D9.1 “Preliminary LCA, LCC and s-LCA”

Acronym:

NEO-CYCLE

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DISCLAIMER

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Executive summary

This deliverable (D9.1) presents the preliminary sustainability assessment developed within the NEO-CYCLE project, integrating environmental Life Cycle Assessment (LCA), economic Life Cycle Costing (LCC) and Social LCA (s-LCA) as a coherent Life Cycle Sustainability Assessment (LCSA) perspective. The document consolidates the work carried out under the relevant tasks during the first project phase, with emphasis on the processes and decision points linked to the core upcycling and recovery routes under development. In line with the project’s iterative approach, this deliverable provides an early, transparent understanding of hotspots, trade-offs and improvement levers, supporting structured decision-making and guiding the refinement of both data collection and process optimisation strategies as the project advances.

Resource scarcity and the strategic importance of Critical Raw Materials (CRMs) continue to intensify the need for circular and resilient supply chains. Rare earth elements (REEs), and particularly Nd, are essential for permanent magnets used across key technologies, while primary extraction and refining remain associated with significant environmental burdens and geopolitical dependency. In this context, NEO-CYCLE addresses the upcycling of End-of-

Life (EoL) NdFeB magnets from hard disk drives (HDDs), aiming to develop viable routes to recover Nd, Fe and B and to strengthen EU access to secondary raw materials. This sustainability assessment is therefore framed not only around performance at process level, but also around the project’s strategic contribution to circularity, traceability and long-term resilience of material flows.

Methodologically, the preliminary assessment follows a gate-to-gate scope consistent with the current Technology Readiness Level (TRL) of the processes, relying on laboratory-scale evidence, partner inputs and model-based inventories. Given the early development stage, data gaps are handled through documented assumptions, proxy datasets and value ranges, supported by scenario and sensitivity considerations. This ensures traceability and provides a robust basis for later updates as pilot-scale data emerge, improving representativeness and comparability across routes and scenarios.

Preliminary results suggest that, from an environmental perspective, impact hotspots are concentrated in specific categories (including eutrophication and resource use), with differences between the assessed process routes already visible. From an economic perspective, labour (and in some cases energy) emerges as a main cost driver, reinforcing the relevance of throughput, automation potential, and energy-efficiency measures. Socially, the s-LCA indicates an overall medium level of social risk, with stronger performance in Worker-related topics and weaker performance in Society-related topics, partly reflecting limited formalisation of public benefits at this stage and incomplete information. While indicative, these findings already support targeted recommendations on data quality, stakeholder information flows, and traceability-oriented actions, including elements connected to Digital Product Passport thinking.

Overall, D9.1 lays the foundation for the next phases of the NEO-CYCLE sustainability assessment by consolidating the baseline understanding of impacts and costs, clarifying limitations inherent to laboratory-scale development, and identifying priority improvement areas. The final assessment will build on this framework by incorporating validated operational data, scale-up assumptions and expanded system boundaries to better capture the full value of upcycling pathways and their contribution to circular and secure access to REEs and associated materials in Europe.

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List of Acronyms

B - Boron

CapEx - capital expenditures

CFC – Chlorofluorocarbon

CRM – Critical Raw Materials

CTU – Comparative Toxic Unit

D - Deliverable

DDP – Discounted Payback Period

EC – European Commission

EDTA - Ethylenediamine tetraacetic acid

EF – Environmental Footprint

EL – Electrochemical Leaching

EoL – End-of-Life

EU – European Union

EV – Electric Vehicle

Fe – Iron

FU – Functional Unit
GHG – Greenhouse Gas
HDD - Hard Disk Drive
IRR – Internal Rate of Return
ISO – International Organisation for Standardisation
LCA – Life Cycle Assessment
LCC – Life Cycle Cost
LCI – Life Cycle Inventory
LCIA – Life Cycle Impact Assessment
LCSA – Life Cycle Sustainability Assessment
M – Month
Nd – Neodymium
NPV - Net Present Value
OECD – Organisation for Economic Co-operation and Development
OpEx - Operating expenditures
PEF – Product Environmental Footprint
PM – Particulate Matter
REE - Rare Earth Elements
REO - Rare Earth Oxide
s-LCA – Social Life Cycle Assessment
SSC – Solid State Chlorination
T – Task
TEA – Techno-Economic Assessment
TRL – Technological Readiness Level
UNEP – United Nations Environment Programme
WP – Work Package

1. Introduction

Resource scarcity is intensifying global efforts to adopt more sustainable development models. These models promote responsible and efficient material use through recycling, upcycling and broader circular strategies. As industries shift towards circular resource management, securing critical raw materials (CRMs) has become a central priority in European initiatives that aim to strengthen material self-sufficiency. Rare earth permanent magnets are essential components in modern energy technologies and help reduce greenhouse gas (GHG) emissions, thereby supporting climate change mitigation. However, the extraction of rare earth elements (REEs) from primary ores continues to involve significant environmental, economic and social challenges. REEs are vital to high-tech industries because they possess unique physical and chemical properties that enable their use in emerging energy systems and advanced manufacturing. Despite their strategic importance, producing REEs still raises critical sustainability challenges linked to high resource intensity and insufficiently developed mitigation technologies. As the global energy transition progresses, demand for REEs continues to rise, stimulating further growth in primary production. In response to these pressures, NEO-CYCLE seeks to develop methods to upcycle End-of-Life (EoL) neodymium–iron–boron (NdFeB) magnets from hard disk drives (HDDs), paving the way for a sustainable recovery of CRMs and greater material independence.

At present, however, less than 1% of rare-earth permanent magnets are actually recycled or upcycled globally, highlighting the gap between the theoretical potential of these secondary sources and their extremely limited real-world recovery. In this vein, NEO-CYCLE aims to upscale selective processes to obtain Nd, Fe and B from HDDs and to demonstrate the ability to upcycle different elements in four case studies: catalysts for pharmaceutical manufacturing, catalysts for polymer development, nanoparticles to serve as catalysts and ammonia for fertilisers. The upcycling processes will be supported by mathematical and computational technologies like Digital Twin. The project also aims to demonstrate the circularity and sustainability of these upcycling concepts. Furthermore, NEO-CYCLE pursues at reaching the market competitively, building the project in cooperation with relevant stakeholders.

In this report, NEO-CYCLE introduces Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social LCA (s-LCA) from the earliest development phases, using provisional datasets derived from laboratory trials and preliminary process models. Given the technology's current Technology Readiness Level (TRL), Life Cycle Inventories (LCIs) are represented by evolving data, proxy values and ranges sourced from ongoing experiments. These inputs are updated iteratively, with transparent documentation of assumptions and the use of scenario analyses to test the robustness of results as the evidence base matures. This early integration of LCA, LCC and s-LCA enables the project to compare alternative recovery routes and identify hotspots. At the same time, it signals that the quantitative results presented remain indicative. These results will be refined as validated measurement data become available and are integrated with project developments beyond month (M)18. Incorporating sustainability assessment methods, covering environmental, economic, and social dimensions, is an important means of supporting sustainable technology development. These assessments play a key role in decision-making and in evaluating the impacts of existing processes, products and technologies.

2. Purpose of the document

The purpose of this deliverable (D) is to report the preliminary sustainability analysis results for the environmental, economic, and social dimensions within the NEO-CYCLE project. It is a direct result of Tasks (T) 9.1 and 9.2, and it aligns with multiple European Commission (EC) recommendations to identify, collect, and comprehend the needs for assessing sustainability elements. D9.1 covers the work conducted during the first 18 months of the project, and the analyses presented here are therefore preliminary and subject to further refinement. The continuation, consolidation, and finalisation of this sustainability assessment will be carried forward under Work package (WP) 10.

This preliminary assessment focused on the developments of WP4, respecting the early-stage progress of the project and the anticipated data needs and availability. Activities commenced in M1 to achieve the proposed goals for D9.1. They typically followed a structured approach: (i) background review and framing; (ii) data collection; (iii) data analysis; (iv) recommendations.

First, this document reports a comprehensive background review of the NEO-CYCLE context, covering REE/ CRM, EU dependence, existing solutions, and the LCA, LCC, and s-LCA concepts. This latter includes the definition, principles, regulations, frameworks, and methodology. It will be followed by the target scenario. Subsequently, it addresses the methodology used in the development of D9.1 and analyses the results of all the sustainability dimensions. D9.1 will present the findings of the environmental, economic, and social impact assessments of the WP4 processes. This will help verify where the most important impacts may be present, make long-term recommendations, and aid decision-making in WP4.

3. Relevant background

3.1. Rare Earth Elements / Critical Raw Materials – Nd, Fe, B

REEs, discovered in the 18th century, comprise 17 metal elements in the periodic table. There are 17 rare earth elements, comprising the 15 lanthanides plus Scandium and Yttrium. Based on their atomic electron layer, they are categorised into light REEs, such as Lanthanum, Cerium, Praseodymium, Neodymium (Nd), Promethium, Samarium, and Europium, and heavy REEs, including Gadolinium, Terbium, Dysprosium, Holmium, Erbium, Thulium, Ytterbium, Lutetium, Scandium, and Yttrium. Although relatively abundant in the Earth’s crust, only a few rare-earth deposits have economically viable concentrations and extracting them at usable purity remains technically challenging[1]. According to the Study on the CRM for the EU 2023 (Final Report)[2] the European Commission's criticality assessment process identifies a set of materials as CRMs based on their high economic importance and significant supply risk. Within this framework, REEs are included in the EU's list of CRMs, reflecting their strategic role in industry and the vulnerability associated with their supply.

NdFeB magnets represent the dominant segment of the global permanent magnet industry, accounting for approximately 45.4% of global market share in 2024. This dominance is driven by their widespread adoption in electrical vehicle (EV) traction motors, with each EV requiring up to 2 kg of NdFeB magnets. Wind turbines may use up to 600 kg of these magnets per unit, further amplifying demand. This massive and expanding demand strongly reinforces the strategic significance of NdFeB magnets in both REE markets and EU industrial policy[3]. NdFeB magnets contain approximately 30% to 40% of REEs that pose significant environmental and supply chain challenges if not properly recovered[4]. NdFeB magnets constitute a critical class of advanced materials that have significantly influenced modern engineering and electronic technologies and, due to their magnetic properties, high performance, versatility, and cost-effectiveness, have become indispensable across the industry. They operate fundamentally in wind turbine generators, particularly offshore, HDDs, electric vehicle traction motors, mobile phones, audio components, industrial motors and magnetic therapy devices and implantable medical tools, such as magnetic resonance imaging machines[5].

In addition, these magnets come in various types based on their production process and characteristics. They can be sintered, bonded, or hot-pressed magnets. Sintered NdFeB magnets have the highest magnetic performance and market share. They are produced by powder metallurgy, and even though they offer very high remanence and coercivity, they can be brittle and corrosion-prone, therefore requiring protective coatings[6]. Bonded NdFeB magnets, made by mixing magnetic powder with polymer binders, enabling complex shapes and isotropic magnetism, have lower magnetic strength. Nonetheless, they are cost-effective, precise, and mechanically robust and commonly used in HDD motors, sensors, and small devices. At last, hot-pressed magnets present high density and strong magnetic properties without requiring the use of heavy REEs. Despite having excellent heat resistance, these magnets are costly and limited to simple shapes.

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[1] Shuai, Z., Zhu, Y., Gao, P., & Han, Y,2024, Rare earth elements resources and beneficiation: A review. Minerals Engineering, 218, 109011 - link

[2] Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. 2023. *Study on the critical raw materials for the EU 2023: Final report*. Publications Office of the European Union - link

[3] Market Growth Reports. (2026). NdFeB market size, share & analysis 2035 report - link

[4] Jin, H., Frost, K., Sousa, I., Ghaderi, H., Bevan, A., Zakotnik, M., & Handwerker, C, 2020. Life cycle assessment of emerging technologies on value recovery from hard disk drives. Resources, Conservation and Recycling, 157, 104781-link

[5] Stanford Magnets, 2025. Key uses of Neodymium-Iron-Boron (NdFeB) magnets. Stanford Magnets - link

[6] Tongchuang Magnetic, 2025. What is NdFeB magnet? A complete guide to neodymium magnets. NdMagnets - link

3.2. Europe’s dependence, value chain asymmetry and solutions

Currently, there are more than 100 identified REE ores worldwide. European REE resources are highly concentrated in a few regions, with Greenland accounting for the overwhelming majority of identified deposits, followed by significantly smaller contributions from Turkey, Norway, and Sweden. When these estimates are compared at the global scale, Europe represents only a minor share of world reserves. Worldwide, REE resources are dominated by China, which holds the largest proportion of known deposits, while other countries such as Vietnam, Brazil, Australia, Russia, India, and the United States each contribute comparatively smaller shares. This distribution highlights both Europe’s limited geological endowment relative to other continents and China’s persistent dominance in REE reserves and production[7].

The widespread application of NdFeB permanent magnets in new energy technologies, electronics, and other sectors reflects their exceptional performance, strong magnetic properties, and versatility. These same qualities have also driven a sustained and consistent increase in global demand[8]. By developing environmentally responsible, socially equitable and economically resilient supply chains, European countries can meet the rising demand for NdFeB magnets and reduce reliance on foreign mineral supplies and the environmental and health impacts of mining. Mining of REE produces toxic waste which may enter the environment through leaching-pond leakages into groundwater, as well as through emissions of waste gases and dust[9].

As a result, there is a growing emphasis on sustainability and resource efficiency, which consequently has pushed Rare Earth Metal Recycling and the NdFeB Magnet Circular Economy to the forefront of industrial planning. To achieve sustainable resource management and mitigate REE supply risk, the adoption of actions like waste recycling and urban mining help to achieve the goal. The advantages are greater since EoL NdFeBs contain about 15 to 30% while natural deposits rarely exceed 5% REEs. Meaning that EoL magnets represent a far richer and more accessible source of REE than most primary ores, thereby making recycling both a strategically and economically advantageous pathway for securing REE supply[10].

Unfortunately, global commercial recycling rates for EoL REE-containing products remain alarmingly low, being estimated at less than 1%. Consequently, there is an urgent need to

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[7] Zhang, Y., Li, X., Wang, J., Chen, H., & Liu, Z, 2025. Environmental impacts and sustainability assessment of rare earth element production: A global perspective. Science of The Total Environment, 937, 179386 - link

[8] Wang, L., Chen, Y., Zhao, H., Xu, J., & Li, M, 2025. Advances in alloy design and applications of NdFeB-based materials. Journal of Alloys and Compounds, 1053, 185152 - link

[9] Harvard International Review, 2020. Not-so-green technology: The complicated legacy of rare earth mining. Harvard International Review - link

[10] Sun, Y., Wang, H., & Chen, L, 2024. Cognitive science perspectives on artificial intelligence: Bridging human and machine learning. Cognitive Systems Research, 80, 100884 - link

develop innovative recycling processes that are not only environmentally beneficial but also economically feasible at an industrial scale[11].

Additionally, the value chain of REE magnets shows a highly asymmetric geographic structure, as illustrated in Figure 1. The activities represented are largely dominated by NdFeB magnets, which account for most permanent-magnet production and the final applications considered. Two overarching patterns emerge. First, geographical concentration increases significantly when moving from upstream extraction to midstream processing and magnet manufacturing, reaching particularly high levels in rare earth oxide (REO) separation, rare earth metal refining and permanent-magnet production. Second, this concentration partially reverses at the level of final applications, where manufacturing activities are more geographically distributed, especially across the European Union (EU) and the United States.

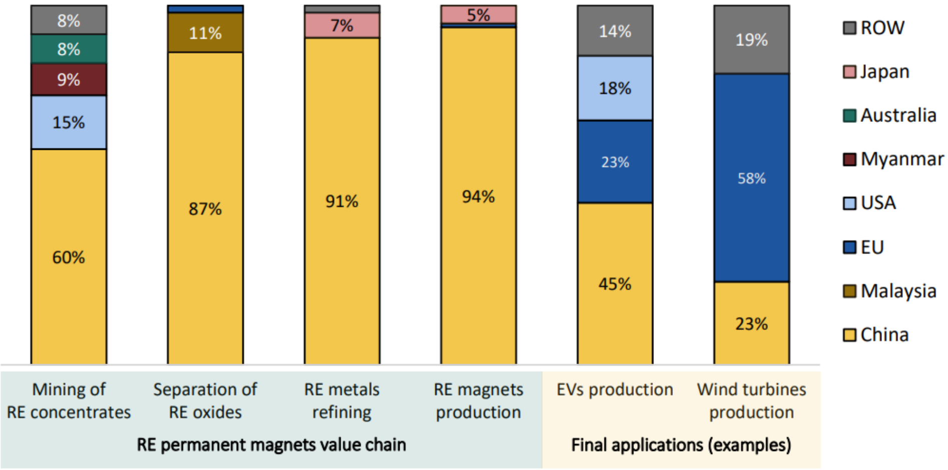

Figure 1 - Geographical concentration of REE magnets value chain. Developed by Rizos, V., et al (2022)

This configuration shows that activities associated with high material leverage, technological lock-in and strategic control are concentrated in a small number of countries, whereas activities related to final assembly and the deployment of clean-energy technologies are far more geographically dispersed. As such, the figure provides a high-level map of where value, control and exposure to social risk are structurally embedded along the rare-earth permanent-magnet value chain[12].

In this context, reducing European dependence is not limited to increasing REE reserves or expanding mining activities but also requires reconfiguring the traditional value chain by creating local alternatives for its most critical stages. The introduction of an end-of-life (EoL) and

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[11] Liu, F., Porvali, A., Wang, J., Wang, H., Peng, C., Wilson, B. P., & Lundström, M. 2020. Recovery and separation of rare earths and boron from spent Nd-Fe-B magnets. Minerals Engineering, 145, 106097- link

[12] Rizos, V., Righetti, E., & Kassab, A. (2022). Developing a supply chain for recycled rare earth permanent magnets in the EU. Centre for European Policies Study CEPS. - link

recycling/upcycling stage is particularly relevant, as it enables part of the processing to be relocated to other regions, generating local value and reducing dependence on primary value chains.

3.3. Processes of recuperation / recycling / upcycling

NdFeB magnets are typically composed of 60 to 70% of Fe, 20 to 30% of Nd, 0.5 to 7% of Praseodymium, 0.2 to 6% of Dysprosium, 0.3 to 1% of B and 0.1 to 0.9% of Aluminium. The recovery of these magnets can be made through hydrometallurgy, pyrometallurgy, electrometallurgy and direct recycling processes. However, in NdFeB magnet recycling, there are many challenges, including material heterogeneity, difficulties in obtaining representative samples, strong magnetic forces, oxidation, and brittleness, which make extraction more complex[13].

Effective REE recovery requires separating them from iron, which can be achieved through various pyrometallurgical processes such as liquid metal extraction, selective chlorination, glass-slag methods, chemical vapour transport, and selective sulphate or nitrate roasting. Unfortunately, some of these methods are highly energy intensive, have low recovery efficiencies of REEs and may also result in secondary environmental pollution[9]. By contrast, hydrometallurgical processes provide a more sustainable alternative, enabling the production of high-purity REE products while generating lower levels of air pollution[10]. Therefore, hydrometallurgical routes are widely considered to be the preferred choice for recovering these elements, offering higher REEs recovery and applicability across all types of magnet compositions[14].

The hydrometallurgical recovery of REEs from EoL permanent magnets starts with leaching the magnets or magnet scrap. The dissolved metals are then separated into individual REE species, such as Nd, and other metals using solvent extraction, ion-exchange, or ionic liquid methods. After separation, the REEs are precipitated either as mixed REE compounds or as individual REE salts. These precipitates can then be converted into REE fluorides or oxides. Despite the effectiveness of this approach, several challenges remain. These include achieving selective dissolution, concentrating, and separating REE species from major coexisting metals, and ensuring the complete recovery of all valuable metals simultaneously. To overcome these limitations, new separation technologies employing novel solvent extractants,

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[13] Kaya, M, 2024. An overview of NdFeB magnets recycling technologies. Current Opinion in Green and Sustainable Chemistry, 46, 100884 - link

[14] Guo, Y., Wang, L., Zhang, Y., & Zhang, J. 2020. Effect of heat treatment on microstructure and mechanical properties of Ti–6Al–4V alloy fabricated by selective laser melting - link

ionic liquids, or ion exchange resins are being explored to improve the extraction of REEs from leaching solutions[15].

Leaching, depending on the level of process complexity, generally dissolves REEs before other metals. The dissolution of NdFeB magnets can occur through several pathways: complete dissolution, either with or without a prior roasting step; selective leaching, which requires pre-roasting to enable preferential extraction of REEs; or selective conversion of REEs within the solid magnet directly into a new solid phase.

The NEO-CYCLE project is closely linked to hydrometallurgical recycling processes because it focuses on developing sustainable methods to recover REEs from NdFeB magnet waste through dissolution and separation techniques like the already existing processes. Moreover, the project focuses not only on recycling spent magnets sustainably but also on upcycling them. This involves recovering REE, Fe and B and transforming them into new products with higher quality and value than the original raw materials. The upcycling approach is particularly relevant for magnets recovered from HDD waste, where the efficient separation and recovery of REEs is a crucial step to enabling circular value chains and improving material quality for higher-value applications[16]. Within this framing, NEO-CYCLE can be understood not only as a project focused on REE recovery but also as an upcycling pathway that seeks to shorten the processing chain and establish industrial alternatives within the EU, closer to consumers, thereby enhancing resilience.

3.4. The need for sustainable processes

The unsustainable consumption of natural resources, as well as pollution of the environment, presents a pressing global concern. Reports show that by 2050, if current consumption rates remain unchanged, humanity will consume almost 140 billion tonnes of minerals, ores, fossil fuels and biomass within a year. Waste will increase almost 70% in comparison to the present. Consequently, the increased discharges of untreated wastewater will pollute more water bodies and natural resources[17]. Furthermore, the world's population is projected to grow by 25% over the next 30 years, increasing from 8 billion to nearly 10 billion people. This expansion will place greater demand on metals, which are fundamental to modern life. They play a critical role in infrastructure development, renewable energy production, and energy storage and distribution. They underpin essential sectors such as housing, construction, healthcare, and transportation, making them indispensable to sustaining global progress and

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[15] Yang, Y., Walton, A., Sheridan, R., Güth, K., Gauß, R., Gutfleisch, O., Buchert, M., Steenari, B.-M., Van Gerven, T., Jones, P. T., & Binnemans, K. 2017. REE recovery from end-of-life NdFeB permanent magnet scrap: A critical review. *Journal of Sustainable Metallurgy* - link

[16] Walton, A., Yi, H., Rowson, N. A., et al., (2015). The use of hydrogen to separate and recycle neodymium–iron–boron-type magnets from electronic waste. Journal of Cleaner Production, 104, 236-241. - link

[17] Mohamed A.E., Ahmed M.I, Ammar H. E, Hussien H., 2025. A framework for integrating sustainable production practices along the product life, 26. - link

meeting the needs of a growing population[18]. Consequently, our reliance on primary and critical metal resources will be largely affected due to the finite nature of the metal reserves and the threat of their depletion at current consumption rates. Accordingly, data concerning the supply and demand of metals, recycling practices, substitution trends, metallurgical innovations, and the current state of climate-friendly metals production should be continuously updated and studied.

To act on this critical topic, European operational models are shifting toward more advanced workflows that can capture value at each stage of the magnet lifecycle. Companies are investing in innovative solutions that improve material recovery efficiency, enhance product consistency, and enable scalable circular routes. Ongoing advancements in processing methods, automation, and digital monitoring are creating more dependable pathways from scrap collection to regenerated magnet production. These technical gains are reinforced by robust research networks, collaborative pilot projects, and a rising focus on scaling circular practices[19].

As the market matures, continued operational evolution is expected to drive higher recovery rates, reduce environmental impact, and strengthen supply chain resilience for end users. Within this broader shift towards circular and climate-neutral industrial systems, the NEO-CYCLE project represents a concrete embodiment of the ambitions outlined in the Process for Planet Roadmap[20]. By developing breakthrough technologies for the sustainable upcycling of NdFeB magnets recovered from EoL HDDs, NEO-CYCLE directly addresses critical raw material scarcity and the environmental impacts associated with primary extraction. Its integrated approach aims to reach high-quality outputs suitable for multiple industrial sectors, including pharmaceuticals, fertiliser production, ammonia synthesis, and polymer manufacturing. Furthermore, the project's multi-stakeholder structure, spanning technology developers, recyclers, small and medium enterprises, public authorities, and research institutions, exemplifies the collaborative and systemic innovation model promoted by the roadmap. By coupling technological advancement with LCA, LCC, and social impact evaluation, NEO-CYCLE contributes directly to the roadmap's vision of creating scalable, resource-efficient, socially responsible, and market-ready circular processes.

3.5. Life Cycle Sustainability Assessment overview

Life Cycle Sustainability Assessment (LCSA) integrates evaluations across the three pillars of sustainability, environmental, economic, and social, by combining LCA, LCC, and s-LCA.

