Ecodesign preparatory study for product specific measures on scarce, environmentally relevant and critical raw materials and on recycled content.

Final Study Report

Phase 2: (mini) Preparatory Study

Electric motors

17 October 2025

Written by: Jana Hack, Robin Barkhausen – Fraunhofer ISI

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Foreword

This report, titled ‘Preparatory Study on Electric Motors’ focused on material aspects, has been prepared by Fraunhofer ISI. However:

It serves to complement the on-going Review study and support the evaluation and impact assessment on ecodesign for the product group “electric motors” (referred to here as the “Review Study”).

The analysis has been conducted by Fraunhofer ISI, taking into account information gathered through desk research activities and expert interviews

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Acronyms

Ag	Silver
Au	Gold
BoM	Bill of Materials
CRM	Critical Raw Material
EED	Energy Efficiency Directive
ELV	End-of-Life Vehicle
ESPR	Ecodesign for Sustainable Products Regulation
IEM	Induction Electric Motor
LVD	Low Voltage Directive
PMM	Permanent Magnet Motor
REE	Rare Earth Elements
R1	Recycled Content Factor
R2	Recycling Output Rate
TENV	Totally Enclosed Non-Ventilated Motor
VSD	Variable speed drive
WBG	Wide Band Gap
WEEE	Waste Electrical and Electronic Equipment

Summary

Scope

This study evaluates the potential for reducing environmental impacts of electric motors with a particular focus on critical raw materials (CRMs), recycled content, and recyclability. It serves as input for the ongoing review study on induction electric motors (IEMs), variable speed drives (VSDs), and permanent magnet motors (PMMs). Motors for electric vehicle traction and those exceeding 1,000 kW are excluded. The study aims to assess design options for increasing recycled content and recyclability, particularly for CRMs like rare earth elements (REEs) and copper, while aligning with the EU's broader circular economy and sustainability goals.

Bill-of-Materials for Base Cases

The detailed environmental analysis was carried out for two representative motor models: an IEM (55 kW, IE4), and a Permanent Magnet Motor (PMM, 55 kW, IE4). Metals dominate the composition of both motors, with steel, cast iron, and copper being the primary materials. PMMs also include permanent magnets containing REEs, which account for 2.2% of the motor's mass. While copper and steel are assumed to have some recycled content (30–37%) in the base case, REEs are assumed to have none. The bill-of-materials (BoM) analysis highlights the material intensity of motors and the potential for improving circularity through targeted measures.

Environmental Impacts for the Baseline Model

The environmental impacts of the motors were assessed across key categories, such as climate change, particulate matter, and resource use. The use phase dominates the overall environmental footprint due to energy consumption, but material-related impacts remain relevant because of a combination of strategic and environmental reasons. For PMMs, permanent magnets strongly influence water use, acidification, and particulate matter, while for IEMs, copper has a high impact on land use. Aluminum in IEMs contributes to ionizing radiation and freshwater ecotoxicity. These findings underscore the importance of addressing material impacts alongside energy efficiency improvements.

Critical Raw Materials: REE and Copper

Permanent magnets in PMMs rely on REEs like neodymium and dysprosium, which are critical for motor performance but pose environmental and strategic risks. REE recycling is currently limited due to technical and economic barriers, such as complex separation processes and high costs. Copper, widely used in motor windings, is already extensively recycled due to its high economic value. Ensuring even higher quantities of high-purity recycled copper for motor applications remains a challenge. Both materials present opportunities for circularity but require tailored approaches to address their unique challenges.

Design and Policy Options

The study explored several design options to increase recycled content and recyclability. For copper, increasing recycled content to 60% could yield modest environmental benefits but faces significant challenges, including limited high-grade scrap availability, verification difficulties, and potential performance degradation. For REEs, introducing 10–30% recycled content in PMMs could reduce greenhouse gas (GHG) emissions by up to 547 tonnes CO_2 equivalent for motors sold in 2030 (considering the 30% target). However, prerequisites include ensuring material quality, scaling recycling infrastructure, and addressing economic viability. Improving REE recyclability to 30% could save over 2.000 tonnes CO_2 equivalent for motors sold in 2030, but this requires investments in advanced disassembly and separation technologies. Stakeholders emphasized the need for harmonization between the Ecodesign for Sustainable Products Regulation (ESPR) and the CRM Act to avoid regulatory overlaps

and streamline implementation. Equivalent for motors sold in 2030, but this requires investments in advanced disassembly and separation technologies. Stakeholders emphasized the need for harmonization between the Ecodesign for Sustainable Products Regulation (ESPR) and the CRM Act to avoid regulatory overlaps and streamline implementation.

Estimates of Magnitude of Impacts

The study estimates the environmental savings potential of the proposed design options. Increasing recycled copper content to 60% could save up to 17.261 tonnes CO_2 equivalent for IEMs in stock by 2030. Scaling recycled REE content to 30% could save 547 tonnes CO_2 equivalent for PMMs sold in 2030, while improving REE recyclability to 30% could save over 2.000 tonnes CO_2 equivalent. These findings highlight the significant potential of REE-focused measures, particularly in PMMs, which are strategically important for industrial applications. However, the study findings suggest to design timing and scope of the measures based on further feasibility analysis, and place an earlier focus on enhancing REE recyclability before mandating recycled content requirements. For copper, a more cautious approach is suggested and upstream measures such as directly targeting end-of-life collection rates seem to be the more effective and feasible options.

Timeline of the Review Study

The “evaluation and impact assessment for the review of the Commission regulation for electric motors and VSDs” started in December 2024, is currently in progress and is expected to be completed in April 2027.

1. MEErP Task 1, Scope

Scope

The scope of this study on critical raw materials (CRMs), recycled content, and recyclability aligns with that of the ongoing review study, as this mini study is intended to serve as input for the review. The review study focuses on induction electric motors (IEM), variable speed drives (VSD), and permanent magnet motors (PMM), excluding those out of scope as displayed in Table 1. The table shows the targeted extended scope of a potential new regulation. Notably, permanent magnet motors for electric vehicle traction are excluded, as well as motors with a power output exceeding 1,000 kW. The power output exclusion pertains to most applications in wind turbines, given that globally, 39% of installed onshore wind turbines have a capacity between 1.5 and 2 MW, while 44% of offshore equipment has a nominal capacity in the range of 5.5 to 6 MW[1].

While the data collection for the review study is currently in progress, this mini study will assess motor technologies and markets broadly, but selects only two representative products, one IEM and one PMM, for the detailed environmental and economic assessment (see section 5).

Table 1: Scope of coverage of this CRM and Recycled Content Study

<table>
<tr><th>Device</th><th>In Scope</th><th>Out of Scope</th></tr>
<tr><td>Induction electric motors</td><td>- Two, four or eight-pole motors
- Voltage of 50 V – 1.000 V
- Power output range of 0,12 kW – 1.000 kW
- Rated on basis of continuous duty operation
- Rated for direct on-line operation</td><td rowspan="3">- Completely integrated motors
- Motor shall not be designed to operate independently or separated from driven unit
- Motors with integrated VSD
- Motors with integrated brake
- Motors Designed for Operation in Extreme Altitudes, Temperatures, or Coolant Conditions
- Motors designed to operate in liquid
- Motors Qualified for Nuclear Safety Applications
- Explosion-Protected Motors for Mining Use
- Motors in Cordless or Battery Devices
- Motors in Hand-Held Operated Equipment
- Motors in Hand-Guided Mobile Equipment
- Motors with Mechanical Commutators</td></tr>
<tr><td>Variable speed drives</td><td>- Rated for operating with one motor
- Voltage of 100 V – 1.000 V
- Power output range of 0,12 kW – 1.000 kW
- Only one AC voltage output</td></tr>
<tr><td>Permanent magnet motors</td><td>- Power output range of 0,12 kW – 1.000 kW</td></tr>
</table>

[1] Carrara et al. (2020): Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system. 10.2760/160859

		- Totally Enclosed Non-Ventilated (TENV) Motors - Substitute Motors for Pre-2022 Integrated Products - Multi-Speed Motors with Switchable Windings - Motors for Electric Vehicle Traction

1.1. Definitions

1.1.1 Motor-related

Products and components that are within the scope of the existing Ecodesign Regulation (1781/2019) on motors are defined as:

Electric motor: 'electric motor' or 'motor' means a device that converts electrical input power into mechanical output power in the form of a rotation with a rotational speed and torque that depend on factors including the frequency of the supply voltage and number of poles of the motor.

Variable speed drive: 'variable speed drive' (VSD) means an electronic power converter that continuously adapts the electrical power supplied to a single motor to control the motor's mechanical power output according to the torque-speed characteristic of the load driven by the motor, by adjusting the power supply to a variable frequency and voltage supplied to the motor. It includes all electronics connected between the mains and the motor including extensions such as protection devices and auxiliaries which are integrated into the VSD.

Energy efficiency: 'energy efficiency' of a motor means the ratio of its mechanical output power to the electrical active input power.

Pole: 'pole' means a north or a south pole produced by the rotating magnetic field of the motor, whose total number of poles determines its base speed.

Continuous duty operation: 'continuous duty operation' means capable of continuous operation at rated power with a temperature rise within the specified insulation temperature class, specified as specific duty types S1, S3 >=80 % or S6 >=80 % as defined in standards.

Phase: 'phase' means the type of configuration of the mains.

Main: 'mains' or 'electric mains' means the electricity supply from the grid.

Motor with mechanical commutators: 'motor with mechanical commutators' means a motor in which a mechanical device reverses the direction of the current.

Cordless or battery operated equipment: 'cordless or battery operated equipment' means an appliance deriving its energy from batteries enabling the appliance to perform its intended function without a supply connection.

Hand-held equipment: 'hand-held equipment' means a portable appliance intended to be held in the hand during normal use.

Hand-guided equipment: 'hand-guided equipment' means a non-road mobile appliance that is moved and guided by the user during normal use.

Totally enclosed non-ventilated: 'totally enclosed non-ventilated (TENV) motor' means a motor designed and specified to operate without a fan, and which dissipates heat predominantly through natural ventilation or radiation on the totally enclosed motor surface.

Regenerative drive: 'regenerative drive' means a VSD that is able to regenerate energy from the load to the mains, i.e. that induces a 180° +/- 20° phase shift of the input current to the input voltage when the load motor is braking.

Drive with sinusoidal input current: 'drive with sinusoidal input current' means a VSD with a sinusoidal waveform of the input current, characterised by a Total Harmonic Content below 10 %[2].

Brake motor: 'brake motor' means a motor equipped with an electromechanical brake unit operating directly on the motor shaft without couplings.

Ex eb increased safety motor: 'Ex eb increased safety motor' means a motor intended for use in explosive atmospheres and certified 'Ex eb', as defined in standards.

Other explosion-protected motor: 'other explosion-protected motor' means a motor intended for use in explosive atmospheres and certified 'Ex ec', 'Ex tb', 'Ex tc', 'Ex db', or 'Ex dc' as defined in standards.

Test load: 'test load' of a VSD means the electrical device used for testing purposes that determines the output current and the output displacement factor cos phi.

Equivalent model: 'equivalent model' means a model which has the same technical characteristics relevant for the technical information to be provided, but which is placed on the market or put into service by the same manufacturer, importer or authorised representative as another model with a different model identifier.

Model identifier: 'model identifier' means the code, usually alphanumeric, which distinguishes a specific product model from other models with the same trade mark or the same manufacturer's, importer's or authorised representative's name.

Witnessed testing: 'witnessed testing' means actively observing the physical testing of the product under investigation by another party, to draw conclusions on the validity of the test and the test results. This may include conclusions on the compliance of testing and calculations methods used with applicable standards and legislation.

Factory acceptance test: 'factory acceptance test' means a test on an ordered product where the customer uses witnessed testing to verify the product's full accordance with contractual requirements, before they are accepted or put into service.

Other relevant products and components that are not yet within the scope of the existing ecodesign Regulation (1781/2019) on motors can be defined as:

Permanent magnet motors: 'permanent magnet motors' means an electric synchronous motor with a 3-phase wound stator, and a rotor that incorporates permanent magnets[3].

1.1.2 Circularity concepts

A JRC 2024 preparatory study for Imaging Equipment sets out definitions of key circularity aspects that apply also for motors, some of which are relevant to this mini-study. The list below provides the relevant terms and definitions from that source (JRC, 2024)[4].

[2] EU's Commission Regulation (EU) 2019/1781

[3] Permanent Magnet Motors_C1.1

[4] Imaging equipment and its consumables - November 2022 (clean).docx

Durability - Ability to function as required, under defined conditions of use, maintenance and repair, until a limiting state is reached (EN45552:2020)

Reliability - Probability that a product functions as required under given conditions, including maintenance, for a given duration without limiting event (EN45552:2020)

Repair - Process of returning a faulty product to a condition where it can fulfil its intended use (EN45552:2020)

Upgrade - Process of enhancing the functionality, performance, capacity, or aesthetics (EN45552:2020)

Reuse - Process by which a product or its parts, having reached the end of their first use, are used for the same purpose for which they were conceived (EN45552:2020)

Remanufacturing and refurbishing - Industrial process which produces a product from used products or used parts where at least one change is made which influences the safety, original performance, purpose or type of the product. (EN45553:2020) Note 1 to entry: The product created by the remanufacturing process may be considered a new product when placing on the market. Refer to the EU Blue Guide [1] for additional information.

Note 2 to entry: Refurbishing is a similar concept to remanufacturing except that it does not involve substantial modifications influencing safety, original performance, purpose or type of the product. It is not covered by this standard.

Recycling - Recovery operation of any kind, by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes excluding energy recovery (EN45555:2019).

Critical Raw Materials - Critical raw material CRM materials which, according to a defined classification methodology, are economically important, and have a high-risk associated with their supply (EN45558:2019)

Post-consumer recycled content - the amount of post-consumer recycled material that goes into the manufacturing of a new product (EN45557:2020)

Among the definitions listed above, it is important to highlight how product modification by refurbishing and remanufacturing processes can influence the consideration of products as legally as “new products” or as “second hand products”. This distinction has an effect on the applicability of ecodesign and energy labelling requirements, which are only applicable at the moment of placing products on the market.

1.2. Standards

The following are a sample of standards which are applicable to **energy-related products in general**. Particularly the standard series EN4555X becomes relevant when defining policy options, as it details the requirements for measuring and reporting certain circular economy related aspects such as material declarations (EN 45558:2019).

IEC 60068-2-31:2008. Environmental testing - Part 2-31: Tests: Rough handling shocks, primarily for equipment-type specimens.

This standard establishes a test procedure for simulating the effects of rough handling shocks, primarily in equipment-type specimens, the effects of knocks, jolts and falls which may be received during repair work or rough handling in operational use. This procedure does not simulate the effects of impacts received during transportation as loosely constrained cargo and does not simulate the effects of shock applied to installed equipment.

EN 45552:2020. General method for the assessment of the durability of energy-related products.

This standard provides a comprehensive framework for assessing the durability of products, ensuring they meet the highest standards of quality and longevity. The standard establishes a general method for evaluating the durability of energy-related products. Durability not only affects the product's performance and reliability but also its environmental impact and cost-effectiveness. By adhering to the guidelines set forth in this standard, manufacturers can ensure that their products are designed to last, reducing waste and promoting sustainability.

EN 45553:2020. General method for the assessment of the ability to remanufacture energy-related products.

This standard provides a comprehensive framework for assessing the remanufacturability of energy-related products. The standard offers a structured approach to evaluate the potential for remanufacturing, ensuring that products can be reused, refurbished, and reintroduced into the market with minimal environmental impact. This not only helps in reducing waste but also in conserving resources, ultimately leading to cost savings and increased profitability.

EN 45554:2020. General methods for the assessment of the ability to repair, reuse and upgrade energy-related products.

This standard provides a comprehensive framework for assessing the ability to repair, reuse, and upgrade energy-related products. This standard is an essential tool for manufacturers, engineers, and sustainability experts who are committed to enhancing the lifecycle of their products while minimizing environmental impact. This standard outlines general methods for evaluating the repairability, reusability, and upgradability of energy-related products. It provides detailed guidelines and methodologies that help stakeholders in the energy sector to improve product design and lifecycle management.

EN 45555:2019. General methods for assessing the recyclability and recoverability of energy-related products.

This standard provides comprehensive guidelines and methodologies for evaluating the recyclability and recoverability of energy-related products, ensuring that they meet the necessary environmental standards and contribute to a circular economy. It helps to provide a structured approach to assess their potential for recycling and recovery. By following the guidelines in this standard, companies can ensure that their products are designed with end-of-life considerations in mind, promoting a more sustainable approach to product development.

EN 45557:2020. General method for assessing the proportion of recycled material content in energy-related products.

This standard provides a comprehensive methodology for assessing the proportion of recycled material content in energy-related products. It is an essential tool for companies aiming to enhance their environmental responsibility and transparency. The standard offers a structured approach to evaluate and report the recycled material content, thereby supporting manufacturers in their efforts to reduce the ecological footprint of their products. This standard not only aids in compliance with environmental regulations but also enhances the marketability of products by aligning them with consumer demand for sustainable solutions.

EN 45558:2019. General method to declare the use of critical raw materials in energy-related products.

This standard is intended to provide a means for information on the use of CRMs to be exchanged up and down the supply chain and with other relevant stakeholders. The standard is intended for use by any public, private or social enterprises involved in the production of energy-related products (including SMEs) and other organisations in the product supply chain. It is also relevant to European market surveillance and trade authorities as well as European policy makers. This standard is horizontal in nature, and can be applied directly to any type of energy-related product. This document sets out a standardised format for reporting use of CRMs in energy-related products.

The following are a sample of standards which are applicable specifically to **motors** but most are not specifically on CRMs or CE. However, DIN EN IEC 60034-23 VDE 0530-23:2019-11 outlines best practices for repairing and reclaiming electric motors and DIN EN 50598-3 VDE 0160-203:2015-09 provides a structured method for ecodesign using life cycle assessment and environmental declarations, enabling transparent environmental impact analysis of electrical systems.

E DIN EN IEC 60034-2-3 VDE 0530-2-3:2025-03

Special procedures for determining losses and efficiency of converter-fed AC machines. This standard defines advanced test procedures for accurately determining energy losses and efficiency in alternating current machines when fed by converters. It supports improved performance analysis of variable speed drive systems.

E DIN EN IEC 60034-2-2 VDE 0530-2-2:2025-03

Specific methods for determining separate losses of large machines from tests. This standard outlines testing procedures for separating and quantifying different types of energy losses in large electrical machines, enhancing precision in performance evaluations and energy optimization.

E DIN EN IEC 60034-2-1 VDE 0530-2-1:2025-03

Standard methods for determining losses and efficiency from tests. Provides standardized test methods for measuring losses and calculating the efficiency of rotating electrical machines, ensuring consistency and comparability across applications.

DIN EN IEC 60034-30-3 VDE 0530-30-3:2024-10

Efficiency classes of high voltage AC motors. Defines efficiency classification levels for high voltage AC motors, helping manufacturers and users select energy-efficient equipment for industrial and utility applications.

DIN CLC IEC/TS 60034-30-2 VDE V 0530-30-2:2024-06

Efficiency classes of variable speed AC motors. Establishes criteria for efficiency classification of AC motors operated with variable speed drives, enabling improved energy performance in adjustable-speed applications.

E DIN EN IEC 61800-9-2 VDE 0160-109-2:2022-11

Ecodesign for motor systems – Energy efficiency determination and classification. Offers a framework for evaluating and classifying the energy efficiency of complete motor systems, supporting compliance with ecodesign requirements and energy labeling.

E DIN EN IEC 61800-9-1 VDE 0160-109-1:2021-02

Ecodesign for power drive systems – General requirements. Specifies general principles for setting energy efficiency standards for power drive systems using the extended product approach and semi-analytic models, promoting holistic energy performance optimization.

E DIN IEC/TS 60034-31 VDE V 0530-31:2020-06

Selection of energy-saving motors including variable speed drives – Application guide. Provides guidance on selecting energy-efficient motors and variable speed drives tailored to specific applications, encouraging energy savings through informed decision-making.

DIN EN IEC 60034-23 VDE 0530-23:2019-11

Repair, overhaul and reclamation. Outlines best practices for repairing and reclaiming electric motors, ensuring service quality, maintaining performance, and supporting sustainability through extended product life.

DIN EN 50598-3 VDE 0160-203:2015-09

Quantitative ecodesign approach through life cycle assessment. Provides a structured method for ecodesign using life cycle assessment and environmental declarations, enabling transparent environmental impact analysis of electrical systems.

DIN EN 60034-30-1 VDE 0530-30-1:2014-12

Efficiency classes of line-operated AC motors. Specifies efficiency classification standards for AC motors connected directly to the power line, guiding users towards energy-efficient motor selection.

1.3. Legislation

1.3.1 Ecodesign Directive

1.3.1.1 Legislative framework

The Ecodesign Directive (1) provides consistent EU-wide rules for improving the environmental performance of products placed on the EU market. The Directive's main aim is to provide a framework for reducing the environmental impacts of products throughout their entire life cycle. As many of the environmental impacts associated with products are determined during the design phase, the Ecodesign Directive aims to bring about improvements in environmental performance through mandating changes at the product design stage.

The Ecodesign Directive is a framework directive, not directly setting minimum requirements: the aims of the Directive are implemented through product-specific Regulations, directly applicable in all EU member states. For a product category to be covered by under the Ecodesign Directive it needs to[5]:

- have a significant volume of sales (indicatively 200,000 units per year throughout the Union market)
- have a significant environmental impact
- present significant potential for improvement in environmental impact (without incurring excessive costs)

Increasing energy efficiency is an important objective of the EU policy (3). A crucial policy instrument for achieving the 2030 EU climate and energy targets is the setting of minimum efficiency requirements for products – through ecodesign –, in combination with informing customers about their energy performance and durability – through energy labelling.

Ecodesign and Energy Labelling regulations are key contributors in product policy supporting the Energy Union objectives and the transition to a Circular Economy. The Commission has

[5] Article 15.2 of Ecodesign Directive 2009/125/EC.

flagged in the Ecodesign Working plan 2016-2019 that ecodesign implementing measures should cover resource efficiency aspects where appropriate, to ensure greater durability, accessibility, design for disassembly and reparability of products entering the market and therefore contribute to the transition towards a more circular economy. Since the coming into force of the first ecodesign directive in 2005, a variety of energy-consuming product groups such as washing machines, refrigerators, etc. have been covered by ecodesign and energy labelling regulations.

Moreover, each ecodesign and energy labelling regulation contains provisions for its future evaluation and possible revision, taking into account the experience gained with their implementation and technological progress.

1.3.1.2 Analysis of policy options implemented under the Ecodesign Directive

The Ecodesign Directive defines an ecodesign requirement as “any requirement in relation to a product, or the design of a product, intended to improve its environmental performance, or any requirement for the supply of information with regard to the environmental aspects of a product”.

