic) costs of the proposed measure for each identified component category, results from the *Wirtschaftsmodul* (economic module in German, see Table 30 in Annex III), developed in the frame of the project EVA II project were used. This is done by estimating three cost items for each component type.

— Removal of a component from a vehicle in a car dismantling facility. This item is quantified by using data on dismantling time for each component type from a previous Empa study (Restrepo et al., 2018) and Swiss labour costs of a skilled person from the sector.
— Transportation of removed components to an e-waste recycling facility. This item is quantified using standard tariffs of Swiss logistics companies.
— Treatment of the removed components in an e-waste recycling facility. This item is quantified by using data on the financial support received by recycling companies in the frame of the existing Swiss EPR financing system for electronics to treat an equivalent category of e-waste. This subsidy aims to augment their revenues obtained through recycling so that they can cover their operating costs. In consequence, recycling revenues, which can only be extracted thanks to the contribution of all three cost items presented above, are exclusively used to compensate for the true operating costs of recycling.

Table 23 presents the main parameters used for the calculations of the economic module. All these parameters are based on the Swiss context. However, it is assumed that the dismantling time by type of component is similar in the European Union.

Table 23. Main parameters used in the calculations of the economic module

Parameter	Value
Average transportation distance of the components	75 km
Labour costs component removal	CHF 85 / hour
Recycling costs	CHF 71 / ton
Transport costs	CHF 3.46 / ton*km

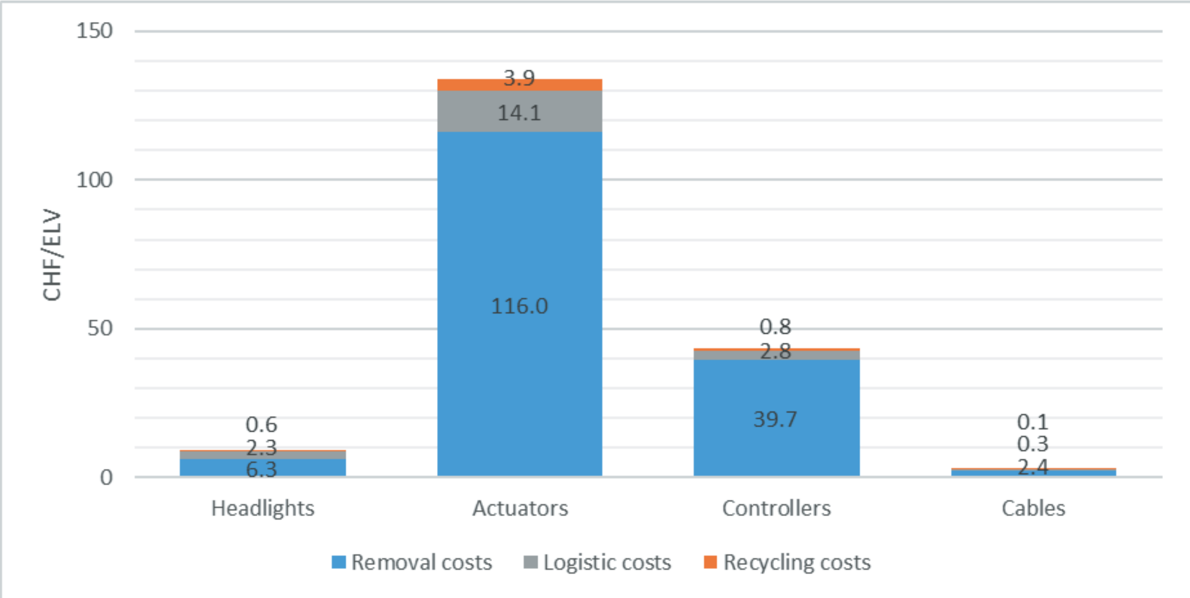
Source: EVA II project (Marmy et al., 2023).

Applying the proposed measure (removal and separate recycling) to all the identified component types contained in an average ELV in Switzerland in 2021 would cost approximately CHF 190 (circa EUR 190) per vehicle (see Figure 9). This amount represents only about 0.5 % of the average price of a new vehicle in Switzerland. Figure 9 shows how this cost is itemised for the average mass of components of each category in an average Swiss ELV in 2021. The dismantling costs dominate the overall costs. Since those are mostly dependent on the dismantling time, this parameter is a good way of estimating costs across local contexts and local currencies. Considering the aggregated list of 41 components targeted in this study, and assuming roughly that burdens would be equivalently distributed over the assessed components, EUR 4.4 per component per ELV could be estimated as the most conservative cost of requirement 3. However, the 'actuators' category represents the highest economic burden for waste management operators from a disaggregated perspective. It can then be assumed that the average cost of requirement 3, also based on the higher additional benefits of 'controllers' and 'headlights' categories, for a shortlist of most relevant components would be less than the estimated cost of EUR 4.4 per ELV.

From a social perspective, this requirement would in principle generate additional job creation in ATFs. Since requirement 3 assesses additional dismantling practices of components that are not targeted by current practices, it is roughly assumed that an analogy can be made with requirement 1 in terms of job creation opportunities (see Section 6.1.3).

Thus, it can be concluded that this requirement scenario will lead to better performances (see Table 24). It will also lead to the generation of potential secondary materials such as Fe, Al, Cu, Ag, Au and more specifically Pd from the assessed category of components. Additional plastics can also be recovered. In addition, there is an added environmental benefit to separately recovering and recycling such categories (especially 'headlights' and 'controllers'), leading also to lower additional costs over waste management operators as compared to the 'actuators' category. However, extracting 41 components at ATF level could be daunting and would create greater burdens on ATFs. Consequently, it is necessary to shortlist the most relevant components to be removed from ELVs and separately recycled.

Figure 9. Requirement 3 – Cost distribution over waste management operators



Source: EVA II project (Marmy et al., 2023).

Afterwards, mandatory removal of additional EEC from the vehicle prior to shredding would also develop innovative business models linked to different processes such as extraction, recycling, reuse, repair and remanufacturing. Thus, such a requirement would not hinder innovation in the sector.

As for additional administrative costs linked to this requirement, they are mainly linked to reporting and would affect waste management operators and public authorities. Similarly to requirement 1, administrative costs are assumed to be limited to moderate, as already existing schemes for reporting could be used for this requirement.

Table 24. Potential impacts of the assessed requirement (average variation compared to the baseline scenario)

	Sc.0	Sc.1
Material flows and SRM production	Baseline	Better performance
Environmental benefits	Baseline	Better performance
Costs for suppliers and OEMs	Baseline	Null
Costs for ATFs and recyclers	Baseline	Moderate(*)
Potential job creation	Baseline	Good performance(*)
Additional revenues and likelihood of increasing recycling/reuse/remanufacturing	Baseline	Best performance
Impacts on innovation	Baseline	Positive
Administrative burden	Baseline	Limited to moderate for waste management operators and public authorities

Source: JRC own elaboration.

(*) Analogy with requirement 1, see Section 6.1.3.

6.3.4. Shortlisting of key components

Based on the results presented in the previous Sections 6.3.1, 6.3.2 and 6.3.3 and in Table 24, one can derive a shortlist of components to be dismantled.

In order to select which types of components should be integrated in requirement 3, the selection criteria (listed below and presented in Figure 10) were applied to all 41 component types considered in this assessment.

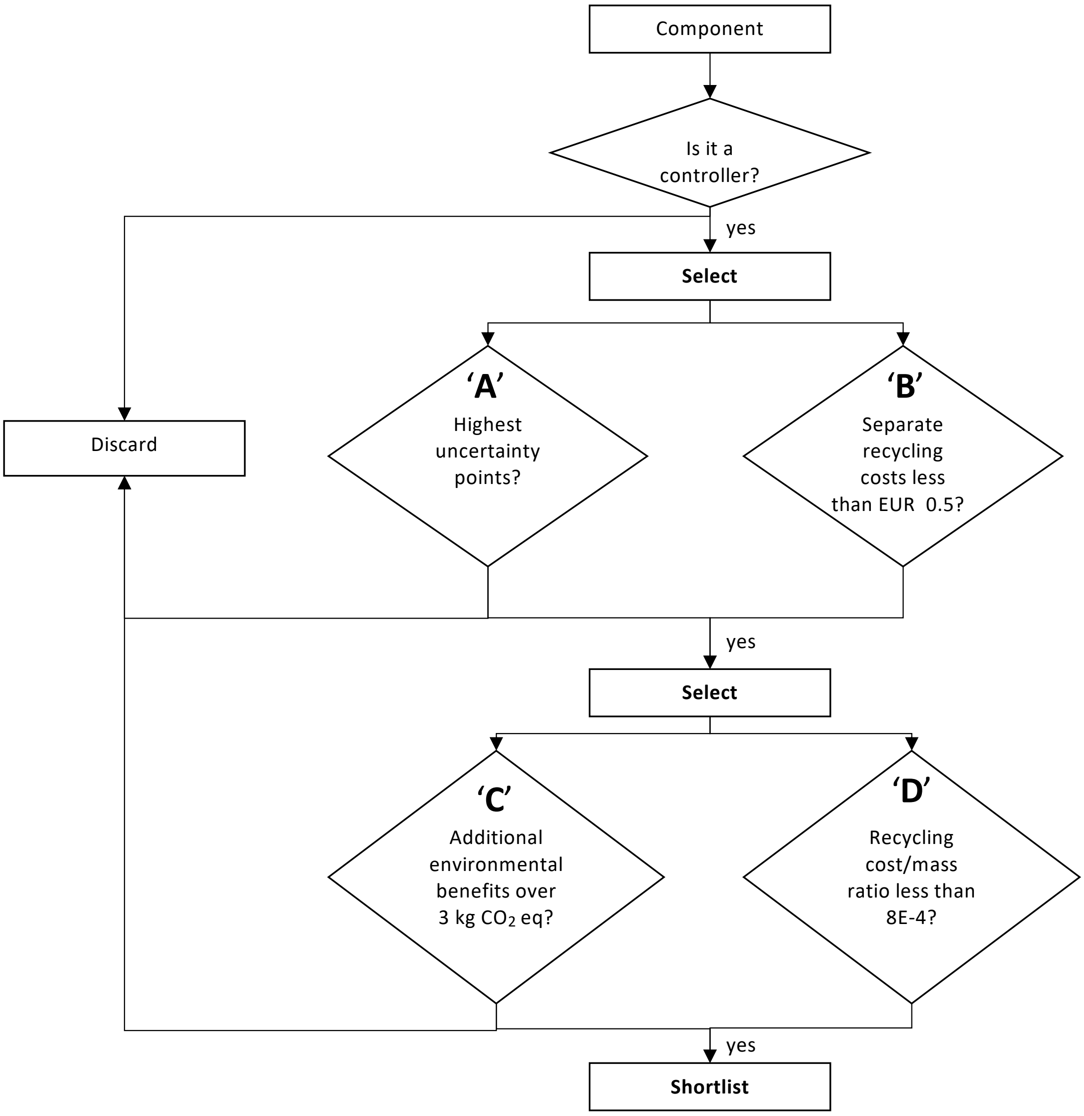
— If the component type belongs to the 'controllers' category, it will be selected for further assessment. Otherwise, it will be discarded. Their separate recycling would generate the highest amount of SRMs, especially for precious metals and Pd, which also leads to higher additional environmental benefits (see Section 6.3.2). 'Controllers' also generate lower overall costs per vehicle (around EUR 45) compared to the overall burdens estimated in Section 6.3.3.
— Either A or B.
    ° A: the robustness of the data used to estimate the costs of removal and separate recycling of a component type is high. This robustness is qualitatively evaluated in EVA II by a scoring system, based on the number of data points and the data collection measure used (Marmy et al., 2023).
    ° B: its separate recycling cost per average ELV is below EUR 0.5.
— Either C or D.
    ° C: the component has an additional environmental benefit of over 3 kg CO_2 eq.
    ° D: the component must have a ratio of separate cost of recycling per mass of the component below 8E-4.

