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EU-MORE

EUropean MOtor
REnovation initiative

Deliverable D2.4 – Analysis of end-of-life practice for electric motors

Authors:
Aníbal de Almeida

Armin Saki

João Fong

Nuno Quaresma

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EU-MORE is an acronym for
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Table of Content

List of Tables

List of Figures

Executive Summary

The EU-MORE Deliverable D2.4 report examines the critical interplay between motor replacement, energy efficiency gains, and the principles of circular economy. As the EU accelerates motor renovation to improve energy efficiency and achieve its climate goals, this report investigates the implications for material use, recycling practices, and resource circularity.

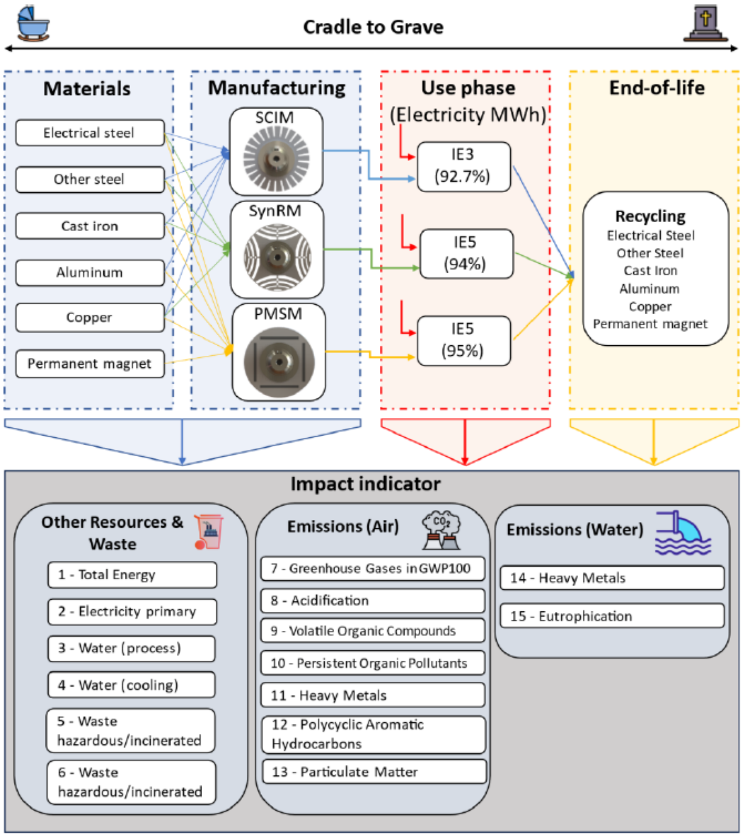
Key findings include:

- **Energy Efficiency Benefits:** Modern electric motors (IE3 and above) significantly outperform older models, offering up to 30% energy savings, which translates into reduced CO_2 emissions in power generation. The table below highlights the energy efficiency benefits.

Motor Type	Efficiency (%)	Annual Energy Use (kWh)	CO_2 Emissions (tons)	Payback Period (Years)
Older Motor (Pre-2000)	80–85	120,000	50	N/A
Modern Motor (IE3)	90–92	100,000	40	3–5
Modern Motor (IE4)	95–96	85,000	35	4–6
Modern Motor (IE5)	97–98	80,000	30	5–7

Note: The power rating of 75 kW reflects the reference motor used in the lifecycle assessments (LCA) from [27]. This provides a basis for comparing energy savings and emissions across efficiency classes.

- **Material Recovery Gaps:** While high recovery rates are observed for materials like copper (90%) and steel (85%), rare earth elements (REEs) used in permanent magnet motors (PMSMs) remain underutilized, with recovery rates estimated to be below 5%. The Figure below illustrates the material flow of electric motors in the EoL cycle.



- **Technological Barriers:** Challenges such as complex motor designs and insufficient automation in disassembly processes hinder the scalability of recycling efforts.
- **Case studies and best practices:** The report provides a set of case studies and best practices on advanced motor recycling infrastructure (achieving high recovery rates for copper and steel), initiatives for rare earth element recovery in PMSMs, as well as integration of Industry 4.0 technologies to enhance motor disassembly and material recovery.
- **Policy Insights:** Robust policies, including recycling mandates, material-specific recovery targets, and incentives for adopting innovative recycling technologies, are essential to align motor replacement strategies with circular economy goals.

The report emphasizes the importance of a well-developed recycling market to mitigate the material demands arising from increased motor production. Trends and recommendations provided in Chapter 8 outline the path forward, focusing on improving recycling infrastructure, fostering cross-sector collaboration, and integrating circular economy principles into motor design. Additionally, the report demonstrates how the electric motor industry can transition towards a sustainable and circular economy. However, achieving these objectives requires continuous technological innovation, supportive policies, and enhanced collaboration across the value chain.

1. Introduction

Electric motors are essential components in various sectors, powering industrial machinery, transportation systems, and household appliances. They account for more than 70% of the EU's total industrial electricity consumption, making them critical for energy efficiency improvements and emissions reductions [1]. With the drive toward sustainability and resource efficiency across Europe, the effective management of electric motors at their End-of-Life (EoL) has gained importance, particularly within the framework of a circular economy.

The *EU-MORE* project (European Motor Renovation) addresses inefficiencies in the lifecycle management of electric motors in order to accelerate motor replacement and supports the transition toward a more sustainable and circular economy. This project also aims to advance motor recycling practices, increase material recovery rates, and reduce environmental impacts associated with motor production and disposal, ultimately supporting the EU's broader climate and energy goals [2][3].

1.1. Electric Motors and Their Role in Industrial Energy Use

Electric motors are indispensable in industrial systems due to their relatively high efficiency, reliability and application versatility, but they also are responsible for a major energy consumption. As global industries struggle to reduce their environmental footprint, electric motors present an important opportunity for achieving energy savings targets and carbon reductions through improvements in motor efficiency [1]. The replacement or renovation of older, inefficient motors with modern, high-efficiency models, associated with motor system improvements can yield energy savings of more than 30% in certain applications [2].

1.1.1. The Impact of Motor Efficiency on EU Sustainability Goals

Improving motor efficiency aligns directly with the EU's objectives to significantly cut greenhouse gas emissions and enhance industrial energy efficiency. Policies that promote electric motor replacement and encourage the adoption of more efficient models are therefore crucial for reaching EU sustainability targets, as well as United Nations Sustainability Goals (UNSDGs). As a result, the *EU-MORE* project places a strong emphasis on replacing inefficient motors, ensuring proper EoL procedures and expanding the availability of financial incentives for renovation and recycling [3].

1.1.2. Linking Accelerated Motor Renovation with Circularity Principles

Increasing the motor replacement rate is a key objective of EU-MORE. However, this can potentially lead to more material consumption due to the manufacturing requirements of higher efficiency classes (within the same motor technology). Although this may appear to challenge the core principles of the circular economy, which emphasizes durability, lifetime extension, and reduced material use, the net improvements associated with high efficiency technologies largely exceed the extra material requirements. Therefore, this strategy aligns with sustainability goals when considered in the broader context of energy efficiency and resource circularity [27][32].

Modern electric motors, especially those classified as IE3 or higher class, deliver significant energy savings that offset the environmental impact of their production. For example, replacing an IE2 motor with an IE3 or IE4 model can reduce operational CO_2 emissions by 20-30% over its lifetime, as demonstrated in lifecycle assessments (LCA). Moreover, a well-functioning motor recycling market ensures that valuable materials such as copper, steel, and rare earth elements are effectively recovered and reintroduced into the supply chain, thereby mitigating resource strain [27][32].

To address the conflicting relationships between increased manufacturing requirements and circular economy principles, EU-MORE emphasizes the dual strategy of maximizing energy efficiency gains and improving recycling rates. The latter involves adopting advanced technologies for motor disassembly, material sorting, and rare earth recovery, which can boost recycling efficiency while minimizing waste. This approach harmonizes accelerated motor renovation with the EU's broader circular economy and climate objectives [27][32].

1.2. The Significance of End-of-Life (EoL) Management for Electric Motors

Effective EoL management for electric motors is vital not only for conserving valuable resources but also for minimizing environmental impacts associated with resource extraction and processing and waste disposal. Motors contain a range of recyclable materials, including copper, steel, aluminum, and sometimes Rare Earth Elements (REEs), which can be recovered and reintroduced into the supply chain. However, EoL practices across the EU remain inconsistent, with many EoL motors being exported outside the EU for recycling due to lower costs, resulting in the loss of valuable resources and an increased environmental footprint from transportation [4].

1.2.1. Resource Recovery and Circular Economy Potential

By implementing robust EoL management practices, the EU can enhance resource recovery and contribute to the development of a circular economy. The *EU-MORE* project emphasizes the importance of resource efficiency and circularity by promoting initiatives that facilitate and promote material recycling and recovery. Particularly relevant are REEs, which are crucial for high-efficiency and high-power density motor designs that are often difficult to recycle due to technological and economic barriers [2][3].

Figure 1 illustrates the closed-loop process for Circular economy framework, emphasizing stages like material recovery, reuse, and cleaner production.

Figure 1: Circular economy framework (Source: The United Nations Industrial Development Organization (UNIDO)).

1.3. Challenges in Motor Recycling and Material Recovery

The recycling of electric motors poses a variety of technical and economic challenges. While metals such as copper, steel, and aluminum are relatively straightforward to recover, REEs are more difficult to extract and require specialized facilities. Additionally, many Member States lack the infrastructure necessary for efficient motor recycling, leading to varying rates of resource recovery across EU [1].

1.3.1. Economic Barriers and Export Practices

Economic considerations heavily influence EoL motor management practices within the EU. Due to lower labor and processing costs, a significant number of EoL motors are exported to non-EU countries for recycling, resulting in both resource loss and increased environmental costs related to transportation.

The *EU-MORE* project seeks to mitigate these challenges by encouraging domestic (at country level) recycling and promotes the development of EU-based recycling infrastructure for electric motors [3][4].

1.4. Objectives and Goals of the EU-MORE Project

The *EU-MORE* project was established to support the EU's climate and resource efficiency goals by promoting the accelerated renovation and recycling of electric motors. The primary objectives of the project include enhancement of motor replacement policies, developing tools for monitoring and evaluating motor renovation outcomes, and facilitating stakeholder collaboration at both national and international levels [1][3].

1.4.1. Policy Development and Stakeholder Engagement

The project not only addresses technical solutions but also advocates for policy reforms that encourage the adoption of best practices across Member States. By engaging stakeholders from different sectors (e.g. motor manufacturers, recyclers, regulators, and end-users), the *EU-MORE* project promotes a collaborative approach to motor renovation and recycling. Through knowledge exchange/transfers between the different stakeholders and policy support, the project aims to create a favorable environment for achieving the EU's sustainability objectives [3].

1.4.2. Contribution to the Circular Economy through Motor Recycling

One of the core goals of *EU-MORE* is to align motor recycling practices with circular economy principles, ensuring that valuable materials are reused and that EoL motors are processed efficiently within the EU. This approach supports the EU's ambitions for a self-sustaining supply chain, reducing dependency on imported raw materials, and contributing to overall resource security [2][4].

1.5. Structure of the Report

This report provides a comprehensive overview of the *EU-MORE* project's objectives, strategies, and impacts. The following sections cover:

- **Electric Motors in the Context of Circular Economy**: Examines the principles of circular economy and their relevance to electric motor recycling.
- **Electric Motors: Repair or Replace**: Discusses the considerations surrounding motor renovation versus replacement, including cost-benefit analyses and environmental impacts.
- **End-of-Life (EoL) for Electric Motors and Recycling Routes**: Reviews current EoL practices, the state of recycling infrastructure in the EU, and technical challenges in material recovery.
- **Metal Recovery in the Recycling Process**: Focuses on the recovery of valuable metals, particularly copper and steel, and explores the challenges in REEs recovery.
- **EU Motor Recycling in Numbers**: Analyzes motor recycling statistics across EU Member States, highlighting successful practices and areas needing improvements.
- **Examples of Good Practices**: Presents case studies of successful motor recycling programs within EU.
- **Trends and Policy Recommendations**: Discusses future trends in motor recycling and offers policy recommendations to support the goals of the *EU-MORE* project.

2. Electric Motors in the Context of Circular Economy

2.1. Introduction to circular economy in electric motors

The concept of the **Circular Economy (CE)** is a transformative framework aimed at designing out waste, keeping products, components, and materials in use for as long as possible, and regenerating natural systems. The term "natural systems" refers to the Earth's ecosystems and their ability to self-regulate and sustain life through cycles that process materials, energy, and resources. These systems operate on circular principles, naturally recycling resources without generating waste. The concept of the circular economy seeks to emulate these natural processes by creating an industrial system that similarly maintains materials in use, reduces waste, and regenerates resources.

As industries increasingly prioritize sustainability, the electric motor industry is uniquely positioned to benefit from CE practices due to its extensive material consumption and energy demands. Electric motors are responsible for **70% of industrial electricity consumption**, making them central to any effort to reduce energy use and material waste [5].

The **Ellen MacArthur Foundation** study [5] defines the CE as an industrial system that aims to eliminate waste and optimize resource efficiency by emphasizing **reuse**, **remanufacturing**, **recycling**, and **upgrading of products**. In the context of electric motors, CE strategies are particularly relevant given the high demand for key raw materials as well as due to the growing market for motors, expected to reach **USD 169 billion (Euro 157.4 billion)** by 2026 [6] [7].

2.2. Importance of electric motors in the circular economy

Electric motors efficiency and durability make them indispensable in sectors like **manufacturing**, **transportation**, **construction**, and **energy production**. As such, they have become a central focus in efforts to reduce industrial carbon emissions and promote energy efficiency.

However, the environmental footprint of electric motors extends beyond energy consumption. The materials used in their construction, including **copper**, **aluminum**, **steel**, and **rare earth elements (REEs)**, are finite and often difficult to source sustainably. **Permanent magnet synchronous motors (PMSMs)**, for example, contain REEs like **neodymium** and **dysprosium**, which are critical for motor performance but come with significant environmental and geopolitical risks and costs [7]. Table 1 lists key materials in electric motors and their significance in the circular economy.

The adoption of circular economy principles in the electric motor industry is essential for reducing resource extraction, minimizing waste, and fostering sustainable practices. By focusing on **reuse**, **remanufacturing**, and **recycling**, industries can reduce their reliance on new raw materials and ensure that valuable resources remain in circulation for longer [5].

Key Points:

- **High Resource Demand**: Electric motors rely on finite resources, particularly metals like copper and rare earth elements, making material recovery crucial.
- **Energy Efficiency**: Motors consume the majority of industrial electricity, which means that improving motor efficiency has a direct impact on reducing energy demand and carbon emissions.

- **Circular Economy Potential**: With proper EoL management strategies, electric motors can significantly contribute to circular economy through material recovery, remanufacturing, and refurbishment.

Table 1 presents the key materials used in electric motors and their importance in the circular economy.

Table 1: Key materials in electric motors and their importance in the circular economy [7].