Circular economy requirements can be classified into measures that enhance effective lifetime, either by improving the durability of the product or its components (reduce), or by increasing reusability and repairability, thereby delaying disposal due to malfunction or technical failure (reuse). Once products reach their end-of-life (EOL), recycling recovers materials and/or components for use as inputs in the production of new products. Accurate information regarding the presence of hazardous substances and critical raw materials (critical sourcing) is vital for recyclers to develop efficient and safe processes. It is important to note that circular economy measures are not an end in itself, but instead a means to an end, such as sustainable development or strategic raw material independence. [6]

There are many types of requirements related to the circular economy, but an analysis of ecodesign implementing measures indicates that they are not all currently utilized in existing ecodesign regulations [7]. Among these is the requirement for mandatory recycled content, which is gaining importance, as evidenced by its inclusion in the 2023/1542 for a Batteries Regulation intended to replace Directive 2006/66/EC on batteries[8]. Notably, legislation on batteries is not governed by the ecodesign framework, despite the preparatory study for this regulation being conducted in accordance with the MEErP. The Batteries Regulation also explicitly addresses the repurposing of batteries for a second life and introduces a battery passport, a digital product passport (DPP) that could enhance the traceability of batteries and boost recycling efforts. Relevant lifecycle data, such as charging cycles to facilitate repurposing, can also be recorded in the DPP. The Batteries Directive from 2006 had already established minimum collection and recycling rates to increase the volume of recycled

[6] Ardente, F.; Mathieux, F. Integration of Resource Efficiency and Waste Management Criteria in European Product Policies—Second Phase: Report n 2 Application of the Project’s Methods to Three Product Groups; Publications Office of the European Union: Luxembourg, 2012.

Bundgaard, A.M.; Mosgaard, M.A.; Remmen, A. From energy efficiency towards resource efficiency within the Ecodesign Directive. J. Clean. Prod. 2017, 144, 358–374.

Mathieux, F.; Ardente, F.; Bobba, S. Ten years of scientific support for integrating circular economy requirements in the EU ecodesign directive: Overview and lessons learnt. Procedia CIRP 2020, 90, 137–142.

[7] Barkhausen, R.; Durand, A.; Fick, K. (2022) Review and Analysis of Ecodesign Directive Implementing Measures: Product Regulations Shifting from Energy Efficiency towards a Circular Economy. https://doi.org/10.3390/su141610318.

[8] Regulation (EU) 2023/ of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC

materials. New approaches can also be found in the EU CRM Act, the Circular Economy Action Plan (CEAP) and the planned Circular Economy Act due for adoption in 2026 [9]. The CEAP explicitly mentions measures against premature obsolescence, a ban on the destruction of unsold but durable goods, and the concept of "product-as-a-service". In the future, some of these elements will likely be integrated into ecodesign implementing measures, as seen also in the inclusion in the scope of the ESPR.[10] Several of such possible circularity measures (such as content declarations, design for disassembly, recycled content or repurposing) are mentioned in studies from the JRC from 2023 and 2025, where the authors investigate circularity measures on critical raw materials in passenger cars and in particular e-drive motors in vehicles[11] [12]. While the focus in those publications is on traction motors, the assessment can also provide relevant insights for industrial motors.

The ESPR, which came into effect in July 2024, replaces the 2009 Ecodesign Directive and broadens its scope from solely energy-related products to encompass nearly all products and sectors, with a few exceptions such as food, feed, and medical products. In addition to focusing on energy efficiency, the ESPR introduces new performance and information requirements concerning product durability, reparability, upgradability, recyclability, the presence of substances of concern, and mandates for the use of recycled materials. This includes the incorporation of recycled content, aimed at ensuring that products entering the EU internal market become increasingly sustainable. While some of these aspects were previously addressed under the Ecodesign Directive for specific product groups, the ESPR provides a more coherent and systematic framework for evaluating sustainability across a wider array of products.

A classification on ecodesign implementing measures which are found in existing ecodesign regulations can be seen in Table 16.

Table 2 Classification of circular economy requirements adopted for ecodesign implementing measures (Barkhausen et al 2022)

Circular Economy Strategy	**Circular Economy Category**	**Circular Economy Requirements**
Reduce	Durability	• Minimum lifetime/warranty • Availability of updates • Installation/maintenance instructions

[9] Circular Economy Act

[10] COM(2020) 798; Proposal for a Regulation of the European Parliament and of the Council Concerning Batteries and WasteBatteries, Repealing Directive 2006/66/EC and Amending Regulation (EU) No. 2019/1020. Publications Office of the European Union: Luxembourg, 2020.

Van Tichelen, P.; Mulder, G.; Durand, A. Preparatory Study on Ecodesign and Energy Labelling of Rechargeable Electrochemical Batteries with Internal Storage under FWC ENER/C3/2015-619-Lot 1: Task 7 Report Policy Scenario Analysis; Publications Office of the European Union: Luxembourg, 2019.

2006/66/EC; Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on Batteries and Accumulators and Waste Batteries and Accumulators and Repealing Directive 91/157/EEC. Publications Office of the European Union: Luxembourg, 2006.

[11] TAZI, N., OREFICE, M., CANDELARESI, D., MARTININI, S., MARCHETTO, A., PULIKOTTIL, T., BOIX RODRÍGUEZ, N., ABDELBAKY, M., CIACCI, L., PEETERS, J.R., LAPKO, Y. and MATHIEUX, F., Circularity measures on critical raw materials and e-drive motors in vehicles, Publications Office of the European Union, Luxembourg, 2025, https://data.europa.eu/doi/10.2760/6053264, JRC140892.

[12] TAZI, N., OREFICE, M., CANDELARESI, D., MARTININI, S., MARCHETTO, A., PULIKOTTIL, T., BOIX RODRÍGUEZ, N., ABDELBAKY, M., CIACCI, L., PEETERS, J.R., LAPKO, Y. and MATHIEUX, F., Circularity measures on critical raw materials and e-drive motors in vehicles, Publications Office of the European Union, Luxembourg, 2025, https://data.europa.eu/doi/10.2760/6053264, JRC140892.

Reuse	Reusability/ Repairability	• Repair/disassembly instructions • Information/warning on non-repairability of spare parts • Design for disassembly or repair • Secure data deletion
Recycle	Recycling Critical sourcing Hazardous substances	• Disassembly/dismantling instructions • Design for dismantling, recycling and recovery • Marking of components • Information on how to dispose • Information on critical raw material content • Information on hazardous material content • Ban of materials

For further specification of the different categories, the EU standards on material efficiency can be taken as a starting point (EN4555X) (see section 1.1.2 for definitions).

While the waste hierarchy places reuse higher than recycling, circularity should not be considered as an end itself but as a means to an end. And indeed, for motors, stakeholders noted that the lifetime energy and greenhouse gas impact of newly manufactured efficient replacement motors can be lower than for repaired/repurposed motors. Therefore, in some cases replacing inefficient motors rather than extending the lifetime of efficient motors is preferable from a life cycle impact perspective. This points to the fact that a thorough impact assessment of different measures is needed before implementation.

To categorize circular economy requirements, the Ecodesign Directive differentiates between specific and generic ecodesign requirements (Article 2). A specific ecodesign requirement is defined as a “quantified and measurable ecodesign requirement related to a particular environmental aspect of a product, such as energy consumption during use, calculated for a given unit of output performance.” In contrast, a generic ecodesign requirement is described as “any ecodesign requirement based on the overall ecological profile of a product without set limit values for specific environmental aspects.”

Within each group of requirements there is a difference in the level of ambition and detail. Furthermore, a differentiation in performance requirements and informational requirements can be made. Informational requirements e.g. necessitate the provision of specific performance values for the product, or require manufacturers to take specific actions, such as providing a list of spare parts on their website. There are informational requirements which are less specific and offer OEMs more flexibility in meeting the criteria. An example is Regulation (EC) No 640/2009 on electric motors, which includes the vague requirement to provide “information relevant for disassembly, recycling, or disposal at end-of-life” without further specifications.

1.3.1.3 Implementing measures on electric motors

Electric motors are regulated under the Ecodesign Directive since 2009 with Commission Regulation (EC) No 640/2009, which was repealed in 2019 with Commission Regulation (EU)

2019/1781. While the scope of the regulation was significantly refined (see Table 2), measures on scarce, environmentally relevant and critical raw materials and on recycled content are not the priority. While regulation (EC) No 640/2009 did include an informational requirement on the subject (“*information relevant for disassembly, recycling or disposal at end-of-life shall be visibly displayed on technical documentation of motors and of products in which motors are incorporated as well as on free access websites of manufacturers of motors and of manufacturers of products in which motors are incorporated”)*[13], this requirement was removed in the 2019 repeal.

Table 3 Subject matter and scope section of the Ecodesign regulation on electric motors, (EC) No 640/2009 and (EU) 2019/1781.

(EC) No 640/2009	(EU) 2019/1781
1. This Regulation establishes ecodesign requirements for the placing on the market and for the putting into service of motors, including where integrated in other products.	(1) This Regulation applies to the following products: (a) induction electric motors without brushes, commutators, slip rings or electrical connections to the rotor, rated for operation on a 50 Hz, 60 Hz or 50/60 Hz sinusoidal voltage, that: (i) have two, four, six or eight poles; (ii) have a rated voltage U N above 50 V and up to and including 1 000 V; (iii) have a rated power output P N from 0,12 kW up to and including 1 000 kW; (iv) are rated on the basis of continuous duty operation; and (v) are rated for direct on-line operation; (b) variable speed drives with 3 phases input that: (i) are rated for operating with one motor referred to in point (a), within the 0,12 kW-1 000 kW motor rated output range; (ii) have a rated voltage above 100 V and up to and including 1 000 V AC; (iii) have only one AC voltage output.
2. This Regulation shall not apply to:	(2) The requirements in section 1, and points (1), (2), (5) to (11), and (13) of section 2 of Annex I shall not apply to the following motors:
(a) motors designed to operate wholly immersed in a liquid;	*[see (EU) 2019/1781 (2) (e)]*
(b) motors completely integrated into a product (for example gear, pump, fan or compressor) of which the energy performance cannot be tested independently from the product;	(a) motors completely integrated into a product (for example into a gear, pump, fan or compressor) and whose energy performance cannot be tested independently from the product, even with the provision of a temporary end-shield and drive-end bearing; the motor must share common components (apart from connectors such as bolts) with the driven unit (for example, a shaft or housing) and shall not be designed in such a way that the motor can be separated in its entirety from the driven unit and operate independently. The process of separation shall have the consequence of rendering the motor inoperative;
	(b) motors with an integrated variable speed drive (compact drives) whose energy performance cannot be tested independently from the variable speed drive;
[see (EC) No 640/2009 2. (d)]	(c) motors with an integrated brake which forms an integral part of the inner motor construction and can neither be removed nor powered by a separate power source during the testing of the motor efficiency;
(c) motors specifically designed to operate: (i) at altitudes exceeding 1 000 metres above sea-level; (ii) where ambient air temperatures exceed 40 °C; (iii) in maximum operating temperature above 400 °C;	(d) motors specifically designed and specified to operate exclusively: (i) at altitudes exceeding 4 000 metres above sea-level; (ii) where ambient air temperatures exceed 60 °C; (iii) in maximum operating temperature above 400 °C; (iv) where ambient air temperatures are less than – 30 °C; or

[13] Annex 2 of Regulation (EC) No 640/2009, requirement active from 16 June 2011.

(iv) where ambient air temperatures are less than – 15 °C for any motor or less than 0 °C for a motor with air cooling; (v) where the water coolant temperature at the inlet to a product is less than 5 °C or exceeding 25 °C; in potentially explosive atmospheres as defined in Directive 94/9/EC of the European Parliament and of the Council (5);	(v) where the water coolant temperature at the inlet to a product is below 0 °C or above 32 °C;
[see (EC) No 640/2009 2. (a)]	(e) motors specifically designed and specified to operate wholly immersed in a liquid;
(d) brake motors;	*[see (EU) 2019/1781 (2) (c)]*
	(f) motors specifically qualified for the safety of nuclear installations, as defined in Article 3 of Council Directive 2009/71/Euratom (8); (g) explosion-protected motors specifically designed and certified for mining, as defined in Annex I, point 1 of Directive 2014/34/EU of the European Parliament and of the Council (9); (h) motors in cordless or battery-operated equipment; (i) motors in hand-held equipment whose weight is supported by hand during operation; (j) motors in hand-guided mobile equipment moved while in operation; (k) motors with mechanical commutators; (l) Totally Enclosed Non-Ventilated (TENV) motors; (m) motors placed on the market before 1 July 2029 as substitutes for identical motors integrated in products placed on the market before 1 July 2022, and specifically marketed as such; (n) multi-speed motors, i.e. motors with multiple windings or with a switchable winding, providing a different number of poles and speeds; (o) motors designed specifically for the traction of electric vehicles.
	(3) The requirements in section 3, and points (1), (2), and (5) to (10) of section 4 of Annex I shall not apply to the following VSDs: (a) VSDs integrated into a product and whose energy performance cannot be tested independently from the product, that is to say that an attempt to do so would render the VSD or the product inoperative; (b) VSDs qualified specifically for the safety of nuclear installations, as defined Article 3 of Directive 2009/71/Euratom; (c) regenerative drives; (d) drives with sinusoidal input current.
except as regards the information requirements of Annex I, points 2(3) to (6) and (12).	

1.3.2 Ecodesign for Sustainable Products Regulation (ESPR)

The Ecodesign for Sustainable Products Regulation (ESPR) replaces the Ecodesign Directive 2009/125/EC, with certain products or articles transitioning on 31 December 2026 or 31 December 2030 (as stated in ESPR Article 79). Like its predecessor, the ESPR serves as a framework regulation that allows for the establishment of ecodesign, performance, and information requirements for specific product groups—or across multiple groups—through delegated acts. The ESPR is broadening the scope to include a wider range of products beyond just energy-related one's. Furthermore, the ESPR emphasizes circular economy principles, focusing on product durability, reparability, recyclability, and reducing waste, while also introducing strict requirements to prevent the destruction of unsold consumer products.

1.3.3 Energy Efficiency Directive (EED)

The Energy Efficiency Directive (EED) (Directive 2012/27/EU) promotes the adoption of energy-saving technologies and circular economy practices within industries. It advocates for the use of high-efficiency motors and the replacement of less efficient ones to minimize the environmental impact of motor usage.

1.3.4 End-of-Life Vehicle (ELV) Directive

The ELV Directive (Directive 2000/53/EC) requires that 95% of a vehicle's materials be reused, recycled, or recovered, with electric motors playing a crucial role in this process. This European Directive emphasizes the need to enhance motor recycling rates, especially for the rare earth elements found in electric vehicles. For our study the Directive is less relevant, since motors for Electric Vehicle Traction are out of scope. Nevertheless, the ELV Directive underlines the strategic importance of recovering materials from permanent magnet motors.

1.3.5 Low Voltage Directive (LVD)

The Low Voltage Directive (LVD) 2014/35/EU ensures that electrical equipment operating between 50 and 1000 V AC or 75 and 1500 V DC is safe for use within the EU. It sets essential health and safety requirements to protect users from electrical, mechanical, and fire hazards. The LVD applies to a wide range of equipment, including many industrial electric motors, but excludes items like vehicle components, medical devices, and equipment for use in explosive environments[14].

1.3.6 WEEE Directive

The WEEE Directive (2012/19/EU) aims to protect the environment and human health by reducing the impact of waste electrical and electronic equipment (WEEE) and improving resource efficiency. The Directive is currently under review[15]. Producers of equipment, including motors (excluding vehicle motors), are responsible for managing their products at end-of-life under the principle of extended producer responsibility. Member States must encourage designs that facilitate reuse, dismantling, and recovery, aligned with the Ecodesign Directive, ensuring producers do not hinder these processes without valid environmental or safety reasons.

Member States must establish systems for separate WEEE collection, allowing free return of waste from consumers and distributors, and achieve a minimum collection rate of 65% of EEE placed on the market or 85% of WEEE generated. Producers must meet recovery and recycling targets, such as recovering 85% and recycling 80% of large equipment containing motors. They must also provide treatment facilities with information to ensure proper and environmentally sound recycling. Hazardous components common in motors, like PCB-containing capacitors and batteries, must be removed and treated safely. Overall, the directive

[14] Directive - 2014/35 - EN - Low Voltage Directive - EUR-Lex

[15] Waste from electrical and electronic equipment – evaluating the EU rules

promotes circular use by integrating design, collection, and recovery requirements for motors and other EEE.

1.3.7 Critical Raw Materials Act

Annex I of the Critical Raw Materials Act [16] lists the strategic raw materials, and Annex II the critical raw materials. The list is presented in the table below.

Table 4: List of Critical and Strategic Raw Materials

Raw Material/Element	Critical Raw Material	Strategic Raw Material
Antimony	X	
Arsenic	X	
Bauxite/alumina/aluminium	X	X
Baryte	X	
Beryllium	X	
Bismuth	X	X
Boron	X	X (metallurgy grade)
Cobalt	X	X
Coking coal	X	
Copper	X	X
Feldspar	X	
Fluorspar	X	
Gallium	X	X
Germanium	X	X
Hafnium	X	
Helium	X	
Heavy rare earth elements 10	X	
Light rare earth elements	X	
Rare earth elements for permanent magnets (Nd, Pr, Tb, Dy, Gd, Sm, Ce)		X
Lithium (battery grade)	X	X (battery grade)
Magnesium (metal)	X	X (metal)
Manganese (battery grade)	X	X (battery grade)
Graphite (battery grade)	X	X (battery grade)
Nickel – battery grade	X	X
Niobium	X	
Phosphate rock	X	

[16] Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020Text with EEA relevance.

Phosphorus	X	
Platinum group metals 28	X	
Scandium	X	
Silicon metal	X	X
Strontium	X	
Tantalum	X	
Titanium metal	X	X
Tungsten	X	X
Vanadium	X	

For permanent magnet motors, particularly neodymium, and to a lesser extent, praseodymium, terbium, dysprosium, gadolinium and cerium are relevant. All of them are classified as strategic as well as critical raw materials due to their strategic importance for the EU, essentiality for the green transition, economic importance and high risk of supply disruption.

Due to their strategic value, two articles in EU Regulation (EU) 2024/1252 are explicitly dedicated to permanent magnets. As permanent magnets hold relevance to the product group of electric motors, the two articles are reproduced below in their original wording.

(EU) 2024/1252 - Article 28: Recyclability of permanent magnets

1. From two years after the date of entry into force of the implementing act referred to in paragraph 2, any natural or legal person that places on the market magnetic resonance imaging devices, wind energy generators, industrial robots, motor vehicles, light means of transport, cooling generators, heat pumps, electric motors, including where electric motors are integrated in other products, automatic washing machines, tumble driers, microwaves, vacuum cleaners or dishwashers shall ensure that those products bear a conspicuous, clearly legible and indelible label indicating:

(a) whether those products incorporate one or more permanent magnets;

(b) if the product incorporates one or more permanent magnets, whether those permanent magnets belong to any of the following types:

- *(i) neodymium-iron-boron;*
- *(ii) samarium-cobalt;*
- *(iii) aluminium-nickel-cobalt;*
- *(iv) ferrite.*

2. By 24 November 2026, the Commission shall adopt an implementing act establishing the format for the labelling referred to in paragraph 1 of this Article. That implementing act shall be adopted in accordance with the examination procedure referred to in Article 39(3).

3. From two years after the date of entry into force of the implementing act referred to in paragraph 2, any natural or legal person that places on the market products referred to in paragraph 1 incorporating one or more permanent magnets of the types referred in paragraph 1, point (b) shall ensure that a data carrier is present on or in the product.

4. The data carrier referred to in paragraph 3 shall be linked to a unique product identifier that provides access to the following:

(a) the name, registered trade name or registered trademark and the postal address of the natural or legal person responsible and, where available, electronic means of communication where they can be contacted;

(b) information on the weight, location and chemical composition of all individual permanent magnets included in the product, and on the presence and type of magnet coatings, glues and any additives used;

(c) information enabling access and safe removal of all permanent magnets incorporated in the product, at least including the sequence of all removal steps, tools or technologies required for the access and removal of the permanent magnet, without prejudice to the provision of information to treatment facilities pursuant to Article 15(1) of Directive 2012/19/EU.

5. For products where the incorporated permanent magnets are exclusively contained in one or more electric motors incorporated in the product, the information referred to in paragraph 4, point (b), may be replaced by information on the location of those electric motors, and the information referred to in paragraph 4, point (c), may be replaced by information on the access and removal of the electric motors, at least including the sequence of all removal steps, tools or technologies required for the access and removal of the electric motors.

6. For products referred to in paragraph 3 for which a product passport is required pursuant to another Union legal act, the information referred to in paragraph 4 shall be included in that product passport.

7. The natural or legal person placing a product referred to in paragraph 3 on the market shall ensure that information referred to in paragraph 4 is complete, up-to-date, and accurate and remains available for a period at least equal to the product's typical lifetime plus 10 years, including after an insolvency, a liquidation or a cessation of activity in the Union of the natural or legal person responsible. That person may authorise another natural or legal person to act on their behalf.

The information referred to in paragraph 4 shall refer to the product model or, where the information differs between units of the same model, to a particular batch or unit. The information referred to in paragraph 4 shall be accessible to repairers, recyclers, market surveillance authorities and customs authorities.

8. Where information requirements relating to the recycling of permanent magnets are established in Union harmonisation legislation for any of the products listed in paragraph 1, those requirements shall apply to the products concerned in place of this Article.

9. Products primarily designed for defence or space applications shall be exempt from the requirements laid down in this Article.

10. From 24 May 2029, this Article shall apply to magnetic resonance imaging devices, motor vehicles and light means of transport that are type-approved vehicles of category L.

11. This Article shall not apply to:

(a) special purpose vehicles as defined in Article 3, point (31), of Regulation (EU) 2018/858;

(b) parts of a vehicle, other than the base vehicle, that have been type-approved in multi-stage type approval of category N1, N2, N3, M2 or M3

(c) vehicles produced in small series, as defined in Article 3, point (30), of Regulation (EU) 2018/858.

12. The Commission is empowered to adopt a delegated act in accordance with Article 38 to supplement this Regulation by providing a list of Combined Nomenclature codes in accordance with Annex I to Council Regulation (EEC) No 2658/87 (44) and product descriptions corresponding to the products referred to in paragraph 1 of this Article with the aim of facilitating the work of customs authorities in relation to those products and the requirements set out in this Article and in Article 29 to the recyclability of permanent magnets.

(EU) 2024/1252 - Article 29 Recycled content of permanent magnets

1. By 24 May 2027 or two years from the entry into force of the delegated act referred to in paragraph 2, whichever is later, any natural or legal person that places on the market products referred to in Article 28(1) which incorporate one or more permanent magnets referred to in Article 28(1), point (b), (i), (ii) and (iii), and for which the total weight of all such permanent magnets exceeds 0,2 kg shall make publicly available on a free-access website the share of neodymium, dysprosium, praseodymium, terbium, boron, samarium, nickel and cobalt recovered from post-consumer waste present in the permanent magnets incorporated in the product.

2. By 24 May 2026, the Commission shall adopt a delegated act in accordance with Article 38 to supplement this Regulation by establishing rules for the calculation and verification of the share of neodymium, dysprosium, praseodymium, terbium, boron, samarium, nickel and cobalt recovered from post-consumer waste present in the permanent magnets incorporated in the products referred to in paragraph 1 of this Article.

