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D5.4: Guidelines on responsible sourcing and sustainability in primary and secondary rare earth element use

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Publishable Summary

This document presents a comprehensive set of sustainability guidelines developed for a short-loop recycling value chain of rare earth elements (REEs) used in permanent magnets (PM). Developed in Horizon Europe MAGELLAN project, this value chain is focused on the recycling and responsible use of REEs in PM use. As REEs become increasingly essential in view of the EU's goals pertaining to the green and digital transitions, there is an urgency to strengthen a secure, ethical, and sustainable supply. These guidelines aim at promoting resilient, transparent, and circular REE value chains that align with recent European legislation, but also high ESG (environmental, social, and governance) standards.

The document is based on analysis of the environmental, social, and economic impacts associated with both REE mining and REE PM recycling. It reviews the current regulatory landscape and frameworks for responsible business conduct and sourcing, including those from the Organisation for Economic Co-operation and Development (OECD), United Nations (UN), and relevant industry-specific initiatives. This review supports the identification of key sustainability considerations across the MAGELLAN value chain, from raw material recovery to manufacturing and integration.

The guidelines are developed through the desk study, and a multi-stakeholder process involving industry partners in semi-structured interviews. While tailored to the MAGELLAN value chain, they are broadly applicable to other REE-related initiatives and industrial actors seeking to strengthen their operations in a rapidly shifting ESG landscape. Ultimately, these guidelines provide a tool for industry representatives and public authorities and thus seek to contribute to a European REE ecosystem that is not only economically and technologically advanced but socially responsible and environmentally sound.

Abstract

This report presents a structured analysis and a set of actionable sustainability guidelines on responsible sourcing and sustainability, for primary and secondary rare earth element (REE) raw materials, with a particular focus on the magnet-to-alloy NdFeB-based permanent magnet recycling route (short-loop) developed in the Horizon Europe project MAGELLAN.

The report begins with an overview of responsible sourcing and sustainability, focusing on (a) primary REE value streams and (b), secondary value streams based on recycling end-of-life (EoL) products and production scraps. It consolidates the environmental, social, and governance (ESG) as well as economic impacts of REE production, such as energy consumption, emissions, waste and radiation management, community and human rights risks, market volatility, and external environmental aspects. The report also examines primary barriers like technological limitations, illegal mining, inconsistent enforcement, public opposition to mining, and the commercial difficulties of expanding REE recycling.

The deliverable then reviews the evolving EU regulatory landscape for REE magnets across the full value chain, including critical raw materials, products, waste, industrial emissions, due diligence frameworks, and maps where these instruments apply, from mining to recycling and remanufacturing. In parallel, it reviews global standards and initiatives for responsible mining, corporate sustainability, and traceability, and compiles EU-level projects and alliances that advance low-impact extraction, ecodesign, circular magnet solutions, and digital product passports. Building on this assessment and on semi-structured interviews with stakeholders across dismantling, scrap handling, recycling, magnet production, and downstream manufacturing, the report identifies practical sustainability challenges and opportunities for the MAGELLAN value chain, including permitting and waste-code fragmentation, export controls, certification burdens, feedstock security, skills needs, and OEM engagement – against the backdrop of tightening ESG disclosure requirements and circular economy targets.

The deliverable translates these insights into targeted sustainability guidelines and accompanying policy recommendations tailored to the MAGELLAN value chain. The guidance is organised into environmental, social, economic/resilience and governance/traceability dimensions, with concrete operational actions by providing both an analytical baseline, and a set of actionable recommendations.

The deliverable supports the alignment of MAGELLAN’s technical solutions and business models with European sustainability objectives and offers transferable guidance for other REE-related industrial initiatives seeking more responsible, resilient and circular value chains.

Glossary

Acronym	Definition
BAT	Best Available Techniques
BREF	BAT Reference Document
CAHRAs	Conflict-Affected and High-Risk Areas
CareMag	Carester's magnet recycling and refining project (Lacq, France)
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CEN-CLC/JTC 24	CEN–CENELEC Joint Technical Committee 24 (Digital Product Passport)
CERA 4in1	CERA 4in1 Certification (DMT Group)
CF	Carbon Footprint
CIRAF	Corporate Risk and Impact Framework
COM	Commission document reference (e.g., COM (2025) 187 final)
CORDIS	Community Research and Development Information Service
CRM	Critical Raw Material(s)
CRMA	Critical Raw Materials Act (Regulation (EU) 2024/1252)
CSDDD	Corporate Sustainability Due Diligence Directive (Directive (EU) 2024/1760)
CSRD	Corporate Sustainability Reporting Directive (Directive (EU) 2022/2464)
DPP	Digital Product Passport
EIT RM	EIT RawMaterials
EITI	Extractive Industries Transparency Initiative
ELV	End-of-Life Vehicles (Directive 2000/53/EC; proposed Regulation)
EoL	End-of-Life
EPR	Extended Producer Responsibility
ERMA	European Raw Materials Alliance
ESG	Environmental, Social and Governance
ESPR	Ecodesign for Sustainable Products Regulation (Regulation (EU) 2024/1781)
ESRS	European Sustainability Reporting Standards under the CSRD
EU	European Union

EURARE	EU FP7 project on European REE resources and processing
EV	Electric Vehicle
EVTM	Electric vehicle traction motor
GRI	Global Reporting Initiative
HPMS	Hydrogen Processing of Magnet Scrap (hydrogen decrepitation)
HREO(s)	Heavy Rare-Earth Oxide(s)
HyProMag	Company/technology on HPMS-based magnet recycling
ICMM	International Council on Mining and Metals
IED	Industrial Emissions Directive (Directive 2010/75/EU; 2024 revision)
IEP	Industrial Emissions Portal Regulation (Regulation (EU) 2024/1244)
IFC	International Finance Corporation
IRMA	Initiative for Responsible Mining Assurance
ISO 23664	ISO 23664:2021 — Traceability of rare earths from mine to separated products
ISO/TC 298	ISO Technical Committee 298 (Rare Earth)
JRC	Joint Research Centre (European Commission)
KPI	Key Performance Indicator
LBMA	London Bullion Market Association
LCA	Life-Cycle Assessment
LMT	Light Means of Transport (battery category)
MRI	Magnetic Resonance Imaging
NdFeB	Neodymium–Iron–Boron permanent magnet alloy
NORM	Naturally Occurring Radioactive Materials
OECD	Organisation for Economic Co-operation and Development
PM	Permanent Magnet
ProSUM	EU project creating the Urban Mine Platform (WEEE/ELV/mining waste data)
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals (Regulation (EC) No 1907/2006)
RECl3	Rare Earth Chloride (e.g., $NdCl_3$)
REE	Rare Earth Element(s)
REE4EU	EU H2020 project on REE alloy production from scrap

REEcover	EU FP7 project on REE recovery from secondary sources
REEPRODUCE	EU Horizon Europe project on industrial-scale REE magnet recycling
REESilience	EU Horizon Europe project on resilient REE supply chains
REIA	Rare Earth Industry Association
REO	Rare Earth Oxide(s)
RMAP	Responsible Minerals Assurance Process
RMI	Responsible Minerals Initiative
SDF	Sustainable Development Framework
SDGs	United Nations Sustainable Development Goals
SecREEts	EU H2020 project on REE extraction from fertilizer streams
SMEs	Small and Medium-Sized Enterprises
SRM	Strategic Raw Material(s)
SUSMAGPRO	EU H2020 project on sustainable recovery and reuse of REE magnets
TRP	Total Rare-earth Production
TSM	Towards Sustainable Mining programme (Mining Association of Canada)
UN	United Nations
UNGPs	UN Guiding Principles on Business and Human Rights
WEEE	Waste Electrical and Electronic Equipment (Directive 2012/19/EU)

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1. Introduction

Rare earth elements (REEs) are essential for modern technologies, yet their supply remains highly concentrated. China currently plays a leading role across the global supply chain of REEs, controlling mining, enrichment technologies, metallurgy, and the production of end-metal products. This control results in the European Unions (EU) near-total industrial dependency on China for these critical materials (Charalampides & Vatalis, 2015a, b; Kamprowski, 2023; Ragonnaud, 2023).

This dependence is a strategic concern, as past trade disputes and the rare-earth crisis (2010-2011) underscored the risk of supply disruptions. Although earlier efforts struggled to reduce dependence, the EU has recently moved to strengthen and professionalise its supply chains (e.g., the 2024 Critical Raw Materials Act and related initiatives) (Schmid, 2019; Kamprowski, 2023; Klossek et al., 2016). The rare earth market is characterized by systemic issues such as market opacity, resource nationalism, and weak international cooperation, which exacerbate the EU's dependence to China. These factors make it challenging for the EU to develop an independent supply chain (Klossek et al., 2016). The EU's dependency on Chinese REEs could hamper its high-tech industries, which rely on these materials for products like electric vehicles and wind turbines. This vulnerability could also affect the EU's transition to low-carbon energy systems (Schmid, 2019).

The EU has recognized the critical nature of REEs and included them in its list of critical and strategic minerals. However, developing a robust and independent supply chain within the EU remains a significant challenge due to the current geopolitical and economic landscape (Charalampides & Vatalis, 2015a, b; Kamprowski, 2023). This underscores the need for proactive measures to strengthen the EU's strategic autonomy regarding critical raw materials (CRM).

REEs comprise of 17 elements (15 lanthanides plus yttrium and scandium) used across electronics, automotive, renewable energy, and defence. Consequently, EU recognises REEs as CRMs (listed as Light and Heavy REEs, with Scandium separately). Building a robust EU supply chain remains challenging, underscoring the need for measures that strengthen strategic autonomy. REEs occur in over 250 minerals, with major producers including China, the United States, and Australia. Large reserves occur in these three countries as well as, Vietnam, Brazil and Russia. China accounts for ~69-70% of global mining (2025), ~90% of refining and ~95% of magnet manufacturing, which has geopolitical implications as demand is rising with clean-energy technologies. Recycling from e-waste and industrial by-products is advancing but remains limited today in EU, with EoL PM recovery constrained by low collection rates and challenging economics.

Currently, REE mining faces environmental challenges, including high energy use, greenhouse gas emissions, water and soil contamination (often involving radioactive elements), and ecological degradation due to land disturbances and poor waste management. These impacts are typically greater than those associated with common metals, particularly during the energy-intensive refining stage (Weng et al., 2016; Zapp et al., 2022). Indeed, the mining and processing of REEs can lead to significant environmental pollution, affecting soil and water quality, and posing risks to human health (Wang et al., 2024; Malhotra et al., 2020). REEs can also accumulate in living organisms, potentially causing health issues such as respiratory damage and genetic changes (Pagano et al., 2018; Khan et al., 2017).

At the same time, REE production is shaped by complex environmental, economic, and geopolitical pressures. Continued innovation is essential to manage these resources sustainably while meeting the growing demand driven by clean energy and high-tech industries (Diao et al., 2024). Ultimately, a responsible balance must be found between resource development and environmental protection (Huang et al., 2016).

Due to the environmental impact and supply risks, recycling REEs from secondary sources like e-waste and industrial by-products is being explored as a sustainable alternative (Dushyantha et al., 2020; Jyothi et al., 2020). However, current recycling methods are not yet economically viable or widely implemented, highlighting the need for further research and development (Jyothi et al., 2020).

1.1 MAGELLAN Horizon Europe

The MAGELLAN Horizon Europe project targets a full REE PM value chain used in electric vehicle traction motors (EVTMs), from end-of-life (EoL) products back to new magnets. Today, this chain is largely linear and import-dependent: REEs such as neodymium (Nd), praseodymium (Pr), dysprosium (Dy) and terbium (Tb) are mined and refined mostly outside Europe, converted into alloys and sintered magnets, integrated into EVTMs, and ultimately discarded or downcycled with limited recovery, high energy use and significant environmental footprints.

MAGELLAN aims to engineer a circular, EU-based value chain by introducing short-loop recycling routes, in which magnets from EoL products like EVTMs, e-scooters and e-bikes are directly reprocessed into new alloys and magnets ("magnet-to-alloy"), complemented by partial neodymium substitution and advanced near-net-shape manufacturing via Powder Injection Moulding (PIM) process.

This reduces primary REE demand, material losses and process energy requirements. The project also develops new rotor designs that facilitate disassembly and magnet removal, improving the economics and technical feasibility of high-quality recycling. With this approach, MAGELLAN targets to have at least 25 wt% of REE recycled content in high-performance PMs. This target would enable for up to ~50% CO_2e emission reduction for magnets, and economic performance benefits compared with conventional PM production.

1.2 Scope of the report

This report develops sustainability guidelines for the MAGELLAN value chain and other recycled REE PM value chains in Europe. The report examines the environmental, social and economic impacts of primary REE production and recycling, reviews the regulatory landscape, and evaluates responsible sourcing frameworks across both mining and EoL product value streams. Building on this foundation, it defines the key sustainability considerations relevant to MAGELLAN's processes, including material recovery, magnet re-engineering, manufacturing, and system integration. The guidelines presented propose a framework in support of the MAGELLAN project partners, as well as various industry actors and stakeholders, and ensure that the MAGELLAN technology pathway aligns with European sustainability objectives, ESG standards, and long-term strategic autonomy goals of the EU.

2. Environmental impacts and sustainability issues of rare earth element production

2.1. Impacts of REE mining

Mining REEs poses specific environmental challenges beyond typical conventional mining impacts due to the unique properties and extraction processes involved (Obregón-Castro et al., 2023). REE mining and refining are both energy-intensive and chemically complex, leading to environmental issues including toxic waste, soil contamination, and radiation hazards (Duan, 2024; Obregón-Castro et al., 2023). REEs are often present in very low concentrations, necessitating the excavation and processing of large quantities of ore (Duan, 2024).

REE mining requires the removal of large volumes of rock and soil. The extraction process involves using toxic chemicals, such as sulfuric and hydrochloric acids to separate the elements, creating highly toxic and acidic waste byproducts (Duan, 2024). When mining and processing occurs in poorly regulated environments, these byproducts can seep into the surrounding soil and water systems, contaminating them with heavy metals like lead and cadmium, which are detrimental to both human health and local ecosystems (Borrego et al. 2012). The disposal of these toxic wastes, often stored in tailing ponds or left in open storage, poses a risk of leakage, especially in cases of poor infrastructure or extreme weather (Zapp et al, 2022).

Water is also essential in REE extraction, both for separating elements from ore and for processing the minerals. While modern mining operations implement effective water recirculation and preservation techniques, this high water demand can strain local water resources, particularly in water-scarce regions, with potential impacts on agricultural and community water supplies. In addition, many rare earth ores contain trace amounts of radioactive elements such as thorium and uranium (e.g., Yang et al., 2013; Zapp et al., 2022). During mining and processing, these radionuclides can be mobilised into dust, waste rock and tailings, creating radiation risks and long-term environmental health concerns if not properly managed.