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[18] T. DebRoy, J.W. Elmer. 2024. Metals beyond tomorrow: Balancing supply, demand, sustainability, substitution, and innovations. Materials today, 80 - link

[19] Analytical Market Research. 2025. Europe rare earth metal recycling and NdFeB magnet circular economy: Size, trends, and growth outlook to 2032. Analytical Market Research - link

[20] A.SPIRE. 2021. Processes4Planet: Strategic Research and Innovation Agenda 2050 (SRIA 2050) - link

Together, these approaches provide a comprehensive framework that captures all three dimensions of sustainability, as illustrated in Figure 2.

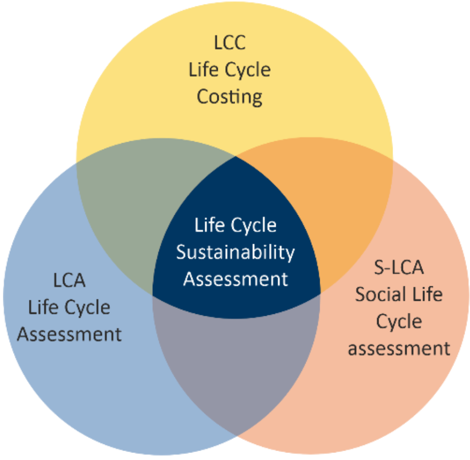

Figure 2 - The three dimensions of LCSA

LCA is a comprehensive analytical tool that evaluates environmental impacts across a product’s entire life cycle, from raw material extraction to production, use, and disposal. Among environmental management tools, LCA is notable for its broad and detailed perspective[21]. LCC focuses on identifying and documenting all costs incurred throughout an asset's useful life, including acquisition, operation, maintenance, and disposal[22]. This analysis aids decision-makers in improving the economic performance of a system over its life cycle. Lastly, s-LCA assesses potential social impacts across a product ‘s or service ‘s life cycle, considering stakeholders such as workers, local communities, and consumers. This assessment is increasingly crucial for a thorough approach to sustainability evaluations[23,24].

The emergence of tools to measure and mitigate environmental impacts began in the 1970s, spurred by the energy crisis and the publication of the Limits to Growth report[25]. Early efforts focused on quantifying energy use and waste in product manufacturing but lacked comprehensive environmental impact assessments. The 1987 Brundtland Report introduced the concept of Sustainable Development, emphasising the need to balance environmental, social, and economic factors[26]. This catalysed interest in LCA, leading to the development of

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[21] M. A. Curran, 2013. Life Cycle Assessment: a review of the methodology and its application to Sustainability. Current Opinion in Chemical Engineering - link

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[23] UNEP , 2009.Guidelines for social life cycle assessment of products - link

[24] A. Zamagni, L. Zanchi, S. D. Cesare e F. S. &. L. Petti, 2021.Theory and Practice on Social Life Cycle Assessment. Life Cycle Engineering and Management of Products - link

[25] D. H. Meadows, D. L. Meadows, J. Randers e B. W., 1972.The Limits to Growth - link

[26] Bruntland Report, 1987. World Commission on Environment and Development: Our Common Future - link

methods to evaluate broader environmental impacts like global warming and resource depletion and making LCA studies more accessible to the public[27,28].

By the late 1980s, inconsistencies in environmental reporting due to varying methods and terminology highlighted the need for standardisation, prompting the Society of Environmental Toxicology and Chemistry to develop the LCA framework in 1990. This initiative led to the first international Code of Practice for LCA, later refined by the International Organisation for Standardisation (ISO) Technical Committee, laying the foundation for globally accepted environmental impact assessments. Continuous improvements, driven by international collaboration, have made LCA a cornerstone of environmental policy, notably endorsed by the European Commission as the most effective tool for evaluating product impacts. Nowadays, LCA is standardised under ISO 14040 and ISO 14044, with the European LCA Platform further enhancing its application, as reflected in its inclusion in the EU's 2023 "Better Regulation" toolbox[29,30,31,32].

3.5.1. Life Cycle Assessment

The ISO standards outline four essential phases of a LCA, as shown in Figure 3. The first phase defines the Goal and Scope, followed by the LCI. The third phase involves conducting the Life Cycle Impact Assessment (LCIA), and finally, the results are interpreted and used to identify opportunities for process improvement. In the first phase, the Goal and Scope establish the foundation of the study by defining its purpose, boundaries, and intended application[33]. The goal ensures that the assessment remains consistent with its initial objectives, such as evaluating environmental impacts and delivering meaningful results, while the scope specifies the system under study, including its characteristics, processes, and activities across the life cycle. At this stage, key decisions are made regarding the product system, such as its application, target audience, functional unit (FU), system boundaries, and data requirements.

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[31] Joint research Centre (JRC), 2021. Life cycle assessment for supporting policies in the EU: an overview of some pilot initiatives for the monitoring and evaluation of policies - link

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[33] Curran, 2017. Overview of Goal and Scope Definition in Life Cycle Assessment. In: Curran, M. (eds) Goal and Scope Definition in Life Cycle Assessment. LCA Compendium – The Complete World of Life Cycle Assessment. Springer, Dordrecht - link

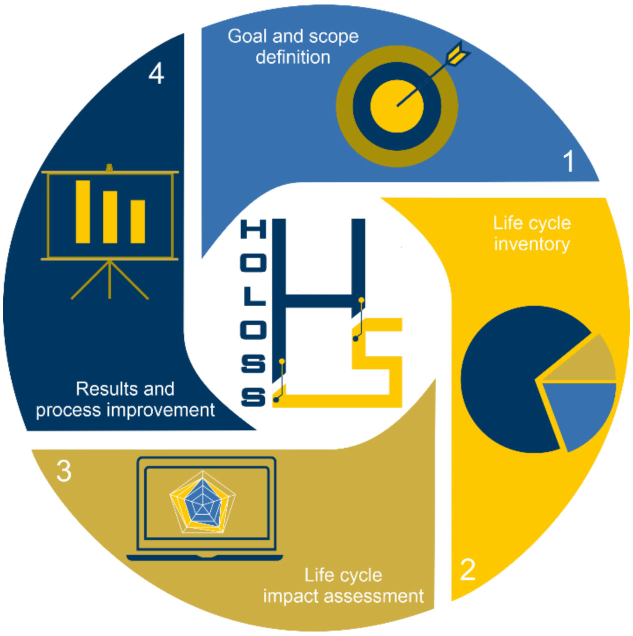

Figure 3- Methodology to assess the LCA by ISO 14040/14044

The FU, a quantified description of the product’s function, serves as the reference point for all impact calculations. Depending on the product, this function may be defined in terms of performance, aesthetics, technical quality, services, or costs. Thus, a precise definition of the FU scale is critical to ensure that the assessment captures the full system inputs and outputs. Furthermore, at this stage the system boundaries need to be defined. This is determined in conjunction with the objective of the project[34]. The typical types of system boundaries are Gate-gate, gate-to-grave, cradle-to-gate, cradle-to-grave and cradle-to-cradle. A gate-to-gate or cradle-to-gate life cycle model allows focusing more on the production processes and materials stages. When the use phase and EoL considerations are relevant for the study, a cradle-to-grave approach should be conducted. Additionally, within this stage, the definition of the methods and indicators used in the study and the consequent requirements related to obtaining, collecting, and processing data, is defined. After the first stage, the LCI is made. It requires extensive quantities of data of foreground and background processes that comprise input and output flows. Input flows include consumed products, wastes and nature resources, and output flows comprise wastes, emissions and final feedstocks or products[35].

The third step aims at associating the LCI results with the impact categories and indicators, such as, climate change, ozone depletion, ecotoxicity, water and land use and acidification.

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[34] International Council of Chemicals Associations, 2020. How to Know If and When it’s Time to Commission a Life Cycle Assessment. An executive guide - link

[35] Saavedra-Rubio et al. 2022. Stepwise guidance for data collection in the life cycle inventory (LCI) phase: Building technology related LCI blocks. Journal of Cleaner Production. 366 - link

This stage helps to evaluate and understand the significance of the impacts on a product system throughout its life cycle[36]. The LCIA phase is designed to evaluate and interpret the significance of environmental impacts associated with a product system across its entire life cycle. To achieve this, LCIA methods first classify emissions into specific impact categories and then convert them into common units, allowing for meaningful comparison.

Several well-established LCIA methods are widely applied[37], such as:

- Eco-indicator 99 takes into account human health damage from climate change.
- ReCiPe 2016, that integrates both midpoint (measures impact between emission and final damage) and endpoint perspectives (shows effects on areas to protect), allowing assessments at the level of specific impacts or broader damage to human health and ecosystems.
- Intergovernmental Panel on Climate Change (IPCC) method is often used to calculate global warming potential.
- Environmental Footprint (EF) method has been developed to support the European Product Environmental Footprint (PEF) initiative, covering a wide range of impact categories including land use, water use, and particulate matter.

Together, these LCIA methods ensure that environmental burdens are consistently classified, characterised, normalised, and weighted, as required by ISO standards.

3.5.2. Life Cycle Costing

LCC refers to the comprehensive assessment of all expenses incurred throughout the lifetime of a product, work, or service, encompassing the initial purchase price and related costs such as delivery, installation, and insurance, the ongoing operating costs including energy, fuel, water consumption, spare parts, and maintenance and end-of-life costs such as decommissioning or disposal, or alternatively, the residual value gained from resale. In certain cases, LCC may also account for externalities, such as the financial impact of greenhouse gas emissions, when specified by relevant directives[38].

Its methodology is very similar to the environmental dimension of the LCA. The goal and scope are defined, the life cycle cost inventory is analysed and the impact assessment (eco-

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[36] Keivanpour, 2024. Life Cycle Approach: An Introductory Overview. In: Circular Economy in Engineering Design and Production. Synthesis Lectures on Sustainable Development. Springer, Cham - link

[37] European Commission, Joint Research Centre, Institute for Environment and Sustainability. 2011. International Reference Life Cycle Data System (ILCD) handbook: Recommendations for life cycle impact assessment in the European context. Publications Office of the European Union - link

[38] European Commission. (n.d.). 2025. Life-cycle costing. Green Forum – European Commission. - link

nomic dimension) is done. In order to develop the LCC inventory, costs from initial investments, operation and management of processes and technologies, costs associated with energy consumptions and waste generation should be considered[39].

To analyse economically the life cycle of a product, financial analysis, or capital budgeting, which is the process of evaluating the economic value of major investments is performed. It typically uses tools, such as Net Present Value (NPV), Internal Rate of Return (IRR), and Discounted Payback Period (DDP)[40]. These methods rely on discounted cash flows to assess whether a project generates returns above its cost of capital.

Within this framework, expenditures are divided into capital expenditures (CapEx), which represent long-term investments in assets like buildings, machinery, or technology, and operating expenditures (OpEx), which cover recurring costs such as salaries, rent, utilities, and maintenance[41]. While NPV and IRR focus on the profitability of investments, LCC extends the analysis by summing all discounted costs over the entire lifespan of an asset, from acquisition and operation to maintenance and disposal.

This comprehensive approach enables organisations to identify cost-effective solutions, justify higher upfront investments that yield lower lifetime costs, compare competing proposals on a total cost basis, optimise maintenance and EoL strategies, and ensure accurate budgeting for future expenses. In essence, LCC bridges traditional capital budgeting with sustainability-oriented financial planning, offering a holistic view of both CapEx and OpEx across the full life cycle of a product or project.

3.5.3. Social LCA

s-LCA aims to evaluate how a product or process affects society throughout its entire life cycle. While it adopts the same overall framework as the traditional LCA, the distinction lies in its focus. s-LCA examines the direct impacts on people, whereas LCA primarily assesses indirect impacts on people that arise through environmental consequences[42].

Two main methodological approaches are distinguished: performance reference point methods and impact pathway methods. Performance reference point methods assess the product system in terms of its social performance or social risk, such as forced labour, child labour, discrimination, and freedom of association. Uses internationally recognised standards like International Labour Organisation conventions, ISO 26000 guidelines, and Organisation for

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[39] Lee, S. 2025. *Life cycle costing in recycling: A comprehensive guide to sustainable materials management*. Number Analytics. - link

[40] Reiter, P. 2018. NPV, IRR and DDP: The language of bankers and investors. Solarthermalworld - link

[41] Investopedia. 2024. Capital expenditure (CapEx): Definition, types, and examples. Investopedia. - link

[42] Jingzheng R., Sara T. 2020. Life Cycle Sustainability Assessment for Decision-Making: Development and applicability of life cycle impacts assessment methodologies - link

Economic Co-operation and Development (OECD) principles. Importantly, these methods do not establish direct causal links between production processes and social outcomes but instead rely on empirical correlations between specific production contexts and socio-economic conditions[43].

Impact pathways methods, by contrast, assess the social impacts of a product or a service using impact pathways as characterisation models comprised of midpoint and/or endpoint indicators similar to environmental LCA. When conducting a s-LCA, first, the goal of the study, as well as its scope, need to be defined. Additionally, the type of impact assessment method and the main topics in which the study is focused on. Afterwards, important data is collected, and the study is performed[44]. A s-LCA study can assess actual social impacts, if assessed with observed and primary data directly collected from stakeholders, or can use proxy indicators, in which potential social impacts are assessed. The potential social impacts are evaluated through social risks, usually measured at country, sector, or company level.

4. Target scenario

NEO-CYCLE aims to demonstrate the upcycling of NdFeB magnets by transforming them into valuable products. D9.1 focuses on the activities developed in WP4, assessing the laboratory-scale extraction and separation of these elements. In this vein, the WP4 tasks were reviewed to construct a process representation. Figure 4 shows the process diagram as a complete workflow for the planned recovery of materials from spent NdFeB magnets. In general, it can be organised into two main operational areas. The first area covers the front-end stages, beginning with magnet demagnetisation, followed by crushing or grinding, sample digestion, and analytical characterisation. These steps prepare the material for selective dissolution, which may occur through solid-state chlorination or other leaching routes, each followed by filtration to separate the dissolved fraction from solid residues.

The second area illustrates the downstream separation of individual element-rich streams. From the filtered leachates, iron-bearing, neodymium-bearing, and boron-bearing solutions are directed into distinct processing pathways, where further filtration, washing, wet-chemistry operations, and crystallisation or calcination steps lead to the formation of isolated output products such as Fe-based phases, Nd oxalate or oxide forms, and boric acid. Optional loops shown in the diagram indicate that some intermediate solutions may return to earlier stages depending on their composition. This scenario was agreed upon with the rest of NEO-CYCLE partners due to the progress of the activities of the project. Due to the early phase of the project, it is possible that some of this process schemes can be changed in later iterations due to minor modifications among the processes' steps.

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[43] European Commission, Joint Research Centre. 2010. Methodological sheets for sub-categories in social life cycle assessment (S-LCA). Publications Office of the European Union - link

[44] United Nations Environment Programme. 2020. Guidelines for social life cycle assessment of products and organizations. - link

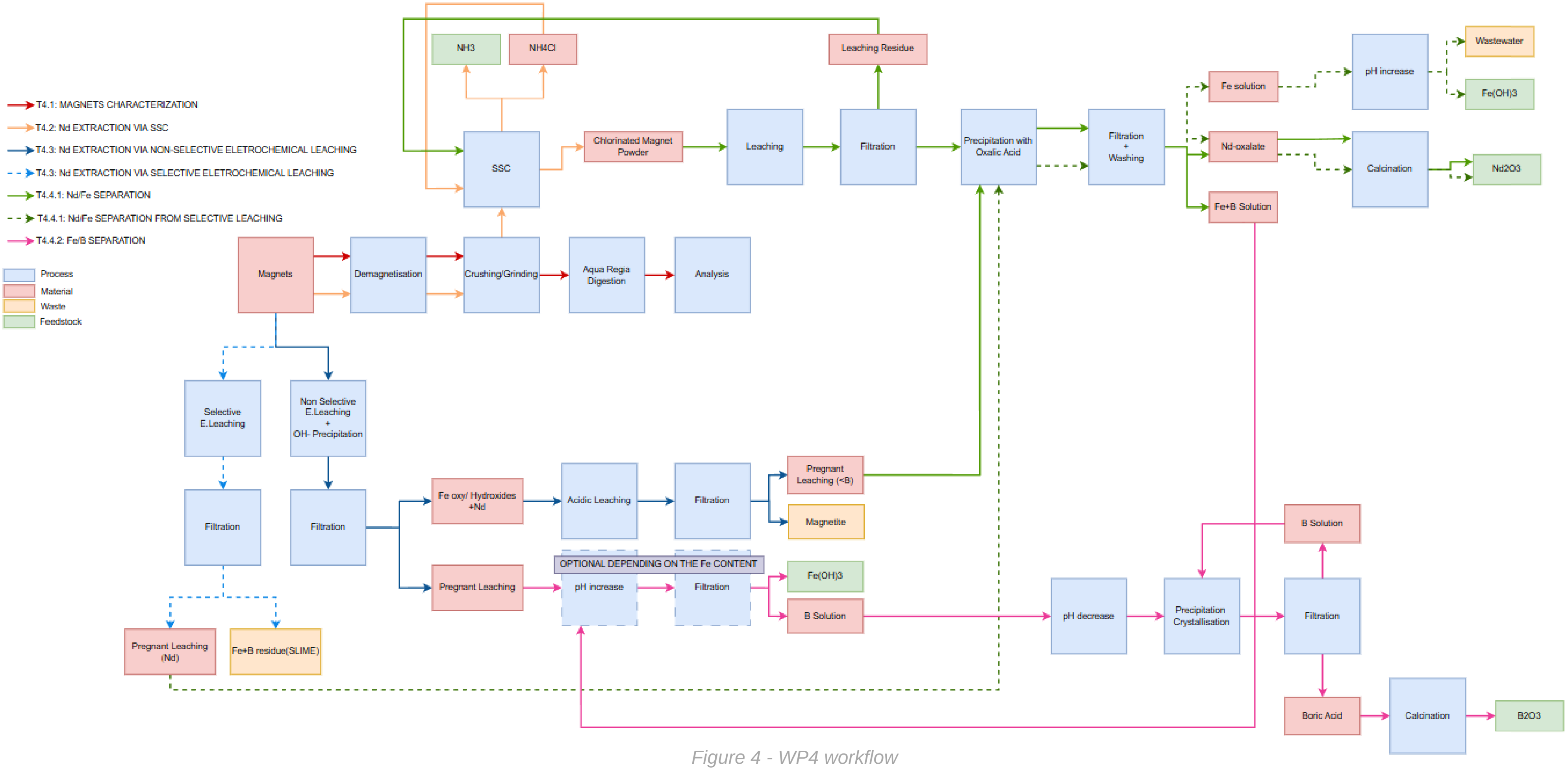


Figure 4 - WP4 workflow

To better understand the target of D9.1, the activities of each of the tasks were organised in workflow diagrams and detailed:

T4.1 – Waste inventory and magnet characterisation: Magnets were firstly collected from desktops, laptops and servers. They then underwent a process of thermal demagnetisation to separate the magnet from its case and demagnetise it. They were then crushed and grinded using different mills, producing a magnet powder for subsequent tasks. Aqua regia digestion was carried out by leaching the material with acid solutions, diluting, and filtering it to then proceed with the chemical composition analysis using Optical Emission Spectroscopy /Mass Spectrometry.

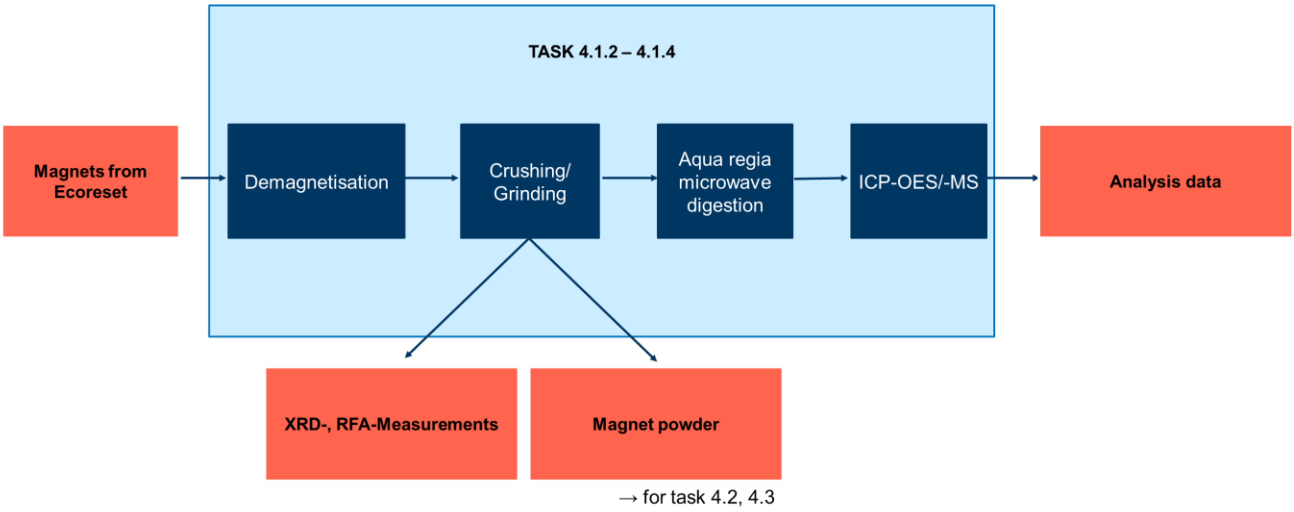


Figure 5 - T4.1 Workflow

T4.2 – Nd extraction via solid-state chlorination (SSC): Magnets are demagnetised and crushed as described previously. After that SSC, a chlorination process, is performed in a rotary kiln by addition of chloride salts. This process converts metal content into water-soluble metal chlorides. During SSC, ammonia is released as a byproduct, which can be captured and later used.

T4.3 – Electrochemical Nd extraction: Electrochemical leaching (EL) involves extracting metal ions from the anode electrode into a solution using an external electric current. This task was carried out using both non-selective and selective leaching. For the non-selective leaching the magnets are submerged in an aqueous Na_2SO_4 solution, that serves as a supporting electrolyte. During this process, a voltage is applied to reduce and deposit REEs on the cathode. Meanwhile, at the anode, dissolution of other metals like Fe can occur. As a result, a leachate containing impurities, suspended solids and REE, such as Nd, Fe and B is obtained. Therefore, there is a need to purify this solution, by filtrating it. The selective EL route will not be considered in D9.1 because no data was available. This is due to the fact that preliminary outputs from this selective route were not showing conclusive results and therefore, the responsible partner decided to focus on the non-selective approach.