The calculation and verification rules shall specify the applicable conformity assessment procedure from among the modules set out in Annex II to Decision No 768/2008/EC of the European Parliament and of the Council (45), with the adaptations necessary in view of the products concerned. When specifying the applicable conformity assessment procedure, the Commission shall consider the following criteria:

(a) whether the module concerned is appropriate to the type of product and proportionate to the public interest pursued;

(b) the nature of the risks entailed by the product and the extent to which conformity assessment corresponds to the type and degree of risk;

(c) where third party involvement is mandatory, the need for the manufacturer to have a choice between quality assurance and product certification modules set out in Annex II to Decision No 768/2008/EC.

3. After the entry into force of the delegated act adopted pursuant to paragraph 2, and in any event by 31 December 2031, the Commission shall adopt delegated acts supplementing this Regulation by laying down minimum shares for neodymium, dysprosium, praseodymium, terbium, boron, samarium, nickel and cobalt recovered from post-consumer waste that must be present in the permanent magnet incorporated in the products referred to in paragraph 1.

The delegated acts referred to in the first subparagraph may apply different minimum shares to different products and may exclude certain products. They shall provide for transitional periods adjusted to the difficulty of adapting the products covered by the measure to ensure compliance.

The minimum share referred to in the first subparagraph shall be based on a prior assessment of impacts, taking into account:

(a) the existing and forecasted availability of neodymium, dysprosium, praseodymium, terbium, boron, samarium, nickel and cobalt recovered from post-consumer waste;

(b) the information collated pursuant to paragraph 1 and the relative distribution of the share of recycled content in permanent magnets incorporated in products referred to in paragraph 1 placed on the market;

(c) technical and scientific progress, including considerable changes in permanent magnet technologies impacting the type of materials recovered;

(d) the effective and potential contribution of a minimum share to the Union's climate and environmental objectives;

(e) possible impacts on the functioning of products incorporating permanent magnets;

(f) the need to prevent disproportionate negative impacts on the affordability of permanent magnets and products incorporating permanent magnets.

4. Where requirements relating to the recycled content of permanent magnets are established in Union harmonisation legislation for any of the products listed in paragraph 1, those requirements shall apply to the products concerned in place of this Article.

5. From the date of application of the requirement set out in paragraph 1, when offering the products referred to in paragraph 1 for sale, including in the case of distance selling, or displaying them in the course of a commercial activity, natural and legal persons placing on the market products referred to in paragraph 1 shall ensure that their customers have access to the information referred to in paragraph 1 before being bound by a sales contract.

Natural and legal persons placing on the market products referred to in paragraph 1 shall not provide or display labels, marks, symbols or inscriptions that are likely to mislead or confuse customers with respect to the information referred to in paragraph 1. Products primarily designed for defence or space applications shall be exempt from the requirements laid down in this Article.

6. For magnetic resonance imaging devices, motor vehicles and light means of transport that are type-approved vehicles of category L, the requirements set out in paragraphs 1 and 5 shall apply from five years after the date of entry into force of the delegated act referred to in paragraph 2.

7. This Article shall not apply to:

(a) special purpose vehicles as defined in Article 3, point (31), of Regulation (EU) 2018/858;

(b) parts of a vehicle, other than the base vehicle, that have been type-approved in multi-stage type approval of category N1, N2, N3, M2 or M3;

(c) vehicles produced in small series, as defined in Article 3, point (30), of Regulation (EU) 2018/858.

To summarize, Article 28 of EU Regulation (EU) 2024/1252 explicitly includes “electric motors” and already defines a labelling requirement that is active from May 2026 onwards, obliging manufacturers to label the presence of permanent magnets and their type (neodymium-iron-boron; samarium-cobalt; aluminium-nickel-cobalt; ferrite). To allow implementation of this requirement, by 24 November 2026, the Commission will adopt an implementing act establishing the labelling format. Furthermore, the requirement includes a type of digital product passport, defined as a “data carrier” that has to be present on or in the product that provides access to information such as chemical composition and instruction for removal of the permanent magnets. If a product is regulated in a separate Union legal act, the information mentioned in this article shall be incorporated in e.g. the product passport. Overall, the individual product information shall remain available for a period at least equal to the product's typical lifetime plus 10 years.

Article 29 furthermore includes a requirement on declaration of recycled content for motors for which the total weight of all such permanent magnets exceeds 0,2 kg. Like the labelling, the recycled content requirement is active from May 2026 onwards. The information on recycled content must be made publicly available on a free-access website and include the share of neodymium, dysprosium, praseodymium, terbium, boron, samarium, nickel and cobalt recovered from post-consumer waste present in the permanent magnets incorporated in the product.

By 24 May 2026, the Commission will adopt a delegated act for establishing rules for the calculation and verification of the share the materials. Furthermore, two years pursuant to the delegated act for the calculation and verification (and in any event latest by 31 December 2031), the Commission shall adopt delegated acts supplementing this Regulation by laying down minimum shares for neodymium, dysprosium, praseodymium, terbium, boron, samarium, nickel and cobalt recovered from post-consumer waste that must be present in the permanent magnet incorporated in the products. Such delegated act may apply different minimum shares to different products and may exclude certain products. Also, they shall provide for transitional periods adjusted to the difficulty of adapting the products covered by the measure to ensure compliance.

Where requirements relating to the recycled content of permanent magnets are established in Union harmonisation legislation for any of the products, those requirements shall apply to the products concerned in place of this Article.

2. MEErP Task 2, Markets

This section offers a very brief look at the market data estimates for electric motors, based on the current figures of the on-going Review Study.

2.1. Motor Sales and Stocks

Table 4 presents the estimated sales of electric motors in five-year increments from 2010 through 2050 for BC4, BC5 and other motor types. The data on IEMs is based on a previous Impact assessment on electric motors[17] [18].

Data for permanent magnet motors was also collected but considered as first estimate, because they were based on only few available data points including expert statements and previous studies[19] [20]. As a main data point, PMMs are assumed to make up 1-2 % of the industrial motor market in 2025[21]. It is additionally assumed that in 2013 between 1,5 and 2 million synchronous motors with NdFeB magnet were produced in the EU. Up to 50% these

[17] Electric Motors - European Commission

[18] IA_report-swd_2019_0343.pdf

[19]factsheet-magnetmaterialien_fi_barrierefrei.pdf

[20] Untersuchung zu seltenen Erden: Permanentmagnete im industriellen Einsatz in Baden-Württemberg

[21] Expert interview, 2025

motors are sold outside of Europe. Motors out of scope including wind turbines and electric vehicles are estimated to make up to 70% of these motors which would need to be deducted, while import data would still need to be added (data still to be collected).

Table 5 Sales of Motors by Type (BAU, thousands of units)

Type	2010	2020	2030	2040	2050
Induction type, >0.75 kW, 1-phase, no t VSD	9.778	10.925	11.483	12.070	12.688
Induction type, 0.12-0.75 kW, 1-phase, no VSD	15.746	16.212	16.372	16.502	16.598
Induction type, 0.12-0.75 kW, 1-phase, with VSD	1.750	2.335	2.644	2.995	3.392
Induction type, 0.12-0.75 kW, 3-phase, no VSD	4.350	4.634	4.734	4.809	4.851
Induction type, 0.12-0.75 kW, 3-phase, with VSD	574	812	990	1.208	1.473
Induction type, 0.75-7.5 kW, 3-phase, no VSD	7.021	5.789	5.731	5.660	5.536
Induction type, 7.50-75 kW, 3-phase, no VSD	912	669	647	617	604
Induction type, 75-375 kW, 3-phase, no VSD	67	45	41	36	38
Induction type, 0.75-7.5 kW, 3-phase, with VSD	1.411	3.632	4.171	4.749	5.405
Induction type, 7.50-75 kW, 3-phase, with VSD	251	630	719	818	905
Induction type, 75-375 kW, 3-phase, with VSD	30	63	73	83	88
Induction type, 375-1000 kW, 3-phase, no VSD	6	5	5	5	5
Induction type, 375-1000 kW, 3-phase, with VSD)	4	6	6	7	8

Table 5 presents the estimated stock of IEMs in five-year increments from 2010 through 2050 in the baseline scenario. The categorisation of motor types according to their motor type, power range, integration of VSD etc. is in line with previous impact assessments[22]. Stock data was calculated by adding sales data over several years per motor type under the consideration of their specific lifetimes. For example, for small motors (0.75kW – 7,5 kW) a lifetime of 9 years, medium a lifetime of 11 years and large motors a lifetime of 16 years was assumed in line with previous assessments[23]. For PMM the same lifetimes were assumed.

Table 6 Stock of Motors by Type (BAU, thousands of units)

Type	2010	2020	2030	2040	2050
Induction type, >0.75 kW, 1-phase, no t VSD	104.945	124.226	134.089	140.947	148.155
Induction type, 0.12-0.75 kW, 1-phase, no VSD	119.313	129.167	130.547	131.674	132.542
Induction type, 0.12-0.75 kW, 1-phase, with VSD	11.289	17.649	20.260	22.945	25.987
Induction type, 0.12-0.75 kW, 3-phase, no VSD	33.051	36.466	37.606	38.281	38.716
Induction type, 0.12-0.75 kW, 3-phase, with VSD	3.707	5.979	7.396	9.023	11.007

[22] IA_report-swd_2019_0343.pdf

[23] IA_report-swd_2019_0343.pdf

Induction type, 0.75-7.5 kW, 3-phase, no VSD	59.547	58.269	51.701	51.236	50.316
Induction type, 7.50-75 kW, 3-phase, no VSD	9.382	8.723	7.239	6.961	6.647
Induction type, 75-375 kW, 3-phase, no VSD	993	928	710	633	592
Induction type, 0.75-7.5 kW, 3-phase, with VSD	10.499	23.561	35.667	40.601	46.217
Induction type, 7.50-75 kW, 3-phase, with VSD	2.175	4.912	7.417	8.445	9.546
Induction type, 75-375 kW, 3-phase, with VSD	343	666	1.041	1.211	1.347
Induction type, 375-1000 kW, 3-phase, no VSD	114	105	94	92	90
Induction type, 375-1000 kW, 3-phase, with VSD)	34	71	101	113	125

2.2. Electricity Consumption of Motors

Table 7 presents the electricity consumption per (induction) motor type. For each type the electricity consumption is calculated based on the primary energy consumption which was calculated by taking the stock data and the motors load factor, operating hours, output power and efficiencies into account[24].

Table 7 Electricity Consumption of EU stock, by Type (BAU, Terawatt-hours per year)

Type	2010	2020	2030	2040	2050
Induction type, >0.75 kW, 1-phase, no t VSD	61.532	68.207	70.710	73.758	77.138
Induction type, 0.12-0.75 kW, 1-phase, no VSD	10.899	11.547	11.417	11.265	11.093
Induction type, 0.12-0.75 kW, 1-phase, with VSD	799	1.201	1.335	1.463	1.603
Induction type, 0.12-0.75 kW, 3-phase, no VSD	15.096	16.299	16.444	16.375	16.202
Induction type, 0.12-0.75 kW, 3-phase, with VSD	1.452	2.027	2.382	2.803	3.311
Induction type, 0.75-7.5 kW, 3-phase, no VSD	138.417	126.094	108.596	106.898	104.453
Induction type, 7.50-75 kW, 3-phase, no VSD	214.373	195.053	159.165	152.454	145.170
Induction type, 75-375 kW, 3-phase, no VSD	427.565	395.120	298.992	266.006	248.369
Induction type, 0.75-7.5 kW, 3-phase, with VSD	16.769	34.410	50.513	56.754	63.867
Induction type, 7.50-75 kW, 3-phase, with VSD	32.207	70.260	104.275	117.816	132.333
Induction type, 75-375 kW, 3-phase, with VSD	94.221	179.144	276.779	320.024	354.260
Induction type, 375-1000 kW, 3-phase, no VSD	207.648	190.543	168.847	164.824	161.820
Induction type, 375-1000 kW, 3-phase, with VSD)	46.734	94.567	131.302	146.188	160.451

[24] A_report-swd_2019_0343.pdf

2.3. End-of-Life (EoL)

2.3.1 Requirements of the WEEE Directive

At end-of-life, motors become part of the waste from electrical and electronic equipment (WEEE). Effective end-of-life (EoL) management of electric motors is essential for conserving valuable materials like copper, aluminium, steel, and rare earth elements (REEs), while reducing the environmental impact of extraction, processing, and disposal. However, inconsistent EoL practices across the EU—often involving the export of motors for lower-cost recycling—undermine resource recovery and hinder circular economy goals[25].

Under the WEEE Directive, motors can either be part of WEEE category 4 ‘Large equipment (any external dimension more than 50 cm)’ or category 5 ‘small equipment’, depending on the application product. After August 2018, the WEEE Directive requires for large equipment a minimum recovery target of 85 % with 80 % to be prepared for re-use and recycling, while for small equipment 75 % shall be recovered, and 55 % shall be prepared for re-use and recycled[26].

As of 2022, the EU-wide collection rate for products under WEEE was 40.6%, indicating that many Member States have not yet met this target[27] .

According to the regulations (EU) 2024/3229 and (EU) 2024/3230, from January 1, 2025, the EU will prohibit the export of all e-waste, including industrial electric motors classified as e-waste, to non-OECD countries, while exports to OECD countries will require a "prior informed consent" procedure. This regulation aims to align with the Basel Convention's updated classifications, ensuring stricter control over hazardous and non-hazardous e-waste shipments to promote environmentally sound management[28].

2.3.2 Markets for recycled metals

The European Union promotes motor recycling through initiatives that support the recovery of valuable metals like copper and aluminium. Economic barriers to EoL motor recycling include high infrastructure and technology costs, particularly for processing rare earth elements, and fluctuating metal prices that reduce profitability. While these challenges hinder investment and operational efficiency, policy measures like the EU Circular Economy Action Plan aim to offset them through incentives such as subsidies, tax credits, and grants that support the development of recycling infrastructure. In monetary terms, the metals embedded in e-waste in 2022 were valued at approximately USD 90 billion, yet only USD 28 billion of this value was recovered [25].

Scientific reports estimate motor recycling in the EU at around 1.5 million tonnes annually, with an economic value of recovered motor materials of more than 2 billion € shown in Table 8 differentiated for different materials. Furthermore, the motor recycling industry in Europe provides approximately 50 000 jobs across various areas, including collection, disassembly, and advanced material processing [25].

[25] Almeida, A.; Saki, A.; Fong, A.; Quaresma, Nuno (2024): D2.4 Analysis of end-of-life practice for electric motors https://eu-more.eu/wp-content/uploads/2025/04/D2.4-Analysis-End-of-Life-Practice-Electric-Motors-Final.pdf

[26] L_2012197EN.01003801.xml

[27] Waste electrical and electronic equipment (WEEE) collection rate (Indicator) | European zero pollution dashboards

[28] Waste shipments - European Commission

Table 8 Economic value of recovered motor materials in Europe[25]

Material	Annual value (Million €)	Market trends
Copper	1 200	High demand in energy infrastructure
Steel	800	Stable due to widespread industrial use
Aluminium	500	Growth in lightweight manufacturing
Rare earth elements	300	Increasing demand for EV applications

Copper recycling presents a major market opportunity, especially as demand surges from clean energy technologies and electric motors, where copper is a critical material due to its superior conductivity and durability. With an estimated 370 million tonnes of copper in use expected to reach end-of-life in the coming years, expanding recycling—particularly from end-of-life products like EV motors—offers a vital secondary supply stream. Direct-use of high-grade scrap and secondary production of lower-grade scrap form the backbone of copper recycling, supported by increasing policy focus such as the EU's Critical Raw Materials Act.

By 2050, secondary copper supply could meet up to 40% of global demand, making it a crucial strategy for reducing reliance on primary mining and advancing a sustainable, circular economy. China, Japan, and South Korea are the main importers of recycled copper, with China focusing on high-grade scrap and Japan and South Korea relying on imports due to their advanced processing capabilities.**Error! Bookmark not defined.**

The market for recycled rare earth elements (REEs) is still small, with most recovery coming from manufacturing scrap and less than 5% from end-of-life products due to technical and economic barriers[29]. However, rising demand from EVs and wind turbines, combined with supportive policies and manufacturer commitments, is expected to significantly increase secondary REE supply, potentially tripling by 2050 under current projections [25].

See 5.4 for a closer analysis of individual material prices.

3. MEErP Task 3, Product usage

In this task, the review study would look at how much the product being evaluated is used. However, for the purposes of the work being conducted in this study of critical raw materials, recycled content and recyclability, the usage of the product is less relevant. The upcoming review study motors will provide updates on product usage in their analysis, it is therefore not included in this report.

[29] factsheet-magnetmaterialien_fi_barrierefrei.pdf

4. MEErP Task 4, Technologies

4.1. Overview

The electric motor market is experiencing significant advancements driven by heightened awareness of energy efficiency among governments and industries. The implementation of minimum energy performance standards (MEPS) has led to the emergence of super- and ultra-premium efficiency motors (IE4 and IE5), which exceed the performance of traditional IEMs. Technologies such as Permanent Magnet Synchronous Motors (PMSM) and Synchronous Reluctance Motors (SynRM) are gaining traction due to their high efficiency, with many applications benefiting from variable speed operations.

Beyond the research conducted for this study, the upcoming review study on motors will provide further updates on technological innovation. The focus in this study is therefore particularly on aspects related to the end-of-life of motors.

4.2. Motor technologies

4.2.1 Induction Motors

IEMs, particularly squirrel cage induction motors (SCIM), remain the dominant choice in fixed-speed applications due to their reliability and efficiency. The latest IEMs available on the market exceed the IE4 efficiency standards, achieving approximately 15% lower losses than conventional high-efficiency motors (IE3 or NEMA Premium). Improvements in efficiency are largely attributed to advanced magnetic materials, optimized rotor and stator designs, and enhanced winding techniques. For instance, increasing the cross-section of stator windings reduces electrical resistance and I^2R losses significantly. Moreover, the adoption of novel winding techniques, such as hairpin winding, allows for better utilization of space and thermal management, further enhancing overall motor performance.

While improving energy efficiency, some of the design optimizations increase the demand for materials like copper and aluminum due to larger magnetic circuits with thinner laminations, or larger copper/aluminium cross-sections in the stator and rotor windings.[30] [31] [32]

4.2.2 Permanent Magnet Motors

Permanent Magnet Motors (PMM), specifically Permanent Magnet Synchronous Motors (PMSM), utilize permanent magnets in the rotor to produce a magnetic field without excitation losses, leading to higher efficiency compared to IEMs. These motors, designed for both high efficiency and compactness, require a frequency converter and position sensors for optimal operation. The use of rare-earth magnets, such as neodymium-iron-boron (NdFeB), enhances torque density and power output. The transition from ferrite to rare-earth magnets is driven by the need for better performance in applications like electric vehicles and industrial machinery.

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[30] Fong, A.; Almeida, A.; Kulterer, K. (2024): D4.1 Motor System Efficiency Trends. https://eu-more.eu/wp-content/uploads/2024/08/EU-MORE-D4.1.Motor-system-efficiency-trends-Final.pdf

[31] Almeida, A. d., Ferreira, F. J., & Baoming, G. (2014). Beyond Induction Motors – Technology Trends to Move Up Efficiency. IEEE Transactions on Industry Applications, 20(3), 2103 - 2114.

[32] Hannan, M. A., Ali, J. A., Mohamed, A., & Hussain, A. (January 2018). Optimization techniques to enhance the performance of induction motor drives: A review. Renewable and Sustainable Energy Reviews, 81, Part 2, 1611-1626.

PMMs exhibit minimal slip, allowing them to operate synchronously with the stator's magnetic field, which drastically reduces rotor losses and enhances overall efficiency.

The dependence on rare-earth materials raises sustainability concerns. Efforts to develop alternative materials are ongoing, aiming to reduce reliance on critical raw materials. Typically, the neodymium (Nd) comprises around 1/3 of the weight of an NdFeB alloy, while iron (Fe) makes up 2/3. Other elements such as Boron (B), Aluminium (Al), Niobium (Nb) or Dysprosium (Dy) (added to increase maximum temperature range[33]) normally make up around 2% of the weight.[30] [34] [35]

4.2.3 Synchronous Reluctance Motors

Synchronous Reluctance Motors (SynRM) are characterized by their simplicity and robust design, lacking permanent magnets and relying on magnetic reluctance for torque generation. These motors operate at synchronous speed, effectively eliminating rotor losses and achieving high efficiency levels, often exceeding IE5. Their construction involves laminated magnetic materials with salient poles, which are optimized for low reluctance. This design yields good power density and cost-effectiveness compared to high-efficiency IEMs. Additionally, SynRMs demonstrate improved efficiency at part-load conditions, making them suitable for various applications, including pumps and fans. While they require an electronic controller for variable speed operation, their straightforward design enhances reliability and performance in harsh environments.[30] [34][34] [32]

4.2.4 Axial Flux Motors

Axial Flux Motors are distinguished by their unique design, where magnetic flux flows parallel to the rotation axis, resulting in a compact and lightweight configuration. These motors consist of disk-shaped stators and rotors, allowing for stacking multiple disks to enhance torque and power density without increasing motor width. The unidirectional magnetic flux path reduces iron losses, while the absence of overhang in windings maximizes active copper use, minimizing heat generation. Axial Flux Motors' design also facilitates better cooling and higher efficiency due to their shorter magnetic paths. These features make them ideal for applications requiring high power density and reliability, such as electric vehicles and industrial machinery. Ongoing developments aim to further optimize their performance and integrate them into modern systems (Falter, 2023; Hao et al., 2022).[30] [36] [37]

4.2.5 Variable Speed Drives

A Variable Speed Drive (VSD) is an electronic system that controls the motor shaft speed by varying the frequency and voltage applied to the stator windings, allowing for efficient matching of motor output to load requirements. VSDs are crucial for energy efficiency, as they enable significant energy savings by adjusting motor performance to varying operational demands, rather than relying on mechanical adjustments like throttling.

[33] Souza et al. (2025): Environmental impacts of electric motor technologies: Life cycle approach based on EuP Eco_report https://doi.org/10.1016/j.eiar.2024.107741

[34] Almeida, A. T., Ferreira, F. J., & Fong, J. (2023). Perspectives on Electric Motor Market Transformation for a Net Zero Carbon Economy. Energies, 16, 1298.

[35] Geng, Y., Sarkis, J., & Bleischwitz, R. (2023). How to build a circular for rare-earth elements. Nature, 619, 248¬251.

