



D9.2 “CIRCULAR INDICATORS AND CRITICALITY INDICATORS”

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Summary of deliverable

In recent years, due to the digital and green transition occurring in the EU, there has been a growing focus on the circularity of materials and processes, especially in the context of critical raw materials. In this context, the need to measure and assess different aspects of circularity in a scientific and replicable way has emerged, therefore several circular economy indicators and frameworks have been developed to quantify the degree of circularity of products, processes, and organizations, also with the aim of comparing alternatives and highlighting potential areas of improvement.

In the context of NEO-CYCLE, a project that is circular by design, this report focuses on identifying and/or adopting existing circularity measuring tools, and/or developing ad-hoc indicators to better understand NEO-CYCLE's circularity. In parallel to the progress in terms of project's maturity, indicators are initially discussed and developed from the methodological point of view, whereas the quantitative assessment will continue in parallel to TEA, energy analyses and LCA, always in synergy, and taking advantage of the better availability of data, which goes hand in hand with the higher level of technological maturity expected as the project advances. In **Chapter One** this report analyzes the circular economy, the concept of critical raw materials, and their intersection, highlighting how the project is pertinent to both aspects.

In **Chapter Two**, this report presents an overview of circular economy indicators and frameworks and describes their limited applicability to NEO-CYCLE, as none of the indicators scrutinized appear to be meaningful as such to the rare earth elements in permanent magnets.

Chapter Three provides a description of circularity in the rare earth element and permanent magnet sectors, highlighting common practices and areas of improvement. It also explores current circularity practices within the sector, providing an overview of the main actors in the EU.

Chapter Four represents the core of this report, as it is dedicated to the list of potential circularity indicators that have been identified. Potential metrics are divided into different categories that are thought to be of interest for the project and gaps in literature are highlighted, to identify where further research is needed and where novel indicators could be developed. The report continues with an overview of future developments, in particular of how the final set of indicators will be selected. The final section also highlights the importance of dialogue with partners, along the entire duration of the project.

Overall, this report provides the context, the methodology, and the tools necessary to assess circularity within the NEO-CYCLE project, to be progressively refined as the project advances and additional or higher quality data becomes available.

1. Introduction

The European Commission has identified the green and digital transitions, also known together as the *Twin Transition*, as pillars of its strategic agenda, outlining comprehensive policies and frameworks to guide Member States over the incoming decades. The *European Green Deal* (2019) aligns with the *Twin Transition* by setting goals for carbon neutrality by 2050 and highlighting the role of digital technologies in achieving a sustainable, competitive and resilient economy.

Raw materials constitute the foundation of this transition: they are present across all major European industrial sectors (aerospace, automotive, electronics, medical and defense) and in all supply chains for high-tech applications. Among these raw materials, rare earths are a subset of 17 chemical elements with unique magnetic, optical and electrical properties, essential for producing permanent magnets, catalysts, batteries and numerous advanced technologies.

However, although Europe is among the world leaders in manufacturing products such as wind turbines, hard drives, electric motors, LEDs and more, it does not carry out significant primary production of rare earths. Ninety-eight percent of its total demand for rare-earth-based permanent magnets is met through imports, particularly from China. This condition of strong external dependence intersects with another structural factor of particular relevance for the European Union: current industrial systems and global supply chains are largely based on linear production and consumption models, in which materials are extracted, processed, used and ultimately discarded. This linear paradigm entails substantial resource inefficiencies, high waste generation and a reliance on primary extraction, often concentrated in a limited number of geographical areas.

The circular economy (CE) model has emerged as a systemic response to the linear economic paradigm, aiming to decouple economic growth from resource use by retaining the value of products, materials and resources within the economy for as long as possible. In the case of rare earths and permanent magnets, the transition towards circular practices – including advanced recycling, recovery of critical materials and remanufacturing – becomes a prerequisite for strengthening Europe's strategic autonomy, mitigating supply risks and ensuring the sustainability of the technologies required for the Twin Transition. Since 2015, with the introduction of the *Circular Economy Action Plan*, the circular economy has been recognized as a central pillar of EU policy, particularly in relation to the European Green Deal and the EU Industrial Strategy (2020).

These strategic frameworks drive innovation, investment and regulatory development towards more sustainable production systems. The concept of circular economy encompasses a set of systemic strategies aimed at maintaining the value of materials through reuse, repair,

remanufacturing, recycling and recovery. According to the European Commission, the circular economy “aims to ensure that the value of products, materials and resources is maintained in the economy for as long as possible and that waste generation is minimized” (Circular Economy Action Plan, 2020).

In parallel, and in response to the raw materials challenge, the European Commission launched the Raw Materials Initiative in 2008, establishing a strategy to address the issue of raw material access within the EU. This initiative seeks to ensure: i) a fair and sustainable supply of raw materials from global markets; ii) sustainable domestic sourcing within the EU; iii) resource efficiency through increased use of secondary materials. Building on this initiative, the Commission has developed a methodology (last revised in 2017) to assess the criticality of raw materials, based on their economic importance and supply risk. Furthermore, in 2024, the Commission introduced the *Critical Raw Materials Act* (CRMA), responding to supply disruptions affecting Critical Raw Materials (CRMs) and structural vulnerabilities within European value chains.

The CRMA aims to secure a safe, resilient and sustainable supply of critical raw materials for the EU, essential to achieving climate and technological objectives, sustaining industrial competitiveness and ensuring the proper functioning of the Single Market. Together, the goals of the Raw Materials Initiative, the EU framework for criticality assessment, and the circular economy agenda clearly demonstrate that circularity and raw material criticality are closely interlinked, encompassing economic, environmental and social (ESG) dimensions. However, measuring and integrating these aspects remains an open challenge when evaluating new processes and new value chain routes – in some cases based on secondary material streams – such as those developed within NEO-CYCLE for the recovery and valorization of permanent magnets.

In this context, the NEO-CYCLE project aims to address the growing criticality of REEs by developing two upcycling processes that focus on using end-of-life (EoL) NdFeB permanent magnets primarily sourced from hard disk drives (HDDs) to recover neodymium, iron and boron, among other substances that will emerge during the recycling process, such as ammonia. The project aims to develop two innovative extraction methods, Solid-State Chlorination (SSC) and Selective Electrochemical Neodymium Extraction (SENE), following a magnet-to-catalyst approach, where the output will be directed towards several end uses, such as the pharmaceutical industry, where neodymium and boron will be used as a catalyst for drugs, the agricultural industry, as fertilizers, the chemical industry, where both iron and neodymium will be used as catalysts, among other industries.

The following sections discuss key definitions and the main concepts related to circular economy, raw material criticality and their relevance within the context of the NEO-CYCLE project.

1.1. Circularity & Circular Economy

Circular economy represents a shift away from the traditional linear economic model that has dominated industrial society for centuries, where raw materials are extracted to create products which are then used and disposed of as waste. This “take-make-waste” approach has led to serious environmental challenges, including resource depletion, pollution and climate change (Parakinen et al., 2024).

There is no universally accepted definition of circular economy, but it usually refers to an economic system where the value of materials and goods is maximized and preserved for as long as possible, that substitutes linear End of Life (EoL) practices with reuse, regeneration, recycling and other circular practices (Pais et al., 2019). Because of the growing attention on this approach from both private and public institutions, such as the European Union, the need for a scientific approach to circularity has emerged, but the lack of a common understanding on what exactly circularity is has led to fragmentation in the approaches.

In general, a key feature of circular economy compared to linear economy is its treatment of EoL products, which are no longer regarded as waste, but as a resource that can be recovered. The circularity paradigm is often articulated through several key strategies often called the “9R Paradigm” (Parakinen et al., 2024), which can be summarized as:

- Smarter product use and manufacturing (Refuse; Rethink; Reduce), which includes strategies that focus on avoiding further/useless production altogether.
- Expand lifespan of product and its parts (Reuse; Repair; Refurbish; Remanufacture; Repurpose), where the focus is on making sure that all the value of a product is utilized.
- Useful application of materials (Recycle; Recover), where the goal is to extract all the embedded value present in an object, either through secondary raw materials or energy

These main principles are the basis of the definition of circular economy given by the Ellen MacArthur foundation (2024), where the concept of circular economy is based on minimizing waste and pollution, circulating products and materials and regenerating natural capital (Ellen MacArthur Foundation, 2024).