The radioactive dust and waste generated are particularly concerning for long-term environmental health (Yang et al., 2013). Contamination can persist for decades, complicating restoration efforts. In countries where environmental regulations are weak, radioactive residues may be stored in unlined ponds, heightening the risk of environmental exposure (Obregón-Castro et al., 2023).

In addition to potential radioactive contamination, mining rare earths releases fine particles and gases that contribute to various other forms of pollution, including heavy metal pollution and fluoride contamination. Fluoride comes from REE ores like bastnäsite, which release fluorine compounds (e.g., HF) during processing (Zapp et al. 2022). Open-pit mining, often employed for REE mining, releases dust and radioactive particulates that can be carried over long distances by the wind, posing inhalation risks. Greenhouse gas emissions are also a concern due to the heavy reliance on energy for extracting and processing rare earths (Duan, 2024; OECD, 2023). REE mining is frequently conducted in countries where environmental regulations may be less stringent, leading to heightened pollution and ecological degradation that impact global air quality and contribute to climate change (Duan, 2024; OECD, 2023; Middleton et al., 2024; Costis et al., 2021). With these issues, ecosystems at large can be challenged. For example, the mining of rare earth ores in China has been linked to the change in ecosystems and heavy contamination of air, water, and soil (Yang et al., 2013). In inner Mongolia, extensive rare earth mining has transformed once-productive agricultural land into industrial wastelands, affecting ecosystems at large (Obregón-Castro et al., 2023; Zapp et al., 2022). Also, the ion-adsorption clay deposits, mined mostly in southern China and Myanmar, are extracted using in-situ leaching techniques that involve ammonium sulphate, often leading to heavy metal pollution in nearby water systems (Yang et al., 2013; Duan, 2024).

Most REE mining to date occurs outside Europe, and the EU remains heavily dependent on imports for rare earths and other CRMs (Council of the European Union, 2025a; European Parliament and Council, 2024a). Under the Critical Raw Materials Act (CRMA), new domestic projects are expected to increase mining and processing within the EU while complying with comparatively stringent EU environmental and social standards and comprehensive impact assessments. The Act seeks to streamline permitting procedures and reduce administrative burden, but project development is still likely to remain slower than in jurisdictions with weaker regulation, with the aim of achieving lower overall ecological impacts.

Emerging research is exploring the recovery of REEs from industrial waste streams like phosphogypsum using bio-inspired adsorptive separation methods, however, commercial deployment is likely to require further process optimization and scale-up, and dilute phosphogypsum sources remain challenging with current process schemes (Smerigan & Shi, 2025a).

In MAGELLAN, extensive research has been conducted to explore and evaluate the potential of REE mining projects in Europe. The result of this research is available in MAGELLAN project deliverable D5.2 - *Report on responsible sourcing of REE from primary sector and synergies with recycling*. Figure 1 illustrates some examples of REE mining projects in Europe and sustainability issues related to them. For more information on these projects, see deliverable D5.2.

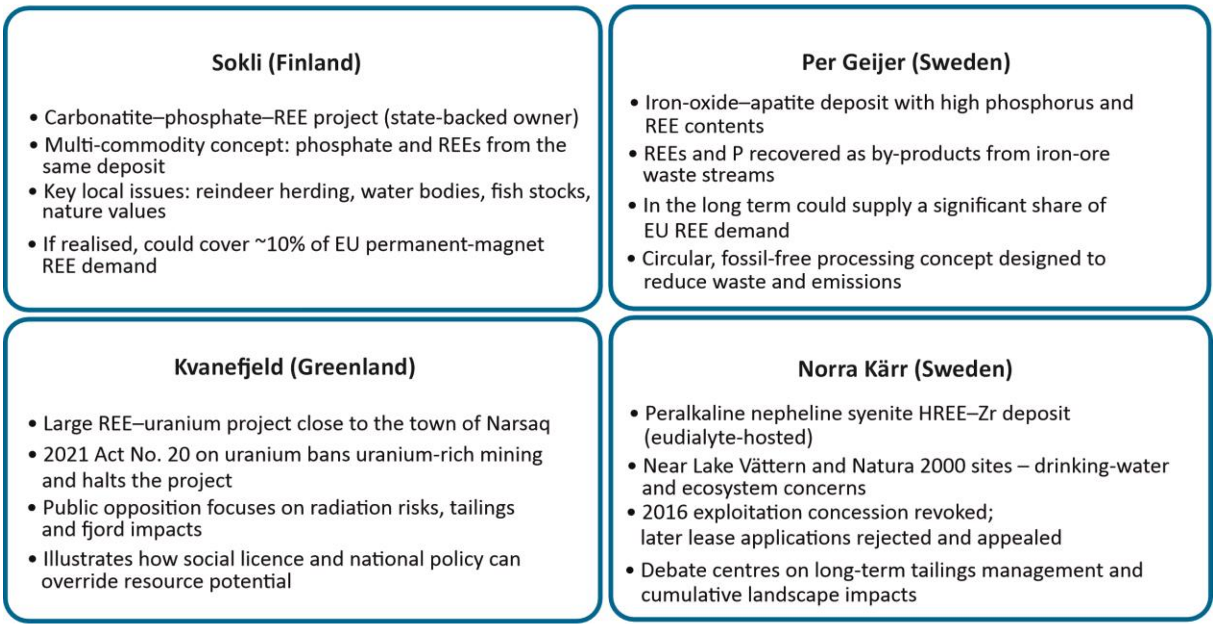

Figure 1. Environmental impacts and sustainability issues of rare earth production: four European example projects.

Sokli (Finland)

The Sokli carbonatite complex (Finland), owned by Finnish Mineral Group, has been studied since the 60s. The main focus of the complex has been on phosphate production (1Mt annually) for fertilizers, and iron concentrate (100kt annually), with a mine life of 24 years. Another focus has been in hard rock phoscorite resource of 100Mt. Since 2020, the company has discovered the untapped potential for REEs within the 20km^2 carbonatite core. A drilling campaign has discovered and outlined preliminary resources grading ~1.2% TREO. The major minerals are carbonates (dolomite & calcite), representing bulk REE minerals of 2.1%. The planning of mining operations takes into account the impacts, in particular on reindeer herding, water bodies, fish stocks and nature tourism. The Sokli deposit has the potential to fulfil nearly 10% of the EU REEs demand alone (Sokli Oy, 2025).

Kvanefjeld (Greenland)

Kvanefjeld is a large, REE–uranium project in southern Greenland. In December 2021, Greenland adopted Parliament Act No. 20 on the prohibition of uranium prospecting, exploration and exploitation above 100 ppm, which has effectively stalled the project (Greenland Parliament, 2021). Greenland's mining context also includes well-documented legacy contamination from the Black Angel (Maarmorilik) Pb–Zn mine, highlighting the long-term environmental risks associated with metal mining in Arctic fjord systems (Søndergaard, 2022; Bagger et al., 2025).

Per Geijer (Sweden)

State-owned LKAB reports that the Per Geijer deposit in Kiruna, northern Sweden, is Europe's largest known REE deposit, with more than 1 Mt REO. Per Geijer is an apatite–iron ore body located roughly 1 km north of the existing Kiruna mine. The REEs occur together with phosphorus in apatite, so they can be recovered as by-products alongside phosphorus products. LKAB's concept is to extract both phosphorus and REEs from iron ore by-product streams using circular, fossil-free processes (LKAB, 2023a, b).

Norra Kärr (Sweden)

Norra Kärr in southern Sweden is a peralkaline nepheline syenite complex that hosts a globally significant heavy rare earth element (HREE) and zirconium deposit, with REEs predominantly occurring in eudialyte-group minerals within an agpaitic nepheline syenite body (Sjöqvist et al., 2013). The project, currently held by Leading Edge Materials, has been advanced through a Preliminary Economic Assessment that confirms its potential as a major HREE–Zr project (Leading Edge Materials, 2021).

Norra Kärr is located close to Lake Vättern and adjacent Natura 2000 areas, which has raised strong concern about possible impacts on drinking-water resources and sensitive ecosystems among local communities and environmental organisations (e.g., Naturskyddsföreningen, 2024; Walter et al., 2023). A previously granted mining lease for the project was annulled by the Swedish Supreme Administrative Court in 2016 citing deficiencies in the underlying environmental and Natura 2000 assessments, highlighting the central role of legal safeguards and social licence to operate in REE project development in environmentally sensitive settings (Högsta förvaltningsdomstolen, 2016; Tasman Metals AB, 2016).

2.2 Impacts of REE recycling

As REEs are becoming increasingly vital for ensuring supply security and minimizing the environmental impact of green technologies in Europe, EU has set an ambitious goal to meet 25% of its critical mineral demand through recycling by 2030. Yet currently, less than 1% of rare earths are being recycled (Onstad, 2024). The projected demand for rare earth-containing magnets is expected to increase to 51kt by 2040 and 58kt by 2050. By 2050, the projected distribution of NdFeB magnet per application is expected to be: EVs (35%), wind turbines (44%), electric bicycles (10%), home appliances (5%), consumer electronics (3%), and other uses (3%), primarily dominated by growing adoption of green technologies. This also shows potential for recycling EoL products containing Nd-based PMs (Rizos, Righetti, & Kassab, 2022).

By 2040, recycled materials could potentially meet between 16% and 34% of the demand, rising to nearly 50% by 2050 under the most optimistic scenarios in the EU (Rizos, Righetti, & Kassab, 2022). In other words, with robust circular economy measures, almost half of the EU's rare earth magnet needs by mid-century might be supplied from recovered magnets rather than mined materials. In this context, enhancing the circularity and recycling of REEs can play a crucial role in reducing EU dependence on primary production and minimizing environmental impact. For instance, one life cycle assessment found that NdFeB magnet-to-magnet recycling can reduce environmental impacts by approximately 64–96% compared with virgin magnet production, depending on the impact category (Jin et al., 2018). Broader reviews of NdFeB recycling from e-waste similarly highlight substantial potential to cut environmental burdens while improving supply security (Perry & Van Veen, 2024).

Establishing a complete rare earth recycling value chain within the EU is essential but faces significant challenges. The low volume of EoL materials, mainly due to insufficient collection and sorting infrastructure, limits large-scale recycling. Consequently, rare earth magnet-containing materials are often undervalued, sold as scrap or lost through landfilling and incineration. Due to the low concentration of rare earth magnets in several products, such as hard disk drives or other consumer electronics, they often have to be extracted manually, which is highly labour intensive and costly (Diehl et al., 2018).

Technical process challenges also hinder the recycling of rare earths. Hydrometallurgical methods produce significant amounts of hazardous chemicals and wastewater and involve multiple processing steps to recover secondary magnets. In contrast, pyrometallurgical approaches are less complex but highly energy-intensive and generate substantial solid waste. The industry is shifting toward shorter-loop processes like Hydrogen Processing of Magnet Scrap (HPMS), which are more efficient but still require high-quality input materials; otherwise, additional processing is needed. Moreover, rare earth metal production is extremely energy-intensive, posing major obstacles to scaling up in Europe due to rising energy costs, worker safety concerns and release of emissions *i.e.,* CO_2, CO, CF_4, C_2F_6, HF etc. (Rizos, Righetti, & Kassab, 2022). There are numerous EU projects and initiatives (e.g. REPRODUCE, SUSMAGPRO, REproMAG, REESILIENCE, REEcover, REE4EU) conducting research on overcoming these challenges either through indirect (chemical processes) or direct (also known as ‘closed’, ‘magnet to magnet’ or ‘short route’) processes.

The key bottleneck lies in the limited maturity of industrial processes that can recover REEs from EoL products at a competitive cost with conventional primary production in China. To address this, Europe must diversify its REE supply and establish a resilient, domestic value chain capable of meeting the CRMA target of sourcing at least 25% of REEs from recycled materials by 2030. Achieving it will demand a full domestic value chain for rare earth magnets, from collection and recovery to re-manufacturing new magnets at scale. While today that chain is still emerging, the potential benefits (supply security, industrial jobs, and environmental gains) are enormous. In summary, boosting the circularity of rare earths, through better design, recycling and reuse, can play a crucial role in meeting Europe’s green tech demand in a sustainable way, complementing primary production and mitigating the environmental impacts associated with rare earth mining and processing.

In MAGELLAN, research has also been conducted to examine the potential of REE PM recycling in Europe. The results of this work are presented in MAGELLAN project deliverable D5.1 - *Report on responsible sourcing of HREE by collection and recycling of EoL products*. Figure 2. Examples of REE recycling projects in Europe highlights some examples of REE recycling activities in Europe and the sustainability considerations associated with them. For further details on REE PM recycling, see deliverable D5.1.

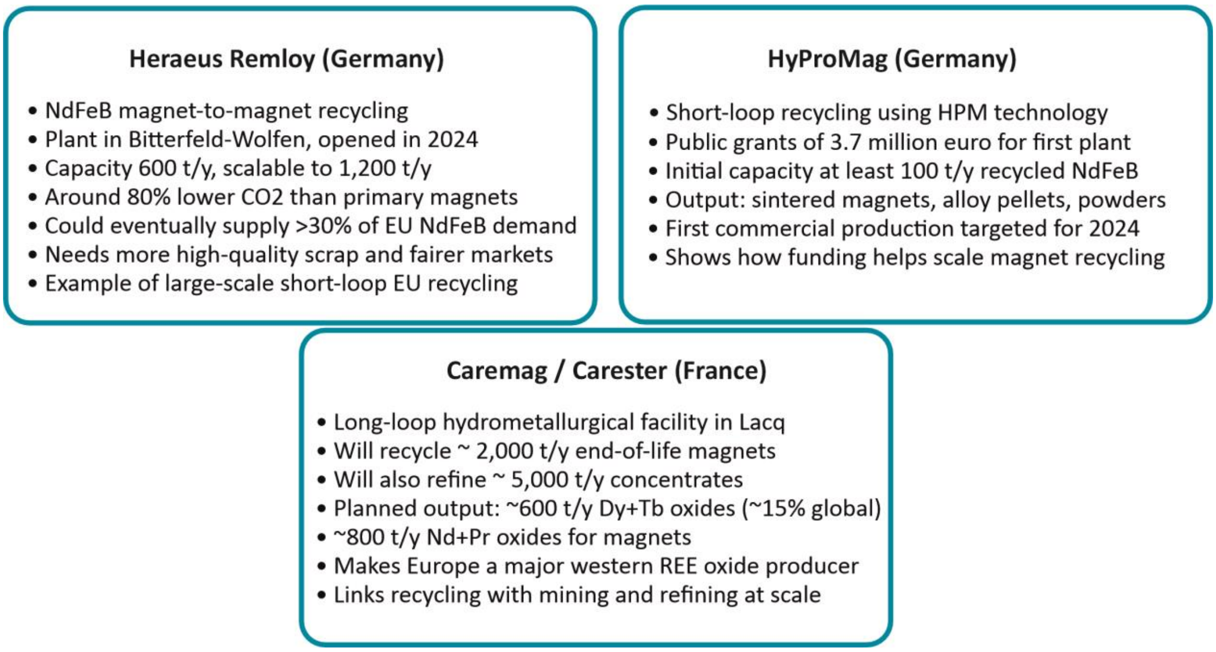

Figure 2. Examples of REE recycling projects in Europe.