[36] Falter, M. (2023). Smaller, Lighter Axial Flux Electric Motor Extends EV Range.https://goinfinitum.com/smaller-lighter-axial-flux-electric-motor-extends-ev-range/

[37] Hao, Z., Ma, Y., Wang, P., Luo, G., & Chen, Y. (2022). A Review of Axial-Flux Permanent-Magnet Motors: Topological Structures, Design, Optimization and Control Techniques. Machines 2022, 10. doi: https://doi.org/10.3390/machines10121178

The current state of technology has seen advancements in power semiconductor materials, particularly with Wide Band Gap (WBG) materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN). These materials improve VSD performance by reducing switching and conduction losses by over 50%, enhancing overall efficiency. WBG devices allow for faster switching speeds, lower on-resistance, and higher voltage ratings, which contribute to better thermal management and power density in VSDs. These innovations enable VSDs to respond quickly to load changes, improving system performance and efficiency while also reducing mechanical wear and noise.[38]

Moreover, stakeholders have added that the current state of technology has seen advancements in power semiconductor materials, particularly with Wide Band Gap (WBG) materials such as Silicon Carbide and Gallium Nitride. These materials improve VSD performance by reducing switching and conduction losses by over 50%, enhancing overall efficiency. WBG devices allow for faster switching speeds, lower on-resistance, and higher voltage ratings, which contribute to better thermal management and power density in VSDs. These innovations enable VSDs to respond quickly to load changes, improving system performance and efficiency while also reducing mechanical wear and noise.

4.3. Trade-offs between material and research efficiency

There is an intricate relationship between material and energy efficiency which can lead to trade-offs between the two.

Due to the significant efficiency gains offered by new motors, the early replacement of inefficient motors is proposed as a strategy that can be environmentally beneficial over the lifetime of motors by reducing the use phase energy consumption, to-date the dominant environmental hotspot (see e.g. EU-MORE project). Although this may conflict with circular economy principles due to the additional material demand for new motors, the advantages of high-efficiency technologies outweigh their additional material costs and environmental impacts [39].

To balance efficiency with circularity, promoting energy efficiency alongside enhanced recycling rates is essential. This involves employing advanced technologies for motor disassembly and material recovery, aligning with the EU's circular economy and climate objectives.

While circularity and efficiency can appear as contrasting alternatives, they can also complement each other. For example, more efficient Synchronous Reluctance Motors (SynRMs), thanks to the reduced losses of SynRM technology, achieve winding temperatures that are up to 30°C lower and bearing temperatures that are up to 15°C lower. This enhancement boosts reliability, extends the motor's lifespan, and lessens maintenance requirements.

4.4. Recycling

Table 8 outlines some of the key components and their materials in electric motors and their importance for recycling.

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[38] https://www.iea-4e.org/wp-content/uploads/2025/03/4E-Policy-Brief-EMSA-8-PECTA-4-20250324.pdf

[39] Auer, J., & Meincke, A. (2018). Comparative life cycle assessment of electric motors with different efficiency classes: A deep dive into the trade-offs between the life cycle stages in an ecodesign context. International Journal of Life Cycle Assessment, 23(8), 1590-1608.

*Table 9 Materials in electric motors and their end-of-life importance (EU-MORE D2.4)**Error! Bookmark not defined.***

Component	**Material**	**Percentage in Motor**	**Importance in CE**
Housing	Cast iron, Aluminum	20-40%	High recyclability
Rotor & Stator	Electrical steel	40-60%	High recyclability
Windings	Copper	8-15%	Highly valuable in recycling
Magnets (PMSM motors)	Rare earth elements (REEs)	5-10%	Low recycling rates, high value

Notes:

1. The weight ranges account for variations in motor sizes and efficiency classes, based on EU-MORE and International Energy Agency data.

2. REEs are only present in PMSMs and not in other common motor types like Squirrel Cage Induction Motors (SCIMs) or Synchronous Reluctance Motors (SynRMs).

3. Percentages are approximate and based on average compositions observed across industrial and commercial motors.

More granular information is provided by motor manufacturer ABB (Table 10), who published end-of-life instructions for low voltage motors, both synchronous and induction, in which they included a component description and a recommendation on end-of-life treatment. While this can only be understood as one example, the manufacturer list does provide insights into motor design and recycling. It shows both the component complexity and the theoretical recommendations for recycling.

Table 10 End-of-life instructions for low voltage motors from manufacturer ABB[40]

Description	**Material**	**Comment**
End shields	Cast iron, aluminum, steel	Recyclable
Bearings	Steel, steel/rubber	Recyclable
Bearing covers	Cast iron, steel	Recyclable
Labyrinth discs	Cast iron, steel	Recyclable
V-rings3)	Rubber	Landfill/energy recovery
Wave springs	Steel	Recyclable
Retaining rings	Steel	Recyclable
Shaft seals	Cast iron	Recyclable
	Steel/rubber	Landfill/energy recovery
Terminal box	Cast iron, aluminum, steel	Recyclable
Terminal box cover	Cast iron, aluminum, steel	Recyclable
Cover gasket	Rubber	Landfill/energy recovery
Cable gland flange	Cast iron, steel, stainless	Recyclable
Terminal blocks, terminal	steel	Landfill/energy recovery
fasteners	Plastic, brass, steel	Recyclable
Terminal fittings, plugs	Brass, stainless steel,	Recyclable
Intermediate flange (nonEx)	Plastic	Landfill/energy recovery
Intermediate flange/	Steel/cast iron	Recyclable
cable bushing (Ex)	Steel, cast iron, resin	Recyclable, landfill

[40] ABB (2023):End-of-life instructions for low voltage motors https://library.e.abb.com/public/19a0c63e0ca34236b107b4776c2691d0/End-of-life%20instructions%20for%20Low%20voltage%20motors_09_2023.pdf

Fan cover	Steel, stainless steel, plastic	Recyclable Landfill/energy recovery
Fan	Plastic Aluminum, steel, stainless steel	Landfill/energy recovery Recyclable
Shaft, key	Steel, stainless steel	Recyclable
Rotor end plates	Steel, cast iron	Recyclable
Rotor core* *(see Table 2 for permanent magnet motors)	Electrical steel Aluminum (Not in SynRM or Permanent Magnet motors)	Recyclable Recyclable
Stator core	Electrical steel	Recyclable
Windings Cables	Copper, Copper & plastic/silicone rubber, resin	Recyclable, landfill Recyclable
Slot insulation	Polyimide film	Landfill/energy recovery
Stator housing	Cast iron/aluminum	Recyclable
Grease outlets	Stainless steel, steel, Rubber	Recyclable, Landfill/energy recovery
Drainage plugs	Plastic Stainless steel	Landfill/energy recovery Recyclable
Fasteners, vibration measurement & grease nipples	Steel, stainless steel	Recyclable

4.4.1 Current recycling practise

The recycling process includes collection, transport, sorting, and disassembly or shredding of machines, followed by metal extraction. Whether shredding or disassembly is chosen depends on the size and components of the machines.

During shredding, machines are cut into small pieces and sorted automatically or manually, which risks improper separation of materials. Nonferrous metals can be separated from iron using magnetic separation; however, even minor material contamination leads to quality loss, e.g., recycled iron has a copper content of 0.25–0.3%, while high-grade iron requires less than 0.02%.[53] Direct reuse of copper and aluminum is normally not feasible due to contamination, necessitating remelting.

Larger machines unsuitable for shredding are handled manually or with robots. [53]

Overall, the recovery process for electric motors achieves high rates for key materials. Under ideal conditions, copper and steel can achieve recovery efficiencies above 95%, while aluminum is slightly lower due to alloy variations. Rare earth metals from permanent magnet motors (PMMs) have the lowest recovery rates due to the complexity of separation. Table 11 shows indicatively reported figures for recovery rates of materials in electric motors.

Many EoL motors are currently discarded or sent to scrapyards. Not only valuable materials like copper and steel are lost there, but also some sources report that only 5% of REEs are recovered (see Table 6). Other reported figures for recovery of REEs are 65%.[41]

[41] https://eu-more.eu/wp-content/uploads/2025/04/D2.4-Analysis-End-of-Life-Practice-Electric-Motors-Final.pdf

Table 11 Different recovery rates of some of the key materials in electric motors (Source: EU More)[25]

Material	**Recovery Rate (%)**	**Challenges**
Copper	90-96	Energy-intensive to recycle, contamination from recycling
Steel	85-98	High recyclability, often contaminated, efficient sorting required
Aluminum	92	Alloy variations affect purity
Rare-earth elements	<5-65	Complex to separate, lack of recycling infrastructure

4.4.2 Permanent magnets and rare-earth elements

Particularly the recovery of rare earth elements (REEs), classified as strategic and critical raw materials by the EU, has gained heightened attention. Permanent Magnet Synchronous Motors (PMSMs) utilize REEs such as neodymium and dysprosium, which are vital for optimal motor performance but present significant environmental and geopolitical risks, alongside high costs.

The strategic necessity of recovering REEs is emphasized by the EU Regulation (EU) 2024/1252, which establishes a framework for securing a sustainable supply of critical raw materials. The regulation states that

> "*most permanent magnets, in particular the most performant types, contain critical raw materials, such as neodymium, praseodymium, dysprosium and terbium, boron, samarium, nickel or cobalt. Their recycling is possible but today only performed in the Union at a small scale or in the context of research projects. Permanent magnets should therefore be a priority product for increasing circularity, thereby fostering a secondary market for permanent magnets and ensuring security of supply of critical raw materials.*"

Indeed, in PMSMs, REEs can account for up to 60% of a motor's cost. These motors are essential for applications such as EVs, and wind generators, which are mostly out of scope for this study, but they are also used in high-performance industrial motor drives (e.g., high torque direct drive equipment and robotics).[42] The share of REEs costs in industrial applications may however be lower according to stakeholders.

In recycling, REEs are particularly challenging to recover due to the complex integration of the magnets within motor components and processing. In their end-of-life instructions for low voltage motors, ABB specifies the components of permanent magnet rotors (see Table 12).

Table 12 Components in permanent magnet rotors from manufacturer ABB[40]

Description	**Material**	**Comment**
Rotor lamination	Electrical steel	Recyclable
D-end endplate	Stainless steel	Recyclable
N-end endplate	Stainless steel	Recyclable
Stud bolts	Stainless steel	Recyclable
Stud bolts nuts	Stainless steel	Recyclable

[42] Li, Z., Hamidi, A.S., Yan, Z., et al. (2021f). A Circular Economy Approach for Recycling Electric Motors in End-of-Life Vehicles: A Literature Review. Resources, Conservation & Recycling, 205(107582).

Permanent magnets	Samarium cobalt or neodymium	Recyclable

Regarding the recycling process of permanent magnets, the manufacturer states that [40]

> *"Permanent magnets (PM) motors contain a rotor that is permanently magnetized by internal magnets. It is generally very difficult to remove the rotor due to high magnetic forces between the rotor and stator. This goes especially for larger motors. In general, removing of rotor is possible using mechanical assistance, but it involves a high safety risk and is not recommended. The base magnetized rotor tends also to pull metallic objects with high force which is another safety issue. In case there is a need to dismantle a PM motor, the entire motors should first be heat treated in an oven with minimum 300 C temperature for several hours. This will demagnetize the magnets after which the dismantling process can continue the normal way. As most of the organic components (glue, resin etc.) will vaporize at the mentioned temperature, special care must be taken to ventilation. Unventilated vapor can form an explosive mixture together with air."*

Currently, the costs associated with remanufacturing and recycling are prohibitively high, especially for smaller motors. The disassembly process is labor-intensive, and current technologies for material separation are not sufficiently advanced to make the recovery of materials like REEs economically viable. Furthermore, there is a notable lack of advanced automation technologies for disassembling electric motors and recovering valuable materials. Without significant investment in new technologies, the recycling and remanufacturing processes will remain labor-intensive, inefficient, and low in cost-effectiveness. [43]

Current efforts to enhance REE recovery are centered on developing improved motor design for easier separation and upgrading the infrastructure for motor disassembly and recycling. An example of a program trying to foster recycling is the electric vehicle motor recycling initiative. With the growing market for Electric Vehicles (EVs), such initiatives have been launched to recover and recycle rare earth elements from EV motors. By collaborating with motor manufacturers, recycling companies have enhanced their capacity to recover REEs, with the goal of establishing a closed-loop ecosystem for these essential materials.

Recyclers of PMMs gain NdFeB magnets mainly from end-of-life industrial motors used in various applications, including household appliances and small machinery[44]. The recycling process begins with the collection of these motors, which poses challenges due to complex waste streams and varying collection efficiencies[45].

Once collected, motors undergo disassembly to recover NdFeB magnets, but this can be difficult as magnets are often deeply embedded, making extraction challenging[46]. Additionally, the design of the motors affects disassembly efficiency; those designed for easier access yield

[43] Li, Z., Hamidi, A.S., Yan, Z., et al. (2021f). A Circular Economy Approach for Recycling Electric Motors in End-of-Life Vehicles: A Literature Review. Resources, Conservation 8< Recycling, 205(107582).

MA12 Presentation (2021f). California Energy Commission: Motor Systems and Circular Economy in Industry.

Danilo, F. de Souza, Silva, P.P.F., Sauer, I.L., Almeida, A.T. de, 8< Tatizawa, H. (2021f). Environmental impacts of electric motor technologies: Life cycle approach based on EuP Eco-Report. Journal of Cleaner Production, 1f56, 11f2366. https://doi.org/10.1016/j.jclepro.2021f.11f2366

International Energy Agency (IEA). (2021f). Recycling of Critical Minerals: Strategies to scale up recycling and urban mining.

[44] Environmental sustainability of NdFeB magnet recycling | Scholarly Publications

[45] Estimates of global REE recycling potentials from NdFeB magnet material - ScienceDirect

[46] Performance comparison of motors fitted with magnet-to-magnet recycled or conventionally manufactured sintered NdFeB - ScienceDirect

higher recovery rates[47]. Coatings further complicate the recycling process, especially if polymeric coatings as epoxy, as they must be removed before effective processing[48].

Recovered NdFeB magnets are processed through direct or indirect recycling routes. Direct recycling methods, such as hydrogen decrepitation, preserve magnetic properties with minimal losses, while indirect recycling involves chemical extraction of individual rare earth elements (REEs)[49]. However, indirect methods can be less economically viable and environmentally friendly due to the use of toxic chemicals and high energy inputs[50]. In some lab-based studies, the recovery of REEs during recycling is 90% or better. This means, the total amount of virgin rare-earth material used in the process is less than 5%[51]. If scaled-up, another study suggests that 18-22% of the global demand for light REE (such as neodymium) used in magnets of PMMs could be met through recycled NdFeB[52].

4.4.3 Barriers

Recycling electric motors poses numerous technical and economic challenges. While recovering metals such as copper, steel, and aluminum is more straightforward, the extraction of Rare Earth Elements (REEs) is more complicated and necessitates specialized facilities (see 4.4.2). Additionally, many Member States lack the infrastructure required for efficient motor recycling, leading to inconsistent resource recovery rates throughout the EU.

Economic considerations significantly influence end-of-life (EoL) motor management practices in the EU. A considerable number of EoL motors are exported to non-EU countries for recycling due to lower labor and processing costs. This practice results in resource loss and escalates environmental costs related to transportation.

Currently, many EoL motors are discarded or sent to scrapyards, leading to the waste of valuable materials like copper, steel, and REEs. Globally, less than 5% of REEs are recovered, despite their essential role in various modern clean energy technologies.

Although progress has been made, challenges persist in scaling these practices across the EU. High costs associated with removing impurities, such as heat treatment for copper windings and additional sorting processes, impede economic viability. Addressing these challenges through policy support and technological innovation is vital for advancing the recycling ecosystem[25].

Electrical steel is an iron alloy that contains added silicon to reduce conductivity, thereby decreasing hysteresis losses. Typically, the silicon content is capped at a maximum of 3.2%, as higher concentrations can cause brittleness[53]. However, silicon acts as a contaminant,

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[47] Estimates of global REE recycling potentials from NdFeB magnet material - ScienceDirect

[48] Performance comparison of motors fitted with magnet-to-magnet recycled or conventionally manufactured sintered NdFeB - ScienceDirect

[49] Estimates of global REE recycling potentials from NdFeB magnet material - ScienceDirect

[50] Environmental sustainability of NdFeB magnet recycling | Scholarly Publications

[51] Comparative Life Cycle Assessment of NdFeB Magnets: Virgin Production versus Magnet-to-Magnet Recycling

[52] Estimates of global REE recycling potentials from NdFeB magnet material - ScienceDirect

[53] Rassolkin et al. (2020): Life cycle analysis of electrical motor-drive system based on electrical machine type. In: Proceedings of the Estonian Academy of Sciences.

meaning that only small amounts of electrical steel can be included in each melting batch without affecting the overall process [54].

Challenges regarding the recyclability of electric motors, specifically to recycle permanent magnets include:

- Complexity of waste streams and varying collection efficiencies
- Difficulties in disassembling motors, as magnets are often deeply embedded
- Inefficient disassembly due to motor designs that hinder access
- Need to remove coatings (e.g., nickel, epoxy) before processing the magnets
- High costs and environmental impacts associated with indirect recycling methods due to the use of toxic chemicals and high energy input
- Insufficient collection and recycling infrastructure for EoL motors
- Loss of materials during collection, disassembly, and recycling processes
- Lack of reliable data on the composition of NdFeB in various applications
- Ineffective application of recycling technologies due to variability in magnet composition

4.4.4 Other circular economy strategies

Despite recycling, different circular economy strategies are perceivable for electric motors, some of which shall be presented hereafter.

Reuse
Reuse involves extending the operational life of motors through minor repairs, such as bearing replacements, and redeploying them in less demanding applications. This straightforward circular economy strategy reduces the demand for new motors and prolongs the service life of existing units. However, careful consideration is needed when deciding to retain an old motor and its associated system, as the disadvantages may often outweigh the benefits in terms of energy consumption and environmental impact.[55]

An example of an initiative fostering reuse is the European industrial motor reuse program. This initiative focuses on collecting, testing, and refurbishing motors from industrial applications, aiming to significantly extending their operational life and reducing the need for new motor production[56].

[54] Hernandez-Millán, R. and Pacheco-Pimentel, J.R. (2017): Recycling rotating electrical machines. https://doi.org/10.17533/udea.redin.n83a07

[55] Tiwari, D., Miscandlon, J., Tiwari, A., 8< Jewell, G.W. (2021). A Review of Circular Economy Research for Electric Motors and the Role of Industry 4.0 Technologies. Sustainability, 13(9668).

[56] EU-MORE Project Team. (2021f). Case Studies on Motor Reuse and Recycling: EU-MORE Circular Economy Initiative.

There are scientific case studies that describe the direct reuse of rare earth permanent magnets in wind turbine generators.[57]

Newly introduced standards, such as stricter substance limits (e.g. RoHs), can sometimes create a conflict between reusing motors to achieve circular economy goals and still complying with updated regulations, according to stakeholders.

Refurbishment
Refurbishment is a process where motors are inspected, cleaned, and repaired to restore them to its full functionality. Refurbished motors often have shorter warranties than new ones but can provide years of additional service at a fraction of the cost of a new motor. Refurbishment may for instance include rewinding to restore its functionality but without achieving a like-new condition.

Remanufacturing
Remanufacturing involves the complete disassembly of a motor, followed by cleaning, replacement of worn components, and reassembling it to like-new condition. This strategy is particularly valuable for large, expensive motors used in industrial applications, as remanufactured motors can offer performance comparable to new ones at a lower cost.

4.5. Digitalisation

Variable Speed Drives (VSDs) play a crucial role in optimizing motor efficiency by adjusting motor speed to match load requirements. By increasing performance and avoiding overdimensioning of motors, materials can be effectively reduced.

But also in the field of circular economy, digital technologies can lead to improvements through concepts such as predictive maintenance or automated disassembly. The emergence of Industry 4.0 technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), and automation, offers significant potential for enhancing end-of-life practices in the electric motor industry. IoT-enabled sensors facilitate real-time monitoring of motor performance, enabling predictive maintenance that can extend motor lifespan by identifying issues like overheating or excessive wear before they escalate, thereby reducing downtime and premature replacements. Additionally, advancements in motor design and automation technologies, including robotics and AI, can streamline the disassembly of electric motors, leading to more efficient material recovery and lower labor costs.

Industry 4.0 also opens up substantial opportunities for remanufacturing through smart lifecycle data for design and end-of-life management, cost-effective and sustainable manufacturing operations, and successful remanufacturing business models. Key technological enablers include smart sensors, cloud computing, robotics, machine-to-machine communication (M2M), and additive manufacturing. [58] [59] [60]

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[57] Hogberg et al. (2016): Direct reuse of rare earth magnets – Wind turbine generator case study. In Proceedings of the XXII International Conference on Electrical Machines (ICEM), September 4–7, 2016, Lausanne, Switzerland. IEEE, 2016, 1625–162

[58] Tiwari, D., Miscandlon, J., Tiwari, A., 8< Jewell, G.W. (2021). A Review of Circular Economy Research for Electric Motors and the Role of Industry 4.0 Technologies. Sustainability, 13(9668).

[59] Yang, S., Raghavendra, A. M. R., Kaminski, J., & Pepin, H. (2018). Opportunities for Industry 1f.0 to support remanufacturing. Applied Sciences, 8(7), 1177.

[60] International Energy Agency (IEA). (2021f). Recycling of Critical Minerals: Strategies to scale up recycling and urban mining.

5. MEErP Task 5, Environment and Economics

5.1. Bill-of-materials for base cases

In the review study of motors, nine representative models will be developed for analysis as base cases (BC) (subject to change):

- BC1: IE4 IEM, 4 kW
- BC2: IE4 PMSM, 4 kW
- BC3: IE4 SynRM, 4 kW
- **BC4: IE4 IEM, 55 kW**
- **BC5: IE4 PMSM, 55 kW**
- BC6: IE4 SynRM, 55 kW
- BC7: IE4 IEM, 200 kW
- BC8: IE4 PMSM, 200 kW
- BC9: IE4 SynRM, 200 kW

For the CRM and Recycled Content analysis, the team selected two of the six base case models for closer analysis:

- BC4: IE4 IEM, 55 kW and
- BC5: IE4 PMSM, 55 kW.