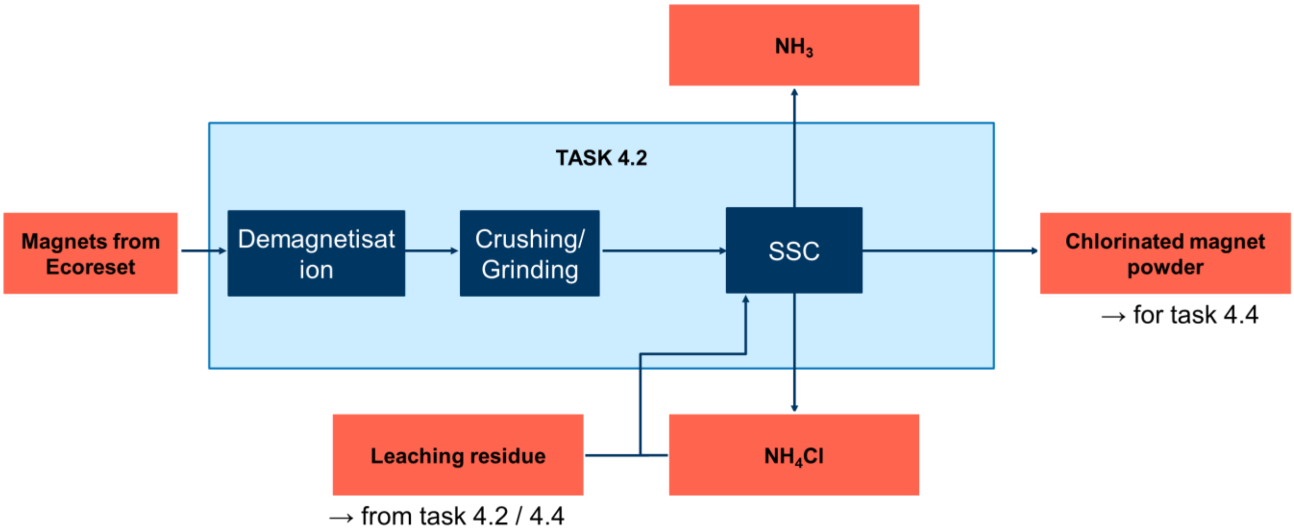


Figure 6 - T4.2 Workflow

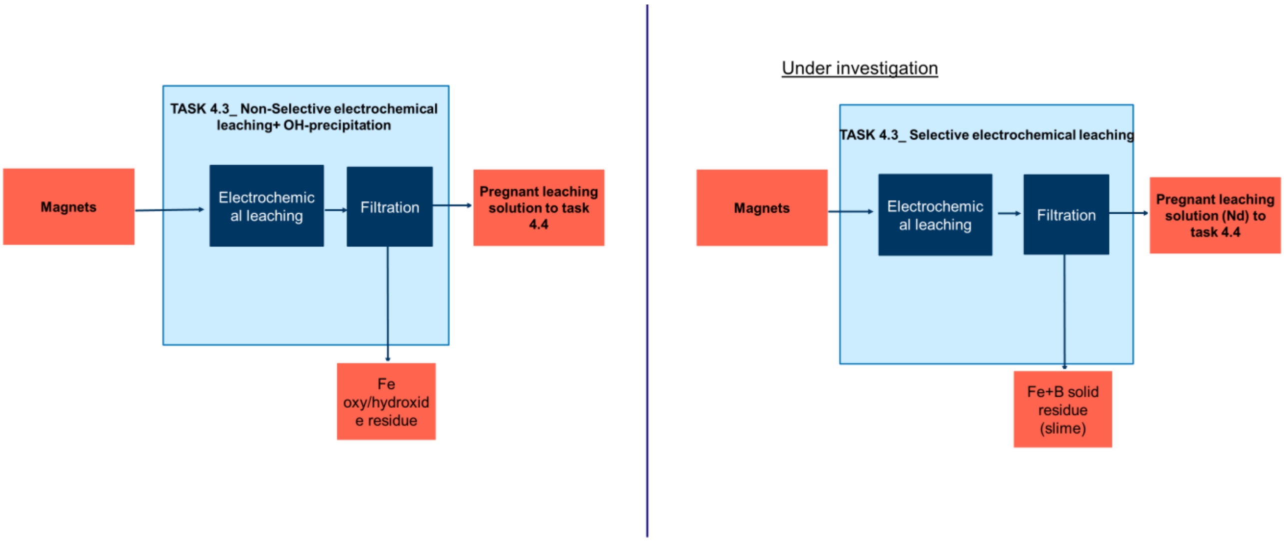


Figure 7 - T4.3 Workflow

T4.4.1 - Metals extraction and selective separation | Separation of Nd/Fe: this process is carried out using two different routes; magnets treated with SSC and magnets treated with Non-selective EL. For SSC, the metals are firstly separated through leaching, at room temperature, followed by filtration, the leachate coming from T4.3 does not need these first steps. These actions are followed by precipitation using oxalic acid, which provides a high level of selectivity towards REE. If the Fe concentration is too high, it should be washed. Nd-oxalate is produced after another filtration and following an optional calcination step that turns it into Nd_2O_3. Other methods like acid leaching were tested as alternatives, where the precipitation is carried out using Na_2SO_4 instead, but they will not be considered in D9.1.

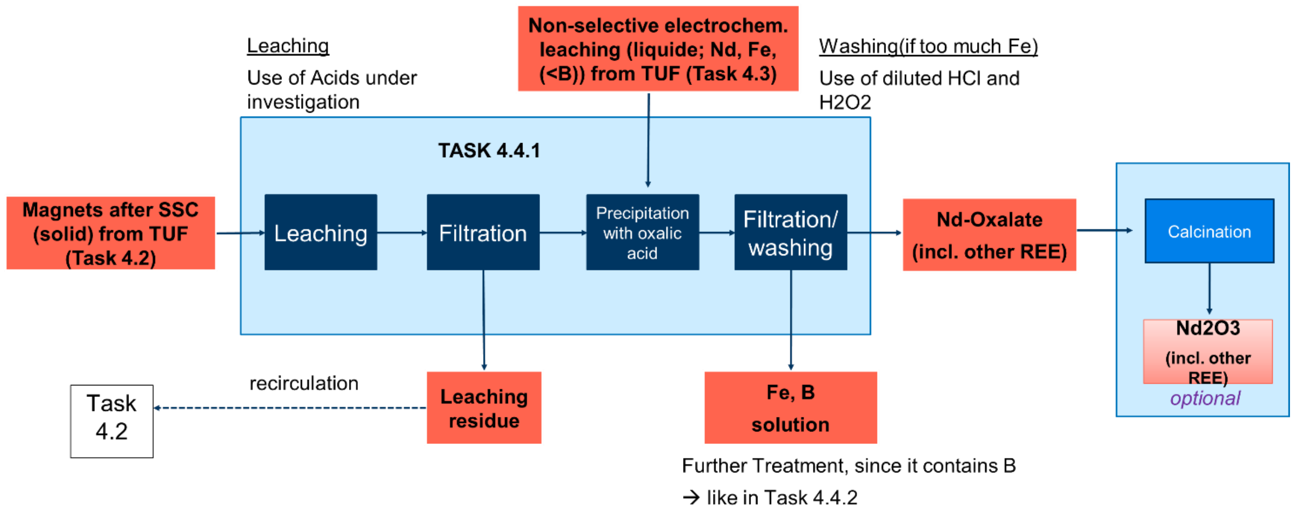


Figure 8 - T4.4.1 Workflow

T4.4.2 - Metals extraction and selective separation | Separation of Fe/B: The leaching coming from previous tasks suffers a pH increase, using NaOH so $Fe(OH)_3$ can be recovered by filtration. After that the B solution has its pH decreased, using H_2O:HCl. This solution can then be precipitated and later filtrated to produce boric acid, which in turn can be transformed in B_20O_3 using the process of calcination.

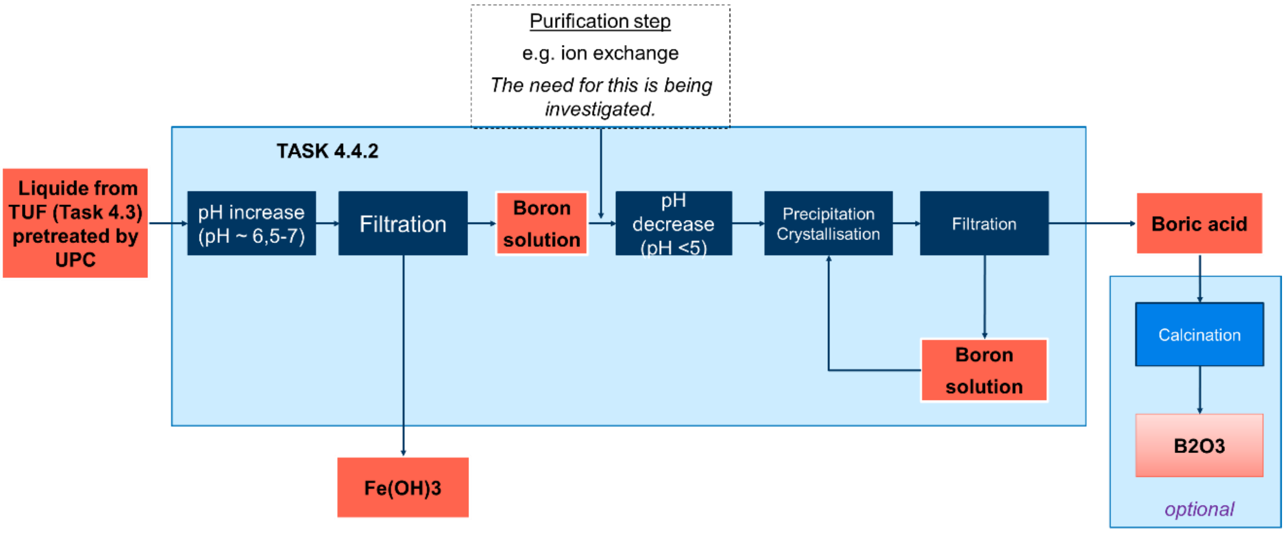
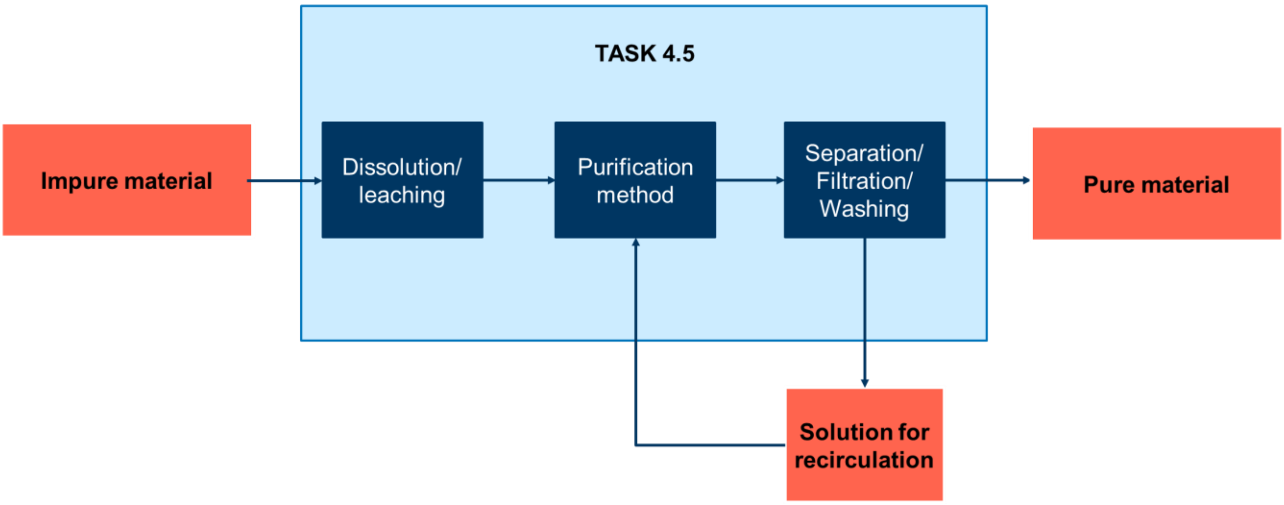


Figure 9 - T4.4.2 Workflow

T4.5 – This task is related to the purification steps needed if the samples provided to the end user do not demonstrate sufficient purity to be upcycled. The impure material is firstly treated with dissolution / leaching, followed by purification methods using, for example, Ethylenediamine tetraacetic acid (EDTA) and cation resin, and it is finally separated through filtration to obtain a pure feedstock.



Still under investigation (which purity is needed)

Purification → maybe…ion exchange, solvent extraction, selective precipitation/ crystallization (but is carried out in the corresponding task)

Figure 10 - T 4.5 Workflow

These activities are aligned with the main objectives of WP4, namely waste inventory and magnet characterisation, process optimisation at lab scale to recover over 95% of Nd, Fe, and B from EoL permanent magnets via SSC and electrochemical extraction, separation of Nd, Fe, and B to reach targeted purities, and impurities evaluation to define contamination limits for new applications.

D9.1 presents the results of T9.1 and T9.2, offering a sustainability assessment of these activities. This aligns with Objective 2 of the project, which focuses on demonstrating the circularity and sustainability of the NdFeB upcycling concept. It is also directly linked to demonstrating the profitability of the processes, verifying their environmental soundness and reduced CO_2 emissions, while developing an upcycling approach that benefits all social actors and population groups.

The process diagram underscores the intrinsic complexity of the operations required to obtain the targeted products, reflecting the multiplicity of interdependent steps that define the overall workflow. In parallel, five laboratory tasks have progressed concurrently during the first eighteen months, each contributing essential experimental data that inform the evolving understanding of the system. The critical nature of this work lies in its foundational role in supporting the robust development of WP5 and subsequent project stages, as these tasks will ultimately frame the methodological boundaries and interpretative validity of the final LCA, LCC, and s-LCA studies (after M18). Accordingly, T9.1 and T9.2 have been developed through sustained, iterative engagement with task leaders and experimental teams (harmonising data formats, clarifying assumptions, and resolving data gaps) to secure the inputs required for the preliminary LCA, LCC, and s-LCA (D9.1).

5. Methodology applied

This section aims to describe the methodology applied in D9.1. It typically pursued the following line of thought: Background review and framing; Data collection; Data analysis; Recommendations. Below each of these steps is described in more detail.

5.1. Background review and framing

Following the KoM, HOLOSS established a structured methodology to align LCA, LCC, s-LCA and Techno-economic assessment (TEA) across T9.1, 9.2, 9.3. Between M3 and M5, HOLOSS led a sequence of alignment and technical meetings (with UNITO) to define system boundaries, indicator sets and cross-task handshakes, and to formalise the distinction between LCC and TEA through explicit decision gates. A strategy was formulated to prevent any overlap in work.

As the WP leader, HOLOSS organised an intermediate meeting between all general assemblies, which took place in M4. During this meeting, the progress of the task was presented, and the objectives for M6 were communicated to the participants. Additionally, to further refine the initial meeting, another session was held with UNITO in M5. In this meeting, the possible goal and scope of the preliminary LCSA were presented, along with the next steps to determine how T9.1 and T9.3 could support each other. The goal, scope, and potential boundaries of the preliminary LCA, LCC and s-LCA were defined until M6, to discuss and integrate possible partner recommendations. Following the M6 meeting held in Athens, the scope and boundaries of the assessment were clearly delineated, providing a solid foundation for the subsequent phases of the project and aligning the consortium’s understanding and expectations regarding the evaluation framework. This framework integrates systematic data collection, robust data analysis and evidence-based recommendations to support transparent decision-making and guide the subsequent phases of the project.

5.2. Data collection

In this stage, the approach combined iterative engagement with technology developers, workflow mapping, validation checkpoints and evaluation, thereby creating a controlled and traceable process for generating consistent and ISO-aligned data foundations. Within this methodological structure, the following activities were undertaken: In M7, HOLOSS initiated a request for workflow diagrams from the partners involved in WP4, setting a deadline for submission by M8. In the same period (M7–M8), HOLOSS also carried out a survey with WP4 task leaders to select the most important stakeholder categories for the s-LCA, and the progress of this task was discussed in WP9 follow-up meetings. This initial step was essential to ensure a comprehensive mapping of processes and to support the later development of LCIs, while simultaneously establishing the foundations for the social assessment. In M8, partners were expected to submit the workflow diagrams requested in M7, and the survey on stakeholder categories continued.

The development of LCIs commenced. From M9 to M11, a questionnaire for the s-LCA was sent to partners for completion. In M11, a meeting involving all WP9 partners was held, during which a living document was established to facilitate ongoing information exchange and promote transparency throughout the work package. In the same month, a dedicated session was organised with WP4 partners to provide guidance on completing the LCIs, the deadline for completion was set for M13. During this session, the FU was defined and subsequently validated by the partners, ensuring consistency and alignment in the data collection process and compliance with ISO-aligned LCA practices. The period from M9 to M11 also marked the completion phase of the s-LCA questionnaire distribution. Between M14 and M16, further data collection and coordination activities were carried out. As there were still a lot of data gaps regarding the LCIs, in October (M14), emails were sent to TUF and IKTS to request a meeting to discuss contributions.

A meeting with WP4 partners (IKTS and TUF) took place in mid-October, during which workflows were requested to be updated by the end of October and data provision was agreed by November (M15). No workflow updates were given. By the end of M15, inputs were collected, a consolidated version of the workflows of WP4 (presented in the target scenario section), and then was circulated for confirmation. In parallel, by M14–M15, completed s-LCA questionnaires were received from all partners. In December (M16), additional clarification questions were sent to better understand some steps of the different processes and some of the inputs in the LCIs.

5.3. Data analysis

5.3.1. Life Cycle Assessment

The LCI data were calculated based on the established FU of 100 g of spent magnets. The chosen method to measure the environmental performance of the processes was the PEF method. It evaluates the environmental performance across 16 environmental impact categories[45]:

- **Climate change**, which is an environmental category that assesses the global warming potential of all GHG emissions, measured in kilos (kg of CO_2) equivalent. It is one of the most important categories, weighting 21% of the total EF.
- **Ozone depletion**: This category assesses whether the process harms the protective ozone (O_3) layer, which is crucial to guard humanity and the environment. This

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[45] MÅLBAR. 2023. 16 environmental impact categories of PEF – and how to obtain a PEF single score through normalization and weighting - link

category weights 6% of total impact and is represented in kilos of trichlorofluoromethane (kg Chlorofluorocarbon (CFC))

- **Particulate Matter (PM) Formation** assesses emissions that generate fine particles which are harmful to human respiratory health. This impact category is expressed in kg of PM2.5, where 2.5 refers to the size of the particle in micrometers (µm).
- **Human Toxicity** and **Ecotoxicity,** expressed in (Comparative Toxic Unit) CTUe and CTUh respectively, assess the potential harm to human health and freshwater ecosystems from exposure to chemicals.
- **Human Toxicity, Non-Cancer**, measures exposure to substances that cause non-cancer health effects such as neurological, respiratory or developmental impacts and is also expressed in CTUh.
- **Eutrophication**. It can be **terrestrial**, **freshwater** and **marine** and is the overfertilisation of the soil, freshwater, or marine systems and can be expressed in mol N_{eq}, kg N_{eq} and kg P_{eq}, respectively.
- **Resource use (fossils).** This category, expressed in MJ, evaluates the consumption of fossil fuels, which is a non-renewable resource that deprives future generations if spent in large quantities.
- **Resource use (minerals and metals**). It takes into account the number of materials contributing to resource depletion and converts them into equivalents of kilograms of antimony (kg Sb_{eq}). This category measures the consumption of various finite and non-renewable rare minerals and metals, which are critical for technological advancements.
- **Water use**, expressed in cubic meters (m^3), evaluates freshwater consumption and its effects on water scarcity and ecosystems.
- **Land use**, expressed in points (Pts), assesses the impact of land occupation and transformation on soil quality and biodiversity.
- **Acidification** regards the product's contribution to environmental acidity, that affects soils, water bodies and ecosystems. In this impact category, the potential impact of substances which contribute to acidification is converted to the equivalent of moles of hydron concentration.
- **Ionising radiation** category evaluates exposure related to radioactive substances caused by nuclear power plant fuels, nuclear weapon testing and other sources. The potential impact of different ionising radiations is converted to the equivalent of kilograms of Uranium-235.
- **Photochemical ozone formation** measures emissions that create ground-level ozone, also named as *smog*, harmful to human health and vegetation, and is expressed in equivalent of kilograms of Non-Methane Volatile Organic Compounds (NMVOC).

After data was collected, HOLOSS associated it with environmental impacts and indicators through the chosen method in the SimaPro software. After the inventory data were compiled, the environmental assessment comprised classification, characterisation, normalisation and weighting[46].

- Classification – Is the assignment of the material and energy inputs and outputs to their corresponding impact categories.
- Characterisation – Quantifies how each input and output contributes to its assigned impact category. Is done by multiplying each flow by a substance or resource specific characterisation factor, which expresses its impact relative to a reference substance. The resulting values are then aggregated within each impact category to produce the corresponding impact indicators.
- Normalisation – Converts life cycle impact assessment results into dimensionless values by multiplying them by normalisation factors, allowing their relative contributions to impact categories to be compared against a reference unit. The resulting normalised indicators express the process's environmental burdens in regard to that reference.
- Weighting – Helps to understand and communicate life cycle assessment results by multiplying the normalised indicators by weighting factors that express the relative importance of each impact category. The resulting weighted values can be compared across categories to understand their significance or aggregated into a single overall score. While ISO 14040 treats weighting as an optional step, it is a mandatory phase in the PEF and Organisation Environmental Footprint methodologies.

5.3.2. Environmental assessment of task processes

In the SimaPro modelling process, the unit processes were constructed using datasets available in the Ecoinvent database. Regarding energy consumption, the input "Electricity, medium voltage {Europe without Switzerland} market for electricity, medium voltage Cut-off, U" was selected. This choice ensures consistency across all tasks by applying the same electricity dataset, thereby facilitating comparability. Furthermore, because all tasks are conducted within European countries, this dataset provides an appropriate geographical representation.

After modelling the processes, environmental results were obtained, providing a basis for evaluating the impacts associated with each task. After obtaining the individual process results, a chain of processes was defined for the feedstocks that can be produced through both methods, SSC and Non-selective EL. This allowed the comparison of the environmental performance of each production route under consistent system boundaries.

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[46] European Commission, Joint Research Centre. (n.d). Life Cycle Assessment (LCA). - link

5.3.2.1. Environmental assessment of feedstocks

Understanding that the production of secondary materials, such as iron hydroxide ($Fe(OH)_3$), boric oxide (B_2O_3), and neodymium oxide (Nd_2O_3) is currently limited to small-scale operations, it becomes possible to identify and compare the key differences between scales and dimensions once upscaling is achieved. At this stage, based on the data collected and calculated for the defined FU, the environmental analysis using the PEF method in SimaPro began with establishing the complete sequence of processes involved in producing the feedstocks at laboratory scale.

To carry out the environmental assessment of the feedstocks manufacturing process, several key assumptions were established. First, the solutions obtained after filtration were considered to be predominantly aqueous and therefore assigned a volumetric mass of 1000 kg/m^3. In addition, a minor adjustment was introduced regarding energy consumption when compared to the WP4 processes previously discussed. Specifically, the electricity input for the environmental assessment was defined according to the electricity mix of the production country, rather than using the broader European electricity mix. Therefore, for instance, to model the processes of energy consumption of a feedstock produced in Germany, “Electricity, medium voltage {DE} market for electricity, medium voltage |Cut-off, U” was selected on the Ecoinvent database.

Iron hydroxide ($Fe(OH)_3$) is a common raw material to produce chemicals and therefore is widely used in the fields of pigments, catalysts, magnetic materials, and others[47]. Since it is an output of the recovery of spent magnets, following the SSC method and Non-selective EL, its production stages are defined in Figure 11 and Figure 12.

As previously noted, $Fe(OH)_3$ may be generated as a product in both methods, SSC and non-selective EL. However, despite both methods following the sequence of processes described, the stream represented in Figure 12 it was not included in the modelling stage. This decision reflects the absence of any available data for pH increase followed by filtration processes. Meaning, the environmental assessment of the production of $Fe(OH)_3$ was only focused towards the manufacturing chain via SSC, shown in Figure 11.

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[47] ChemSky. 2024. Iron oxide production methods and production process, what are the commonly used raw materials -link

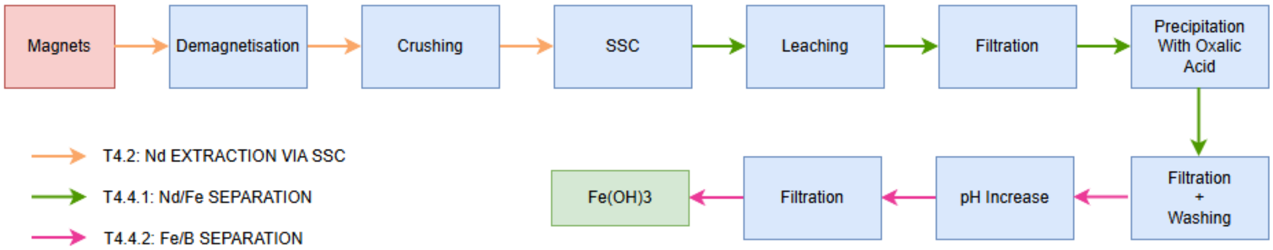

Figure 11 - Manufacture processes of Fe(OH)3 as a secondary material, via SSC

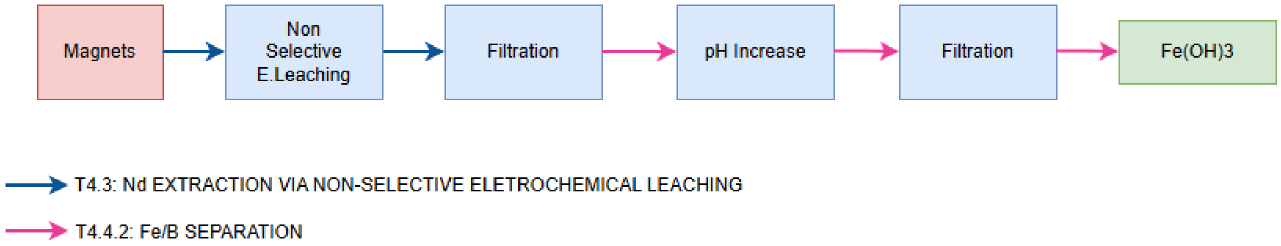

Figure 12 - Manufacture processes of Fe(OH)3 as a secondary material, via Non-selective EL

Another feedstock that is a result of the upcycling of spent magnets methods is B_2O_3. Since it is possible to produce boron trioxide through either SSC or Non-selective EL, both manufacturing routes, illustrated in the following figures, were modelled.