Heraeus Remloy, short loop recycling (Germany)

Heraeus Remloy's Bitterfeld-Wolfen plant, opened in 2024, is Europe's largest NdFeB recycling facility with a capacity of 600 tpa (scalable to 1,200 tpa). The process cuts CO_2 emissions by around 80% versus primary production and could eventually supply up to 30% of Europe's magnet demand. Still, the facilitctiony faces challenges in securing sufficient scrap volumes and competing with low-cost Chinese magnets, highlighting the need for stronger collection networks, market conditions and supportive policies (Heraeus Group 2024).

Hypromag, short loop recycling (Germany)

HyProMag GmbH has been awarded a €3.7 million grant to develop Germany's first Hydrogen Processing of Magnetic Scrap (HPMS)-based rare earth magnet recycling and manufacturing plant in Baden-Württemberg. The initial design foresees a minimum capacity of around 100 tons per year of recycled NdFeB in the form of sintered magnets, alloy pellets and powders, with a modular layout that can be scaled up to approximately 100–350 tpa and, in a next phase, potentially to around 750 tpa. The plant will be situated in Germany to deploy the patented HPMS process. As of late 2025, the site near Pforzheim is under construction, with key equipment such as the HPMS vessel and jet mill installed and ready for commissioning; first production of NdFeB alloy powder is now expected in early 2026, subject to permitting (Mkango Resources, 2022; Maginito, 2023; Mkango Resources, 2025a, b).

Carester, long loop recycling (France)

The Caremag facility will recycle 2,000 tons of magnets, and refine 5,000 tons of mining concentrates annually, positioning itself as Europe's first large-scale rare earth recycling facility and the largest western producer of purified heavy rare earths. With an output of 600 tons of Dysprosium and Terbium oxides – representing around 15% of the global production – and

800 tons of neodymium and praseodymium oxides, Caremag will play a vital role in supplying key materials for electric vehicles, wind turbines, and advanced electronics (Carester, 2025).

2.3 Social implications of REE mining and recycling

Mining of REEs often takes place in rural and indigenous areas, where local communities depend on the land for the local economy, whether it be livelihoods, or notably agriculture, fishing, and livestock herding. Mining activities can also have an adverse impact on preservation of cultural heritage among the local communities and on indigenous or local community health (Tsosie, 2024; Schlosberg & Carruthers, 2010).

Globally, there are examples notably in Africa and countries like China, Mongolia, and Brazil, of large-scale mining projects causing displacement of local communities, disrupting their agricultural practices and traditional ways of life. Loss of livelihood and access to resources can lead to economic hardships and increased poverty for these communities, as they may lack the skills or opportunities to transition to other forms of employment. However, there is evidence of both positive and negative effects of mining-induced displacement (Owen & Kemp, 2014; Ofori et al., 2023).

Indeed, indigenous populations often have deep spiritual, cultural, and historical ties to the land where REEs are mined. Mining activities can not only threaten their way of life but also undermine their traditional knowledge systems and cultural practices. For instance, in Australia, mining operations have affected the Gunditjmara people and other Indigenous groups, leading to social and cultural upheaval. Conflicts between indigenous peoples and state or corporate interests are not uncommon in other parts of the world (Schlosberg & Carruthers, 2010).

REE mining and refining processes can expose not only members of local communities but especially workers to various toxic substances, including radioactive elements, heavy metals, and toxic chemicals such as solvents and acids used in the process. Long-term exposure can cause severe health problems, including respiratory diseases, cancer, and neurological damage or reproductive issues. In China, where the vast majority of REE mining occurs, miners have reported high levels of exposure to harmful chemicals and heavy metals, leading to various health complications (Wang et.al., 2024).

Mining and REE mining, particularly in low and middle-income countries, often occurs under poor working conditions. Workers may face hazardous machinery, exposure to dust, lack of proper safety equipment, and long working hours. Child labour and forced labour are also reported in some mining operations (ILO, 2019). In some regions of Mongolia and Brazil, workers, including children, are involved in hazardous mining activities without sufficient protective gear or compensation (ILO, 2016; Brazilian Regulatory Standard NR-22, 2018). Poor working conditions increase the risk of accidents, injuries, and fatalities among workers, and can lead to long-term chronic health conditions that may limit their ability to work and support their families (World Bank & Pact, 2021; Charles et al., 2019).

Recycling routes for REEs, especially recovery from e-waste, shift social risks from mining areas to waste-handling sites and create distinct opportunities and challenges. Where collection and treatment are formalized under extended producer responsibility, recycling can support decent jobs, skills development, and regional value retention in Europe (European Commission, 2020a). Yet globally, a large share of e-waste is still processed informally, exposing workers and nearby communities, including children and pregnant women, to toxicants and unsafe working conditions (WHO, 2021; WHO, 2024). Documented collection and recycling rates remain insufficient relative to rapidly growing e-waste volumes (ITU & UNITAR, 2024). In the EU, policy instruments aim to steer these impacts toward positive outcomes.

2.4 Economic factors to consider in REE mining and recycling

Economic considerations play a crucial role in shaping the sustainability of rare earth element mining and recycling. REE mining and processing come with high capital and operational costs (Jowitt et al., 2023). Furthermore, geopolitical concentration of REE production, particularly in China, creates market vulnerabilities and price volatility, complicating efforts toward supply chain diversification and sustainable sourcing (OECD, 2023). This reliance on a few dominant producers, especially China, leads to market volatility and makes long-term investment in sustainable practices uncertain (Fritz et.al. 2023, see also Wübbeke, 2013).

The initial investment in REE mining projects is substantial due to the need for specialized equipment and complex refining processes. These factors contribute to high entry barriers. REE mining also demands significant capital for infrastructure and environmental management, which can incentivize companies to prioritize short-term profitability over long-term sustainability (Duan, 2024). Moreover, the profitability of REE mining is heavily influenced by fluctuating global demand and prices, which are sensitive to trade policies, tensions and technological shifts (Wübbeke, 2013; Duan, 2024). For example, export restrictions by dominant producers have historically disrupted global markets, encouraging the exploring of technological diversification, alternative sources or investment in recycling technologies.

On the recycling side, economic feasibility remains a challenge. Although recycling REEs from electronic waste (e-waste) and industrial by-products is environmentally favorable, the processes are still often less cost-effective than primary mining due to technological limitations and low recovery rates (Binnemans et al., 2013; Smerigan & Shi, 2025b). However, advancements in separation techniques and policy incentives may improve the economic viability of recycling over time.

Another key factor is the externalization of environmental costs, particularly in jurisdictions with weak regulatory enforcement. In some cases, the economic benefits of REE mining (*e.g.,* employment and infrastructure development) are offset by long-term environmental remediation costs and public health impacts, which are not internalized by mining companies (Oladipo et al., 2023). Sustainable economic models therefore require integrated cost-benefit analyses that factor in environmental degradation, social externalities, and lifecycle impacts of REEs. In recent years there has been significant efforts to build resilient, low-impact supply chains (OECD, 2023; Duan, 2024).

Economic viability has so far been the greatest barrier, high processing costs (energy, reagents, skilled labor) and the expense of disassembling products mean that recycling can be more costly than mining. On the other hand, rising demand for NdFeB magnets (EVs, wind power) is expected to improve the business case over time, and new business models (shared facilities, collocation with existing scrap operations) are emerging.

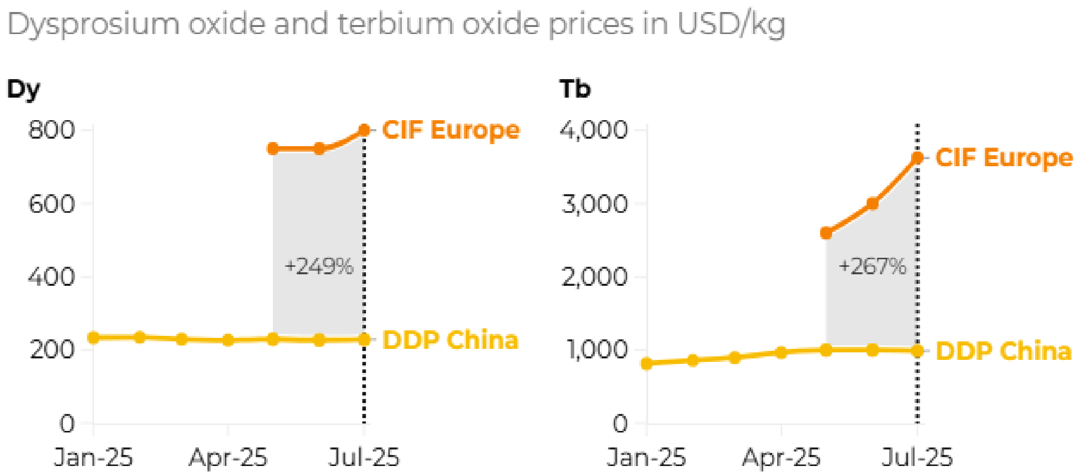

Figure 3. Price difference of HREOs between European and Chinese markets (BENCHMARK, 2025).

The main barrier to REE magnet recycling today is commercial viability impacting the confidence to invest. Recycled material remains more expensive than low-cost virgin material from China, making it difficult for businesses to adopt. European magnet producers face prices that can be 50–200% higher than Chinese suppliers (Figure 3), while the market offers no price premium for local, sustainable, or recycled content. In cost-driven sectors such as automotive, wind, and electronics, this erodes competitiveness and leads customers to prioritise lower prices over supply chain resilience. As long as the market fails to reward sustainability in particular, manufacturers may continue to favour short-term cost savings (Rizos et al., 2022).

This issue cannot be resolved through supply-side measures alone. Without demand for European material, no domestic project can succeed. Manufacturers of products and components must acknowledge their role: investing in supply chain resilience by integrating European secondary REE sources at least partially is essential. If they do not, current dependencies will only deepen carried by the rising demand.

2.5. Barriers to Sustainable REE production and recycling

Sustainable REE production faces significant barriers, including technological limitations and low technological readiness in emerging mining and recycling flowsheets. Reported REE recovery can vary widely depending on the feedstock and processing route, and data/scale-up uncertainties complicate robust sustainability assessments (Smerigan & Shi, 2025b, see also Yang et.al., 2017). Despite recent advancements in bio-inspired extraction methods and cleaner technologies, these solutions are not yet cost-competitive with conventional mining practices.

Weak or inconsistent regulatory frameworks in some regions present a significant barrier to sustainable practices. While some countries have stringent environmental regulations, others lack adequate enforcement mechanisms, resulting in insufficient oversight and management of environmental impacts (Oladipo et al., 2023). The lack of uniform international standards further exacerbates this issue, as companies operating in multiple jurisdictions may exploit weaker regulations, undermining global sustainability efforts (OECD, 2023). The absence of policies that incentivize sustainable mining or recycling practices limits the ability of industry to invest in sustainability.

Public opposition to mining, particularly those in ecologically sensitive areas, is a significant issue to consider, constituting a barrier to sustainable REE mining. In many cases, communities experience the negative effects of pollution, displacement, and environmental degradation (Oladipo et al., 2023). There are many recent examples of community protests also within Europe and examples demonstrating that the process of seeking public acceptance, including through active stakeholder engagement, should not be underestimated (Eerola & Komnitsas, 2025). If not considered, the opposition or social resistance can result in delays, causing increased operational costs and reputational risk or jeopardizing progress altogether.

The supply chain for REEs is very complex and fragmented, often involving multiple stages of production and processing across different regions. There is a significant difficulty in tracking the origin of REEs, making it challenging to ensure that all stages of the supply chain adhere to sustainable practices (Jowitt et al., 2023). Illegal mining remains a significant issue, with studies showing that in China, 50% of dysprosium, a critical HREE, was obtained from illegal sources between 2000 and 2019 (Xiao et al., 2022). All in all, the barriers to sustainable REE mining are multifaceted and require coordinated efforts across technological innovation, policy reform, and market adaptation.

Securing financing is also a major barrier for advancing REE production in the EU, as modern project finance can only be obtained after rigorous due diligence that demonstrates full compliance with high ESG standards. Requirements related to environmental protection, water and tailings management, community engagement and labour conditions are mandatory prerequisites rather than optional commitments. In this way, financing functions as a quality assurance mechanism, ensuring that only REE mining projects capable of meeting high environmental and social standards can proceed. As the importance and criticality of REEs has been recognized globally, economic areas have been adopting varying mechanisms to support the financing of REE projects. In United States, for example, the state has provided equity, offtake agreements and price floors for individual projects to support the creation of a national supply chain (MP Materials, 2025). In late 2025, EU also published their RESourceEU Action Plan to provide more direct financing support for CRM projects (European Commission, 2025f) in both mining and recycling.

Material circularity and recycling are far more than a sustainability measure - it is a strategic lever to reduce Europe's dependence on rare-earth imports while simultaneously addressing price volatility, ESG risks, and decarbonization. Yet Europe's recycling capacity remains largely in pilot phases, preventing material from reaching the market at competitive prices. Many start-ups face financial and scaling constraints, slowing the ramp-up of technologies that could supply between 24% and 48% of European NdFeB demand by 2050, as shown in Figure 4 (Rizos, Righetti, & Kassab, 2022).