According to the Review Study, the aggregated Bill of Materials are as follows:

Table 13: Bill of Materials for base case 4, an IEM, 55 kW, IE4 and corresponding entries in the EcoReport-Tool

(BC4)	Weight (grams)	Material category	Virgin material dataset	Recycled material dataset	R1	R2	A
Rotor and stator core	239,7	Metals	302-Grain oriented electrical steel	303-Recycled Grain oriented electrical steel	30%	85%	20%
Rotor cage	18,6	Metals	52-Aluminium ingot mix (high purity) primary production, aluminium casting single route, at plant 2.7 g/cm3, >99% Al	123-Recycling of aluminium into aluminium ingot - from post-consumer collection, transport, pretreatment, remelting production mix, at plant aluminium waste, efficiency 90%	30%	85%	20%
Stator winding	55,8	Metals	61-Copper Concentrate (Mining, mix technologies); copper ore	124-Recycling of copper from clean scrap; collection, transport,	37%	74%	20%

			mining and processing; single route, at plant; Copper - gold - silver - concentrate (28% Cu; 22.3 Au gpt; 37.3 Ag gpt)	pretreatment; production mix, at plant; copper content in input scrap 90%, copper losses 1%			
Housing (frame, end shields)	168,2	Metals	300-Cast iron	301-Recycled Cast iron	30%	76%	20%
Shaft, Bearings	49,1	Metals	87-*Steel cold rolled coil blast furnace route single route, at plant carbon steel	126-Secondary steel slab electric arc furnace route, from steel scrap, secondary production single route, at plant carbon steel	30%	85%	20%
Impregnation resin	2,8	Plastics	4-Epoxy plastic polymerisation of liquid epoxy resins with a latent hardener (amine) production mix, at plant petrochemical based	not available	0%	0%	50%
Insulation	2,2	Plastics	2-Aramid fibre low-temperature solution polymerisation of m-phenylene diamine with isophthaloyl chloride production mix, at plant petrochemical based	40-*Recycling of post-consumer waste polypropylene (PP) collection, sorting, transport, washing, granulation, pelletization production mix, at plant 48,9% recycling rate	0%	0%	50%
Paint	2,2	Other			0%	0%	50%

Table 14: Bill of Materials for base case 5, an IE4 PMSM, 55 kW Motor and corresponding entries in the EcoReport-Tool

(BC 5)	**Weight (kg)**	**Material category**	**Virgin material dataset**	**Recycled material dataset**	**R1**	**R2**	**A**
Rotor and stator core	119,0	Metals	302-Grain oriented electrical steel	303-Recycled Grain oriented electrical steel	30%	85%	20%
Permanent magnet	6,2	Metals	304 - Rare earth	305 – Recycled rare earth	0%	0%	20%
Stator winding	38,6	Metals	61-Copper Concentrate	124-Recycling of copper from clean	37%	74%	20%

			(Mining, mix technologies); copper ore mining and processing; single route, at plant; Copper - gold - silver - concentrate (28% Cu; 22.3 Au gpt; 37.3 Ag gpt)	scrap; collection, transport, pretreatment; production mix, at plant; copper content in input scrap 90%, copper losses 1%			
Housing (frame, end shields)	91,2	Metals	300-Cast iron	301-Recycled Cast iron	30%	76%	20%
Shaft, Bearings	20,9	Metals	87-*Steel cold rolled coil blast furnace route single route, at plant carbon steel	126-Secondary steel slab electric arc furnace route, from steel scrap, secondary production single route, at plant carbon steel	30%	85%	20%
Impregnation resin	1,7	Plastics	4-Epoxy plastic polymerisation of liquid epoxy resins with a latent hardener (amine) production mix, at plant petrochemical based	not available	0%	0%	50%
Insulation	1,1	Plastics	2-Aramid fibre low-temperature solution polymerisation of m-phenylene diamine with isophthaloyl chloride production mix, at plant petrochemical based	40-*Recycling of post-consumer waste polypropylene (PP) collection, sorting, transport, washing, granulation, palletisation production mix, at plant 48,9% recycling rate	0%	0%	50%
Paint	1,1	Other			0%	0%	50%

As shown in Table 9 and Table 10 the BOMs of the base cases are similar with regard to most components, but differ in their total weights which are ranging from 280 kg and 540 kg (excluding packaging material).

5.2. Recycling parameters for the EcoReport-Tool

5.2.1 Simplified Circular Footprint Formula

The 2024 EcoReport-Tool (ERT) calculates the environmental impacts of raw materials, excluding the end-of- life (EoL) phase, using a simplified version of the Circular Footprint Formula (CFF) [61] [62]:

(1-R1) x Ev + R1 x (A x Erec + (1-A) x Ev).

The impacts at end-of-life due to material recycling are computed from:

(1-A) x R2 x Erec.

The benefits at end-of-life due to material recycling (avoidance of virgin material use) are computed from:

For non-electronics: - (1-A) x R2 x Ev

For electronics: - CF x Amount x (1-A) x R2 x SUM (Credits for Cu, Au, Pd, Pt, Ag)

where:

Ev the virgin material impact for the environmental parameter, computed as the total input material mass (kg) multiplied by the unit impact for the applicable virgin material dataset for the environmental parameter (impact/kg).

Erec the recycled material impact for the environmental parameter, computed as the total input material mass (kg) multiplied by the unit impact for the applicable recycled material dataset for the environmental parameter (impact/kg).

R1 (recycled content): the proportion of material in input to the production that has been recycled from a previous system

R2 (recycling output rate): the proportion of the material in the product that will be recycled in a subsequent system. R2 considers the efficiencies in the collection and recycling processes. R2 shall be measured at the output of the recycling plant.

A the allocation factor of burdens and credits between supplier and user of recycled materials. The “A” factor in the CFF allows to allocate impacts and/or benefits between the use of recycled materials as input (i.e. recycled content) and recycling at the end-of-life (i.e. recycling output rate). It avoids potential double counting due to recycled materials being subsequently used in other products, or vice versa [63].

[61] MEErp _Ecoreport tool_v1.7.xlsxcEuropean Commission, Joint Research Centre, Eynard, U., Ardente, F., Gama Caldas, M., Spiliotopoulos, C. and Mathieux, F., Ecoreport tool - Manual, Publications Office of the European Union, Luxembourg, 2024,chttps://data.europa.eu/doi/10.2760/473257, JRC133597.

[62] The ERT does not consider the impacts from incineration (with or without heat recovery), nor of landfilling, fugitive, or missing masses at EoL.

[63] If R1=R2 (e.g. all recycled material coming from a washing machine is reused for a washing machine)

- R1 x A x Erec is counted in raw material input impacts
  (1-A) x R2 x Erec is counted as EoL impact
  Hence, if R1=R2, the entire Erec (impact from recycled materials) is counted.
- (1 - R1 x A) x Ev is counted in raw material input impacts
  -(1 - A) x R2 x Ev is counted as EoL benefit (avoided virgin materials)
  Hence, if R1=R2, (1-R1) x Ev (impact from virgin materials) is counted.

5.2.2 Allocation factor A

The current study uses the default values for allocation factor A, which are 20% for metals and 50% for all other material types. Hence, for recycling of metals, only 20% of the benefits are assigned to the production phase, and 80% to the EoL phase.

5.2.3 Factor R1, recycled content

- **Metals**

For BC4, metals are the heaviest overall material group in the product, constituting 98,7% or about 531,4 kilograms of the total mass of the motors. Of these, steel is the most common metal, with 288,8 kg. Cast iron is the second most common at 168,2 kilograms of total mass of metals. Next is copper, at 55,8 kilograms.

For the BC5, metals are also the heaviest overall material group in the product, constituting 98,6% or about 279,7 kilograms of the total mass of the motors. Of these, steel is the most common metal, with 139,9 kg. Cast iron is the second most common at 91,2 kilograms of total mass of metals. Next is copper, at 38,6 kilograms.

For aluminium, the default for R1 (recycled content) in the ERT is 30%. For copper and steel, the default in ERT is 0%. The reason for this difference is unknown. Eurostat[64] however provides data for the contribution of recycled materials to raw materials demand, e.g. end-of-life recycling input rates. An IAI Factsheet also confirms that 30% has also been used for steel.

For steel the recycled content of the baseline is therefore adapted to R1 = 30%. It must be noted, that for stainless steel produced in Europe up to 80% of recycled material can be used according to a major European stainless steel producer[65].

Table 15: End-of-life recycling input rates (source: Eurostat cei_srm010)

	Eurostat estimate for 2013	**Eurostat estimate for 2016**	**Eurostat estimate for 2019**	**Eurostat estimate for 2022**	**EcoReport - Tool v.1.7 default values**
Aluminium	35%	12%	12%	32%	30%
Copper	20%	55%	17%	55%	0%
Iron	22%	24%	32%	31%	0%

As already mentioned in Table 11, high recovery rates are an established practice already. The 2024 Factsheet on copper recycling from an industry association (Kupferverband) [66] supports the assumption of higher recycled content rates. The factsheet states, that on average, copper products worldwide contain more than 30 percent recycled content. The share of recycled materials in copper production (classic recycling rate) is around 40 percent

[64] Eurostat online database, accessed January 2025.

[65] One Aperam: Four Segments, One Vision - aperam

[66] https://kupfer.de/wp-content/uploads/2024/10/2024_Factsheet_Recycling_EN.pdf

in Europe, significantly higher than the global average. The value of 37% has been used in the analyses (R1 = 37%).

For all other materials, no default is available in the ERT. For the materials impregnation, insulation and paint (see Table 13 and Table 14), the study therefore used R1=0%.

5.2.4 Factor R2, recycling output

The ERT specifies that the value for R2 (recycling output rate) shall take into account the efficiencies in the collection and recycling processes. The default values incorporated into the ERT were also partly adjusted for this analysis of motors.

For aluminium and steel, the ERT gives a default value for R2 of 85%. For cast iron no dataset with default values was available. It was therefore assumed that 98% of the collected mass is recycled (R2=78%*98%=76%). For copper, the ERT gives a default value for R2 of 0%, which is too pessimistic as Table 11 indicates. Based on EURIC's metal recycling fact sheet and other sources, it is assumed that 95% of the collected mass is recycled (R2=78%*95%=74%). The factsheet states that 70% of copper in EoL products is recycled and 90% of copper in civil infrastructure is recycled[67].

5.3. Mass distribution for the baseline

Figure 1 shows the distribution of masses over all the material types for BC4 and BC5, based on the bill of materials presented in section 5.1.

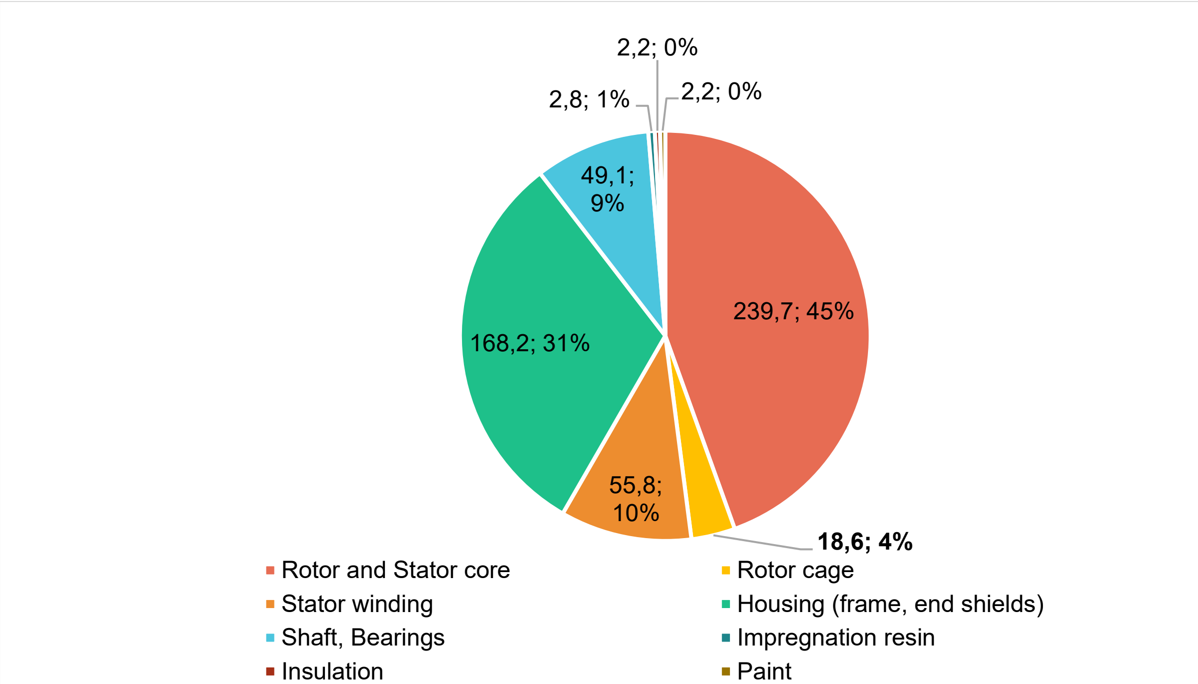

Figure 1: BC4: Mass distribution per components? for SCIM IE4 55kW

[67] euric_metal_recycling_factsheet.pdf

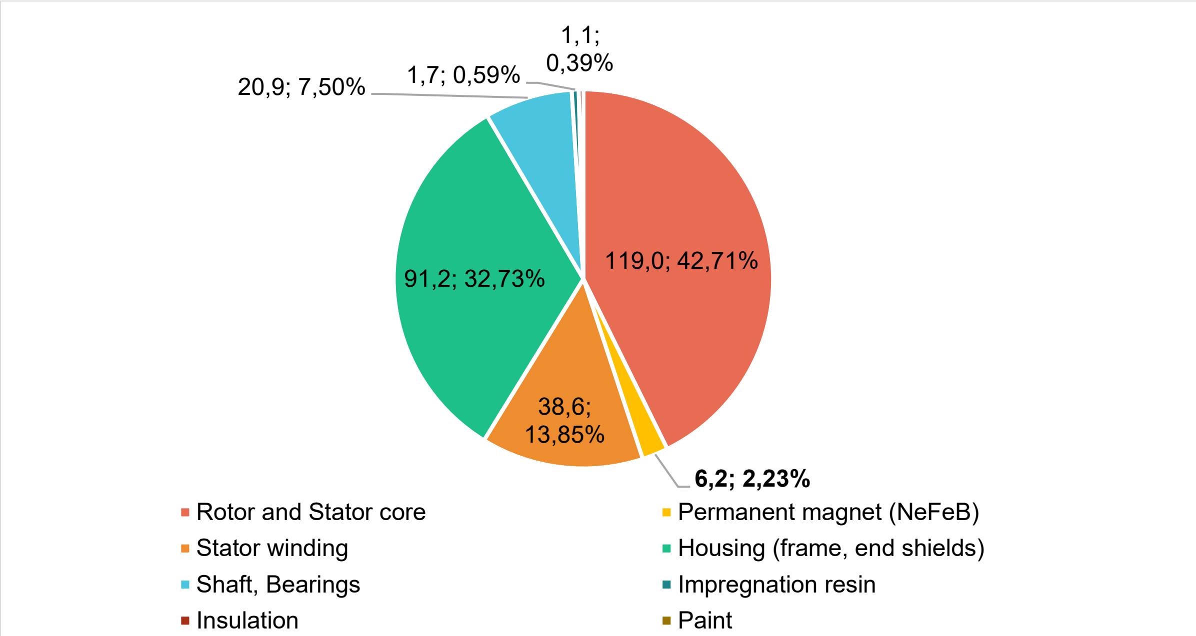

Figure 2: BC5: Mass distribution per components? for PM IE4 55 kW

As can be taken from the figures above, PMMs and IEMs can be mainly differentiated by the rotor cage, which appears in IEMs made for example from aluminium, while PMMs have permanent magnets instead. In general, the rotor and stator core take up more than 40% of the mass in both cases, while housing takes up more than 30%. Remaining materials take up a similar share in both motors.

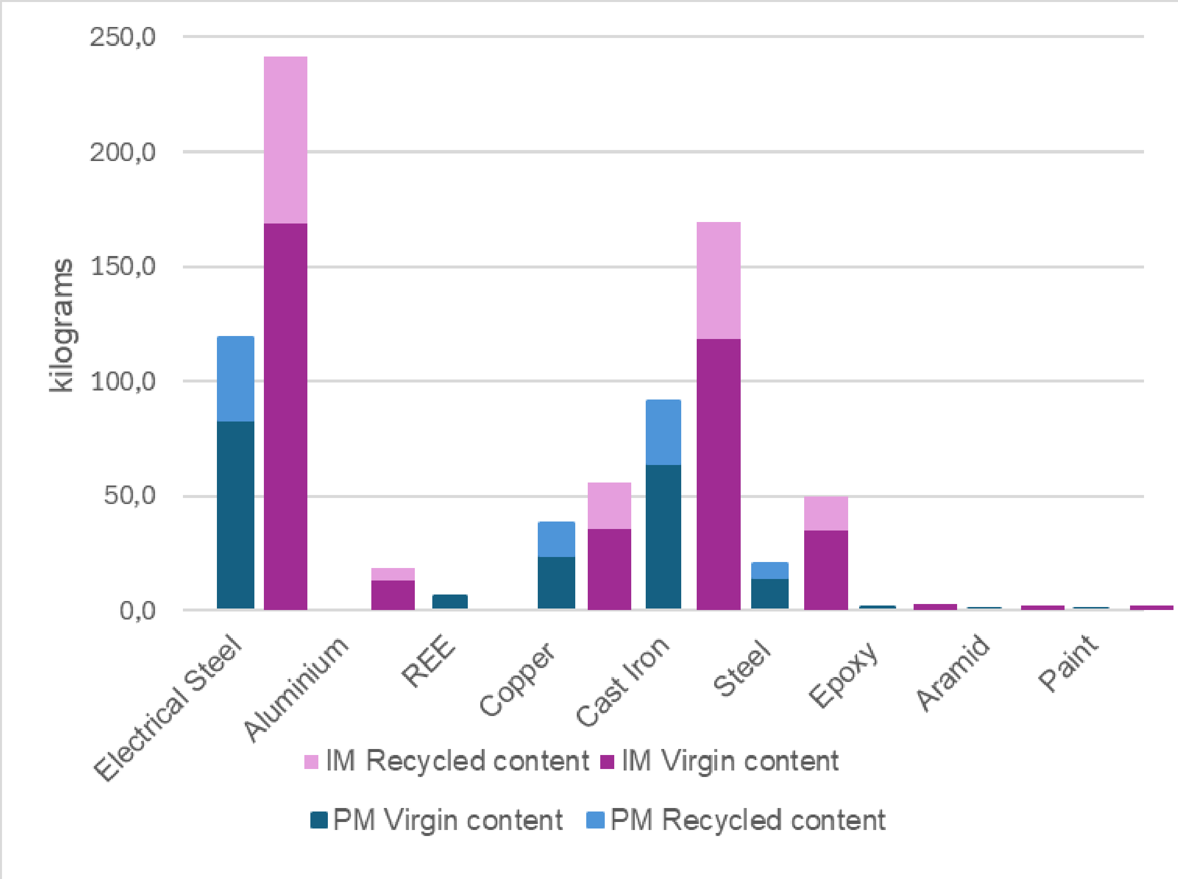

Figure 3: Virgin and recycled material in input for BC4 (pink) and BC 5 (blue)

Figure 3 shows the share of virgin and recycled content (R1 value) which is assumed for IEMs (BC4) and PMM (BC5). Apart from the difference in weight, it shows how the share of recycled content is comparable, with aluminium in IEMs as an exception, which has a recycled content share of 30%, while REE in the PMM does not contain recycled content in the baseline.

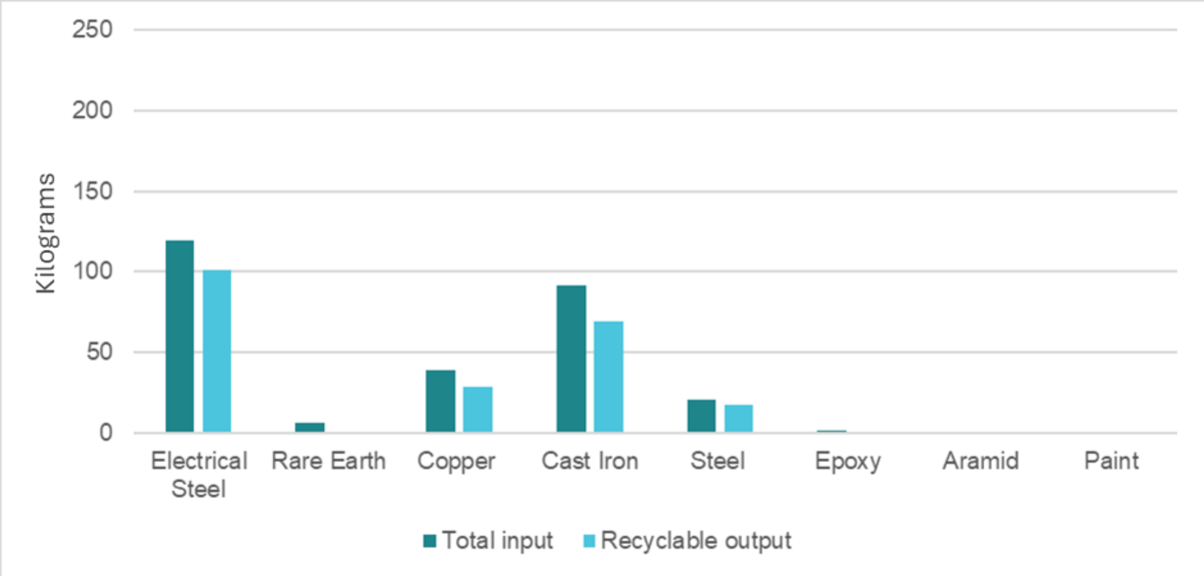

Figure 4: PM IE4 55 kW

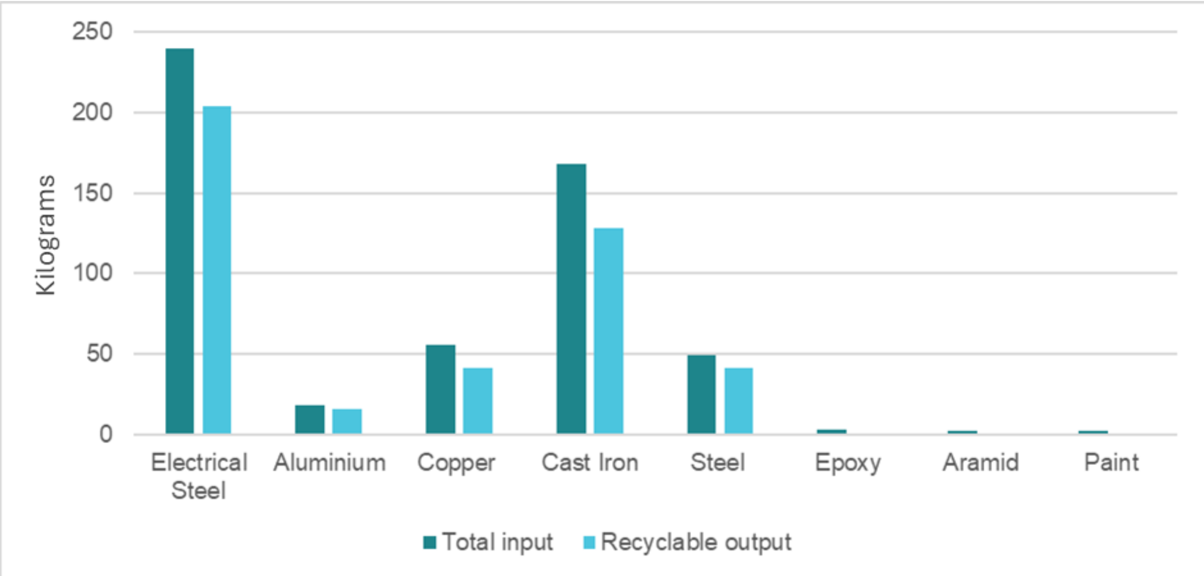

Figure 5: SCIM IE4 55 kW

Figure 4 and Figure 5 show the recyclability (R1) for IEM (BC4) and PMM (BC5) by illustrating the amount of recyclable output that would be recyclable after the use phase of the respective motor. It can be taken from the figures, that steel and iron would contribute the strongest to a recyclable output in absolute numbers.