All these initiatives are applicable to three interconnected systemic levels: micro level (products, consumers, companies); meso-level (territories and clusters); macro level (cities, regions, nations), based on the scale at which they operate (Saidani et al., 2017).

Although several institutions provide definitions of CE, in the context of this report it was decided to adopt the definition of the European Commission: the CE “aims to ensure that the value of product, materials and resources is maintained in the economy for as long as possible, and that the generation waste is minimized” (European Commission, 2020). The OECD, for example, emphasizes the importance of maximizing material value and minimizing waste

generation throughout the lifecycle, promoting analytical tools and policy measures that enhance resource efficiency, improve recycling and reduce environmental impacts across value chains (OECD, 2024).

These concepts can be applied through a series of different strategies, depending on the sector and process considered. Several conceptual frameworks have been proposed to support the implementation of CE strategies in production systems and although no framework specifically developed to assess the circularity of REEs has been identified, these strategies offer useful guiding principles for the analysis of material flows and value retention.

The CE is considered essential for achieving climate neutrality by 2050, ensuring long-term competitiveness and strengthening the resilience of the European economy. Therefore, it represents a strategic priority for the EU, which in recent years has intensified its efforts in this direction by promoting major policy initiatives, including the EU Circular Economy Action Plan (2020), introducing measures on eco-design, key sector value chains and waste management, the European Green Deal (2019) and the EU Industrial Strategy (2020).

In sectors heavily exposed to supply risks, such as the REE and permanent magnet sector, the transition towards circularity is essential. In response to European policies, these industries face increasing pressure to reduce environmental impacts, improve material efficiency and recover value from residues and waste. In this context, CE strategies can support more sustainable practices, including the collection of all scrap material present in EU soil, magnet reutilization and extension of products' life cycle and the use of secondary raw materials.

1.1.1 Circularity for NEO-CYCLE

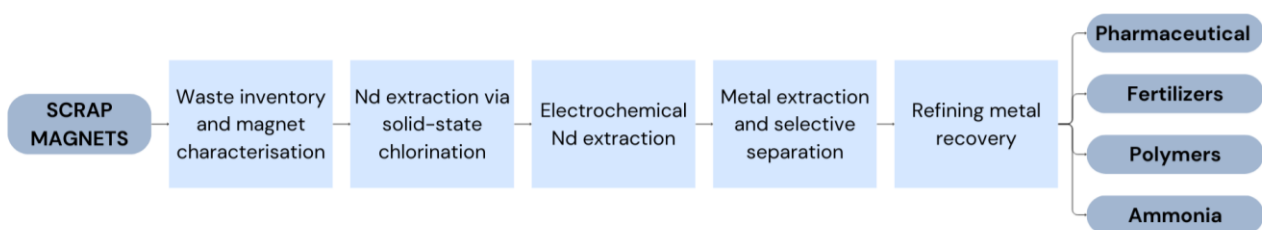


Figure 1: Simplified flow chart of the NEO-CYCLE project

The NEO-CYCLE project, as it is based on developing upcycling processes and recovering waste flows, is clearly positioned in the circular economy paradigm. The material source for this project is HDDs, which is part of the wider category of Waste Electrical and Electronic Equipment (WEEE), and is regulated by the European Waste Electrical and Electronic Equipment Directive. HDDs contain permanent magnets to function, which means that they contain different CRMs, such as REEs and boron. As it often is the case, for HDDs reuse strategies

appear to be more sustainable than recycling, although they present a series of concerns regarding data privacy (Frost et al., 2020), moreover, functional recycling (in this context magnet-to-magnet recycling) is ranked higher in terms of desirability as a strategy by Frost et al. (2020).

It is important to remember the concept of functional recycling, which is a type of recycling in which the obtained secondary material can directly replace the primary raw material input it originally came from. Moreover, in the guidelines for circular economy, maintaining functionality is considered as part of the circularity objectives, to preserve the values of the material (Blengini et al., 2017). NEO-CYCLE does not practice functional recycling, as the recovered materials are not being reintroduced in the same application as they were before, meaning they are not used to manufacture new permanent magnets, but they are used in different industries, as it has been discussed in previous sections.

1.2. Critical Raw Materials and Criticality

The modern world depends heavily on a wide range of raw materials to support technological advancement, industrial production, economic growth and human development. This is especially true for the green and digital transition, which relies on several CRMs. Many of these materials come from limited geographic sources or face supply chain vulnerabilities that could disrupt entire industries and have significant effects on economies and communities.

The concept of criticality developed as a framework to identify which materials, among all those who play a role in human life at large, have the greatest risk of causing issues to economic security and technological development in the event of supply disruptions, given how likely issues are to arise. This approach helps governments, institutions and businesses to understand which of these materials require strategic planning in terms, for example of recycling efforts, development of alternatives or substitution, or stockpiling.

Fundamentally, criticality is a risk assessment concept that emerged to evaluate raw materials across multiple dimensions of vulnerability and importance. The most widely adopted framework evaluates criticality through two primary dimensions: supply risk, defined as the probability of supply disruption and economic importance, defined as the severity of the consequences should a supply disruption event occur (Blengini et al., 2020). However, some researcher have proposed expanding this framework to a three-dimensional approach, where materials are considered to be critical if they show high risk in at least two over these three categories: economic importance, supply risk and thermodynamic rarity, defined as the amount of energy needed to obtain a certain element from the earth's crust using prevailing technologies (Calvo et al., 2018).

The concept of criticality is inherently subjective and context-dependent, as it varies significantly based on the perspective of the evaluator, in particular when it comes to private companies and public institutions, but also among different geographic locations. For this reason, several countries and regions have compiled and updated their own critical raw materials list based on their specific circumstances in the past years. It is important to note that geological scarcity alone does not mean that the material is intrinsically critical.

The assessment of criticality usually follows established methodological frameworks that are based on the criticality matrix concept, which was developed in 2008 by the US National Research Council, where the vertical axis represents supply risk and the horizontal axis economic importance. Once criticality thresholds for both measures are fixed, a material is considered critical if it is placed in the upper-right quadrant of the graph. To do this assessment it is needed to calculate the material's supply risk, by evaluating factors such as global supply concentration, substitutability, recyclability, import reliance and government performance of main supplying countries among others. Economic importance is assessed by quantifying how essential the material is to the economy in terms of the value added of the sectors that use said material or other forms of revenue impacts (Blengini et al., 2017).

1.2.1. Critical Raw Materials in the European Union

The EU's methodology for assessing critical raw materials is based on the previously described methodology of combining economic importance and supply risk. In particular, for the EU, economic importance is calculated by assessing the production of each material associated with key European sectors and multiplying it by the sector's gross value added to the EU's GDP, then correcting the value obtained with a substitution index which considers the technical and cost performance of available substitutes. Supply risk is calculated by measuring the risk of supply disruption divided into several categories encompassing different risk factors, such as geopolitical and environmental ones. The calculation is based on the concentration of primary supply from raw materials producing countries using the Herfindahl-Hirschman Index (HHI), which considers the country's governance performance (Blengini et al., 2017; Gisleiv et al., 2018).

The European Union's Critical Raw Materials list has undergone substantial changes and expansion since its establishment. The first assessment occurred in 2011, where fourteen CRM were identified after a previous study which established the framework and methodology (Grilli et al., 2017). Afterwards, every three years the list has been reviewed and expanded up to the most recent one, published in 2023, where thirty-four critical raw materials were identified (Grohol et al., 2023):

- Antimony
- Arsenic
- Baryte
- Bauxite
- Beryllium
- **Bismuth**
- **Boron/Borate**
- **Cobalt**
- Coking coal

- Copper
- Feldspar
- Fluorspar
- **Gallium**
- **Germanium**
- Hafnium
- **Heavy REEs**
- Helium
- **Light REEs**
- **Lithium**
- **Magnesium**
- **Manganese**
- **Natural graphite**
- **Nickel**
- **Niobium**
- Phosphate rock
- Phosphorus
- **Platinum group metals**
- Scandium
- **Silicon metal**
- Strontium
- Tantalum
- **Titanium metal**
- **Tungsten**
- Vanadium

Of these CRMs, sixteen of them have also been classified as strategic and have been highlighted in bold in the list above. Strategic raw materials (SRM) are a subset of critical raw materials that are specifically important for key applications such as in the green, digital, space and defense sectors and could face supply risks in the future. Technically, nickel and copper should not be included in the CRM list, as according to EU methodology they do not place in the upper-right quadrant of the criticality matrix, but as they have been identified as strategic elements and the SRM list is a subset of the CRM list, they have also been included in the latter. (Grohol et al., 2023)

1.2.2. Criticality within the NEO-CYCLE project

Of the materials that the NEO-CYCLE project aims to recover and reintroduce into the economic cycle, two of them are part of the 2023 CRM list: boron and neodymium, which is part of the light REE group. Despite their name, REEs are not actually “rare”, but the criticality emerges a complex variety of economic, technological and geopolitical factors.