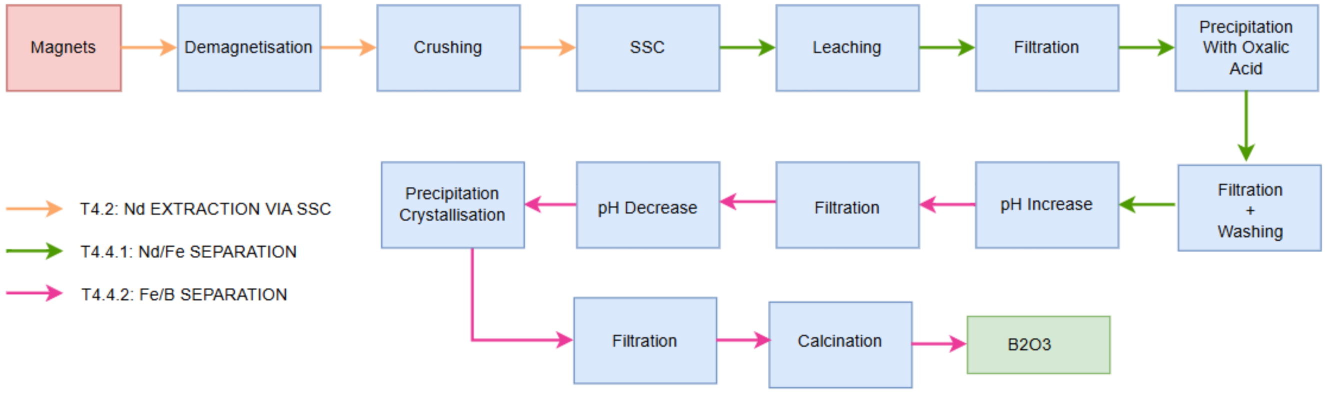

Figure 13 - Manufacture processes of B_2O_3 via SSC

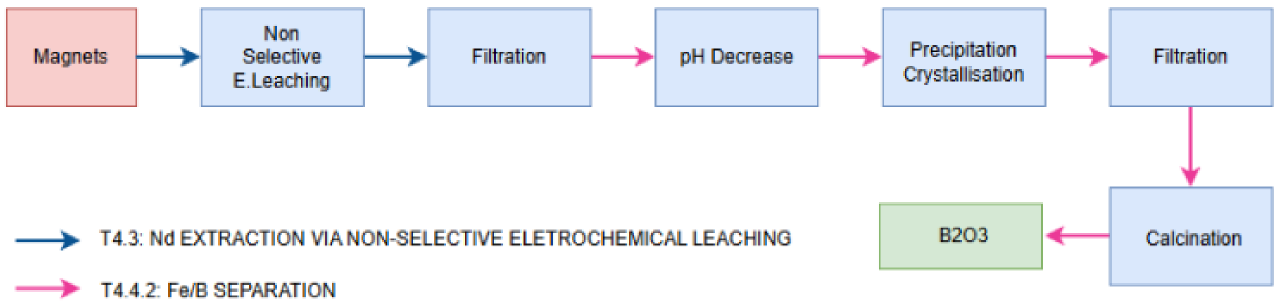

Figure 14 - Manufacture processes of B_2O_3 via Non-selective EL

Finally, the upcycling of spent magnets yields an additional feedstock, Nd_2O_3, via the SSC route or Non-selective EL, illustrated by the workflow in Figure 15 and Figure 16.

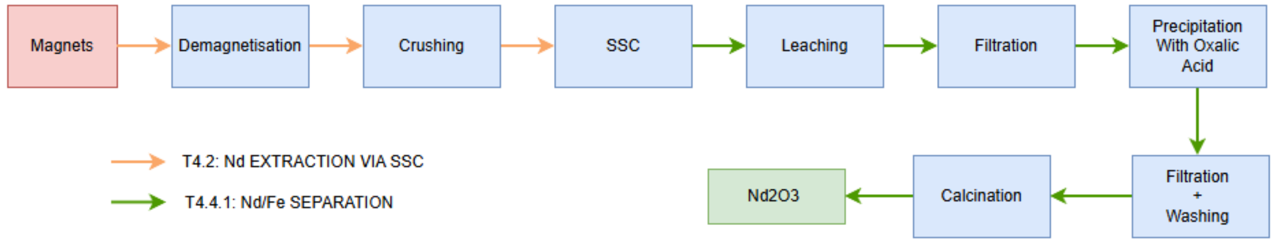

Figure 15 - Manufacture processes of Nd_2O_3 via SSC

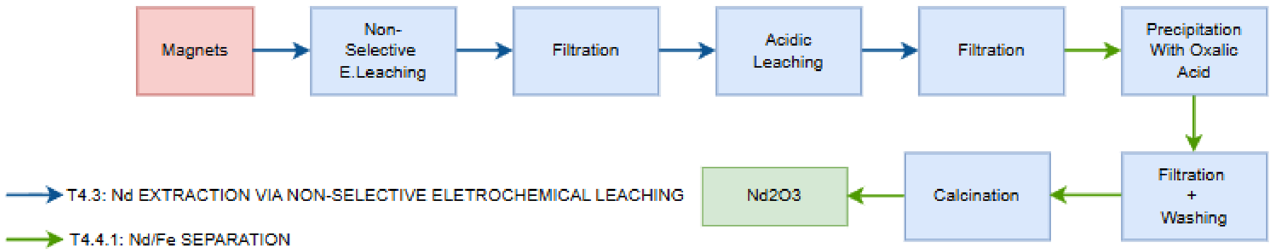

Figure 16 - Manufacture processes of Nd_2O_3 via Non-Selective EL

5.3.3. Life Cycle Costing

As previously mentioned in Section 3.5.2, a comprehensive LCC analysis involves calculating several indicators across the entire life cycle of a material or product. However, due to the early stage of NEO-CYCLE, where processes are still being optimised, data on life cycle durations, costs, investments, return rates and payback periods remain limited or insufficient. For this reason, HOLOSS pursued a low-TRL-adapted LCC formulation, concentrating on those cost components that can be robustly evidenced and replicated for the activities delineated in the target scenario. Using the data collected in the LCI regarding material, equipment, maintenance, labour, and energy costs, it was possible to identify the main expenditure hotspots. The analysis was also performed with respect to the FU of 100 g of spent magnets. All calculations were based on working-hour utilisation, reflecting the operational reality of the NEO-CYCLE processes. This approach provides a transparent and robust foundation for more detailed economic assessments in later stages of the project once discounting parameters and broader system boundaries are defined. The LCC approach also followed the basis set by the environmental analysis.

5.3.3.1. Economic assessment of task processes

The associated costs for all tasks in WP4 were calculated with respect to the FU. Yearly equipment and maintenance costs were converted into working-hour-based values, following the standard assumption of 8 h/day, 5 days/week and 52 weeks/year, resulting in 2080 h/year. Since the actual electricity tariff was not yet available at this stage, an average European electricity price of 0.19 €/kWh[48] was assumed. Based on these calculations, the scenario offering the most favourable economic outlook for recovering minerals from spent magnets was also examined.

5.3.3.2. Economic assessment of feedstocks

Based on the manufacturing routes defined in the previous section for producing the mineral feedstocks, the cost of transforming 100 g of spent magnets into the different individual elements was also calculated. These values were then compared with the standalone market prices of purchasing these elements directly, providing a basis for comparison and an initial indication of potential future profitability margins.

5.3.4. Social LCA

To analyse the data gathered from the social questionnaires, the reference scale approach was used. This method compares the results of the questionnaire with predefined reference scales. For this purpose, HOLOSS answered the questionnaire using the ideal responses, based on United Nations Environment Programme (UNEP) guidelines, PSILCA and insights from the ORIENTING project, creating a scale for comparison. A scoring system was then created to associate the level of compliance with a corresponding level of risk. Since both qualitative and quantitative questions were included in the questionnaire, two separate scoring approaches were developed. The same scoring values were used in both cases to ensure comparability and consistent risk attribution. Failure to respond or unknown answers were given a percentage of compliance of 0. Tables 1 and 2 showcase these scoring systems.

To make the comparison, the questionnaires were first scored individually, and then the average of the three questionnaires was calculated to assess the potential highest social risk at this stage of the project. A score was first attributed to each of the subcategories and was then averaged to obtain the score of the category. The final score was obtained by calculating

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[48] Eurostat. 2025. Electricity price statistics, Statistics Explained - Link

the average of all four categories. The identified risks were then compared to the social risks of mining REE.

Table 1 - s-LCA score for qualitative answers.

Qualitative Assessment		
Percentage of Compliance	**Score**	**Risk level**
0-25%	-2	Very High Risk
26-45%	-1	High risk
46-55%	0	Medium risk
56-99%	1	Low risk
100%	2	No risk

Table 2 - s-LCA score for quantitative answers

Quantitative Assessment		
Comparison with the average of the country	**Score**	**Risk level**
-100% to -74%	-2	Very High Risk
-75% to -24%	-1	High risk
-25% to 25%	0	Medium risk
+26% to +75%	1	Low risk
+76% to +100%	2	No risk

5.4. Recommendations

Following the assessment of sustainability impacts across all dimensions, HOLOSS carried out an additional review of the relevant scientific and technical literature. The aim of this review was to identify practical measures and design considerations that, if considered when scaling up the analysed processes, could play a key role in lowering the impacts related to REE recovery in the NEO-CYCLE project.

6. Preliminary sustainability assessments

6.1. Background review and framing

When combining the analysis of the three pillars of sustainability, the first steps are common for all of them, to define the goal, scope and boundaries of the analysis. This framing allows the sustainability assessments to be carried out in the most pertinent stages and processes of the project.

The goal of this preliminary assessment was set as follows: perform a preliminary sustainability analysis, encompassing environmental, economic and social assessment, of the NEO-CYCLE processes to provide recommendations for improvements. The scope of this analysis, as previously described in the Target Scenario section, is the set of processes of WP4. A gate-to-gate approach was also agreed upon, since at this stage of the project the main source of data is the laboratory. Within gate-to-gate boundaries, the analysis is able to efficiently detect where to improve in single, isolated processes, which is the goal of D9.1[49].

6.2. Data collection

Data collection happened in four major occasions that were crucial for the development of the LCSA. In each of these occasions, partner collaboration was requested and heavily incentivised to avoid data gaps and to provide the most accurate results possible at this early stage of the project. Since an LCSA is only as good as the data behind it[50], ensuring robust and complete inputs was essential from the outset.

6.2.1. Workflow diagrams

Workflow diagrams were requested from the partners of WP4. These diagrams should showcase the steps carried out in each of the tasks, as well as the initial input and final product of each task. An example was provided by HOLOSS to demonstrate the type of diagram needed, as shown in Figure 17.

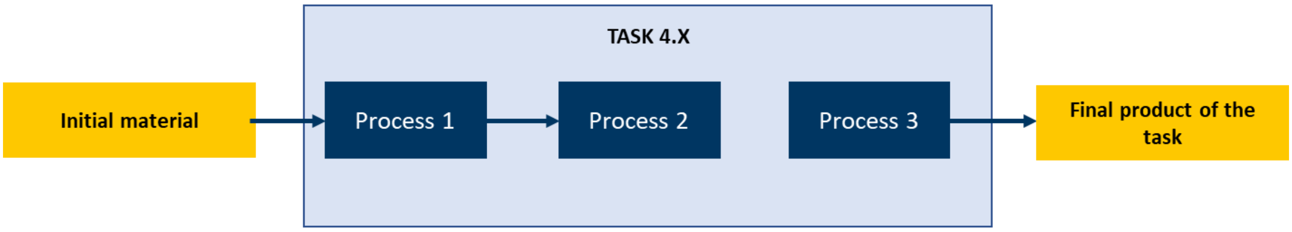

Figure 17 - Workflow example provided to WP4 partners.

Workflow diagrams for all tasks were received and validated on different occasions, and the final version was previously presented in the Target Scenario section.

The early stages of the NEO-CYCLE project, with a lower TRL, are also reflected in the workflow diagrams, as some steps and activities are still under investigation. Additionally, some optional steps were included to better understand the fate of the obtained feedstocks. With

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[49] Sustainability Directory. 2025.When is a “gate-to-gate” LCA most appropriate in a supply chain? - Link

[50] Zamagni, A., Pesonen, H.-L., & Swarr, T. 2013. Life cycle sustainability assessment: What is it and what are its challenges? In A. Finkbeiner (Ed.), Towards life cycle sustainability assessment. Springer - Link

these workflow diagrams, the flow of materials throughout the activities of WP4 became easier to understand. These flows can serve as a starting point for future analyses since the activities represented here are expected to be replicated when the project is scaled up (WP5).

6.2.2. Life Cycle Inventory

After defining the activities of each of the WP4 tasks, and following the steps of ISO 14040/14044, the next step was to gather the LCI of each of these tasks. The LCI records all flows and products in and out of processes, including product flows, waste flows and other production information identified as relevant. For this purpose, HOLOSS sent a file designed to collect all the quantitative data from the processes of WP4. The FU was defined as 100 g of NdFeB magnets. This amount was defined to align the calculations with the values currently used in the laboratories, ensuring easier communication and consistency in the orders of magnitude applied. It can be reviewed and adjusted in later stages of the project, once more accurate data become available, and the processes are further optimised. The file was divided into inputs relevant for LCA and for LCC. For LCA, basic data on inputs, outputs and costs involved in the processes was requested, mainly focused on mass, energy and outputs. For LCC, data on costs involved in production was requested, mainly focused on inputs, energy, labour and outputs. To make the process more comprehensible, the data was requested per activity and per task, following the structure indicated in the workflow diagrams.

The early stage of the process was also reflected in the data received, as some inputs collected were mainly assumptions that had to be calculated to respect the FU. Furthermore, the LCC section, which requires detailing costs, was more difficult to estimate at this stage, since laboratories, where most of the tasks are carried out, are sometimes disconnected from the actual costs of the processes.

Although important for the LCC analysis, cash-flow data could not be provided by the partners, since at the stage of collecting information, they were still exploring materials and processes. As a result, they are not yet able to reliably predict this type of cost-related data.

6.2.3. Social impact categories survey

In order to define the impact categories for which the preliminary s-LCA would target, a survey was carried out with WP4 partners. Partners were asked to rank the following categories (from UNEP guidelines [51]) by relevance to them:

Workers - to evaluate factors such as freedom of association, salaries, working hours/shifts, equal opportunities, health and safety, employment relationship, etc.

Local Community - to evaluate factors such as access to material/immaterial resources, community engagement, local employment, delocalisation, etc.

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[51] Traverso, M., Valdivia, S., Luthin, A., Roche, L., Arcese, G., Neugebauer, S., ... & Zamagni, A. (2021). Methodological sheets for subcategories in social life cycle assessment (S-LCA) 2021. - link

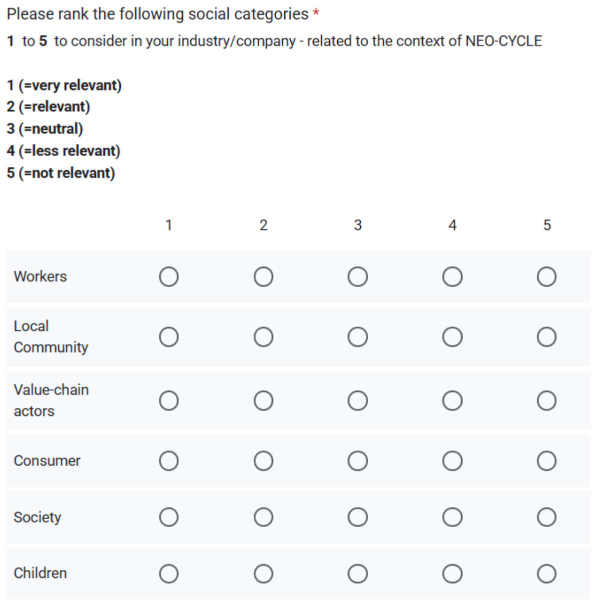
Value chain actors - to evaluate factors such as fair competition, supplier relationships, promoting social responsibility, etc.

Consumer - to evaluate factors such as consumer health and safety, feedback mechanism, transparency, etc.

Society - to evaluate factors such as public commitment to sustainability, contribution to economic development, technology development, poverty alleviation, etc.

Children - to evaluate factors such as concerns in marketing practices, health of children as consumers, available education in local community.

The system of classification is present in Figure 18.



Please rank the following social categories *

1 to 5 to consider in your industry/company - related to the context of NEO-CYCLE

1 (=very relevant)
2 (=relevant)
3 (=neutral)
4 (=less relevant)
5 (=not relevant)

	1	2	3	4	5
Workers	○	○	○	○	○
Local Community	○	○	○	○	○
Value-chain actors	○	○	○	○	○
Consumer	○	○	○	○	○
Society	○	○	○	○	○
Children	○	○	○	○	○

Figure 18 - System of classification for social categories provided to WP4 partners

Results of the ranks are present in Table 3.

Table 3 - Average results of the classification of social categories

Social Category	Average Rank
Workers	3.00
Local Community	2.67
Value-chain actors	2.17
Consumer	2.50
Society	2.17
Children	4.00

According to the partners, the most relevant social categories are society, value-chain actors and local community. These categories are also analysed with great relevance in other s-LCA assessments of REE and magnets, and as such, the results of this ranking within the NEO-CYCLE partners are in harmony with the literature[52, 53, 54]. However, in previous studies, the worker category is also highlighted, which is not the case in NEO-CYCLE (second lowest relevance). This difference occurs because the questionnaire was only carried out within European entities, where worker rights are generally more protected and respected and therefore not perceived as highly critical by the partners.

6.2.4. Social LCA questionnaire

Following the definition of the most important social categories, the three highest-ranked (society, value-chain actors and local community) and one of high literature relevance (workers), HOLOSS created a S-LCA questionnaire. Different subcategories were identified using UNEP guidelines and PSILCA database – Table 4. The reason for the selection of each of the subcategories was also presented to the partners to provide a better understanding of the reasoning behind the questions.

For Workers: The inclusion of the “**Health & Safety**” subcategory is essential to understand the safety needs of the chemical industry, given that this sector presents a high degree of risks and hazards. The information collected is also important to later develop a comparative analysis; The inclusion of the “**Child Labour**” subcategory is crucial, particularly within an industrial sector. The information collected will be helpful to provide awareness on the existence of Child Labour; The “**Forced Labour**” subcategory was included due to a necessity to analyse existing practices and its alignment with EU regulations and standards. The information collected will then be used to perform comparisons and complement the social analysis; The “**Fair Salary**” subcategory was selected in this case due to previously identified inconsistencies in the chemical industry. It must be included in the questionnaire to complete missing information about the industry practices.

For Society: The "**Public commitment to sustainability issues**" subcategory was selected because it is important to assess how organisations are communicating their objectives in the sustainability dimensions. It will identify the best practices and improvements in this area; "**Contribution to economic development**" is being assessed to understand the benefits organisations have on local and national economies; The inclusion of the "**Prevention and mitigation of conflicts**" subcategory is important to appraise the strategies that are being carried out regarding social tensions. It undertakes the organisation's commitment to social

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[52] Werker, J., Wulf, C., Zapp, P., Schreiber, A., & Marx, J. (2019). Social LCA for rare earth NdFeB permanent magnets. Sustainable Production and Consumption, 19, 257-269. - link

[53] Mariga, V. Sustainability analysis in the mining sector: a case study on new recycling technologies for sulphidic mine residues valorisation. - link

[54] Wulf, C., Zapp, P., Schreiber, A., Marx, J., & Schlör, H. (2017). Lessons learned from a life cycle sustainability assessment of rare earth permanent magnets. Journal of industrial ecology, 21(6), 1578-1590. - link

cohesion and stability; The inclusion of the "**Prevention and mitigation of conflicts**" subcategory is important to appraise the strategies that are being carried out regarding social tensions. It undertakes the organisation's commitment to social cohesion and stability; "**Corruption**" is addressed to investigate the organisation's strategies for anti-corruption. The collected data will give insights for the alignment with international standards; The subcategory "**Technology Development**" will evaluate how organisations are promoting innovation and technological advancement. It is important to address how technology is being used to contribute to sustainable progress.

For Value Chain Actors: The "**Fair Competition**" subcategory was included to evaluate whether organisations adhere to principles of equity and avoid practices that distort market dynamics. Information collected will help ensure a level playing field for all actors in the value chain and promote compliance with relevant regulations; The "**Supplier Relationship**" subcategory is crucial for assessing the quality and transparency of interactions between organisations and their suppliers. This data helps to identify responsible sourcing practices and foster long-term, mutually beneficial partnerships; "**The Respect of Intellectual Property**" subcategory has been included to analyse how organisations safeguard and honour the rights associated with innovations and creative works. Insights gained will help measure compliance with legal standards and encourage a culture of innovation throughout the value chain.

For Local Community: The "**Access to material resources**" is being addressed to evaluate how organisations are impacting community's access to essential resources. The data gathered will help understand challenges related to resources at a local level; The "**Delocalisation and migration**" subcategory will help understand how organisations are influencing population movement. Data will help understand challenges and opportunities related to these population movements; "**Safe and healthy living conditions** " will analyse how the practices carried out by the organisation are influencing the safety of surrounding communities. This data will help understand the contribution of the organisation to public health; The "**Local employment**" subcategory is involved to assess the contribution of the organisation to the creation of local jobs. This will contribute to understanding the value of providing employment opportunities for local residents.

Table 4 - Subcategories used in que s-LCA questionnaire

Stakeholders	Subcategories				
Workers	Health & Safety	Child labour	Forced labour	Fair Salary	
Society	Public commitment to sustainability issues	Contribution to economic development	Prevention and mitigation of conflicts	Corruption	Technology development
Value Chain Actors	Fair competion	Supplier relationship	Respect of intellectual property		
Local Community	Access to material resources	Delocalization and migration	Safe and healthy living conditions	Local employment	

6.3. Data analysis

6.3.1. LCA

Following the data collected, aligned with the established FU, 100 g of spent magnets, the first step to perform the environmental impact assessment was to run simulations in the SimaPro software. To have a better understanding and detailed analysis of the EF regarding WP4, results were first obtained for all processes studied on each task.

Subsequently, a comprehensive manufacturing pathway was defined, integrating the processes examined in each task for every feedstock derived from the upcycling of spent NdFeB magnets. In practice, this involved establishing a sequential set of operations for producing iron hydroxide ($Fe(OH)_3$), boric oxide (B_2O_3), and neodymium oxide (Nd_2O_3). The EF of each corresponding manufacturing line was then assessed and compared to the EF of the manufacture of a similar virgin material. This step will be particularly valuable when comparing the upscaled processes to be explored in future work.

6.3.1.1. Environmental assessment of Task Processes

Results obtained through the software for T4.1 regarding the magnets' characterisation are illustrated on the graphic of Figure 19.

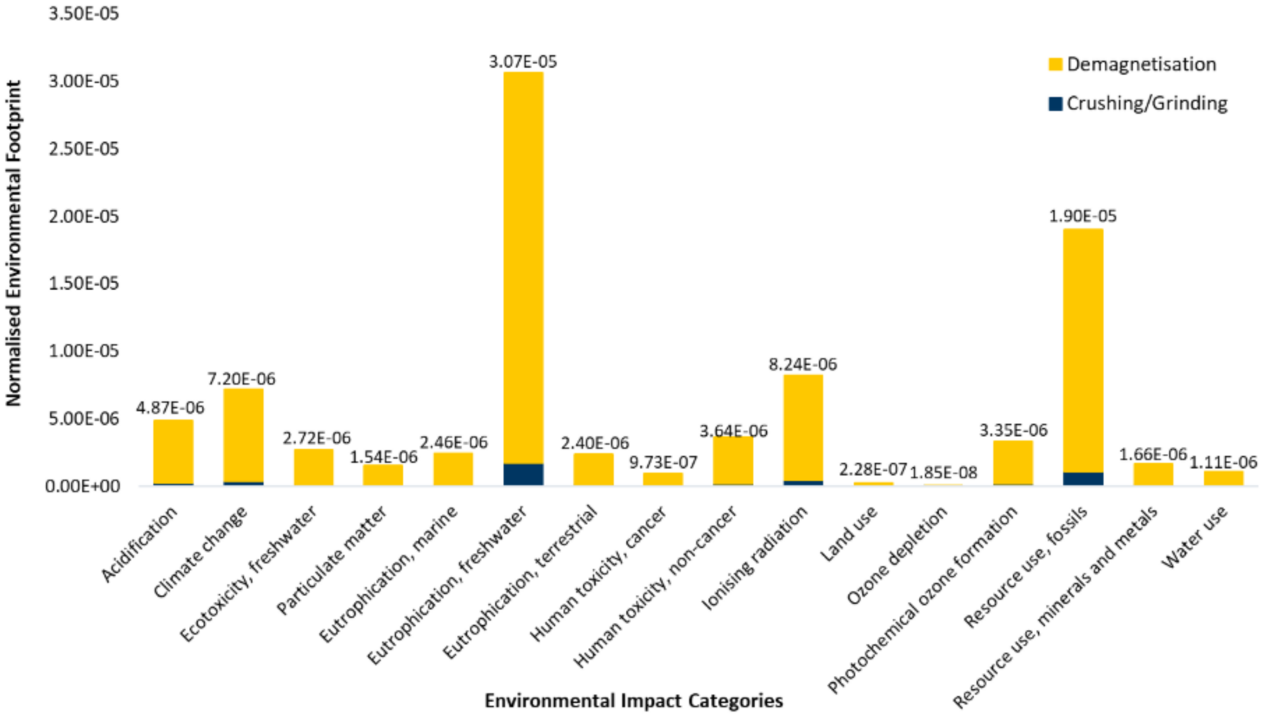

Figure 19 - EF of T4.1 processes

Through Figure 19, it is possible to conclude that the demagnetisation process contributes more than 94% to the normalised total footprint of each impact category, which is 0.0001. Another visible conclusion is that freshwater eutrophication and resource use (fossils) impact categories present the highest EF, reflecting the characteristics of the European electricity mix, which relies on a combination of fossil fuels, nuclear power and renewable energy sources.