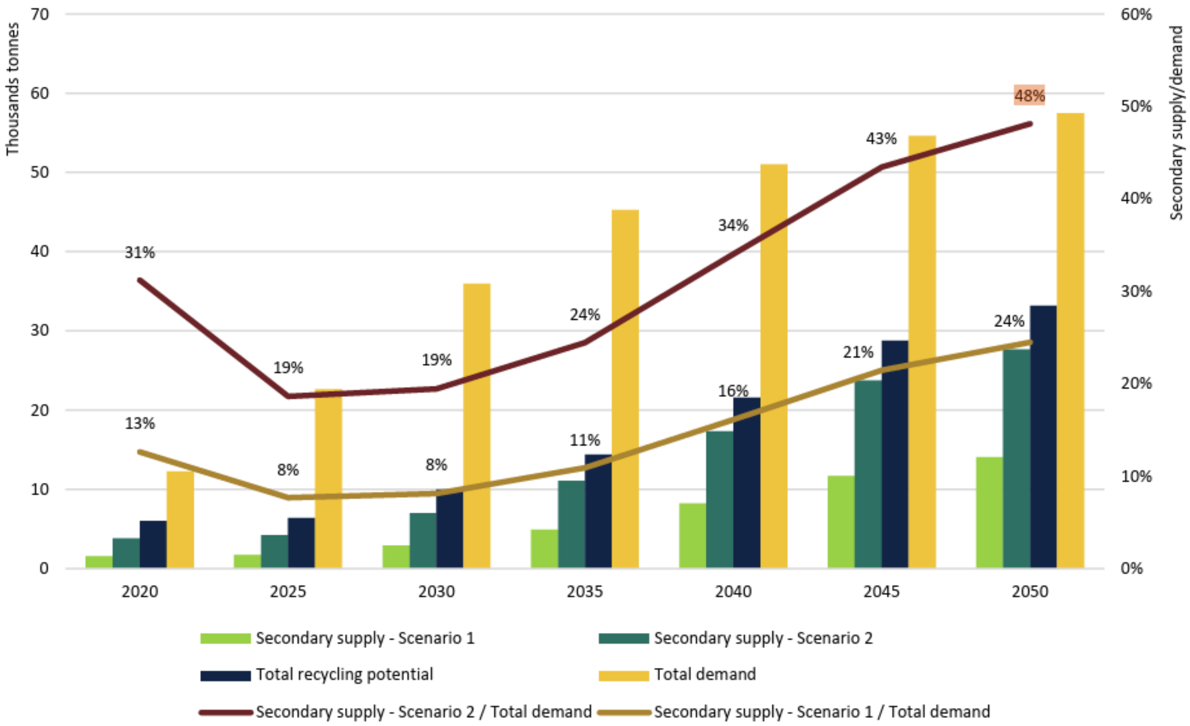

Figure 4. NdFeB magnet aggregate demand, total recycling potential, secondary supply, and secondary supply demand ratio in the EU (Rizos, Righetti, & Kassab, 2022).

3. Overview of directives and regulation related to REE PM recycling in EU

The EU has put in place a set of regulations and directives that shape a secure, responsible and sustainable supply of REEs across the full value chain, from mining and processing to product design, EoL recovery and recycling. This chapter summarises the most relevant EU frameworks including the CRMA (Regulation (EU) 2024/1252), the Ecodesign for Sustainable Products Regulation (Regulation (EU) 2024/1781), the Batteries Regulation (Regulation (EU) 2023/1542), the Waste Electrical and Electronic Equipment Directive (Directive 2012/19/EU), the Industrial Emissions Directive as amended (Directive (EU) 2024/1785) and the End-of-Life Vehicles Directive (Directive 2000/53/EC), and indicates where they act along the REE value chain (see also Binnemans et al., 2013; Figure 5).

The list is not exhaustive. A range of additional EU and national legislation, spanning chemicals regulation, waste and circular economy directives, climate and energy policy, corporate sustainability due diligence, and trade-related instruments, also plays a significant role in shaping how European companies manage REE supply chains across mining, processing, and EoL. Several of these complementary frameworks will be discussed further below (Section 3.8). It should also be noted that frameworks such as the EU Conflict Minerals Regulation are shaping expectations pertaining to responsible sourcing practices, particularly where rare earths intersect with conflict-affected and high-risk areas. These instruments reinforce the EU's commitment to secure, ethical, and sustainable access to REEs.

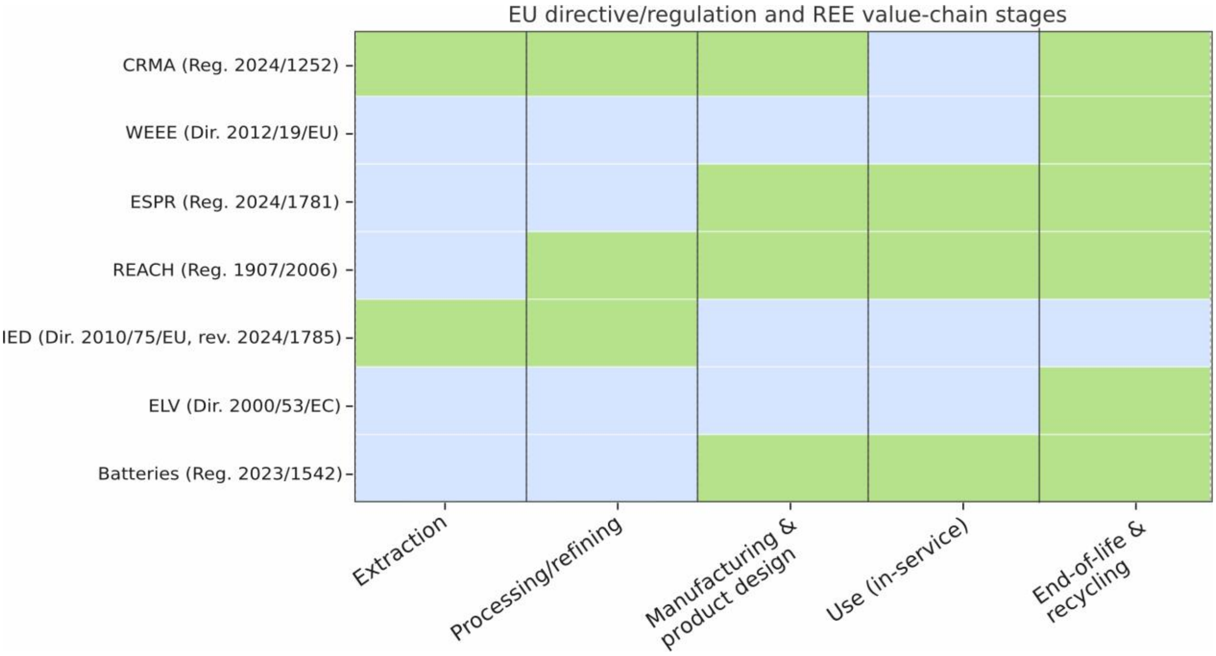

Figure 5. EU directives and regulations and their relations to REE value chain stages.

3.1 Critical Raw Materials Act (CRMA)

The CRMA, adopted in 2024, forms the cornerstone of the EU's strategy for securing access to CRMs, including REEs. It establishes strategic benchmarks for 2030: at least 10% of strategic raw materials must be extracted domestically, 40% processed within the EU, and 25% sourced through recycling. Furthermore, no more than 65% of any strategic material should originate from a single third country (European Parliament and Council, 2024a).

The Act aims to strengthen the EU's resilience and security in obtaining essential raw materials crucial for industries such as clean energy, digital technologies, and defence. With growing concerns about dependence on China and other third countries for resources like REEs, lithium, and cobalt, the CRMA aims to diversify supply chains, enhance domestic production and promote recycling. REEs are specifically highlighted in the CRMA as critical due to their economic importance and supply risks.

Key provisions of the Act include:

- Diversification of supply through new partnerships.
- Development of domestic mining and refining capacity within the EU.
- Recycling initiatives to reduce reliance on primary resources.
- Investment in research to improve mining and material recovery technologies.
- Strategic reserves to buffer against disruptions.

The Act aims to diversify the EU's supply chains by strengthening partnerships with non-EU countries rich in REEs, such as Australia, Canada, and the United States. The Act is encouraging new mining projects within Europe, particularly countries like Sweden and Finland, which have untapped REE reserves. Ultimately, the act seeks to reduce supply vulnerabilities, ensure sustainable sourcing, and improve EU self-sufficiency in CRMs.

The CRMA establishes product-specific requirements for PMs. According to Article 28, operators must provide labeling and information to facilitate recycling; the Commission will adopt an implementing act by November 24, 2026, specifying the label and data-carrier format. The data carrier will become mandatory two years after that act takes effect. These requirements apply to magnetic resonance imaging devices, motor vehicles, and L-category light vehicles starting from May 24, 2029.

Under Article 29, the Commission will adopt a delegated act by May 24, 2026, establishing calculation and verification rules for recycled content. Public disclosure for listed products will begin on May 24, 2027, or two years after that delegated act enters into force, whichever is later. This disclosure applies when the total weight of incorporated PMs exceeds 0.2 kg and must be posted on an open-access website. Article 29 also allows future minimum recycled content levels to be set through delegated acts.

Article 31 establishes an environmental footprint declaration framework to be set by delegated acts. The obligation applies only to those critical raw materials for which calculation and verification rules have been adopted. By 24 November 2026, a report identifying priority CRMs is to be submitted, followed, within 12 months, by an assessment of necessity and proportionality. The declaration obligation may then be applied only to CRMs covered by such rules. For any such CRMs placed on the market, the environmental-footprint declaration is to be made available on a free-access website (Regulation (EU) 2024/1252, Arts. 28, 29 and 31).

Joint Research Centre and EIT RawMaterials, held a stakeholder workshop on 29–30th 2025 October in Stuttgart to validate the key methodological components and identify practical implementation needs for CRMA Article 29. Participants broadly endorsed the essential elements required to calculate and verify recycled content, including supply-chain structures (short/long loop, open/closed loop), feedstock types (pre- and post-consumer), recycling processes and yields, the unit of calculation and point of measurement, chain of custody (CoC) models, as well as documentation, archiving and conformity assessment requirements.

For mass-balance approaches, controlled blending was seen as the most feasible model. Stakeholders strongly supported the development of standardised templates across the value chain and agreed that a 10-year retention period for evidence is appropriate.

Participants endorsed a tiered conformity assessment system (first-, second-, and third-party), with third-party verification necessary for regulatory or market-facing claims. Existing certification schemes (such as TÜV, UL 2809 and SCS Global) were considered suitable starting points but will require adaptation to the specific characteristics of magnet value chains.

3.2 Waste Electrical and Electronic Equipment (WEEE) Directive

The WEEE Directive (Directive 2012/19/EU) provides the regulatory framework for the collection, treatment, and recycling of electrical and electronic equipment. As REEs are embedded in many electronic components, this directive plays a critical role in facilitating the recovery of REEs from EoL products.

Implementation remained uneven across EU Member States already many years ago, with national policies and infrastructure significantly influencing recovery efficiency (Milovantseva & Fitzpatrick, 2015) and this challenge continues. Improvements in WEEE handling and enforcement are essential to maximize REE recycling. From 2019, Member States must meet collection targets of at least 65% of average EEE placed on the market or 85% of WEEE generated. Performance remains uneven, which limits REE recovery potential.

3.3 Ecodesign for Sustainable Products Regulation (ESPR)

The Ecodesign for Sustainable Products Regulation (Regulation (EU) 2024/1781) establishes an EU framework for setting product-specific ecodesign requirements by delegated acts. It entered into force on 18 July 2024 and replaces the previous Ecodesign Directive 2009/125/EC. The ESPR also introduces a Digital Product Passport (DPP) containing harmonized product information to improve traceability and to support reuse, repair and recycling. The Commission's Ecodesign for Sustainable Products and Energy Labelling Working Plan 2025–2030 (COM (2025) 187 final, 16 April 2025) identifies priority product groups and sets out the planning for the first delegated and implementing acts. For REEs, design-for-disassembly requirements and DPP data are directly relevant, as they can facilitate the recovery of REE-bearing components. Together, the regulation and the DPP framework enhance traceability of critical materials and support more efficient reuse and recycling (European Parliament and Council, 2024b; European Commission, 2025a).

3.4 REACH Regulation (EC 1907/2006)

REACH was intended to govern the registration, evaluation, and authorization of chemical substances within the EU. Though not REE-specific, it was designed to include REE compounds used in various industrial applications and ensures that human health and the environment are protected during production and processing (European Parliament and Council of the European Union, 2006). It also contributes to transparency and data availability regarding the environmental risks of REE use, thereby supporting sustainable recycling and substitution strategies (Tsydenova & Bengtsson, 2011).

3.5 Industrial Emissions Directive (IED)

The Industrial Emissions Directive (IED) (Directive 2010/75/EU) is the EU's main instrument for regulating pollution from large industrial installations. It requires integrated permits based on Best Available Techniques (BAT) and associated emission limit values to control emissions of heavy metals, dust and other pollutants to air, water and soil. The Directive aims to ensure a high level of protection of human health and the environment, provide a level playing field for operators across the EU, guarantee access to information, public participation, and avoid unnecessary administrative burdens (European Commission, 2020a).

Around 50,000 installations fall under the IED, accounting for more than 20% of EU emissions of key air pollutants, roughly 20% of pollutant releases to water and about 40% of greenhouse gas emissions (European Commission, 2022). In 2024, the Directive was revised to broaden its scope and strengthen its contribution to zero-pollution and climate-neutrality goals (Directive (EU) 2024/1785). The revised text entered into force on 4 August 2024, with transposition required by 1 July 2026 and reporting to the new Industrial Emissions Portal starting in 2028 (European Parliament and Council, 2024c).

The revision explicitly expands the IED to include specific extractive activities and the management of tailings and waste rock. Annex I, activity 3.6 now encompasses the mining and processing of industrial minerals and metals above certain capacity thresholds, incorporating REE mining and processing into BAT-based permitting where relevant. The impact assessment estimates that up to approximately 850 extraction sites may eventually be covered, including facilities handling ores and wastes containing naturally occurring radioactive materials (NORM) (European Commission, 2022). For REE-related industrial processes, the IED framework thus sets common minimum environmental performance standards and a structured governance process (the "Sevilla process") that can enhance transparency, support public acceptance, and help ensure consistent management of emissions and waste from REE projects across Member States (Directive 2010/75/EU; Directive (EU) 2024/1785; European Commission, 2022; European Parliament and Council, 2024c).

3.6 End-of-Life Vehicles Directive

The End-of-Life Vehicles (ELV) Directive 2000/53/EC sets rules for the environmentally sound treatment of vehicles at end of life. It restricts certain hazardous substances and requires high recovery performance: 95% reuse and recovery and at least 85% reuse and material recycling by average vehicle weight. EVs and hybrids are relevant for REEs because permanent-magnet motors, electronics and some components contain rare earth elements.