The designation of REEs as critical by the European Union stems largely from China’s dominance in production, as approximately 90% of worldwide supply comes from this single country. At the same time, the importance of REEs is considered quite high, as they are widely used in different technologies, from electric vehicles to wind turbines, to electronic goods, to more highly technological applications such as those in the medical and pharmaceutical fields. The concentration of REE mining within few countries creates inherent supply risk for both governments and companies.

There are also technical challenges of REE production that make it hard for production to be expanded, such as limited know-how and long development time for mines and refining plants, to which stringent environmental regulations need to be added as constraints to the development of a European primary production supply chain. The long timeline and upfront investment needed for the development of primary production is another factor that makes circularity a better approach to address REE criticality concerns in the EU, as usually about

eight to fifteen years and over one billion euros are needed to develop a mine, to which a refining plant needs to be added (Lai et al., 2024). One other factor that contributes to REE's criticality is a difficulty in finding acceptable substitutes. Indeed, despite efforts, some REEs are essentially irreplaceable at the moment without losing quality and performance or without increasing criticality, factors that are especially true when it comes to magnets utilized in the electric vehicles manufacturing industry, where a certain level of performance needs to be achieved with strict mass and volume constraints (Liu et al., 2024).

Boron is also included in the 2023 EU CRM list due to a combination of high economic importance and concentrated supply, and much like rare earth elements, boron is partly critical due to its strong geographic concentration, mainly in Türkiye. Boron plays a key role in several strategic applications, such as permanent magnets, glass and ceramics, detergents and technologies related to energy and defence (SCRREEN2, 2023). The limited number of suppliers, combined with growing demand from clean energy and high-performance material sectors, make the EU vulnerable to potential supply disruptions, considering that substitution options can be limited without compromising performance and at an acceptable price, not unlike what the situation is for REEs. (Huang et al., 2020)

1.3. Key takeaways in the context of NEO-CYCLE

NEO-CYCLE is positioned at the intersection of between circular economy and criticality goals, as it is designed to enhance circularity in the permanent magnet sector by developing recycling pathways and at the same time address the high level of criticality of REEs, by contributing to the EU's internal supply of these elements. These aspects are embedded in the project's objectives and approaches: by developing innovative processes for the recovery of valuable and heavily critical materials like REEs, NEO-CYCLE aims to improve resource-use efficiency, valorize waste, reduce overall waste generation and, at the same time, strengthen the resilience of the European supply of critical raw materials essential for the green transition. The project explicitly builds on this dual perspective by linking circular economy strategies with the specific geopolitical, economic and technical challenges of REEs.

From a circular perspective, NEO-CYCLE demonstrates how innovative process technologies can intervene at different stages of the material life cycle. On the one hand, the processes developed within the project focus on the valorization of waste streams and end-of-life products, enabling the recovery of valuable elements from materials that are currently poorly or not at all recovered, such as permanent magnets originating from electrical and electronic equipment.

These processes contribute to closing the loops between primary and secondary production of rare earth elements, reducing dependence on primary extraction and the environmental burden associated with waste disposal. On the other hand, NEO-CYCLE also addresses the issue of the quality and reintegration of recovered materials, developing pathways that enable their reintroduction into high-value applications. In this way, the project goes beyond recycling

in the narrow sense and promotes a “closed-loop” circularity, improving overall resource-use efficiency and contributing to a more sustainable use of critical raw materials along the entire value chain.

Regarding criticality, NEO-CYCLE aims to reduce the European Union’s dependence on non-EU external suppliers of critical and strategic raw materials, such as neodymium, boron and iron. By enabling the sustainable exploitation of currently underutilized secondary resources (such as hard disk drives), the project contributes to unlocking domestic supply potential within Europe. This directly supports the objectives of the EU Critical Raw Materials Act, fostering the development of a more secure, sustainable and resilient supply of critical raw materials required for the green transition.

2. Existing circular economy indicators and frameworks

This chapter aims to provide a brief overview of circular economy indicators and existing circularity frameworks, with the aim of assessing their applicability to the REE and permanent magnet sectors. The objective is not to provide an exhaustive description of all circular economy metrics available, instead, it is to focus on a selected set of potentially relevant existing frameworks that are commonly used at different levels, given the absence of circularity frameworks specifically developed for the REE and permanent magnet sectors.

2.1. Circular economy indicators

The transition to a circular economy has created an urgent need for accurate and scientific methods to measure circularity, which fundamentally aims to evaluate the ability of products or processes to preserve the quality and quantity of materials, as well as assessing how effectively companies transition from linear to circular business models. There has been an uprise of effort in this direction over the past decade, but at the moment there is still a lack of standardization and no unified approach, causing issues, for example with consistency or when tools or frameworks are applied to different contexts. These phenomena have prompted researchers to find ways to approach measuring circularity from a scientific, rigorous and unified perspective (Rigamonti & Mancini, 2021).

Circular economy indicators serve as crucial monitoring and evaluation tools designed to measure and quantify progress towards circular economy principles, which have been discussed in the previous chapter. In a circular economy context, these indicators provide quantitative measures to evaluate the efficiency of resource use, the effectiveness of waste reduction strategies and the overall sustainability of products and processes. The need for systematic measurement has driven the development of numerous circularity indicators in recent years, with some measuring inherent circularity while others depict the consequences of circular economy loops, such as the impacts on sustainability (Saidani et al., 2017, 2019).

Many of the most widely used indicators focus on aspects such as material flows and recycling rates, and the fact that these metrics are relatively simple to calculate and communicate, making them attractive for high level monitoring and reporting purposes. However, they tend to prioritize mass-based flows and overlook material quality, functional performance and the strategic role of specific materials within products. Other indicators aim to capture broader aspects of circularity, such as product lifetime extension, reuse potential, ease of disassembly and design-for-recycling (Matos et al., 2024). These indicators shift the focus from EoL management to upstream design choices and value retention strategies. The issue with indicators of this kind is that they are often relying on qualitative scoring systems or expert judgement. Their qualitative nature can hinder comparability and reproducibility across different studies or sectors.

More recent approaches attempt to integrate environmental performance into circularity assessment, for example by weighing circular material flows by their associated environmental impacts or by linking circularity indicators with life cycle assessment results. These hybrid approaches acknowledge that circularity is not the goal in and of itself, but rather the means to achieve environmental sustainability. There can be issues with their indicators as well, since they tend to be quite complex and require specific data. (Rigamonti & Mancini, 2021)

For critical materials such as REEs, existing indicators present several limitations. First, mass-based indicators tend to underestimate the importance of materials that are used in small quantities but provide high functional value (Bobba et al., 2023a). Moreover, few indicators account for supply risk, geographical concentration, strategic relevance, and all other aspects that regard REEs and other raw materials' criticality. Finally, many indicators implicitly assume short product lifetimes and fully established recycling system, while these assumptions do not always apply to permanent magnets embedded in complex objects which have long life spans, such as wind turbines, also considering that there is no well-established REE recycling value chain in Europe, at the moment (Glogic et al., 2021). As a result, while the most commonly used circularity indicators can provide useful information, they are insufficient to fully capture the circularity performance of REEs and permanent magnets. This reinforces the need for adapted or innovative indicators within the NEO-CYCLE project.