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:

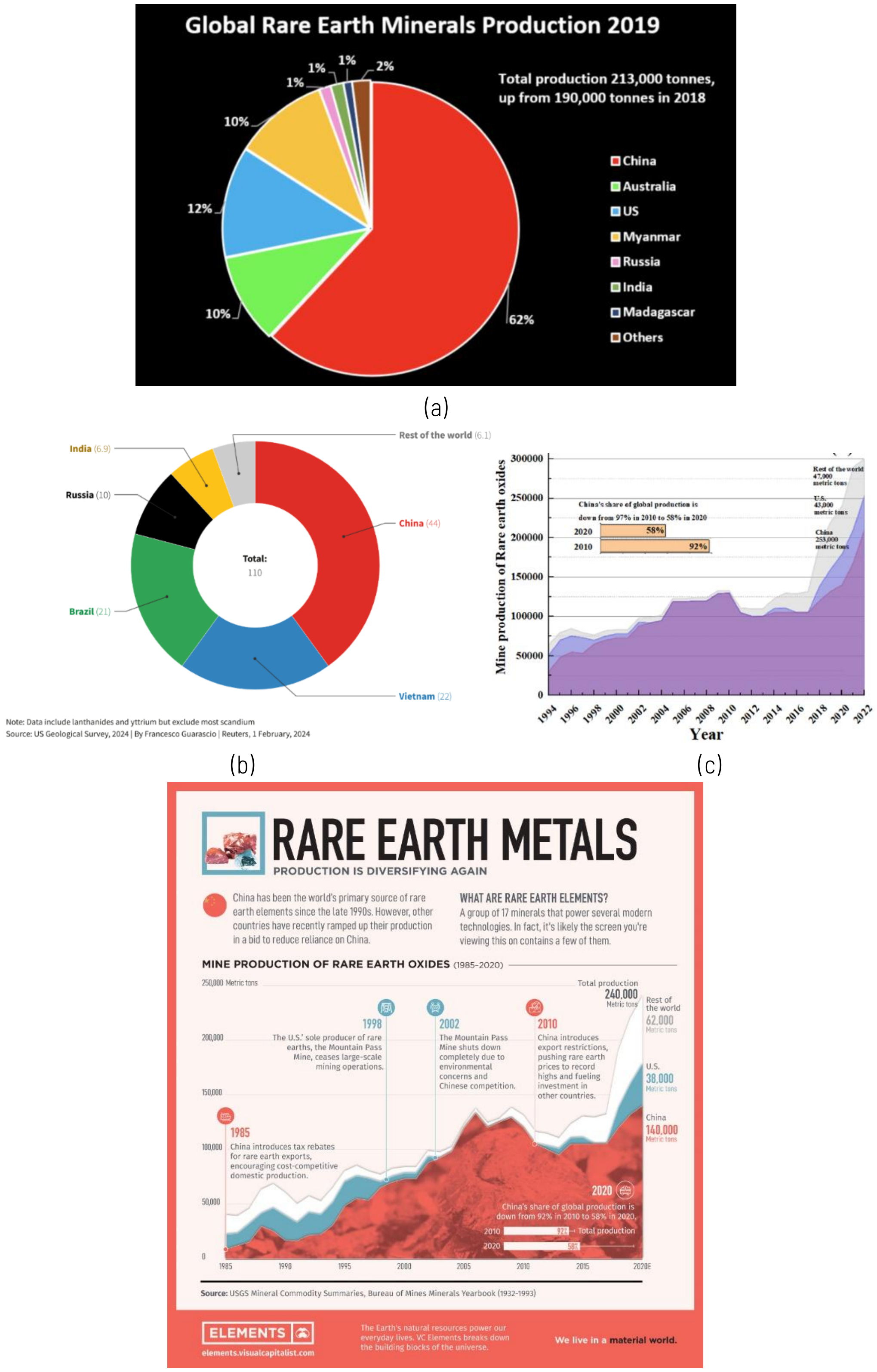
1. The weight ranges account for variations in motor sizes and efficiency classes, based on EU-MORE and International Energy Agency data.
2. REEs are only present in PMSMs and not in other common motor types like Squirrel Cage Induction Motors (SCIMs) or Synchronous Reluctance Motors (SynRMs).
3. Percentages are approximate and based on average compositions observed across industrial and commercial motors.

2.3. Lifecycle of electric motors: from production to end-of-life

2.3.1. Raw Material Extraction and Production

The production of electric motors requires the extraction of raw materials such as **copper**, **aluminum**, **steel**, and **Rare Earth Elements (REEs)**. These materials are essential for motor construction, particularly in **Permanent Magnet Synchronous Motors (PMSMs)**, in which REEs can account for as much as **60% of the motor's cost** and are indispensable for motors used for example in **high performance industrial motor drives** (e.g. high torque direct drive equipment and robotics), Electric Vehicles (EVs), and in wind generator systems [7][8].

The extraction of REEs and other materials used in motors is energy-intensive and environmentally harmful. Moreover, the global supply of REEs is highly concentrated in China, which controls over **60% of global production**, creating vulnerabilities in the supply chain [7]. Figure 2 illustrates global rare earth mineral deposits and production.


(a)

(b)

(c)

(c)

Figure 2: Global rare earth mineral deposits and production. a) Total production 213 thousand tons (Source: Reuters). b) In millions of tons of rare earth oxide equivalent (Source: Reuters). c) Total global REEs production. Adapted from USGS National Minerals Information Center, 2023 [7]. d) Mine production of rare earth oxide (source: USGS Mineral Commodity Summaries).

2.3.2. Usage phase

During the **use phase**, electric motors consume substantial amounts of electricity. However, technological advancements, such as the introduction of **Variable Speed Drives (VSDs)**, have improved the efficiency of modern motors systems. Nonetheless, energy consumption during the use phase accounts for over **90% of the motor's total environmental impact**, making motor efficiency a key area of focus for reducing industrial energy demand [8]. Table 2 compares the energy efficiency of old versus modern electric motors.

Many industries, especially in the **manufacturing** and **automotive** sectors, are replacing older motors with newer, more efficient models to reduce energy bills, carbon footprints and comply with energy regulations. **Life cycle Assessments (LCAs)** show that upgrading older motors to high-efficiency alternatives combined with motor system optimization can significantly lower energy use and associated emissions over time [8]. Table 2 presents a comparison of energy efficiency of old vs. modern electric motors.

Table 2: Comparative energy efficiency of old vs. modern electric motors [6].

Motor Type	Efficiency (%)	Annual Energy Use (kWh)	CO_2 Emissions (ton)	Motor Size (kW)	Efficiency Class	Operating Hours (hours/year)
Older Motor (Pre-2000)	80-85%	120,000	50	100	IE1/No Classification	3000
Modern Motor (Post-2010)	90-95%	85,000	35	100	IE3-IE4	3000

Assumptions:

1. **Motor Size**: Comparison assumes a 100kW motor, typical for industrial applications.
2. **Operating Hours**: Based on an average of 3,000 operating hours per year, which is standard for many industrial settings.
3. **Efficiency Class**: Older motors correspond to pre-IE classification or IE1, while modern motors represent IE3 and IE4 classifications.
4. **Energy Use and CO_2 Emissions**: Calculated based on average grid emission factors and energy savings data from referenced studies.

2.3.3. End-of-Life Management

The **end-of-life (EoL)** phase of electric motors is crucial for closing the material loop in the circular economy. Many EoL motors are currently discarded or sent to scrapyards, where valuable materials like **copper**, **steel**, and **rare earth elements** are lost, less than **5%** of REEs are recovered globally, even though they are essential for many modern clean energy technologies [7].

Table 3 presents the recovery rates of key materials in electric motors and Figure 3 illustrates the life cycle phase of a typical electric motor.

Table 3: Recovery rates of key materials in electric motors [4] [7] [12].

Material	Recovery Rate (%)	Challenges
Copper	90%	Energy-intensive to recycle
Steel	85%	High recyclability, often contaminated
Rare Earth Elements (REEs)	<5%	Complex to separate, lack of recycling infrastructure

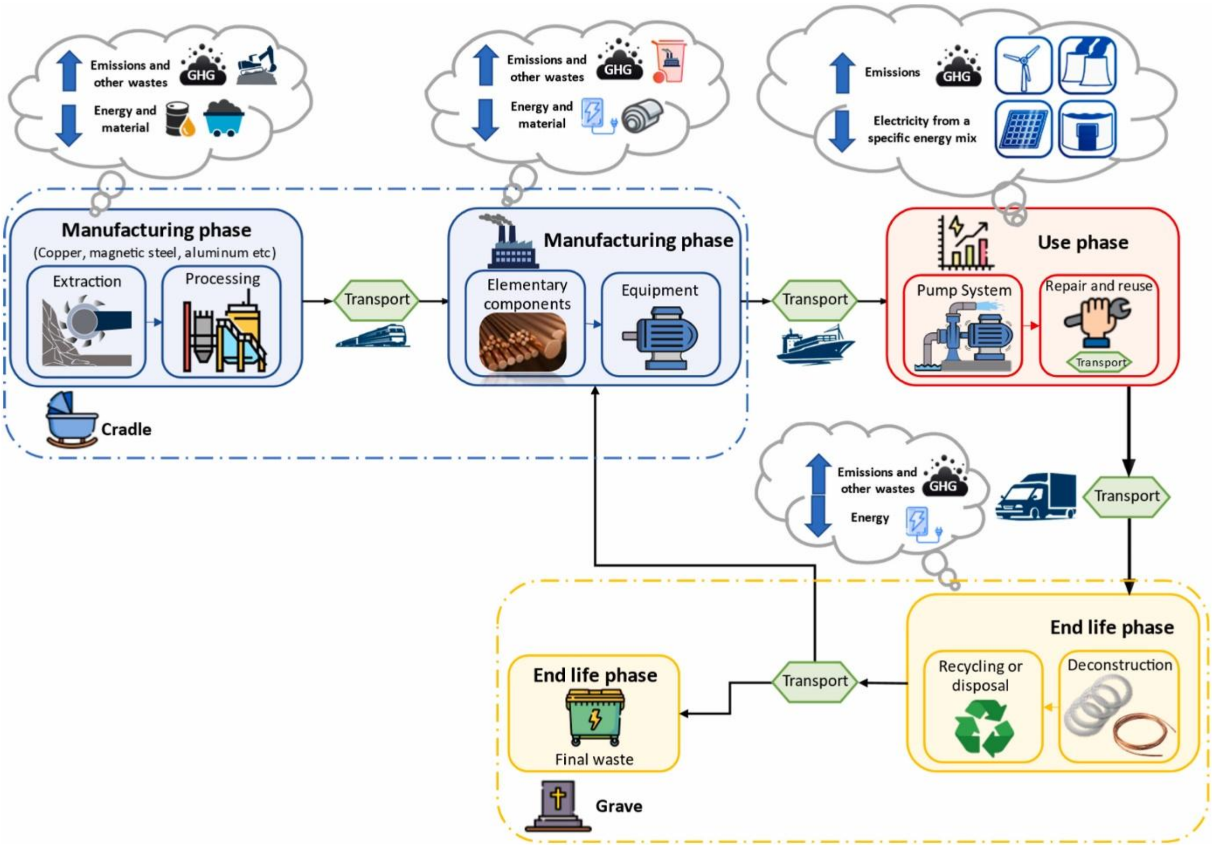


Figure 3: Life cycle phase of a typical electric motor [11].

2.4. Circular economy strategies for electric motors

Adopting circular economy principles in the electric motor industry involves several strategies that extend the lifecycle of motors and reduce waste. These include **reuse**, **refurbishing**, **remanufacturing**, and **recycling**.

2.4.1. Reuse

Reuse involves extending the operational life of motors by conducting minor repairs (e.g. bearing replacement) and redeploying them in other less intensive applications. This is the simplest form of circular economy strategy, reducing demand for new motors and extending the service life of existing units [5] [7]. However, careful consideration should be given on the decision to keep an old motor and the associated motor system in use as the disadvantages often outweigh the benefits both in terms of energy use and of environmental impact.

2.4.2. 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 [7].

2.4.3. 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.

Table 4 compares the reuse, refurbishment, and remanufacturing.

Table 4: Comparison of reuse, refurbishment, and remanufacturing [5].

Strategy	Process	Advantages	Challenges
Reuse	Minor repairs and testing	Immediate reuse, low cost	Limited to motors in good condition
Refurbishment	Inspection and part replacement	Cost-effective, extends motor life	Shorter lifespan than remanufactured
Remanufacturing	Complete disassembly and reassembly	High-quality restoration, like-new condition	Expensive, requires skilled labour

2.4.4. Recycling

Recycling focuses on recovering valuable materials from EoL motors. **Rare earth elements (REEs)** are much more difficult to recover due to their complex integration into motor components and processing. Currently, efforts to increase the recovery of REEs are focused on developing better motor design separation technologies and improving the infrastructure for motor disassembly and recycling [7].

2.5. Challenges in adopting circular economy practices for electric motors

Several barriers hinder the large-scale adoption of circular economy strategies for electric motors.

2.5.1. Complexity of motor design

Modern electric motors are made up of multiple materials, which makes them difficult to disassemble at the end of their life. **Permanent Magnet Synchronous Motors (PMSMs)**, in particular, rely on rare earth magnets that are deeply embedded in the motor, making them challenging to recover [7][8].

2.5.2. High costs of remanufacturing and recycling

The costs associated with remanufacturing and recycling are often prohibitive, especially for smaller motors. The disassembly process is labour-intensive, and current technologies for material separation are not yet advanced enough to make the recovery of materials like REEs economically viable [8].

2.5.3. Technological barriers

There is a lack of advanced **automation technologies** for disassembling electric motors and recovering valuable materials. Without substantial investment in new technologies, the recycling and remanufacturing processes will continue to be labour-intensive, inefficient with a low cost-effectiveness [11][32].

2.6. Technological innovations and Industry 4.0 in circular economy

The rise of **Industry 4.0** technologies, including the **Internet of Things (IoT)**, **Artificial Intelligence (AI)**, and **automation**, holds significant promise for overcoming the barriers to circular economy adoption in the electric motor industry.

2.6.1. Predictive maintenance

IoT-enabled sensors allow real-time monitoring of motor performance, enabling predictive maintenance that can extend motor lifespan by detecting potential issues such as overheating, excessive vibration or wear before they cause failure or damage. This reduces downtime and the need for premature replacement of motors [32].

2.6.2. Automated disassembly

Improved motor design, automation technologies, such as **robotics** and **AI**, can streamline the disassembly of electric motors, allowing for more efficient material recovery. These technologies can improve the speed and precision of recycling processes, reducing labour costs and improving the economic viability of motor recycling [5].

The advent of Industry 4.0 has presented immense opportunities to unlock the potential of remanufacturing. In this section, the opportunities that Industry 4.0 bring to remanufacturing are discussed based on the three aspects previously mentioned, namely, Smart Life Cycle Data for Design for Remanufacturing and EOL Management, Smart Factory for cost-effective and green remanufacturing operations, and Smart Services for a successful remanufacturing business model. Figure 4 describes the three application areas and technical enablers from Industry 4.0. The technology enablers are presented in the outer rim of the circle, and include smart sensors, cloud computing, robotics, machine-to-machine communication (M2M), additive manufacturing, and others [24].

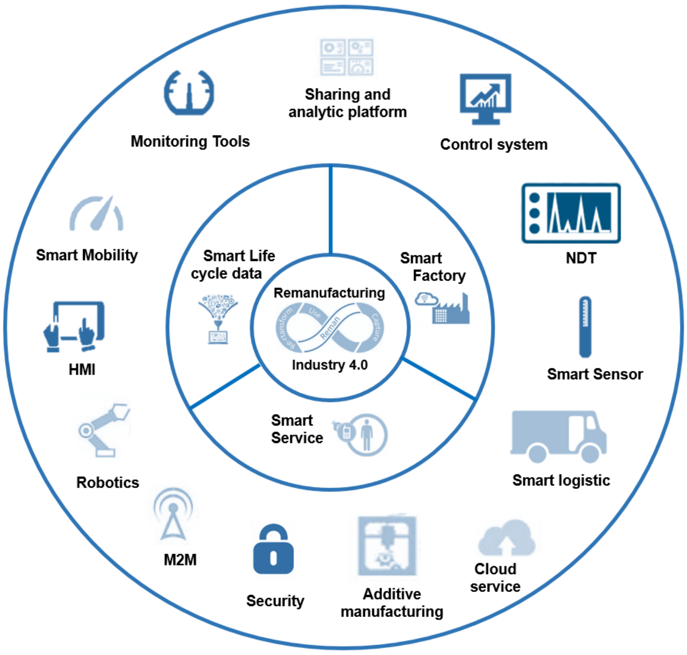


Figure 4: The three application areas and technical enablers from Industry 4.0 [24].