The EF results of the SSC process, studied in T4.2, illustrated by the graphic in Figure 20, conclude that freshwater eutrophication, ionising radiation, and resource use are the most impacted environmental categories. This may be to the fact that a leachate is produced during this process and requires ammonium chloride and a large amount of energy. According to literature, the effect of electricity demand on ionising radiation category is due to the European electricity mix grid, which includes nuclear and fossil sources[55].

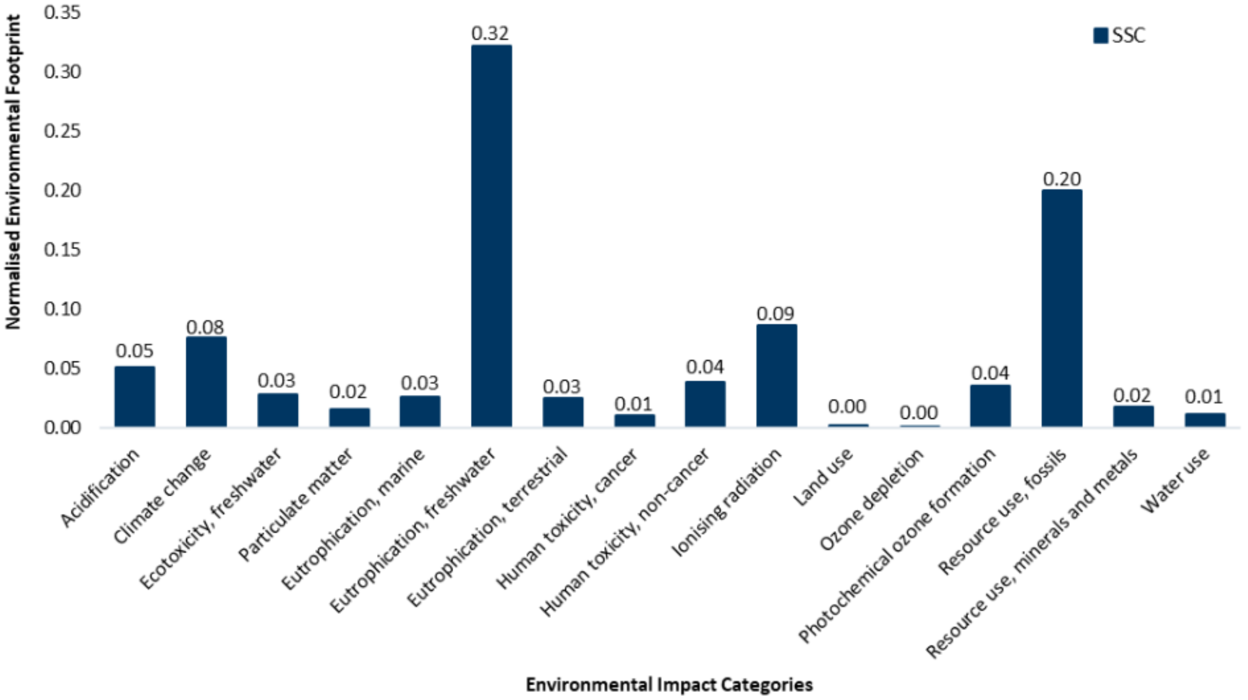

Figure 20 - EF of T4.2 processes

T4.3 examines an alternative to the SSC process: non-selective EL. The results indicate that freshwater eutrophication and resource use (minerals and metals) are the two impact categories with the highest EF. This outcome is mainly linked to the upstream burdens associated

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[55] A. Becci, F. Beolchini, A. Amato. 2021. Processes. Environmental and Green Processes: Sustainable Strategies for the Exploitation of End-of-Life Permanent Magnets - link

with the materials, chemicals and equipment required for the EL process. These inputs typically involve mineral extraction, metal production and emissions to water, which strongly influence both eutrophication and resource-use indicators.

In addition, Figure 21 further shows that the filtration processes are the dominant contributors to the overall EF, regardless of the impact category, accounting for roughly 60% of the total, followed by non-selective EL at about 20%. This contribution is primarily linked electricity consumption, the use of filter paper and sodium sulphate, in filtrations and EL, respectively.

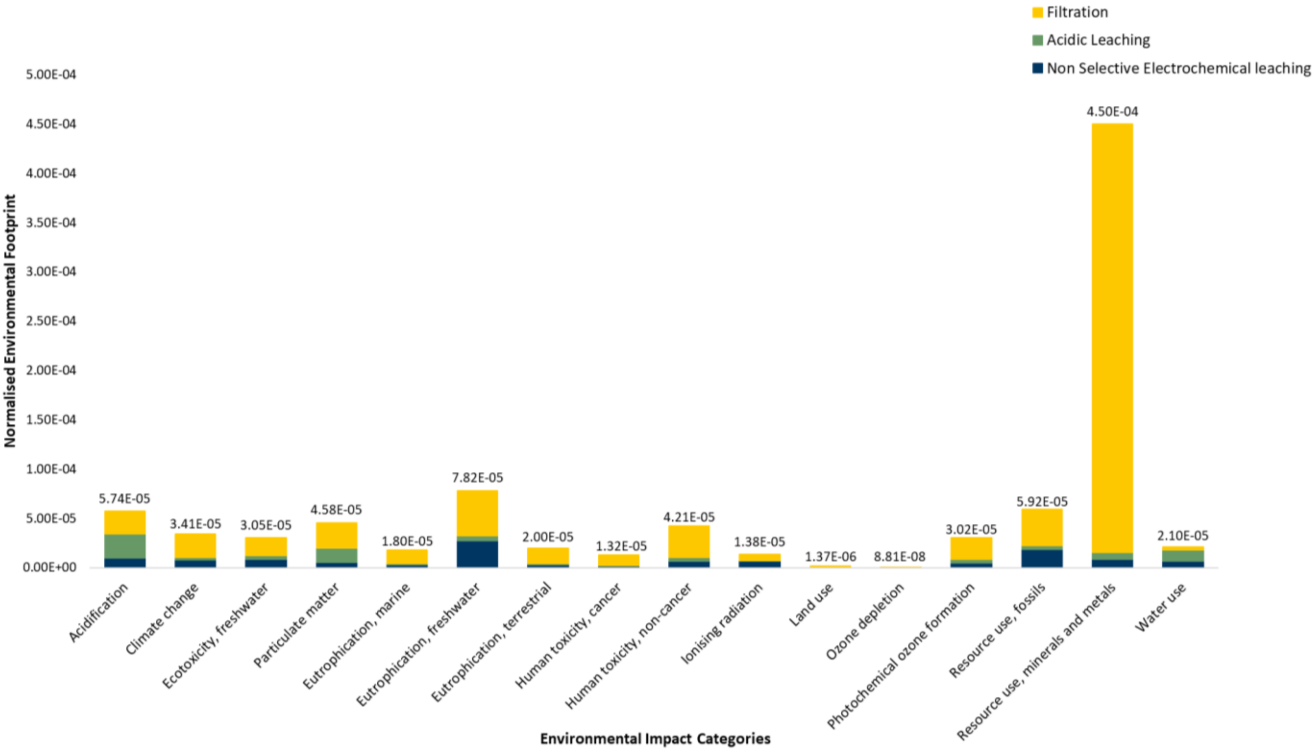

Figure 21 - EF of T4.3 processes

EF results, obtained through the SimaPro software, regarding T4.4.1, Nd/Fe separation processes, considers the chemicals, water, and energy consumption throughout the leaching, filtration, precipitation, and drying stages of the separation process, as well as the calcination process to obtain neodymium oxide. The total EF of the T4.4.1 studied process is approximately 0.011.

Figure 22 shows that the stages of Nd/Fe separation with the greatest environmental impact are the calcination the final filtration and drying stage, contributing on average 78% and 11% to the total results, respectively. This is largely driven by the consumption of energy and oxalic acid, and the impacts associated with the precipitation process itself. The findings are consistent with the overall EF across the environmental categories, where ionising radiation, freshwater eutrophication, and resource use emerge as the most affected. These outcomes reflect the influence of wastewater generation and electricity demand, which is tied to Europe’s electricity mix.

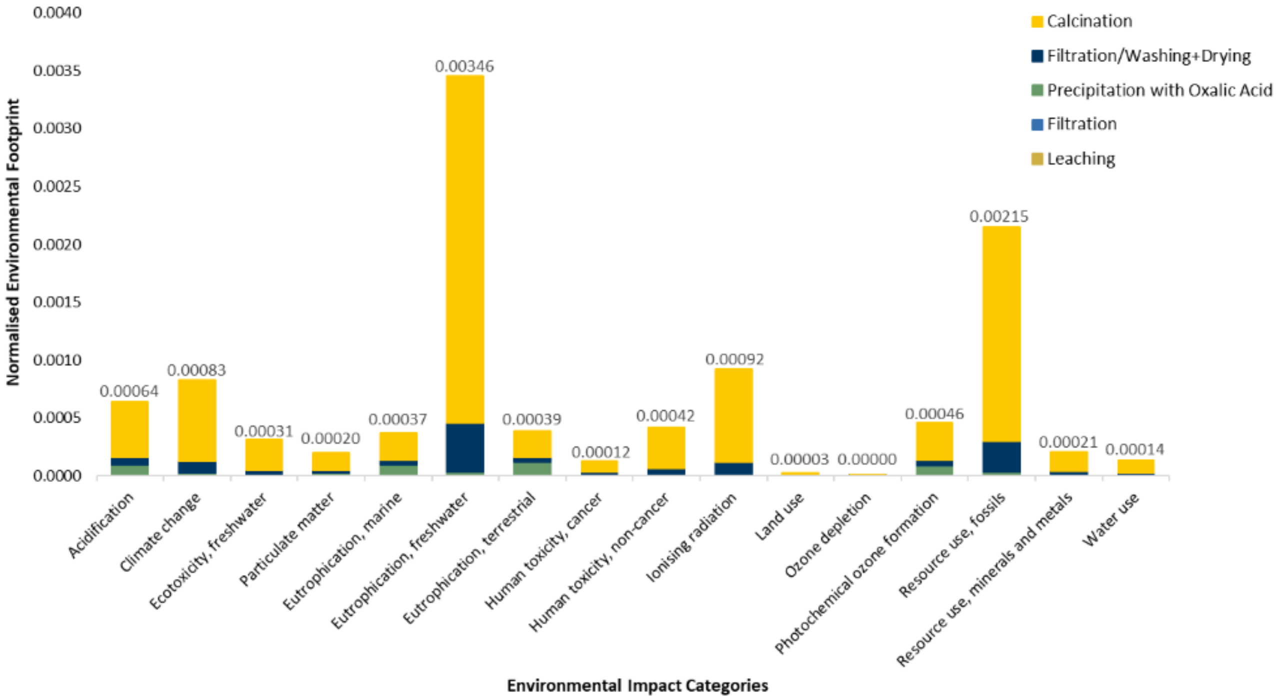

Figure 22 - EF of T4.4.1 processes

Regarding the EF results associated with the T4.4.2 processes, focusing on Fe/B separation, it is important to note that the solutions produced by SSC and EL have different requirements, which leads to distinct outcomes. The leaching solution resulted from T4.3, since its Fe content is insignificant, it is directly submitted to a pH decrease and precipitation, as a way to obtain Boric Acid. Differently, the leaching solution from T4.2 is submitted firstly to a pH increase followed by filtration, and only after goes through the same separation steps as the solution from SSC. The EF for Fe/B separation processes when using a solution derived from the SSC process is presented in the Figure 23.

The normalised EF results reveal that among the Fe/B separation processes, calcination is the most environmentally intensive step, contributing approximately 74% for the total EF, indicating high energy consumption as the main cause of overall results. On the other hand, solutions that resulted from the hydrometallurgical process of T4.3, that are submitted to T4.4.2 separation processes, do not require the pH increase followed by filtration stages. The respective results are illustrated in the graphic of Figure 24.

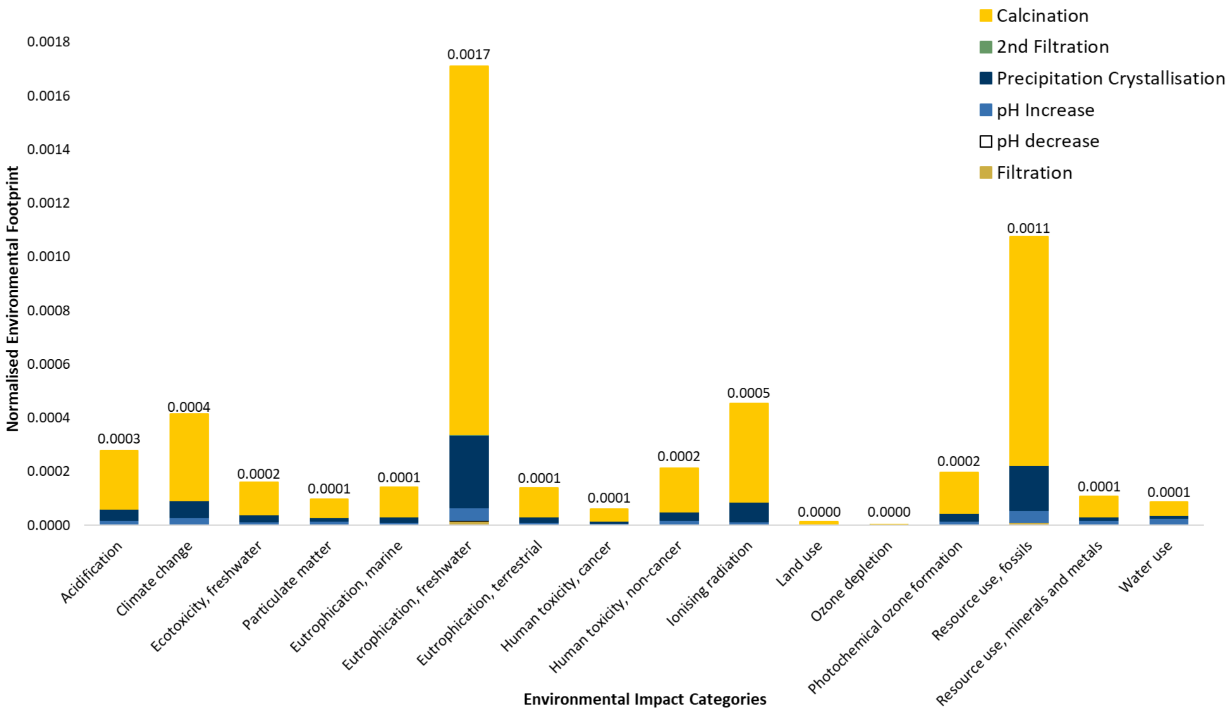

Figure 23 - EF of Fe/B separation processes for SSC samples (T4.4.2)

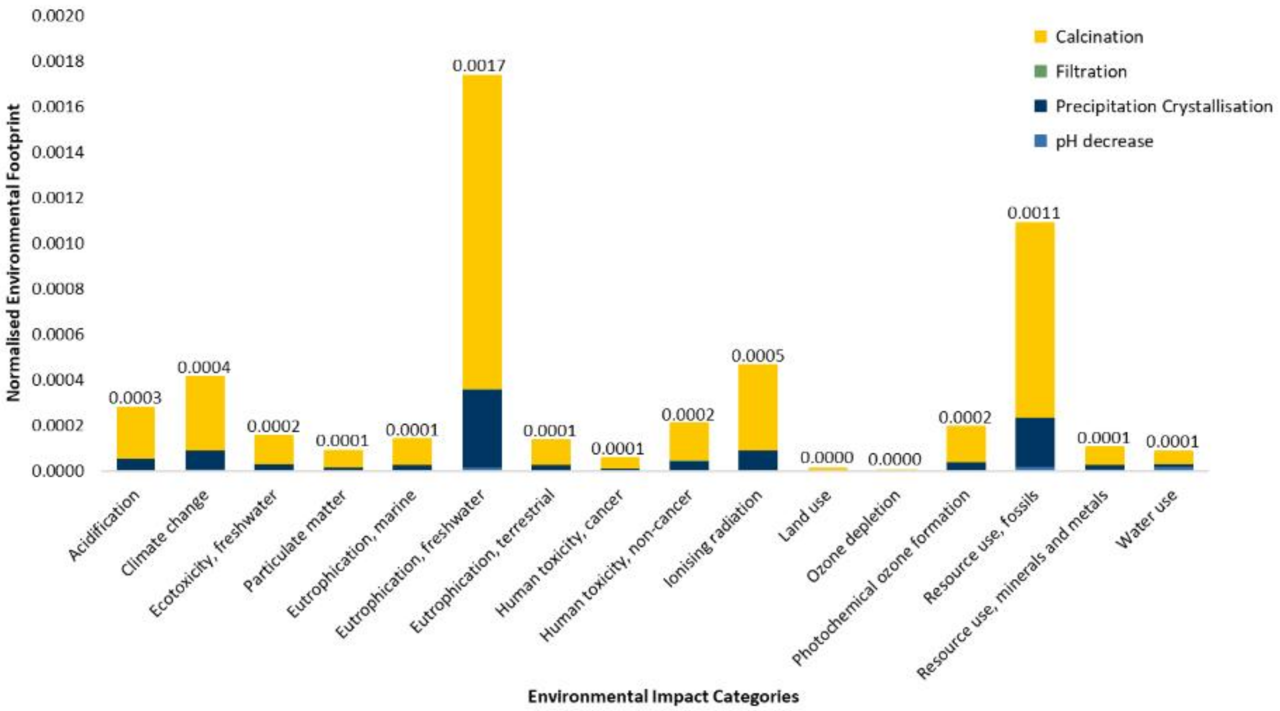

Figure 24 - EF of Fe/B separation processes for non-selective EL samples (T4.4.2)

Identical to other processes and tasks, the most affected categories of T4.4.2 for samples obtained after T4.3 processes are freshwater eutrophication, ionising radiation, and resource use, justified by the energy consumption and production of wastewater. In this case, like the samples obtained after SSC, calcination is the process with the highest EF, contributing on average 75% for each impact category. By comparing the separation of Fe and B from solutions obtained through SSC and EL, it is possible to conclude the similarity of its environmental burden results. Even though solutions from non-selective EL require less separation process, its total EF is equal to the one for output solutions of SSC.

Lastly, results were obtained for T4.5 processes, focused on purifying the final feedstock solutions from T4.4.1, to refine metal recovery, and are illustrated in the graphic from Figure 25. This process is currently being investigated, and it may not be adopted if purity level is high enough. Therefore, it is considered an optional step that depends on WP6 purity requirements. Analysis of the EF results shows that the purification stage is the largest contributor, accounting for approximately 99% of the total impact. This stage primarily affects toxicity (human and freshwater) and resource use due to the significant amounts of EDTA required. EDTA is highly resistant to natural biological and chemical degradation, meaning it persists in water systems for extended periods once released, which can lead to the accumulation of stable complexes with essential trace metals. Therefore, its release can potentially disrupt aquatic ecosystems and harm organisms that depend on these metals for survival[56] . Since EDTA is recirculated within the task processes, the overall EF should be smaller than the one obtained and presented in Figure 25.

To identify the most environmentally sustainable process for recovering NdFeB from spent magnets, two scenarios were defined. Scenario 1, illustrated by the workflow of Figure 26, focuses on hydrometallurgical methods, and includes processes from T4.3, T 4.4.1 and 4.4.2. Scenario 2, shown in Figure 27, applies to the SSC method, incorporating the processes from T 4.1, T4.2, T 4.4.1, T 4.4.2. T4.5 processes were excluded from both scenarios because the required purity is already achieved.

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[56] NBINNO. (n.d). 2025. The environmental footprint of EDTA: Challenges and alternatives - link