In the past years, several circularity indicators have been developed, encompassing different perspectives and with different goals. In this section, some of the most commonly used indicators will be presented. Indicators usually are classified into three categories: macro indicators, which focus on regions or nations; meso indicators, which focus on specific areas such as eco industrial parks; micro indicators, which focus on individual products, companies, or materials. At the macro level, indicators such as Domestic Material Consumption, Resource Productivity or Waste Generation per capita can be employed; at the meso-level, indicators focus on waste (for example the percentage of tailings repurposed or reprocessed), water and energy (for example energy and water consumption per unit of secondary raw material obtained); at the micro level indicators can measure a wide range of circularity aspects based on the characteristics of the product or process, but a common example is the Material Circularity Indicator (MCI), which evaluates the general circularity of the study object, or the Ease of Disassembly metric, which measures how accessible are the singular parts of a product with the goal of recyclability)

2.2. Circular Economy frameworks

Circularity frameworks are a set of tools and methodologies with the aim of facilitating the transition from a linear economy to a circular economy through a wide range of circularity approaches through “closing the loop” and working towards lowering the need for primary raw materials (Horn & Proksch, 2022).

They can follow different approaches, such as the previously discussed “R-based” one, which consists in ranking circularity strategies from most to least desirable. They can have a different number of “R” strategies, from the most basic one, the 3R framework (Reduce, Reuse, Recycle), to more complex one, like the 10R framework (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover), also these strategies can be further classified into those which aim to close resource loops, slow down the loops or make resource flows more efficient (*Guidelines for Measuring Circular Economy : Conference of European Statisticians, 2024*).

Another way to classify circularity frameworks is based on whether they are applicable at the macro, meso, or micro level. At the macro level, frameworks are primarily designed to support policymaking, strategic planning and progress monitoring at the national and international (such as European) scale. These frameworks typically work to reduce environmental damages and improve dependence from imports, and they usually focus on aggregate material flows, resource efficiency, waste generation and other social and economic factors. Several macro-level frameworks have been for example developed by EU countries, and they often follow the structure of the Circular Economy Monitoring Framework, developed by the European Commission (Papamichael et al., 2023). There are also several complementary tools such as the EU Raw Materials Scoreboard that can be helpful to integrate circularity with raw material criticality. One drawback of these frameworks is the lack of specificity, and due to their more general nature, they are not developed to capture the unique characteristics of different sectors or products.

Meso-level circularity frameworks aim to capture the spatial and socio-economic dimensions of circular economy. Indicators employed at this level are often related to material inputs and outputs, waste management performance, recycling infrastructure, and public awareness, but there are several drawbacks, similar to the macro level, as they can lack specificity to the region the framework is applied to, or the actual process or product, so a need for more specific frameworks has emerged. Moreover, meso-level circularity indicators appear to be quite underdeveloped when compared to their macro and micro counterparts, but their importance emerges also as they constitute a bridge between national policy objectives and implementation of those goals at the company level, especially when it comes to assess the territorial impact of policies and new technologies alike.

At the micro level, circularity frameworks focus on measuring and reporting the performance of individual companies, facilities, and products or processes. At this level there are several examples of corporate sustainability reporting standards, voluntary disclosure frameworks, and dedicated circularity assessment tools. The most commonly used frameworks are Sustainability Reporting Standard (ESRS), the Global Reporting Initiative (GRI), the Sustainability Accounting Standard (SAS) and business-oriented tools such as the Circular Transition Indicators (CTI) and Circulytics among others. While these frameworks are the most specific among the three categories, they are still multipurpose tools, so by nature they need to be

applied to multiple contexts and cannot reflect each sector's specificities, which can cause issues when applied to projects like NEO-CYCLE, where the fact that elements like REEs and boron have a series of characteristics that make them unique materials to assess. Despite these factors, they provide tools to actually carry out circular economy principles, as they help translate policy objective into measurable performance indicators and they enable comparability across products, processes, and even different organizations and sectors.

2.3 Key takeaways for NEO-CYCLE

The review of circularity indicators and frameworks highlights several methodological gaps that are relevant to the NEO-CYCLE project and that should be addressed. Given the lack of circularity indicators specifically designed for REEs and permanent magnets, NEO-CYCLE should avoid relying on a single, standard circularity metric, but instead utilise a set of indicators, which should combine multiple complementary indicators to capture the unique characteristics of the scrap material used and the material obtained. Since many common indicators are mass based and therefore underestimate the importance of low-volume, high impact materials like boron and REEs, NEO-CYCLE should prioritise functional and value-oriented indicators alongside those based on mass.

The specific characteristics of the NEO-CYCLE project allow it to explicitly link circularity assessment with criticality reduction, which mechanisms still to be understood, allowing the demonstration of the link between environmental benefits and socio-economic benefits. To ensure consistency with European policy objectives and future scalability, NEO-CYCLE should align its circularity assessment framework with existing EU monitoring tools, but those should be adapted to NEO-CYCLE's specific context and address any preexisting tool's shortcomings when applied to the project.

3. Overview of circularity in the Rare Earth and Permanent Magnet sector

3.1. Circularity in the rare earth and permanent magnet sector

Because of the critical role that REEs and permanent magnets play in a wide range of strategic technologies, circularity has been gradually emerging as a strategic priority within these industries, to address the various supply and environmental risks associated with them. These elements are classified as critical raw materials due to their high economic relevance and elevated supply risk, due in particular to the strong supply chain concentration, which exposes European downstream industries to geopolitical, economic and logistical vulnerabilities. Moreover, the primary production of REEs is associated with significant environmental impacts linked to the intensive use of chemicals, energy, and land, and the production of large volumes of waste. From a European perspective, developing an in-house primary production sector could face significant obstacles, from regulatory ones to difficulties linked to a lack of know-how and infrastructure. In this context, focusing on recovering REEs from EoL routes represents an alternative way to address the various concerns linked to REEs.

Circularity offers a strategic pathway to address these challenges by reducing dependence on primary raw materials, mitigating supply risks and lowering environmental impacts across the value chain. Many circularity strategies could be employed, but compared to bulk metals such as steel, aluminum and copper, the REEs sector is characterized by relatively small volumes and a necessity for the material to be of a certain quality and purity to ensure performance. Because of these factors, generic circular economy approaches might not be directly applicable to REEs and permanent magnets. For example, reuse strategies for permanent magnets could not be effective, because of several factors including the lack of labelling on goods containing permanent magnets that specify the exact composition of their magnets and many more.

Recycling pathways in the REE and permanent magnet sectors can be broadly classified into short loop and long loop approaches, depending on the extent to which the material is processed before being reintroduced into the value chain. Short loop recycling refers to processes that create new magnets from scrap material without separating the single REEs, for example using the hydrogen decrepitation technique, which involves using hydrogen to break up the magnets into a powder which will then be pressed into new magnets. Long loop recycling involves the complete chemical processing of EoL magnet scrap to recover REE oxides using a wide variety of techniques, both traditional, like pyrometallurgical and hydrometallurgical processes, and innovative, like bioleaching processes. Short loop recycling is faster and less environmentally impactful, but long loop recycling is more versatile and produces a better-quality output. Both recycling pathways are currently employed and contribute to circularity in the REEs sector, but in different ways. Short loop recycling is useful in close loop supply

chains, where the magnets composition is exactly known, while long loop recycling allows for a broader recovery of materials and more potential uses for the materials obtained.

3.1.1. The circular Rare Earths and permanent magnets value chain

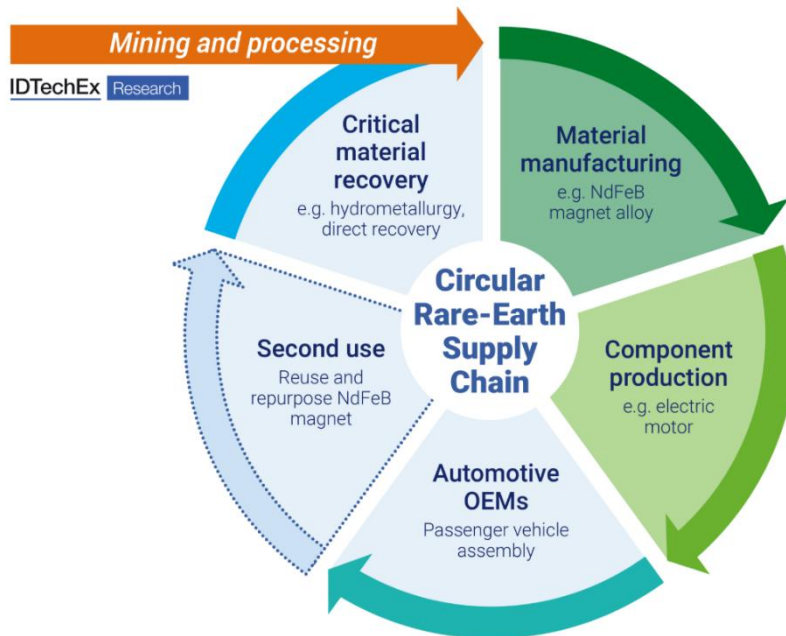


Figure 2: Example circular critical material supply chain for rare-earth elements. Source: IDTechEx (Howley, 2024)