2.7. Case studies and best practices

Several case studies demonstrate the high effectiveness of circular economy strategies for electric motors:

2.7.1. European industrial motor reuse program

This initiative focuses on collecting, testing, and refurbishing motors from industrial applications, significantly extending their operational life and reducing the need for new motor production [10].

2.7.2. Electric vehicle motor recycling initiative

As the market for Electric Vehicles (EVs) expands, new initiatives have emerged to recover and recycle rare earth elements from EV motors. By partnering with motor manufacturers, recycling companies have improved their ability to recover REEs, creating a **closed-loop ecosystem** for key materials [7].

Table 5 presents case studies of the circular economy in electric motors.

Table 5: Case studies of circular economy in electric motors [10].

Project	Country	Focus	Outcome
European Industrial Motor Reuse Program	EU	Motor refurbishing	Extended motor life, reduced material consumption
EV Motor Recycling Initiative	Germany	Motor recycling	Improved REE recovery, reduced environmental impact

2.8. Policy and regulatory framework supporting circular economy

The European Union has established several regulations to support the circular economy for electric motors:

2.8.1. Ecodesign Directive

The **Ecodesign Directive** sets **Minimum Energy Efficiency Standards (MEPS)** for electric motors, ensuring that they meet specific performance criteria to reduce energy consumption over their lifecycle, leading to overall costs reductions [8][10].

2.8.2. Energy Efficiency Directive

The **Energy Efficiency Directive (EED)** encourages industries to adopt energy-saving technologies and circular economy practices. It promotes the use of high-efficiency motors and the replacement of inefficient models to reduce the environmental impact of motor use [10].

2.8.3. End-of-Life Vehicle (ELV) Directive

The **ELV Directive** mandates that **95% of a vehicle's materials** must be reused, recycled, or recovered, with electric motors being a key component in this effort. This European Directive highlights the importance of improving motor recycling rates, particularly for rare earth elements used in EVs [7].

2.8.4. Addressing Policy Gaps for Industrial Motor Recycling

While the WEEE (Waste Electrical and Electronic Equipment) Directive effectively regulates the recycling of many electronic devices, it explicitly excludes 'large-scale stationary industrial tools,' under which many industrial motors fall. This exemption creates a gap in EU policies for recycling industrial motors, despite their significant material and energy recovery potential. Industrial motors, often found in manufacturing and large-scale infrastructure, are critical to achieving circular economy objectives but lack comprehensive regulatory guidance specific to their recycling. Addressing this gap could involve:

- Introducing mandatory recycling targets for industrial motors within the scope of the Ecodesign Directive, ensuring alignment with circular economy principles.
- Expanding the WEEE Directive or developing a complementary directive to include guidelines and incentives for industrial motor recovery and recycling.
- Promoting traceability and standardized dismantling processes for industrial motors to improve material recovery rates, particularly for rare earth elements and copper. Additionally, harmonizing policies across EU member states will ensure that industrial motor recycling practices are optimized and consistent, avoiding fragmentation in recycling markets.

2.9. Conclusion and Future Outlook

Electric motors are fundamental to modern industry, and their integration into the circular economy is essential for reducing the environmental impact of their production, use, and disposal. By adopting strategies such as **reuse**, **remanufacturing**, and **recycling**, industries can extend motor lifespans and recover valuable materials, reducing the need for virgin resources and minimizing waste.

However, overcoming the challenges of **material recovery**, **high remanufacturing costs**, and **technological limitations** will require collaboration between **industry stakeholders**, **policymakers**, and **technology developers**. The **EU-MORE Project** represents a significant step toward fostering innovation in sustainable motor management practices and advancing the circular economy across Europe [10].

3. Electric Motors Repair or Replace

3.1 Overview of Repair vs. Replacement Decisions

Electric motors play a vital role in industrial applications, accounting for approximately 70% of electricity consumption in industries [11]. Decisions about whether to repair or replace a motor often hinge on factors such as motor age, operational efficiency, cost considerations, and the availability of new technology. Motors can often exceed their expected lifespan by decades, which has led to concerns about energy inefficiency and emissions from outdated models [18]. In Figure 5, the Decision Flowchart for Motor Repair vs. Replacement is illustrated.

Modern high-efficiency motors, such as those classified as IE3, IE4, and IE5, offer significant advantages over older models. However, repair remains a viable option for many operators due to lower immediate capital costs and the availability of services like rewinding, which can extend motor life but limited to maintaining the motor efficiency [17].

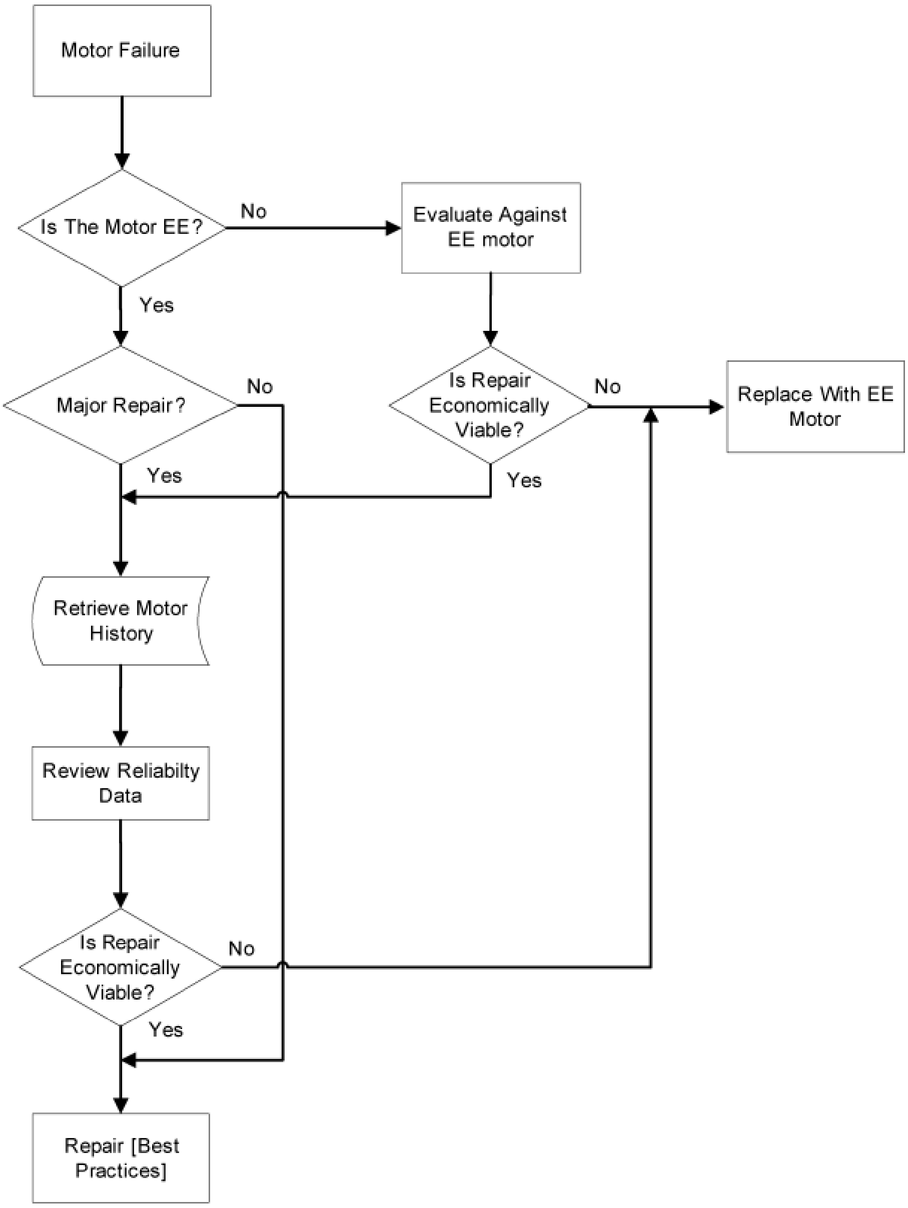


Figure 5: The Decision Flowchart for Motor Repair vs. Replacement, EE: Energy Efficient [25].

3.2 Cost and Efficiency Comparison

The choice between repair and replacement is often driven by the relative costs and efficiency gains achievable through replacement. The operational efficiency of older motors, typically categorized as IE2 or lower, is markedly less than newer IE4 or IE5 motors. The International Energy Agency (IEA) has reported that replacing IE1 motors with IE4 motors can reduce energy consumption by up to 20-30% [15] [18].

The cost-benefit analysis must weigh the upfront investment of a new motor against the long-term energy savings and reduced operating costs. For industries where motors are used intensively, replacing an older motor with an IE5 model, for example, could yield substantial savings in energy costs over time. However, this may not always be feasible in sectors with limited budgets or where downtime costs are prohibitive [16] [19]. In Table 6, the comparison of the average costs and energy savings associated with repairing versus replacing motors across different efficiency classes (IE1 to IE5) is presented.

Table 6: Comparison of the average costs and energy savings associated with repairing versus replacing motors across different efficiency classes (IE1 to IE5) [15] [18] [19].

Motor Class	Repair Cost (€)	Replacement Cost (€)	Energy Savings (%)	Annual Energy Use (kWh)	Payback Period (Years)
IE1	500	1,500	0%	25,000	N/A
IE2	700	1,800	5-10%	23,750	2-3
IE3	900	2,200	15%	21,250	3-5
IE4	1,200	3,000	20%	20,000	4-6
IE5	N/A	4,500	25-30%	17,500	5-7

Motor Size (kW): 5-20 (KW)

Annual Energy Use (kWh): Estimated annual energy consumption, assuming an average operational duration of 5,000 hours per year.

In

Table 7, the comparative energy efficiency of old vs. modern electric motors is addressed.

Table 7: Comparative Energy Efficiency of Old vs. Modern Electric Motors [27].

Motor Type	Efficiency (%)	Annual Energy Use (kWh)	CO2 Emissions (tons)	Payback Period (Years)
Older Motor (Pre-2000)	80-85	120,000	50	N/A
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Modern Motor (IE5)	97-98	80,000	30	5-7

Note: The power rating of 75 kW reflects the reference motor used in the lifecycle assessments (LCA) from [27]. This provides a basis for comparing energy savings and emissions across efficiency classes.

3.3 Environmental Impact Analysis

Environmental sustainability has become an increasingly important aspect of motor repair and replacement decisions. A Life Cycle Assessment (LCA) approach evaluates environmental impact across all phases—from raw material extraction to disposal. Squirrel Cage Induction Motors (SCIMs), commonly of IE3 efficiency, are often associated with relatively lower environmental impacts in terms of manufacturing and recycling compared to newer models like Permanent Magnet Synchronous Motors (PMSMs). However, this is not universally true, as demonstrated in [11]. While PMSMs rely on rare earth metals, which pose challenges in extraction, recycling, and disposal, their superior energy efficiency over the lifecycle can result in lower net environmental impacts, particularly in regions with clean energy grids. The overall impact of PMSMs is highly context-dependent, influenced by factors such as energy mix, operational efficiency, and the availability of advanced recycling technologies [11] [15].

Synchronous Reluctance Motors (SynRMs) which can also reach IE5 efficiency and offer a more sustainable option without sacrificing efficiency [11] [16]. IE5 SynRMs use about the same amount of active materials as IE3 induction motors. Because of its lower losses SynRM technology offers up to 30°C lower winding temperatures and up to 15°C lower bearing temperatures, which increases the reliability, prolongs the motor lifetime, and reduces the need for maintenance. Lower energy usage and maintenance needs also result in lower total cost of ownership, increasing not only energy- but also cost efficiency. Lower bearing temperatures are an important factor in reducing life-cycle costs because bearing failures cause about 70% of unplanned motor outages [9].

Table 8 summarizes the results of the life cycle impact assessment displaying the main impact categories with their main drivers for motors manufacturing.

Table 8 - Life cycle impact assessment displaying the main impact categories with their main drivers for motors manufacturing [27].

Main Impact category	Main drivers
Resource Depletion, fossil + mineral	Copper, Brazing
Human toxicity, cancer effects	Electrical sheets, Iron (die-cast), Steel
Human toxicity, non-cancer effects	Electrical sheets, Copper, Steel
Acidification	Electrical sheets, Coper, Steel
Global warming potential	Electrical sheets, Assembly process, Copper

In Figure 6 it can be seen that the greatest contributor of climate impact is the stator (43 %) followed by the rotor (30 %) and housing (13 %), etc. Since the stator contains a lot of iron and copper and also weights the most, it is not very surprising. The rotor, which is another big component, weights a bit less. According to SimaPro, production of iron has a bigger climate impact than production of electrical steel. However, transportation of the components differs slightly, all components of the rotor are from short distances. For the stator, all components are also typically from short distances [26].

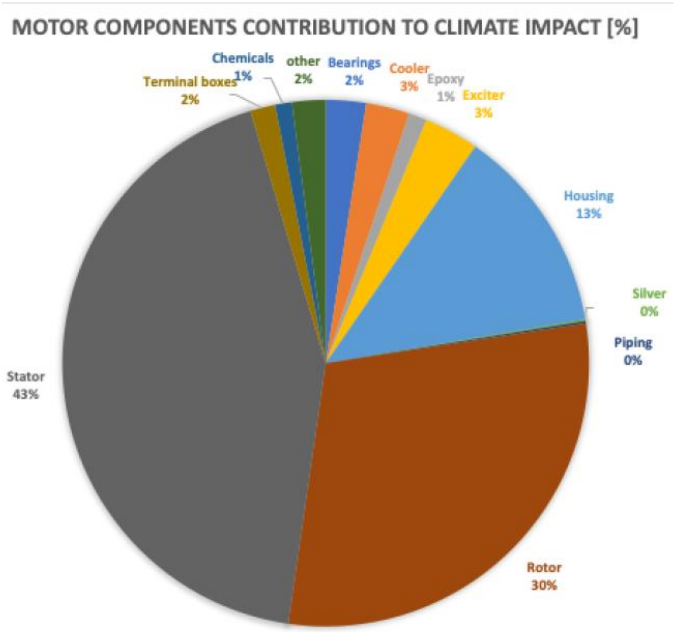

Figure 6: The motor components contribution to climate impact in kg CO2 eq including all motor components. The part called "other" is transportation of the motor and energy in the factory in Västerås [26].

The drive components have a total impact of 68.3 tonnes CO2 eq. In the Figure 7 it can be seen that the semiconductor contributes the most, 34.3 tonnes CO2 eq followed by housing with 14.6 tonnes CO2 eq and cooling with 7.03 tonnes CO2 eq. Processes which have a big contribution of CO2 eq are transportation by aircraft and aluminum production. This network is also bigger in reality, but an automatic cut-off is used which focuses on the major contributors [26].

In Figure 7 it can be seen that the greatest contributor of climate impact is the semiconductor (50 %) followed by housing (21 %) and cooling (11 %). The semiconductor contains many different materials and constitutes a big part of the drive, which contributes to the major climate impact [26].

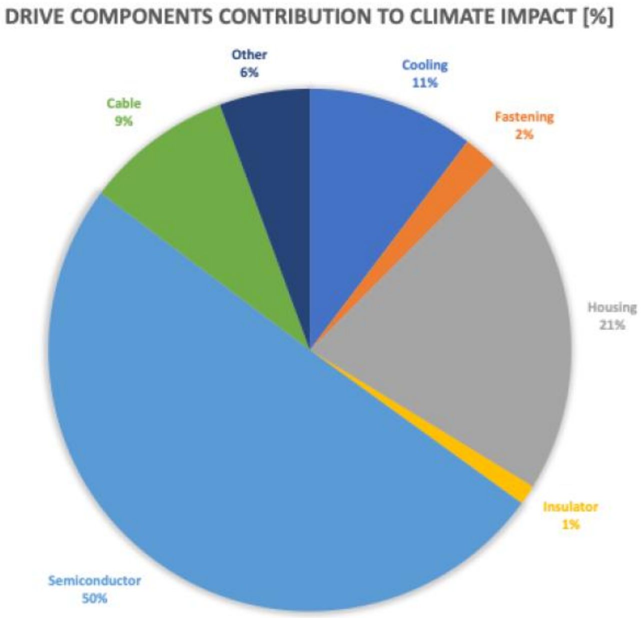

Figure 7: The drive components contribution to climate impact in kg CO2 eq. The part called "other" is transportation of the drive and energy in the factory in Turgi [26].