5.1. Use phase assumptions for the baseline

Estimates of product lifetime and power consumption and operating hours are in line with previous impact assessments. Using those estimates, the total electricity consumption over the lifetime of the product was estimated in order to compare the environmental footprint of the materials used in the product with the energy in use phase.

Table 16: Service life, power consumption and operating hours for base case motor (IE4)

Modelling input estimations	**0.75kW – 7,5 kW (BC 1 - 3)**	**7,5kW – 75 kW (BC 4 - 6)**	**75 kw – 375 kW (BC 7 - 9)**
Product (service) life in years	9	11	16
Power for BC (kW)	4	55	200
Conversion Efficiency (%)	87,2%	93,3%	96,3%
On-mode power consumption (kW)	0,59	3,9	6,19
On-mode number of hours per year	2.800	3.500	7.000
Total energy consumption (MWh)	14,79	152,35	691,45

Given the inputs in the ERT is used to estimate the environmental impacts of the materials and end-of-life (including impacts and credits), comparing this to the environmental impacts of the use phase energy consumption, assuming an average EU electricity mix. The figures below present the results for the base case (for R1=37% for copper as well as R1=0% and R2=0% for REE) scenario. The yellow shaded portions of the environmental impact represent the impact from energy-in-use and the orange shaded portions represent the impact from the materials and end-of-life treatment. These impacts are over the whole lifetime of the motors from the estimates in the table above (11 years for BC 4 and 5 as part of the medium sized motor category in the power range of 7,5-75 kW).

Figure 6 shows the environmental impacts for the IEM, comparing materials and end-of-life treatment with energy-in-use. For almost all indicators, energy-in-use dominates.

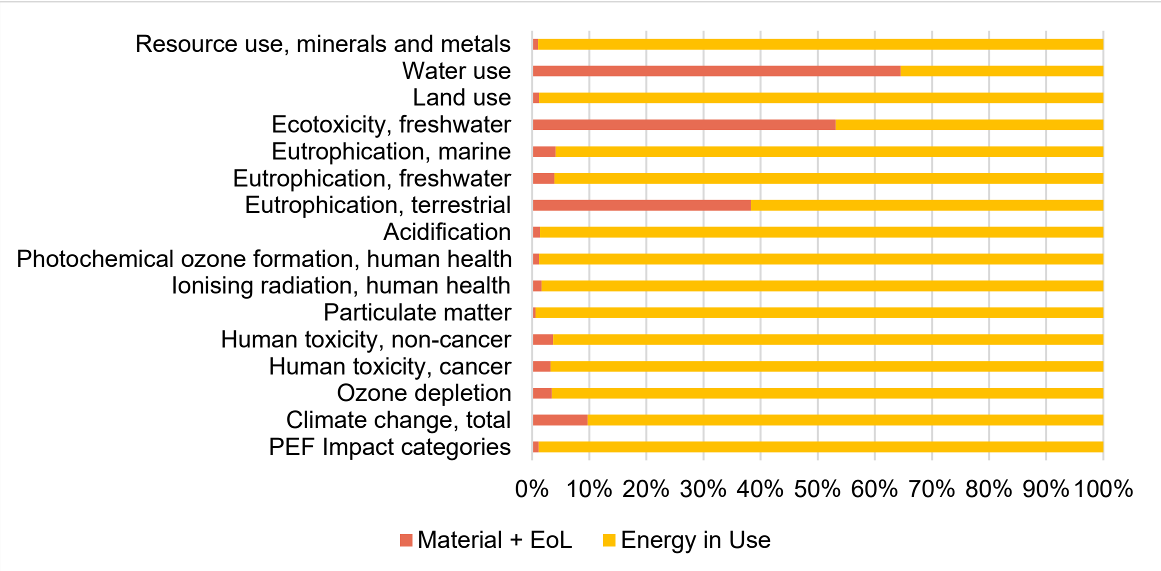

Figure 6: Environmental impacts comparison for materials and end-of-life and energy-in-use for the basecase

IEM (BC4)

For the PMM, the same overview was calculated and a very similar result was found. A large majority of environmental impact indicators are dominated by the energy-in-use.

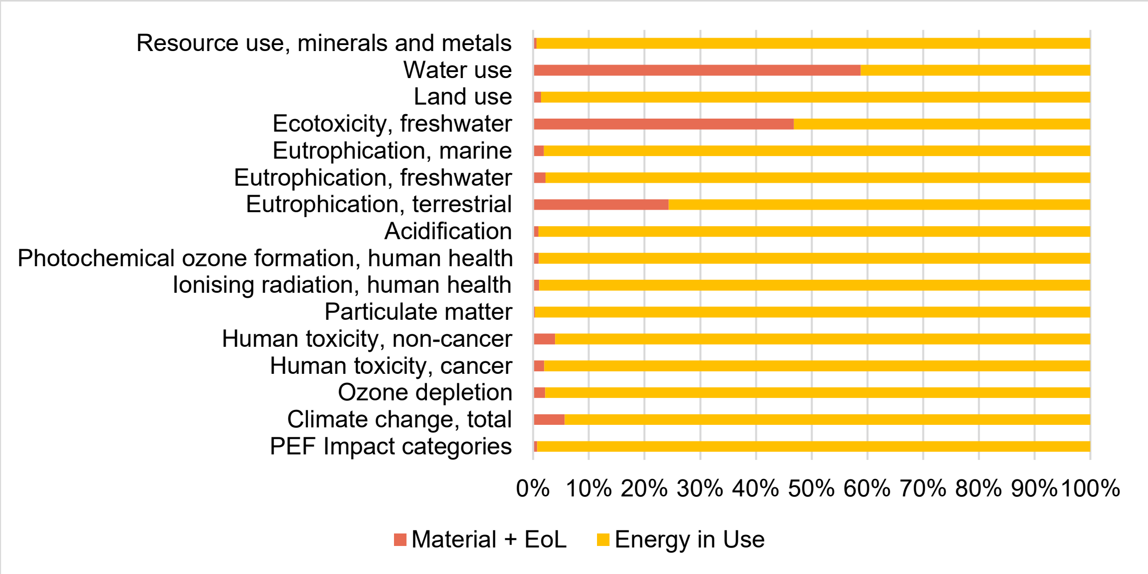

Figure 7: Environmental impacts comparison for materials and end-of-life and energy-in-use for the basecase PMM (BC5)

5.2. Environmental impacts for the baseline models

While Figure 6 and Figure 7 emphasize the high relevance of the use phase for the total impact of the two base cases, it is important to also assess the environmental impacts more closely on a material level. Data for the assessed impact categories were taken from the database of the ERT and where necessary complemented with data from ecoinvent. As illustrated in Figure 8 and Figure 9, different materials have varying influences on specific impact categories. For example, electrical steel[68] largely influences freshwater Eutrophication, while Copper has a strong land use impact.

[68] While electrical steel is environmentally relevant, this study focuses on CRMs in electric motors, while electrical steel is currently assessed in a parallel study.

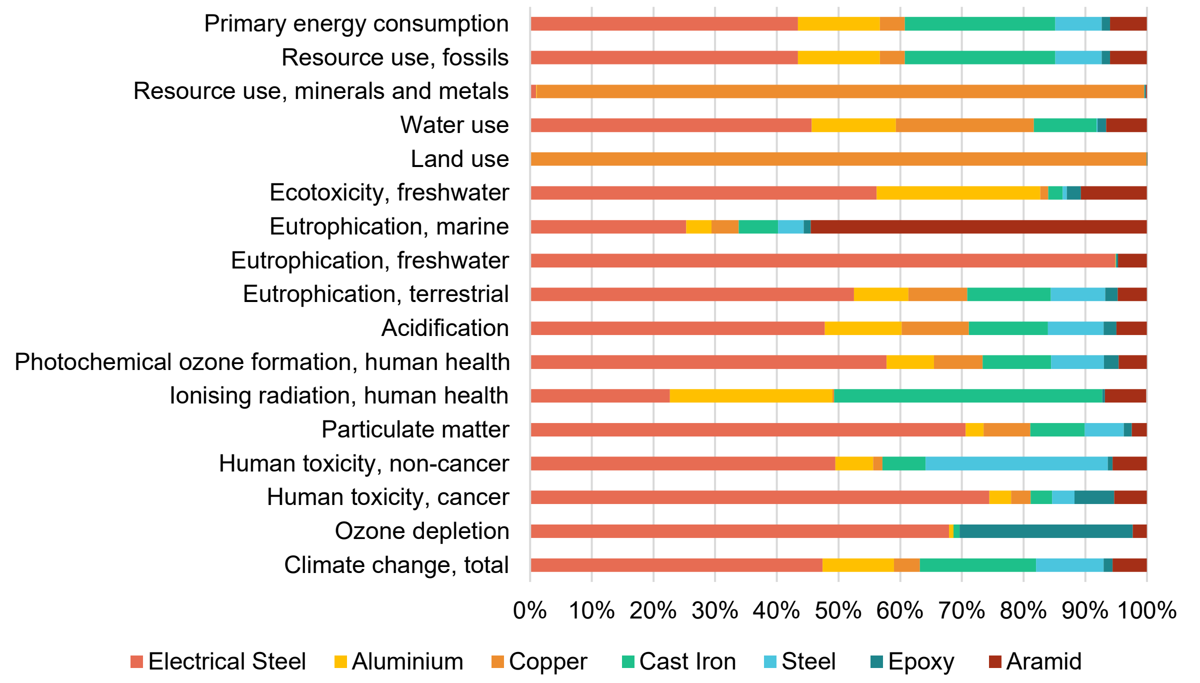

Figure 8: Shares of environmental impacts by material category, for BC4 SCIM IE4 55 kW

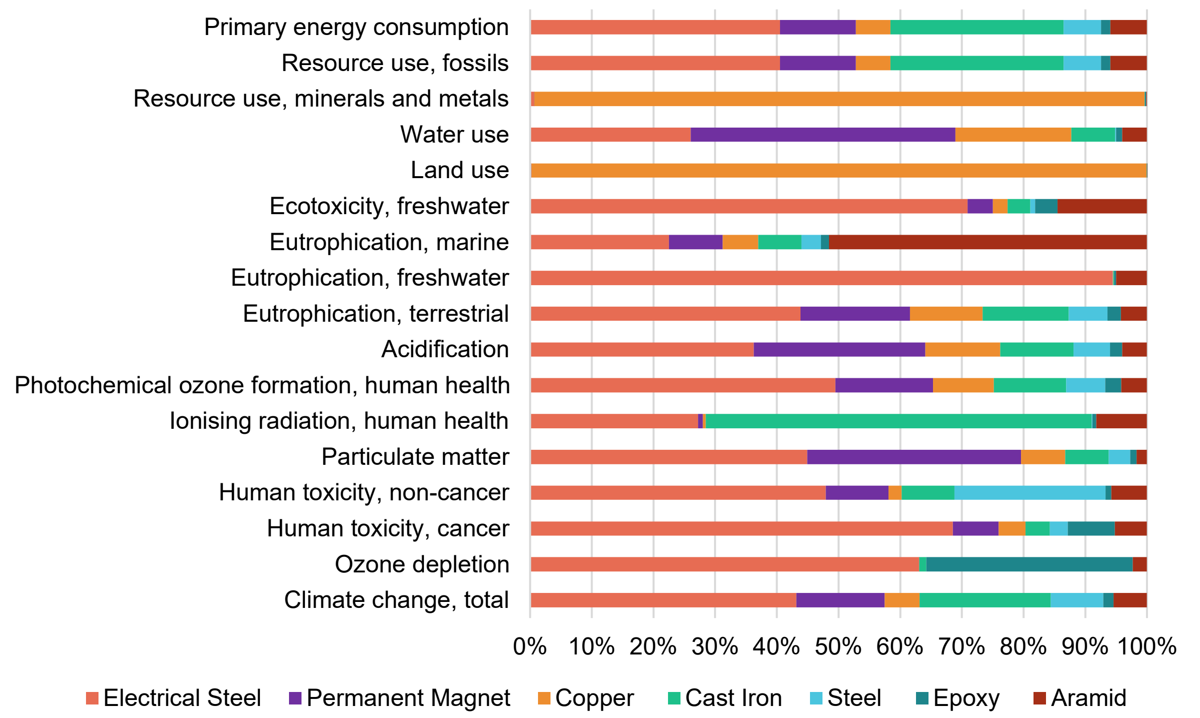

Figure 9: Shares of environmental impacts by material category, for BC5 PM IE4 55 kW

The PMM values show, that Particulate matter, Acidification and water use are impact categories that are influenced by the permanent magnet more strongly than compared to the aluminium in IEMs. In contrast, ionising radiation and freshwater Ecotoxicity are impact categories that depend more on the aluminium content.

To provide more detail (i.e., with absolute values in the relevant units) on these impacts, the results are presented in tabular form below with the percentages of impact directly underneath the values. Due to the number of environmental indicators, the results are divided into two parts. The first part gives the mass and the impacts for the first 8 environmental parameters; the second part gives the impacts for the remaining 8 parameters. Table 11 shows the total impacts, i.e. the sum of raw material impact, EoL impact and EoL credit for virgin material avoidance (negative impact), and the impact shares, per material category. Impact shares larger than 50% have been highlighted in bold.

Table 17: Reference Environmental impacts for a PM IE4 55kW (BC5), computed using 2024 ERT, including impacts from raw materials and end-of-life impacts and benefits

Material	**Climate change, total**	**Ozone depletion**	**Human toxicity, cancer**	**Human toxicity, non-cancer**	**Particulate matter**	**Ionising radiation, human health**	**Photochemical ozone formation, human health**	**Acidification**
Units	Kg CO2 eq	*kg CFC-11 eq*	*CTUh*	*CTUh*	*disease incidence*	*kBq U235 eq*	*kg NMVOC eq*	*mol H+ eq*
Electrical Steel	2,57E+02	1,61E-06	3,21E-07	3,89E-06	5,38E-05	1,56E+01	8,16E-01	9,11E-01
share	43%	**63%**	**69%**	48%	45%	27%	49%	36%
Permanent Magnet	8,52E+01	2,33E-11	3,46E-08	8,23E-07	4,15E-05	4,38E-01	2,61E-01	6,99E-01
share	14%	0%	7%	10%	35%	1%	16%	28%
Copper	3,37E+01	2,15E-10	2,05E-08	1,72E-07	8,55E-06	2,49E-01	1,63E-01	3,05E-01
share	6%	0%	4%	2%	7%	0%	10%	12%
Cast iron	1,27E+02	2,94E-08	1,86E-08	6,98E-07	8,49E-06	3,58E+01	1,94E-01	2,99E-01
share	21%	1%	4%	9%	7%	63%	12%	12%
Steel	5,09E+01	-9,25E-11	1,36E-08	1,99E-06	4,17E-06	5,11E-02	1,04E-01	1,48E-01
share	9%	0%	3%	24%	3%	0%	6%	6%
Epoxy	9,85E+00	8,56E-07	3,57E-08	7,82E-08	1,23E-06	3,51E-01	4,27E-02	4,99E-02
share	2%	33%	8%	1%	1%	1%	3%	2%
Aramid	3,22E+01	5,89E-08	2,44E-08	4,68E-07	2,02E-06	4,70E+00	6,91E-02	1,01E-01
share	5%	2%	5%	6%	2%	8%	4%	4%
Total	**5,96E+02**	**2,56E-06**	**4,69E-07**	**8,12E-06**	**1,20E-04**	**5,71E+01**	**1,65E+00**	**2,51E+00**

Material	**Euthrophication, terestrial**	**Euthrophication, freshwater**	**Euthrophication, marine**	**Ecotoxicity, freshwater**	**Land use**	**Water use**	**Ressource use, minerals and metals**	**Ressource use, fossils**
Units	*mol N eq*	Kg P eq	Kg N eq	*CTUe*	pt	*m3 water eq. of deprived water*	*kg Sb eq*	*MJ*
Electrical Steel	2,24E+00	1,24E-01	2,13E-01	7,96E+03	6,39E+02	1,04E+02	4,16E-04	2,93E+03
share	*44%*	***94%***	*23%*	*71%*	*0%*	*26%*	*1%*	*40%*
Permanent magnet	9,09E-01	1,98E-05	8,23E-02	4,60E+02	6,95E+02	1,71E+02	6,73E-06	8,92E+02
share	*18%*	*0%*	*9%*	*4%*	*0%*	*43%*	*0%*	*12%*
Copper	6,01E-01	1,60E-04	5,43E-02	2,73E+02	6,52E+05	7,49E+01	6,32E-02	4,04E+02
share	*12%*	*0%*	*6%*	*2%*	***100%***	*19%*	***99%***	*6%*
Cast iron	7,15E-01	1,86E-04	6,66E-02	4,12E+02	4,10E+02	2,86E+01	2,61E-05	2,03E+03
share	*14%*	*0%*	*7%*	*4%*	*0%*	*7%*	*0%*	*28%*
Steel	3,22E-01	3,94E-05	2,97E-02	8,45E+01	3,77E+01	4,50E-01	5,43E-06	4,37E+02
share	*6%*	*0%*	*3%*	*1%*	*0%*	*0%*	*0%*	*6%*
Epoxy	1,12E-01	3,65E-04	1,23E-02	4,09E+02	1,94E+01	4,07E+00	1,21E-04	1,11E+02
share	*2%*	*0%*	*1%*	*4%*	*0%*	*1%*	*0%*	*2%*
Aramid	2,15E-01	6,61E-03	4,88E-01	1,63E+03	2,00E+00	1,60E+01	7,75E-05	4,29E+02
share	*4%*	*5%*	***52%***	*15%*	*0%*	*4%*	*0%*	*6%*
Total	**5,12E+00**	**1,32E-01**	**9,46E-01**	**1,12E+04**	**6,54E+05**	**3,99E+02**	**6,39E-02**	**7,23E+03**

The assessment of absolute values for BC4 confirm the high influence of permanent magnets on water use and Acidification. It is further noticeable, that copper is very dominantly influencing land use impact category unlike all other materials.

Table 18: Reference Environmental impacts for a SCIM IE4 55kW (BC4), computed using 2024 ERT, including impacts from raw materials and end-of-life impacts and benefits

Material	**Climate change, total**	**Ozone depletion**	**Human toxicity, cancer**	**Human toxicity, non-cancer**	**Particulate matter**	**Ionising radiation, human health**	**Photochemical ozone formation, human health**	**Acidification**
Units	*Kg CO2 eq*	*kg CFC-11 eq*	*CTUh*	*CTUh*	*disease incidence*	*kBq U235 eq*	*kg NMVOC eq*	*mol H+ eq*
Electrical Steel	5,18E+02	3,25E-06	6,47E-07	7,84E-06	1,08E-04	3,13E+01	1,64E+00	1,84E+00
share	*46%*	***67%***	*73%*	*49%*	***69%***	*22%*	***56%***	*46%*
Aluminium	1,33E+02	3,46E-08	3,24E-08	1,03E-06	4,72E-06	3,70E+01	2,31E-01	5,04E-01

share	*12%*	*1%*	*4%*	*6%*	*3%*	*26%*	*8%*	*13%*
Copper	4,88E+01	3,10E-10	2,96E-08	2,49E-07	1,24E-05	3,60E-01	2,36E-01	4,41E-01
share	*4%*	*0%*	*3%*	*2%*	*8%*	*0%*	*8%*	*11%*
Cast iron	2,34E+02	5,43E-08	3,43E-08	1,29E-06	1,57E-05	6,59E+01	3,57E-01	5,51E-01
share	*21%*	*1%*	*4%*	*8%*	*10%*	*46%*	*12%*	*14%*
Steel	1,20E+02	-2,17E-10	3,19E-08	4,67E-06	9,79E-06	1,20E-01	2,44E-01	3,48E-01
share	*11%*	*0%*	*4%*	*29%*	*6%*	*0%*	*8%*	*9%*
Epoxy	1,64E+01	1,43E-06	5,96E-08	1,30E-07	2,05E-06	5,85E-01	7,11E-02	8,32E-02
share	*1%*	*29%*	*7%*	*1%*	*1%*	*0%*	*2%*	*2%*
Aramid	6,44E+01	1,18E-07	4,89E-08	9,36E-07	4,04E-06	9,39E+00	1,38E-01	2,01E-01
share	*6%*	*2%*	*6%*	*6%*	*3%*	*6%*	*5%*	*5%*
Total	**1,13E+03**	**4,88E-06**	**8,84E-07**	**1,61E-05**	**1,57E-04**	**1,45E+02**	**2,92E+00**	**3,96E+00**

	Euthrophication, terestrial	**Euthrophication, freshwater**	**Euthrophication, marine**	**Ecotoxicity, freshwater**	**Land use**	**Water use**	**Ressource use, minerals and metals**	**Ressource use, fossils**
Units	*mol N eq*	*Kg P eq*	*Kg N eq*	*CTUe*	*pt*	*m3 water eq. of deprived water*	*kg Sb eq*	*MJ*
Electrical Steel	4,52E+00	2,50E-01	4,29E-01	1,60E+04	1,29E+03	2,10E+02	8,37E-04	5,89E+03
share	*51%*	*94%*	*24%*	***55%***	*0%*	*44%*	*1%*	*42%*
Aluminium	8,01E-01	6,76E-05	7,35E-02	8,05E+03	1,43E+02	6,62E+01	8,31E-05	1,89E+03
share	*9%*	*0%*	*4%*	*27%*	*0%*	*14%*	*0%*	*13%*
Copper	8,69E-01	2,31E-04	7,85E-02	3,95E+02	9,43E+05	1,08E+02	9,14E-02	5,84E+02
share	*10%*	*0%*	*4%*	*1%*	***100%***	*23%*	***99%***	*4%*
Cast iron	1,32E+00	3,43E-04	1,23E-01	7,61E+02	7,56E+02	5,27E+01	4,81E-05	3,74E+03
share	*15%*	*0%*	*7%*	*3%*	*0%*	*11%*	*0%*	*26%*
Steel	7,57E-01	9,26E-05	6,98E-02	1,99E+02	8,86E+01	1,06E+00	1,28E-05	1,03E+03
share	*9%*	*0%*	*4%*	*1%*	*0%*	*0%*	*0%*	*7%*
Epoxy	1,87E-01	6,08E-04	2,05E-02	6,82E+02	3,23E+01	6,78E+00	2,02E-04	1,85E+02
share	*2%*	*0%*	*1%*	*2%*	*0%*	*1%*	*0%*	*1%*
Aramid	4,31E-01	1,32E-02	9,76E-01	3,26E+03	4,01E+00	3,20E+01	1,55E-04	8,57E+02
share	*5%*	*5%*	*55%*	*11%*	*0%*	*7%*	*0%*	*6%*
Total	**8,88E+00**	**2,65E-01**	**1,77E+00**	**2,94E+04**	**9,45E+05**	**4,77E+02**	**9,27E-02**	**1,42E+04**

Table 18 also confirms previous assumptions and the strong land use impact of copper. Absolute values show comprehensively, how aluminium does not influence a specific impact category particularly strong.

5.3. Material costs for virgin vs. recycled copper and steel

Table 19 shows an overview of virgin and recycled material prices for some of the metals found in electric motors. Some of the prices are furthermore visualized in Figure 10.
The data is derived from the German Mineral Resources Agency (DERA).