According to this rationale, the following three types of components were finally selected:

— inverter (for EVs);
— control module / valve box automatic transmission;
— infotainment control unit (sound, navigation and multimedia).

Knowing the average mass of each component type per average ELV of each drive train, and combining that with the expected future amount of ELV collected and recycled from the EU vehicle fleet (similar to the one presented in Section 6.1), it is possible to assess the potential additional benefits at the EU Level (see Table 25).

Figure 10. Criteria and logic flow for shortlisting the most suitable components



Source: JRC own elaboration. Thresholds were estimated for the sake of this study.

Table 25. Potential additional benefits of the shortlisted components, calculated at the EU level

	2030	**2035**	**2040**
Secondary Cu, in t	3 340	3 397	3 628
Secondary precious metals (Au and Ag), in t	14.8	15.1	16.1
Secondary Pd, in t	0.6	0.6	0.7
Estimated separate recycling costs of the three components, per car, in EUR (based on EVA II)	5.9	5.9	5.9
Estimated net additional environmental benefits of the three components, per fleet, in tCO_2eq	67 807	68 956	73 651

Source: EU fleet based on JRC forecast and EVA II project results

6.4. Requirement 4: Information request for specific CRMs in the vehicle and targeted labelling of CRM-based components (requirement for OEMs)

The requirement for the declaration of CRMs has already been applied before in the context of ecodesign requirements for servers and data storage products ([47]). The latter requested (in Annex II, Section 3.3 ([48]) compulsory information on CRMs (mainly cobalt and Nd) at component level. This requirement was introduced to prevent the lack of information on CRM present in the targeted products and to provide an incentive for recyclers to disassemble and target such materials. The requirement was judged to be feasible and enforceable within the ecodesign regulation for servers.

Against the background of this enforceable instrument and its application in relation to servers and data storage products, the same instrument would be applied to Nd and Dy at the REPM level of e-drive motors and to Ga in a size-fixed controller category in order to target the same failures and cover the same objectives for dismantlers and recyclers. It is hence likely to be enforceable for vehicles. The assessment of the impacts of this requirement is also based on the assessment of the original one, and is adapted from the results of the evaluation of the original requirement.

It was stated in the Commission staff working document assessing the original requirement for servers and data storage products ([49]) that, once separated, Nd scrap can be further processed to recover the CRM. Due to the different types and sizes of e-drive motor technologies available on the EU market, an information requirement at this component level would encourage the separation at early stages of disassembly in the ATFs. A similar assessment could also be applied to the benefits of requesting succinct information on Ga use at controllers' level greater than 10 cm^2 and sensors. The previous JRC report also mentioned the lack of information on the use of this CRM in vehicles (Løvik et al., 2021). In addition, the initial assessment of information on weight and location of REEs, the requested additional information on the number of REPMs and on their coating and gluing/assembly within the rotor could significantly increase dismantler and recycler knowledge to adapt the necessary operations to efficiently extract the REPMs from the e-drive motor.

The available standards on material efficiency, including those developed under CEN/CLC/JTC 10 ([50]) (e.g. EN 45558 – General method to declare the use of CRMs in energy-related products) could also be used to make the enforcement of this requirement easier at e-drive motor level.

Labelling parts or products with specific material content (to ease depollution or sorting) would in principle incentivise the dismantling and separate collection of the e-drive motor at ATFs.

As for impacts (see Table 26), since the form of the envisaged legislation is a regulation (linked to 3RTA), no costs for transposition into national legislation are envisaged. The estimated administrative burden for OEMs and public authorities is mainly concentrated in reporting and documentation delivery from suppliers to OEMs and their enforcement. Since the automotive industry is already equipped with material and component communication channels (e.g. the international material data system and the international dismantling information system), costs of compliance are deemed to be limited. It was also stated in the ecodesign regulation for server assessment that the administrative burden has been significantly lowered by requesting weight ranges of targeted CRM instead of weight, and by referring to the location of the CRM at component level. From an EoL value chain perspective, more time would be needed for ATF and recycler employees to investigate and look up information on CRMs in their input materials, which may lead to further processing time per input waste and products. However, this will also provide further revenues from the sales of CRMs. The estimated overall additional costs for ATFs and recyclers are then supposed to be low to medium. The requirement adapted to the e-drive motors would increase ATFs' and recyclers' knowledge on this component and is likely to increase the uptake of recycling, reuse and remanufacturing measures. EoL flows might slightly increase thanks to the implementation of this requirement if supported by the assessed requirements 5.1 and 5.2 on e-drive motors and requirement 5.3 on selected controllers. It is also estimated that very limited additional benefits would be generated from the implementation of this requirement. In addition, it is unlikely that this requirement would impact job creation. This measure is not intended to hinder innovation or the development of new technologies.

([47]) Regulation (EU) 2019/424, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R0424.

([48]) See footnote 54.

([49]) https://ec.europa.eu/transparency/documents-register/api/files/SWD(2019)106_0/de00000000060780?rendition=false.

([50]) https://standards.cencenelec.eu/dyn/www/f?p=205:7:0::::FSP_ORG_ID:2240017&cs=18A65BEA4289B745403E9407952618CE3.

Table 26. Potential impacts of the assessed requirement of CRM information request for OEMs. Sc. 0 is the baseline scenario and Sc. 1 is the improved scenario applying the assessed requirement.

	Sc. 0	**Sc. 1**
Material flows and SRM production	Baseline	Limited performance
Environmental benefits	Baseline	Very limited additional benefits
Costs for suppliers and OEMs	Baseline	Zero to low costs
Costs for ATFs and recyclers	Baseline	Low to medium costs
Potential job creation	Baseline	Unlikely
Additional revenues and likelihood of increasing recycling/reuse/remanufacturing	Baseline	Additional revenues Small contribution
Impacts on innovation	Baseline	Unlikely
Administrative burden	Baseline	Limited for OEMs and public authorities

Source: JRC own elaboration, based on the assessment of the original requirement for servers and data storage products ([51]).

6.5. Recommendations from the impact assessment

The performances of each requirement are summarised in Table 27. Although each of the developed requirements tackles a specific circularity/market failure, they all contribute to the increase of CRM circularity in vehicles.

Requirement 1 on the mandatory removal of e-drive motors from e-ELVs can provide a high additional share of materials (Al and Cu) and clearly contributes with a significant added value to the quantity and quality of secondary materials from ELV treatment. The obligation to separately treat and recover e-drive motor materials could also promote the development of REPM recycling and its separate treatment in the EU, and potentially also the recycling of Si-steel. This requirement would also generate higher environmental savings, both by reusing e-drive motor parts and by recycling them. Such a requirement would also have a positive impact on innovation, as it would increase R & D activities for waste management operators to optimise EoL processes. The suggested timeline for this requirement to be implemented would be rather short (1 to 3 years after the entry into force of the regulation): the time needed for waste management operators to adapt and set up the necessary investments to efficiently handle the removal of e-drive motors. Such lead time could also be used to develop the necessary standards, monitoring and logistic organisation to ease the implementation of the requirement. Ultimately, additional social impacts would be expected from the reuse of e-drive motors, leading to the development of second-hand markets, the remanufacturing of e-drive motors and the availability of affordable EVs on the market.