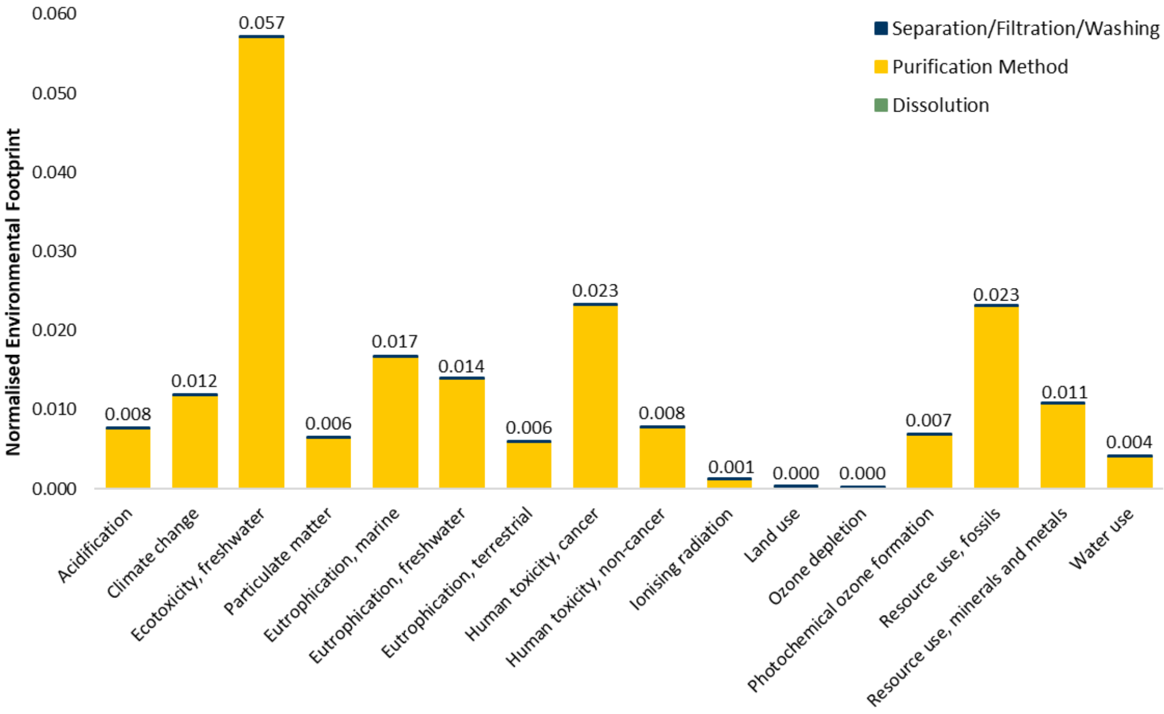

Figure 25 – EF of T4.5 processes

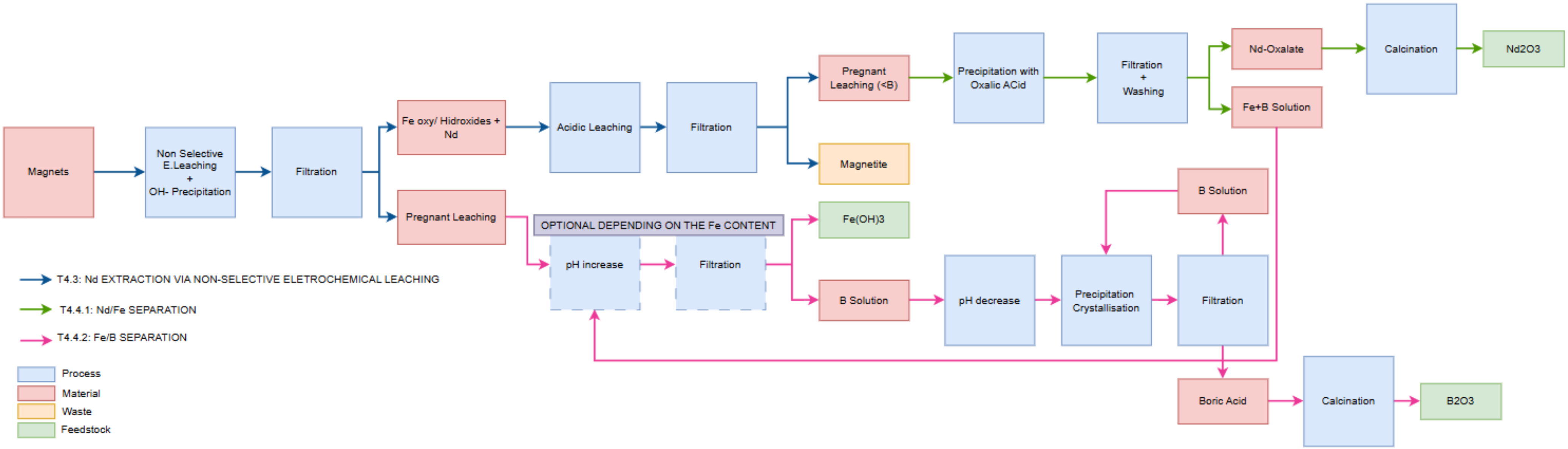

Figure 26 - Scenario 1 workflow diagram

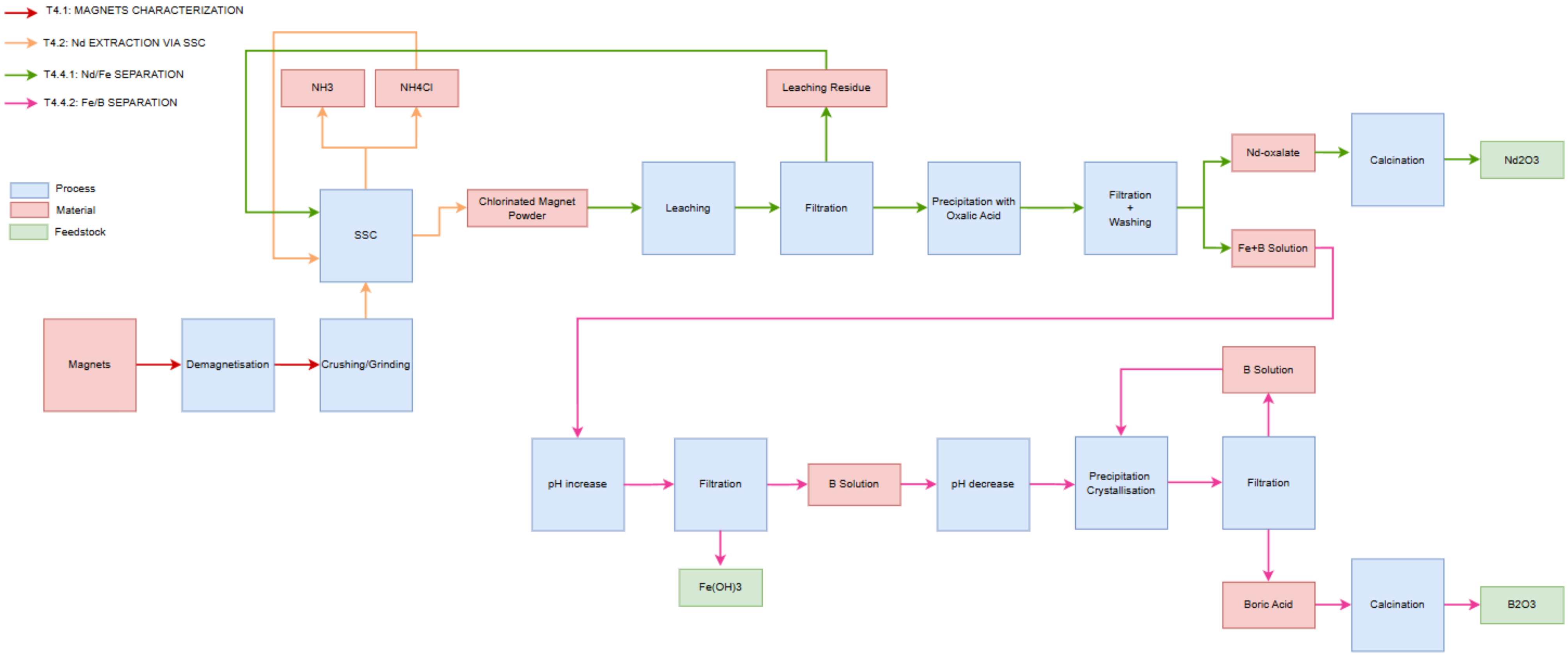

Figure 27 - Scenario 2 workflow diagram

Based on the results, illustrated in Figures 28 and 29, Scenario 1 demonstrates the lowest EF. It is important to note that these results could further improve if wastewater and chemicals are recirculated within the process and could be significantly different when applied in a larger scale.

The results are justified by the underlying process characteristics. SSC's high energy consumption directly increases its climate change, fossil resource use and ionising radiation impacts. The production of leachate contributes to freshwater eutrophication, ecotoxicity, and human toxicity indicators. Meanwhile, the electrochemical process avoids many of these burdens by operating under more controlled conditions with fewer inputs and much less energy consumption. Despite SSC's higher impacts, the possibility of recycling the generated wastewater introduces a circularity advantage. By reintegrating treated leachate back into the process, the overall EF is reduced, partially compensating results and improving resource efficiency. Additionally, these results should be interpreted cautiously, as they reflect only laboratory-scale conditions.

These findings align with conclusions found on literature, which demonstrate through comparative LCAs that environmental impacts vary significantly depending on process configuration, energy demand, and chemical inputs[57]. Similarly, the comparison between the two main upcycling of spent magnets, SSC and non-selective EL, shows that operational requirements, particularly energy use and materials consumption, are the primary drivers of the EF.

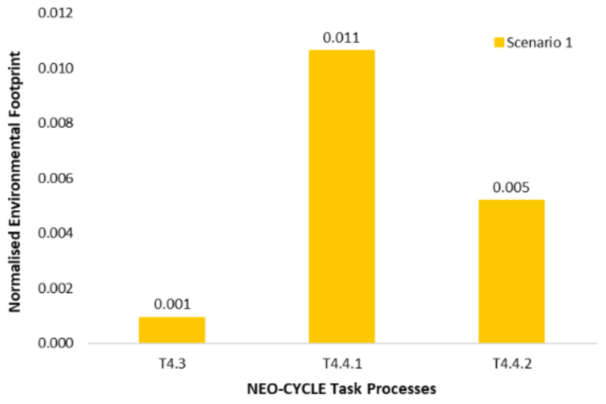

Figure 28 - Normalised EF of tasks from scenario 1

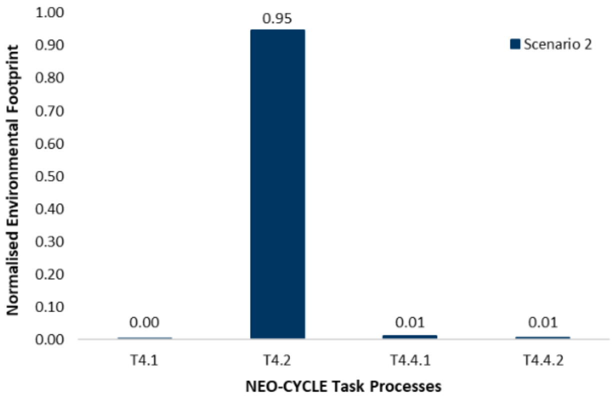

Figure 29 - Normalised EF of Tasks from Scenario 2

The normalised total EF of scenario 1 is approximately 98% smaller than the total EF of Scenario 2, but the most affected environmental impact categories are the same in both, freshwater eutrophication, resource use and ionising radiation. Both scenarios include processes

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[57] J. Marx, A. Schreiber, P. Zapp. 2018. Sustainable Chemistry & Engineering: Comparative Life Cycle Assessment of NdFeB Permanent Magnet Production from Different Rare Earth Deposits, 6 - link

that are energy-demanding and therefore consume larger amounts of resources, leading to a higher footprint in resource use.

6.3.1.2. Environmental assessment of Feedstock production

Having analysed magnets upcycling processes, studied on WP4, in chapter 6.3.1.1, the next phase was to perform a detailed environmental analysis on the whole production chain of the feedstocks. In this case, the feedstocks are secondary materials collected and obtained through the recovery processes of spent magnets, via non-selective EL and SSC.Understanding that the production of secondary materials, such as iron hydroxide ($Fe(OH)_3$), boric oxide (B_2O_3), and neodymium oxide (Nd_2O_3) is currently limited to small-scale operations, it becomes possible to identify and compare the key differences between scales and dimensions once upscaling is achieved. As the process transitions to larger production levels, additional efficiencies and challenges are likely to emerge, offering deeper insight into the overall system's performance, and consequently a better understanding of its EF.

Through the recovery processes applied in 100 g of spent NdFeB magnets, by adopting the SSC method, a total amount of 130 g of $Fe(OH)_3$ is obtained. This product, considered to be a secondary material, has a total EF of 0.188, being ionising radiation and resource use the two main impact categories affected, as illustrated in the graphic from Figure 30. This result mostly arises from the energy consumption of magnets' recycling processes.

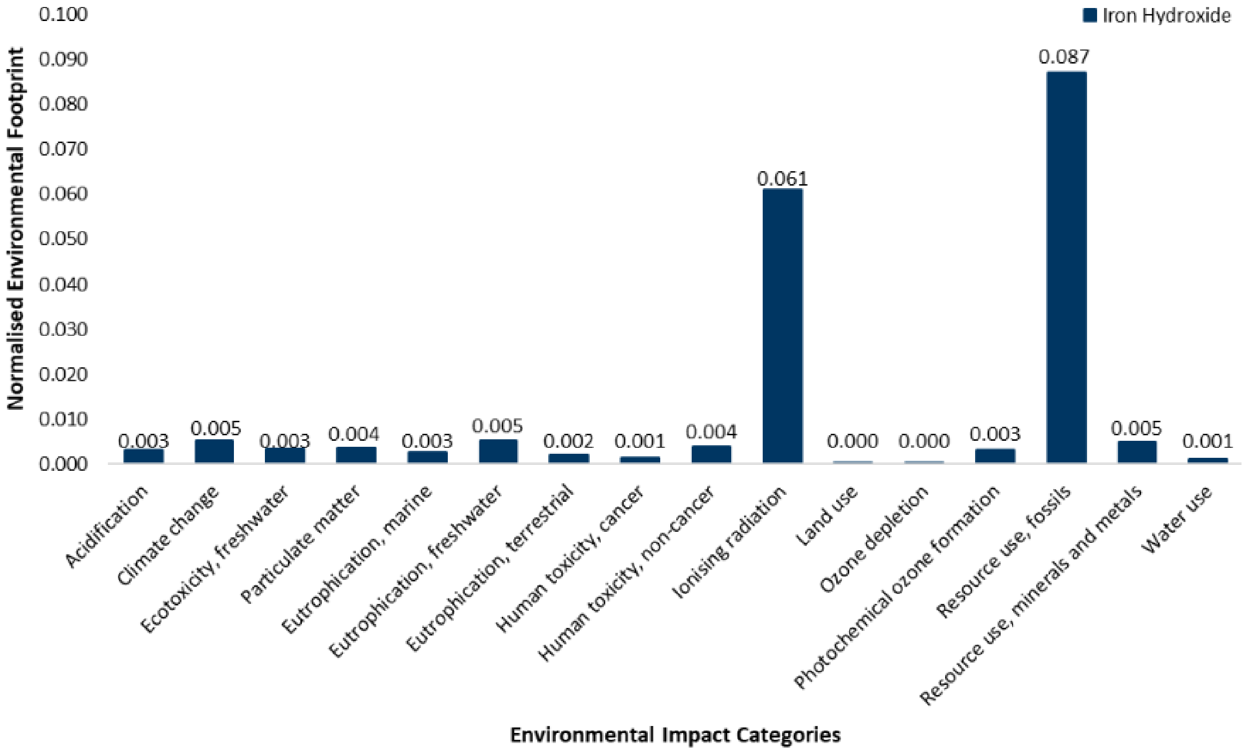

Figure 30 - Normalised EF of the manufacture of $Fe(OH)_3$ as a secondary material (SSC)

As it is known, another way to produce $Fe(OH)_3$ is through mining processes, making this product a primary or virgin raw material. The production of virgin material, which requires significant chemical inputs and large volumes of water, generates substantial water pollution[58]. As a result, it contributes notably to freshwater ecotoxicity and eutrophication, as seen in Figure 31.

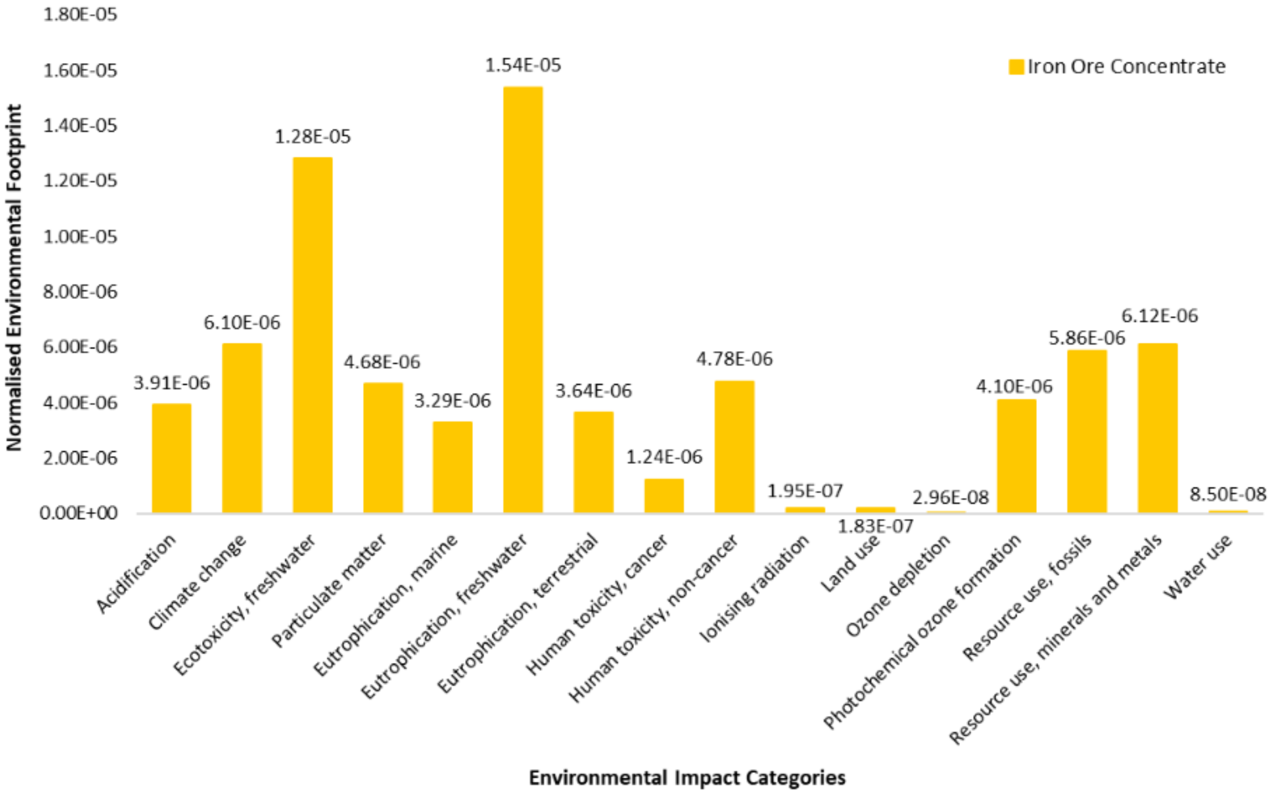

Figure 31 - EF of the manufacture of $Fe(OH)_3$ as a primary material

In addition to $Fe(OH)_3$, through the recovery processes applied in 100 g of spent magnets it is also possible to produce B_2O_3, via SSC, resulting in 0.325 g, and non-selective EL, producing 0.369 g. Results about the manufacturing of B_2O_3 through Non-selective EL and SSC, found in Figures 32 and 33 respectively, show significant differences between both routes.

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[58] Common Good Ventures**.** (n.d.). 2024. Iron and the environment: Assessing the environmental effects of iron extraction and use - link

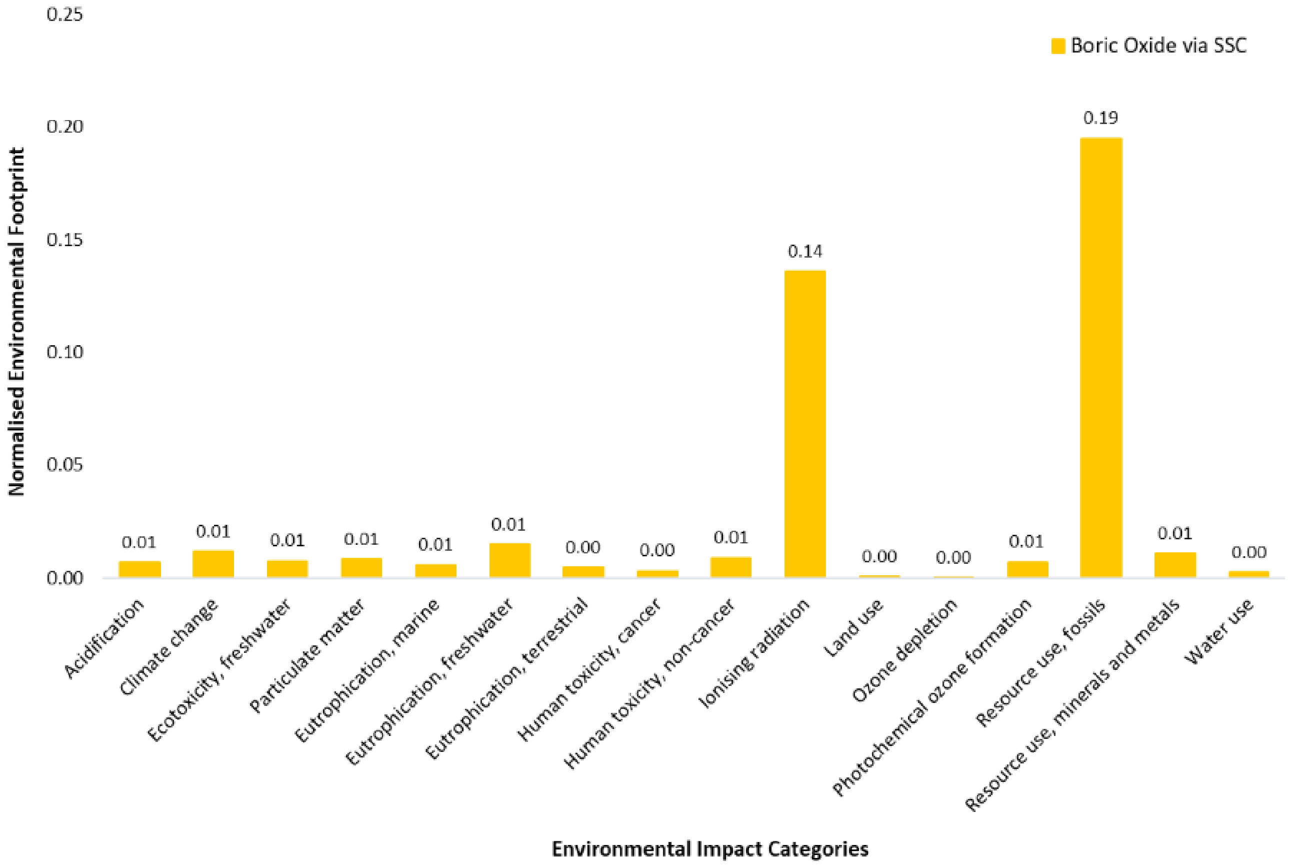
Boric Oxide via SSC
Normalised Environmental Footprint
0.25
0.20
0.15
0.10
0.05
0.00
Environmental Impact Categories
Acidification 0.01
Climate change 0.01
Ecotoxicity, freshwater 0.01
Particulate matter 0.01
Eutrophication, marine 0.01
Eutrophication, freshwater 0.01
Eutrophication, terrestrial 0.00
Human toxicity, cancer 0.00
Human toxicity, non-cancer 0.01
Ionising radiation 0.14
Land use 0.00
Ozone depletion 0.00
Photochemical ozone formation 0.01
Resource use, fossils 0.19
Resource use, minerals and metals 0.01
Water use 0.00

Figure 32 - EF of the manufacture of B_2O_3 via SSC

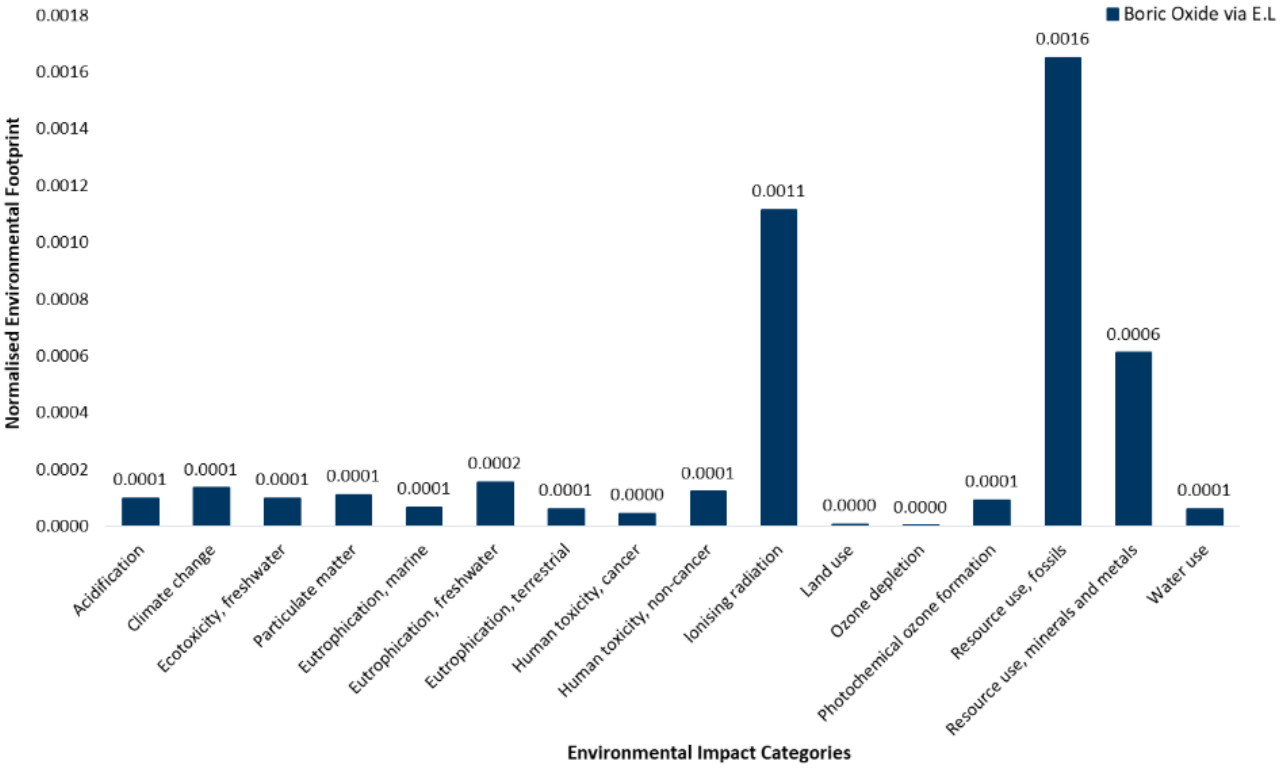

Figure 33 - EF of the manufacture of B_2O_3 via Non-selective EL

Boric oxide obtained through the WP4 activities in spent magnets via hydrometallurgical process has a total EF, 0.0044, with its main contributions arising from ionising radiation and resource use. In comparison, the EF of boric oxide produced via SSC of spent magnets, has a total value of 0.42, where the dominant impact categories are, ionising radiation, and resource use (fossils). Confirming the differences, already seen in chapter 6.3.1.1, between recovery methods, the SSC route for spent magnets is especially material and energy intensive, therefore has the highest environmental impact results.

To better comprehend the differences between the production processes of boric acid as a secondary material and as a primary or virgin material, an environmental assessment of virgin material production was also conducted.

The manufacturing processes of virgin material exhibit a very low EF with resource use (minerals and metals) identified as the most affected impact category, since they are associated with raw material extraction through mining. These results, shown in Figure 34, may be explained by differences in process maturity and energy and material consumption. The processes are mature, large-scale, and highly optimised.