In July 2023, the Commission proposed replacing the Directive with a directly applicable ELV Regulation covering the full life cycle (from design to EoL). The proposal links design requirements with dismantling and pre-treatment, including separate removal and treatment of batteries and REE-containing PMs/components, to improve CRM recovery. In June 2025, the Council of the European Union adopted its general approach (formal negotiating mandate), which includes a mandatory target for recycled plastics in vehicles and leaves room to set future targets for other materials, potentially including CRMs. The file is still in co-decision; final obligations may change, pending trilogue negotiations with the European Parliament (Council of the European Union (2025a).

ELV rules work alongside the Batteries Regulation 2023/1542 (battery removal and downstream treatment) and the CRMA/ESPR measures on design and information, which together influence how REE-bearing parts are identified, removed and recycled. (See Sections 3.1 and 3.7 for details.)

Planned revisions to the ELV Directive under the EU Circular Economy Action Plan are expected to better address emerging issues like electric vehicle battery recovery and the inclusion of rare earth-containing components in recycling streams (European Commission, 2020b; European Commission, 2023a).

3.7 EU Battery Regulation (2023/1542)

Regulation (EU) 2023/1542 entered into force on 17 August 2023 and applies progressively from 18 February 2024, replacing the former Batteries Directive with directly applicable rules across the battery life-cycle (placing on the market, information and labelling, carbon-footprint disclosure, due diligence, collection, treatment and end-of-life) (European Parliament and Council, 2023).

From 18 February 2027, a digital battery passport is required for each electric-vehicle (EV) battery, each light-means-of-transport (LMT) battery and each industrial battery >2 kWh; on the same date, all batteries must bear a QR code that provides access either to the passport (for EV/LMT/industrial >2 kWh) or to category-appropriate information (Article 13(6), Annex VI; Article 77, Annex XIII; European Parliament and Council, 2023).

The Regulation also requires the battery passport to be fully interoperable with Digital Product Passports established under the ESPR framework (European Parliament and Council, 2023, Art. 78(a); European Parliament and Council, 2024b; Battery Pass Consortium, 2023). Article 7 introduces carbon-footprint (CF) declarations at battery-model and plant level, followed by CF performance-class labelling and, later, maximum CF thresholds. For EV batteries, the declaration applies from 18 February 2025 or within the time windows linked to the delegated/implementing acts; other categories follow on a staggered schedule (Article 7). Methodology and timing have been developed via Commission/JRC work and secondary legislation planning (European Parliament and Council, 2023; Joint Research Centre (JRC), 2023; Joint Research Centre (JRC), 2025)

Recycling performance is strengthened through both overall recycling efficiencies and material-specific recovery targets. Minimum recycling efficiencies must be achieved by 31 December 2025, 65% for lithium-based batteries (rising to 70% by 31 December 2030), 75% for lead-acid (80% by 2030), 80% for nickel-cadmium, and 50% for other waste batteries, while material-specific recovery targets apply by 31 December 2027 (90% for Co/Cu/Pb/Ni; 50% for Li) and tighten by 31 December 2031 (95% for Co/Cu/Pb/Ni; 80% for Li) (Annex XII; European Parliament and Council, 2023; European Commission, 2025b).

Member-state collection targets are phased in for portable and LMT batteries. Producers must meet at least 63% collection for portable batteries by end-2027 and 73% by end-2030, and 51% for LMT batteries by end-2028 and 61% by end-2031 (51% for LMT batteries by end-2028 and 61% by end-2031 (European Parliament and Council, 2023, Art. 48; European Commission, 2022).

Minimum shares of recycled content apply from 18 August 2031 to cobalt (16%), lead (85%), lithium (6%) and nickel (6%) in the relevant categories, with higher thresholds from 18 August 2036 (Co 26%, Pb 85%, Li 12%, Ni 15%). REEs are not included in these minima at present (Regulation (EU) 2023/1542 Article 8; European Parliament and Council, 2023).

Supply-chain due-diligence obligations for specified raw materials used in batteries (cobalt, natural graphite, lithium, nickel) apply to in-scope operators, including third-party verification and disclosure (Articles 48–53). By Regulation (EU) 2025/1561, the application date was postponed from 18 August 2025 to 18 August 2027, with associated guidance timelines extended (European Parliament and Council, 2023, Arts 48–53; European Parliament and Council, 2025).

The Regulation sets no REE-specific quotas or recycled-content thresholds. Its effects on REE circularity are therefore indirect but material: QR-enabled passports, enhanced collection, stricter recycling and recovery performance, and CF transparency together improve traceability and EoL flows for REE-containing components in battery-equipped products, while any REE-specific measures are primarily developed under the CRMA/ESPR framework (European Parliament and Council, 2023; European Parliament and Council, 2024a, 2024b; Battery Pass Consortium, 2023). Earlier JRC work had already highlighted advanced recycling of critical raw materials from batteries as a key opportunity for the circular economy and security of supply in the EU (Mathieux et al., 2017).

3.8 Summary and Outlook

EU policy on REEs now covers the entire value chain, from primary mining to EoL recovery. The CRMA offers a strategic framework and introduces product-specific obligations for PMs that will gradually strengthen information, traceability, and circularity requirements in mainstream applications (European Parliament and Council, 2024a). Specifically, CRMA Article 28 will establish the label and data carrier format for magnet information through an implementing act due by November 24, 2025, after which the label and data carrier will become mandatory two years later for the specified product groups; Article 29 sets the rules for calculation and verification of recycled-content disclosure by May 24, 2026, with public disclosure starting from May 24, 2027 (or two years after the delegated act takes effect, whichever is later). For motor vehicles and MRI devices, application dates under Article 28 include May 24, 2029. Meanwhile, Article 31 outlines a phased approach toward environmental footprint declarations for selected CRMs (European Parliament and Council, 2024a).

The Ecodesign for Sustainable Products Regulation (ESPR) complements CRMA by establishing a horizontal framework for product-specific ecodesign requirements through delegated acts and by introducing Digital Product Passports (DPPs). The ESPR came into force on July 18, 2024; the Commission's 2025–2030 working plan directs the initial phases of delegated and implementing acts (European Parliament and Council, 2024b; European Commission, 2025a). For REE-relevant products, design for disassembly and DPP data models are expected to improve access to magnet-bearing components and enable more effective recovery and verification along the supply chain.

EoL flows are shaped by several instruments. The WEEE Directive sets ambitious collection targets (65% of EEE placed on the market or 85% of WEEE generated from 2019), but performance remains uneven across Member States, limiting available REE-bearing feedstock from electronics (European Parliament and Council, 2012). The Batteries Regulation introduces powerful measures: QR-enabled battery passports starting February 18, 2027, for EV, LMT, and industrial batteries over 2 kWh; staged carbon-footprint requirements; stronger recovery targets; and extended producer responsibilities. Due-diligence obligations for specific raw materials were postponed to August 18, 2027, by Regulation (EU) 2025/1561 (European Parliament and Council, 2023; European Parliament and Council, 2025). Together, these measures improve traceability and collection logistics and indirectly support REE recycling where magnets and electronics are integrated into battery-powered products.

Environmental performance at the plant level is strengthened by the revised Industrial Emissions Directive (IED) and the new Industrial Emissions Portal Regulation. The 2024 IED revision must be transposed and applied over the coming years, aligning permitting processes with current BAT conclusions, while the portal regulation offers a standardized public reporting system from 2028 onwards (European Parliament and Council, 2024c; European Parliament and Council, 2024d).

Vehicle-related REE flows will be affected by the proposed End-of-Life Vehicles (ELV) Regulation, which replaces the existing directive; in June 2025, the Council adopted its position, and the file remains in co-decision (Council of the European Union, 2025b). REACH continues to serve as the foundational framework for chemical management, ensuring safe handling, data accessibility, and risk control for REE compounds used in mining, processing, and manufacturing.

Looking ahead to 2026–2029, the key implementation milestones include: adoption of CRMA's magnet-labelling format (late 2025) and recycled-content rules (mid-2026), public disclosure of recycled content (from mid-2027), staged application of Article 28 requirements to specific product groups (including vehicles and MRI starting from 24 May 2029), battery passport rollout (from February 2027), transposition and operationalization of the revised IED (by July 2026), and the first public reporting to the Industrial Emissions Portal (from 2028).

Standardization efforts under CEN/CENELEC will be essential for operationalizing data carriers, identifiers, and magnet-access/removal information, ensuring interoperability with ESPR-DPP schemas. Collectively, these measures reduce strategic supply risk, improve environmental performance, and support circular REE flows by making product information accessible, aligning plant-level benchmarks, and establishing the legal framework for scaled collection, dismantling, and recycling across key value chains.

It must also be noted that these developments must be read in the context of the firm support to circularity at regulatory and policy levels, also in view of climate change mitigation and supporting a green, sustainable economy at EU level. The EU's Circular Economy Action Plan adopted in 2020 is a good example. It aims to steer the EU's transition towards a circular economy, contributing to the achievement of climate neutrality by 2050. It is aimed at making sustainable products the norm, by implementing initiatives along the entire lifecycle. The Plan is a central pillar of the European Green Deal, aiming to transition the EU towards a sustainable, resource-efficient economy by promoting recycling, reducing waste, and enhancing product design (European Commission, 2020b).

4. Responsible sourcing and sustainability in REE production

Responsible sourcing and sustainability in REE production span the entire value chain, from primary mining to recycling and secondary raw materials. At the mining stage, REE projects can generate significant ESG risks, but they also offer opportunities to support local development when well governed. Over the past decade, a dense landscape of international standards, EU regulations and industry initiatives has emerged to address these risks and drive better performance. These frameworks set expectations for due diligence, transparency, stakeholder engagement and impact reporting, and increasingly link ESG performance to access to financing and markets. This chapter provides an overview of how such initiatives apply to primary REE mining and supply, with a particular focus on European and international frameworks that are most relevant for the MAGELLAN value chain and for actors sourcing REEs from both within and outside the EU.

4.1. Responsible sourcing and sustainability initiatives for primary mining production

Primary mining production refers to the extraction of raw materials from the earth, including REEs. Ensuring responsible sourcing and sustainability at this stage is crucial, as it sets the foundation for the entire supply chain. Key concerns include environmental impacts (land disturbance, water use, carbon emissions), social issues (working conditions, community impacts), and governance challenges (transparency and ethics in operations). Various international frameworks and initiatives have been established to promote ethical mining practices and align the sector with modern sustainability standards (OECD, 2016; IRMA, 2022; EITI, 2023).

Responsible sourcing and sustainability in European primary mining are increasingly shaped by EU policy, industry innovation, and external pressures. Key initiatives include regulatory frameworks, technological advancements, and voluntary sustainability practices, all aiming to balance environmental, social, and economic impacts.

Responsible mining relies on internationally recognized standards and third-party certification systems. The Initiative for Responsible Mining Assurance (IRMA) provides a comprehensive standard with more than 420 auditable requirements and best practices for large-scale mines, covering business integrity, social responsibility, and environmental management (IRMA, 2022). The OECD Due Diligence Guidance establishes a framework for responsible mineral supply chains for minerals from conflict-affected and high-risk areas (OECD, 2016). The Extractive Industries Transparency Initiative (EITI) enhances accountability by requiring public reporting of extractive sector revenues (including mining), contracts, and ownership structures (EITI, 2023).

Many mining companies (e.g., company sustainability reports; ICMM member commitments) have committed to sustainability goals such as reducing greenhouse gas emissions, implementing water conservation measures, and improving tailings management (ICMM, 2020; ICMM, 2021). Best practices, such as renewable energy integration at mine sites, dry-stack tailings storage, and enhanced waste management strategies, are becoming more common. Corporate social responsibility efforts also emphasize community engagement and revenue-sharing agreements to promote sustainable development.

Social sustainability in mining regions focuses on community engagement, transparent decision-making, and balancing economic benefits with environmental concerns. Local participation and recognition of community priorities are essential for long-term acceptance (Suopajärvi et al., 2016; Mancini & Sala, 2018).

Europe’s responsible sourcing and sustainability initiatives in primary mining are multifaceted, combining regulatory action, technological innovation, and stakeholder engagement. While progress is evident, ongoing challenges include fully integrating local community needs, improving environmental performance, and clearly demonstrating contributions to sustainable development.

European industry actors sourcing REEs from outside the EU must navigate multiple overlapping frameworks, including national laws, voluntary standards, and trade agreements. There are also a number of relevant regional initiatives (such as the African Mining Vision, a pan-African policy initiative). These frameworks increasingly emphasize due diligence, ESG aspects, and traceability, aligning with EU expectations (i.e. Directives such as CSDDD, CSRD, and the Critical Raw Materials Act). In addition, emerging trade and investment agreements, such as minerals partnerships and free trade deals, are beginning to embed sustainability and responsible sourcing provisions, which will shape access, compliance obligations, and investment conditions for REE supply chains. MAGELLAN and similar initiatives must interface with these global norms, notably if and when sourcing from or collaborating with partners in China, Africa, or other strategically interesting regions.

Reporting guidelines for responsible sourcing and sustainability in European mining are shaped by international standards, EU policies, and industry-specific frameworks. The most widely used guidelines are the Global Reporting Initiative (GRI), the United Nations Sustainable Development Goals (SDGs), and various sector-specific criteria and tools. Companies often reference the UN Sustainable Development Goals (SDGs) in their reporting, but comprehensive explanations of their contributions are sometimes lacking (Ivic et al., 2021; Endl et al., 2019).

Responsible sourcing in REE production increasingly relies on internationally recognized sustainability frameworks (see Table 1, below) that promote ethical, transparent, and environmentally sound practices. The International Council on Mining and Metals (ICMM) Principles establish a baseline for environmental stewardship, human rights, health and safety, and stakeholder engagement, requiring continuous improvement and respect for communities and ecosystems. Complementing this, the Global Reporting Initiative (GRI) Standards, including the new Mining Sector initiative (GRI, 2024), provide a widely adopted framework for disclosing ESG-impacts, enabling stakeholders to assess performance on emissions, labour practices, and community engagement, while ISO 26000 covers social responsibility, emphasizing stakeholder engagement.

Recent developments indicate a trend toward harmonization and consolidation of ESG related frameworks, to streamline compliance and strengthen trust. It can be assumed that this shift is partially driven by developments around the debate on due diligence in Europe (e.g., CSRD, CSDDD) and investor expectations for transparent, responsible supply chains. ESG performance is firmly linked to financing conditions and market access, positioning these frameworks as tools for aligning mining and recycling operations with global sustainability objectives and those of the European Green Deal (ICMM, 2025; GRI, 2024; IISD, 2024).