This sensitivity analysis is based on the Value-corrected substitution method. This means that environmental impact is allocated to the recycled materials based on the price variations for virgin material and recycled material. If the price of virgin material is high compared to the price of recycled material, more environmental impact will be allocated to the studied product system. See the climate impact in Figure 8. The sensitivity analysis shows that changing the allocation of environmental impact lowers the total climate impact from 4380 tonnes CO2 eq to 4370 tonnes CO2 eq. Since the use phase is the biggest contributor, the results do not change very much. Looking at the climate impact of the components of the motor and drive without the use phase and comparing it to the base-case scenario it shows a difference of 14 tonnes CO2 eq. This means that the climate impact decreases with approximately 22% when allocating the environmental impact to the recycled materials and the next product systems. This indicates that allocation of environmental impact can make a big difference for the components of the motor and drive since a lot of metals are recycled with maintained quality. It does however not impact the overall results very much since the use phase is not impacted by this change [26].

A study by Orlova et al. (2016) shows that the environmental impact is by far the greatest for the use phase for three different types of motors, synchronous reluctance motor (SynRM), permanent magnet assisted synchronous reluctance motor (PMSynRM) and induction motor (IM), see Table 9 Many studies, including the one by Orlova et al. (2016), define the system function of the motor as an energy converter and not as an end-use device (Autsou *et al.*, 2018; Ayyappan *et al.*, 2019). This means that only the losses are considered in the use phase for the life cycle assessment [26]. These motors were assumed to be operating for 3000 hours over 15 years or more, see Table 10.

Table 9 -Three different types of motors and their environmental impact at different Lifecycle stages in percentage (Orlova et al., 2016) [26].

Type of Motor	Production (%)	Distribution (%)	Use (%)	End of Life (%)
SynRM	1.404	0.017	98.515	0.064
PMSynRM	1.807	0.21	98.086	0.086
IM	1.980	0.21	97.9	0.100

Table 10 - Technical information about the motors for the use phase (Orlova et al., 2016).

Parameters	SynRM[1]	PMSynRM[1]	IM
Lifetime (years)	More than 15	More than 15	15
Operating Hours	3000	3000	3000
Efficiency (%)	70	90	87.6
Output power (kW)	10	10	10

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[1] Although there is not much experimental data, because of its lower losses, SynRM technology offers lower winding and bearing temperatures, thus leading to longer lifetimes compared to induction motors.

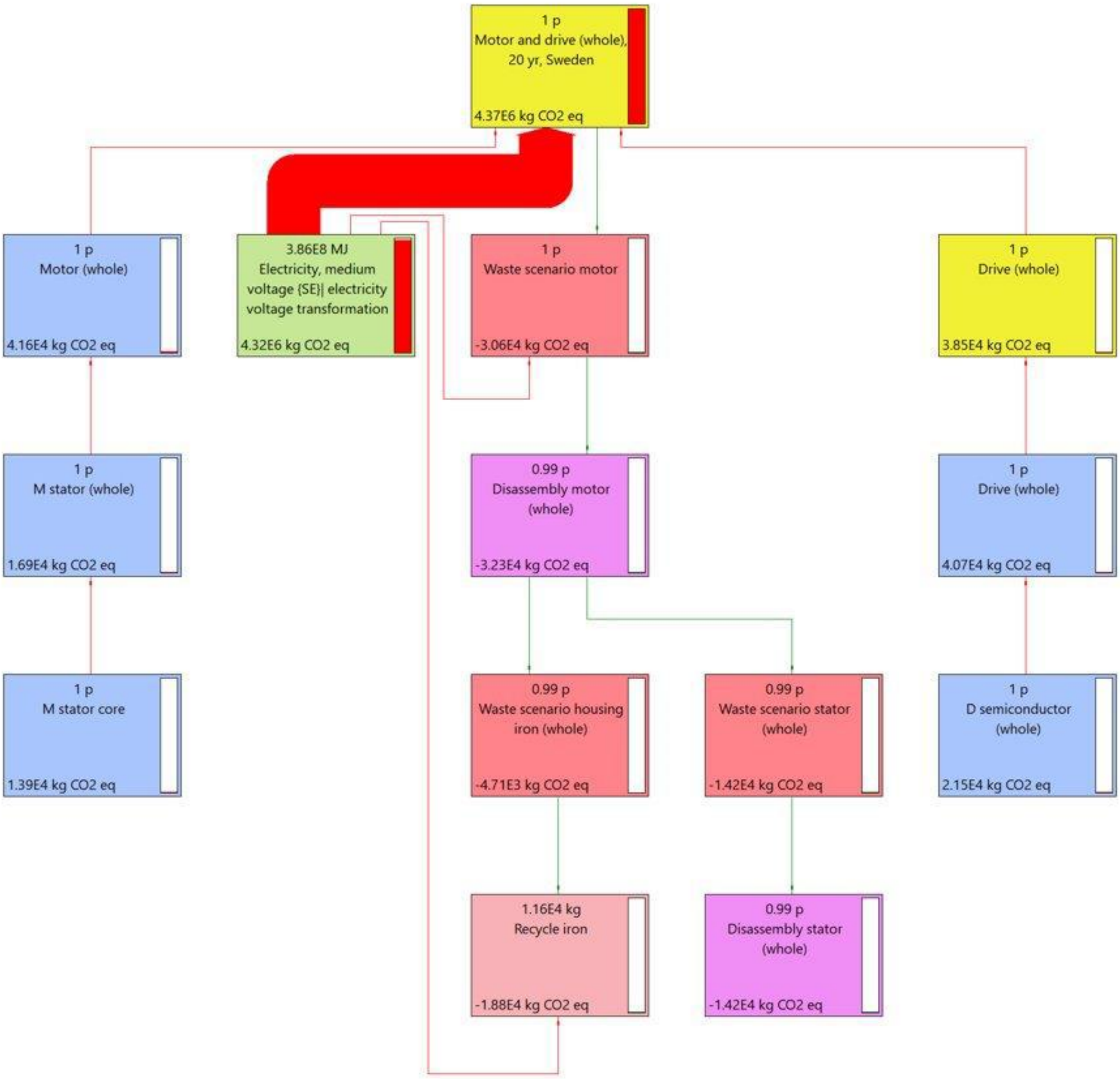


Figure 8: Motor and drive used in Sweden for 20 years, like the base-case scenario but with allocation of environmental impact to the recycled material according to environmental impact to the recycled material according to the value-corrected substitution method [26].

A. Jerome et al. [28] have investigated the inquiry "Is the repair of energy-consuming products environmentally advantageous?" through an examination of the case of high voltage electric motors. This study looks at the life cycle environmental and resource depletion impact of use extension and improved efficiency by design of a long-lived and energy intensive product through the case of HV motors. The energy losses during the use phase dominate the life cycle impact, both for GW and mineral resource depletion, due to the long lifetime, high energy output and intensive use of HV motors. Therefore, improving energy efficiency leads to more significant life-cycle environmental impact reductions than extending the use by repair. Unlike EuP with shorter and less intensive use, the potential benefit from reuse is also low for resource depletion impact and when very low carbon electricity mixes are used. The environmental performance of energy intensive HV motors is also highly sensitive to energy efficiency reduction when performing repair, especially in the case of a carbon-intensive electricity mix. A small energy efficiency reduction leads to the repair not being beneficial. Measures to guarantee a high quality of repaired EuP with an intensive use need to be included for use extension to be beneficial. Regarding the inclusion of requirements promoting use extension in the European Ecodesign directive and similar policy initiatives, efforts should be channeled on ensuring high energy efficiency by design for EuP with intensive and long use [28].

Furthermore, in case of slow development of energy efficiency, ensuring a more durable design would be more relevant than repair which would lead to little benefit while risking impairing the product's energy efficiency performance. Prioritizing these efficient and durable designs as well as ensuring proper maintenance of energy efficiency would benefit users of energy intensive EuP [28].

Finally, the use of resources for electricity production and transmission is as important as the resources in the product. Instead of a trade-off between resource and energy efficiency with the more energy-efficient design being more resource intensive as in other studies, energy efficiency also leads to a reduction of resource depletion impact. This highlights the importance of including resource use from electricity production and transmission when exploring CE strategies, especially for energy intensive EuP [28]. Figure 9 illustrates a simplified flowchart of the system.

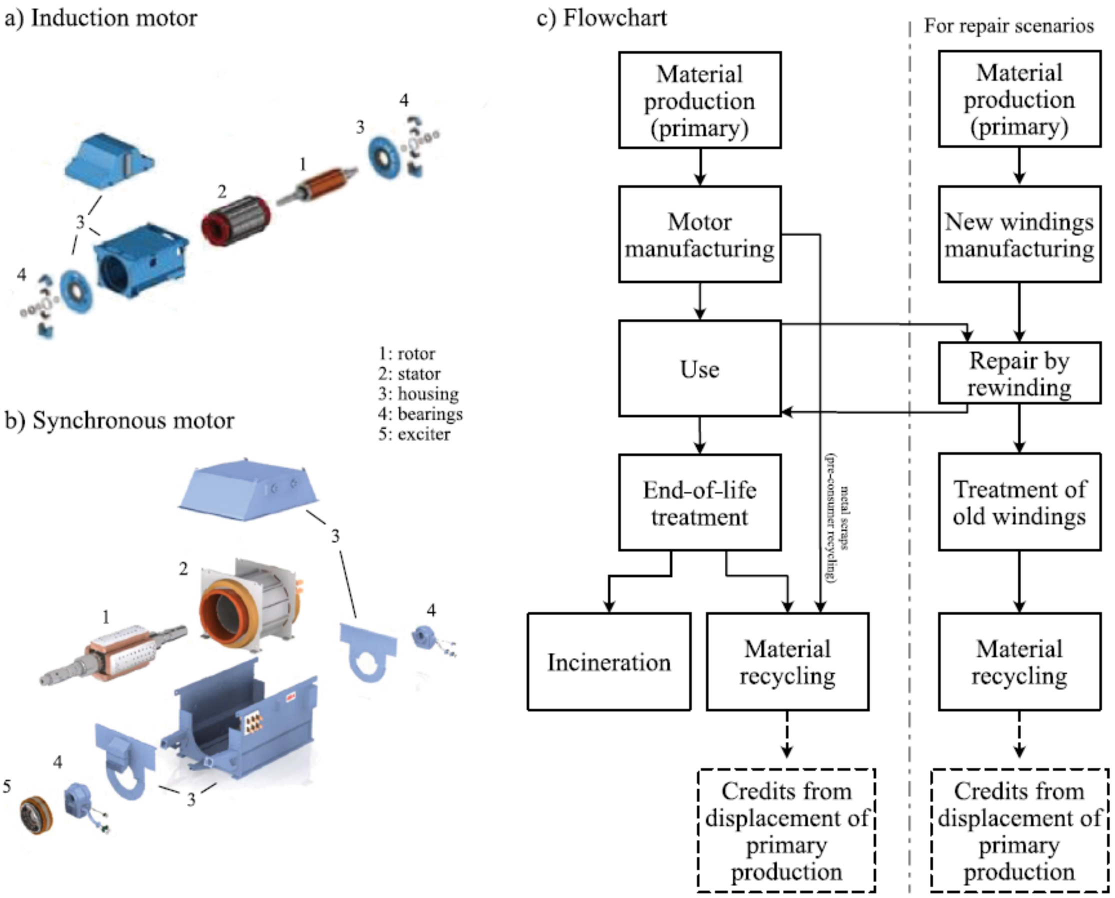


Figure 9: Exploded view of the products under study: a) an IM and b) SM, and c) a simplified flowchart of the system [28].

3.4 Non-Energy Benefits (NEBs) of Replacement

In addition to energy savings, the replacement of old motors with high-efficiency models can yield several Non-Energy Benefits (NEBs). These benefits include improved reliability, lower maintenance needs, and reduced downtime, which collectively enhance operational efficiency and output quality [20] [18]. NEBs resulting from electric motor replacement will be further analyzed and developed in EU-MORE Deliverable D4.4.

Furthermore, replacing outdated motors with newer models can reduce noise levels and vibration, contributing to safer and more comfortable work environments. Regulatory compliance is another key NEB, as higher-efficiency motors meet or exceed environmental standards, which helps avoid future costs or penalties [20]. Table 11 summarizes some examples of NEBs related to electric motor replacement.

Table 11 - Non-Energy Benefits of Motor Replacement [18] [20].

Benefit	Description
Increased Reliability	New motors are less prone to breakdowns and have a longer lifespan due to their lower losses leading to higher proactivity [18].
Reduced Maintenance Costs	Higher efficiency reduces wear and tear, lowering maintenance frequency [20].
Improved Safety	Enhanced safety due to lower vibration and heat emissions [20].
Regulatory Compliance	Higher efficiency meets stricter environmental standards [20].

3.5 Case Study: Repair and Replacement Practices in the EU

The European motor industry provides insights into repair and replacement practices across sectors. In industries such as steel, cement, and chemical manufacturing, where operational efficiency is paramount, motor replacement is generally prioritized over repair. For example, in the steel industry, the shift to synchronous motors led to a 20% reduction in energy costs and improved process uptime [21] [22].

An in-depth study of motor replacement in the EU manufacturing sector also highlights the trend towards high-efficiency motor adoption, especially in industries with high energy demand. Incentive programs by national governments further encourage these industries to adopt efficient motors, reducing both energy consumption and operational costs [18]. Table 12 presents the industry-specific practices in motor repair and replacement.

Table 12: Industry-Specific Practices in Motor Repair and Replacement [21] [22].

Industry	Preferred Option	Key Benefits
Steel Manufacturing	Replacement	Reduced energy costs, increased uptime [21]
Chemical Industry	Replacement	Improved process control, compliance [22]
Food Processing	Repair	Lower costs, manageable downtime [18]

3.6 Recycling and End-of-Life Considerations

End-of-life (EoL) considerations for electric motors are crucial, particularly for sustainable recycling and disposal. The European Union promotes motor recycling through initiatives that support the recovery of valuable metals like copper and aluminum. Despite this, challenges persist in recycling motors with complex components, such as PMSMs, which contain rare earth materials that are costly and difficult to separate [6] [13].

Recent policy innovations focus on improving the recyclability of electric motors by mandating the use of recyclable materials and supporting local recycling infrastructure. By establishing circular economy practices, the EU aims to keep valuable materials within Europe, thereby reducing the environmental impact of motor disposal [23] [16].

4. End of Life for Electric Motors and Recycling Routes

This chapter details the end-of-life (EoL) management of electric motors, with a focus on dismantling, recycling routes, environmental and economic considerations, and case studies.

4.1 Importance of EoL Management for Electric Motors

Electric motors at their end of life contain valuable materials that can be recovered, reducing demand for virgin materials and supporting circular economy objectives. EoL practices are increasingly essential as electric motors contribute significantly to industrial material flows, with substantial potential for reuse and recycling [22][23].

For instance, Figure 10 illustrated exploded view of a Low Voltage (LV) motor.