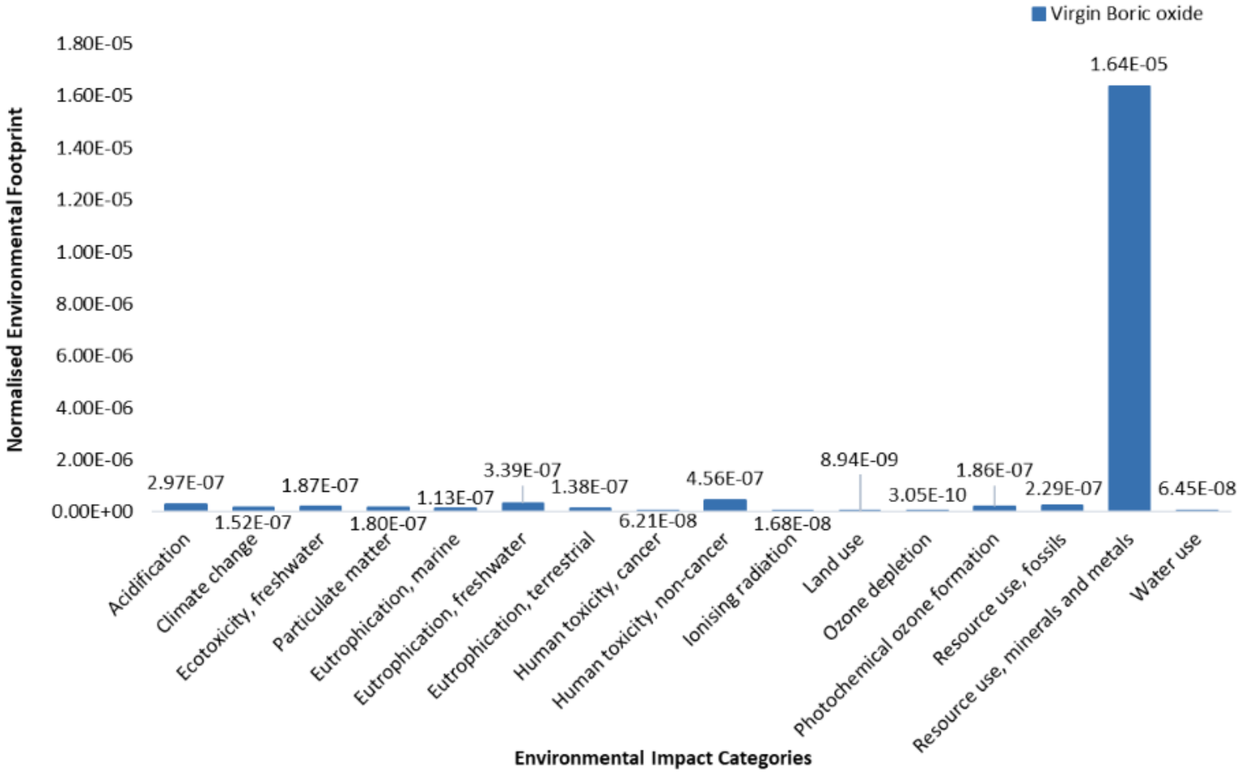

Figure 34 - EF of the manufacture of B_2O_3 as virgin material

Nonetheless, comparing the two NEO-CYCLE manufacturing routes, not considering their production scale, producing boric oxide via non-selective EL has the lowest EF. Thus, this method is considered quite promising regarding B_2O_3 production. This analysis will be further advantageous when compared to the upscaled feedstock production.

Moreover, following the separation of Nd/Fe processes after SSC, as examined in T4.4.1, approximately 29 g of Nd oxalate can be recovered. Subsequent calcination of this material yields around 13 g of neodymium oxide. The processes involved in the recovery of REE in spent magnets, culminating in the production of neodymium oxide, were evaluated, and their EF was assessed, as illustrated in Figure 35 and Figure 36.

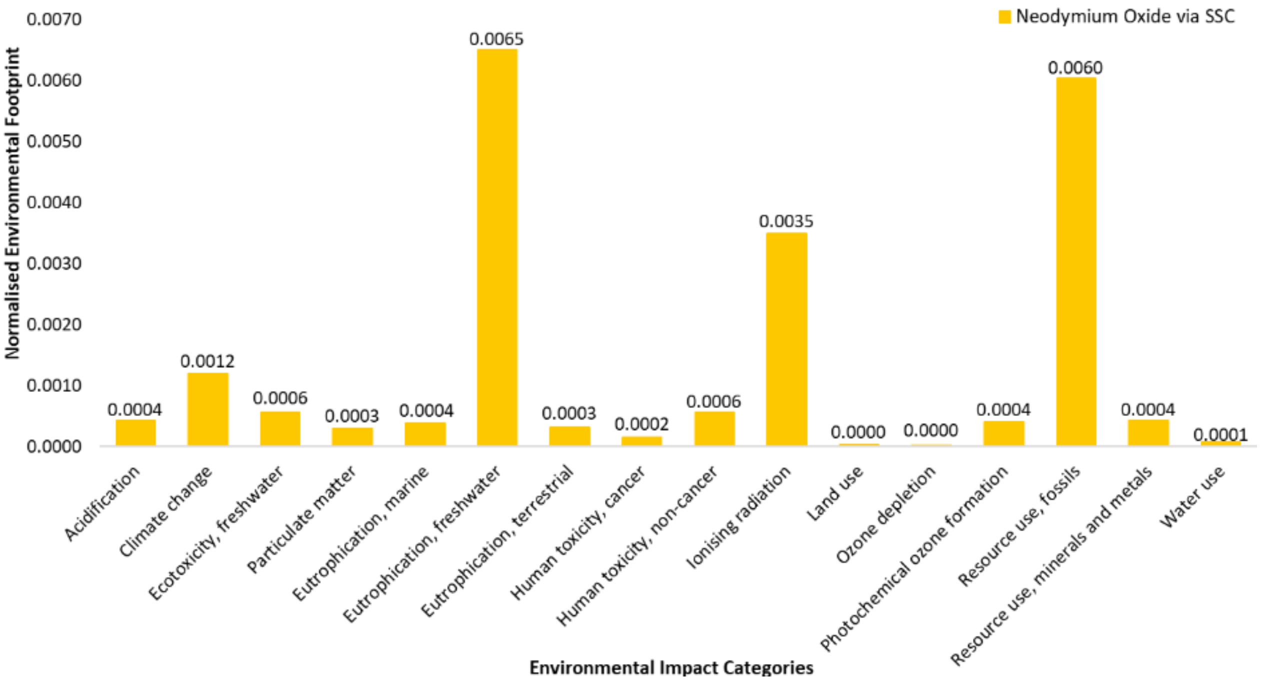

Figure 35 - EF of the manufacture of Nd_2O_3 as secondary material, via SSC

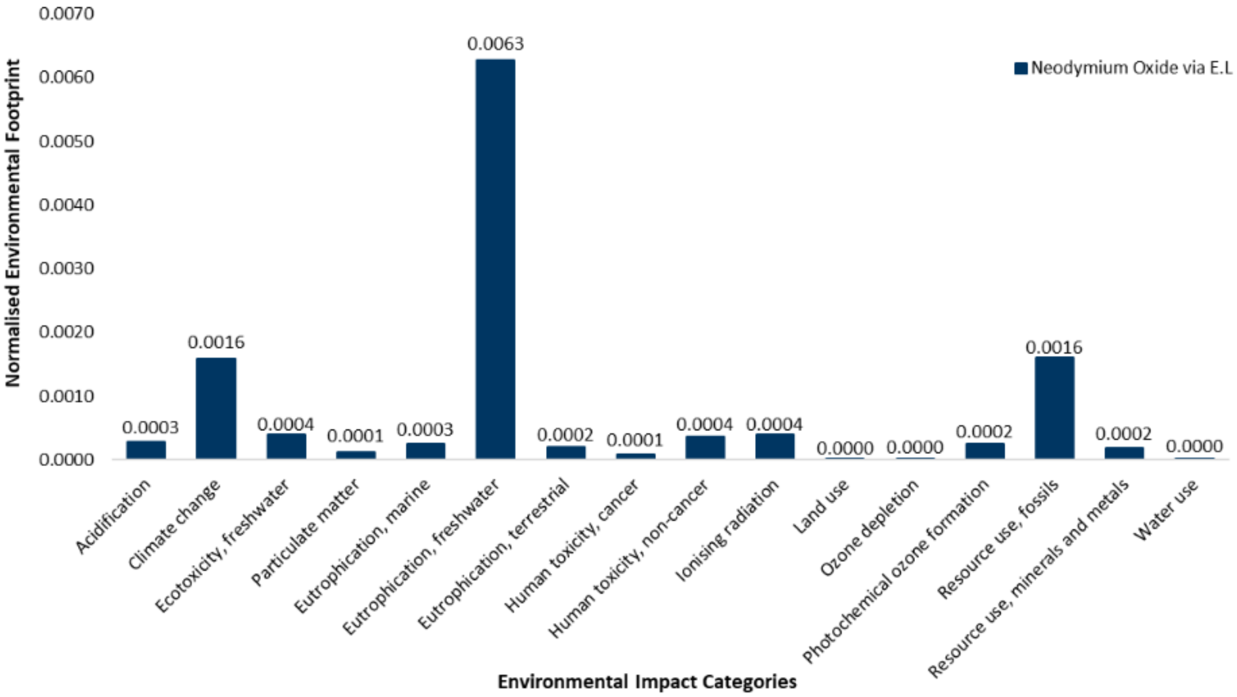

Figure 36 – EF of the manufacture of Nd_2O_3 as secondary material, via Non-Selective EL

To further evaluate the differences between producing Nd_2O_3 as a virgin material and as a secondary product, the manufacture of neodymium oxide through conventional mining and refining was established as the benchmark. Its associated EF was then quantified. The results are presented in the graphic shown in Figure 37.

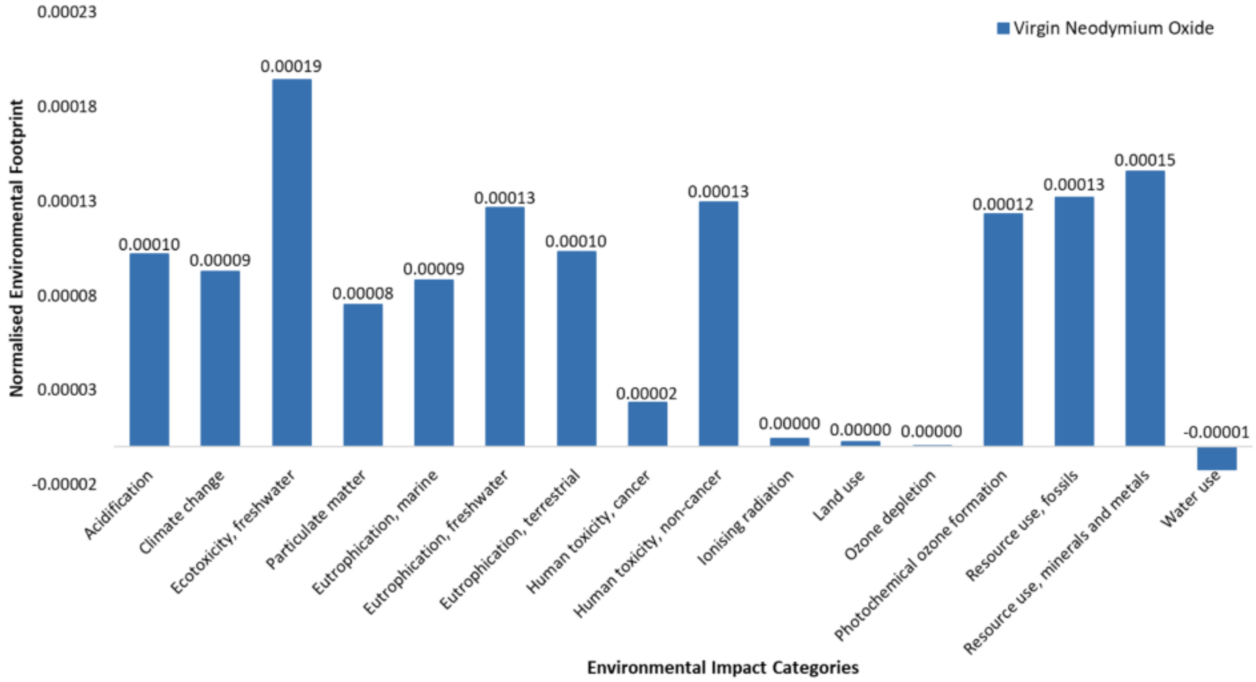

Figure 37 - EF of the manufacture of Nd_2O_3 as virgin material

The EF of the benchmark production is 0.0013. Its impact categories with the highest footprint are freshwater ecotoxicity and resource use. Mining and beneficiation of REE ores generate large volumes of waste containing not only neodymium but also other REEs, heavy metals, and radioactive elements such as thorium and uranium. These contaminants can leach into rivers and groundwater, where they accumulate and affect aquatic organisms[59].

Additionally, ores often contain only a few percent REO. Extracting usable material requires moving and processing huge quantities of rock, which increases land use, energy demand, and water consumption. LCAs of REE production consistently identify high resource intensity[60]. Moreover, processes such as solvent extraction, chloride conversion, and calcination require significant thermal and electrical energy, increasing overall resource use.

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[59] Revel, M., van Drimmelen, C. K. E., Weltje, L., Hursthouse, A., & Heise, S. 2025. Effects of rare earth elements in the aquatic environment: Implications for ecotoxicological testing. Critical Reviews in Environmental Science and Technology, 55(5), 334–375. – (link)

[60] Zapp, P., Schreiber, A., Marx, J., & Kuckshinrichs, W. 2022. Environmental impacts of rare earth production. MRS Energy & Sustainability, 9, 215–229 - (link)

It is entirely expected that the NEO-CYCLE process, vias SSC and non-selective EL, show a higher EF than the benchmark, 0.021 and 0.012, respectively. The results are explained since NEO-CYCLE WP4 processes are operated at laboratory-scale, where processes are inherently less efficient and require more energy, chemicals, and manual steps per unit of product. Laboratory-scale systems lack the economies of scale, heat recovery, optimised solvent extraction circuits, and integrated process flows that characterise mature industrial mining and refining operations. Therefore, as previously mentioned, the main contributor for the EF of the production of feedstock is the amount of electricity consumed. Along with the use of other raw materials or chemicals, it affects mostly freshwater eutrophication, resource use, and ionising radiation.

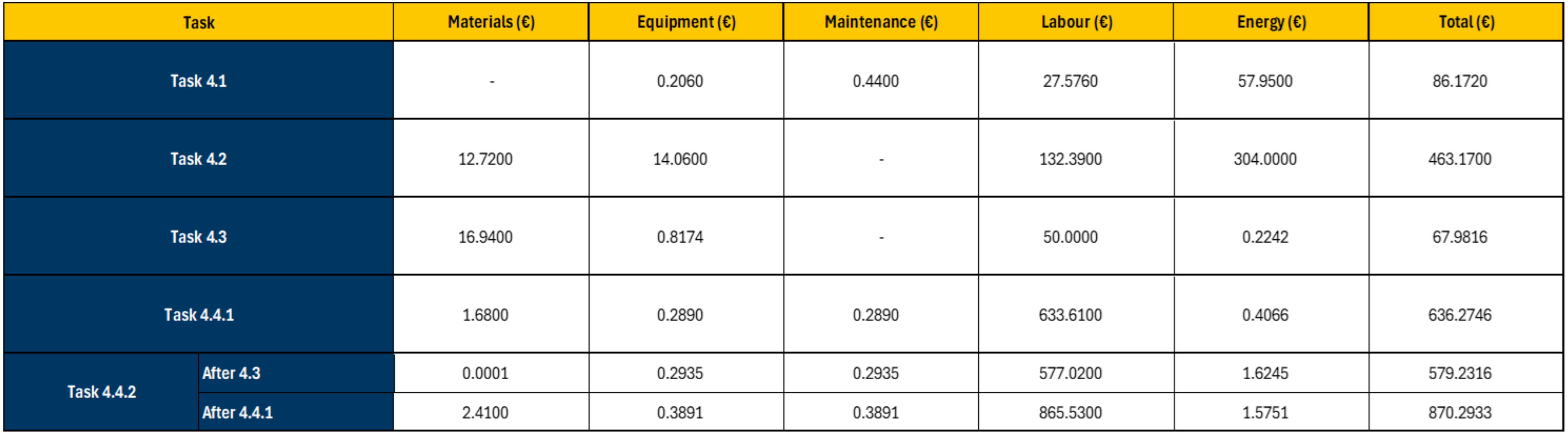
6.3.2. LCC

Following the collection of economic data through the LCIs, the provided cost information was used to carry out a preliminary economic analysis and identify the main cost-driving activities. Calculations were carried out in accordance with the predefined and validated FU and adjustments were made when necessary to ensure full alignment with the FU requirements.

6.3.2.1. Economic assessment of task processes

Table 5 shows the results of the calculations related to the costs of the processes carried out in each of the tasks.

Table 5 - Cost assessment of each of the tasks. Costs are calculated in respect to the FU: 100g of NdFeB magnets Values correspond exclusively to the processes related to each task.

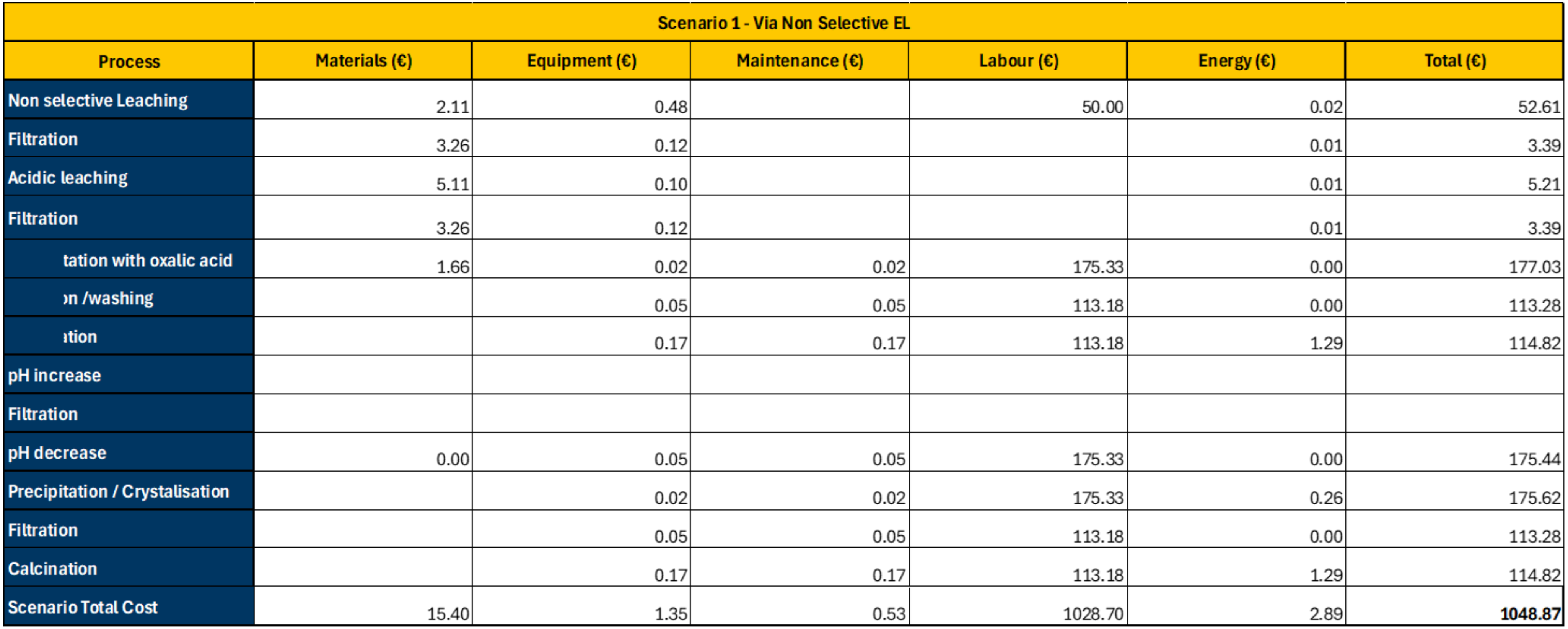


Task		Materials (€)	Equipment (€)	Maintenance (€)	Labour (€)	Energy (€)	Total (€)
Task 4.1		-	0.2060	0.4400	27.5760	57.9500	86.1720
Task 4.2		12.7200	14.0600	-	132.3900	304.0000	463.1700
Task 4.3		16.9400	0.8174	-	50.0000	0.2242	67.9816
Task 4.4.1		1.6800	0.2890	0.2890	633.6100	0.4066	636.2746
Task 4.4.2	After 4.3	0.0001	0.2935	0.2935	577.0200	1.6245	579.2316
	After 4.4.1	2.4100	0.3891	0.3891	865.5300	1.5751	870.2933

For T4.1, the cost structure is clearly energy-dominated, with approximately 67% of total expenditure arising from energy consumption. Labour also represents a significant share of the costs, while equipment depreciation and maintenance contribute only marginally. When analysing T4.2, energy consumption again emerges as the main cost driver, with specialised labour also representing a substantial portion of the total cost. T4.3 is not capital-intensive; instead, its economic profile is largely driven by operational effort rather than equipment-related expenses. The results of T4.4.1 show that the process is overwhelmingly dominated by labour costs, which account for more than 99% of total expenditure. The cost analysis of both pathways in T4.4.2 leads to the same conclusion, with labour representing a similarly high percentage of the overall costs. These preliminary costs show that the early-stage processes are predominantly dominated by labour, which is expected at this phase of the project, when most activities are still being optimised. In addition, because the work is carried out in specialised laboratories, the professionals involved have higher qualifications and therefore represent a higher cost. Across all tasks, material costs remain comparatively low, while equipment and maintenance expenses contribute only marginally to the overall cost structure.

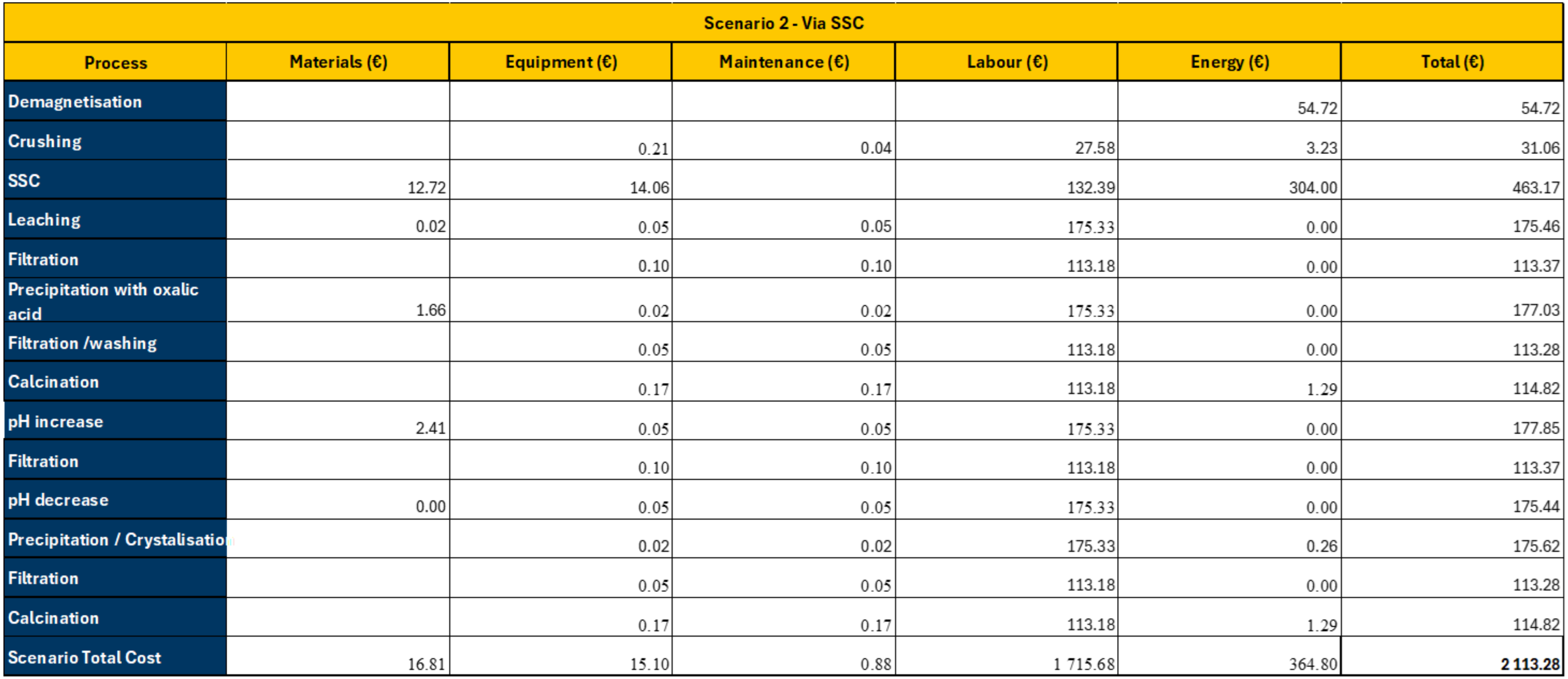
To evaluate the most economically sustainable pathway for recovering Nd, Fe and B from spent magnets, the costs of the scenarios previously defined in Chapter 6.3.1.1 (Figures 26 and 27) were also analysed. The corresponding cost breakdowns for these scenarios are presented in Tables 6 and 7, providing a basis for comparison and supporting the identification of the most cost-effective recovery route.