Table 1. Sustainability standards for mineral commodities

Mineral Commodity	Standard System / Responsible Organization	Sustainability Standard	Systems' Abbreviation
All mineral resources	International Council on Mining and Metals (ICMM)	Sustainable Development Framework (SDF)	ICMM
	Initiative for Responsible Mining Assurance (IRMA)	Standard for Responsible Mining	IRMA
	Towards Sustainable Mining (TSM)/ Mining Association of Canada (MAC)	TSM Protocols and Frameworks	TSM
	CERA 4in1 / DMT GROUP	CERA 4in1 Performance Standard (CPS)	CERA 4in1
	International Finance Corporation (IFC) / World Bank Group	Performance Standards on Environmental and Social Sustainability	IFC
	Responsible Minerals Assurance Process (RMAP)/ Responsible Minerals Initiative (RMI)	RMAP Mineral Supply Chain Due Diligence (DD) Standards + (voluntary) ESG Standard	RMAP

Table 2 provides a non-exhaustive overview of frameworks and initiatives shaping responsible sourcing and transparency. Collectively, they reflect a growing trend toward mandatory human rights and environmental due diligence, and integration of ESG principles into corporate strategies, driven by investor expectations, and societal demand for sustainable sourcing.

Table 2. Descriptions of international frameworks, standards, and initiatives relevant to responsible sourcing and traceability in REE supply chains.

Framework / Standard / Concept	Description	Thematic Area
UN Guiding Principles on Business and Human Rights	A global framework that establishes the responsibilities of states and businesses in terms of human rights ('respect, protect and remedy'). Foundation for many sustainability and risk policies.	Human Rights / Due Diligence / Governance
The OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas (CAHRAs)	Authoritative guide for responsible sourcing from conflict-affected and high-risk areas. Basis for EU and international due diligence frameworks.	Due Diligence / Traceability
Chinese Due Diligence Guidelines	National guidance aligned with the OECD framework, tailored to Chinese companies engaged in mineral supply chains.	Due Diligence / Governance
ICMM Demonstrating Value – Guide to Responsible Sourcing	Practical guide for mining companies to integrate responsible sourcing in operations, developed by ICMM.	Sustainability / Certification
LBMA Responsible Sourcing Programme	Compliance framework for gold and silver refiners, ensuring sourcing is conflict-free and transparent, aligned with OECD.	Certification / Traceability
CIRAF (Cobalt Industry Responsible Assessment Framework)	Tool used by the cobalt and mining supply chains to assess and manage ESG risks and community impacts.	ESG Risk Management
EITI (Extractive Industries Transparency Initiative)	International initiative promoting transparency and accountability in extractive sectors through country-level reporting.	Transparency / Governance

Global frameworks for responsible mineral sourcing offer a rich foundation of practices that MAGELLAN can adapt to the REE recycling context. The OECD Due Diligence Guidance and the UN Guiding Principles on Business and Human Rights (UNGPs) emphasize a risk-based, iterative approach to identify and mitigate human rights risks and related environmental impacts across complex supply chains. Interestingly, these principles are also echoed in China's Due Diligence Guidelines for Responsible Mineral Supply Chains, which are intended to apply to and increasingly invoked in relation to REE flows from high-risk regions, such as Myanmar. Meanwhile, sector-specific initiatives provide practical tools for implementing traceability systems, supplier assessments, and third-party audits, mechanisms that could be tailored to the PM value chain. ICMM and EITI emphasize transparency and further underscore the importance of public accountability and community involvement. Together, this selection of frameworks, as a non-exhaustive list presented in Table 2, point to a convergence around core principles such as traceability, transparency and stakeholder engagement. For solutions like MAGELLAN, embedding and strengthening these elements could enhance credibility, investor confidence, and long-term resilience.

In parallel – and with reference to Chapter 3 on regulation – it is important to highlight recent developments that relate to the frameworks above. Notably, the EU's evolving "Omnibus" package (launched in February 2025), aiming to simplify and harmonize sustainability legislation is central for actors in the REE value chain. This package includes proposals to amend the Corporate Sustainability Reporting Directive (CSRD) requiring companies to report on their environmental, social and governance performance, the Corporate Sustainability Due Diligence Directive (CSDDD) aiming to foster due diligence in global value chains, and the EU Taxonomy Regulation (EU-Tax-VO) with focus on environmentally sustainable economic activities. With this, the Commission has a target to achieve at least 25% reduction in administrative burdens, and at least 35% for SMEs until the end of this mandate (European Commission, 2025c). While these changes seek to cut administrative burdens, they have sparked concerns over regulatory uncertainty and potential setbacks in sustainability efforts. The Omnibus proposal is currently still subject to approval by the European Parliament and the Council. Many sustainability professionals, politicians and civil society organizations are emphasizing the importance of regulatory clarity and alignment with international standards.

For the MAGELLAN value chain, this evolving regulatory and policy direction is of interest: smaller actors in the REE value chain, such as recyclers or dismantlers, may benefit from extended timelines and simplified compliance pathways. At the same time, it is evident that responsible sourcing, ESG reporting, and lifecycle traceability are rapidly becoming regulatory imperatives, central for managing reputational risk. These aspects will be addressed further in Chapter 5, as it pertains to the MAGELLAN solution.

4.2. Responsible sourcing and sustainability initiatives for REE mining

Europe currently has no operating REE mines, though some large deposits have been identified in Nordic and Greenlandic terrain. State-owned and private mining companies are advancing several of these projects through exploration and permitting, with an eye toward production in the 2030s. The near-term progress is concentrated in deposit definition, pilots, and midstream processing. The EU's CRMA designates "Strategic Projects," sets permitting clocks (27 months for mining; 15 months for processing/recycling), and in March 2025 selected 47 projects (not just REE) across Member States (European Commission, 2025d), with a complementary list outside the EU in June 2025 (European Commission, 2025e). These measures shorten, but do not eliminate, decade-scale lead times typical for complex REE exploration, mining and metallurgy as well as Nordic permitting (e.g., LKAB, 2023a).

Taken together, these EU measures are shifting REE projects from voluntary ESG pledges to codified "responsible-by-design" requirements. Under the CRMA, recognition as a Strategic Project brings faster permitting and financing but presupposes high environmental and social safeguards, circularity measures, and community engagement. The Regulation also enables rules on PMs' recyclability/recycled content and requires Member States and operators to assess recovery from extractive wastes (European Parliament and Council, 2024a; European Parliament and Council, 2024b; European Commission, 2025d; European Commission, 2025e; European Commission, 2025a). In parallel, economy-wide instruments, ESRS corporate reporting standards, the Corporate Sustainability Due Diligence Directive (CSDDD), and the Ecodesign for Sustainable Products Regulation (ESPR) with its Digital Product Passport, intend to push transparent chain-of-custody and product-level data across mining and midstream processing. In practice, this policy stack sets the performance bar Nordic and Greenlandic REE projects must clear during 2020s pilots to be investable at scale in the 2030s. The next section, therefore, focuses on the technical levers that most directly meet these requirements, targeted extraction and beneficiation, water-loop closure and dry-stack tailings, optimized hydrometallurgy (including radionuclide control), and traceable midstream separation that readies magnets for recycling.

As discussed in chapter 2, REE mining presents specific sustainability challenges due to their low natural abundance, requiring extensive ore extraction and complex chemical separation processes. This results in significant waste, including radioactive byproducts, and is concentrated in a few geopolitical regions. Sustainable REE production requires improvements in mining practices, environmental management, and stricter regulatory oversight (USGS, 2023).

Several governments have introduced sustainability regulations for REE mining. China, the dominant producer, has implemented strict environmental controls and industry consolidation measures to curb illegal mining and pollution (USGS, 2023). The European Union promotes responsible REE sourcing through its Critical Raw Materials Act, which encourages sustainable mining and recycling (European Commission, 2023b). The CRMA and related policies encourage harmonization, technological innovation, and skills development to support responsible mining and reduce environmental impacts (Correia et al., 2024). In Canada, REE mining projects are generally subject to federal and provincial/territorial impact assessment regimes, which include mandatory opportunities for public and Indigenous community participation for designated projects, and are framed by Canada’s Critical Minerals Strategy (Government of Canada, 2019; Impact Assessment Agency of Canada, 2025; Natural Resources Canada, 2023).

Traceability plays a crucial role in ensuring transparency, accountability, and ethical sourcing within critical mineral supply chains, especially REEs. Effective traceability systems allow verification of material origins, processing conditions, and compliance with environmental and social standards throughout the entire supply chain. In June 2024, China introduced new regulations mandating detailed traceability for rare earth supply chains. These regulations require mining, processing, and exporting companies to meticulously document and digitally report their activities to a government-operated tracking system. The primary goals are to enhance supply chain oversight, prevent illegal mining, and curtail unauthorized exports (Reuters, 2024).

New international standards are starting to support REE sustainability by embedding traceability requirements across the supply chain. Within ISO/TC 298 Rare earth, standards such as ISO 23664:2021 and the newer ISO 17887:2025 define traceability systems for REE flows from mine or separated products through to PMs, specifying the data that must be recorded at each step and enabling a verifiable chain of custody for both primary and recycled materials (ISO, 2021; ISO, 2024; ISO, 2025). CEN/TC 472 Rare Earth Elements mirrors this work for the European context but explicitly includes sustainability, traceability and recycling in its scope, which supports harmonised indicators for circular use of REEs and alignment with EU CRM policy (CEN-CENELEC, 2023) Together, these initiatives can help companies demonstrate responsible sourcing, distinguish recycled content from primary production, and provide auditable information to regulators and downstream customers.

European and international efforts to strengthen sustainability in REE mining offer transferable lessons for developing guidelines for the MAGELLAN value chain. Policies such as the CRMA, reporting standards, and emerging traceability systems demonstrate how, transparent data flows, and codified environmental and social expectations can steer the industry towards better performance. China's recent traceability regulations and the development of technical standards also show how to support accountability across complex supply chains.

4.3. Responsible sourcing and sustainability initiatives for EoL product value streams

Responsible sourcing and sustainability initiatives are more developed for the mining sector than for the recycling sector, currently creating a discrepancy in oversight for EoL value streams compared to mining. Established frameworks in mining include criteria for social and environmental performance. EoL value streams for critical materials, electronics, and batteries are only partially addressed through broader policy instruments presented above, such as the EU Battery Regulation, the WEEE Directive, and EPR schemes. These frameworks focus mainly on collection and recycling targets, while concrete responsible sourcing and due diligence requirements for recyclers themselves remain limited. Some established mining frameworks, such as RMI and IRMA, have started to include circularity aspects, which could help supply chain operators from mining and recycling to work within similar responsible sourcing frameworks.

RMI has extended its RMAP process to include a dedicated "Recycled or Scrap Material" audit pathway, providing recyclers with a structured approach to due diligence, traceability, and risk assessment (RMI, 2023). Although originally developed for recycled inputs in metals such as tin, tantalum, tungsten, gold, and cobalt, the model should be adaptable for broader secondary raw materials systems. By defining clear audit criteria for environmental and social performance, the RMAP recycled-material track helps align recycling operations with the established responsible sourcing expectations, traditionally applied to mining companies (RMI, 2023).

IRMA is also developing a dedicated 'IRMA Standard for Responsible Recycling and Reprocessing', designed to extend IRMA's mining assurance model to secondary production (IRMA, 2022). The draft includes requirements for worker protections, environmental management, community engagement, and transparent public reporting, mirroring the structure of IRMA's mining framework. By applying the same performance-based audit approach to recycling facilities, the initiative provides recyclers with a credible route to demonstrate responsible sourcing and operational integrity comparable to certified primary mineral producers (IRMA, 2022).

From the regulatory side, EU's new battery regulation has mandatory due diligence obligations for all companies placing batteries on the EU market. It requires comprehensive documentation of environmental and social risks, carbon footprint indicators, and origin data through DPP's for batteries. These mechanisms extend responsible sourcing requirements across the full life cycle of battery materials and create strong incentives for recycling companies to implement traceability, risk mitigation, and quality assurance systems like those used in regulated mining sector (European Parliament and Council, 2023).

The initiatives mentioned above can provide a foundation for introducing responsible sourcing practices into REE PM recycling in the future, with limited existing governance or certification tools currently available. Collectively, they can support traceable EoL material loops, improve market confidence in secondary rare earth supply, and help the sector to converge toward the responsible sourcing norms already established in mining. Several EU Strategic Projects directly advance responsible sourcing of REE through increased recycling and processing capacity. In France, CAREMAG focuses on processing REE materials, while MagREEsource's MagFactory project scales up industrial REE magnet recycling using hydrometallurgical and metallurgical recovery routes. Italy's LIFE INSPIREE project targets the recovery of REEs from EoL products, supporting circularity through separation and purification technologies. In addition to these strategic recycling projects, Puławy Rare Earths Separation Plant in Poland, establishes midstream separation capacity for converting both primary and recycled feeds into high purity oxides needed for magnet production. LKAB's ReeMAP project in Sweden provides integrated extraction and processing capabilities for recovering REEs from mining by-products.

The EU's selection of Strategic Projects related to REE recycling provides an important foundation for strengthening responsible sourcing and sustainability across EoL product value streams. By prioritising large scale, transparent, and technologically advanced recycling initiatives, the CRMA framework helps establishing reliable secondary supply chains that meet high environmental and social performance requirements. These projects demonstrate how recycled REE feedstocks can be integrated into responsible sourcing systems alongside primary materials, supported by traceability, auditable reporting, and circularity criteria embedded in EU policy. As these recycling projects mature, they can supply verifiable, sustainably recovered rare earths to PM producers and downstream industries, reducing dependence on environmentally intensive mining while enabling companies to align with ESG expectations, human rights and environmental due diligence regulations, and emerging product-level sustainability standards.

5. Sustainability guidelines for the MAGELLAN value chain

This chapter presents targeted guidelines and policy recommendations to address the sustainability challenges associated with the MAGELLAN value chain. These guidelines and recommendations are informed by the sustainability context outlined in Chapter 2, the regulatory frameworks detailed in Chapter 3, and the sustainability initiatives and systems explored in Chapter 4, as well as direct stakeholder input from across REE recycling and PM manufacturing sectors.

To gather direct stakeholder input, a series of interviews were conducted with key industry stakeholders to have detailed insights on current PM recycling practices. The discussions explored technical steps, operational challenges, supply chain considerations, and emerging opportunities within the PM recycling value chain. Inputs from these experts helped in validating the identified sustainability issues, identifying areas for process improvement, and understanding how industry action and expectations align with best sustainability practices. These interviews were complemented by discussions and events involving other stakeholders, ensuring that perspectives from policy, research, and civil society informed the analysis. It became evident that industry partners also maintain active dialogue with all stakeholders, reinforcing collaborative approaches to innovation and compliance.

A set of topics and questions used during the interviews are in Appendix 1.