Similarly, mandatory removal of the three selected controllers in requirement 3 would also generate additional revenues for waste management operators, and the requirement's added value lies in the recovery of additional strategic, precious and critical metals from ELV flows (mainly Cu, Ag, Au and Pd). This requirement would also increase the quality of treatment. The mandatory removal of EEE and EECs was also investigated in the support studies for the ELVD review (Baron et al., 2022) and in the support study for the ongoing Swiss ordinance on e-waste to recover critical and STMs (Marmy et al., 2023). The rationale behind such assessment in different support studies is to make it so that EEC parts removed from vehicles fall under the scope of the WEEE directive. The latter directive excludes EECs from means of transport, and the ongoing electrification of vehicles (and other mobile systems) reduces the potential of recovering SRMs from additional waste streams. Further studies (also in the ongoing revision of the WEEE directive) would further assess the cost–benefits of extending the scope of the directive to include these EECs and other categories. Here, the timeline suggested for the implementation of this requirement would be 3 years after the entry into force of the new ELVD/3RTA regulation, in order to provide suitable lead time for waste management operators to set up the necessary investment and organise their logistics flows. This requirement targets one component mainly existing in EVs (inverter) and the two remaining components (control module or valve box for automatic transmission and infotainment control

([51]) SWD(2019) 106 final.

unit) that are available in all drive train types. Although such components would appear at first glance to be only available for higher and recent segments, the continuous electrification and modernisation of new vehicles put on the market in the last decade would ensure their continued availability in ELVs reaching ATFs in the coming decades. It is also unlikely that current PSTs would be able to target and recover materials from the assessed components, and additional investigations would be required to further assess the recoverability after shredding of the targeted CRMs from controllers. In such case, derogations should in principle apply if recyclers can remove materials from the EEC group using semi-automated sorting or PST, contingent upon them reaching the same efficiency as manual removal.

OEM strategies to increase the circularity of the automotive value chain are ongoing, and the 'circular by design' principle is at the core of such strategies. The investigated design requirement 2 for OEMs to ease the disassembly of e-drive motors would in principle optimise the removal or disassembly of e-drive motors at ATF level for recycling or reuse respectively. Such a requirement would significantly increase innovation and partnership across the automotive value chain to optimise the design for circularity of e-drive motors. Its performance would then be markedly enhanced if combined with requirement 1. The current version of this requirement focuses on reporting instruments and voluntary strategies of OEMs to avoid fastening and joining techniques that hinder the reuse or recycling of e-drive motors upon reaching ATFs. It is also an initial prerequisite to improve the ecodesign of e-drive motors. It allows for instance at a later stage the necessary time required to remove or disassemble the e-drive motor from the vehicle to be estimated. All operations and tools used in such processes could also be assessed and would ultimately converge towards a standardisation of tools, steps and processes to remove and disassemble the e-drive motor in an easy and optimised way. The requirement could also lead to a more detailed disassembly requirement targeting disassembly depth of the e-drive motor to extract selective parts from the latter for reuse, remanufacture and recycling purposes.

The previous JRC report (Løvik et al., 2021) on material composition trends in vehicles and the use of CRMs in vehicles mentioned the clear lack of data on some CRMs used in vehicles, such as Ga. Requirement 4 contributes to tackling this and provides the necessary instruments to report the indicative weight and location of Ga used in vehicles put on the market. Such information is relevant for monitoring CRM use in vehicles and for the establishment of potential processes at waste management operator level to facilitate the recoverability of this CRM. As for REEs used in PMs, the reporting on these CRMs and their labelling would increase their monitoring and would make them more visible and thus more easily targeted by ATFs to be separated from the ELVs prior to shredding. The necessary information on their numbers, location, coating and fastening techniques used would complement the ecodesign requirement 2 for e-drive motors. The scope of this requirement could also be potentially extended to cover the EEC group, since providing the necessary information on the location and the amount of targeted EECs would in principle optimise waste management operations to effectively remove such components from ELVs.

Overall, from a material flow perspective, requirements 1 and 3 for ATFs generate additional SRMs and spare-part flows to the EU markets. Requirements 2 and 4 for OEMs do not contribute to SRM production but do help increase the efficiency of requirements 1 and 3 for recyclers. From environmental and partial cost–benefit perspectives, all the assessed requirements provide relevant additional benefits compared to current practices. They also contribute to a higher level of job creation and to the development of innovative business models across the automotive value chain.

Looking at the assessed requirements, and together with the measures developed in the support study for the impact assessment of the ELVD (Baron et al., 2022), some requirements may overlap and synergies between the assessed measures in both studies can be further developed to increase CRM and material circularity in vehicles. The next section highlights some of the main synergies.

Table 27. Performances of the assessed requirements, each compared to their respective baselines (NB: the requirements are not compared with each other).

	1 – E-drive motor requirement for ATFs (Sc.1)	**2 – E-drive motor design requirement for OEMs (in combination with requirement 1)**	**3 – EEC group requirement for ATFs**	**4 – Information request of selected CRM**
Material flows and SRM production	Best performance	Better performance	Better performance	Limited performance(*)
Environmental-based assessment	Better performance	Better performance	Better performance	Very limited additional benefits(*)
(Partial) cost–revenues assessment (for ATFs)	Moderate	Very low costs and increased revenues(*)	Moderate	Low to medium costs with additional revenues(*)
Potential job creation (only ATFs)	Good performance	Very low(*)	Good performance(*)	Unlikely(*)
Additional revenues (for recyclers)	Best performance	Increased revenues(*)	Best performance	Additional revenues(*)
Additional burdens on type-approval authorities, Member States or OEMs (if applicable)	Null	Low to medium(*)	Null	Zero to low costs(*)
Impact on innovation	Positive(*)	Positive(*)	Positive(*)	Unlikely(*)
Administrative burden	Limited to moderate for waste management operators and public authorities(*)	Limited for OEMs, moderate for public authorities(*)	Limited to moderate for waste management operators and public authorities(*)	Limited for OEMs and public authorities(*)

Source: JRC own elaboration.

(*) Based on qualitative assessment or analogies with similar requirement in other legislation packages.

6.6. Accompanying measures and analysis of synergies

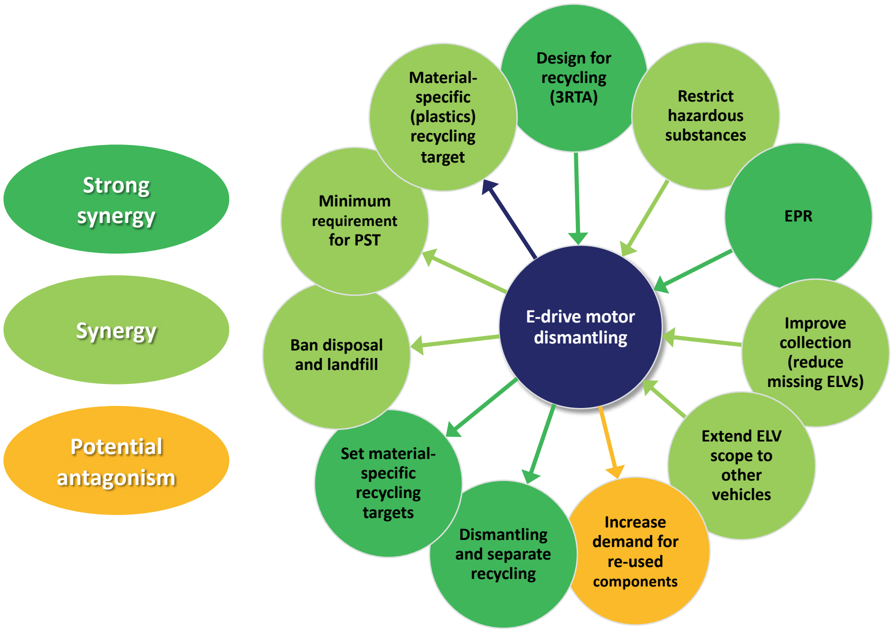
The analysis above mainly considered the impacts that would be incurred should a certain measure be implemented, however the measures may also affect each other when implemented together. Furthermore, as mentioned above, different policy options and measures have been analysed in other studies prepared to support the impact assessment of the ELVD (see for example Baron et al. (2022)). This includes measures developed to improve the circularity of vehicles, measures developed to improve their collection (reducing the number of missing vehicles), and policy options developed to extend the directive to additional vehicle categories.

To further enhance the analysis of the measures analysed in the scope of this study, this section takes a qualitative look at the synergetic effects of these measures in comparison with other measures, including those developed in other studies performed as part of the ELVD review.

For each of the measures reviewed in this study, a figure is included below to show the various relations and a short discussion explaining the main effects.

Looking at the requirement to dismantle the e-drive motor, the strongest synergies (see Figure 11) are expected with measures looking into other dismantling requirements to support recycling, and measures relating to the development of recycling targets for specific materials. The current measure is assumed to have a positive effect in both cases. In addition, at the design stage, measures developed in relation to the 3RTA could also affect this measure as, among other things, it is envisioned that OEMs would need to provide information on how to dismantle components with a potential for reuse and for improved recycling when removed prior to shredding. The availability of such information could support quicker removal of the e-drive motor and thus lower ATF costs related to this requirement. A strong synergy is also expected with measures developed on EPR. Should the costs of e-drive motor dismantling exceed the expected benefits, the EPR could be involved to allow cost compensations in some cases, and could also affect the development of modulation fees in the future. Though the connection is not as strong, the e-drive motor dismantling can also be expected to have a positive effect on measures relating to the performance of PST operators and in relation to a ban on landfill (it will be easier to achieve PST minimum performance, as dismantling the motor will remove valuable materials that could end up in post-shredder fractions). This will also have a positive effect on the need to send fractions to landfill where this is still practiced. This requirement could have a negative effect on the reuse of e-drive motors as already mentioned above, seeing as, in particular, revenues for REPM material may make recycling more attractive than reuse. Provisions to improve vehicle collection can be expected to have a positive effect on this requirement, though this is expected to be more relevant in the future as currently there are not many vehicles with e-drive motors that are exported (legally or illegally).