Table 6 - Costs related to feedstock recovery via Non-Selective EL



Scenario 1 - Via Non Selective EL						
Process	**Materials (€)**	**Equipment (€)**	**Maintenance (€)**	**Labour (€)**	**Energy (€)**	**Total (€)**
Non selective Leaching	2.11	0.48		50.00	0.02	52.61
Filtration	3.26	0.12			0.01	3.39
Acidic leaching	5.11	0.10			0.01	5.21
Filtration	3.26	0.12			0.01	3.39
tation with oxalic acid	1.66	0.02	0.02	175.33	0.00	177.03
on /washing		0.05	0.05	113.18	0.00	113.28
ation		0.17	0.17	113.18	1.29	114.82
pH increase						
Filtration						
pH decrease	0.00	0.05	0.05	175.33	0.00	175.44
Precipitation / Crystalisation		0.02	0.02	175.33	0.26	175.62
Filtration		0.05	0.05	113.18	0.00	113.28
Calcination		0.17	0.17	113.18	1.29	114.82
Scenario Total Cost	15.40	1.35	0.53	1028.70	2.89	**1048.87**

Table 7 - Costs related to feedstock recovery via SSC



Scenario 2 - Via SSC						
Process	**Materials (€)**	**Equipment (€)**	**Maintenance (€)**	**Labour (€)**	**Energy (€)**	**Total (€)**
Demagnetisation					54.72	54.72
Crushing		0.21	0.04	27.58	3.23	31.06
SSC	12.72	14.06		132.39	304.00	463.17
Leaching	0.02	0.05	0.05	175.33	0.00	175.46
Filtration		0.10	0.10	113.18	0.00	113.37
Precipitation with oxalic acid	1.66	0.02	0.02	175.33	0.00	177.03
Filtration /washing		0.05	0.05	113.18	0.00	113.28
Calcination		0.17	0.17	113.18	1.29	114.82
pH increase	2.41	0.05	0.05	175.33	0.00	177.85
Filtration		0.10	0.10	113.18	0.00	113.37
pH decrease	0.00	0.05	0.05	175.33	0.00	175.44
Precipitation / Crystalisatio		0.02	0.02	175.33	0.26	175.62
Filtration		0.05	0.05	113.18	0.00	113.28
Calcination		0.17	0.17	113.18	1.29	114.82
Scenario Total Cost	16.81	15.10	0.88	1 715.68	364.80	**2 113.28**

For Scenario 1, the total cost is 1048.87 €. From 100 g of spent magnets, 13 g of Nd_2O_3 and 0.369 g of B_2O_3 are recovered. No data are available for $Fe(OH)_3$, since the Fe pathway is optional in this scenario. For Scenario 2, the total cost is 2113.27 €. From the same 100 g of magnets, 13 g of Nd_2O_3, 0.325 g of B_2O_3 and 130 g of $Fe(OH)_3$ are recovered.

To identify the most favourable scenario, the output of Nd should be the primary focus of the comparison, as it is the most valuable element and the one with highest strategic relevance for Europe. Nd is the key driver of the economic viability of these processes, and previous studies consistently highlight the recycling and upcycling of REEs from NdFeB magnets as a crucial end-of-life flow. These studies emphasise Nd as the main target due to its criticality and high supply-risk, reinforcing its importance in shaping sustainable and resilient recovery pathways[61]. Additionally, the recycling and upcycling routes for REEs are being studied to preserve their value or enhance it through processes that maximise material recovery and quality, like chemical and hydrometallurgical processes[62].

Since Nd is the most valuable output and both scenarios recover the same amount, Scenario 1, which relies on Non-selective EL, emerges, at this stage of the project, as the most economically sustainable pathway for recovering this element.

Scenario 1 is 50.37% cheaper than Scenario 2 overall. The largest differences arise from labour costs, which are 40% lower in Scenario 1, and from energy consumption, where Scenario 1 is 99% cheaper. Although less influential in the final cost distribution, it is also noticeable that equipment-related costs are considerably higher in Scenario 2, likely due to the specificity and technical requirements of the equipment used.

Due to its low market price, the recovered quantity of $Fe(OH)_3$ is not sufficient to make Scenario 2 economically more favourable than Scenario 1. Moreover, Scenario 1 includes an optional step that can also recover Fe, further reducing any potential economic advantage that Scenario 2 might otherwise present.

6.3.2.2. Economic assessment of feedstocks

To follow the comparison made in the LCA between the recovered feedstocks in NEO-CYCLE and the cost of purchasing them from mining activities, the production cost of each feedstock was calculated. At this stage of the project, this allows assessing how much it would cost to recover each element individually. The flows considered include only the activities required to obtain each individual element, providing an indication of how much it would cost if the aim were to recover only one specific material. These calculations follow the process

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[61] Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., & Rydberg, T. 2011. Life cycle assessment: Past, present, and future. Journal of Cleaner Production, 19 - Link

[62] Kumar, A., & Singh, R. K. 2025. A systematic review of life cycle sustainability assessment (LCSA) methods and applications. Sustainable Futures, 17 - Link

flows previously defined in Section 6.3.1.2. Table 8 presents the summarised prices of both pathways, NEO-CYCLE processes and market price.

Table 8 - Costs of producing the same quantity of feedstock via NEO-CYCLE processes compared with purchasing it on the market (from mining operations)

Feedstock	NEO-CYCLE (€/g)	Market (€/g)
Nd_2O_3	Via SSC – 95.60	0.081[63]
	Via non-selective EL – 36.132	
B_2O_3	Via SSC – 6143.14	0.00046[64]
	Via non-selective EL – 1721.26	
$Fe(OH)_3$	Via SSC – 10.91	0.00167[65]

Results show a significant disparity between the cost of recovering feedstocks in NEO-CYCLE and the prices at which these materials are available on the market after mining, with market prices being considerably lower. This outcome is consistent with the fact that the activities in WP4 are mostly carried out at laboratory scale. At this stage, the cost per gram is inflated by the low quantities of material recovered, the underutilisation of equipment, and the nature of the operations, which require specialised labour in these early phases.

The LCC literature reports similar challenges in low-TRL technologies, indicating that economic results at this stage must be interpreted with caution before considering scale-up[66].

As it stands, the recovery of REEs is not economically competitive with current market prices. This aligns with previous studies, which have shown that the treatment of REE magnets faces significant economic barriers, typically linked to scale limitations, low productivity, limited automation, product-quality constraints and insufficient integration within the value chain[67].

Despite the cost discrepancies, the relevance of recovering REEs in NEO-CYCLE extends far beyond short-term economic value. It lies in establishing a secondary European source of Nd, B and Fe, strengthening regional availability of these critical materials. By doing so,

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[63] Shanghai Metals Market. 2026. Neodymium oxide: Price of rare earth oxides per ton today. Accessed on 28th of January 2026 - link

[64] U.S. Geological Survey. 2025. Mineral commodity summaries 2025. U.S. Department of the interior - link

[65] Trading Economic. 2026. Iron ore. Accessed on 28th of January 2026 - link

[66] Pérez-López, P., & Feijoo, G. 2024. Life cycle assessment and circularity: Synergies, challenges and future research needs. Environmental Impact Assessment Review, 104 - link

[67] Al-Qahtani, H. M., Al-Shetwi, A. Q., & Al-Mutairi, N. 2024. Life cycle assessment of renewable energy systems: A comprehensive review of methods, challenges, and future directions. Energy Reports, 12 - link

these processes help reduce the current extreme dependence on external suppliers, fully aligning with EU priorities on critical raw materials[68] and circularity[69].

6.3.3. s-LCA

The interpretation of the s-LCA results in D9.1 should consider that social impacts and risks depend not only on the operational performance of a process, but also on the characteristics of the value chain in which it is embedded. Highly geographically concentrated chains, such as the REE magnet value chain, also concentrate economic power, influence and exposure to risks, creating asymmetries between those who bear the risks and those who benefit from the generated value. This is further reinforced by previous studies[52], which note that the absence of circular options in value-chain assessments reflects the current state of knowledge and data availability in s-LCA. Addressing this gap would enable future assessments to evaluate whether circular approaches can mitigate or shift social risks associated with highly concentrated primary supply chains, thereby supporting more comprehensive sustainability and industrial policies.

With this in mind, and using the scoring systems presented in Section 5.3.5, the average social risks for WP4 were calculated. These results are illustrated in Figure 38.

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[68] European Commission. 2023. Critical Raw Materials Act - link

[69] European Commission. 2024. Circular Economy Strategy - link

Table 9 - Social risks within the WP4 value chain

	Subcategories							Average social score	Social risk level
Stakeholder category	**Health & Safety**	**Child labour**	**Forced labour**	**Fair Salary**		**Category score**	**Risk Level**	0,081944444	Medium risk
Workers	1	2	2	0,333333333		1,333333333	Low risk		
	Public commitment to sustainability issues	**Contribution to economic development**	**Prevention and mitigation of conflicts**	**Corruption**	**Technology development**	**Category score**	**Risk Level**		
Society	-1,333333333	-2	0,333333333	0,666666667	-0,333333333	-0,533333333	High risk		
	Fair competion	**Supplier relationship**	**Respect of intellectual property**			**Category score**	**Risk Level**		
Value Chain Actors	-0,666666667	-0,333333333	0,333333333			-0,222222222	Medium risk		
	Access to material resources	**Delocalization and migration**	**Safe and healthy living conditions**	**Local employment**		**Category score**	**Risk Level**		
Local Community	-0,333333333	-0,333333333	0,333333333	-0,666666667		-0,25	Medium risk		

From this figure it is possible to see that, overall, the average score of the project is approximately 0, which means that there is a medium social risk. This result is obtained by considering the four selected stakeholder categories. The Workers category shows the best performance, indicating low risk, while Society emerges as the main social hotspot, presenting a high level of risk. Both Value chain actors and Local community show medium risk. These results are coherent with the selection of the categories done by the partners.

The Worker category, which is highlighted in previous relevant studies as one of the most important categories to consider[70], does not pose a significant risk at this stage of the process. This is plausible because the project is European-based, where legal and institutional requirements mitigate risks related to child and forced labour[71]. The lower results in fair salary reflect a higher uncertainty in the data provided, due to the fact that some of the partners who answered are laboratories, which tend to be more disconnected from financial departments[72]. Finally, results in health and safety also reflect a tendency of good practices across European actors, these results are worsened by a general lack of security and safety training, that should be more than 12h per year, per worker[73].

The Society category presents the highest risk in the assessment, with a score close to - 1. This result is driven by the low scores in the subcategories Public Commitment to Sustainability Issues and Contribution to Economic Development. These outcomes reflect the profile of the entities that answered the questionnaire‒either laboratories from research centres and universities or industries that have not yet formalised the sustainability or economic benefits of their innovations. This is particularly expected given the low TRL stage of NEO-CYCLE. Nonetheless, these aspects will receive greater attention through the developed LCSA, which will help highlight sustainability and economic considerations.

Value chain actors' results are of higher risk due to the lack of answers in this section of the questionnaire, that count as 0% compliance. Previous studies have already identified this category as critical when analysing REE magnet value chains[74]. Again, the nature of the entities that answered the questionnaire also come into play, as labs and research teams are usually more disconnected from value chain practices.

For the Local Community category, which presents a medium level of risk, the results can be explained by the fact that research teams often hire people from outside their local areas[75]. This effect is counterbalanced by industries, which typically recruit employees from nearby

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[70] Zampori, L., & Sala, S. 2017. Feasibility of product environmental footprint implementation in the European Union. Journal of Industrial Ecology, 21 - link

[71] European Commission. 2024. Corporate sustainability due diligence - link

[72] Applied Clinical Trials. 2024. Life sciences: Fragmented data, disconnected teams - link

[73] European Agency for Safety and Health at Work. 2023. OSH in Europe: State and trends 2023 - Link

[74] Suh, S., & Yang, Y. 2020. On the uncanny capabilities of consequential life cycle assessment. Current Opinion in Environmental Science & Health, 13 - Link

[75] The Royal Society. 2017. International mobility of researchers: A review of the literature - Link

locations[76]. When scaling up the process, and as more actors in the value chain become industrial partners, these results will likely change, posing lower risks to local communities.

To expand the meaning of these results, they can be compared to existing knowledge on the social impacts of mining REE. This mining activity can be used as a benchmark for comparison with the processes of WP4, much like in the LCA analysis.

The Worker category usually presents a high risk in social analyses of mining activities. This is because workers, specifically miners, often face precarious conditions and a lack of adequate safety measures[77]. Fair salary is also considered a high-risk aspect, since many mining operations are informal or illegal and therefore poorly documented, particularly outside Europe[78]. When analysing the Society category, it is possible to observe a high level of risk across several subcategories[79]. The finite nature of REE increases competition for resource exploitation, which can lead to conflicts and corruption. Recent geopolitical developments further reinforce this concern[80].

In the Value Chain Actors category, fair competition appears to be the most affected subcategory[81]. This is due to the limited availability of these resources, which creates a strong dependency on a small number of markets that can influence or dictate conditions. For that, it can also pose high societal risk[82]. In the Local Community category, REE mining can directly affect communities by creating job opportunities but also by generating environmental and social conflicts[83]. Moreover, mining activities can restrict access to material resources by destroying or polluting them. These impacts, alongside land acquisition, can ultimately lead to forced migration[84]. Based on this analysis, it is evident that this category can also present a high level of risk. Moreover, the mining industry is typically male dominated. Although not analysed in depth here, by including gender considerations, like it is the case of NEO-CYCLE, this social discrepancy will also be addressed. Despite being in the early stages of the project, the activities of NEO-CYCLE can contribute to reducing the social risks associated with mining REE. This becomes evident when comparing the preliminary s-LCA results with the qualitative social impacts of REE mining reported in the literature.

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[76] Organisation for Economic Co-operation and Development. 2024. Job creation and local economic development 2024. OECD Publishing - Link

[77] Huang, Y., Li, Y., Wang, X., & Zhang, L. 2024. Global research trends in life cycle assessment: A bibliometric and visual analysis. BMJ Open, 14 - Link

[78] PBL Netherlands Environmental Assessment Agency. 2023. Social impacts of mining critical raw materials - Link

[79] Zhang, Y., Li, X., Wang, L., & Chen, H. 2023. Life cycle assessment of critical raw materials: A systematic review of methods and applications. Sustainability, 17 - Link

[80] Zhang, X., Li, M., & Chen, Y. 2025. Critical raw materials and the energy transition: A global assessment of supply risks and sustainability challenges. Energy Research & Social Science, 109 - Link

[81] Werker, J., Wulf, C., Zapp, P., Schreiber, A., & Marx, J. 2019. Social LCA for rare earth NdFeB permanent magnets. Sustainable Production and Consumption, 20 - Link

[82] University of Cambridge. 2024. Resilience of Critical Minerals Supply Chains - Link

[83] Tercero-Espinoza, L., & Soulier, M. 2014. Material flow analysis and resource policy: A case study on critical raw materials. Resources, 3 - Link

[84] Li, J., Wang, S., & Zhao, H. 2023. Life cycle sustainability assessment of critical raw materials: A comprehensive review of methods and indicators. Sustainability, 17 - Link

6.4. Recommendations

This section aims to propose measures to improve the results of the analysis across the three sustainability dimensions. These recommendations should be considered when scaling up the processes and when upcycling the obtained feedstocks. By applying them, the project should, in theory, be guided towards a more sustainable pathway.

- Environmental Recommendations

The laboratory-scale assessment of the NEO-CYCLE upcycling processes for spent magnets shows that certain steps are particularly energy intensive, while others contribute significantly to environmental burdens through the consumption of raw materials such as oxalic acid. Overall, the dominant environmental impacts are associated with resource use, freshwater eutrophication, and ecotoxicity. Because energy-related impacts vary considerably between countries due to differences in electricity mixes, the results highlight the importance of integrating renewable energy sources to achieve cleaner and more sustainable upcycling pathways[85]. Waste generation and its subsequent treatment also play a relevant role in shaping the EF.

Having a more detailed examination of the full production chain for feedstocks derived from the upcycling processes shows that the two manufacturing routes, SSC and non-selective EL, exhibit similar environmental impact profiles, although with distinct magnitudes. Their main contributions arise from freshwater eutrophication, ionising radiation, and resource use. These impacts stem largely from the energy-intensive nature of the processes, the need for specific material inputs, and the generation of wastewater or other waste material[86].

When comparing the production of secondary feedstocks from spent magnets, developed in NEO-CYCLE, with the equivalent production chain based on ore concentrates, the former shows a higher EF. This difference is expected, as the NEO-CYCLE processes are assessed at an experimental scale, whereas primary production routes for virgin materials are already optimised and operate at industrial scale. Uncertainties related to the origin of REEs may also influence the comparative results. Nonetheless, its EF is predicted to be similar to the one obtained for virgin materials, defined as benchmarks.

Key opportunities for reducing environmental impacts include improving energy efficiency, enhancing wastewater recovery and treatment, and increasing the use of recycled materials as process inputs[87]. Additionally, recirculating both wastewater and critical reagents within the upcycling chain could substantially reduce the overall environmental burden. Finally, this type of assessment should serve not only to identify the most sustainable upcycling route for spent magnets but also as a benchmark for evaluating the upscaled processes. It provides a

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[85] REN21. 2024. Why is renewable energy important - Link
[86] United Nations Economic Commission for Europe. 2021. Life cycle assessment of electricity generation options - Link
[87] Sovacool, B. K. 2019. *Toxic transitions in the lifecycle externalities of energy systems*. Environmental Research Letters - Link

framework for how emerging technologies should be environmentally assessed and optimised, supporting their evolution toward more sustainable and resource-efficient solutions[88].

- Economic Recomendations

The economic hotspots identified are likely a consequence of the laboratory-scale conditions under which the processes were analysed, and these cost intensities will probably be reduced once the system is scaled up. Nonetheless, several measures can be proposed to decrease process costs. First, manual operations should be prioritised for automation and mechanisation. In the extraction of magnets from HDDs, both the removal and disassembly steps represent economic challenges that could be mitigated by studying the automation of these operations. Increasing automation would improve process speed and consistency, while also reducing labour intensity[89].

To improve the cost-effectiveness of the processes, it is also necessary to increase throughput and the effective hours of operation, meaning more material processed per batch. Routes that rely on more expensive equipment, such as SSC, would particularly benefit from this, as higher production volumes would dilute equipment-related costs across a larger output[90]. Another way to reduce process costs is to combine, whenever possible, two or more stages, for example, precipitation and filtration − into a single operation[91].To reduce energy costs, a common recommendation is to use more efficient equipment, which becomes particularly important during long heating or cooling stages. Additionally, whenever possible, recovering or recirculating heat would further decrease energy consumption costs.

As a transversal recommendation, implementing a routine of sensitivity-based LCC analysis, even at laboratory scale, could help reduce costs by identifying activities or cost drivers that can be optimised early on.

Finally, it is important to note that the overall cost of these processes will be further diluted not only through scale-up, but also when the life-cycle boundaries are expanded to include the upcycling activities of the recovered elements, which will add substantial value to the project.

- Social Recommendations

In order to improve the s-LCA results, the main priority should be to repeat the questionnaire and promote information exchange between departments, ensuring the missing information

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[88] Van Nielen, S., Miranda Xicotencatl, B., Tukker, A., & Kleijn, R. 2024. Ex-ante LCA of magnet recycling: Progressing towards sustainable industrial-scale technology. Journal of Cleaner Production - Link

[89] Burkhardt, C., Ortiz, F., Daoud, K., Björnfot, T., Ahrentorp, F., Blomgren, J., & Walton, A. 2024. Automated high-speed approaches for the extraction of permanent magnets from hard-disk drive components for the circular economy. Magnetism, 4 - Link

[90] Zhang, Y., Li, H., & Xu, Z. 2024. Life cycle sustainability assessment of critical raw materials in emerging energy technologies. Journal of Cleaner Production, 445 - Link

[91] Sprecher, B., & Kleijn, R. 2025. Critical raw materials and the circular economy: Emerging trends in global supply, demand, and policy. Journal of Industrial Ecology, 2 - Link

is collected and incorporated into the analysis. This would improve the overall scores and provide more meaningful insights for the social assessment, allowing the focus to shift toward real risks instead of uncertainties created by incomplete or unavailable information.

The worker category showed the best results, although there is still room for improvement. Regarding fair salary, proxies and estimations could be used to avoid missing or incomplete answers. When the process is scaled up or industrialised, industries should consider the living wage of employees in each specific country, while also accounting for their role and specialisation within the overall process[92]. Regarding Health & Safety, the social risk can decrease if occupational health and safety management systems are established (like ISO 45001). This should be accompanied by employee training and education about the implemented processes, improving awareness, safety and compliance with norms[93].

To decrease the social risk in the Society category, two key subcategories must be addressed. The public commitment to sustainability, can be strengthened through clearer metrics and more transparent decision-making processes. LCA results can support the definition of public policies and Key Performance Indicators (KPIs), transforming environmental commitment into verifiable compliance that entities can later report through specialised Environmental, Social, and Governance (ESG) or sustainability reports[94]. The contribution to economic development subcategory can be improved by using the LCC and TEA results to define a plan for regional/local value creation, thus decreasing the risk[95].

Despite being affected by the lack of answers, there are actions that can help the Value Chain Actors category reduce its social risk by improving transparency and strengthening information flows across the system[96]. Applying traceability tools and data-sharing practices throughout the value chain can mitigate this risk, and the Digital Product Passport developed in NEO-CYCLE will provide significant support for this purpose[97]. Supplier relationships and clear codes of conduct should also be implemented to ensure consistent data transfer and reliable information exchange among the different actors involved[98].

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[92] Bovea, M. D., Ibáñez-Forés, V., Pérez-Belis, V., & Quemades-Beltrán, P. 2018. Environmental impact of the end-of-life management of electric and electronic toys. Journal of Cleaner Production, 172 - Link

[93] Podrecca, M., Molinaro, M., Sartor, M., & Orzes, G. 2024. The impact of ISO 45001 on firms' performance: An empirical analysis. Corporate Social Responsibility and Environmental Management, 31 - Link

[94] Kumar, A., & Singh, R. 2023. Sustainability assessment of critical raw materials using integrated life-cycle approaches. Cogent Engineering, 10 - Link

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[96] Gardner, T. A., Benzie, M., Börner, J., Dawkins, E., Fick, S., et al. 2018. Transparency and sustainability in global commodity supply chains. World Development, 121 - Link

[97] Zhang, A., & Seuring, S. 2024. Digital product passport for sustainable and circular supply chain management: A structured review of use cases. International Journal of Logistics Research and Applications, 27 - Link

[98] Vandenbroucke, S. E. M. 2023. The portrayal of effectiveness of supplier codes of conduct in improving labor conditions in global supply chains: A systematic review of the literature. Regulation & Governance, 18 - Link

Finally, to decrease the social risk in the local community, community development agreements can be established to strengthen the relationship between industries and local populations and promote more inclusive long-term collaboration[99]. Furthermore, implementing mechanisms for complaint management and damage remediation can reduce the social risk associated with NEO-CYCLE processes by ensuring accountability, improving transparency, and addressing community concerns effectively[100].

7. Conclusion

D9.1 serves as a preliminary report of the sustainability results from the activities carried out during the first 18 months of NEO-CYCLE, with a particular focus on the processes developed in WP4. It is the direct output of T9.1 and T9.2. The document highlights the strategic relevance of REEs, the European dependence on foreign markets, and the role that upcycling NdFeB magnets from HDDs can play in strengthening circularity and supply-chain resilience.It becomes clear that LCSA studies should be applied in the early stages of projects aiming to recover REEs. For this reason, WP4 was thoroughly analysed using a gate-to-gate sustainability assessment, which resulted in the definition of different processing routes for the various feedstocks.

Regarding the results, the LCA identified eutrophication and resource use as the most affected impact categories, with the non-selective EL scenario emerging, for now, as the most environmentally sustainable pathway. The LCC showed that costs are mainly dominated by labour, and in some cases by energy consumption, with the same scenario also proving to be the least expensive. The S-LCA indicates that the project is currently associated with a medium level of social risk, showing its strongest performance in the Worker category and its weakest in the Society category, largely influenced by the fact that public benefits are not yet fully formalised at this stage.

Although, at this preliminary laboratory-scale stage, the results indicate that primary mining still performs better in some sustainability criteria, this does not mean that the project cannot deliver valuable processes. NEO-CYCLE’s evaluation should also consider its strategic contribution to providing the EU with alternative access routes to Nd, Fe and B through secondary materials. Also considering the recommendations presented, D9.1 establishes an operational basis to guide optimisation efforts and data collection for scale-up. These results will feed into the consolidation and finalisation work of WP10, supporting the transition toward demonstration and scaling stages. In the long term, this will contribute to improved sustainability, transparency, and traceability across the value chain.

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