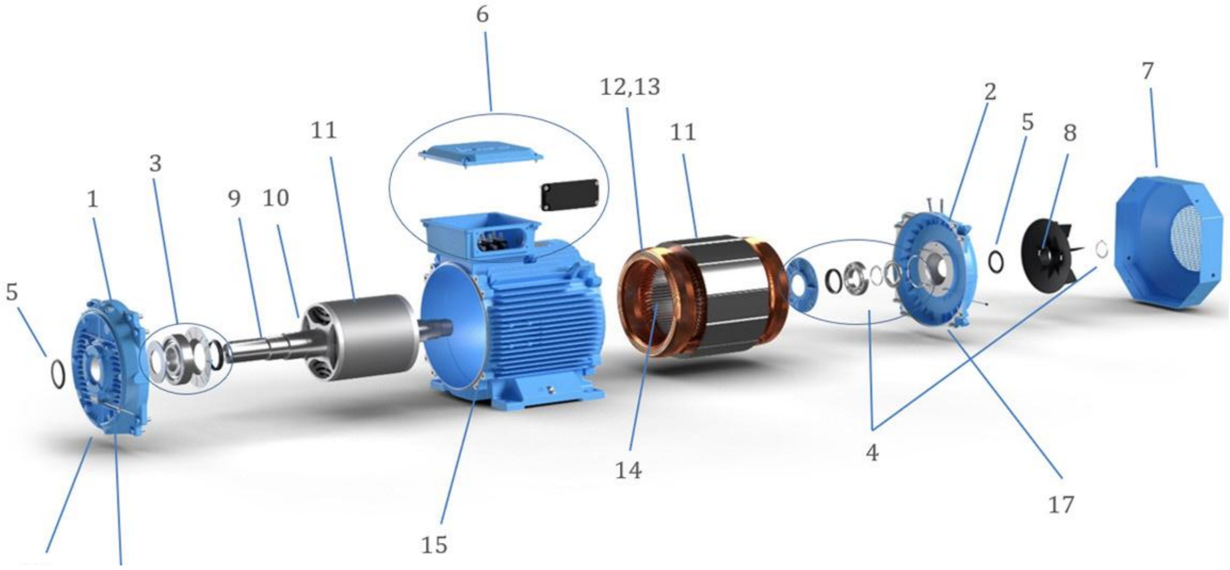


Figure 10: Exploded view of a Low Voltage (LV) motor. Numbers showing where the different components are positioned, more information can be seen in Table 13 [12].

More information can be found in Table 13. This table presents the primary material composition of electric motors, including metals such as copper, steel, and aluminum, which are prioritized for recovery.

Table 13: Description of components of the motor, the position in the Figure 10 and their respective material composition. The last comment column displays how the material should be managed at the end of life [12].

Position	Description	Material	Comment
1,2	End-shields	Cast iron, aluminum, steel	Recyclable
3,4	Bearings Bearing covers Labyrinth discs V-rings3) Wave springs Retaining rings	Steel, steel/rubber Cast iron, steel Cast iron, steel Rubber Steel Steel	Recyclable Recyclable Recyclable Landfill/energy recovery Recyclable Recyclable
5	Shaft seals	Cast iron Steel/rubber	Recyclable Landfill/energy recovery
6	Terminal box Terminal box cover Cover gasket Cable gland flange Terminal blocks, terminal fasteners Terminal fittings, plugs Intermediate flange (non- Ex) Intermediate flange/ cable bushing (Ex)	Cast iron, aluminum, steel Cast iron, aluminum, steel Rubber Cast iron, steel, stainless steel Plastic, brass, steel Brass, stainless steel, Plastic Steel/cast iron Steel, cast iron, resin	Recyclable Recyclable Landfill/energy recovery Recyclable Landfill/energy recovery Recyclable Recyclable Landfill/energy recovery Recyclable Recyclable, landfill
7	Fan cover	Steel, stainless steel, plastic	Recyclable Landfill/energy recovery
8	Fan	Plastic Aluminum, steel, stainless steel	Landfill/energy recovery Recyclable
9	Shaft, key	Steel, stainless steel	Recyclable
10	Rotor end plates	Steel, cast iron	Recyclable
11	Rotor core* *(see Table 2 for permanent magnet motors)	Electrical steel Aluminum (Not in SynRM or Permanent Magnet motors)	Recyclable Recyclable
12	Stator core	Electrical steel	Recyclable
13	Windings Cables	Copper, Copper & plastic/silicone rubber, resin	Recyclable, landfill Recyclable
14	Slot insulation	Polyimide film	Landfill/energy recovery
15	Stator housing	Cast iron/aluminum	Recyclable
16	Grease outlets	Stainless steel, steel, Rubber	Recyclable, Landfill/energy recovery
17	Drainage plugs	Plastic Stainless steel	Landfill/energy recovery Recyclable
18	Fasteners, vibration measurement & grease nipples	Steel, stainless steel	Recyclable

4.2 Dismantling and Recycling Processes

Dismantling electric motors involves the separation of various components, especially metals. This process varies depending on motor type, particularly for permanent magnet motors (PMMs) which contain rare earth elements [12].

4.2.1 Dismantling Stages

The dismantling process follows multiple stages to maximize the recovery of core materials while minimizing waste. Standard procedures include initial disassembly, component sorting, and specialized steps for PMMs to handle rare earth elements [23].

Table 14 outlines the typical dismantling stages, based on the guidelines from ABB's motor recycling instructions, highlighting steps tailored for permanent magnet motors [12].

Table 14: Key Stages in Dismantling Electric Motors [12].

Stage	Description
Disassembly	Separation of motor housing and components
Material Sorting	Segregating metals (copper, aluminum, steel) and plastics
Rare Earth Handling	Specialized handling for PMMs to recover rare earths
Shredding	Size reduction for improved material processing

4.3 Material Recovery and Recycling Routes

Material recovery from electric motors includes routes for core metals, with an emphasis on high-value materials such as copper and aluminum. PMMs require additional processes for extracting rare earth elements [22].

4.3.1 Standard Recycling Routes

Electric motors comprise high amounts of recyclable materials, particularly metals. Established routes for these materials are crucial for maintaining recycling efficiency and ensuring high recovery rates.

4.3.2 Rare Earth Element Recovery from PMMs

Recycling PMMs is challenging due to rare earth metals. Techniques such as hydrometallurgical and pyrometallurgical processing are used to recover these elements, essential for reducing reliance on primary mining [23]. Table 15 presents details concerning the primary recycling techniques for recovering rare earth elements in PMMs.

Table 15: Techniques for Rare Earth Element Recovery in PMMs [12] [23].

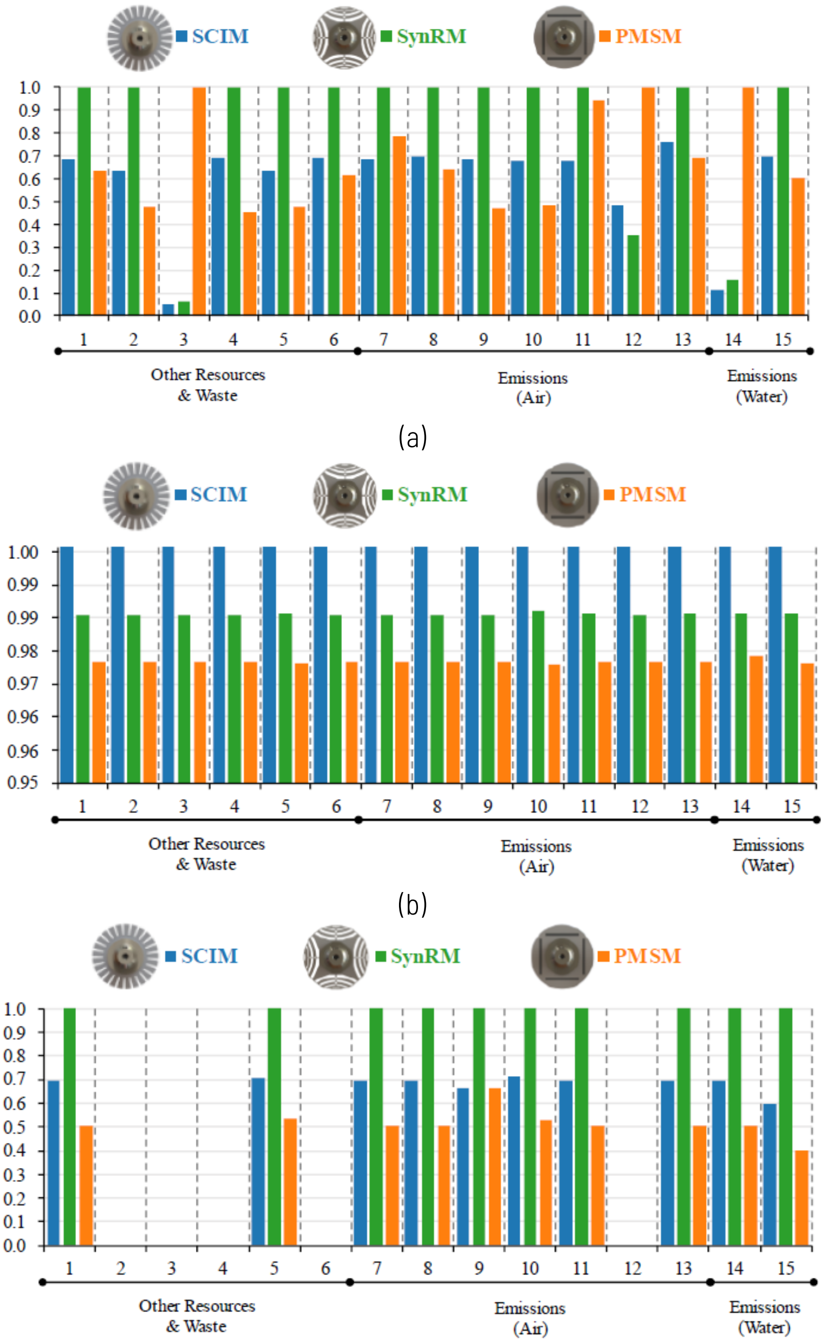
Technique	Description
Mechanical Separation	Physically separates metals and non-metal components
Hydrometallurgical Process	Uses chemical dissolution to extract rare earth metals
Pyrometallurgical Process	High-temperature processing to separate metals from impurities

4.4 Environmental Impacts of Recycling Routes

Recycling electric motors has distinct environmental impacts depending on the materials and methods used. SynRM and PMSM motors, while efficient in operation, entail higher environmental costs due to rare earth elements, which are resource-intensive to recycle [11].

4.4.1 Environmental Impacts of Different Types of Motors in Motor Recycling

Danilo et al. have investigated the environmental impacts of electric motors in motor recycling for the case studies of PM, SCIM, and SynRM types. The results are presented in Figure 11.



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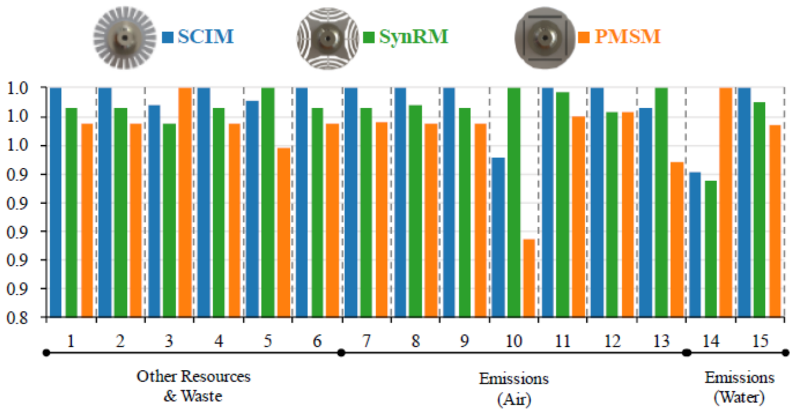


(d)

Figure 11: Environmental impacts of the electric motors [11]. a) Manufacturing phase. b) Use phase. c) End-of-life phase. d) Total.

4.4.2 Lifecycle Emissions in Motor Recycling

Lifecycle assessments (LCA) quantify emissions from each stage in a motor's lifecycle. While recycling reduces the need for virgin materials, improper handling can result in significant emissions, highlighting the need for optimized recycling methods [1].

Table 16 provides emission data across different motor types and lifecycle stages, drawn from World Energy Outlook 2021's LCA data and supplemented by studies on environmental impacts of efficient technologies [1] [11].

Table 16: Emissions by Motor Type and Lifecycle Stage (for Motors Rated at 10 kW) [1] [11].

Motor Type	Manufacturing Emissions (CO_2-eq)	Use Phase Emissions (CO_2-eq)	Disposal Emissions (CO_2-eq)	Notes
SCIM	120 kg	500 kg	80 kg	Based on 20 years of operation at 3,000 hours/year.
PMSM	200 kg	400 kg	150 kg	Includes rare earth material processing impacts.
SynRM	150 kg	450 kg	100 kg	Lacks rare earths; emissions depend on steel content.

4.5 Economic and Policy Considerations

Economic and policy-related factors impact the feasibility and efficiency of motor recycling. High recycling costs, coupled with volatile material prices, present challenges. Policies like the EU Circular Economy Action Plan aim to mitigate these issues through financial incentives [23].

4.5.1 Economic Barriers to EoL Recycling

Recycling infrastructure requires significant investment, especially for handling rare earth elements. Variable market prices for recovered metals also affect the profitability of recycling operations [22].

Table 17 highlights the cost challenges and incentives derived from circular economy policies [1][23].

Table 17: Economic Barriers and Policy Supports in EoL Recycling [1] [23].

Factor	Description
Metal Price Volatility	Fluctuations in metal prices impact recycling revenue
Technology Costs	High costs for specialized recycling equipment
Policy Incentives	Subsidies, tax credits, and grants to support recycling infrastructure

4.5.2 Policy Initiatives Promoting EoL Practices

Several policies support sustainable EoL practices by setting recycling targets and providing financial aid. The EU's Circular Economy Action Plan and member-state-specific initiatives encourage recycling and recovery, especially for high-impact materials like those in electric motors [29].

4.6 Case Studies of EoL Recycling Practices in the EU

Various EU countries have adopted innovative EoL recycling practices. Germany's advanced recycling infrastructure emphasizes efficient metal recovery, while Switzerland implements closed-loop recycling practices under stringent regulations [23].

Table 18 lists specific recycling best practices and policies in selected EU countries, showcasing effective approaches to motor recycling.

Table 18: Best Practices in EoL Motor Recycling Across EU Countries [29].

Country	Key Recycling Practices	Policy Support
Germany	Advanced metal recovery processes	National recycling targets
Switzerland	Closed-loop recycling systems	Regulations on hazardous materials
Sweden	Support for rare earth element recovery	Compliance with EU Circular Economy

5. Metal Recovery in the Recycling Process

This chapter addresses the critical aspects of metal recovery in the recycling of electric motors. Effective recovery processes enable the efficient extraction of valuable metals such as copper, aluminum, and steel, supporting circular economy goals. Each section below provides details on the steps, challenges, and best practices in metal recovery. In the end-of-life stage, the primary materials used to produce the electric motor were considered recyclable, as shown in Figure 12.

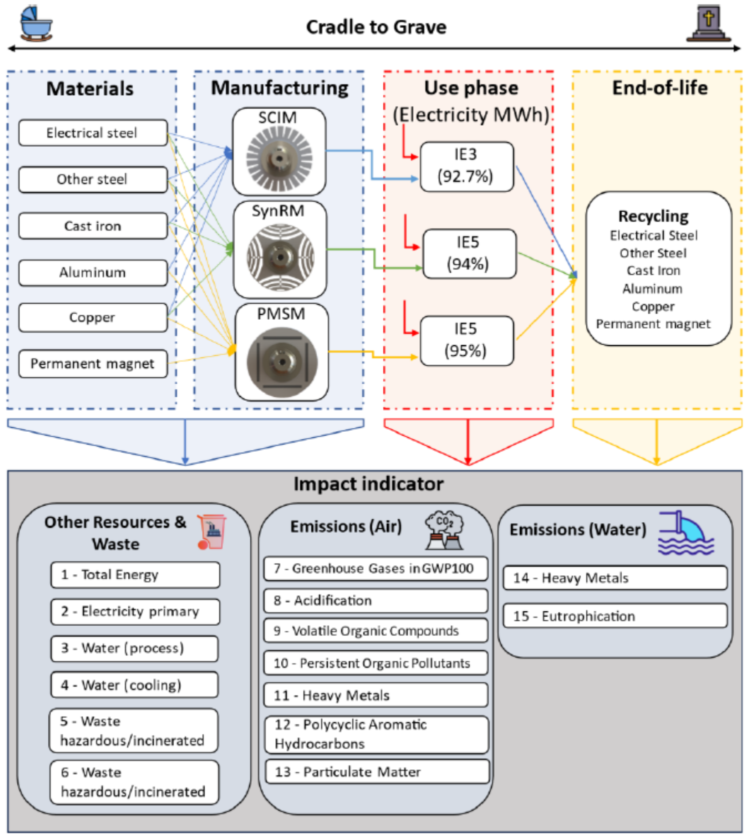


Figure 12: Comprehensive flowchart of materials in electric motors in the EoL cycle [11].