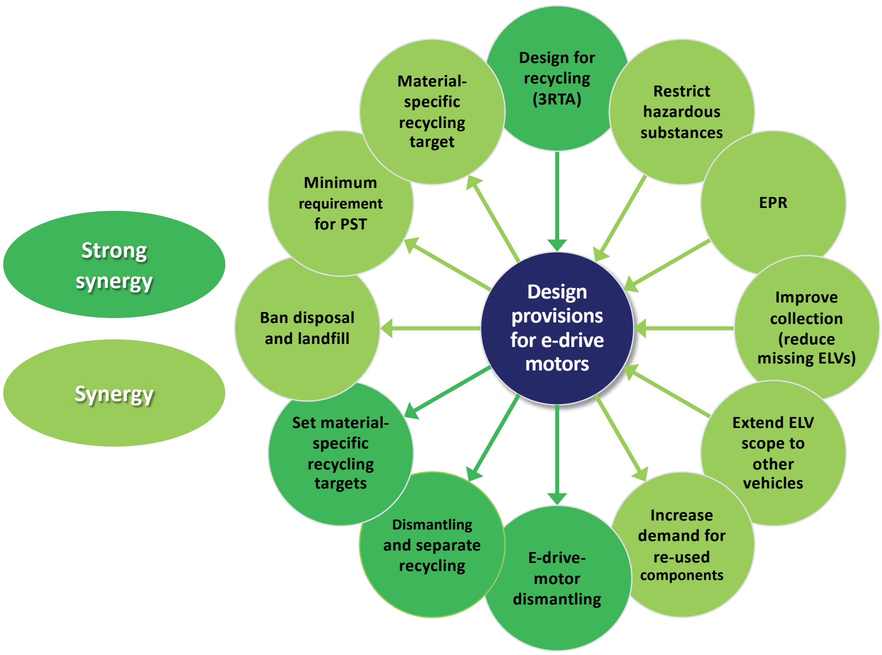
Figure 11. Overview of the e-drive motor mandatory removal (requirement 1) synergies with other measures under investigation in the ELVD revision



Source: JRC own elaboration.

The relation between the requirement for the design of the e-drive motor and other measures and policy options is presented in Figure 12. This requirement could contribute to the removal of the e-drive motor both for recycling and for reuse, and as such would have positive effects on similar provisions to the requirement on the dismantling of the e-drive motor. However, in this case, without an obligation to remove these components, impacts would be lower and thus most synergies are not considered to be strong.

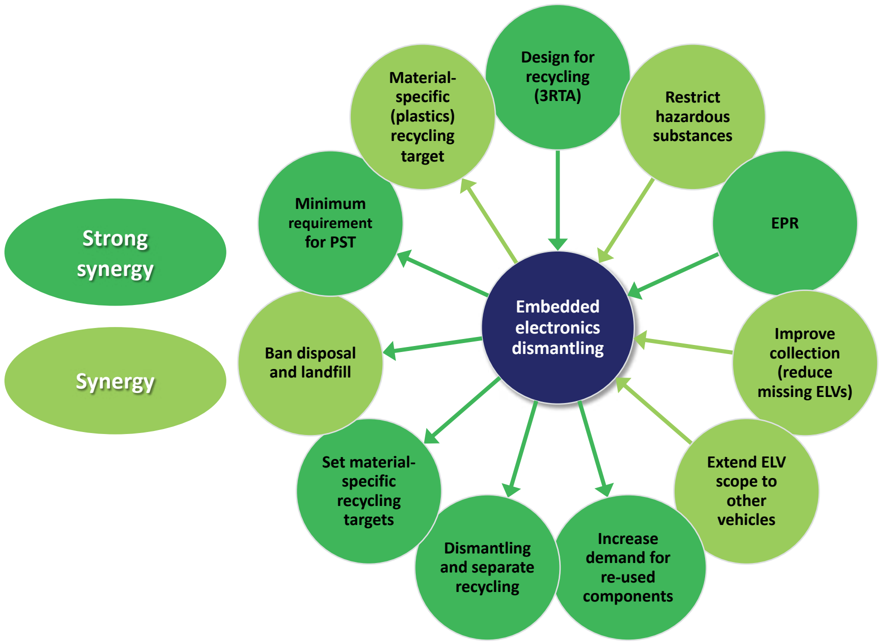
Figure 12. Overview of synergies between e-drive motor design provision (requirement 2) and other measures under investigation in the ELVD revision



Source: JRC own elaboration.

Similar to the requirement on the dismantling of the e-drive motor, the requirement to dismantle EECs has strong synergies with measures developed to improve recycling (dismantling and separate recycling, and material-specific recycling targets), as shown in Figure 13. In this case, a strong synergy with measures for increasing the demand for reused components is also expected, as where the demand is higher, ATFs will be able to consider component removal to supply secondary markets. Here too, should costs be higher than expected benefits, the development of the EPR could be relevant to ensure that compensations are granted where needed or to consider the level of design for dismantling when developing fee modulation. As it is said that larger and more luxurious vehicles are more prone to exports (and usually have a higher level of electrification), provisions to improve collection will have a positive effect on this measure and on the availability of EECs for removal.

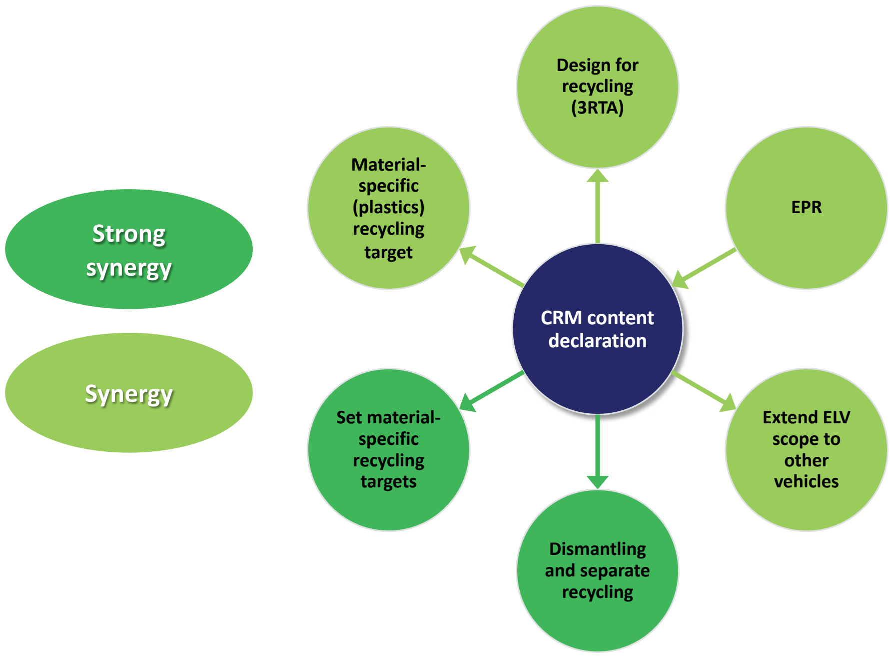
Figure 13. Overview of synergies between the mandatory removal of embedded electronics (requirement 3) and other measures under investigation in the ELVD revision



Source: JRC own elaboration

As presented in Figure 14, a requirement to declare the content of CRMs in vehicles may not lead directly to higher recycling in the short term, however it would create a higher awareness as to where relevant amounts of CRMs are located and could support the development of provisions in the future. Thus, the synergies in this case are not as strong as shown for previous requirements and are in most cases developing prerequisites for more ambitious future legislation. The main difference is for dismantling and separate recycling, where ATFs could consider such information for voluntarily developing more CRM recycling in the future, it should become clear that the efforts would be lower than expected gains.

Figure 14 Overview of synergies between the declaration of CRM content (requirement 4) and other measures under investigation in the ELVD revision



Source: JRC own elaboration

7. Conclusions and perspectives

At the request of Commission's DG for Environment and DG Internal Market, Industry, Entrepreneurship and SMEs, in the context of supporting the ongoing review of the ELVD and the 3RTA, the JRC conducted this study in joint collaboration with Chalmers University, Empa and the Oeko-institute. The study was also conducted in the light of the goals of the CRM Act defining critical materials to the EU value chains and providing inter alia directions to promote their circularity and resource efficiency.

The aim of the study was to evaluate the most feasible requirements (coupling measures and targeted materials/components) to increase the circularity of critical and other raw materials in passenger cars. The analysis initially focused on the current state of the ELV management, which corresponds to a range of circularity failures for many materials, including CRMs in vehicles. The project team first concluded that measures to tackle such failures should not only address the ELV management and the waste management operators but also the manufacturing of vehicles and the OEMs. Measures were paired with specific materials, resulting in four requirements from the inventoried list of policy options. These requirements, listed here, were adapted to the automotive sector to target the previously individuated circularity failures of CRMs and other materials:

— requirement 1 on the mandatory removal of e-drive motors by ATFs;
— requirement 2 on design provisions for e-drive motors;
— requirement 3 on the mandatory removal of selected EECs by ATFs;
— requirement 4 on information request for specific CRMs contained in vehicles and their labelling.

For each requirement, one or more scenarios were assessed against a previously defined baseline scenario, evaluating in particular:

— material flows and SRM production;
— environmental impacts;
— socioeconomic impacts, including impacts on innovation and administrative burdens.