To understand how the REE and permanent value chain can become circular, it is fundamental to understand its characteristics and principal nodes. The value chain, summarized in *Figure 1*, is complex and comprises a sequence of tightly interlinked steps which are sensitive to disruption. It typically begins with the extraction of rare earth ores, followed by the beneficiation and chemical separation of the singular rare earth oxides, which are then converted into their metal form, which is used to manufacture permanent magnets. These magnets become key components of several goods, from wind turbines to electric vehicles to electronic objects. Not all REEs are used to fabricate permanent magnets, but can become catalysts for several industrial processes, be used in other industries from the ceramics one to highly technological employs such as the pharmaceutical industry. (Voncken, 2016)

Several critical nodes can be identified along this value chain. Upstream stages, particularly mining and separation, are associated with high environmental impacts and strong geographic concentration. Midstream stages, such as alloying and magnet manufacturing, are characterized by high technical complexity and strict quality requirements, which limits the ability to substitute materials or tolerate impurities. Downstream, the integration of magnets into complex products often results in limited accessibility at the EoL stage, which makes scrap material collection, dismantling and sorting challenging. The latter, in particular, limits

short-loop recycling pathways due to difficulties in knowing the exact composition of scrap magnets. These critical nodes have a direct influence on the circularity potential of the sector. Material losses can occur at multiple stages, including during manufacturing, use, and EoL treatments. For example, the fact that permanent magnets are embedded into products such as electric motors poses as an obstacle to the recovery of all the available quantity of scrap metal, lowering the potential output of recycling activities. (Rizos et al., 2022)

The value chain diagram presented highlights the main material flows, identifying the points at which circularity strategies can be applied, mainly divided into reuse strategies and recycle strategies. In this context, NEO-CYCLE focuses on the development of two technological processes to recover materials from spent magnets, therefore it operates in the “Critical materials recovery” of the REE circular value chain.

3.1.2. Circularity strategies in the REE and permanent magnet value chain

Circularity strategies in the REEs and permanent magnet sectors can differ from those traditionally applied to bulk metals, due to the characteristics of rare earth elements, the complexity and variety of magnet composition, and the high sensitivity of the magnetic performance to the magnet’s quality and composition. Because of these factors, effective circularity in this sector requires specific strategies, and therefore specific indicators to be measured.

At the product level, design and labelling strategies can play a central role. For example, due to the complexity of many goods that contain magnets, such as electric vehicles, design for disassembly can improve the ability to access the magnet scrap. Moreover, clear labelling on the magnets can improve the effectiveness of magnet-to-magnet recycling, ensuring less material loss and a lower environmental and economic impact of the recycling process. This allows, at the process level, to focus on a combination of short-loop and long loop recycling strategies, the latter allowing for the recovery of heterogeneous or contaminated magnet scrap, also permitting a wider variety of potential uses for the obtained material, as it is separated into singular rare earth oxides. Lastly, at the system level, integrated European circular strategies need to be implemented through the development of an integrated recycling supply chain.

Despite the growing attention to circular economy and the several concerns about relying on primary production for REEs in the EU, the sector currently lacks a consolidated and integrated circularity framework compared to those developed for bulk metals, such as the ICMM framework (ICMM, 2024). Existing initiatives related to rare earths and permanent magnets are distributed across different areas, such as policy driven strategies, research projects, and industrial actions. Due to the fragmentary and uncoordinated nature of these efforts, a unified framework to assess circularity performance across the whole REE and permanent magnet value chain has yet to be developed, which should ideally include an agreed set of principles

and metrics specifically tailored for the characteristics of the sectors, similarly to what has been developed for the metals and minerals supply chain (ICMM, 2025).

At the moment there are initiatives and organizations addressing circularity related aspects in the sector, but still these efforts remain uncoordinated and have yet to be unified into a singular framework. Industry associations such as the Rare Earth Industry Association (REIA), promote industry cooperation and knowledge exchange, and have developed a REE and permanent magnet specific LCA product category rules (REIA 2024). At the same time, European entities such as EIT RawMaterials, the European Raw Materials Alliance (ERMA), and other organizations such as the International Energy Agency (IEA), despite working in different ways to address various concerns related to REEs and permanent magnets, are not specifically dedicated to this industry. On the industry front, current circularity approaches are driven by a limited number of pilot-scale initiatives, rather than fully established and commercially operating businesses. In the past years several recycling companies dedicated to REE recovery from permanent magnets have been emerging, such as HyProMag and Urban Mining Company, alongside chemical companies like Solvay and Carester, which are focusing on long-loop recycling pathways to recover oxides (Solvay, 2024; Carester, 2025). Notably, several of these projects are funded by both public organizations such as the EU and private businesses, especially operating in the automotive industry, such as Stellantis, Volkswagen Group and BMW (Carester, 2024; Volkswagen Group, 2025; BMW Group, 2025). It is important to remember that despite the efforts, these projects, especially the European ones, are still at the pilot stage, and none have reached the commercial stage.

Both institutional and industrial efforts will be summarized in Table 3.1. Despite growing momentum and increasing efforts from both public and private institutions, circularity is still underdeveloped across the sectors that employ REEs and permanent magnets in their products. Part of this gap could be addressed by the development of an industry specific framework that assesses circularity performance across the value chain, followed by the development of ad-hoc indicators to accurately and appropriately measure said circularity. This effort could be a step further to achieve industry wide cooperation and coordination, allowing for the development of an integrated UE REE and permanent magnet recycling value chain. This could alleviate several of the concerns related to REEs, including the high supply risk that industries using REEs are currently exposed to.

Table 1: Companies and institutions active in the REE and permanent magnet recycling sector.

<i>Name</i>	<i>Type of organisations</i>	<i>Principal circularity strategies</i>	<i>Source</i>
<i>HyProMag</i>	Recycling business	Short-loop recycling of NdFeB magnets via hydrogen decrepitation; recovery of magnetic powder	(HyProMag, 2025)

<i>Noveon Magnetics / Urban Mining Company</i>	Recycling business	Magnet-to-magnet recycling of NdFeB magnets; production of sintered magnets from recycling rare earth materials	(Noveon, 2025)
<i>Carester/Caremag</i>	Recycling business	Long-loop magnet-to-oxide recycling facility in France; should reach commercial stage by the end of 2026	(Carester, 2025)
<i>Solvay</i>	Chemical company	Is currently developing a REE recycling line in France to extract REE oxides from magnet scrap	(CRS Europe, 2025)
<i>SusMagPro</i>	Project	European project with the goal of recycling REE magnets	(European Commission, 2019; SusMagPro, 2023)
<i>EIT RawMaterials</i>	European platform	Gives support to circular economy projects on several topics including REE recycling	(Gauß et al., 2021)
<i>ERMA</i>	Policy and industrial alliance	Strategic support to circular value chains for REE and permanent magnets; facilitation of industrial recycling projects	(European Commission, 2021)
<i>REIA</i>	Industry association	Promotion of sustainable and circular REE value chains; facilitation of dialogue between industry, policymakers and researchers; support to recycling, responsible sourcing and diversification of REE supply	(REIA, 2025)

<i>JRC</i>	European public research body	Development of critical raw material indicators; material flow analysis of REE; assessment of recycling potential and circularity pathways to support EU policy making	(European Commission, 2026) (Mathieux, 2017)
<i>General Motors</i>	End-user	Signed a REE magnets deal with Noveon Magnetics	(Zadeh, 2025)
<i>Mkango Resources</i>	Mining company	Funds REE recycling processes internally (magnet-to-oxide) and through HyProMag	(Mkango, 2025)
<i>Stellantis</i>	End-user	Plans to source part of the REE it needs from Carester	(Carester, 2024)

3.2 Key takeaways for NEO-CYCLE

The overview of circularity in the REE and permanent magnet sector has highlighted both the strategic relevance of circular approaches and the structural challenges that currently limit their widespread adoption. Due to the criticality of REEs, the strong geographical concentration of supply, and the high environmental impacts associated with primary production, circularity emerges as a key lever to enhance supply security and sustainability, particularly from a European perspective. The analysis has shown that circularity in the sector is characterized by small volumes, oftentimes strict purity requirements, and the fact that the source material, permanent magnets, are often embedded into complex products, factors that constrain the applicability of generic circular economy strategies. Despite increasing momentum from several research projects, industrial pilots, and institutional initiatives, circularity efforts remain fragmented.