The data illustrates the economic value of the various materials. For example, the price of neodymium is around ten times higher than that of new copper. Similarly, the price of Praseodymium-neodymium from NdFeB magnetic scrap with 61,17 $/kg is about ten times higher than that of recycled copper.

Also compared to the most valuable materials needed for high performing traction batteries the prices of REEs are higher, e.g. 102,28 $/kg for primary neodymium against 41,25 $/kg for primary cobalt (the highest price materials in modern NMC batteries). Compared to gold, on the other side, the price of neodymium is 600 times lower.

Table 19 Virgin and recycled material prices (based on data from the German Mineral Resources Agency (DERA[69]), JRC[70], Institute for rare Earths and Metals,[71] EURIC[72] , JP Morgan [73]and Stormcrow[74])

Material	Price (US$ / kg) multi-sourced data from 2020-2025	Dataset
Aluminium	2,2-2,38	LME, high grade primary
Aluminium (recycled)	1,33-1,60	New aluminium alloy scrap (Angel)
Aluminium (recycled)	0,96-1,25	Cast aluminium scrap (Aster)
Copper	8,3-9,19	LME, grade A
Copper (recycled)	7,18-7,82	Chopped copper wire scrap (kasus)
Copper (recycled)	6,80-7,54	Chopped copper wire scrap (katze)
Copper (recycled)	5,13-5,52	Brass scrap (magda), rolled brass scrap 63

[69] https://www.deutsche-rohstoffagentur.de/DERA/DE/Produkte/Rohstoffpreise/Preismonitor/preismonitor_node.html

[70] production_costs_from_the_iron_and_steel_industry_-_final_online.pdf

[71] EuRIC_Circular_Metals_Strategy_Final.pdf

[72] Current prices for rare earths | Institute for Rare Earths and Metals

[73] The Outlook For Aluminum, Steel & Copper Prices | J.P. Morgan

[74] 20210308-Stormcrow-UCore-Initiation-Final.pdf

Copper (recycled)		5,85-6,67	Gunmetal scrap (radar), gunmetal scrap I
Iron ore		0,10-0,12	Iron ore (any origin) fines, spot price, c.f.r. China, 62% FE
Steel (recycled)		0,28-0,30	Steel scrap (grade E1), old steel scrap
Steel (recycled)		0,33-0,34	Steel scrap (grade E2/E8), new steel scrap
Steel (recycled)		0,33	Steel scrap (grade E3) Heavy steel scrap
Steel (recycled)		0,33-0,34	Steel scrap (grade E4), shredded steel scrap
Steel (recycled)		0,26-0,27	Steel scrap (grade E5), steel chips
Steel (recycled)		0,85-1,17	Steel scrap (V2A), chromium-nickel alloyed exw Germany
Steel (recycled)		1,96-1,97	Steel scrap (V4A), chromium-nickel alloyed exw Germany
Rare earth elements (REE)	Neodymium (Nd)	64-102,28	Neodymium (metal), min. 99%, fob China
	Dysprosium (Dy)	302-420,25	Dysprosium (metal), min. 99%, fob China
	Samarium (Sm)	13,09-14	Samarium (metal), min. 99 % fob China
	Praseodymium (Pr)	94-115,57	Praseodymium (metal), min. 99%, fob China
	Terbium (Tb)	850-1.554,59	Terbium (metal), min. 99%, fob China
	REE (recycled)	61,17	Praseodymium-neodymium from NdFeB magnetic scrap, PrNd = 50%[75]
Gold (for reference)		62.384-103.461	99,5% fine, London, afternoon
Cobalt (for reference)		33,08-41,25	LME, min. 99,8%
Lithium (for reference)		9,77	Lithiumcarbonate, battery quality, Li2Co3 = 99,5%
Nickel (for reference)		15,2-19,27	Primary, min. 99,8%

[75] Magnets in electric motors differ may their share of PrNd. There is limited data available on virgin and recycled REE prices

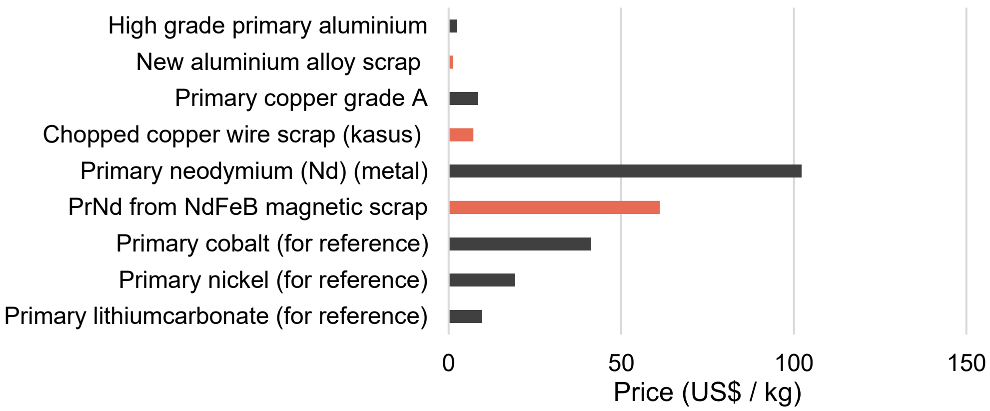

Figure 10 Selected virgin and recycled material prices (based on data from the German Mineral Resources Agency (DERA)) (to be noted: due to data availability the price for recycled REE (PrNd) and from Lithium is from April 2025, while all other prices reflect the average from 2020-2024.)

Evidently, the market price alone gives only limiedt information on the economic viability of any recycling process, since the quantities of materials that can be recovered are not included.

Therefore, we take as a first approximation the total mass of materials in selected motor types. Taking for example the bill-of-materials for base case 5 (IE4 PMSM, 55 kW) presented in Task 5.1, we find that the motor contains 6,2 kg of permanent magnets and 38,6 kg copper stator windings. Taking the recycled material prices from above this amount equals a material value of 189,6$ for the permanent magnets (6,2kg x 61,2$/kg x 50%[76]) and 39,5$ for copper (38,6kg x 9,2$/kg) (assuming a 100% recovery rate).

For a 200 kW motor these values would increase to 639,3$ for permanent magnets (20,8kg x 61,2$/kg x 50%) and 824,3$ for copper (89,7kg x 9,2$/kg).

[76] Assuming a concentration of 50% for praseodymium-neodymium (PrNd) in the REE scrap.

6. MEErP Task 6, Design Options

6.1. Introduction and timeline

This chapter describes the assessment of design options, linked to potential future Ecodesign requirements, for:

- Recycled metal content in motors
- Recyclability of PMM motors at end of life; and
- Recycled content and recyclability of Critical Raw Materials used in motors

This mini study on recycled content, recyclability and CRM for motors had a limited schedule and budget, therefore it relied primarily on preliminary data collection and EcoReport-Tool analyses that will be handed over to the review study team working on motors for DG Environment. It is expected that the parallel review study team will conduct further investigations into these and other policy options, conduct additional data collection and analysis, and address any comments received from this stakeholder consultation, incorporating the final recommendations into the Commission's Working Document for a new regulation on electric motors.

6.2. Design options for recycled content

In order to support the development of a circular economy, it is desirable to foster an increase in recycled copper and REEs used in new products, derived from post-consumption or post-industrial sources. Requiring the use of recycled copper and REE materials could potentially stimulate waste collection and investment in recycling capacity by increasing demand for recycled metals.

However, the maturity of the recycling market and current recycling practices have to be taken into consideration and might impede the usefulness of such targets. E.g. for copper, the recycling market is well established because of the material's intrinsic value and because its wide applicability creates strong market incentives for its recovery and reuse. Recycled copper can have the same quality as copper from primary, mined sources and can be used in a wide range of applications. Once recovered at the end of a product's life, copper is reabsorbed into new manufacturing cycles by high-quality recyclers. Since recycling copper where possible is already well established, it remains unclear whether targets would generate additional recycling that is in proportion to the administrative burdens. The practical challenges of stakeholders moreover include verifying recycled content. Since primary and secondary metals are of almost identical quality and value, and are often processed together for technical reasons, it is difficult to distinguish between recycled and virgin materials. Nevertheless, the design option of recycled copper will be assessed theoretically to shed light on potential environmental impacts (refer to the discussion in section 6.2.2 regarding the contentious nature of the utility of establishing a recycled content target and the compelling arguments that may be presented against it).

For REEs there are clear indications on the political will to implement a recycled contents target in Article 29 of the Critical Raw Materials Act. The requirement is supposed to cover motors, where the total weight of permanent magnets exceeds 0,2 kg. Starting with an information requirement on the recycled from 2026. Two years pursuant, minimum shares are ought to be defined for neodymium, dysprosium, praseodymium, terbium, boron, samarium, nickel and cobalt recovered from post-consumer waste that must be present in the permanent magnet incorporated in the products.

In implementing a recycled content requirement, EN 45558 provides a standardized method for declaring the presence and quantity of critical raw materials (CRMs) in energy-related products. It supports transparency by guiding manufacturers to identify, quantify (where possible), and report CRMs at the product, component, or material level using supply chain or analytical data. This helps promote circular economy practices and informed resource management.

6.2.1 According to stakeholders however, information about recycled REE content is currently not yet provided by suppliers, as there are no legal requirements for suppliers to provide this data. Therefore, it is currently still difficult to require recycled content in REEs before such legal requirements are in place. It is moreover important to note that requirements for the use of recycled permanent magnets must be consistent with the availability of the material from domestic European sources. For Europe's strategic autonomy, it is essential to have both the technologies and the capacities available within the EU at competitive prices. Smelting or reprocessing rare earths from magnets in non-EU countries, for example, would be contrary to this goal.

Overview of Design options

Option 1: Recycled content requirement, part of copper mass

For this option, the requirements could be drafted to read as follows:

Starting on 1 January 20XX, any new industrial electric motor placed on the market shall contain at least 60% of recycled copper recovered from post-consumer or post-industrial waste motors. This percentage of recycled copper shall be calculated as the mass of recycled copper contained in the product divided by the total mass of copper (both virgin and recycled) contained in the product as sold, excluding packaging. As can be taken from Table 11 and statements by the German Kupferverband even higher percentages of recycled copper are already used in the industry[77].

Option 2: Recycled content requirement, part of REE mass (low)

For this option, the requirements could be drafted to read as follows:

Starting on 1 January 20XX, any new industrial electric motor containing permanent magnets placed on the market shall contain at least 10% of recycled REE recovered from post-consumer or post-industrial waste motors. This percentage of REE shall be calculated as the mass of recycled REE contained in the product divided by the total mass of REE (both virgin and recycled) contained in the product as sold, excluding packaging.

Option 3: Recycled content requirement, part of REE mass (high)

For this option, the requirements could be drafted to read as follows:

Starting on 1 January 20XX, any new industrial electric motor containing permanent magnets placed on the market shall contain at least 30% of recycled REE recovered from post-consumer or post-industrial waste motors. This percentage of REE shall be calculated as the

[77] https://kupfer.de/wp-content/uploads/2024/10/2024_Factsheet_Recycling_EN.pdf

mass of recycled REE contained in the product divided by the total mass of REE (both virgin and recycled) contained in the product as sold, excluding packaging.

6.2.2 Impact reduction due to recycled content: copper

This section discusses the reduction in environmental impacts for a unit product when recycled content (factor R1) for copper is raised.

For base case BC4, metals represent around 98,7% of the mass. Most of this is ferrous metal (various types of steel and iron) which are recyclable. Non-ferrous metals include aluminum and also copper, which is on the Critical Raw Materials list and thus of special interest in this study.

For base case BC5, metals represent around 98,6% of the mass. Most of this is ferrous metal (various types of steel and iron) which are recyclable. Non-ferrous metals include copper and REE.

For the baseline scenario it has been assumed that the recycled metal content in current motor manufacturing is 30% for ferrous metals, and 37% for copper.

Table 16 shows the reduction in environmental impacts when increasing the recycled copper content from 37% (baseline) to 60% in BC4. The table shows the baseline impacts, the alternative impacts for R1=60%, and the difference between the two (savings). The changes seem rather marginal, however this is mainly due to the strong dominance of the use phase. The impact changes are stronger for the increased recycled copper content, when excluding the use phase. E.g. water use decreases by 1,1% and climate change by 0,2%.

Table 20: Summary of the reduction of environmental impacts compared to the baseline, when using 10% and 30% recycled content in input to the production for BC4

BC4 (Induction motor)								
Material	Climate change, total	Ozone depletion	Human toxicity, cancer	Human toxicity, non-cancer	Particulate matter	Ionising radiation, human health	Photochemical ozone formation, human health	Acidification
Units	Kg CO2 eq	*kg CFC-11 eq*	*CTUh*	*CTUh*	*disease incidence*	*kBq U235 eq*	*kg NMVOC eq*	*mol H+ eq*
60% recycled copper (R1)								
Change	2,33E+00	-9,15E-12	1,45E-09	1,15E-08	6,11E-07	-1,06E-02	1,15E-02	2,16E-02
Reference	6,46E+04	2,63E-05	1,10E-05	2,21E-04	2,11E-03	2,73E+04	1,06E+02	1,97E+02
% total change	*0,00%*	*0,00%*	*0,01%*	*0,01%*	*0,03%*	*0,00%*	*0,01%*	*0,01%*
% change (Material impacts)	*0,21%*	*0,00%*	*0,16%*	*0,07%*	*0,39%*	*-0,01%*	*0,39%*	*0,54%*

Material	**Euthrophication, terestrial**	**Euthrophication, freshwater**	**Euthrophication, marine**	**Ecotoxicity, freshwater**	**Land use**	**Water use**	**Ressource use, minerals and metals**	**Ressource use, fossils**
	mol N eq	Kg P eq	Kg N eq	*CTUe*	pt	*m3 water eq. of deprived water*	*kg Sb eq*	*MJ*
60% recycled copper (R1)								
Change	4,20E-02	1,12E-05	3,79E-03	1,91E+01	4,68E+04	5,35E+00	4,54E-03	2,75E+01
Reference (total result)	3,96E+02	2,14E-01	3,83E+01	3,03E+05	6,22E+05	2,21E+04	4,99E-02	1,12E+06
% total change	*0,01%*	*0,01%*	*0,01%*	*0,01%*	*7,53%*	*0,02%*	*9,09%*	*0,00%*
% change (Material impacts)	*0,47%*	*0,00%*	*0,21%*	*0,06%*	*4,96%*	*1,12%*	*4,90%*	*0,19%*

Table 21 shows the reduction in environmental impacts when increasing the recycled copper content from 37% (baseline) to 60% in BC5. The table shows the baseline impacts, the alternative impacts for R1=60%, and the difference between the two.

Table 21: Summary of the reduction of environmental impacts compared to the baseline, when using 10% and 30% recycled content in input to the production for BC5

BC 5 (PMM)								
Material	Climate change, total	Ozone depletion	Human toxicity, cancer	Human toxicity, non-cancer	Particulate matter	Ionising radiation, human health	Photochemical ozone formation, human health	Acidification
Units	Kg CO2 eq	*kg CFC-11 eq*	*CTUh*	*CTUh*	*disease incidence*	*kBq U235 eq*	*kg NMVOC eq*	*mol H+ eq*
60% recycled copper (R1)								
Change	1,6E+00	-6,3E-12	1,0E-09	8,0E-09	4,2E-07	-7,3E-03	7,9E-03	1,5E-02
Reference	6,4E+04	2,5E-05	1,1E-05	2,2E-04	2,1E-03	2,7E+04	1,1E+02	2,0E+02
% total change	*0,00%*	*0,00%*	*0,01%*	*0,00%*	*0,02%*	*0,00%*	*0,01%*	*0,01%*
% change (Material impacts)	*0,27%*	*0,00%*	*0,21%*	*0,10%*	*0,35%*	*-0,01%*	*0,48%*	*0,59%*

Material	Euthrophication, terestrial	Euthrophication, freshwater	Euthrophication, marine	Ecotoxicity, freshwater	Land use	Water use	Ressource use, minerals and metals	Ressource use, fossils
	mol N eq	Kg P eq	Kg N eq	*CTUe*	pt	*m3 water eq. of deprived water*	*kg Sb eq*	*MJ*
60% recycled copper (R1)								
Change	2,9E-02	7,8E-06	2,6E-03	1,3E+01	3,2E+04	3,7E+00	3,1E-03	1,9E+01
Reference	3,9E+02	1,7E-01	3,8E+01	3,0E+05	5,2E+05	2,2E+04	3,9E-02	1,1E+06
% total change	*0,01%*	*0,00%*	*0,01%*	*0,00%*	*6,27%*	*0,02%*	*7,96%*	*0,00%*
% change (Material impacts)	*0,57%*	*0,01%*	*0,28%*	*0,12%*	*4,95%*	*0,93%*	*4,92%*	*0,26%*

6.2.3 Impact reduction due to recycled content: REE

This section discusses the reduction in environmental impacts for a unit product when recycled content (factor R1) for REE (up to 30%) is raised. It must noted that due to a current lack of data, not all impact categories were explored. The underlying dataset for recycled REE was based mainly on two studies[78] [79].

For BC5, REEs, as part of the permanent magnet, represent 2,2% of the mass (sections 5.3 and 5.5). There are various technologies to recycle the magnet. A typical composition of an NdFeB alloy for permanent magnets consists mainly of iron and neodymium. For the baseline scenario it has been assumed that the recycled REE input to motor manufacturing is 0%.

Table 16 shows the reduction in environmental impacts when increasing the recycled REE content from 0% (baseline) to 10% and 30%. The table shows the baseline impacts, the alternative impacts for R1=10% and R1=30%, and the difference between them (savings).

[78] Life cycle assessment of regeneration technology routes for sintered NdFeB magnets

[79] Comparative Life Cycle Assessment of NdFeB Magnets: Virgin Production versus Magnet-to-Magnet Recycling

Material	**Climate change, total**	**Ozone depletion**	**Human toxicity, cancer**	**Human toxicity, non-cancer**	**Particulate matter**	**Photochemical ozone formation, human health**	**Acidification**	**Euthrophication, marine**	**Ecotoxicity, fresh water**
Units	**Kg CO2 eq**	***kg CFC-11 eq***	***CTUh***	***CTUh***	***disease incidence***	***kg NMVOC eq***	***mol H+ eq***	**Kg N eq**	***CTUe***
10% recycled REE (R1)									
Change	**1,11E+00**	**2,84E-13**	**3,41E-10**	**9,97E-09**	**5,66E-07**	**3,89E-03**	**6,00E-03**	**1,05E-03**	**4,78E+00**
Reference	**6,4E+04**	**2,5E-05**	**1,1E-05**	**2,2E-04**	**2,1E-03**	**1,1E+02**	**2,0E+02**	**3,8E+01**	**3,0E+05**
% change	***0,002%***	***0,000%***	***0,003%***	***0,005%***	***0,027%***	***0,004%***	***0,003%***	***0,003%***	***0,002%***

Material	**Climate change, total**	**Ozone depletion**	**Human toxicity, cancer**	**Human toxicity, non-cancer**	**Particulate matter**	**Photochemical ozone formation, human health**	**Acidification**	**Euthrophication, marine**	**Ecotoxicity, fresh water**
Units	Kg CO2 eq	*kg CFC-11 eq*	*CTUh*	*CTUh*	*disease incidence*	*kg NMVOC eq*	*mol H+ eq*	Kg N eq	*CTUe*
30% recycled REE (R1)									
Change	3,34E+00	8,51E-13	1,02E-09	2,99E-08	1,70E-06	1,17E-02	1,80E-02	3,14E-03	1,44E+01
Reference	6,4E+04	2,5E-05	1,1E-05	2,2E-04	2,1E-03	1,1E+02	2,0E+02	3,8E+01	3,0E+05
% change	*0,005%*	*0,000%*	*0,009%*	*0,014%*	*0,080%*	*0,011%*	*0,009%*	*0,008%*	*0,005%*

6.2.4 Other

Recycled content requirements for e.g. impregnation resin, insulation or paint have not been studied.

6.3. Design options for recyclability

Another measure to support the development of a circular economy in the EU is to promote design options that facilitate recyclability of products at the end of life. This includes techniques such as designing products to be easily disassembled, for parts and materials to be individually marked to facilitate sorting, and for any critical raw materials (CRMs) to be easily identified to maximise the potential for recovery. In this context, it is important to avoid overlaps with the CRM Act (see 1.4.7), which for example already addresses the goal of improving the recycling of Rare Earth Elements (REE) from permanent magnets through (1) Designing products to be easily disassembled via disassembly information, (2) Marking of parts to facilitate sorting and (3) CRMs to be easily identified.

The overall recyclability calculation for the EU market is based on two key factors – the collection rate of used motors and the percentage of the recovered used motors that can ultimately be separated, sorted and recycled. In the EcoReport-Tool, the percentage recyclability referenced only takes into consideration the second of these factors – namely, the amount of material that can be recovered from a unit at the end of life.

To address recyclability of the product at end of life, Table 22 sets out a system by which products can be designed for disassembly. Policy options on recyclability could be based around either a minimum value, a mandatory point score or to make it an information requirement with a view to making it mandatory in the next review.

The target audience for disassembly or CRM information would be recyclers, treatment facilities, regulators.

Including information on products which supports dismantling for recyclers can significantly increase the recycling percentage as previous studies show in other product contexts[80].

However, it must be noted that instead of manual dismantling, motor recyclers currently often use automated shredding and sorting, and are therefore not benefitted by product documentation for disassembly guidance. Therefore, future studies need to better estimate those product types (e.g. motor sizes) for which manual dismantling is financially viable and hence would benefit from enhanced product documentation.

[80] Ease of disassembly of products to support circular economy strategies

Table 22: Overview of approaches to address recyclability at end of life for electric motors

Type	#	Parameter	Principle	Benefit
Service-related Parameters	1	Dismantling information and condition for access	Scoring based on information provided	Scoring based on information provided
	2	Information on composition	Scoring based on disclosure of material composition of the product; points based on percentage of mass of product disclosed	Recyclers get valuable information regarding expected yield and adequate pre-treatment requirements
	3	Information on CRMs	Scoring based on disclosure of the quantity and location of CRMs and SRMs in the product	Recyclers get valuable information regarding expected yield
Dismantling Related Parameters	4	Number of steps for the dismantling of priority parts (dismantling depth)	Scoring based on the number of dismantling	Scoring based on the number of dismantling
	5	Type of tools needed to dismantle priority parts	Level of complexity in terms of tools needed for dismantling a priority part, from low to high complexity. No tools, basic tools, commercial tools, proprietary tools.	Tools needed to dismantle a component can be a proxy of the disassembly complexity

In this context, a no-regret option is the informational requirement on disassembly, recycling or disposal at end-of-life, which had already been included in Commission Regulation (EC) No 640/2009, but was removed in the 2019 repeal (Commission Regulation (EU) 2019/1781):

> *Information relevant for disassembly, recycling or disposal at end-of-life shall be visibly displayed on technical documentation of motors and of products in which motors are incorporated as well as on free access websites of manufacturers of motors and of manufacturers of products in which motors are incorporated.*

6.3.1 Impact reduction due to recyclability of REE

This section discusses the reduction in environmental impacts for a unit product when the recyclability at end of life (factor R2) for REE is raised from 0% (baseline) to 10% and to 30%. Data are for a unit product of PMM (BC5) with the BoM presented above. Compared to the baseline, only the factors R2 for recyclability have been changed. Factors R1 (recycled content) and A (allocation factor) remain the same. Table 23 and Table 24 provide the top-level reduction of environmental impacts compared to the reference case, when 10% and 30% recyclability (instead of 0%) is used for REE.