The impact assessment leads to the conclusion that all four requirements on their own provide added value to the quantity (e.g. REEs) and quality (e.g. steel and Al) of SRMs in the EU from ELV management. They contribute to reducing the environmental impact of vehicles and result in extra revenues and additional job creation at ATF level. All four requirements investigated do not hinder innovation and contribute to the development of R & D in the automotive value chain. Requirements targeting e-drive motors (i.e. 1, 2 and 4) contribute significantly to the proper management of EoL e-drive motors, filling an important missing step in their value chain and promoting their circularity by establishing practices of reuse, remanufacturing and recycling in Europe. Requirement 3 results in an increased flow of secondary precious metals, especially Pd, and secondary Cu with consequent environmental benefits when targeting controllers in particular. From a socioeconomic perspective, requirement 3 would have similar benefits to requirement 1.

Synergies can arise when coupling these requirements with each other or with other requirements investigated within the support study for the impact assessment of the ELVD and that of the 3RTA: for instance, requirements 1, 2 and 4 together significantly increase the circularity of e-drive motors. On the other hand, the requirements might lose their effectiveness if not properly supported by monitoring and EPR schemes for the deployment at ATF level of the same requirements. The deployment of such requirements in the EU automotive value chain could also be accompanied by a set of measures and instruments to increase their efficiency, such as standards and monitoring schemes.

This initial analysis of the investigated requirements in this *Science for Policy* report paves the way for tackling the circularity or market failures of critical and other raw materials and thus for increasing the circularity of the automotive value chain and the EU economy. Follow-up studies are planned to build a comprehensive analysis of each targeted material and to address some limitations on data availability and parameter sensitivity encountered in this study. They should also cover the reassessment and the leveraged benefits of synergies that can be achieved by the different potential policy packages.

Data and knowledge will also be collected from previous and ongoing EU-funded projects on CRMs and vehicles (in the non-exhaustive list in Annex IV). The requirements which were not shortlisted because of lack of feasibility in this study (e.g. requirements targeting Ti or Mg) might be further assessed in the next project and some shortlisted requirements (e.g. requirement 1) might be further expanded (e.g. disassembly of the e-drive motor into its components).

Another potential follow-up measure would be the extension of scope of the study to other vehicle categories; namely lorries, buses and motorcycles. These vehicles are not under the current scope of the ELVD/3RTA directives and represented in 2019 circa 52 million vehicles (15% of EU vehicles). These vehicles do not abide by specific legal requirements on their design or end-of-life phases, leading in principle to the loss of an important share of SRM, including CRMs. Most of lorries and trucks are generally exported outside Europe at their end-of-life, as the absence of a structured end-of-life value chain for these vehicles aggravates their circularity failures. Besides, current EU ATFs are not adapted to properly treat and collect most of these vehicles. From a CRM perspective, and considering the electrification of this fleet, together with the stringent EU environmental standards (e.g EURO 6 or 7), an increase of technology devices in vehicles is expected, and thus of CRMs in lorries and buses. A higher power range of these vehicles also means the multiplication of e-drive motors within the drive train. As for motorbikes, most existing electric two-wheelers are based on REPM motors with REE in magnets and laminated Si-steel. The opportunity to widen the scope of the ELVD/3RTA to these vehicles will thus have a positive impact leading to higher circularity of CRMs in all vehicles. It should also in principle foster the setting up of up-to-date treatment and recovery facilities for these vehicles in the EU and contribute further to the development of EU CRM value chains and thus to the CRM Act objectives.

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List of abbreviations and definitions – Glossary

%wt	Weight percent
3RTA	Directive on the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability (Directive 2005/64/EC)
ABS	Acrylonitrile butadiene styrene
Ag	Silver
Al	Aluminium
ATF	Authorised treatment facility
Au	Gold
BEV	Battery electric vehicle
Component category	Group of components serving similar functionalities in the product (e.g. lighting family)
Component type	A subgroup from a component category constituting an element of a larger product (e.g. a vehicle), made up of one or more parts, all necessary to a specific function
Connection	Physical link between parts or components
CRM	Critical raw material, see EU definition ([52])
CRM part	Component part containing CRM
Cu	Copper
Disassembly	'Reversible' removal aiming to extract a component for reuse and recycling purposes
Disassembly depth	The extent to which the disassembly process is performed, including number of steps required to disassemble selective parts from the component
Disassembly sequence	Successive order in which the disassembly tasks are carried out
Dismantling	'Destructive' removal of a component from the vehicle
Dy	Dysprosium
Ease of disassembly	Operations (and techniques and processes) to optimise the disassembly sequence of the component
e-drive motor	electric drive motor
EEC	Embedded and electronic component
EEE	Electrical and electronic equipment
e-ELV	End-of-life electric vehicle
ELV	End-of-life vehicle
ELVD	End-of-life vehicle directive, Directive 2000/53/EC
EoL	End of life
EPR	Extended producer responsibility
EU	European Union
EV	Electric vehicle
e-waste	electronic waste
Fastening	Connection of different parts/components with a certain degree of freedom of motion
Fe	Iron
FOEN	Swiss Federal Office for the Environment
Ga	Gallium
HDS	High demand scenario
HEV	Hybrid electric vehicle
ICEV	Internal combustion engine vehicle
JRC	Joint Research Centre
kt	kilotons
LCA	Life cycle assessment
LDS	Low demand scenario
Measure	Policy instrument, at product or waste level, with the purpose of producing a specific impact to tackle a specific market/circularity failure
MFA	Material flow analysis

([52]) https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en.

Mg	Magnesium
Mn	Manganese
Nd	Neodymium
OEM	Original equipment manufacturer
OREA	Swiss ordinance on the return, take-back and disposal of electrical and electronic equipment
Part	Constituting element of a component which cannot be further separated
PC/ABS	Polycarbonate-acrylonitrile butadiene styrene
PCB	Printed circuit board
Pd	Palladium
PGM	Platinum group metal
PHEV	Plug-in hybrid electric vehicle
PM	Permanent magnet
PMMA	Poly(methyl methacrylate)
PP	Polypropylene
PST	Post-shredding technology
Pt	Platinum
R & D	Research and development
REE	Rare-earth element
Removal	This definition is intended to be aligned with the one given in Directive 2012/19/EU: the extraction (manual or mechanical) of the component so that it is contained in an identifiable stream within the treatment process.
REPM	Rare-earth permanent magnet
Requirement	Combination of a measure and the targeted material(s) or component(s) to which it is applied. A requirement has a specific timeline, formulation and stakeholder target
Review clause	Systematic review, defined in EU legislation, to ensure that the text (or articles) continue to meet their intended objectives efficiently and effectively
RMIS	Raw materials information system
Sc.	Scenario
Si	Silicon
Si-steel	Silicon steel, also referred to as electrosteel or lamination steel, is an iron alloy with silicon metal (a CRM) as the main additive
SLF	Shredded light fraction
SRM	Secondary raw material
STM	Scarce technology metal
Ti	Titanium

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Annex I. Materials and CRM used in vehicles (non-exhaustive list)

Table 28. Materials and CRM used in vehicles (non-exhaustive list)

Material	Main use in vehicles	Top EU sourcing (primary and/or refined)	Use share in automotive sector	Additional remark
Al	Chassis, vehicle body	Guinea, Russia	21 %	Expected increase in use in automotive applications, especially wrought Al; Al alloys contain CRMs
Beryllium	Vehicle electronics, auto components	USA	17 %	CRM
Boron	Magnet, engine brakes (possibly strengthening agent for steel alloys)	Türkiye		CRM
Cu	Electronics, e-motors	Poland, Germany	6 %	Expected increase in use in automotive applications
Mg	Die cast, alloys	China	50 %	CRM, expected increase for lightweight use
Niobium	Steel alloys	Brazil	23 %	CRM, is also used in small quantities in e-drive motors
Ag	Electronics, solders	Mexico, Germany	8 %	Precious metal
Ti	Alloys	Norway	3 %	CRM

Source: (European Commission, 2020; Løvik et al., 2021; RMIS, 2023).

Annex II. Non-selected pairs for further assessment in the current project

Table 29 presents a list of the discarded pairs (measure / material-component) for further assessment in the current project. Pairs were discarded if there was:

— an absence of either market and/or circularity failure criteria;
— an absence of prerequisites or preliminary steps to implement the investigated measure for the targeted CRM or component;
— either an absence or a lack of information leading to the need for further assessment for experts to assess the suitability of the investigated measure for the targeted CRM in the frame of the current analysis.

Table 29. Non-selected pairs (material-component / measure) for further assessment in the current project

Targeted part	Targeted material	Measure	Justification for not selecting this measure in the current study
e-drive motor	REEs in PMs	Recycled content of REEs in PMs	Demand for PM e-drive motors is expected to increase more rapidly than PM becoming available for recycling at EoL, hence the possible recycled content level should therefore be low in the short term. Whereas secondary Nd/Dy from post-consumer wastes can significantly contribute to the supply of SRMs in the long term, pre-consumer wastes are most likely to contribute to the recycled content measure in the short term. However, OEMs in the EU are still fully import dependent along the PM value chain, leading therefore to little quantities of available pre-consumer waste in the EU. Recycling of PM at an industrial scale is lacking for the majority of waste streams, including for EoL e-drive motors. Moreover, the expected quality of secondary Nd/Dy is unknown and it is not yet certain what the impact would be on the functionality of REPMs in new vehicles. Analysis: — discard this measure for REEs in PM of e-drive motors; — separate collection, sorting and recycling (e.g. through recycling efficiency measures) is a prerequisite to possibly enhance such a measure in the long term; A further dedicated assessment is needed to evaluate the introduction of this measure.
e-drive motor	REEs in PMs	Recycling efficiency measures	The absence of recycling infrastructure currently hinders possible measures to increase the recycling efficiency of REEs in vehicles. REEs end up being downcycled in the best-case scenario (mixed with ferrous fractions), or lost when they are shredded with other materials. Analysis: — discard this measure for REEs in e-drive motor; — separate collection, sorting and recycling is a prerequisite to possibly enhance such a measure in the long term; A further dedicated assessment is needed to evaluate the introduction of this measure.