Based on the current state of circularity described in this chapter, several considerations emerge. First, despite the growing interest in the REE and permanent magnet recycling sector, there is no globally recognized institution to coordinate circularity efforts, for example by developing a dedicated framework. Second, while there are both privately and publicly funded projects currently active in the EU with the goal of recycling REEs from permanent magnets, none of them has reached commercial level at the moment. NEO-CYCLE positions itself in a

setting with growing interest from multiple agents, both public and private, in a sector that has yet to reach maturity, especially in the EU.

4. Circularity and Criticality indicators for the NEO-CYCLE project

As highlighted in the previous chapters, the need to transition towards circular economy models in the REE and permanent magnet sectors is increasingly recognised as a strategic priority, yet it remains challenging to assess in a scientific and consistent manner. Existing circularity frameworks can provide helpful guidance, but do not capture the specific characteristics of REE and permanent magnet value chains. In particular, the absence of a set of circularity indicators developed specifically for this industry that is widely accepted and utilised limits the ability to set appropriate targets and monitor performance and progress over time. This chapter proposes a set of circularity indicators that could be used to assess circularity in the NEO-CYCLE project, building on an extensive review of scientific literature, existing circular economy frameworks and ongoing European initiatives. These indicators are intended to capture several dimensions of circularity that are relevant for NEO-CYCLE, including material circularity, resource efficiency and management, and economic value retention. The resulting list of indicators, presented in *Table 2* to *Table 10* is comprehensive yet non-exhaustive and is designed to support different organisational and operational scales along the value chain.

4.1. Proposed indicators

Despite the growing body of literature on circular economy assessment, the measurement of circularity remains challenging for REEs and permanent magnets, as it has been discussed in the previous chapters, because there is no shared circularity framework developed for this sector, and very few indicators have been found that were specifically created for this purpose. Since the REE and permanent magnet value chain is particularly complex, before potential indicators are proposed, it is necessary to determine which aspects of circularity are to be measured by identifying the most relevant dimensions of circularity for the NEO-CYCLE project.

The NEO-CYCLE project is circular by design, as it aims to upcycle permanent magnet scrap from spent HDDs to recover iron, boron, and neodymium, with the aim of making the permanent magnet value chain more circular and more based in Europe, to address several concerns such as supply interruption risks and the environmental challenges of primary production. Because of these components that make the project circular, the categories of material circularity, where the indicators included aim to measure the degree to which the process is circular; recycling and End-of-Life performance, where indicators measure the performance of the recycling process; resource efficiency and process performance, in which indicators measure how efficiently resources are used.

Although NEO-CYCLE is a circular project, it still needs several inputs and outputs to function. Because of this, the categories of resource use, which aims to quantify how efficiently resources such as water and energy are utilized by processes, and waste generation and

management, to assess the amount of waste generated and the efficiency of its treatment. Because of the strategic nature of the project, the strategic relevance category was selected with the aim to capture NEO-CYCLE’s impact on the criticality of the raw materials it aims to recover. Another category selected is economic value and value retention, to measure economic impact of the project.

Table 2: Indicator categories

CATEGORY	DESCRIPTION	ADEQUATENESS OF LITERATURE
MATERIAL CIRCULARITY	Indicators that describe the degree of circularity of a process	Medium
RECYCLING AND EOL PERFORMANCE	Indicators that focus on the recycling process itself	High
RESOURCE EFFICIENCY AND PROCESS PERFORMANCE	Indicators that measure how efficiently resources are used and how value is preserved throughout the processes	Low
RESOURCE USE	Indicators that assess how resources, mainly energy and water are utilized in processes	High
WASTE GENERATION AND MANAGEMENT	Indicators that measure the effectiveness of recycling processes and pathways	Medium
STRATEGIC RELEVANCE	Indicators that focus on the effectiveness of strategies to reduce criticality	Low
ECONOMIC VALUE AND VALUE RETENTION	Indicators that highlight the economic viability of the project and the link with techno-economic assessment	Medium
PRODUCT DESIGN AND LIFETIME EXTENSION	Indicators that assess the material inflow	-
CIRCULAR ECONOMY TOOLS	Tools other than indicators that aim to measure circularity	-

The focus of the NEO-CYCLE project is the development of recycling pathways for permanent magnets contained in HDDs to recover critical raw materials and thus support the creation of a European value chain for these elements and improve on their supply risk, while aiding the development of high-tech European industries and mitigating environmental damage. Based on these considerations, several criticality categories have been identified, and for each category several indicators have been identified. In the future there will be a further selection of indicators, ideally one or two for each category, which will be used to assess NEO-CYCLE’s circularity performance.

To aid with readability, sources for each indicator will be provided in *Table 11* at the end of this section.

4.1.1. Material circularity

This category was selected because, at its core, the NEO-CYCLE project aims to develop circular process for the recovery of REEs and other raw materials, therefore a process' circularity was identified as a fundamental aspect to be measured. This subset of indicators aims to describe the degree of circularity, or how "closed" the loop is, how dependent it is on primary raw material inputs, which are central aspects of evaluating a circular process. In other words, these indicators allow the assessment of how successful a process is at reintroducing recycled REEs into production processes and can be used to compare different technologies and processes.

Table 3: Proposed indicators for material circularity. References: see Table 11

<i>Acronym</i>	<i>Indicator</i>	<i>Unit</i>	<i>Description</i>
<i>CIR</i>	Circular input rate	%	EoL-RIR improvement because it includes all circularity strategies such as reuse and regeneration of goods/materials, not only recycling
<i>CM</i>	Circularity metric	%	Secondary material use/total material consumption
	Linear flow index		The amount of a material flowing in a linear fashion (unrecoverable waste + virgin material) / total mass flow
	Material circular inflow	%	Share of non-virgin input in a process
	Outflow circular content	%	% by mass of reused, recycled, or recirculated material from outflow
<i>RIR</i>	Potential material circular outflow	%	% of recovery potential / % of actual recovery
	Recycling input rate		

4.1.2. Recycling and EoL performance

As NEO-CYCLE is centered on the development of recycling pathways, indicators focusing on the technical performance of recycling and recovery processes were found to be particularly relevant. These indicators aim to measure several aspects of recycling processes, such as recovery rates, process yields and the overall effectiveness of EoL treatments. By enabling the evaluation of how efficiently critical materials are recovered by the system, they measure more strictly technical and quantitative aspects of the project.

Table 4: Proposed indicators for recycling and EoL performance. References: see Table 11

<i>Acronym</i>	<i>Indicator</i>	<i>Unit</i>	<i>Description</i>
	Actual recovery of EoL materials	%	the amount of EoL metal recovered by the company to the market size, and it applies not only to metals used in renewable energy systems but across all sectors where metals are in use.
	Overall process yield	%	Useful output mass/input mass
<i>RDI</i>	Recycling desirability index		Measures the desirability of recycling a given product based on the number and type of materials it contains and the security of its supply. The indicator also accounts for the technological maturity (TRL) of the process
	REE recovery rate	%	Recovered REE/REE in magnet
<i>ALR</i>	Average loss rate	%	Percentage of scrap material lost during the recycling process
<i>CMU</i>	Circular material use rate		Recycled material/overall material intake by the system, originally developed for countries

4.1.3. Resource efficiency and process performance

While the previous category focuses on effectiveness, this subset assesses how efficiently resources are used throughout the system and how material and economic value is preserved, which are prerequisite for industrial feasibility and are fundamental when evaluating scalability potential. This is particularly relevant for NEO-CYCLE, as these indicators help evaluate whether recycling value chains can achieve performance comparable (or improved) to primary production.