Focusing on the specific sustainability dimensions relevant to MAGELLAN, the chapter identifies key barriers and opportunities and proposes actionable, state-of-the-art recommendations to guide implementation. The analysis integrates both literature-based insights and stakeholder perspectives to ensure the guidelines are practical, forward-looking, and aligned with European sustainability objectives.

In addition to the sustainability guidelines, a set of policy recommendations were informed by the research and stakeholder interviews and are presented in chapter 5.3. These recommendations reflect the practical needs, recurring themes, and improvement opportunities highlighted during the discussions.

5.1. Sustainability considerations for the MAGELLAN value chain

From the stakeholder interviews, the following considerations were observed related to the sustainability of PM recycling value chains, and the short-loop REE PM recycling process developed in MAGELLAN. Quotes have been adapted for clarity.

Environmental challenges

Environmental challenges are manifold, and particularly acute in the early stages of the recycling value chain, namely EoL collection, scrap handling and shredding. For example, the handling of lithium-ion batteries within EoL vehicles poses significant fire risks due to their instability when damaged. Facilities have responded by implementing storage with monitored temperatures, heat sensors, and on-site fire response capabilities. Dust and diffuse emissions from scrap piles and vehicle movement are mitigated through water sprinkling systems and exhaust filtration.

Although the PM recycling processes differ from battery handling, short-loop recycling processes used in PM manufacturing are associated with lower environmental impacts, and carry potential to reduce greenhouse gas emissions and water consumption.

Interview insights also highlight the environmental trade-offs of demagnetization processes. Heating PM to facilitate removal can release various elements and smoke, requiring filtration systems to minimize emissions. The environmental footprint of demagnetization varies depending on the size and composition of the rotor and equipment, underscoring the need for scalable, low-emission solutions.

> “The short loop now developed has the lowest environmental impact we can imagine on permanent magnet production.” – Industry representative

In magnet manufacturing, environmental performance depends on managing hazardous substances and wastewater. One actor emphasized that compliance and closed-loop systems are essential for minimizing impacts and meeting legal requirements.

"We handle cobalt under strict checks and use a closed-loop evaporator system to treat all wastewater before discharge, as required by local legislation." – Industry representative

Social responsibility

Social sustainability is addressed, among other efforts, through local employment and community engagement. Manual dismantling operations provide opportunities for socially reintegrated workers, contributing to inclusive labour practices. Facilities often engage with nearby communities through open days and consultations, fostering transparency and trust.

One upstream actor emphasized the importance of anchoring operations locally, noting that their facilities are embedded in regional communities and provide employment across a range of skill levels. They also highlighted proactive engagement with residents during permitting processes to address concerns and build trust.

Compared to primary mining, urban mining is perceived as more socially acceptable. It avoids the historical and environmental burdens associated with traditional extraction. At the same time, an industry actor noted that being located in an industrial zone does not fully eliminate social frictions, emphasizing the importance of due diligence measures.

"We sometimes face many complaints, which is challenging, even though we operate in an industrial zone where such issues should be expected." – Industry representative

Economic barriers

Economic viability remains a central concern. Manual dismantling is labour-intensive and limits scalability, while the financial risks are significant. Economic viability is threatened by global price volatility, especially due to dependence on Chinese price-setting.

Extended Producer Responsibility schemes, often controlled by OEMs, may restrict recyclers' access to feedstock, complicating business models. The fragmentation of PMs across dozens of components increases labour time and extraction costs, and fewer than an estimated 5% of magnets in today's vehicles are recovered in practice. This is not due to lack of material value but because the cost, labour and technical effort required to access and sort them exceed recoverable value. The lack of consistent waste streams and the need for specialized partnerships further constrain economic feasibility.

"If the market price drops, recycled magnets become too expensive compared to virgin materials." – Industry representative

Economics and price were indeed repeatedly stressed as the biggest barrier to scaling recycled PM production, also stressing the concern about raw material cost. The concern was raised about collection being poorly addressed by legislation.

"Raw materials can represent up to 80% of total magnet cost, far outweighing labour and energy. Lowering raw material costs is critical for competitiveness." – Industry representative

Technological barriers

Technological innovation is essential to overcome manual processing limitations. Automation offers potential for increased efficiency and competitiveness but requires significant investment and careful feasibility studies. Yet, the large variety of PM geometries, coatings, chemistries, and assembly procedures across products creates a major obstacle to automation. The diversity of product designs complicates dismantling (‘reverse engineering’, as one interviewee described it) and requires adaptable solutions.

In PM manufacturing, variability in feedstock composition presents challenges for alloy design and process optimization. Variation in alloy chemistry is directly linked to dispersed and heterogeneous PM sources, requiring advanced sorting and characterization technologies. Innovations in these areas can enhance yield and reduce emissions, contributing to more sustainable production.

“There is plenty of space for developing new technologies that will bring more sustainability for magnet fabrication overall.” – Industry representative

The interviews highlighted parallel innovation tracks: continuous optimization in magnet plants and breakthroughs in upstream hydrometallurgical processing. It was noted that in magnet production, innovation is constant, reducing rare earth grades, streamlining steps, and adopting faster, more efficient technologies.

“Hydrometallurgical processes could see major breakthroughs, with startups developing alternatives to conventional solvent extraction.” – Industry representative

Governance and ESG issues

Environmental, social, and governance (ESG) considerations are increasingly integrated into organizational strategies. Some actors have proactively developed ESG reports, tracking performance across emissions, energy use, and social impact. Sectoral agreements with regional authorities set targets for energy reduction and emissions control.

Internal due diligence systems are used to assess supplier compliance, particularly in sectors with stringent regulatory requirements. These systems help ensuring responsible sourcing and production practices, even in the absence of mandatory ESG reporting. A recurring theme in the stakeholder interviews was responsible sourcing challenges, ESG-issues and the lack of level playing field compared to Chinese competitors.

“Cobalt is one of the most problematic metals. We can only source from approved smelters and countries, and follow strict lists, which might restrict options and create comparative advantages to countries like China”. – Industry representative

Due diligence and risks

Human rights and environmental due diligence processes and risk mitigation were a cross-cutting theme emerging in discussions with MAGELLAN solution stakeholders. Responsible sourcing begins with the collection of waste materials within defined geographic regions. High valorisation rates, up to 98%, are achieved through comprehensive processing strategies that minimize landfill and incineration. This approach reflects a commitment to resource efficiency and environmental sustainability.

Supplier screening processes include administrative checks, origin verification, and compliance assessments. These measures are adapted from established practices in regulated industries and applied to emerging recycling operations. The lack of systematic information on magnet types and locations poses challenges for human rights and environmental due diligence. Overall, many respondents noted the increased attention to due diligence, compliance and reporting, in line with EU regulatory developments.

"Customers anticipate upcoming regulations and are actively seeking solutions to comply. This growing awareness is driving increased demand for regulatory-ready offerings." – Industry representative

Traceability and Digital Product Passports

Traceability is a cornerstone of responsible sourcing, but its implementation faces practical barriers. Digital Product Passports (DPPs), while promising, may be difficult to apply in recycling contexts due to damaged or missing identifiers, lack of standardization, and limited transparency from PM manufacturers. Product complexity amplifies these barriers: magnets are small, numerous, and often lack traceable identifiers, making DPP integration challenging.

Insights from other initiatives, such as the MaDiTraCe project also support these findings, and have noted that current traceability solutions are fragmented and sector-specific, lacking holistic integration. There is a clear need for interoperable systems that address traceability, certification, and data security in a unified way.

Despite these challenges, there is ample potential; traceability tools can support the qualification and quantification of urban mines. Waste codes and labelling systems offer alternative pathways to track material flows and facilitate targeted recovery. The absence of standardized waste codes makes it difficult to identify and classify waste streams containing permanent magnets and other REE-bearing components, which limits tracking, quantification, and recovery of valuable materials from urban mines.

"Any step that helps qualify and quantify urban mines is a good point... DPPs or waste codes could potentially be beneficial to enhance traceability." Industry Representative

"DPPs are good, but continued adaptation for practical application, and education are needed." - Industry representative

From a PM producer's perspective, the main value of "magnet passports" lies in enabling efficient recycling and process control. However, even though traceability in itself was welcome, some respondents warned against overcomplicating standards at this stage, worried that overstretching with traceability now could create unnecessary hurdles.

Certifications and standards

Certifications such as ISO 9001 and environmental compliance standards are widely adopted. However, among interviewees concerns exist about the administrative burden of additional sector-specific certifications. Standardization efforts, including European level focus on rare earths, are viewed as central for industry organization and policy alignment. Standardisation is also crucial to address the lack of common design-for-recycling guidelines.

Several magnet producers also comply with occupational health and safety and automotive quality management standards (e.g. ISO 14001, ISO 45001 and dedicated automotive QMS schemes), integrating sustainability considerations into existing audit and certification frameworks.

Policy and coordination

The key policy issues affecting the rare earth and PM value chain are regulatory fragmentation, permitting delays, and inconsistent ESG expectations. Stakeholders highlighted that permitting procedures for recycling facilities vary significantly across EU Member States, creating uncertainty and slowing investment. Several actors emphasized the lack of harmonized waste codes and traceability frameworks, which complicates compliance with due diligence requirements and undermines material recovery efforts. Policy also does not yet address the fundamental challenge of PM dispersion across complex products, meaning recyclability is largely dictated by design choices outside the control of recyclers. Moreover, while some companies have adopted voluntary ESG reporting, others operate under sector-specific or regional standards, leading to uneven transparency and accountability – achieving a level playing field is paramount. Interviewees stressed the need for coordinated EU-level policy action to streamline permitting, standardize ESG expectations, and ensure recyclers to have equitable access to feedstock under Extended Producer Responsibility schemes (see also Chapter 5.3).

"Long-term predictability is of essence when speaking about policy and regulatory developments, the industry must have time to adapt." - Industry representative

Export Controls and geopolitical risks

Cross-border movement of waste materials is increasingly constrained by regulatory requirements. Notification processes for hazardous waste can delay trials and impede collaboration, even within the EU. These restrictions challenge the development of efficient recycling networks and regional hubs.

Policy initiatives must balance environmental protection with industrial feasibility. Sudden regulatory changes, such as export bans, can disrupt operations if not accompanied by adequate infrastructure and transition planning.

One industry actor stressed that dependence on a single dominant supplier country limits Europe's bargaining power:

"If you don't have options, you don't have any leverage. We probably pay 50, maybe 100% if not more, higher price than the local market does, we have no alternatives." – Industry representative

Strategic Coordination and OEM Engagement

Strategic coordination across the value chain is essential to ensure alignment between upstream recyclers, midstream processors, and downstream manufacturers. This includes harmonizing permitting procedures, facilitating cross-border collaboration within the EU, and establishing regional recovery hubs.

Original Equipment Manufacturers (OEMs) and Tier 1 suppliers play a pivotal role in shaping the value chain. Their procurement decisions influence the viability of recycling and PM manufacturing projects. They also largely determine the complexity, accessibility, and recyclability of PMs through design choices, which currently favour product performance over material recovery. Long-term offtake agreements are important in view of securing investment and scaling operations.

Interviews brought forward that the strategic value of magnets is often underestimated. Although they represent a small fraction of product cost, their absence can hamper entire production lines. Recognizing this risk and incorporating resilience into sourcing strategies is important.

From a circular-economy perspective, industry actors were cautiously optimistic about the medium-term potential of recycled PMs, provided that infrastructure and policy support materialize.

"I think we can reach those 25 %, maybe even more of recycled magnets in Europe, but investments in infrastructure and recycling companies will be essential." – Industry representative

5.2. Sustainability guidelines

The following guidelines for the MAGELLAN value chain have been developed based on the current industry best practices and tailored to the short-loop recycling process developed in MAGELLAN. These guidelines are intended primarily as practical support for industrial actors, to encourage industry-led action. These include, but are not limited to:

- Upstream stakeholders, such as dismantlers, battery and motor collectors
- Midstream operators, including magnet extractors, sorters
- Downstream manufacturers, such as magnet producers
- Corporate and operational decision-makers, including ESG specialists
- Technology developers and R&D teams
- Supply chain and logistics professionals

The guidelines are classified under several categories related to sustainability. While the guidance draws from overarching sustainability principles and regulatory frameworks, as well as interviews conducted, it is tailored to the practical realities of industrial implementation. Not all recommendations will be equally relevant or applicable to every actor. The diversity of roles and operational contexts across the value chain means that actors are encouraged to:

- Identify the sections most relevant to their activities, based on their position in the value chain (e.g., upstream, midstream, downstream)

- Adapt the recommendations to reflect their specific risk situations, resource constraints, and strategic priorities and national regulations

- Engage collaboratively with other actors to address shared challenges and opportunities

5.2.1 Environmental Sustainability

Objective: Minimize environmental impacts across the REE recycling and PM manufacturing value chain by embedding emissions control, resource efficiency, and waste reduction into operations.

Practical Actions:

a. Implement fire prevention systems for lithium-ion battery handling, including temperature-controlled storage, heat sensors, and on-site suppression equipment (*e.g.,* among dismantlers or battery collectors).

b. Use water sprinkling and exhaust filtration to control dust and diffuse emissions from dismantling and scrap handling zones.

c. Evaluate the environmental impact of existing methods and prioritize low-emission alternatives.

d. Prioritize short-loop recycling processes that reduce greenhouse gas emissions and water consumption compared to conventional methods (e.g., among magnet extractors or sorters).

e. Monitor and minimize emissions from demagnetization and separation processes through filtration and thermal management.

f. Design pre-treatment steps to minimize waste and maximize material recovery, including optimization for magnetized vs. demagnetized outputs.

g. Integrate recycled feedstock into production lines where technically feasible, and track environmental performance improvements.

h. Quantify and report environmental savings (e.g., CO_2 avoided, water saved) from the use of secondary REEs.

i. Collaborate across the value chain to improve the environmental profile of incoming materials.

5.2.2 Social Responsibility

Objective: Promote inclusive employment, safe working conditions, human rights and community engagement throughout the REE value chain.

Practical Actions:

a. Create inclusive employment opportunities in dismantling and manual processing roles, particularly for reintegrated workers or those with limited formal qualifications.

b. Provide safety training and tools to reduce injury risks in repetitive or at-risk tasks.

c. Engage local communities through early and meaningful consultations and transparent communication about environmental safeguards.

d. Address recruitment challenges by investing in training for magnet-specific dismantling and sorting skills (e.g., among midstream actors).

e. Support cultural change within operations to shift from shredding to effective and efficient selective dismantling.

f. Ensure fair labour and decent work practices across all processing steps, especially where outsourced.

g. Communicate the social benefits of using recycled REEs in product marketing and stakeholder engagement.

h. Participate in regional workforce and other development initiatives to increase awareness and support skills pipelines, including efforts to advance education and specialized training in the sector.