Targeted part	Targeted material	Measure	Justification for not selecting this measure in the current study
e-drive motor and EEC group	Cu	Recycled content of Cu	Absence of market failure for Cu recycling; specific recycled content measures may not improve overall circularity of Cu. Analysis: — discard this measure for Cu in the targeted parts; — insufficient Cu circularity can probably be further addressed using more relevant measures (e.g. material recovery level) – Such a measure will not be investigated in the current project.
e-drive motor and EEC group	Cu	Recycling efficiency measures	High-quality recycled Cu can be recovered with improved processing and recovery. High recovery of Cu from ELVs would also increase the quality of other fractions otherwise poisoned by Cu contamination, e.g. in Fe and/or Al flows. Copper in ELVs is already recovered at high rates. Lack of substantial circularity failure would rule out the further investigation of this measure for Cu in the current project. Analysis: — discard this measure for Cu in the targeted parts.
Cu rich components in e-drive motor and in EEC group	Cu	Ease of disassembly	Copper can be sorted and recycled using current shredding and recycling technologies. Although the current designs may lead to the proliferation of meatballs (mainly from e-motors) in the shredded fraction, such a flow can be further sorted to recycle Cu. There is an absence of a substantial enough circularity failure to engage the investigated measure for Cu. Analysis: — discard this measure for copper in the targeted parts.
EEC group	REEs in PMs	Recycled content of REEs in magnets	Similar assessment as the e-drive motors. Separate collection and extraction are even more difficult, since the small magnets are supposed to be distributed within the vehicle in small quantities, which makes the dismantling costs prohibitive. Analysis: — discard this measure for REEs in PM of EEC group; A further dedicated assessment is needed to evaluate the introduction of this measure.
EEC group	Precious metals and PGMs (Au, Ag, Pd)	Recycled content of precious metals and PGMs	Absence of market or circularity failure for precious metals or PGMs; specific recycled content measures may not improve their overall circularity. Analysis: — discard this measure for the targeted materials in the targeted parts; — insufficient circularity can probably be further addressed using more relevant measures (e.g. material recovery level). Such measures would not be investigated in the current project.

Targeted part	Targeted material	Measure	Justification for not selecting this measure in the current study
EEC group	Precious metals and PGMs (Au, Ag, Pd)	Recycling efficiency measures	Similar discarding assessment as the e-drive motor. Analysis: — discard this measure for the targeted materials in the targeted parts.
EEC group	Precious metals and PGMs (Au, Ag, Pd)	Ease of disassembly	Potentially relevant measure to further enhance the further extraction through disassembly of the targeted materials from the targeted parts, although the economic viability does not appear to be guaranteed. However, there is a lack of relevant information needed to further investigate this measure in the current project. Analysis: — discard this measure for precious metals and PGMs in the targeted parts in the current project.
EEC group	Precious metals and PGMs (Au, Ag, Pd)	Mandatory declaration	Absence of market and circularity failures that could be addressed by this measure. Analysis: — discard this measure for the targeted parts.
EEC group	REEs in REPMs	Recycling efficiency measures	Similar discarding assessment as the previous parts. Analysis: — discard this measure for REEs in REPMs of the targeted parts; A further dedicated assessment is needed to evaluate the introduction of this measure.
EEC group	REEs in PM	Ease of disassembly	No relevant economic viability. Low material content. Analysis: — discard this measure for REEs in the targeted parts.
Vehicle body/ parts	Mg die cast	Recycled content of Mg	Absence of circularity failure for Mg die cast in vehicle that could be addressed by this measure. Analysis: — discard this measure for Mg die cast in vehicle
Vehicle body/ parts	Mg die cast	Mandatory removal of Mg parts prior to shredding	Technological advances (PSTs) in sorting shredded fractions allow, in principle, the recovery of die cast Mg from the automotive shredded residues. If no PSTs are used, such a flow is downcycled in the best-case scenario or lost in other base metal flows. Still, further assessment is required to estimate the potential benefits for the recycling outputs of mandatory removal of Mg die cast parts prior to shredding, which goes beyond the scope of this project. Analysis: — discard this measure for Mg die cast in vehicle parts and the vehicle body in the current project.
Vehicle body/ parts	Mg die cast	Ease of disassembly	Absence of relevant circularity failure for Mg die cast that could be addressed by this measure. Analysis: — discard this measure for Mg die cast in vehicle parts and vehicle body.

Targeted part	Targeted material	Measure	Justification for not selecting this measure in the current study
Vehicle body/ parts	Mg die cast	Mandatory declaration	Absence of market and circularity failure for Mg die cast that could be addressed by this measure. Analysis: — discard this measure for Mg die cast in vehicle parts and the vehicle body.
Vehicle body/ parts, electronics	Ga	Recycled content of Ga	Very low information on Ga content in vehicles (Løvik et al., 2021), hence difficult to assess the benefit of such a measure. Post-consumer Ga recycling is lacking on an industrial scale. Analysis: — discard this measure for Ga in vehicle parts.
Vehicle body/ parts, electronics	Ga	Recycling efficiency measures	Very low information on Ga content in vehicles (Løvik et al., 2021), and even less in ELV fraction, hence difficult to assess the benefit of such a measure. The economic value of Ga recycling from WEEE was reported to be negligible (Andersson et al., 2019). Analysis: — discard this measure for Ga in vehicle parts.
Vehicle body/ parts, electronics	Ga	Ease of disassembly	Very low information on Ga content in vehicles (Løvik et al., 2021), hence difficult to assess the benefit of such measure. Analysis: — discard this measure for Ga in the targeted parts.
Vehicle body/ parts, electronics	Ga	Mandatory removal of Ga parts prior to shredding	Very low information on Ga content in vehicles (Løvik et al., 2021), hence difficult to assess the benefit of such a measure. Analysis: — discard this measure for Ga in the targeted parts.
Vehicle body/ parts	Ti	Recycled content of Ti	Very low information on Ti content in vehicles (Løvik et al., 2021), hence difficult to assess the benefit of such a measure. Analysis: — discard this measure for Ti in vehicles.
Vehicle body/ parts	Ti	Recycling efficiency measures	Very low information on Ti content in vehicles (Løvik et al., 2021), hence difficult to assess the benefit of such a measure. Analysis: — discard this measure for Ti in vehicles.
Vehicle body/ parts	Ti	Ease of disassembly	Very low information on Ti content in vehicles (Løvik et al., 2021), hence difficult to assess the benefit of such a measure. Analysis: — discard this measure for Ti in vehicles.

Targeted part	Targeted material	Measure	Justification for not selecting this measure in the current study
Vehicle body/ parts	Ti	Mandatory removal of Ti parts prior to shredding	Very low information on Ti content in vehicles (Løvik et al., 2021), hence difficult to assess the benefit of such a measure. Analysis: — discard this measure for Ti in vehicles.
Vehicle body/ parts	Ti	Information request and possible labelling of component with CRM	Very low information on Ti content in vehicles (Løvik et al., 2021). Information on material content could in principle help in assessing the use of Ti in vehicles and its circularity. However, the current instrument is not suitable, as the component using Ti and its location in the vehicle are unknown. Analysis: — discard this measure for Ti in vehicles in this current project; — further assessment is needed to define how Ti is used in vehicle and how to improve its circularity.

Annex III. Supplementary information from the EVA II project

Requirement 3 (see Section 5.3 for the requirement and Section 6.3 for its assessment) is mainly based on the EVA II report. The synthesis of this study led by Empa is available in (Marmy et al., 2023).

Further parts of this study are detailed in Table 30.

Table 30. Description package of the EVA II project

Reference (in German)	Content
Marmy, C.; Capelli, M.; Böni, H.; Bartolome, N.; Marseiler, U., *Projekt EVA II: Synthesebericht,* Empa, St. Gallen, 2023.	Overview of the overall objectives of the EVA II project and summary of the main results of the project.
Løvik, A. N.; Marmy, C.; Restrepo, E.; Widmer, R., *Projekt EVA II: dynamisches Stoffflussmodul – Schlussbericht*, Empa, St. Gallen, 2021.	Description of the dynamic MFA model of the overall model with illustrative results of vehicle, EEE and material mass flows in Switzerland. Unpublished, available on demand.
Marmy, C.; Capelli, M.; Böni, H., *Projekt EVA II: Materialverwertungsmodul – Schlussbericht,* Empa, St. Gallen, 2023.	Description of the recycling model, and quantities of recovered materials for each category and type of embedded EEE. Unpublished, available on demand.
Marmy, C.; Capelli, M.; Böni, H., *Projekt EVA II: Wirtschaftsmodul – Schlussbericht*, Empa, St. Gallen, 2023.	Description of the economic model, and cost of removal and separate recycling for each type of embedded EEE. Unpublished, available on demand.
Capelli, M.; Marmy, C.; Böni, H.; Beloin-Saint-Pierre, D.; Hischier, R., *Projekt EVA II: Ökobilanzmodul – Schlussbericht*, Empa, St. Gallen, 2023.	Description of the LCA model, and environmental benefits of removal and separate recycling for each type of embedded EEE. Unpublished, available on demand.
Marmy, C.; Capelli, M.; Böni, H., *Projekt EVA II: Zukünftige Materialflüsse in der Schweizerischen Fahrzeugflotte – Schlussbericht*, 2023, Empa, St. Gallen.	Description of the methodology and results of all experiments and data collection activities performed, along with a description of the structure of the database containing all required results and data within EVA I. Unpublished, available on demand.
Marmy, C.; Bartolomé, N.; Marseiler, U.; Toledo, L.; Capelli, M.; Pangaribuan, K.; Widmer, R.; Böni, H., *Projekt EVA II: Versuche und Datenbeschaffung – Schlussbericht*, Empa, St. Gallen, 2023.	Description of the vehicle fleet development scenarios and discussion of their impact on material flows in the Swiss car recycling system. Unpublished, available on demand.