Table 23: Impacts reductions due to recyclability R2 = 10% for REE in BC5

Material	**Climate change, total**	**Ozone depletion**	**Human toxicity, cancer**	**Human toxicity, non-cancer**	**Particulate matter**	**Photochemical ozone formation, human health**	**Acidification**	**Euthrophication, marine**	**Ecotoxicity, fresh water**
Units	Kg CO2 eq	*kg CFC-11 eq*	*CTUh*	*CTUh*	*disease incidence*	*kg NMVOC eq*	*mol H+ eq*	Kg N eq	*CTUe*
10% recyclability REE (R2)									
Change	4,4E+00	1,1E-12	1,4E-09	4,0E-08	2,3E-06	1,6E-02	2,4E-02	4,2E-03	1,9E+01
Reference	6,4E+04	2,5E-05	1,1E-05	2,2E-04	2,1E-03	1,1E+02	2,0E+02	3,8E+01	3,0E+05
% change	*0,007%*	*0,000 %*	*0,013 %*	*0,018 %*	*0,107 %*	*0,015 %*	*0,012%*	*0,011 %*	*0,006 %*

Table 24: Impacts reductions due to recyclability R2 = 30% for REE in BC5

Material	**Climate change, total**	**Ozone depletion**	**Human toxicity, cancer**	**Human toxicity, non-cancer**	**Particulate matter**	**Photochemical ozone formation, human health**	**Acidification**	**Euthrophication, marine**	**Ecotoxicity, fresh water**
Units	kg CO2 eq	*kg CFC-11 eq*	*CTUh*	*CTUh*	*disease incidence*	*kg NMVOC eq*	*mol H+ eq*	Kg N eq	*CTUe*
30% recyclability REE (R2)									
Change	1,3E+01	3,4E-12	4,1E-09	1,2E-07	6,8E-06	4,7E-02	7,2E-02	1,3E-02	5,7E+01
Reference	6,4E+04	2,5E-05	1,1E-05	2,2E-04	2,1E-03	1,1E+02	2,0E+02	3,8E+01	3,0E+05
% change	*0,021%*	*0,000 %*	*0,038 %*	*0,055 %*	*0,321 %*	*0,044 %*	*0,037%*	*0,033 %*	*0,019 %*

The tables indicate that the impact reductions that can be achieved through increasing the R2 recyclability of REE seem relatively low in comparison to Design options regarding copper. However, scaled-up to the market size the saving potential are still relevant as will be described in detail as part of Task 7. When comparing the impact categories, the tables show that particulate matter, Photochemical ozone formation and non-cancerous human toxicity are the most influenced by these Design options.

7. MEErP Task 7, Scenarios

7.1. Estimations for the market relevance of rare earths in industrial motors compared to other applications

To provide an estimation about the strategic relevance of permanent magnets used in industrial applications the marked assumptions laid out in Task 2 are compared against data on the rare earth material demand for EVs and wind power plants (Table 25).

Table 25: Comparison of magnet amount in PMMs vs in electric vehicles and wind power plants. [81]

		2020	2030
EV	EV sales (million cars)	1,4	7,3
	Nd-Fe-B (t)	**2.000**	**10.400**
Wind power plant	Annual wind capacity addition (GW)	17	47
	Nd-Fe-B (t)	**7.300**	**21.700**
4kW PMM	PM motor sales 4 kW	719.172	981.726
	Kg/ 4 kW motor	0,9	0,9
	NdFeB (t) 4 Kw motors	**647**	**884**
55kW PMM	PM motor sales 55 kW	121.949	163.976
	Kg/ 55 kW motor	6,2	6,2
	NdFeB (t) 55 Kw motors	**756**	**1017**
200kW PMM	PM motor sales 200 kW	12.145	16.618
	Kg/ 200 kW motor	20,8	20,8
	NdFeB (t) 200 Kw motor	**253**	**346**

Table 25 shows the weight of permanent magnets in industrial PMMs in comparison to the amount in electric vehicles and wind power plants. The NdFeB included in the three most relevant PMM motor categories (small 0,75-7,5 kW, medium 7,5-75 kW and large 75 – 375 kW) adds up to 1.656 tonnes in 2020 and increases to 2.246 tonnes in 2030.

[81] Roland Gauß, Carlo Burkhardt, Frédéric Carencotte, Massimo Gasparon, Oliver Gutfleisch, Ian Higgins, Milana Karajić, Andreas Klossek, Maija Mäkinen, Bernd Schäfer, Reinhold Schindler, Badrinath Veluri. Rare Earth Magnets and Motors: A European Call for Action. A report by the Rare Earth Magnets and Motors Cluster of the European Raw Materials Alliance. Berlin 2021.

Based on this data, magnets from PMMs make up an estimated 15% in weight out of the permanent magnet demand in 2020 (out of the three applications). With the expected strong increases in EV sales and wind power adoption, this share decreases to an estimated 7% by 2030.

The comparison highlights how the magnets in PMMs account for a relatively small percentage of the magnets sold in the EU compared to EVs and wind power, though not insignificant. It has to be noted that the data assumptions for the industrial PMM market rely on several assumptions as laid out in Task 2 and therefore can only be taken as a rough estimation that requires more in-depth investigations that exceed the scope of this mini study.

7.2. Savings potential compared to sales & stock in 2030

This section provides an estimate of environmental impact savings for the measures considered regarding recycled copper as well as REE and recyclability of REE and their potential when scaling up to estimated sales and stock values for motors in 2030. These saving potentials consider the design options as described in Task 6. The savings are calculated on a unit-basis for the base case motors are therefore multiplied by the projected sales and stock in 2030 to estimate the magnitude of the savings potential overall from these measures.

Table 26: Sales and Stock estimates in 2030 for BC4 and BC5 motors

Type	**2030 Sales (units)**	**2030 Stock (units)**
IEM, 55 kW, IE4	718.933	7.417.193
PM, 55 kW, IE4	163.976	1.565.010

Based on the sales and stock estimates in Table 26, the first scenario explored the potential GHG savings for an increase of recycled copper content from 37% to 60%. The scenario can be applied to both the IEM and PMM. It must be noted again, that this scenario aligns with a trend that is being ambitiously pursued within the industry already, driven by the promising economic return from recycling copper which has been widely recognized by stakeholders.

Table 27: Saving potentials for scenario 1 scaled-up to Sales and Stock estimates in 2030 for BC4 and BC5

Scenario 1	**GHG savings/unit (kg CO2 eq)**	**2030 Sales (tonnes CO2 eq)**	**2030 Stock (tonnes CO2 eq)**
60% recycled copper content			
IEM, 55 kW, IE4	2,33E+00	9.707	17.261
PMM, 55 kW, IE4	1,61E+00	264	2.519

The difference between saving potentials regarding CO2 emissions for IEMs in comparison to PMMs is illustrated in Figure 11. It shows that the saving potential is extensively higher for

IEMs, which in mainly due to their market dominance and hence higher sales numbers as stated in Table 26.

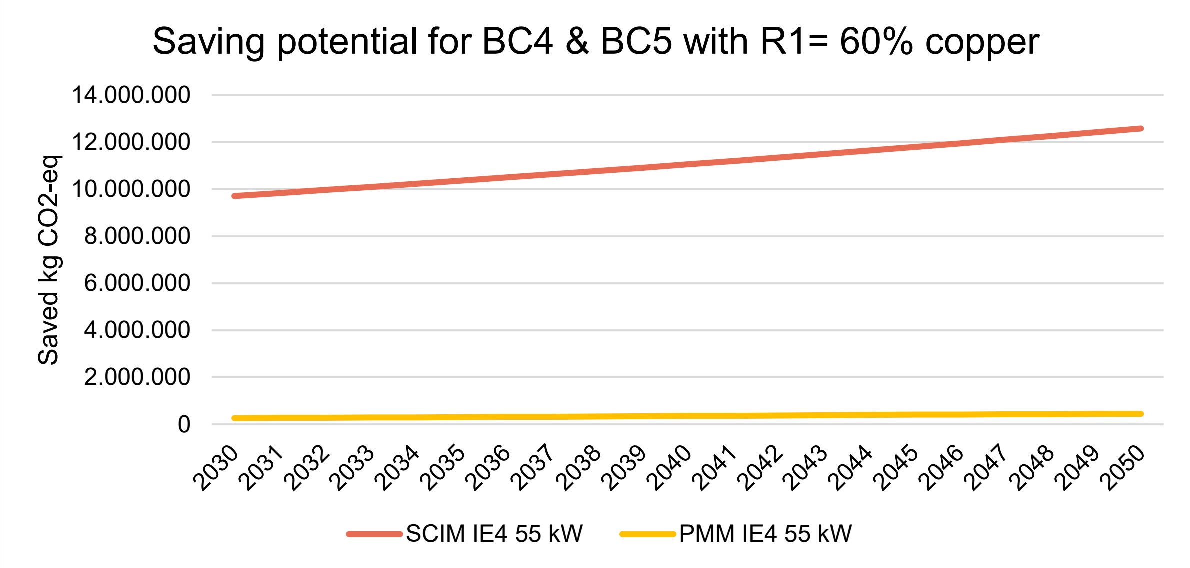

Figure 11: Saving potential for copper Design Option (R1 = 60%) applied after 2030 on BC4 and BC5

The second and third scenario displayed in Table 28, explore an increased recycled content share of REE from 0% (baseline) to 10% and 30%, applied to PMMs. Results of the scenarios show how these measures can lead to GHG savings of 182 tonnes (10%) and up to 547 tonnes (30%) CO2 eq for motors sold in 2030.

Table 28: Saving potentials for increased REE recycled content scaled-up to Sales and Stock estimates in 2030 for BC5

Scenarios 2 & 3	**GHG savings/unit (kg CO2 eq)**	**2030 Sales (tonnes CO2 eq)**	**2030 Stock (tonnes CO2 eq)**
10% recycled REE			
PMM, 55 kW, IE4	1,11E+00	182	1.737
30% recycled REE			
PM, 55 kW, IE4	3,34E+00	547	5.227

The fourth and fifth scenario displayed in Table 29, explore an improved recyclability regarding REE from 0% (baseline) to 10% and 30%, applied to PMMs. Results of the scenarios show how these measures can lead to GHG savings of 729 tonnes (10%) and up over 2.187 tonnes (30%) CO2 eq for motors sold in 2030.

Table 29: Saving potentials for improved REE recyclability scaled-up to Sales and Stock estimates in 2030 for BC5

Scenarios 4 & 5	**GHG savings/unit (kg CO2 eq)**	**2030 Sales (tonnes CO2 eq)**	**2030 Stock (tonnes CO2 eq)**
10% recyclability REE			
PMM, 55 kW, IE4	4,45E+00	729	6.959
30% recyclability REE			
PMM, 55 kW, IE4	1,33E+01	2.187	20.879

Finally, Figure 12 compares the potential savings of the four scenarios regarding BC5 the impact category climate change in kg CO2-eq as well as one best-case scenario combining the most impactful Design options. As stated in 2.3.2, the sales and stock values for PMMs can only be considered to be first estimates, which still need to be confirmed as part of the main study. Therefore the scaled-up saving potentials can also be considered estimates only.

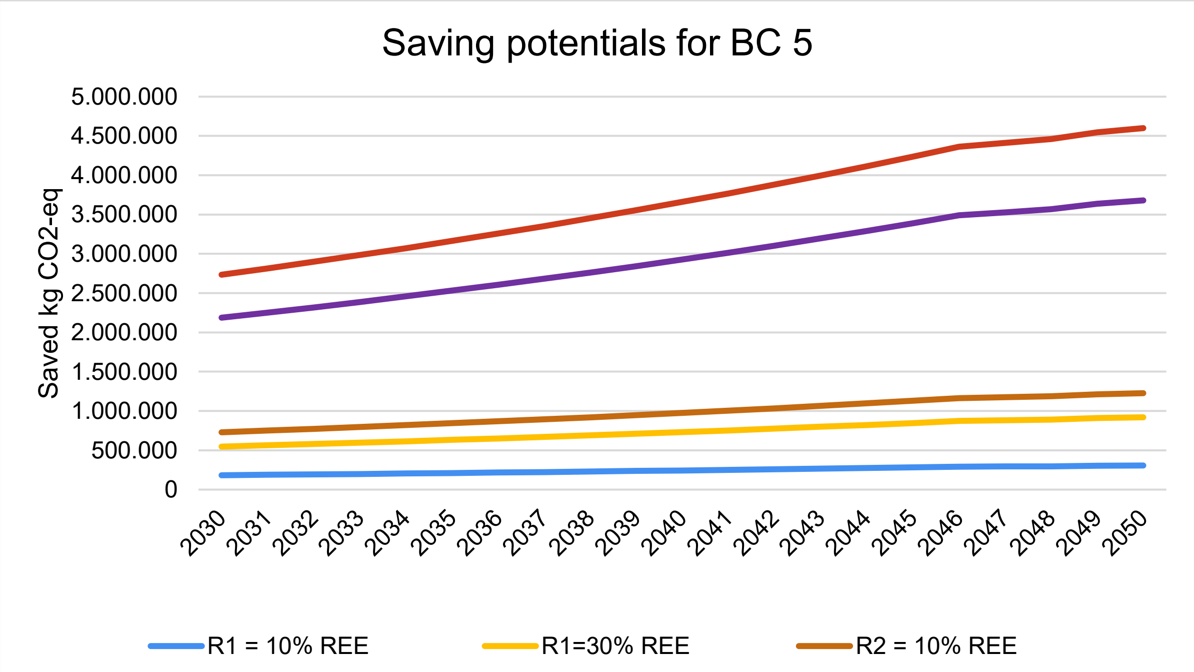

Figure 12: Saving potential for five REE Design Options and an ideal combination of two best-case Design Options (applied after 2030 on BC5)

As can be taken from the figure and table above, scenarios 1 (R1 = 60% copper) and 2 (R1 = 10% REE) are estimated to not exceed a saving potential of 500 tonnes per year between 2030 and 2050. With a slight increase in CO2-eq savings scenarios 3 (R1 = 30% REE) and 4 (R2 = 30% REE) show a higher saving potential in comparison. With a strongly increasing saving potential, scenario 5 (R2 = 30% REE), shows to be the most promising measure among the explored scenarios for PMMs.

In addition, the two most promising measures (R1 = 10% REE and R2 = 30% REE), have been combined as illustrated in red. As can be taken from the graph, the combination could increase GHG savings over the years up until 2050 even further.

To conclude, this study aimed to evaluate the potential for reducing environmental impacts in IEMs and PMMs through applying product specific measures on scarce, environmentally relevant and critical raw materials and on recycled content. The study underscores the significant potential associated with increasing the recycled content of copper in IEMs. This initiative is already gaining traction within the industry, yielding considerable environmental benefits due to the high market penetration of IEMs. Conversely, while PMMs currently occupy a smaller market share, their future relevance warrants careful consideration, especially in terms of their strategic implications. The exploration of introducing recycled content for REEs is still in its nascent stages; however, it holds promise for greater impact. The findings suggest that it is essential for the industry to prioritize measures that enhance the recyclability of REE before implementing recycled content requirements. Establishing robust material flows and collection infrastructure is an essential first step towards REE recycling. Effective disassembly and the application of advanced recycling technologies are further necessary to produce high-quality recycled products. To achieve these objectives, comprehensive information on material compositions, as well as the tools and techniques required for efficient dismantling and recycling, must be developed. This will be a focal point for further investigation in the upcoming main review study.

8. Conclusion

This study comprehensively evaluated the potential for reducing environmental impacts in electric motors by exploring design options focused on increasing recycled content and enhancing recyclability, particularly for CRMs like REEs and copper. The analysis assessed five design options, including increasing recycled copper content to 60% and introducing recycled REE content at levels of 10% and 30%. Additionally, the study examined the recyclability of REEs at end-of-life. The environmental impacts of these measures were analysed across key categories, such as climate change, particulate matter, and resource use, revealing that the use phase dominates the overall environmental footprint of motors, but material-related impacts remain relevant particularly for REEs and copper.

The findings highlight that increasing the recycled content of REEs and copper could contribute to a more circular economy by reducing dependency on virgin materials, lowering greenhouse gas (GHG) emissions, and conserving valuable resources. However, the feasibility and effectiveness of these measures vary significantly between the two materials.

The Potential and Challenges of Increasing Recyclability and Recycled REE Content

Introducing recycled REE content in PMMs offers relevant environmental and strategic benefits. Increasing the recycled content of REEs could reduce the environmental impacts associated with their extraction and processing, which are energy-intensive and often involve significant ecological degradation. For example, scaling recycled REE content to 30% could lead to GHG savings of up to 547 tonnes of CO_2 equivalent for motors sold in 2030.

Moreover, enhancing REE recycling aligns with the EU's strategic goals of reducing supply chain vulnerabilities and fostering resource independence. By establishing robust recycling systems, the EU could mitigate the geopolitical risks associated with REE supply, as these materials are predominantly sourced from a few global suppliers.

However, while the potential benefits are clear, several prerequisites (derived based on desk research and stakeholder feedback) must be met or accompanying measures added to enable the successful implementation of recycled REE content requirements:

- **Material Quality and Availability**: More research is needed for better understanding the impact that impurities in recycled REE materials can have on magnet performance. Currently, little recycled REE material is used due to poor availability. To avoid market distortions, the height of potential recycled content targets must be set according to available quantities. Aligning targets with the timing of recycling rates can ensure to secure supply of recycled materials.

- **Certification and verification**: While recycled REE content is already in place for some permanent magnets, introducing ambitious targets for larger market shares, requires traceable certifications that allow for verification. Such certification or monitoring scheme must be designed in parallel.
- **Recycling Infrastructure and Economic Viability**: Currently, many recycling companies are not technically or logistically equipped to manage motors with different types of magnets separately or to subject them to special or manual separation processes. As long as iron, copper, and aluminum remain the value-determining fractions in motor recycling, there is little incentive for separating REEs. These metals can be recovered in sufficient quantities and quality through shredding, both when processed with the rest of the product and when motors are shredded separately. Targets should therefore first be tailored to those motor types where more nuanced dismantling is economically attractive, while still considering the strategic importance and potentially future price increases of virgin REEs. More research is needed to better understand the cost of recycled REE materials

  Design Adjustments: To facilitate the separation of permanent magnets, it is possible to reduce the strength of adhesives or remove coatings. When proposing such design-for-recycling measures, concerns around quality problems must be considered, such as magnets detaching from the shaft or degradation of motor energy performance due to rust or reduced magnetic force. A balance must be stuck between use phase performance and recyclability.

Given these challenges, the study underscores the importance of prioritizing **recyclability measures** first to those motor types that allow for more economic recovery of REEs. Any recycled content targets and their potential design must be carefully balanced with available material flows and accompanying measures to ensure material availability and verification.

The Potential and Challenges of Increasing Recycled Copper Content

Copper is a key material in electric motors, particularly in windings, where its high electrical conductivity is essential for motor efficiency. Increasing the recycled content of copper could theoretically reduce the environmental impacts of motor production, as copper mining and processing are associated with significant GHG emissions and resource depletion. For example, increasing recycled copper content to 60% could yield GHG savings of up to 17.261 tonnes of CO_2 equivalent for IEMs in stock by 2030.

However, significant challenges and barriers to increasing recycled copper content must be noted:

- **Market Dynamics and existing recycling practices**: Recycled copper is a scarcity market where demand exceeds supply. The main issue lies in increasing end-of-life collection rates and adequately regulating exports of copper scrap and recycled copper to ensure a sufficient supply of recycled material. Metals with high economic value, like copper, are already extensively recycled due to market incentives. Their inherent worth drives collection, sorting, and reprocessing, making additional regulations for minimum recycled content potentially redundant and administratively burdensome.
- **Material Quality and supply constraints**: High-purity copper is critical for motor performance. Impurities in recycled copper, such as oxygen, degrade electrical conductivity, increase losses, and reduce motor lifespan, making it unsuitable for key components like windings. The potential lack of supply of high-grade copper scrap

could impede technical feasibility. Diverting recycled copper to motors could negatively impact other applications, meaning such measures would not create a net environmental benefit at the EU scale. This makes the savings potential estimated in the study unrealistic.

- **Verification Challenges**: Differentiating between virgin and recycled copper is technically challenging. Stakeholders express concerns about the lack of enforcement mechanisms and anti-circumvention safeguards.
- **Upstream Barriers and administrative hurdles**: The main barrier to higher recycling rates lies upstream, in the capture and quality of end-of-life scrap. This issue is best addressed through improved collection, design for disassembly, and advanced sorting and pre-processing technologies. According to stakeholder feedback, high recycling rates are also hindered by burdensome administrative procedures that restrict and slow the shipment of CRM-containing waste within the EU and disincentivize its import. As an example for this, stakeholders reference the full compliance of the EU with the Basel e-waste entries without derogations, unlike other OECD countries.

Given the challenges of mandating higher recycled copper content in electric motors, a variety of alternative approaches for copper were suggested by stakeholders. Recycled copper content requirements could for example be introduced at the manufacturing level, targeting base materials like copper wires or bars rather than finished products. This would ensure recycled copper is used without compromising motor performance, particularly in windings that require high-purity copper. Concerns about supply constraints and verification however would still exist.

Improving end-of-life collection rates and maximizing copper recovery from recycling streams are also critical. Investments in advanced sorting and pre-processing technologies can address current limitations in capturing high-quality copper scrap. Additionally, streamlining administrative procedures for shipping CRM-containing waste within the EU could enhance material flow and support recycling efforts. Finally, establishing certification pathways for post-industrial and post-consumer recycled content at copper smelters would improve transparency and ensure verifiable integration of recycled copper. These measures, combined with investments in purification technologies, can address supply constraints and create a more sustainable framework for copper use in motors

Stakeholders generally emphasize the need for differentiated timelines for implementing design options, particularly for small and medium-sized enterprises, to account for varying capacities and resources. Additionally, overlaps with existing regulations, such as the CRM Act and the WEEE Directive, should be avoided. Harmonization between the ESPR and the CRM Act is essential to streamline regulatory implementation and prevent double regulation.

In conclusion, while measures on REEs and copper present both opportunities for increasing recycled content, the study recommends prioritizing efforts on REEs due to their strategic importance and the significant environmental benefits associated with their recycling. This focus must be accompanied by measures to address the prerequisites for successful implementation, including ensuring material quality, scaling recycling infrastructure, and fostering economic viability. For copper, the study suggests a more cautious approach, emphasizing upstream measures to improve collection, sorting and recycling rates rather than imposing recycled content requirements on motor manufacturers.

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