Table 5: Proposed indicators for resource efficiency and process performance. References: see Table 11

<i>Acronym</i>	<i>Indicator</i>	<i>Unit</i>	<i>Description</i>
	Material productivity	€/kg	Revenue from production/total material moved
<i>RII</i>	Resource intensity index		Rate of variation of resource inflow consumption/rate of variation of revenue per unit of time
<i>VRE</i>	Value-based resource efficiency		Value added/monetary value of input (output value/weighted sum of all resource inputs)

4.1.4. Resource use

This category includes indicators that capture how a process utilizes resources such as energy and water, which are both key elements of sustainability in a broader sense and circularity, to ensure that circular processes are not overly intensive in terms of water and energy consumption. These indicators are highly relevant to NEO-CYCLE as they allow the alignment of circularity goals with the broader European objectives of decarbonization and climate change management.

Table 6: Proposed indicators for resource use. References: see Table 11

<i>Acro- nym</i>	<i>Indicator</i>	<i>Unit</i>	<i>Description</i>
<i>EI</i>	Energy intensity	kWh/kg	Total energy use/output mass
	Renewable energy share	%	Renewable energy/total process energy
<i>CWD</i>	Circular water discharge	%	m3 of circular discharge / m3 of water inflow (circular water discharges are those consistent with their availability for all purposes and of appropriate water quality)
	Ratio of water re-use or recirculation		Total water used for a certain process / water withdrawn from all sources
	Total water consumption	m3	Water withdrawal - water discharge (it measures the water not available anymore in the ecosystem)
<i>TWW</i>	Total water withdrawal	m3	Water withdrawal by type of source
<i>WI</i>	Water intensity	m3/unit	total water consumption/output
<i>WRR</i>	Water recycling rate	%	Volume of processed water recirculated/total water use

4.1.5. Waste generation and management

This category focuses on the generation of waste and residues throughout the processes, as well as their potential valorization. It was included to ensure consistency with the circular economy principles discussed in previous chapters, such as waste prevention. For NEO-CYCLE, these indicators help identify whether recycling pathways effectively reduce overall waste generation or merely shift the burden, while also supporting the evaluation of residue management strategies and the degree to which by-products are reintegrated into production.

Table 7: Proposed indicators for waste generation and management. References: see Table 11

<i>Acro- nym</i>	<i>Indicator</i>	<i>Unit</i>	<i>Description</i>
<i>TPW</i>	Total production from waste	€	value of production with waste material as feedstock
	Total reactive waste generation	kg	Total generation of waste causing acidic seepage
<i>WTP</i>	Waste-to-product ratio	kg/kg	Waste produced/product produced

4.1.6. Strategic relevance

This subset of indicators explicitly links circularity assessment with the reduction of criticality and supply risk. It was selected to reflect the strategic dimension of NEO-CYCLE, which aims to contribute to European supply security of critical raw materials. Indicators in this category assess the extent to which circular strategies reduce dependence on primary imports and enhance resilience of the value chain. As this is a core element of the NEO-CYCLE project, this category should be further developed through dialogue with partners, which could bring out more metrics from literature, and through the development of novel indicators to fully reflect the strategic nature of the project.

Several areas of potential interest have been identified, including:

- reduction of import dependency, where an indicator could quantify the percentage of EU demand covered by NEO-CYCLE
- mitigation of supply risk, which would for example quantify the impact of NEO-CYCLE on the HHI
- reduction of exposure to supply risks, such as price volatility or geopolitical factors
- Quote of output employed in strategic sectors

Dialogue with partners should expand this list and identify other areas where indicators from literature are insufficient.

Table 8: Proposed indicators for strategic relevance. References: see Table 11

<i>Acro- nym</i>	<i>Indicator</i>	<i>Unit</i>	<i>Description</i>
	Contribution to EU supply	%	Ratio between the output of recovered material and the total annual EU consumption of said material, used to assess the contribution of recycling activities to EU supply security

<i>PW-ADP</i>	Performance-weighted abiotic resource depletion	(amount of element in exam/kg of good)/adp * (benefit produced by the good/demand for that benefit)
<i>REI</i>	Supply chain risk exposure index	Ratio of the risk exposure index reduced by the project over the previous risk exposure index for the REE supply chain

4.1.7. Economic value and value retention

Since economic performance is a fundamental condition for the long-term viability of circular economy practices, this category was selected to measure the processes' ability to generate and retain economic value along the value chain. In the context of NEO-CYCLE, these indicators complement techno-economic assessment by linking it specifically to circularity and it is not intended as a substitute for TEA or LCC, but simply a set of indicators that capture circularity in economic terms.

Table 9: Proposed indicators for economic value and value retention. References: see Table 11

<i>Acronym</i>	<i>Indicator</i>	<i>Unit</i>	<i>Description</i>
<i>CEI</i>	Circular economy index	Currency	Measures the economic value of the materials embedded in a certain good, aims to measure the economic effectiveness of a recycling process, it's the ratio of recycled material value from EOL products compared to total material value in recycling processes needed to produce new versions of the same product
<i>PLCM</i>	Product level circularity metric	Currency	Ratio between the economic value of recirculated parts and economic value of all parts of a certain good

4.1.8. Product design and lifetime extension

These indicators are not directly relevant to NEO-CYCLE's objectives, as they address upstream design choices that influence a product's longevity, disassembly and recyclability. They have been included in this list as they could help assess potential scrap metal inflows both in terms of their quantity and quality, which is a fundamental aspect for a process like NEO-CYCLE which relies on these materials to operate.

Table 10: Proposed indicators for product design and lifetime extension. References: see Table 11

<i>Acronym</i>	<i>Indicator</i>	<i>Unit</i>	<i>Description</i>
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<i>eDIM</i>	Ease of disassembly metric		Based on the tools and the number of steps needed to disassemble and reassembly a certain good, with a database that gives a score for each of the inputs
<i>LI</i>	Longevity indicator	n. of months	lifetime of the product + years added by reuse/refurbishing + years added by recycling the materials
<i>EZWP</i>	expanded zero waste practices	%	% of zero waste practices employed by a process/organisation from a list proposed in the paper

4.1.9. Tools and composite indicators

This category encompasses integrated tools and composite indicators that aim to combine multiple dimensions of circularity at the same time. It was included as single point indicators, as much as they can be extremely reductive and fail to capture all the multidimensionality of circularity, they can be more digestible than a long list of indicators and therefore be easier to communicate, aiding dialogue with a wider range of partners and audiences. They sacrifice scientific rigor and accuracy for ease of communication, so they are intended to be support tools.

Table 11: Circularity tools. References: see Table 11

<i>Acronym</i>	<i>Indicator</i>	<i>Unit</i>	<i>Description</i>
<i>CC</i>	Circularity calculator		Online tool to calculate several circularity indicators based on a series of inputs
<i>CEIP</i>	circular economy indicator prototype		excel spreadsheet with a series of prompts to assess a product or process' circularity
<i>CET</i>	circular economy toolkit		Online tool that quantifies the improvement potential of a product/process in terms of circularity
<i>CP</i>	Circular pathfinder		algorithm that aims to find the best circularity strategy for a certain good
<i>CIP</i>	circularity potential indicator		Online tool that evaluates the circularity potential of industrial products during design, development or benchmarking phases through a series of questions

4.1.10. Summary of indicators

Table 12: Summary of proposed indicators and tools with references

<i>Category</i>	<i>Indicator</i>	<i>Source</i>
<i>Criticality</i>	Contribution to EU supply	Raw materials scoreboard, CRMA

	Performance-weighted abiotic resource depletion	(Sherwood et al., 2022)
	Supply chain risk exposure index	(Gao et al., 2016)
<i>Design</i>	Ease of disassembly metric	(Peeters et al., 2018)
	Expanded zero waste practices	(Veleva et al., 2017)
	Longevity indicator	(Franklin-Johnson et al., 2016)
<i>Economy</i>	Circular economy index	(Di Maio & Rem, 2015)
	Product level circularity metric	(Linder et al., 2017)
<i>Material circularity</i>	Circular input rate	(Bobba et al., 2023b)
	Circularity metric	ICMM, ESRS E5
	Linear flow index	Material Circularity Indicator (https://www.ellenmacarthurfoundation.org/material-circularity-indicator)
	Material circular inflow	CTI
	Outflow circular content	ISO 59020
	Potential material circular outflow	CTI
	Recycling input rate	Eurostat
<i>Recycling/EoL</i>	Actual recovery of EoL materials	ICMM
	Overall process yield	ISO 59020
	Recycling desirability index	(Al Amin et al., 2017)
	REE recovery rate	ICMM
	Average loss rate	Calculation of the recycling rates according to Waste Framework Directive
	Circular material use rate	Eurostat (2018)