The following information and data were reported here to ease the reading of the analysis of its impacts reported in Section 6.3.

- List and data of the 43 assessed components in the EVA II project (Table 31);
- Structure of the material recovery module used for the assessment of requirement 3 (Figure 15);
- Mass flow diagram of the recycling of 'headlights' category, as modelled in the EVA II project (Figure 16).

Table 31. Assessed components in the EVA II project

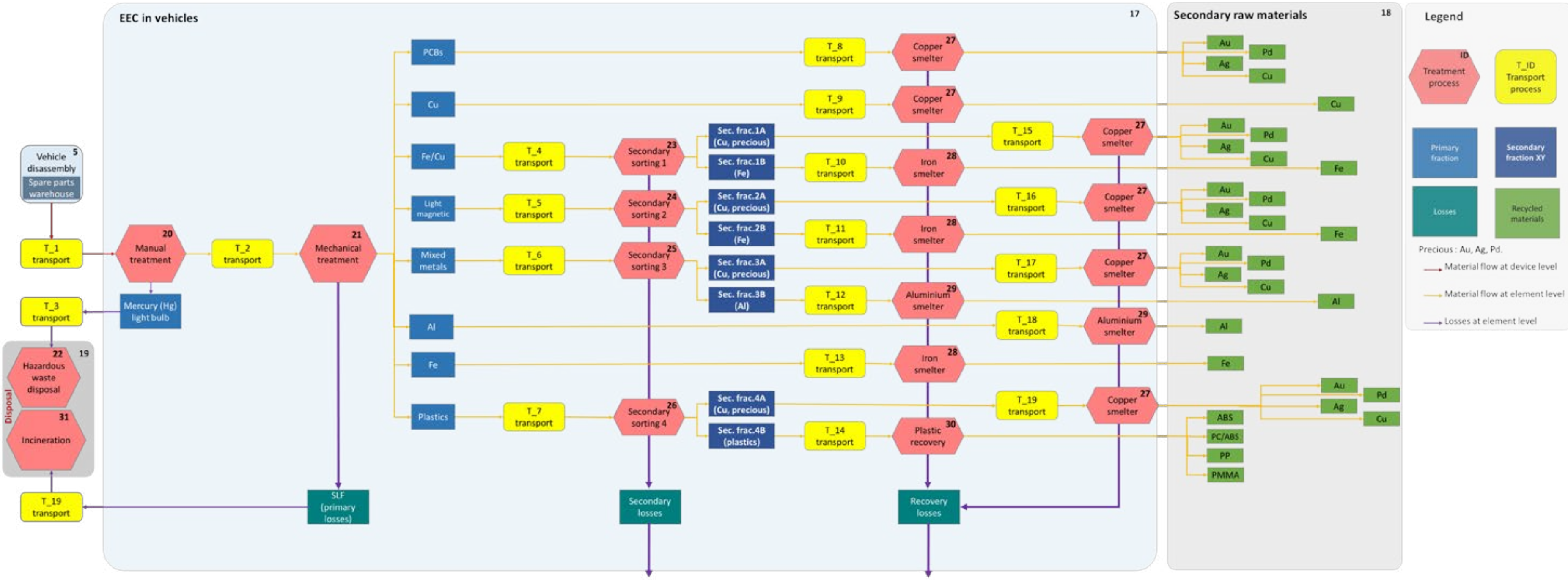
Component ID	Component type	Device category	Average device mass (g)	Average dismantling time (minutes)	Number of data points on dismantling time	Uncertainty Score ((+) = 0 data points, estimation, + = 1–5 data points, ++ = 5–10 data points, +++ = more than 10 data points)	Dismantling rate to be used as used spare parts in the Swiss context	Average count per vehicle in 2021 fleet (calculated)
01	Actuators active chassis	Actuator	3333	1.50	3	+	0.00	1.000
02	Brake system actuators (e.g. Anti-lock braking system (ABS), electronic stability control (ESC))	Actuator	1967	13.11	21	+++	0.41	1.000
03	Starter	Actuator	3265	25.64	26	+++	0.58	0.995
04	Battery management system	Controller	250	20.00	0	(+)	0.00	0.005
05	Throttle actuator	Actuator	484	1.39	6	++	0.09	0.999
06	Direct current to direct current (DCDC) converter	Controller	603	0.30	4	+	0.00	1.000
07	Electric drive motor induction (for EVs)	Actuator	63333	25.00	0	(+)	0.00	0.000
08	Electric drive motor PM (for EVs)	Actuator	31332	25.00	0	(+)	0.00	0.005
09	Window regulator	Actuator	1025	8.89	57	+++	0.39	2.820
10	Generator/alternator	Actuator	5969	15.91	26	+++	0.32	0.995
11	Inverter (for EVs)	Controller	13550	1.50	1	+	0.00	0.005
12	Instrument cluster / information display	Controller	741	3.07	37	+++	0.48	1.000
13	Wiring harness (cable bundle)	Cable-like	1300	1.70	20	+++	0.00	1.000
14	Fuel pump	Actuator	886	0.74	10	++	0.00	0.999

Component ID	Component type	Device category	Average device mass (g)	Average dismantling time (minutes)	Number of data points on dismantling time	Uncertainty Score ((+) = 0 data points, estimation, + = 1–5 data points, ++ = 5–10 data points, +++ = more than 10 data points)	Dismantling rate to be used as used spare parts in the Swiss context	Average count per vehicle in 2021 fleet (calculated)
15	Radiator fan motor	Actuator	2319	8.32	46	+++	0.25	0.999
16	Loudspeaker	Actuator	338	0.50	19	+++	0.29	3.000
17	On-board charger (for EVs)	Controller		10.00	0	(+)	0.00	0.001
18	External charging cable (for EVs)	Cable-like		0.00	0	(+)	0.00	0.001
19	Wiper motor	Actuator	1544	6.71	49	+++	0.75	1.500
20	Headlights (front and rear)	Lights	2223	1.12	25	+++	0.00	4.000
21	Fuse box/distributor	Controller	593	2.25	5	++	0.00	1.000
22	Seat adjustment motor	Actuator	1030	1.54	5	++	0.00	0.325
23	Drive motor control unit	Controller	712	6.66	29	+++	0.74	0.780
24	Onboard power supply / body control unit	Controller	350	2.75	13	+++	0.03	1.000
25	Brake and chassis control unit (e.g. ABS, ESC)	Controller	813	4.63	0	(+)	0.16	1.000
26	Driver assistance control unit	Controller	1074	2.91	29	+++	0.05	1.000
27	Driver assistance sensors control unit	Controller	355	1.49	10	+++	0.00	1.000
28	Infotainment control unit (sound, navigation and multimedia)	Controller	1610	2.73	36	+++	0.09	0.980
29	Passenger protection control unit	Controller	282	9.07	26	+++	0.17	0.990

Component ID	Component type	Device category	Average device mass (g)	Average dismantling time (minutes)	Number of data points on dismantling time	Uncertainty Score ((+) = 0 data points, estimation, + = 1–5 data points, ++ = 5–10 data points, +++ = more than 10 data points)	Dismantling rate to be used as used spare parts in the Swiss context	Average count per vehicle in 2021 fleet (calculated)
30	Automatic air conditioning control unit	Controller	362	0.90	11	+++	0.07	1.000
31	Control module / valve box automatic transmission	Controller	1635	0.97	6	++	0.00	1.000
32	Wash water pump	Actuator	101	0.34	10	++	0.00	1.000
33	Central locking system	Actuator	716	1.48	32	+++	0.03	1.000
34	Amplifier	Controller	1672	0.78	1	+	0.00	1.000
35	Air injection pump	Actuator	1295	15.00	0	(+)	0.00	0.999
36	Loading flap (for EVs)	Actuator	706	0.50	0	(+)	0.00	0.001
37	Door, liftgate or sunroof motor	Actuator	419	0.59	4	+	0.00	0.500
38	Power steering actuator	Actuator	2164	4.78	11	+++	0.30	0.140
39	Mirror adjustment motor	Actuator	165	0.50	0	(+)	0.00	0.770
40	Start–stop control unit	Controller	450	0.43	2	+	0.00	1.000
41	Capacitor array (for EVs)	Controller			0		0.00	0.005
42	Transfer case	Actuator	1399	30.00	0	(+)	0.00	0.500
43	Vehicle control unit (for EVs)	Controller		4.63	0	(+)	0.00	0.005