5.1 Why Recycling is Essential?

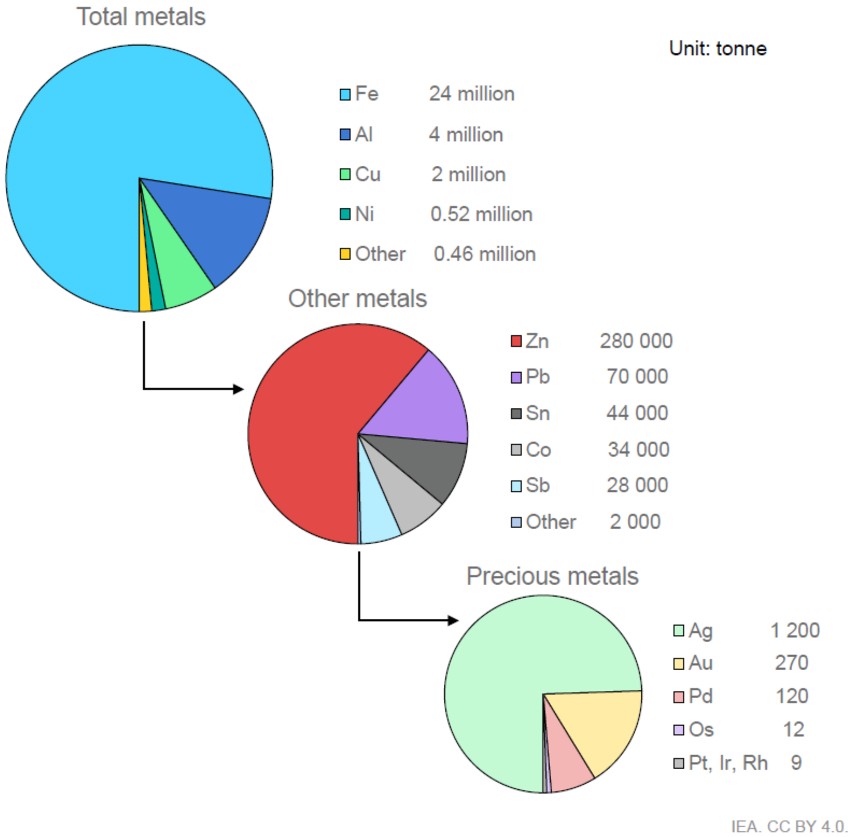
The global energy system is undergoing a significant transformation toward clean energy technologies, which fundamentally differ from those reliant on fossil fuels. This transition places an unprecedented demand on minerals critical for clean energy systems. Lithium, nickel, cobalt, manganese, and graphite are pivotal for battery technologies, while rare earth elements are indispensable for permanent magnets used in high performance industrial drives, elevators, wind turbines, and electric vehicle (EV) motors. Moreover, electricity infrastructure demands vast quantities of copper and aluminum, with copper forming the backbone of most electrical technologies.

The shift toward clean energy intensifies the need for these minerals, potentially creating supply challenges and raising security concerns that differ from those traditionally associated with fossil fuels. Unlike fossil fuels, which are consumed during use, minerals and metals in clean energy systems can be recovered and recycled at the end of their lifecycle. This opens the door to a circular economy for clean energy, reducing dependence on mining and enabling sustainable resource use [32].

Figure 13 illustrates the estimated volume of metals contained in e-waste, 2022.

5.1.1 Benefits of Recycling

Secondary Supply and Reduced Primary Extraction Recycling creates an additional supply source, lessening the dependence on new mining operations. While recycling cannot fully replace the demand for primary materials, it can significantly reduce the burden. Analysis indicates that without increasing recycling efforts, the global investments required in mining to achieve net-zero emissions by 2050 would rise by USD 240 billion—or 30%—by 2040 [32].



Notes: Fe = iron; Zn = zinc; Pb = lead; Sn = tin; Sb = antimony; Ag = silver; Au = gold; Pd = palladium; Os = osmium; Pt = platinum; Ir = iridium; Rh = rhodium; Ru = ruthenium.
Source: IEA analysis based on Baldé, Kuehr, Yamamoto et al., International Telecommunication Union and United Nations Institute for Training and Research (2024). Global E-waste Monitor 2024.

Figure 13: Estimated volume of metals contained in e-waste, 2022 [32].

5.1.2 Improved Resource Security

Recycling strengthens resource security for countries with high deployment of clean energy technologies but limited domestic mineral reserves. By diversifying supply chains and building domestic recycling infrastructure, nations can buffer against geopolitical disruptions, ensuring a stable and resilient resource flow [32].

5.1.3 Environmental Benefits

Recycling significantly lowers the environmental footprint of clean energy technologies. On average, recycled minerals emit 80% less greenhouse gas (GHG) than virgin materials due to less energy-intensive processes. For example, aluminum recycling reduces emissions by 90%, and manufacturing nickel-rich lithium-ion batteries with recycled materials can cut emissions by 28%. The environmental advantages vary depending on the energy mix and recycling methods used [32].

5.1.4 Waste Reduction

Effective recycling mitigates the enormous waste generated by end-of-life technologies such as EV batteries, solar panels, and wind turbines, which otherwise risk overwhelming landfills and polluting ecosystems. Additionally, recycling addresses manufacturing waste and mine tailings, further minimizing environmental harm [32].

5.1.5 Current Recycling Practices and Future Prospects

While base metals like steel and aluminum have well-established recycling systems, critical energy transition minerals such as lithium, cobalt, and rare earth elements are not yet widely recycled. Currently, recycling feedstock is dominated by electronic waste and manufacturing scrap. However, this dynamic is expected to shift after the current generation of EVs reaches the end of its lifecycle in the coming decades. Scaling up recycling infrastructure and fostering collaboration between manufacturers and recyclers will be crucial for realizing these benefits.

Recycling is not only a strategy for addressing material shortages but also a pathway to enhance environmental sustainability, reduce waste, and build a robust clean energy future [32].

5.2 Recycling Process

Recycling involves converting materials that contain recoverable metals into usable products through various processing stages. This feedstock for recycling falls into two main categories: **manufacturing scrap** and **end-of-life scrap**. Manufacturing scrap consists of materials or products that fail to meet quality standards during production, while end-of-life scrap includes items like electric vehicle (EV) batteries, solar panels, wind turbines, and their permanent magnets. A broader approach, known as *urban mining*, considers all human-made objects—such as electronics, industrial equipment, electrical wiring, and even buildings—as potential reservoirs of recoverable metals [32]. Figure 14 illustrates overview of the recycling process for energy transition minerals.

5.2.1 Stages of the Recycling Process

The first step in recycling involves **collection and transportation** of the feedstock, often the most challenging phase due to historically low collection rates, regulatory hurdles, and safety issues. Once collected, materials undergo **pre-treatment and recovery stages**. These steps vary based on the type of feedstock but typically include sorting, separation, and processing [32].

For instance, in **battery recycling**, recovery methods include *pyrometallurgy* (high-temperature processing) and *hydrometallurgy* (chemical-based extraction). Recovered materials are then transformed into secondary supply products. Depending on the level of processing, these products can be reused in the same application (closed-loop recycling) or repurposed for different applications (open-loop recycling). In some cases, certain scrap types bypass processing entirely and are directly used by fabricators as "direct-use scrap" [32].

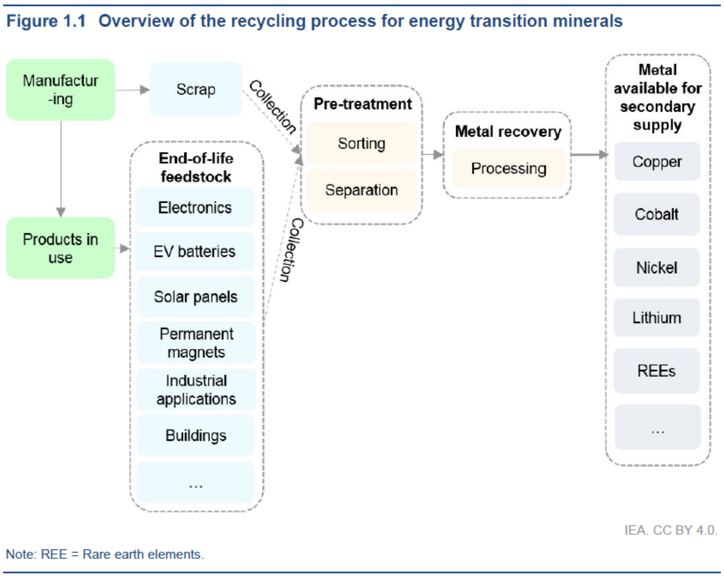


Figure 14: Overview of the recycling process for energy transition minerals [32].

5.2.2 Key Characteristics of Recycled Metals

Unlike many other materials, metals—including specialty alloys—can be recycled repeatedly without losing quality. The specific metals recovered depend on the original feedstock. For instance:

- EV batteries yield materials like nickel, cobalt, manganese, and lithium, particularly from lithium nickel manganese cobalt oxide (NMC) batteries.
- Solar panels provide secondary sources of copper, aluminum, silver, and silicon.
- Wind turbines contain base metals such as aluminum, copper, and nickel, as well as rare earth elements from their permanent magnets.

Currently, copper is most commonly recycled from industrial and construction applications, but end-of-life EV batteries are emerging as a growing source of secondary copper [32].

5.2.3 Exploring Unconventional Sources

In addition to traditional recycling, waste from mining processes—commonly known as **tailings**—is being reevaluated. These tailings, previously considered waste, often contain minerals that were not initially economical or technologically viable to extract. For example:

- Older copper mine tailings may contain lower-grade copper ore that can now be economically processed.
- Tailings may also hold by-products like cobalt, which have gained value due to their importance in clean energy technologies.

This approach, while not classified as secondary supply in the strict sense, offers a way to reclaim value from waste streams and align with the objectives of the energy transition [32].

5.3 Importance of Metal Recovery in Electric Motor Recycling

Metal recovery plays a central role in the end-of-life processing of electric motors, offering both environmental and economic benefits. The primary metals recovered from electric motors include copper, steel, and aluminum. These metals have high recycling rates and are essential for manufacturing new electric motors and other products. Effective recovery reduces reliance on primary metal extraction, helping to decrease the environmental footprint of motor production [14]. Table 19 highlights the percentage of material composition of the motors with different IE classes, with copper and steel being the largest components.

Table 19: Material composition of the motors with different IE classes. The IE2-motor is the reference for the percentages displaying the increase for certain material groups when the efficiency is increased [27].

Material group (assigned generic treatment processes)	IE2	IE3	IE4
Electric sheets (stamping)	271 KG	10%	10%
Cast Iron (die casting)	271 KG	0%	0%
Copper (wire drawing)	69 KG	4%	10%
Other Steel (stamping and bending)	64 KG	0%	0%
Packaging Material (wooden pallet production)	24 KG	0%	0%

Material group (assigned generic treatment processes)	IE2	IE3	IE4
Aluminum (extruding)	19 kg	5%	5%
Impregnation Resin	5 kg	20%	20%
Others: Other materials with mass below 5 kg and no difference between the IE classes: Plastics (injection molding), Insulation, Paint (painting), Rubber, Brass (stamping and bending), Solder (brazing) & Grease	9,8 kg	0%	0%

Figure 15 displays the material fractions that have been increased in quantity to reach the higher efficiency levels accordingly. These material groups then have been matched to a corresponding, most representative LCI processes in GABI, reflecting the inputs, like crude oil or copper ore, and outputs, like CO2-emissions or metal scrap, of this manufacturing step.

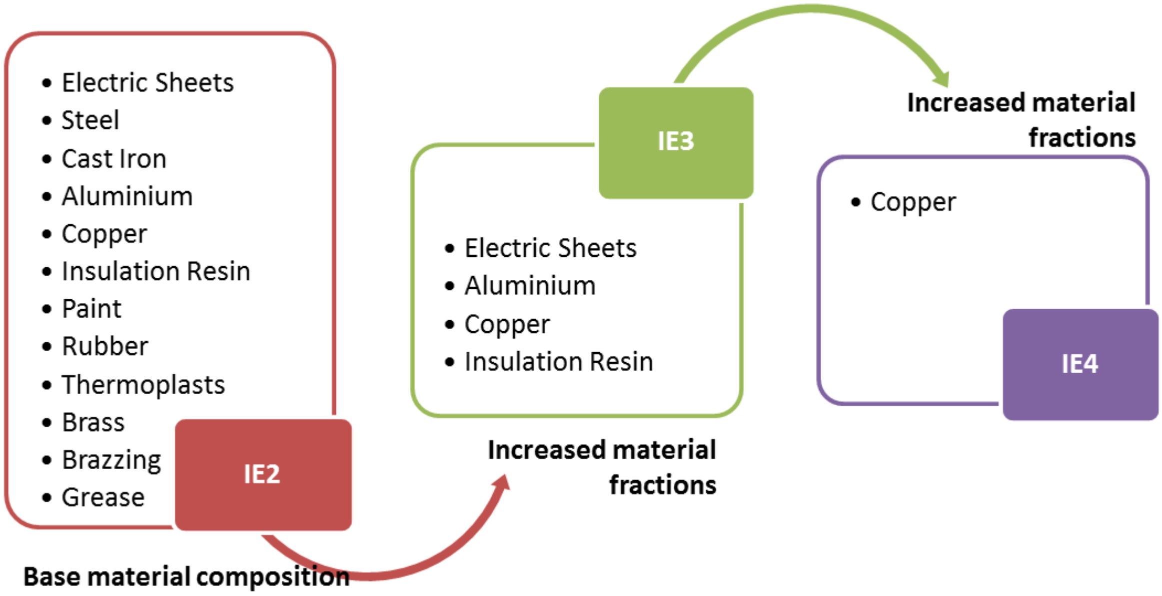


Figure 15: Display of material fractions increased, from the base material composition of an international efficiency class 3 (premium efficiency) and 4 (super premium efficiency) as defined in IEC 60034-1-30. No material fractions decrease in this regard [27].

5.4 Key Steps in Metal Recovery

Metal recovery involves a series of steps designed to separate, purify, and recycle metals from electric motors. Each step is essential for maximizing yield and quality.

5.4.1 Disassembly and Sorting

The first step in metal recovery is disassembly, where motors are broken down into their component parts. This step often includes sorting materials into different streams for specialized recycling processes, which is especially crucial for copper and steel [23]. Table 20 lists the steps in the disassembly and sorting stages of metal recovery, highlighting the processes involved in recovering each metal type.

Table 20: Steps in Metal Recovery from Electric Motors [12].

Step	Description
Disassembly	Separating motor parts into core material groups
Sorting	Grouping metals based on magnetic and non-magnetic properties
Shredding	Reducing size for further processing
Metal Separation	Magnetic separation and eddy current techniques for purity

5.4.2 Shredding and Magnetic Separation

After initial sorting, the motor components undergo shredding and magnetic separation. Magnetic separation helps in isolating ferrous metals (like steel), while non-ferrous metals such as copper are collected separately [14]. Figure 16, a comprehensive overview of magnetic separation content is provided.