<i>Resource efficiency</i>	Material productivity	(Lèbre et al., 2017)
	Resource intensity index	ISO 59020
	Value-based resource efficiency	(Di Maio et al., 2017)
<i>Resource use</i>	Circular water discharge	ISO 59020
	Energy intensity	ISO 59020
	Ratio of water reuse or recirculation	ISO 59020
	Renewable energy share	ISO 59020
	Total water consumption	GRI 303
	Total water withdrawal	GRI 303
	Water intensity	ISO 59020
	Water recycling rate	CTI (water circularity); GRI 303
<i>Tools</i>	Circularity calculator	https://circularitycalculator.nl/
	circular economy indicator prototype	(Jayakodi et al., 2024)
	circular economy toolkit	http://circulareconomytoolkit.org/Assessmenttool.html
	Circular pathfinder	(van Dam S.S. et al., 2017)
	circularity potential indicator	https://circulareconomyindicators.com/cpitol.php
<i>Waste</i>	Total production from waste	(Lèbre et al., 2017)
	Total reactive waste generation	(Lèbre et al., 2017)
	Waste-to-product ratio	ICMM

4.2. Indicator selection and validation within the NEO-CYCLE project

The set of indicators presented in section 4.2 is intentionally broad and comprehensive, as it reflects the diversity of circular economy metrics identified in the literature that are potentially applicable to a project like NEO-CYCLE. However, not all indicators are equally relevant or feasible in this context, and for this reason a structured selection and validation process is required to identify a reduces subset of indicators that will be effectively applied within the project, with the goal of capturing as much information as possible while avoiding redundancy. The selection process will be based on a stakeholder-driven approach and will involve

the distribution of a dedicated questionnaire to the NEO-CYCLE project partners, which will focus on selecting a number of the indicators presented in *Tables 4.1 to 4.9*. Each indicator will be evaluated by partners based on a common understanding of its definition and scope as provided in the accompanying description derived from literature.

Project partners will be asked to assess and score each indicator according to a set of qualitative criteria which will include:

- Relevance for the NEO-CYCLE project
- Data availability for the calculation of the indicator
- Perceived robustness
- Ease of interpretability

The involvement of partners representing different stages of the value chain and different aspects of the project will ensure that the final indicator set will capture multiple perspectives and avoid a purely theoretical or technical approach. The outcome of this process will be a validated and manageable set of circularity indicators that will be consistently applied across project activities.

4.3. Key takeaways for NEO-CYCLE and future developments

A set of indicators that can be considered relevant for NEO-CYCLE has been identified, with the aim of capturing several of circularity aspects of the REE and permanent magnet sector. Because the circularity aspects are many, the list of indicators is rather large and data availability is limited, the final choice, data gathering and calculations need a collective effort from several project partners. The goal will therefore be to identify new indicators, highlight gaps and shortcomings and collect expert contributions on which aspects of circularity should be quantified when developing novel indicators.

Taking into account NEO-CYCLE's progress in terms of project's maturity, in this deliverable indicators are discussed and developed from the methodological point of view, whereas the quantitative assessment will continue in parallel to TEA, energy analyses and LCA, always in synergy, and taking advantage of the better availability of data, as the project advances. For this reason, data gathering and draft calculations will continue for the rest of the project and the consolidated set of indicators and their numerical values will be incorporated in deliverable 10.2, unless otherwise stated.

4.3.1. Future developments

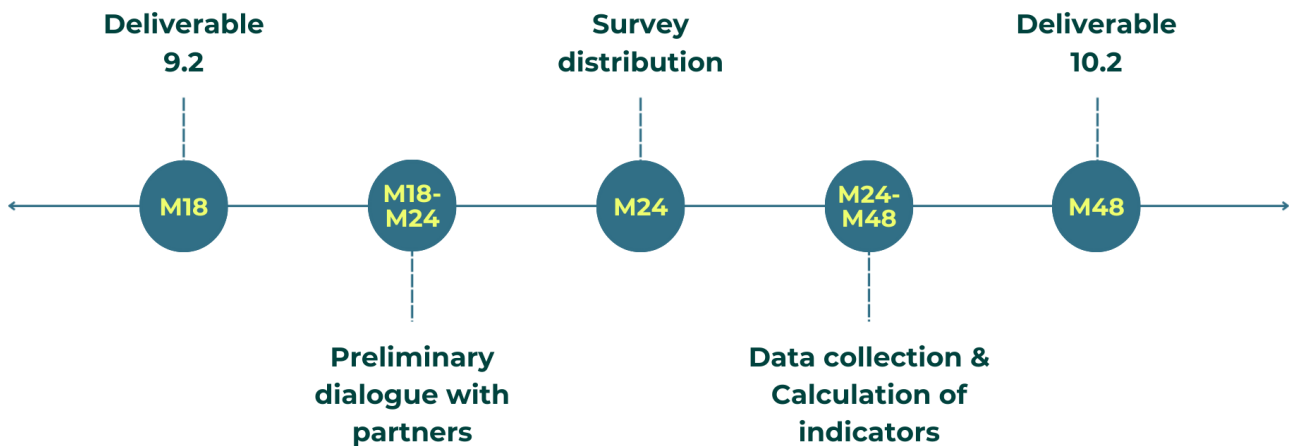


Figura 1: Future developments in the NEO-CYCLE project

In the future, the following steps will ideally be conducted to continue measure circularity within the NEO-CYCLE project:

- The list of indicators contained in this deliverable will be shared with partners at month 18, where initial feedback on the proposed set of indicators will be collected.
- In the following six months, dialogue with partners will be implemented with the goal of collecting more feedback and preliminary data. The kinds of data that will be available in the future will also be identified, to make sure that selected indicators will be possible to calculate.
- From month 24, a formal survey will start to be distributed, asking partners to rank indicators based on several factors, which have been previously discussed.
- In the following months up until the final deliverable, data will be collected as made available, and indicators will be calculated. During this phase communication with partners will still be made a priority to make sure that indicators accurately reflect the project's needs as it develops and that data is accurate and up to date
- At month 48, through Deliverable 10.2, the final results of the circularity assessment will be delivered, marking the end of the project.

Throughout the whole project, based on existing literature, the experience gained and dialogue with partners, a circularity framework specific for the REE and permanent magnet sector will be developed.

5. Conclusions

The NEO-CYCLE project is at its core a project that aims to improve circularity and reduce the criticality of CRMs in the EU by developing upcycling processes for permanent magnets used in HDDs.

From a circularity perspective, NEO-CYCLE aims to close the loop of the permanent magnet value chain by developing two innovative processes to recover REEs, boron, and iron from WEEE, the SSC process and the SENE process. In terms of criticality, NEO-CYCLE recovers two CRMs through its processes, neodymium and boron, therefore contributing to reducing the EU's dependence on imports and its exposure to all other supply risks that are associated with high levels of concentration of production. Moreover, although REE recycling is at the moment seen as the main strategy to building a European REE supply chain, the sector is still underdeveloped; in this context, NEO-CYCLE contributes to the development of the European REE value chain.

Despite growing interest from both private companies and public institutions, measuring the benefits of circularity business models remains a challenging task. This is due to multiple factors, such as the broadness of the concept of criticality, which means that there is no official definition of circularity and there is no fixed set of principles. As a consequence, there also is not a single way to assess circularity, which has led to the development of several indicators and frameworks, but none of them have been built with REEs or permanent magnets in mind.

To assess circularity in NEO-CYCLE, several potentially applicable or adaptable indicators have been identified, from which a final subset will be short listed through a dialogue with NEO-CYCLE partners. Beyond measuring the project's circularity, the goal is to address further aspects that existing indicators do not cover, also by means of novel indicators.

Whereas indicators were discussed and developed from the methodological perspective, the quantitative assessment will continue in parallel to TEA, energy analyses and LCA, always in synergy, and taking advantage of the better availability of data, as the project advances. Data gathering and iterative calculations will continue for the rest of the project and the consolidated set of indicators and their numerical values will likely be incorporated in deliverable 10.2.

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