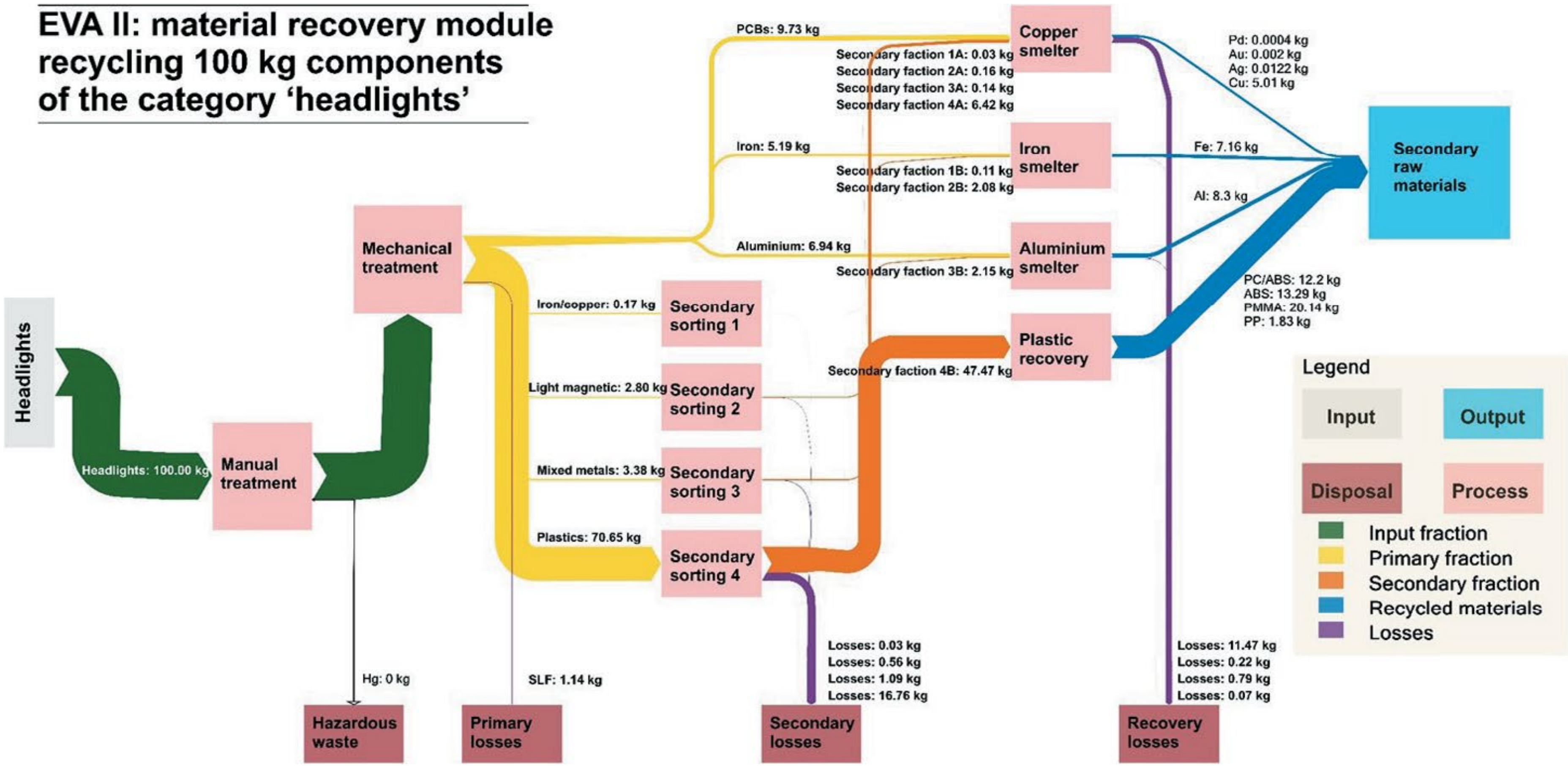
Source: (Marmy et al., 2023)

Figure 15. Structure of the material recovery module used for requirement 3 assessment



Source: Adapted from the EVA II project (Marmy et al., 2023).

Figure 16. Sankey diagram of the recycling of 100 kg of headlights in an E-waste recycling facility, as modelled in the material recovery module of the EVA II project



Source: JRC elaboration, adapted from EVA II project (Marmy et al., 2023). PCBs in this figure refer to printed wiring boards.

Annex IV. List of ongoing EU-funded projects addressing CRM in vehicles

A non-exhaustive list of ongoing projects on CRM circularity in vehicles that have received funding from the EU. Batteries-related projects were excluded from this inventory. Roadblocks and challenges to be tackled in the follow-up project on CRM in vehicles will also build on the knowledge and data constructed in these projects.

Table 32. List of ongoing EU-funded projects addressing CRM in vehicles

Project	Description/objective	Estimated final technology readiness level	Project duration
CIRC-UITS	The circular Integration of independent reverse supply chains for the smart reuse of industrially relevant semiconductors project (CIRC-UITS) will focus on demonstrating the improvement to the circularity of automotive and mass electronics sectors through the reuse of semiconductors from different sources, and on supporting the reuse and remanufacturing of semiconductors as new (high added-value) components and products in these sectors.	Not applicable	From January 2023 to December 2025
EM-TECH	EM-TECH (innovative e-motor technologies covering e-axles and e-corners vehicle architectures for high-efficient and sustainable e-mobility) brings together 10 participants from industry and academia to develop novel solutions to push the boundaries of electric machine technology for automotive traction, including through the adoption of recycled PMs and circularity solutions.	Not applicable	From January 2023 to December 2025
Fatigue4Light	The 'Fatigue4Light' project plans to investigate lightweight solutions adapted to the chassis part of EVs that will render them up to 30 % lighter and safer. The sustainability of the proposed solutions, including recovery of CRMs, will be based on an eco-design approach, supported by environmental and socioeconomic studies.	Not applicable	From February 2021 to January 2024
SisAl pilot	Innovative pilot for silicon production with low environmental impact using secondary Al and Si raw materials.	7	From May 2020 to April 2024
ALMA	The advanced light materials and processes for the eco-design of electric vehicles project (ALMA) will develop a novel BEV structure for a passenger car with 45 % weight reduction potential compared to the current baseline (15 % additional reduction if compared to prior-art solutions) at affordable costs (below EUR 3/kg saved of additional cost), thus enabling up to 2.2 KWh/100 km efficiency increase and 11 % LCA improvement.	9	From February 2021 to January 2024
BIORECOVER	The BIORECOVER project will develop a sustainable and safe process based on biotechnology for the selective extraction of a range of CRMs from primary and unexplored secondary sources.	Not applicable	From June 2019 to May 2023
BlackCycle	The BlackCycle project has an upcycling ambition, targeted at creating a circular economy of the EoL tyre for technical applications like the tyre industry by producing high technical SRMs from EoL tyres.	Not applicable	From May 2020 to August 2023
eMONIC	eMONIC will develop the necessary automation of the production of new electric motors based on innovative winding technology. https://sci-mo.de/	9	From July 2022 to June 2024
FLAMINGo	FLAMINGo will focus on manufacturing strengthened Al metal matrix composites with elevated properties compared to current Al alloys used in automotive applications.	Not applicable	From February 2021 to January 2025

Project	Description/objective	Estimated final technology readiness level	Project duration
FutuRaM	The future availability of secondary raw materials (FutuRaM) project seeks to: (1) develop knowledge on the availability and recoverability of SRMs within the EU, with a special focus on CRMs, to enable fact-based decision-making for their exploitation in the EU and in non-EU countries; and (2) disseminate this information via a systematic and transparent SRM knowledge base.	Not applicable	From June 2022 to May 2026
GYROMAGS	The green recycling route for SM-CO permanent magnet swarf project (GYROMAGS) aims to develop a green and simple method based on electro-deoxidation of the oxidised PM swarf, which will require much less energy consumption and a negligible amount of acids and chemicals compared to the conventional methods.	Not applicable	From June 2022 to May 2024
HEFT	A novel concept of a low cost, high power density and highly efficient recyclable motor for next-generation mass-produced EVs.	Not applicable	From December 2022 to May 2026
OCARINA	Novel recycling and reprocessing of PMs.	Not applicable	From February 2022 to April 2024
PASSENGER	The pilot action for securing a sustainable European next generation of efficient RE-free magnets project (PASSENGER) will develop innovative solutions to resolve issues relating to EU dependency on rare-earth raw materials for PMs. The aim will be to reduce bottlenecks in the material supply chain and diminish the environmental impact.	7	From May 2021 to April 2025
RECO2MAG	RECO2MAG will produce resource-efficient sintered NdFeB PMs with lowered Dy content and improved energy products to be applied in novel e-motors.	4–5	From January 2022 to December 2024
REEPRODUCE	The REEPRODUCE project aims at setting up, for the first time, a resilient and complete European REE-recycling value chain on an industrial scale for the recovery of REEs at a competitive cost compared to REE primary production (at least 25 % cheaper) with environmentally friendly and socially sustainable technologies.	7	From May 2022 to April 2026
REESilience	Resilient and sustainable CRM REE supply chains for the e-mobility and renewable energy sectors and strategic sectors.	Not applicable	From July 2022 to June 2026
REFMAG	The Bulk rare earth free permanent magnets (REFMAG) project aims to apply a new processing route to synthetise manganese bismuth (MnBi) PM, a rare-earth free alternative to the currently used NdFeB magnets.	Not applicable	From April 2022 to September 2023
SALEMA	SALEMA proposes a circular economy model using scrap metal as an alternative source of CRM and finding suitable CRM substitutes in alloying systems.	7	From May 2021 to April 2024
SUSMAGPRO	SUSMAGPRO aims to develop a recycling supply chain for rare earth magnets in the EU and demonstrate these new materials on a pilot scale within a range of application sectors.	7	From June 2019 to November 2023

Project	Description/objective	Estimated final technology readiness level	Project duration
TREASURE	The TREASURE project will develop a scenario analysis and simulation tool to assess the positive and negative implications of circular economy practices and principles in car manufacturing to facilitate the adoption of CRM recovery and a circular economy in this sector.	Not applicable	From June 2021 to May 2024
VOLTCAR	The design, manufacturing, and validation of ecocycle electric traction motor project (VOLTCAR) proposes high-speed, PM-assisted synchronous reluctance technology with a drastic reduction in rare material utilisation.	Not applicable	From February 2023 to January 2026

Source: JRC own elaboration.

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