5.2.3 Economic Sustainability and Resilience

Objective: Strengthen the economic viability and adaptability of REE recycling and magnet production through flexible business models, risk mitigation, and supply chain optimization.

Practical Actions:

a. Develop flexible and adaptive pricing models for incoming material (e.g., tolling, hybrid ownership) to accommodate feedstock variability.

b. Use digital resources to track material flows and support transparent communication with customers.

c. Build redundancy into collection networks to buffer against inconsistent supply volumes.

d. Plan for material identification uncertainty (e.g., ferrite vs. neodymium) and integrate risk buffers into cost models, recalling that recycled materials can be an insurance against future supply shocks.

e. Invest in modular processing equipment that can adapt to different PM geometries and compositions.

f. Explore collaboration opportunities between dismantling and processing operations to reduce logistics costs and improve operations.

g. Secure long-term offtake agreements with OEMs to stabilize demand for recycled REEs.

h. Quantify cost savings or risk mitigation benefits from using local, traceable feedstock in procurement strategies.

i. Advocate for public procurement criteria that rewards circular sourcing and supply chain resilience.

5.2.4 Innovation and Technological Advancement

Objective: Accelerate innovation in dismantling, separation, and manufacturing technologies to improve safety, efficiency, and environmental performance.

Practical Actions:

a. Automate high-risk or repetitive dismantling steps (e.g. rotor separation) to improve safety and efficiency.

b. Pilot demagnetization technologies that reduce emissions and energy use compared to conventional heating.

c. Share dismantling protocols and lessons learned across facilities to accelerate learning.

d. Invest in PM magnetic scanning and composition profiling tools to improve sorting accuracy and alloy compatibility, and notably in Sensor-Based Sorting technologies.

e. Develop adaptable pre-treatment lines capable of handling both magnetized and demagnetized inputs.

f. Collaborate with research institutions to test and scale up new separation and purification techniques.

g. Integrate feedstock characterization data into alloy design and process control systems.

h. Support R&D for low-impact magnet manufacturing processes using secondary materials.

i. Participate in cross-sector innovation platforms to share insights and develop scalable solutions, notably collectors and designers, pertaining to design for recyclability.

j. Extend product lifetime through repair and reuse to prevent losses from recycling. This includes designing components for easy disassembly and re-integration

5.2.5 Governance and ESG Integration

Objective: Embed environmental, social, and governance (ESG) principles fully into decision-making, reporting, and supplier engagement across the value chain.

Practical Actions:

a. Establish internal ESG tracking systems covering emissions, energy use, workforce diversity, and community engagement.

b. Contribute to sectoral agreements or voluntary reporting frameworks to benchmark and share progress.

c. Align operational decisions with regional sustainability targets and circular economy goals.

d. Ensure ESG criteria are embedded in supplier selection and procurement processes.

e. Report on the ESG benefits of using recycled REEs in investor and stakeholder communications.

5.2.6 Responsible Sourcing and Traceability

Objective: Ensure ethical sourcing and full traceability of REE materials from collection to final product.

Practical Actions:

a. Source scrap locally to reduce exposure to unethical supply chains and improve traceability confidence.

b. Apply supplier screening and onboarding checks to verify origin, compliance, and business legitimacy.

c. Maintain batch-level tracking of incoming material to support downstream traceability.

d. Implement harmonized waste codes for REE-containing products to improve tracking and recovery.

e. Support the development of Digital Product Passports (DPPs) adapted to recycling contexts, including damaged or identifier-free components.

f. Participate in pilot testing of interoperable traceability systems.

g. Require traceability documentation from suppliers and integrate it into quality assurance systems.

h. Use traceability data to support compliance with human rights and environmental due diligence and ESG reporting requirements.

i. Advocate for unified frameworks that combine traceability, certification, and data security.

5.2.7 Strategic Coordination

Objective: Strengthen collaboration across the REE ecosystem to improve logistics, policy alignment, and long-term supply security.

Practical Actions:

a. Participate in regional recovery hubs and cross-border collaboration initiatives to streamline logistics and share infrastructure.

b. Engage in long-term sourcing strategies with OEMs and Tier 1 suppliers to stabilize demand and support investment.

c. Recognize the strategic importance of PMs and REEs in supply chain planning, even when their cost share is limited.

d. Collaborate with policymakers to ensure regulatory timelines and developments align with market feasibility and readiness.

e. Coordinate with municipalities and extended producer responsibility (EPR) schemes to access EoL products and improve collection efficiency.

f. Share dismantling data with processing partners to improve process planning and material flow forecasting.

5.3. Policy recommendations to support permanent magnet recycling in EU

The MAGELLAN value chain proposes a systemic shift in how REEs are sourced, recovered, and reintegrated into European industrial ecosystems. It emphasizes a value-chain approach that integrates upstream dismantling, midstream sorting and processing, and downstream manufacturing. This model prioritizes urban mining as a feasible alternative to primary mining.

From a policy perspective, MAGELLAN has tremendous potential to support circularity, traceability, and strategic autonomy. As such, it supports Europe's strategic autonomy and circular economy ambitions under the CRMA and the Circular Economy Action Plan, among others. However, the REE PM value chain does not merely require technical innovation; it demands bold changes across the areas of regulation, trade and governance, as emphasised by interviewees. Without coherent policy development, even the most advanced recycling technologies will struggle to scale or compete with imported virgin materials.

While it must be noted that not all industry actors viewed the policy aspects in the same way, and there were various views on the policy landscape, there was a clear understanding among interviewees that policy and regulatory timelines should be predictable (and synchronized with the development of dismantling, sorting, and processing infrastructure) to avoid unintended bottlenecks and support long-term planning and economic sustainability.

The following recommendations, across seven selected policy areas and different dimension of sustainability, aim to position the MAGELLAN solution in the context of ongoing global and EU debates on CRMs, ESG integration, and traceability. Many of them directly or indirectly support recent or ongoing policy developments within the EU, but some also anticipate future regulatory trends, including DPPs, mandatory ESG reporting, and procurement reforms which continue to embed sustainability and circularity into future-proof and resilient, green EU policies.

1. Enable Circular Infrastructure and Regional Hubs

To meet CRMA objectives, dismantling and processing infrastructure must expand through sustainable and streamlined permitting and simplified cross-border waste protocols.

• Harmonizing of permitting procedures across the EU

• Simplify shipment procedures and protocols for waste and secondary materials in the EU

• Invest in regional recovery hubs for logistics and reduction of emissions

2. Align Regulation with Industrial Feasibility

Regulatory developments and timelines to align with the readiness of industrial actors.

• Manage regulatory changes (e.g., requirements for recycled content) supported by infrastructure

• Adjust hazardous waste classifications for pre-treated materials

• Allow pilot exemptions to foster innovation and capacity building

3. Reinforce Recognition of REE Permanent Magnets as Strategic Components

REEs are already acknowledged in EU raw material policies, but REE PMs should be more explicitly recognized and classified as strategic under resilience planning.

• Explicit recognition of REE PMs as strategic components at EU level

• Prioritize REE PMs and REEs in raw materials strategies and planning

• Support sustainable domestic sourcing through new incentives

4. Embed Circularity in Public and Private Procurement

Procurement criteria should reflect lifecycle sustainability and traceability, consistent with green procurement in the EU.

• Include criteria for recycled content, traceability, and local sourcing in tenders.

• Encourage OEM long-term offtake agreements with recyclers and processors, as well as vehicle take-back schemes for secondary PM feedstock and partnerships with dismantlers and recyclers for predictable material flows

• Encourage procurement, which reflects lifecycle cost, not just upfront cost

5. Strengthen ESG and Due Diligence Integration

Environmental, social, and governance (ESG) frameworks should evolve to capture circularity, aligned with international standards.

• Enhance human rights and environmental due diligence systems that verify material origin and supplier compliance

• Support for SMEs with tailored and adapted compliance tools

6. Advance Traceability and Certification Systems

Support for the development and use of Digital Product Passports and waste codes will be critical for responsible sourcing and certification.

• Harmonize waste codes for REE-products

• Adapt Digital Product Passports (DPPs) to recycling

• Integrate traceability, certification, and data security in frameworks

• Facilitate collectors' equipment procurement and training to ensure standardized, data capture and certification compliance

7. Stabilize Markets and Investment

De-risk sustainable investments, considering price volatility, through financial instruments and incentives and enable capacity development.

• Provide financial incentives for automation, innovation, and feedstock assessment

• Implement price stabilization mechanisms (tax credits, grants) to support recyclers

• Facilitate early-stage capital investment to enable capacity development and technological upgrades.

Table 3. Summary of key policy levers: a sustainable MAGELLAN value chain

Policy Domain	**Recommended Actions**
Permitting and Compliance	Streamline permitting and cross-border processes for recycled materials across EU
Infrastructure Development and Capacity Building	Invest in regional recovery hubs; support pilot exemptions to foster innovation and training
Strategic Recognition	Classify magnets and REEs as strategic elements at policy level; integrate into resilience planning
Procurement Reform and Circularity	Embed circularity in public tenders; incentivize OEM offtake agreements, and promote vehicle take-back schemes and partnerships with dismantlers
ESG Integration	Enhance and tailor ESG reporting and due diligence systems for REE PMs and the circularity context
Traceability Systems	Harmonize waste codes & develop interoperable DPPs
Market Stabilization and De-risking Measures	Provide financial incentives where feasible (tax credits, grants); reduce price volatility through price buffers

6. Conclusion

The transition toward a climate-neutral, digitally enabled European economy will depend on secure, sustainable, and responsibly sourced REEs. This report has examined the environmental, social, and economic impacts associated with both primary mining and secondary recycling of REEs, highlighted the regulatory landscape shaping these activities, and reviewed the initiatives and standards guiding responsible production across the value chain. The evidence reinforces that while REE production is technically feasible in Europe, its upscaling and long-term viability hinges on reducing environmental burdens, strengthening social safeguards, ensuring economic competitiveness, and improving transparency.

Both mining and recycling of REEs carry environmental impacts, but case studies show that better processes, low-impact technologies, and circular systems can reduce them. Ensuring social community acceptance, worker safety, and fair value distribution is essential. Economically, high costs, volatile markets, and competition from cheaper imports make coordinated policy support and stable offtake agreements necessary.

The current regulatory framework anchored in the CRMA, WEEE, ESPR, IED, REACH, ELV, and the Battery Regulation, alongside other existing and recent directives and policies at European level having an impact on the industry, provide a strong foundation but also reveals fragmentation and uneven enforceability. Greater coherence across product-group requirements, unified waste legislation, and responsible sourcing provisions will be critical to enabling a stable investment environment and ensuring traceability across complex supply chains.

In response, the guidelines developed for the MAGELLAN value chain outline a pathway for a more transparent and sustainable REE value chain in Europe. The recommendations call for reducing environmental impacts, improving worker safety and community engagement, strengthening economic stability through flexible models and partnerships, accelerating innovation in dismantling and recycling, embedding ESG principles, ensuring full traceability, and enhancing coordination across industry and policymakers as well as other key stakeholders, such as academia and civil society, to secure sustainable REE supply.

Overall, responsible sourcing and sustainable REE production require a systemic approach that bridges primary and secondary value streams, aligns industry incentives with regulatory expectations, and leverages technological innovation to close information gaps. By adopting the proposed guidelines and promoting forward-looking policy recommendations, the MAGELLAN project and partners are well placed to contribute to establishing a resilient, circular, and ethically grounded REE ecosystem.

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Appendices

Appendix 1. Interview process for stakeholder analysis

To gather information from relevant stakeholders involved in the MAGELLAN value chain a series of semi-structured interview were conducted with several stakeholders including company representatives from:

- Orano SA (France)
- Comet Traitements (Belgium)
- BLC - The Battery Lifecycle Company GmbH (Germany)
- IFP Energies nouvelles (IFPEN) (France)
- Magneti Ljubljana (Slovenia)

The interviews took place between July and November 2025 and followed a semi-structured approach that allowed key themes to be explored consistently while leaving room for participants to elaborate on specific challenges and opportunities relevant to their expertise. This approach enabled the collection of comparable insights across organisations while still capturing the diversity of perspectives present in the sector. The guiding questions for the interviews are presented below.

GUIDING QUESTIONS

- **Introduction**
  - Can you describe your organization's role and tasks?
- **Sustainability**
  - What *environmenta*l challenges does your organization face *e.g.,* collecting complex waste, using hazardous chemicals, wastewater, emissions, circularity etc. and what solutions are you implementing/proposing to address them?
  - What are the key *social implications* and how does your organization address the social impacts (such as fair labour practices, diversity and inclusion, local community engagement)?
  - What are the key *economic barriers* for recycled permanent magnets to develop product which are competitive to conventional primary production in China?
  - Have you identified any specific *technological innovations or developments* that could enhance sustainability or efficiency within your stage of the REE recycling value chain?
  - To what extent are sustainability and ESG considerations integrated into your organization's strategy, governance, and decision-making processes, and how do you track or measure sustainability performance (*e.g.,* through KPIs, internal reporting, or third-party certifications)?

- **Responsible sourcing**
    - What processes, tools, or frameworks does your organization currently use to ensure *responsible sourcing/production* and what strategies are implemented to mitigate and assess the risks in the supply chain?
        - Are there other standards, or frameworks you would like to see introduced/implemented?
    - Does traceability of supply chain, labelling and Digital Product Passport (DPPs) a game changer for recycling industry and what are the barriers (*e.g.,* lack of acceptance, confidentiality, technological limitations, no short-term solution etc)?
    - Do you have certifications, audits mechanism in place and how new standards (*e.g.,* CEN TC 472 "Rare earth elements") can help your process?
    - How do you foresee implementation/benefits for responsible sourcing approaches in recycling industry (*e.g.,* establishing strong management systems for procuring raw materials, products, or services in a way that have ethical, social, environmental, and economic impacts across the entire supply chain)?
- **Impacts of policies**
    - How do you see the current policy, and regulatory environment and how is it impacting your business?
    - What specific regulatory/policy changes do you anticipate in the future, and what are your suggestions for improvement?
    - How recent effects on export controls from China and US tariff wars effecting industries in Europe and how are you preparing for the market shift?
    - How do you see the role of end user (OEMs/Tier 1) to develop a sustainable and competitive EU rare earth value chain?
- **Final reflections**
    - Would you like to highlight anything else with regards to sustainability?
    - Would you like to highlight anything else that the upcoming guidelines should entail, to make them particularly useful?