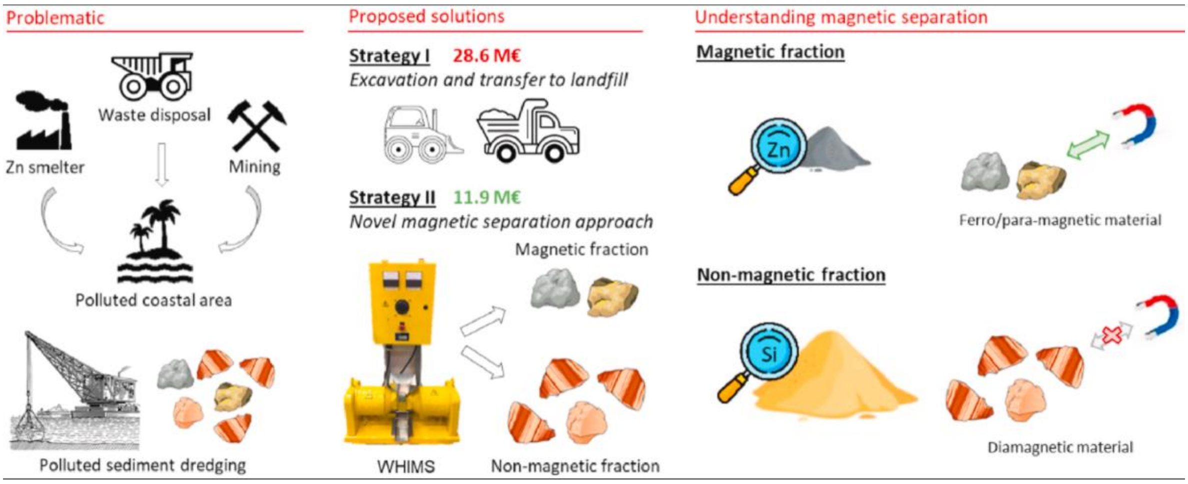


Figure 16: Comprehensive overview of magnetic separation content [30].

5.5 Challenges in Metal Recovery

Despite the benefits, metal recovery from electric motors faces significant challenges, including contamination, mixed material compositions, and the complexity of motor design. Contaminants like insulation materials and coatings can hinder efficient recycling [26].

5.5.1 Contamination and Purity Issues

Achieving high-purity metals during recovery is challenging, as insulation and other non-metallic materials must be removed. Processes like hydrometallurgical treatment can help purify metals but add cost [23]. Table 21 summarizes typical contaminants found in electric motors and their impact on the purity and quality of recovered metals.

Table 21: Common Contaminants and Their Effects on Metal Recovery [12].

Contaminant	Impact on Recovery
Insulation	Reduces copper purity, requires additional processing
Coatings	Interferes with metal separation
Mixed Alloys	Affects aluminum and steel quality

5.5.2 Economic and Technological Barriers

High costs of recycling technologies and fluctuating market prices for metals can limit the feasibility of metal recovery. Economic support and innovation in recycling technology are essential for addressing these barriers [14].

5.6 Copper Recycling: A Critical Pathway for Sustainability

The expansion of copper recycling is pivotal in addressing the growing demand for critical minerals, particularly for clean energy technologies. Copper, with its unparalleled properties such as high conductivity, durability, ductility, and corrosion resistance, is indispensable for applications in electric motors, electric vehicles (EVs), batteries, solar panels, wind turbines, and power networks. In the context of electric motors, copper is particularly significant due to its role in windings, wires, and other essential components. Its efficient recovery and recycling are vital for supporting the circular economy and ensuring a sustainable supply of materials for electric motor production and refurbishment.

Given the growing demand for copper, both mining and recycling are needed. The mine production in 2023 reached 22 million tons. The International Copper Study Group[2], monitors detailed global information on copper mine projects with annual capacities above 100,000 tonnes. All together they represent 10 million tonnes of copper. Together with this projection in mining capacity, recycling is also expected to grow. Copper in use is estimated around 370 million tonnes[3], which will come to end-of-life in the coming years, representing an important source for secondary copper.

5.6.1 Why Focus on Copper in Electric Motor Recycling?

Electric motors are among the most copper-intensive devices in use today. The metal's superior electrical conductivity and mechanical properties make it indispensable for motor windings, connections, and other critical components. This section emphasizes copper due to its central role in electric motor recycling and the opportunities it presents for reducing waste, closing material loops, and ensuring the sustainability of motor production and maintenance processes [32].

5.6.2 Types of Copper Scrap

Copper recycling relies on two main sources of scrap [32]:

1. **Manufacturing Scrap:** This "new scrap" is generated during production processes and consists of off-spec materials such as cathodes, rods, and bars. This category already boasts high recycling rates, often through closed-loop systems that ensure minimal waste.
2. **End-of-Life Scrap:** Sourced from products at the end of their lifecycle, including EV motors, power cables, and consumer electronics, this "old scrap" poses greater challenges due to its multi-material composition. Enhanced processes are required to separate and recover copper efficiently from these products, presenting significant potential for expansion.

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[2] Source: https://icsg.org/copper-factbook/ page 9.

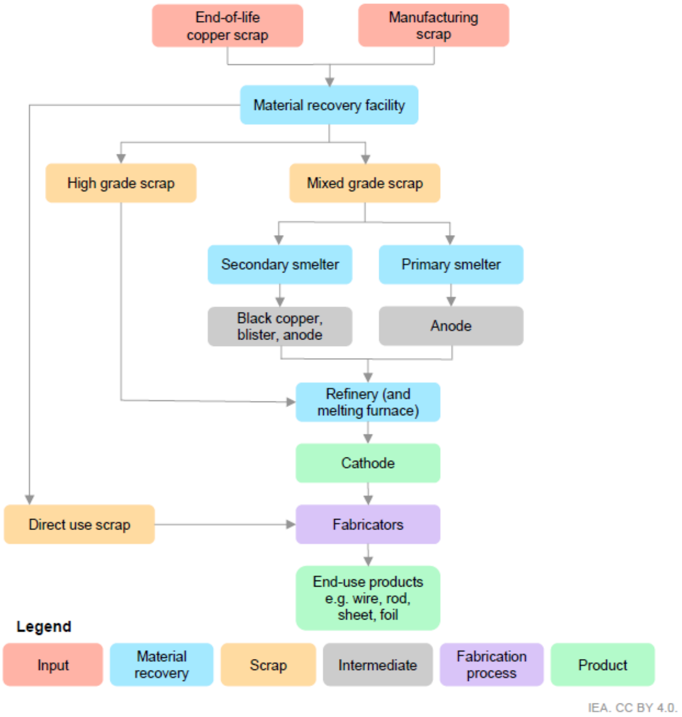
[3] Source: https://internationalcopper.org/wp-content/uploads/2017/12/ica-copper-recycling-201712-A4-HR.pdf.

5.6.3 Recycling Processes and Pathways

Copper scrap is recycled through two primary pathways [32]:

1. **Direct-Use Scrap:** High-grade scrap, often referred to as "No. 1 scrap," is directly reused by fabricators to produce semi-finished goods such as wires and rods. This method is both energy-efficient and cost-effective, requiring only a melting furnace.
2. **Secondary Production:** Lower-grade scrap, typically "No. 2 scrap," undergoes processing in primary or secondary smelters to remove impurities. After smelting, the material is refined into copper cathodes. This pathway is critical for recycling end-of-life scrap and meeting stringent quality requirements for diverse applications.

Figure 17 illustrates copper scrap recycling processes and pathways.



IEA. CC BY 4.0.

Figure 17: Copper scrap recycling processes and pathways [32].

5.6.4 Current Challenges and Market Trends

Copper scrap recycling is influenced by copper prices and economic activity. Higher industrial output drives scrap generation, while economic slowdowns reduce availability and collection efforts. Regional trade dynamics also play a role [32]:

- **China:** A leading importer, China sources high-grade scrap from countries like the United States, despite imposing restrictions on low-grade scrap to address environmental concerns.
- **United States and Europe:** Both regions face challenges in processing lower-grade scrap due to limited domestic capacity. However, policies such as the European Union's Critical Raw Materials Act (CRMA) aim to boost domestic recycling rates and control scrap exports. An example of increasing processing capacities is the Circular project in Spain.

- **Asia (excluding China):** With advanced processing infrastructure in countries like Japan and Korea, the region heavily relies on scrap imports, emphasizing the importance of robust global scrap trade systems.

5.6.5 Policy and Investment Opportunities

Expanding copper recycling requires strategic actions, including [32]:

- Increasing collection rates for end-of-life products such as building wiring, EV motors, and consumer electronics.
- Enhancing sorting technologies and scaling up secondary smelting capacity.
- Implementing stricter regulations on scrap trade and providing economic incentives for domestic recycling efforts.
- Addressing energy cost challenges for secondary smelters, especially in regions with high fuel prices.

Copper's infinite recyclability, combined with robust recycling systems, holds immense potential to reduce reliance on primary mining, and support the clean energy transition. In the electric motor sector, where copper is a cornerstone material, its efficient recycling aligns with the broader goals of sustainability and the circular economy. Strengthening infrastructure, fostering international partnerships, and enacting supportive policies will be essential for realizing this potential.

5.7 The Importance of Traditional Metal Recycling, with a Focus on Copper

Expanding the recycling of end-of-life scrap from traditional industries is vital to easing the strain on critical mineral supplies. Copper plays a key role in numerous electrical applications., Enhancing copper recycling is a pivotal strategy to ensure the global transition to a renewable and electrified energy system [32].

5.7.1 Rising Opportunities in Secondary Copper Supply

With a projected increase in copper scrap availability, opportunities for secondary copper supply are growing. Scrap volumes are expected to surge after 2030, driven by consumption trends. While scrap availability aligns with consumption growth until 2030, it is set to exceed demand growth afterward. In the APS, total scrap volumes—prior to collection and processing losses—are forecast to rise from 16 million tonnes (Mt) today to 19 Mt by 2030 and 28 Mt by 2050, representing 70% of expected demand.

Construction will remain the largest source of end-of-life copper scrap, but contributions from electric vehicles (EVs) and energy storage systems are expected to increase dramatically, expanding over 35 times between 2030 and 2050. To capitalize on this potential, improving collection rates and expanding secondary processing capacities are essential actions [32].

5.7.2 Policy Interventions to Enhance Secondary Supply

The share of secondary copper supply in total demand has stagnated since 2015, but the anticipated influx of end-of-life scrap post-2030 offers an opportunity to reverse this trend. A range of policy measures can help boost secondary supply, including:

- Increasing collection rates for legacy applications like construction and cables.
- Mandating recycling requirements and improving sorting technologies.
- Expanding investment in secondary smelters and processing facilities.

Fostering collaboration across the copper recycling supply chain—from scrap collectors to pre-processors and smelters—can enhance capacity utilization and improve the efficiency of scrap trade.

In the APS, secondary copper supply's share of total demand is expected to rise significantly, from 17% today to nearly 40% by 2050 (excluding direct-use scrap). [32].

5.8 Unlocking the Untapped Potential of Metal Recovery from E-Waste, Mine Waste, and Magnets

5.8.1 E-Waste Recycling: A Growing Opportunity

Despite increasing awareness, the recovery of metals from e-waste remains underutilized and requires significant attention from both industries and policymakers. In 2022, only 25% of the global e-waste generated was documented as properly collected and recycled. This starkly contrasts with the fivefold increase in global e-waste generation since 2010, which has outpaced collection and recycling efforts. Consequently, the share of recycled e-waste has declined.

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. With just 80 of 193 countries having implemented e-waste regulations as of mid-2023, there is considerable room for improvement in global policy frameworks. Enhanced actions, such as stricter regulations, penalties for illegal dumping, better traceability systems, and advancements in pretreatment technologies, could substantially improve the recovery of critical minerals from e-waste [32].

5.8.2 Rare Earth Element Recycling from Permanent Magnets

The recycling of rare earth elements (REEs) from permanent magnets remains limited, but the rapid growth of electric vehicles (EVs) and wind energy systems presents a promising opportunity to expand these efforts. At present, most recycled REEs come from manufacturing losses, with end-of-life magnet recycling facing significant challenges, including collection rates below 5% and economic constraints.

The increasing use of permanent magnets in EV motors and wind turbines has the potential to boost collection rates. However, recyclers often prioritize more readily accessible or higher-value materials, such as copper and battery metals, over REEs. Addressing this requires targeted policies, including financial incentives for REE recycling, mandatory recycling initiatives, and commitments from manufacturers to incorporate recycled content in new products.

Under the Announced Pledges Scenario (APS), secondary rare earth supply is projected to triple by 2050, contributing to a more secure and diversified supply of these critical materials [32].

5.8.3 Technological Pathways: "Short Loop" vs. "Long Loop" Recycling

Rare earth recycling generally follows two distinct technological pathways: the "long loop" and the "short loop" [32]. Figure 18 illustrates magnet rare earth recycling pathways.

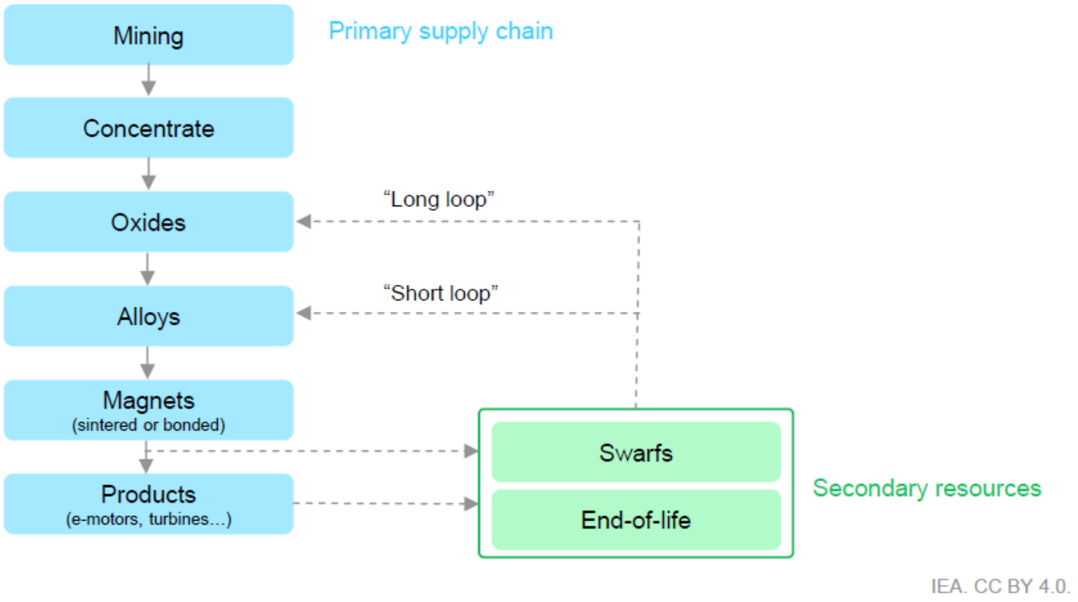


Figure 18: Magnet rare earth recycling pathways [32].

1. Long Loop Recycling:

This traditional approach focuses on extracting rare earth oxides from waste materials. The process involves reprocessing waste into oxides, requiring similar infrastructure and capabilities to refining mine. Long loop recycling provides greater flexibility in handling feedstock with varying compositions and impurities, making it suitable for contaminated materials like manufacturing scrap (e.g., swarf). Swarf, often generated during cutting processes, is typically oxidized or contaminated, making it ideal for long-loop reprocessing to recover rare earth oxides [32].

2. Short Loop Recycling:

Also referred to as "magnet-to-magnet" recycling, this pathway involves directly recycling permanent magnets into reusable alloys without breaking them down into oxides. Advances in technology, such as hydrogen-based magnet recycling processes, have made short-loop recycling more viable. This method emphasizes maintaining the integrity of the material for reuse in applications like electric motors or wind turbines.

Efficient short-loop recycling depends heavily on advanced sorting systems and accurate tracking of magnet composition. Understanding the grades and chemical makeup of magnets during the process can significantly enhance recycling efficiency, allowing for better recovery of high-quality materials.

By balancing these two pathways, the recycling industry can address various challenges, from managing contaminated feedstock to maximizing material reuse in a cost-effective and sustainable manner [32].

5.8.4 Recovering Minerals from Mine Waste

Mining waste presents an underexplored opportunity to transform environmental liabilities into valuable resources. Annually, mining activities produce roughly 100 billion tonnes of waste, with additional substantial volumes already stored in active, inactive, and closed tailings facilities. By 2030, the accumulated volume of mine waste is expected to grow nearly 90% compared to 2020 levels.

Reprocessing mine waste—commonly referred to as tailings—can not only reduce waste generation but also mitigate environmental issues such as water contamination, soil pollution, and safety risks. Additionally, at closed or abandoned mining sites, reprocessing can serve as a means of environmental remediation.

Historically, the minerals in mine waste were considered economically unviable for recovery. However, the declining quality of primary ore and rising concerns over future supply shortages have made tailings reprocessing increasingly attractive. For instance, in Chile, the amount of copper recoverable from mine waste with higher grades than primary sources is forecast to grow from 1.6 million tonnes in 2005 to 5.6 million tonnes by 2050.

Realizing the potential of mine waste reprocessing requires several measures, including comprehensive mapping of waste resources, investments in research and development for new recovery technologies, financial incentives for waste reuse, and addressing liability issues related to abandoned mining sites. These actions could help turn mining waste into a valuable secondary source of critical minerals while reducing environmental risks [32].

5.9 Advances in Metal Recovery Techniques

Advances in recycling technology, including pyrometallurgical and hydrometallurgical methods, have improved the recovery rates for metals in electric motors. These methods help recover high-purity metals while minimizing environmental impact.

5.9.1 Hydrometallurgical Recovery

Hydrometallurgical processes use chemical treatments to dissolve and separate metals, allowing for the efficient recovery of copper and rare earth elements. This process is particularly effective for permanent magnet motors (PMMs) containing rare earth metals [26]. Table 22 compares the two main recovery methods in terms of efficiency, environmental impact, and cost.

Table 22: Comparison of Pyrometallurgical and Hydrometallurgical Processes [12].

Process	Efficiency	Environmental Impact	Cost
Pyrometallurgical	Moderate	High	Moderate
Hydrometallurgical	High	Lower	Higher

5.9.2 Pyrometallurgical Recovery

In pyrometallurgical processes, high temperatures are used to melt and separate metals. While effective for bulk metals like steel, this method has higher energy demands and environmental impacts compared to hydrometallurgical processes [27].

5.10 Case Studies of Successful Metal Recovery Practices

Various EU member states have established effective metal recovery programs. Germany, for instance, has advanced metal sorting and recovery infrastructure, while Sweden's recycling systems emphasize the recovery of rare earth elements from PMMs [14]. Table 23 presents examples of metal recovery practices and policies in different EU countries, showcasing successful approaches to motor recycling.

Table 23 - Metal Recovery Practices in Selected EU Countries [29].

Country	Recovery Practice	Key Outcomes
Germany	High-efficiency magnetic separation	Increased steel and copper yield
Sweden	Rare earth recovery for PMMs	Reduced dependency on mining
France	Closed-loop aluminum recycling	High aluminum purity in reuse

6. EU Motor Recycling in Numbers

This chapter provides detailed statistics and analysis of motor recycling across Europe, covering material recovery rates, environmental benefits, economic impacts, and case studies of leading countries.

6.1 Overview of Motor Recycling in Europe

Electric motors are responsible for approximately 70% of industrial electricity use in Europe, making their recycling crucial for sustainability goals. Recycling electric motors enables the recovery of valuable materials such as copper, steel, and aluminum, while significantly reducing the environmental footprint associated with primary resource extraction. Europe recycles around 1.5 million tonnes of electric motors annually, aligning with the EU's Circular Economy Action Plan to reduce waste and improve resource efficiency [26][11][31].

6.2 Material Recovery Rates

6.2.1 Recovery Efficiency by Material Type

The recovery process for electric motors achieves high rates for key materials. Copper and steel have 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 [12][11][31]. Table 24 shows recovery rates.

Table 24: Recovery Rates by Material Type [11][12].

Material	Recovery Rate (%)	Challenges in Recovery
Copper	95	Contamination from insulation
Steel	98	Efficient sorting required
Aluminum	92	Alloy variations affect purity
Rare Earths	65	Complex separation from PMM components

6.2.2 Innovations in Material Recovery

Advancements in automated disassembly, chemical processing, and magnetic separation have improved recovery rates, particularly for rare earth elements. These innovations help address contamination issues and improve the sustainability of motor recycling [27][30][31].

6.3 Environmental Impact of Recycling

6.3.1 Emission Reductions Through Recycling

Recycling 1 tonnes of copper avoids approximately 500 kg of CO_2 emissions compared to primary production. Similarly, steel and aluminum recycling save 1.5 and 4 tonnes of CO_2 per tonne, respectively. These savings contribute to reduced environmental impact and align with EU decarbonization targets [27][28].

6.3.2 Energy Savings in Recycling Processes

Recycling metals from motors consumes significantly less energy compared to primary extraction. For instance:

- Aluminum recycling uses only 5% of the energy needed for primary production.
- Copper recycling requires 10-15% of the energy consumed during mining and smelting [26][27][31].

6.4 Economic Contributions of Motor Recycling

6.4.1 Revenue from Recovered Materials

The annual economic value of recycled motor materials in Europe is substantial, driven by the high demand for metals in renewable energy and manufacturing sectors. Copper alone generates €1.2 billion annually [26][27][31]. Table 25 shows Economic Value of Recovered Motor Materials in Europe.

Table 25: Economic Value of Recovered Motor Materials in Europe [27][31].

Material	Annual Value (Million €)	Market Trends
Copper	1,200	High demand in energy infrastructure
Steel	800	Stable due to widespread industrial use
Aluminum	500	Growth in lightweight manufacturing
Rare Earths	300	Increasing demand for EV applications

6.4.2 Job Creation and Technological Development

The motor recycling industry supports around 50,000 jobs in Europe, spanning collection, disassembly, and advanced material processing. Technological advancements in recycling methods are boosting efficiency and reducing costs, further enhancing the economic viability of the industry [11][27][31].

6.5 Case Studies: Leading Countries in Motor Recycling

6.5.1 Germany

Germany utilizes advanced magnetic separation technologies to achieve near-perfect recovery rates for ferrous and non-ferrous metals. The country's regulatory focus on the circular economy promotes continuous investment in cutting-edge recycling infrastructure [12][30][31].

6.5.2 Sweden

Sweden emphasizes the recovery of rare earth metals from permanent magnet motors through chemical separation techniques. These processes help meet sustainability goals while reducing reliance on primary mining [27][30][31].

6.5.3 France

France integrates Industry 4.0 technologies into recycling systems, improving sorting and processing accuracy while minimizing costs and emissions [26][11][30]. Table 26 presents country-specific recycling metrics.

Table 26: Country-Specific Recycling Metrics [11] [30] [31].

Country	Recovery Rate (%)	Focus Area
Germany	98	Magnetic ferrous materials separation
Sweden	92	Rare earth element recovery
France	90	Industry 4.0 integration

7. Examples of Good Practices

This chapter explores pilot projects and established practices that demonstrate effective strategies in motor recycling, reuse, and material recovery. These examples provide insights into innovative approaches addressing challenges while maximizing economic, environmental, and technological benefits.

7.1 Collaborative Initiatives Between Manufacturers and Recyclers

Several pilot projects within the EU highlight successful collaborations between electric motor manufacturers and major metal recycling companies. These initiatives emphasize local recovery of old motors from end-users and recycling of constituent materials within Europe [3][14][22].

- Example Initiatives:
    - Discounts are offered to motor end-users on replacement motors or service activities like maintenance, reflecting the economic value of the recovered metals. This incentivizes recycling while promoting sustainability reporting by providing environmental and destruction reports after scrapping [14][22].

7.2 Innovations in Material Recovery

7.2.1 Enhanced Recovery Efficiency

Technological advancements have significantly improved the recovery of materials from electric motors. Automated disassembly and magnetic separation techniques demonstrate high efficiency in recovering copper, aluminum, and rare earth elements [6][10] 16]. Table 27 presents the recovery rates achieved through magnetic separation.

Table 27: Recovery Rates Achieved Through Magnetic Separation [29][30].

Material	Recovery Rate (%)	Contamination Level
Copper	96	Low
Aluminum	92	Moderate
Rare Earths	65	Moderate

7.2.2 Application of Industry 4.0 Technologies

Innovative Industry 4.0 technologies, such as predictive maintenance and automated sorting, are being integrated into recycling facilities. These technologies enhance operational efficiency, reduce waste, and improve the purity of recovered materials [2][24].

7.3 Economic and Environmental Benefits

7.3.1 Revenue Generation and Cost Savings

Material recovery contributes to significant economic value, with recovered metals such as copper and steel generating millions of euros annually. This revenue supports local industries, reduces reliance on imported raw materials, and promotes job creation in the motor recycling sector [4][18][19].

7.3.2 Reduced Carbon Footprint

Recycling significantly reduces greenhouse gas emissions compared to primary production. For example:

- Recycling copper saves approximately 500 kg CO_2 per tonne.
- Aluminum recycling consumes only 5% of the energy required for primary production [6][8][15].

7.4 Case Studies: Exemplary Recycling Programs

7.4.1 Germany: Advanced Infrastructure for Motor Recycling

Germany employs advanced magnetic separation technologies to achieve high recovery rates for ferrous and non-ferrous metals. The country's circular economy regulations drive continuous investments in state-of-the-art recycling facilities [12][19][22].

7.4.2 France: Integration of Circular Economy Principles

France has successfully implemented circular economy strategies in motor recycling. Industry 4.0 technologies, such as automated sorting and material tracking, ensure high recovery efficiency and environmental compliance [13][23][26].

7.4.3 Sweden: Rare Earth Element Recovery

Sweden focuses on recovering rare earth elements from permanent magnet motors through innovative hydrometallurgical techniques. These methods reduce dependence on mining and address critical material shortages [14][22] 27].

7.5 Challenges and Future Directions

Despite progress, challenges remain in scaling up these practices across the EU. High costs associated with removing impurities, such as heat treatment for copper windings and additional sorting steps, hinder economic feasibility. Addressing these issues through policy support and technological innovation will be crucial in advancing the recycling ecosystem [3][17][20].

8. Trends and Policy Recommendations

8.1 Introduction

This chapter explores emerging trends in electric motor recycling and sustainability, offering policy recommendations to enhance circular economy practices. Drawing from industry reports, academic studies, and expert workshops, this section provides actionable strategies for improving recycling efficiency, resource recovery, and regulatory frameworks [1][3].

8.2 Current Trends in Motor Recycling and Sustainability

8.2.1 Integration of Circular Economy Principles

The adoption of circular economy strategies, including reuse, remanufacturing, and recycling, has gained significant momentum. These approaches not only reduce material waste but also address environmental concerns by lowering greenhouse gas emissions associated with raw material extraction and processing [2][5][13].

In addition to technological advancements, the integration of circular economy principles into motor replacement strategies is vital for sustainability. Key trends include:

- **Design for Recycling (DfR):** Encouraging manufacturers to design motors with simplified disassembly processes and fewer material combinations to facilitate recycling.
- **Industry Collaboration:** Establishing partnerships between motor manufacturers, recyclers, and policymakers to ensure the effective recovery of high-value materials.
- **Life-Cycle Analysis (LCA):** Using LCAs to quantify the environmental benefits of replacing older motors with newer models, highlighting energy savings that justify increased material use.

Policy recommendations include mandatory recovery targets for critical materials, particularly REEs, and providing economic incentives for adopting advanced recycling technologies such as automated disassembly and hydrometallurgical processing [9][27][32].

8.2.2 Industry 4.0 and Technological Innovation

The application of Industry 4.0 technologies, such as predictive analytics, robotics, and smart sorting systems, has improved recycling efficiency and material recovery rates. Automated disassembly processes are particularly impactful for motors with complex designs [24][26].

8.2.3 Focus on Rare Earth Element Recovery

Increased attention is being directed toward recovering rare earth elements from permanent magnets in electric motors. Rare earth recycling is critical for reducing dependence on imported raw materials and supporting the production of energy-efficient motors [7][14].

8.3 Challenges in Policy Implementation

8.3.1 Economic Barriers

High labor and energy costs for processing End-of-Life (EoL) motors within the EU often lead to the export of materials to countries with lower operational costs. This trend undermines local recycling efforts and results in a loss of valuable resources [16][21].

8.3.2 Fragmented Regulatory Frameworks

The lack of uniform recycling standards across EU member states complicates material recovery and prevents the optimization of recycling processes [4][13][29].

8.3.3 Technological Gaps

Recycling rare earth elements and advanced motor designs remains technically challenging due to insufficient infrastructure, uncertainty about the degree of the new technologies extended lifetime, and expertise in specialized recovery techniques [6][26].

8.4 Policy Recommendations

1. **Support for EU-Based Recycling**:
    - Introduce financial incentives for EU-based recycling firms to offset high operational costs.
    - Impose higher environmental standards and CO_2 taxes on the export of recyclable materials to encourage local processing [17][19].
2. **Certification and Standardization**:
    - Promote the treatment of EoL motors by certified waste companies to ensure environmentally compliant recycling.
    - Provide end-users with environmental and destruction reports to enhance transparency and sustainability reporting [3][21].
3. **Design for Recycling and Disassembly**:
    - Mandate "design for disassembly" principles in motor production standards to facilitate cost-effective recycling.
    - Encourage the use of recyclable materials and modular designs to simplify disassembly and material recovery [13][23][25].
4. **Investment in Rare Earth Recycling**:
    - Establish policies to support the development of rare earth recycling infrastructure.
    - Encourage public-private partnerships to fund research and development in rare earth recovery technologies [7][18][28].
5. **Material Flow Analysis and Recycling Efficiency Studies**:
    - Conduct studies to track material flow and identify inefficiencies in recycling processes.
    - Quantify the percentage of recycled materials used in new motor production to guide policy improvements [3][20].

A critical gap exists in EU recycling policies for industrial motors, which are excluded from the WEEE Directive. We recommend expanding existing frameworks or creating a dedicated policy for industrial motor recycling. This would include recovery targets, economic incentives for material recovery technologies, and improved regulatory alignment across member states to close the industrial motor recycling gap.

8.5 Case Studies in Policy and Practice

8.5.1 Germany: Regulatory Support for Local Recycling

Germany's strict environmental regulations and advanced recycling technologies have positioned it as a leader in motor recycling. The country achieves high recovery rates for both ferrous and non-ferrous metals through innovative processes [19][22].

8.5.2 France: Integration of Industry 4.0 in Recycling

France has embraced Industry 4.0 technologies to enhance sorting and material recovery. These innovations have significantly reduced operational costs and improved environmental outcomes [5][13].

8.5.3 Sweden: Rare Earth Recovery Initiatives

Sweden has implemented pilot projects for recovering rare earth elements from permanent magnets, addressing critical material shortages while reducing reliance on mining [7] [14].

8.6 Conclusion

The future of electric motor recycling lies in fostering innovation, harmonizing policies, and building sustainable infrastructure. By integrating circular economy principles, leveraging advanced technologies, and supporting EU-based recycling initiatives, stakeholders can unlock the full potential of resource recovery while minimizing environmental impacts.

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- OIKOKIKLIOS S.A., Greece
- The Rotating Company, Belgium
- VDP Industries, Belgium
- Avonmore Electrical Co. Ltd, Ireland
- CPM Engineering, UK

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